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Eclogitic amphibolites from the Grampian Moines

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ABSTRACT. Amphibolites from the Grampian Moines of Scotland contain clinopyroxene–plagioclase symplectites and plagioclase–hornblende coronas around garnet. The clinopyroxene–plagioclase symplectites are interpreted as former omphacites. It is inferred that an eclogitic garnet–omphacite–quartz assemblage once existed, but has since undergone partial reaction to an amphibolite facies hornblende–plagioclase assemblage. An early high-pressure metamorphic event occurred in parts of the Moine.

KEYWORDS: amphibolites, eclogites, symplectites, coronas, Moines, Grampian Mountains.

THE purpose of this paper is to describe an assemblage from the Moines which provides evidence for an early high-pressure metamorphic event. Recent work within the Grampian Moines (to the SE of the Great Glen Fault) has distinguished a relatively high-grade basement, metamorphosed at kyanite–sillimanite grade (Central Highland Division) from a cover, metamorphosed under lower amphibolite facies conditions (Grampian Division, see fig. 1). It has been suggested that the Central Highlands Division represents Grenvillian Basement while the Grampian Division was first metamorphosed during a postulated Morarian Orogenic Event at 750 Ma (Piasecki, 1980, cf. Powell *et al.*, 1983 and Roberts and Harris, 1983). Later Caledonian (Grampian) reworking also occurred (Piasecki, 1980; van Breemen and Piasecki, 1983). As the Moine is polyorogenic, the age of metamorphic assemblages within it is often open to speculation.

Winchester (1974) has mapped mineral zones, within the Moine, on the basis of the mineralogy of calcsilicates of given CaO/Al_2O_3 ratio. Much of the Moine lies within his clinopyroxene zone which he equates with the metapelitic sillimanite zone. However, this correlation is not rigorous according to Wells (1979, 1981) who estimated fairly high pressures for the area, well within the kyanite field. These estimates were themselves based on poorly constrained thermodynamic models however. Much of the area has certainly experienced sillimanite grade conditions at some stage (Ashworth, 1979; Piasecki, 1980). The conditions of the various metamorphic events in this area are obviously poorly known.

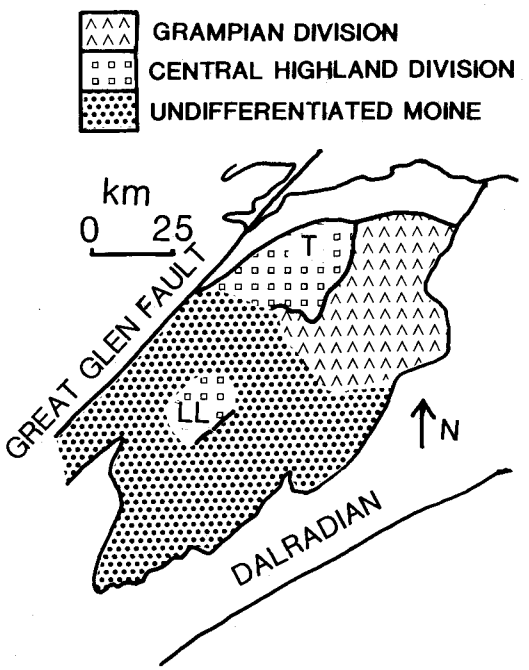

FIG. 1. Sketch map of the Scottish Highlands showing the location of the Tomatin (T) and Loch Laggan (LL) metabasites. After Piasecki (1980).

A garnet–clinopyroxene paragenesis in metabasites, reported in the early literature (Hinxman and Anderson, 1915) has been reinvestigated in this study. Garnet–clinopyroxene assemblages are preserved within a small metabasite body about 4 km south of Tomatin (National Grid Reference NH 792252, fig. 1). This body is infolded with migmatitic gneisses which contain fibrolitic sillimanite.

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Petrography. The metabasites contain the assemblage garnet-hornblende-plagioclase-clinopyroxene-quartz-ilmenite-sphene-apatite. Epidote, zoisite, biotite, and retrogressive blue green amphibole also occur occasionally. Textures are illustrated in fig. 2.

