Coronite and eclogite formation in olivine gabbro (Western Norway): reaction paths and garnet zoning

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ABSTRACT. Gabbros and dolerites in the Western Gneiss Region of Norway have been subjected to a high P-T regime and preserve evidence of the existence of several stages in the consequent reaction sequence. Incomplete reaction stages are characterized by corona structures between relict igneous phases and by frequent pseudomorphs after igneous olivine, plagioclase and augite. The increasing degree of reaction is recorded by successive increases of modal garnet, omphacite and phlogopite ($\pm$ orthopyroxene) to produce eclogite, often with excellent pseudomorphic preservation of the igneous fabric.

Pseudomorphic replacement of olivine by orthopyroxene (in coronas and aggregates) and of plagioclase by local assemblages of garnet, spinel, and sodic plagioclase, is interpreted as a transient reaction stage with restricted and selective diffusion between the original mafic and felsic domains. Complete eclogitization is compatible with more extensive diffusion, especially of Na and Al (on a mm scale) leading to omphacite production by replacement of olivine, augite, and orthopyroxene. Concomitant reactions in the felsic domains lead to total replacement of the transient phases by garnet, with or without inclusions of minute omphacite grains.

Strong Ca zoning of garnet in the coronites is interpreted as a relict growth zoning, attributed to local controls by diffusion and subreactions in the plagioclase host and to local garnet + plagioclase + spinel equilibria. In contrast, complete eclogitization is associated with diffusional homogenization of garnet by $(Mg,Fe)Ca_{-1}$ and $MgFe_{-1}$ exchange with omphacite $\pm$ phlogopite.

KEYWORDS: coronites, eclogites, garnet zoning, gabbro, Norway.

MEDIUM to coarse grained gabbros and dolerites in the Western Gneiss Region (WGR) of Norway are characterized by variable persistence of relict igneous phases, corona structures and frequent pseudomorphism (Gjelsvik, 1952; Griffin and Heier, 1973; Griffin and Råheim, 1973; Tørudbakken, 1982; Mørk, 1985a, b). Total transformation to eclogite, indistinguishable from adjacent country rock eclogites, has been attained in local

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zones which are distributed both within the meta-igneous bodies (Mørk, 1985a) and, more frequently, in marginal parts of the bodies (Griffin and Råheim, 1973; Tørudbakken, 1982). Some earlier workers have interpreted the corona and eclogite formation as the result of a single step cooling process from igneous temperatures, and considered that the dolerites intruded at a late stage in the orogenic history (Griffin and Heier, 1973; Griffin and Råheim, 1973). Radiometric dating of gabbro protoliths (Tørudbakken, 1982; Mearns, 1984) and of the eclogite minerals (Griffin and Brueckner, 1980; Mearns, 1984) suggests, however, a more complex history, involving Precambrian gabbro intrusions and Caledonian eclogite formation, rather than one-stage cooling.

A time sequence between corona formation and eclogite metamorphism is most successfully established in the Bergen Arcs, south of the WGR, where Precambrian granulite-facies coronites have been locally transformed to eclogite in Caledonian shear zones (Austrheim and Griffin, 1985). In contrast, the much better preservation of relict igneous phases in gabbros and dolerites in the northern part of the WGR may suggest a different intrusion and metamorphic history in these areas. The possibility of a two-stage model for coronite and eclogite formation should, however, be examined for the entire area.

This paper deals with a relatively iron-rich olivine gabbro from Flemsøy (northern part of WGR) which has preserved a series of reaction stages from corona gabbro to equilibrated eclogite. In an earlier paper (Mørk, 1985a) this transition was correlated with the regional metamorphism and the formation of the adjacent country-rock eclogites at metamorphic conditions reaching $T > 700$ °C and P 15-20 kbar. The transformations occurred syntectonically, but reactions have occurred both within high-strain zones and in more static low-strain conditions. The estimated metamorphic conditions, combined with recent radiometric

dating of samples with different amounts of reaction to eclogites (Mørk and Mearns, 1986), suggest that in this case also, the igneous intrusion and the eclogite-forming metamorphism belong to two different geological events, Precambrian and Caledonian.

This occurrence is remarkable for the existence of several transitional reaction stages retaining the original fabric, together with completely recrystallized eclogites with similar bulk-rock compositions. This allows the study of the effects of the regional high P–T metamorphism on relatively dry rock systems where the influence of the original mineralogy is observable, with implications for detailed reaction paths and reaction mechanisms. The great variation in the degree of high-P–T reaction over even short distances (10 cm scale) within this body suggests extensive metastability and local kinetic controls on the eclogite transition, although the reactions occurred during prograde metamorphism, under relatively high-P–T conditions.

The present paper attempts to summarize (1) the spatial control on the development of reactions in these rocks with particular attention to early and transitional reaction stages, and (2) relations between the degree of reaction and the textural and compositional variation in the minerals. The observations have implications for the interpretation of mineral zoning and formation of mineral inclusions in eclogites derived from medium to coarse grained gabbroic rocks.

The field distribution of the variably eclogitized rocks is given elsewhere (Mørk, 1985a; fig. 1); the rocks described here are all from the same 200×100 m² gabbro body, an intrusion situated within migmatitic gneisses.

Modal and textural variations

Table I summarizes the total modal variations recorded in rocks showing varying degrees of transition to eclogite. Note the distribution of the relict igneous phases plagioclase (Pl_0), augite (Cpx_0), and olivine (Ol_0), and the metamorphic reaction products orthopyroxene (Opx), spinel (Spl), garnet (Gnt), omphacite (Omp), and amphibole (Amp). Ilmenite (Ilm) and phlogopite (Phl) occur in both the igneous and metamorphic assemblages.

Corona minerals (Opx, Gnt) have been interpreted as metamorphic reaction products and may represent early stages of the transformation history (Mørk, 1985a). A possible alternative interpretation of the coronas will also be presented in the final section.

The transition from coronite GE15 to eclogite GE4a involves a gradual stepwise increase in garnet, omphacite, phlogopite, orthopyroxene at the expense of igneous plagioclase, olivine, and augite (Table I). However, even in the rock with smallest degree of reaction (coronite GE15, Table I, fig. 1a, b, e), metamorphic phases constitute more than 40% of the mode.

The original igneous fabric defined by cumulus olivine and plagioclase and intercumulus (subophitic) clinopyroxene is preserved by pseudomorphic replacements in all the stages of reaction. Eclogite GE4a (Gnt + Omp + Phl + Ilm + Amp) is closest to metamorphic equilibrium with recrystallization within both the garnet and omphacite domains (fig. 1d), but garnet domains may still mimic the original plagioclase.

The textural and mineralogical development within each pseudomorphic igneous domain (olivine, clinopyroxene, and plagioclase) is summarized below, and can be related to the total amount of reaction (GE15 to GE4a; Table I).

1. Olivine breakdown proceeds by inward growth from simple orthopyroxene coronas around olivine in the coronites (GE15; fig. 1e) to replacement by successive multiple corona layers or complete pseudomorphism by fine-grained orthopyroxene aggregates in the transitional rocks

Table I. Modal analyses; increase of eclogitization from GE15 to GE4a

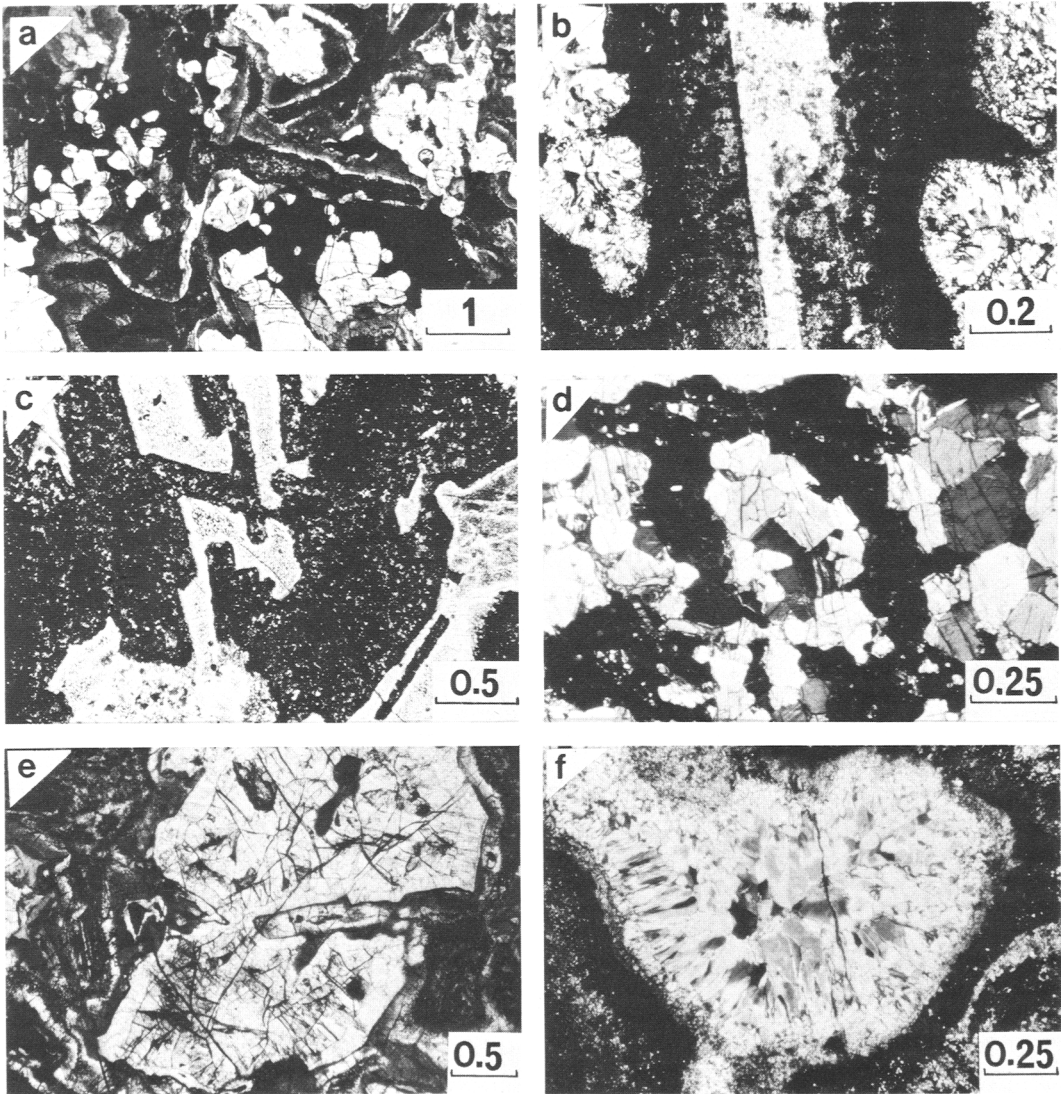|		$\dfrac{\text{\% Gnt}}{\text{Gnt+Pl}}$	Pl_0	Cpx_0	Ol_0	Ilm	Phl	Opx	Spl	Gnt	Omp	Amp	Other
Flemsøy	GE15	67.1	15.4	14.7	17.0	3.2	5.6	10.9	*	31.4	*	1.6	0.2
	GE4c	87.2	5.1	15.3	11.1	1.7	6.9	16.5	*	34.6	*	8.8	*
	GE14	91.9	3.5	4.6	8.4	.7	11.6	18.5	2.0	39.8	11.0	*	–
	GE12	100	–	–	2.3	4.1	12.0	–	–	38.2	43.4	*	–
	GE7	100	–	–	–	1.2	12.7	–	–	43.0	43.1	–	–
	GE4a	100	–	–	–	2.5	11.9	*	–	41.5	38.3	3.3	0.4
Grøtshornet	GR1	6.6	47.9	13.7	14.3	1.4	3.6	5.7	–	3.4	5.1	4.9	–