The clinopyroxene is always present as a symplectitic intergrowth with plagioclase. This intergrowth is absent from the majority of thin sections, but in some samples may account for up to 40% of the rock. Relatively large (up to about 2 mm) idiomorphic crystals of clinopyroxene are intergrown with and include smaller crystals of plagioclase. The two minerals are intergrown on the scale of about 50 μm. Symplectitic intergrowths of pyroxene and plagioclase are found in many eclogites and are known to have resulted from the unmixing of an omphacitic clinopyroxene (Wilkstrom, 1970; Mysen, 1972; Mysen and Griffin, 1973). These intergrowths are usually fine grained and vermicular (see fig. 6 of Mysen, 1972). Less often they are coarser and idiomorphic (see fig. 5 of Mysen, 1972; Griffin and Raheim, 1973). This type is most similar to those found in the Tomatin eclogitic amphibolite (compare fig. 2 with fig. 5 of Mysen, 1972). On account of these strong similarities, the symplectites found in this study are interpreted as unmixed omphacites.

The symplectitic intergrowths are replaced by variable amounts of hornblende which may grow as a reaction rim around symplectite and is always present between the symplectite and garnet corona. Small hornblendes also grow within the symplectite. The progressive replacement of symplectite by

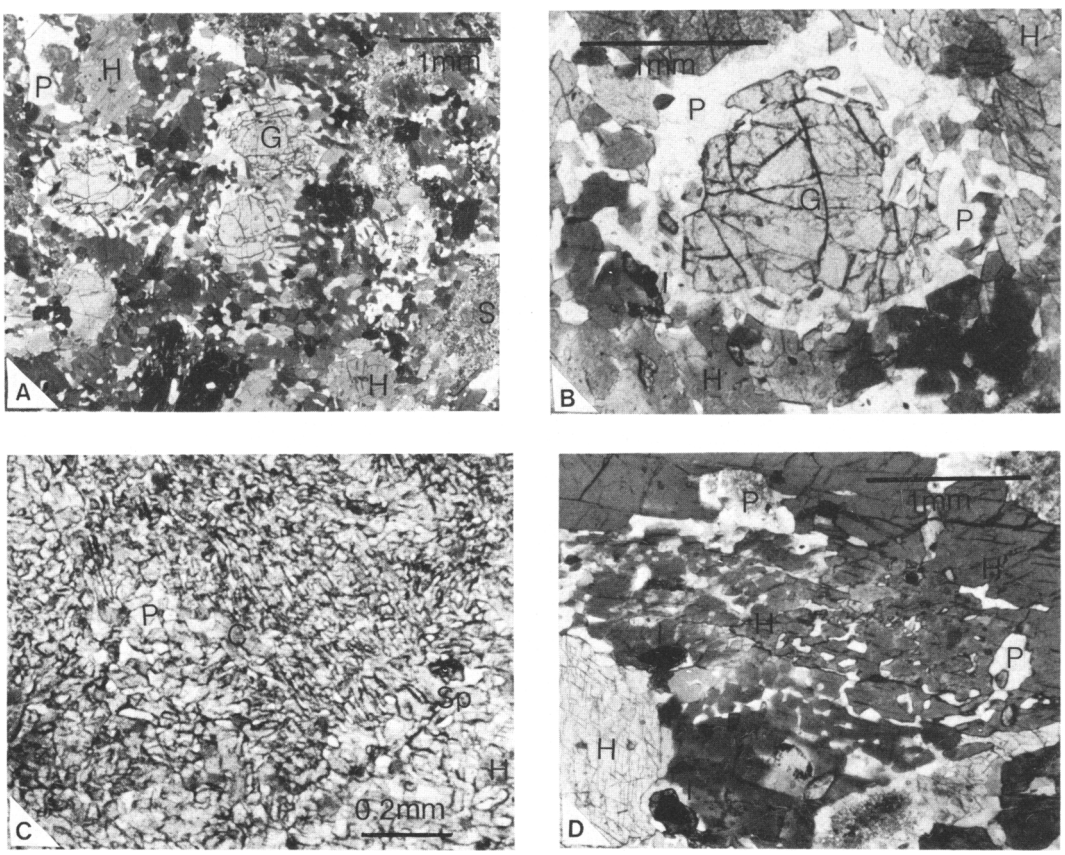

FIG. 2. Textures in the Tomatin eclogitic amphibolite. A Resorbed garnets separated by hornblende and plagioclase from remnant symplectite. B Partially resorbed garnet surrounded by plagioclase corona and large hornblendes. C Area of symplectite. D Hornblende resulting from replacement of symplectite with included droplets of plagioclase. [G—Garnet, H—Hornblende, P—Plagioclase, S—Symplectite, C—Clinopyroxene, Q—Quartz, Sp—Sphene, I—Ilmenite.]

hornblende leads to the disappearance of clinopyroxene. Relatively large (up to 1 mm long) hornblendes result, sieved by droplets of plagioclase. Later growth and recrystallization leads to larger (up to about 3 or 4 mm long) hornblendes which do not contain plagioclase inclusions. Minor amounts of plagioclase are present along grain boundaries.

Garnets are surrounded by coronas of plagioclase, often also with minor hornblende. Growth of the corona may lead to the total replacement of garnet by a spherical area of plagioclase. Frequently needles of hornblende within the corona are orientated radially to the garnet and are optically continuous with larger hornblendes outside the corona. Rims of hornblende generally separate the coronas from remnant symplectite.

Quartz occurs in most rocks, but generally not in the plagioclase coronas around garnet; however, it is nearly always present as inclusions within garnet. Reaction rims of hornblendes occur between quartz and garnet corona and between quartz and remnant symplectite. Ilmenite occurs close to garnet and in areas formerly occupied by garnet, while sphene occurs as inclusions within hornblendes and within symplectites. Ilmenite is commonly rimmed by sphene, particularly when not in the close vicinity of garnet. Biotite, epidote and blue-green amphibole are modally unimportant late phases occupying the centres of spherical areas of plagioclase and hornblende, which have completely replaced garnet. Zoisite occurs sometimes as inclusions within garnet.

The textures present, the diopside–plagioclase symplectites and garnets rimmed by plagioclase coronas, are typical of those occurring in many eclogites (e.g. Mysen and Griffin, 1973; DeWit and Strong, 1975; Droop, 1983). They are consistent with the operation of a multivariant eclogite → amphibolite reaction of the form:

$$\text{garnet} + \text{omphacite} + \text{quartz} + H_2O \rightarrow \text{hornblende} + \text{plagioclase}.$$

Chemical mineralogy. Representative mineral analyses are given in Table I. Garnets are zoned with decreasing grossular and spessartine com-

TABLE I. Microprobe analyses from the Tomatin eclogitic amphibolite

	Hornblende Analyses							
	Symplectite	Garnet Corona	Large amphibole	Clinopyroxene	Reintegrated Pyroxene (symplectite)	Plagioclase (symplectite)	Plagioclase (garnet corona)	Garnet
Wt%								
Na	1.05	1.86	1.67	0.38	2.38	6.96	4.64	0.04
Mg	12.79	8.99	10.21	12.83	8.31	0.02	0.02	2.19
Al	7.53	12.65	12.23	0.89	9.32	26.09	29.55	21.74
Si	47.32	41.59	44.20	52.15	55.92	58.29	53.17	38.17
K	0.16	0.43	0.33	0.06	0.10	0.16	0.17	0.06
Ca	11.96	11.73	12.06	23.82	17.52	7.85	12.23	14.18
Ti	0.62	1.18	1.06	0.08	0.07	-	0.02	0.13
Mn	0.16	0.20	0.18	0.11	0.13	0.01	0.01	2.92
Fe	14.03	16.41	15.37	8.65	6.76	0.35	0.19	21.55
TOTAL	95.62	95.04	97.31	98.97	100.51	99.73	100.00	100.98
Mole%				6(0)	6(0)	8(0)	8(0)	12(0)
Na	0.30	0.55	0.48	0.03	0.17	0.61	0.41	-
Mg	2.85	2.07	2.26	0.72	0.43	-	-	0.25
Al	1.33	2.30	2.15	0.04	0.38	1.38	1.58	2.00
Si	7.08	6.41	6.58	1.97	2.00	2.62	2.41	2.97
K	0.03	0.09	0.06	-	-	0.01	0.01	-
Ca	1.91	1.93	1.92	0.96	0.67	0.38	0.59	1.18
Ti	0.07	0.14	0.12	-	-	-	-	0.01
Mn	0.02	0.03	0.02	-	-	-	-	0.19
Fe	1.75	2.11	1.91	0.27	0.22	0.01	-	1.40
TOTAL	15.35	15.62	15.50	4.02	3.87	5.00	5.01	8.02

ponent from core to rim. Centre compositions are about $alm_{45}pyr_9gross_{38}spess_8$. Clinopyroxenes are typically $di_{70}hed_{28}jad_2$.