* present in small amounts.

FIG. 1. Scale bar in millimetres. (a) Coronite GE15. Cumulus olivine with thin orthopyroxene coronas (white), surrounded by subophitic clinopyroxene (black). Plagioclase laths are clouded by spinel and garnet inclusions (central parts) surrounded by a more homogeneous garnet corona. (b) Coronite GE15; (crossed polars). Close up of relict igneous plagioclase. The black rim is garnet corona, while black small grains are inclusions of garnet and spinel. Note the homogeneous, better preserved central part of plagioclase. (c) Transitional rock GE12; (crossed polars). Garnet pseudomorphing igneous plagioclase laths (black). Note omphacite as minute inclusions in garnet and as a 'pseudomorphic' replacement of the original interstitial augite. (d) Eclogite GE4a; (crossed polars). Recrystallized idioblastic fabric of garnet (black) and omphacite (grey). Note that garnet may still mimic the original plagioclase domains. (e) Coronite GE11 (similar to GE15). Cumulus olivine with corona of orthopyroxene surrounded by garnet corona replacing plagioclase. (f) Transitional rock GE4c; (crossed polars). Aggregate of orthopyroxene forming a pseudomorph after olivine. Omphacite occurs in the fine-grained outer rim.

(GE14; fig. 1*f*). Fine-grained omphacite is often present in the outer rim of such aggregates, and increases in abundance relative to orthopyroxene from reaction stage 1 to stage 2 (fig. 1*f*). In advanced transitional rocks (GE12) and eclogites (GE7), the original olivine domain is completely pseudomorphed by polygonal omphacite aggregates.

2. The original intercumulus augite domains are preserved up to the advanced transitional stage (GE12; fig. 1*c*, 2*a*). Reactions within the augite domains involve exsolution of opaque phases and chemically continuous transformation to omphacite within the original grain. Recrystallization to polygonal omphacite aggregates has started at the advanced stage 2 (GE12; fig. 2*a*) and is complete in the eclogites (figs. 1*d*, 2*b*).

3. Pseudomorphs after plagioclase show a successive development from stage 1 coronites to stage 2 transitional rocks. In stage 1, garnet is most commonly restricted to coronas in outer parts of

the pseudomorphs, and coexists with sodic plagioclase containing spinel needles in the central parts of the pseudomorph. The garnet–plagioclase relations are shown for GE15 (fig. 1*b*). The homogeneous garnet corona in the outer part of the pseudomorph is in contact with an 'outer' aggregate of pyroxene that has replaced olivine. The 'inner' contact between garnet corona and the relict plagioclase is irregular (fig. 2*c*). Garnet has also formed as small clots and euhedral crystals in a thin zone within plagioclase near the garnet corona (figs. 2*c*, 3*a*). This zone has a dark appearance due to its content of fine-grained, nearly unresolvable inclusions of garnet, spinel needles and a K-mica. The central part of this pseudomorph is more homogeneous with dispersed minute spinel needles in a matrix of intermediate plagioclase (An_{32-40}; fig. 3*a*).

The transition to stage 2 (GE14) involves gradual extension of the outer garnet layer at the expense of
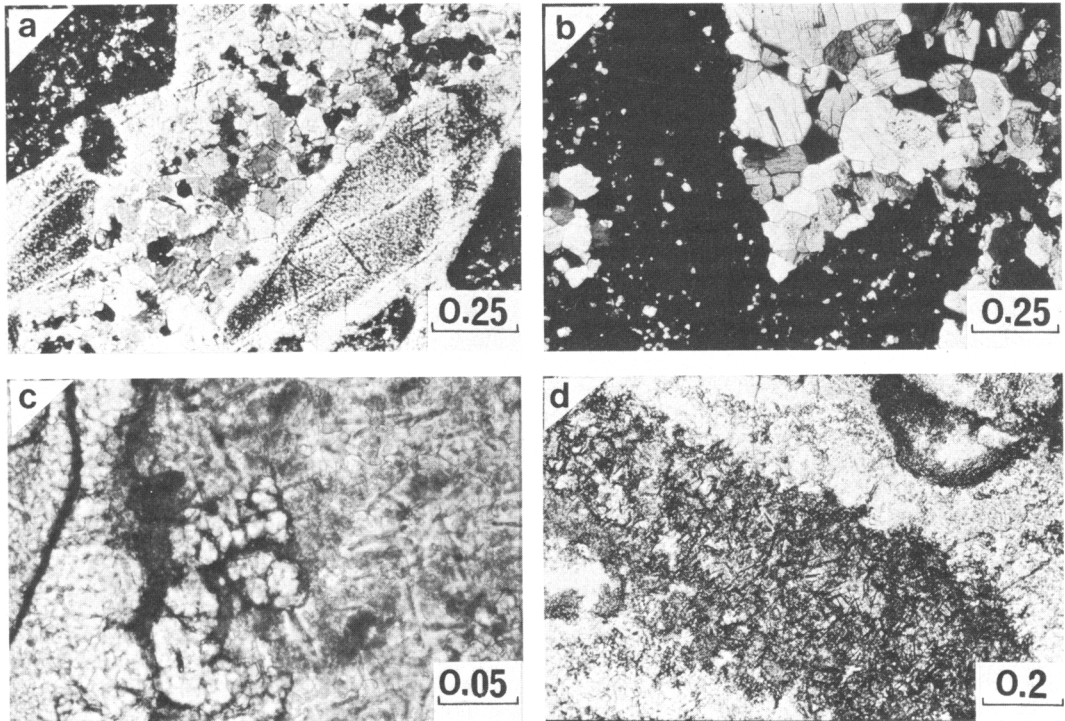

FIG. 2. (*a*) Transitional rock GE12; (crossed polars). Breakdown of relict ophitic clinopyroxene; now omphacite. Note exsolution of fine-grained opaque grains, and the localized formation of omphacite subgrains. (*b*) Eclogite GE7; (crossed polars). The igneous intercumulus domain is replaced by a polygonal aggregate of omphacite, while cumulus plagioclase is replaced by garnet. Note minute omphacite inclusions in garnet. (*c*) Coronite GE15; close up of garnet corona (left) with irregular contact to plagioclase (right) containing needles of spinel. Note garnet occurrence also as clots (and small euhedra which are not visible here) within plagioclase. (*d*) Transitional rock GE14. Advanced garnet corona with spinel needles and relict igneous plagioclase only preserved in a restricted central part of the pseudomorph.

plagioclase, and is also recorded as a modal increase in the Gnt/(Gnt + Pl) ratio (Table I). Spinel inclusions increase in size up to 0.1 mm, while plagioclase becomes more sodic (Table II). The end product of this transition is the complete pseudomorphism of plagioclase by garnet with or without minute inclusions of omphacite (figs. 1d, 2b). Commonly, garnet pseudomorphs after plagioclase are most homogeneous in a thin outer inclusion-free rim, observed in both stage 2 and stage 3 rocks (fig. 1c, f; stage 2).

Chemical variation of clinopyroxene and garnet

Texturally, clinopyroxene may be divided into two different types: Cpx_0, preserving the igneous intercumulus crystal fabric, and Cpx_1, neoblasts and recrystallized aggregates. Mean values of Cpx_0 and Cpx_1 analyses are compared for rocks with different degrees of reaction (Table II). The acmite content (Ac), calculated on the basis of charge balance (Mørk, 1985a), is high both in Cpx_0 and Cpx_1, independent of the amount of eclogite transformation. In contrast, the jadeite component (Jd) of the Cpx_0 relicts increases steadily with the degree of reaction, substituting for tschermacks (Ts) and diopside (Di) components, while Cpx_1 is omphacitic throughout the rock series.