Defocused microprobe scans have been carried out (Table I) in an attempt to estimate the composition of original omphacite. ZAF corrections have been repeated in order to account for the fact that nearest neighbour interactions in a mineral of homogeneous composition are different from those in an aggregate of the same composition. It is impossible for an omphacitic clinopyroxene to unmix isochemically to diopsidic clinopyroxene and plagioclase unless at least one of the phases is non-stoichiometric. Mysen and Griffin (1973) suggested that the stoichiometry of the phases was preserved through oxidation of iron in the omphacite during unmixing. There is no suggestion of the presence of ferric iron in the analyses of symplectitic clinopyroxene presented here. In a study of a number of symplectites Wilkstrom (1970) found that it was essentially sodium that was lost during unmixing. The reintegrated analysis here does not contain sufficient cations for a pyroxene. If sodium was the only cation lost during unmixing, an original jadeite content of about 35% would be suggested.

Plagioclase compositions are very variable. Those within garnet coronas have compositions from an_{50} to an_{60}, while those within symplectites average about an_{40}. Recrystallized plagioclases outside garnet coronas vary between an_{30} and an_{40}. Hornblendes within garnet coronas have low M/FM ($\sim$ 45) and high Mn and Al contents. Those within symplectites have high M/FM ($\sim$ 65) and low Mn and Al contents. Larger hornblendes, resulting from growth and recrystallization of symplectite hornblendes, usually have intermediate but variable M/FM ($\sim$ 50). These large hornblendes are zoned in decreasing Na and tetrahedral Al.

The compositional variations in the product phases, plagioclase and hornblende, indicate the presence of chemical potential gradients on the scale of about 1 mm in the rock during amphibolitization. These gradients show that grain boundary diffusion was relatively slow compared to other steps in the reaction.

Reaction model. The relative movements of different components and the reactions occurring during amphibolitization may be considered. The reactions derived will depend upon the reference frame adopted (Gresens 1967), commonly selected as one of constant Al or Si. Reactions occurring around garnet and during replacement of the symplectitic intergrowth have been estimated assuming Al immobility. Each reaction results in a volume increase of approximately 10%:

(i) production of plagioclase corona around garnet

$$\underset{\text{GARNET}}{Fe_{1.36}Mg_{0.28}Mn_{0.17}Ca_{1.19}Al_2Si_3O_{12}} + 0.16SiO_2 + 0.29Na_2O \rightarrow \underset{\text{PLAGIOCLASE}}{1.29Ca_{0.55}Na_{0.45}Al_{1.55}Si_{2.45}O_8} + 1.36FeO + 0.28MgO + 0.17MnO + 0.48CaO;$$

(ii) for the replacement of symplectitic intergrowth by amphibole

$$\underset{\text{INTEGRATED SYMPLECTITE ANALYSIS}}{3.55Ca_{0.67}Na_{0.17}Al_{0.38}Mg_{0.43}Fe_{0.22}Si_{2.00}O_6} + 1.3MgO + 0.90FeO + 0.07TiO_2 + 0.02MnO + H_2O \rightarrow Na_{0.30}K_{0.05}Ca_{1.96}Mg_{2.83}Mn_{0.02}Fe_{1.68}Ti_{0.07}Al_{1.35}Si_{7.09}O_{22}(OH)_2 + 0.15Na_2O + 0.43CaO.$$

SYMPLECTITE HORNBLENDE

Reaction of eclogite to amphibolite is achieved by coupled reactions occurring at two sites; garnet coronas and in symplectites. Various components diffused between these sites are illustrated in fig. 3. The consumption of quartz during the corona forming reaction is in agreement with petrographic observations; hornblende reaction rims between quartz and corona and the absence of quartz from garnet coronas. Consumption of quartz during these reactions indicates that the eclogitic assemblage garnet–omphacite–quartz was once present, a conclusion supported by the quartz inclusions in garnet.

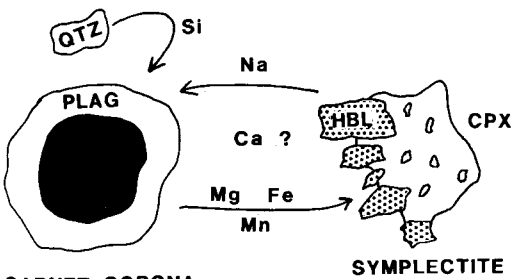

FIG. 3. Suggested reaction scheme based on the assumption of aluminium immobility.