Table II. Clinopyroxene variation expressed by Ac and Jd; mean values, compared with modal variations of clinopyroxene and with plagioclase composition.

Samp. loc.	"Cpx_0"	"Cpx_1"	Modal % Cpx total	Pl % An
GE15	Jd_0Ac_{14}	n.a.	14.7	24-40
GE4c	$Jd_{10}Ac_9$	$Jd_{25}Ac_{10}$	15.3	n.a.
GE14	$Jd_{16}Ac_{10}$	$Jd_{29}Ac_9$	15.6	13-22
GE12	$Jd_{27}Ac_5$	$Jd_{27}Ac_{11}$	43.4	n.p.
GE7	n.p.	$Jd_{33}Ac_{10}$	43.1	n.p.
GE4a	n.p.	$Jd_{24}Ac_{14}$	38.3	n.p.

n.a. = not analysed, n.p. = not present

The intergrain chemical variation for clinopyroxene is most significant for Cpx_0, which may range from sodic augite to omphacite within transitional rocks (Mørk, 1985a, fig. 7). The total effect is both an increase in modal clinopyroxene and in Jd content with increase of reaction. The increase of omphacite at the expense of olivine and orthopyroxene implies that both Na and Al must have been transported to these sites, and accompanied by complete consumption of plagioclase.

Garnet compositions represented by mean values of EMP analyses from each rock show a regular decrease of grossular content and a slight increase in the ratio Mg/(Mg + Fe) with increasing degree of reaction (Table III). The relatively high Mg/(Mg + Fe) values for garnet in GE14 and GE12 are partly the result of more Mg-rich bulk compositions.

Table III Garnet compositions; mean values, compared with modal abundance of garnet.

Samp.loc.	Pyr	Alm	Gross	Spess	Mg/(Mg+Fe)	Mode
GE15	28.7	43.6	26.5	1.2	.40	31.4
GE4c	35.0	46.8	16.9	1.3	.43	34.6
GE14	37.6	39.3	14.9	.8	.49	39.8
GE12	39.5	42.2	17.7	.6	.48	38.2
GE7	45.5	43.6	10.1	.8	.51	43.0
GE4a	42.6	48.2	8.4	.8	.47	41.5

Garnets are most heterogeneous in the coronites and transitional rocks with distinct Ca-zoning across corona layers, while garnets in the extensively reacted rocks are poorer in Ca and more homogeneous. The zoning is examined in more detail for coronite GE15 and transitional eclogite GE12.

Coronite. A section across a 2.5 mm broad pseudomorph after igneous plagioclase, where garnet forms an outer 0.1–0.15 mm thick corona on each side of the pseudomorph, is shown in fig. 3a. The garnet shows a consistent increase of Ca at the expense of both Fe and Mg across the corona towards the plagioclase contact. The Ca-gradient is strongest in the zone adjacent to plagioclase. The Mg/Fe ratio is fairly constant in the outer part of the corona adjacent to pyroxene, but shows a significant decrease towards plagioclase in the zone with strong Ca variation.

Transitional eclogite. A profile across a c. 1.5 mm broad garnet domain, entirely pseudomorphing plagioclase, is shown in fig. 3b. This garnet domain is fairly homogeneous, but shows a slight decrease in Ca in the outer parts.

Core and rim compositions for other garnet and garnet domains in completely eclogitized samples suggest a similar Ca zoning.

Total reactions

Since the rocks have fairly similar bulk chemical compositions (Mørk, 1985a), the modal variations (Table I) can be related to the degree of reaction. A set of reactions in the subsystems Mg(Fe)–Ca–Al–Si and Mg(Fe)–Na–Al–Si, with Fe–Mg solid
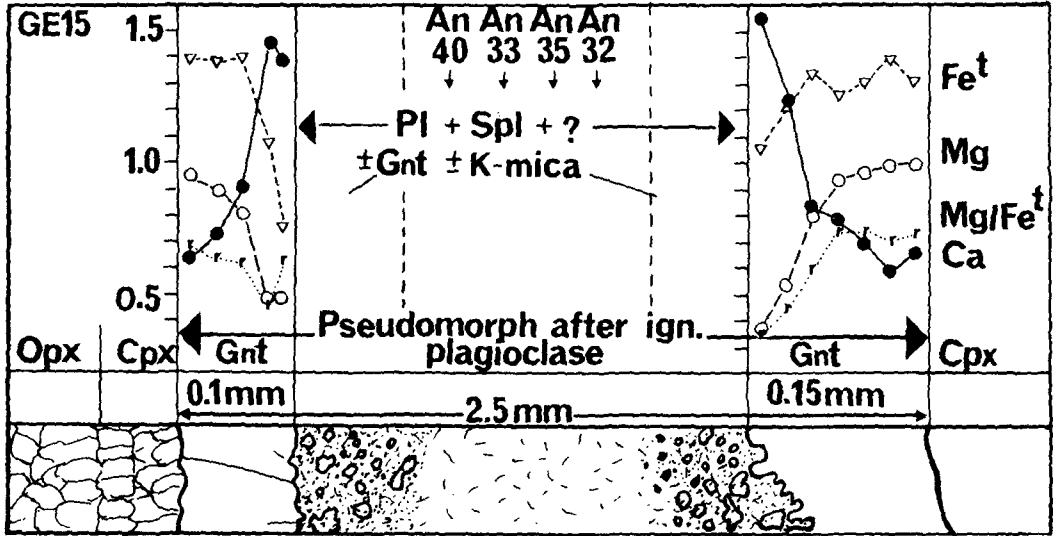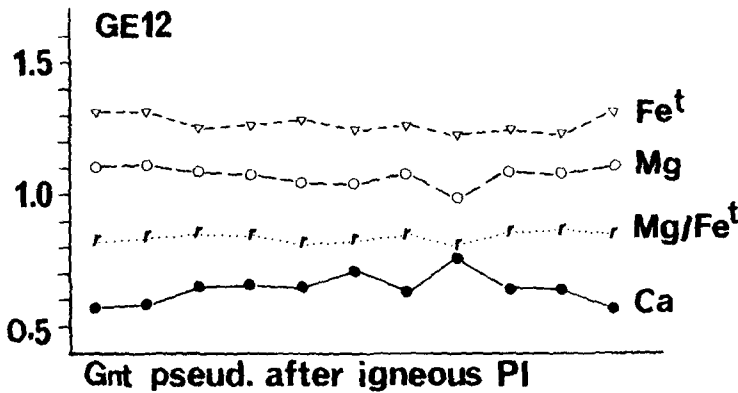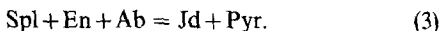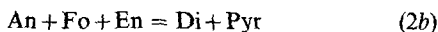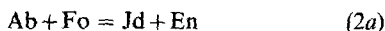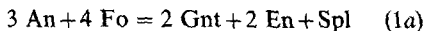
FIG. 3. (a) Coronite GE15. Chemical zoning of garnet occurring as corona in the outer part of a pseudomorph after igneous plagioclase (see fig. 2 (c) expressed by cations per 12 oxygens. Ca increases towards central parts of the pseudomorph on both sides. The central part consists of sodic plagioclase with frequent inclusions of spinel. (b) Transitional rock GE12. Chemical zoning across garnet which has entirely replaced igneous plagioclase. The rims on both sides are in contact with omphacite.

solutions expressed in terms of Mg-end members for simplicity, can account for the modal variations and the total changes of mineral compositions:

$$3\,An + 4\,Fo = 2\,Gnt + 2\,En + Spl \quad (1a)$$

$$Ab + Fo = Jd + En \quad (2a)$$

$$An + Fo + En = Di + Pyr \quad (2b)$$

$$Spl + En + Ab = Jd + Pyr. \quad (3)$$

In addition, the increase of modal phlogopite suggests reactions in a more complex system including the igneous Ti-rich phlogopite, ilmenite,

and the orthoclase component of both plagioclase and a fluid phase.

Reaction (1a) corresponds to the formation of Ca-rich garnet $(Ca_{1.5}Mg_{1.5}Al_2Si_3O_{12})$ and spinel $(MgAl_2O_4)$ by preferential replacement of plagioclase, and of orthopyroxene by replacement of olivine. It is a probable reaction for the advanced corona stage. The observed increase in the Na content of plagioclase relative to normative An-contents can be related to preferential breakdown of the An component to form garnet. However, to explain the observed Gnt:Spl:Opx modal ratios and the Ca-poor parts of the zoned garnets

in coronite GE15, additional subreactions are required. Possible candidates are (1b) An + Fo = Gnt, where Gnt = $CaMg_2Al_2Si_3O_{12}$, and reaction (2a).

Reactions (2a) and (2b) are possible subreactions needed to produce transitional rocks from stage 1 coronites. (2a) corresponds to the observed increase of modal orthopyroxene at the expense of olivine and the continuous increase of Jd in relict igneous clinopyroxene. (2a) and (2b) can be combined in a composite reaction

$$2 Pl + 2 Fo = 2 Omp + Pyr \qquad (2c)$$

which accounts for both the formation of omphacite neoblasts, the modal increase of garnet and the decrease of Ca relative to Fe + Mg in garnet, proportionally to the degree of reaction. The total reaction (2c) excludes orthopyroxene. This is produced as a transient phase by (2a), as evidenced by its modal increase in transitional rocks, while it is consumed in omphacite-forming reactions (2b) in the more advanced reaction stages.