The eclogitic assemblage is clearly not cofacial with sillimanite-bearing assemblages in surrounding migmatitic gneisses. This may be explained by the preferential preservation of eclogitic assemblages in metabasites. Metabasic eclogite facies rocks require water for amphibolitization while a metapelite produces water along the same P–T path. Reaction in the metabasites is inhibited by the

slow diffusion of water to the sites of reaction and slow diffusion of other components as a result of the lack of water (Heinrich, 1983).

The following sequence of events is inferred. On uplift after the initial eclogite-forming event, diopside-plagioclase symplectites were produced from original omphacite. A later influx of water resulted in reactions leading to the growth of hornblende and the formation of plagioclase coronas around garnet. As water was consumed and the sites of reaction became increasingly separated by reaction products, reaction was inhibited. These reactions are likely to reflect a decrease in pressure.

Extent of eclogitic paragenesis. Another garnet amphibolite, collected by J. Clayburn from near Laggan Bridge (National Grid Reference NN 579927), shows remarkable textural similarities to the rocks described above, although it contains no clinopyroxene. It contains the assemblage garnet–hornblende–plagioclase–ilmenite–sphene–quartz. Garnets are surrounded by plagioclase–hornblende coronas without quartz and are sometimes totally resorbed. Quartz is abundant, but is always separated from garnet coronas by a reaction rim of hornblende. Hornblende contains 'droplets' of plagioclase and sphenes, similar to the texture of hornblende replacing symplectite in the Tomatin eclogitic amphibolite. It is suggested that this rock also once contained the assemblage garnet–omphacite–quartz.

Garnets rimmed by plagioclase coronas are also described by Piasecki (1980) and may be similar to the above. These occur in metabasites within the slide zone separating the Central Highland Division from the Grampian Division. Eclogitic assemblages were probably widespread at some stage, but are now only rarely preserved.

Age. Grenvillian, Morarian, and Grampian orogenic events are postulated for the Grampian Moines (Piasecki, 1980; see also Powell *et al.*, 1983, Roberts and Harris, 1983). Unfortunately evidence is not available to indicate to which of these orogenic events the eclogite facies assemblages belong. The eclogitic assemblage and surrounding non-cofacial sillimanite gneisses may represent different portions of a P–T path, in which tectonic thickening was followed by thermal relaxation, during only one orogenic event, or they may preserve the effects of different orogenic episodes. The amphibolite garnets, now surrounded by plagioclase coronas, described by Piasecki (1980) are, however, believed by him to have grown during a Morarian event.

Conclusions. Garnet amphibolites from the Grampian Moines contain symplectitic intergrowths of clinopyroxene and plagioclase, interpreted as unmixed omphacites. A former, possibly extensive, paragenesis of garnet–omphacite–quartz existed within the area, indicative of an early high-pressure metamorphic event.

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REFERENCES

Ashworth, J. (1979) In *The Caledonides of the British Isles—reviewed* (A. L. Harris, C. H. Holland and B. E. Leake, eds.). Spec. Publ. geol. Soc. London **8,** 357–62.
De Wit, M. J., and Strong, D. F. (1975) *J. Geology,* **83,** 609–27.
Droop, G. T. R. (1983) *J. metamorphic Geol.* **1,** 3–12.
Gresens, R. (1967) *Chem. Geol.* **2,** 47–65.
Griffin, W. L., and Raheim, A. (1973) *Lithos,* **6,** 21–40.
Heinrich, C. A. (1983) *Contrib. Mineral. Petrol.* **81,** 30–8.
Hinxman, L. W., and Anderson, E. M. (1915) *The Geology of mid Strathspey and Strathdearn.* Mem. Geol. Surv. Scotland.
Mysen, B. O. (1972) *Contrib. Mineral. Petrol.* **34,** 315–25.
——and Griffin, W. L. (1973) *Am. Mineral.* **58,** 60–3.
Piasecki, M. A. J. (1980) *J. geol. Soc. London,* **137,** 412–59.
Powell, D., Brooke, M., and Baird, A. W. (1983) Ibid. **140,** 813–23.
Roberts, A. M., and Harris, A. L. (1983) Ibid. **140,** 88–92.
van Breemen, O., and Piasecki, M. A. J. (1983) Ibid. **140,** 47–62.
Wells, P. R. A. (1979) Ibid. **136,** 663–71.
——(1981) Ibid. **138,** 206–9.
Wilkstrom, A. (1970) *Norsk. Geol. Tiddskr.* **50,** 137–55.
Winchester, J. A. (1974) *J. geol. Soc. London,* **136,** 663–71.

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