The total eclogitization would require a combination of reactions (2a, b) and (3) for garnet and omphacite production at the expense of both relict igneous phases and transient orthopyroxene and spinel; this requires exchange between different subsystems.

In order to interpret the different reaction stages both P and T changes and spatial variables must be considered. Petrological modelling would also require knowledge of the time sequence of the different reactions and reaction stages. If the coronites are interpreted as representative of the initial reaction stages in the metamorphic development, both the total and the stepwise change in mineralogy, mineral chemistry and mineral homogenization from coronite GE15 to eclogite GE4a would be compatible with a prograde eclogite-forming metamorphism. A P increase relative to the igneous protolith assemblage has been proposed on the basis of thermobarometry (Mørk, 1985a) from equilibrated eclogites in the body. The problem is therefore reduced to the interpretation of the coronites and the incomplete reaction stages.

Element mobility and reaction mechanisms

The rocks with incomplete reactions are characterized by (1) pseudomorphism, (2) corona structures, (3) inclusions of phases in one another, (4) a large number of solid phases, and (5) zoning of product garnet. These factors all suggest chemical disequilibrium down to the mm scale and imply that diffusion between the original igneous domains has been incomplete during the reaction. Such features are often associated with retrograde transformations; corona formation is in many cases related to deuteric or metamorphic hydration reactions (Esbensen, 1978; Austrheim and Robins, 1981; Emmett, 1982). Under dry conditions (low element mobility) they would also be expected to form during prograde metamorphism. Factors that would increase the element mobility and thereby enhance reaction include deformation and an increase in fluid content (see summary by Brodie and Rutter, 1985). The catalytic effect of an intergranular fluid has been pointed out in many corona studies as a necessity for dissolution and reaction (Ahrens and Shubert, 1975; van Lamoen, 1979; Brady, 1983; Mongkoltip and Ashworth, 1983; Nishiyama, 1983). In the Flemsøy gabbro, complete reaction has occurred in high-strain areas where a foliated eclogite fabric has developed, but locally also in low-strain areas without destruction of the relict igneous fabric. The presence of a fluid phase is indicated by the increase of Cl-bearing phlogopite and of oxidation with increasing degree of reaction (Mørk, 1985a, and Table I).

Pseudomorphic replacements and corona structures are apparently closely associated during the metamorphic reaction, representing different spatial regimes in terms of reaction sites and type of diffusion. The growth of coronas may lead to a change in reaction kinetics by isolating the reactant minerals from the intergranular fluid as shown experimentally by Brady (1983); volume diffusion across a massive corona is likely to be several orders of magnitude slower than intergranular diffusion through the rock matrix, for the specific textures described here. At low degrees of strain and low fluid contents the result is that the whole rock system is split into different chemical subsystems, isolated by low volume diffusion across the corona or with only selective diffusion between the different domains (cf. Mørk, 1985b). The corona structures are favoured at grain contacts between olivine and plagioclase, leading to a reduction of the strong compositional gradients for Fe and Mg by growth of orthopyroxene and garnet coronas. In the case of plagioclase, Al and Si are often considered as the slowest-diffusing species (McConnell, 1975; Dowty, 1980; Mongkoltip and Ashworth, 1983). Accordingly, different types of Al-rich phases are produced in subreactions within the plagioclase host in coronitic rocks, e.g. kyanite, spinel, and corundum (Mørk, 1985b), kyanite (Austrheim and Robins, 1981), and spinel (McLelland and Whitney, 1980). Some of these have also been observed elsewhere as symplectitic intergrowths in the corona phases (Esbensen, 1978; Mongkoltip and Ashworth, 1983).

Here, the incomplete reaction stages are characterized by low mobility of Na, Al, and Ca on a scale

of less than 0.1 to 10 mm, i.e. retention within pseudomorphs after plagioclase, while selective diffusion of Fe and Mg into relict plagioclase domains must have occurred for the garnet and spinel to form.

The low availability of alumina for the olivine breakdown reactions is supported by studies of chemical zoning across an orthopyroxene aggregate (fig. 1*f*) that has replaced olivine. Central parts of the aggregate are nearly alumina-free, while the outer grains adjacent to garnet show an increase up to 1.25 wt. % (Mørk 1985*a*, fig. 6). An alternative interpretation, that the Al variation is related to temperature decrease during the orthopyroxene growth (cf. Wood, 1974; Obata, 1976) is not supported by the increasing grain-size of successive orthopyroxene layers (cf. McConnell, 1975, assuming that the growth was controlled by diffusion).

In contrast, complete eclogitization requires extensive redistribution of Na, Al, and Ca out of the plagioclase domains to form omphacite at olivine, ortho- and clinopyroxene sites, and implies mobility of these elements over distances greater than 0.1 to 10 mm. The greater element mobility associated with complete reaction is also reflected by the homogenization of the garnets and by the presence of fewer phases than are found in the coronites. The shielding effect of the garnet coronas, combined with low diffusion rate of Al in plagioclase, the low deformability of plagioclase under dry conditions (Brodie and Rutter, 1985) and the stabilization of sodic plagioclase in the isolated felsic subsystem (cf. Gasparic and Lindsley, 1980) would all retard complete eclogitization. Furthermore, the isolated olivine + orthopyroxene and garnet + plagioclase subsystems are stable to higher pressures than the original olivine + plagioclase system (cf. Herzberg, 1978). The continued growth of the transient phase orthopyroxene (replacing olivine) while sodic plagioclase and spinel persist in the felsic domains (GE14) does not therefore *necessarily* represent *P* and *T* different from the eclogite-forming conditions. Petrographical and mineral–chemical relations indicate that these phases have grown during the prograde metamorphism, not far below the metamorphic peak.

Garnet growth and development of zoning

The growth of garnet is characterized texturally by: (1) growth as coronas and from isolated nucleii within plagioclase; (2) complete pseudomorphism of plagioclase by garnet; (*a*) as massive pseudomorphic domains apparently not, or only locally, recrystallized; (*b*) associated with subgrain-formation or recrystallization to polygonal coarser-

grained aggregates within the pseudomorphs. 2*a* and 2*b* may both contain omphacite inclusions, which are most frequent and have smallest grain size in 2*a*.

Thus, the garnet formation can be divided into two stages. The first is the progressive growth across the plagioclase domain by a chemical replacement mechanism, starting at the plagioclase contact. Fe and Mg diffuse into plagioclase in marginal areas, accompanied by shorter range redistribution of Ca, Al, Si, and Na within central parts of the plagioclase domain to form sodic plagioclase and spinel. As reaction proceeds, more extensive diffusion of these elements out of the plagioclase subsystem occurs. Inclusions of omphacite may form by the complete consumption of plagioclase (subreaction 2*c*, 3). In the second stage, grain-boundary adjustments occur within the pseudomorphic garnet domain, facilitated by deformation, as evidenced by the foliated mica-fabric in these rocks.

Growth zoning of garnet (Tracy, 1982) may form in step 1, but note that Fe and Mg diffusion through the growing corona layer would also control the extent to which garnet can replace plagioclase. Also note that in contrast to common interpretations of zoning, the central part of the garnet domain is younger than the marginal parts. Step 2 can be associated with chemical modification by diffusion. Step 1 can be studied in the coronites and is exemplified here by GE15 (fig. 3).

A first approach considers a simple growth zoning and assumes that garnet started to grow in the zone adjacent to pyroxene. This model would imply that all the successive garnet layers have been in contact with plagioclase. Breakdown of the An component to form garnet and spinel and the observed increase in Na in the adjacent plagioclase suggest that the strong Ca increase would be compatible with growth under increasing pressure (cf. Ghent 1976). The accompanying abrupt decrease in Mg/Fe from 0.71 in the outer rim to 0.36 close to plagioclase is, however, not compatible with a prograde 'surface equilibrium' growth. One possibility is that the contrasting rim compositions may reflect different types of surface equilibria, and that the Ca-rich rim was never in equilibrium with the mafic phases outside the pseudomorph. Thus, the Ca zoning may be attributed to equilibrium with plagioclase at changing *P* and *T* conditions preserved by limited volume diffusion across the garnet corona, while Fe and Mg have equilibrated with pyroxene only adjacent to the pyroxene.

Another alternative is that the abrupt changes recorded in the zoning profiles are related to early changes of phase equilibria. Ca-rich garnet is often formed in local assemblages with transient Al-rich

phases, for instance corundum and spinel (Mørk, 1985b). The start of spinel formation by breakdown of plagioclase (reaction 1a) would increase the availability of Ca for garnet formation, and could explain the sudden change in the Ca-gradient.

The above considerations were based on garnet growth by inward invasion of plagioclase. It is also possible that the garnet corona has expanded both towards adjacent plagioclase and outward into the pyroxene, and again that the relatively constant Mg/Fe ratio in the outer part of the corona reflects local equilibrium with clinopyroxene at constant P and T, while the other side was controlled by 'exchange' with plagioclase.

The equilibria discussed above are different from those in the completely eclogitized samples where garnet is in equilibrium with omphacite and phlogopite. The decrease in Ca in garnet with degree of total transformation is consistent with reactions 2 and 3 which produce Mg,(Fe)-rich garnet and lead to a plagioclase-free assemblage. Simultaneously, the garnet development in the sequence from coronites to the completely reacted eclogites has been associated with increased diffusion between the original mineral domains, with a thorough redistribution of elements at the mm scale. This is especially clear for elements like Na,Al and Mg,Fe which were originally absent in the original olivine and plagioclase domains respectively, but became completely redistributed at advanced reaction stages.

The homogenization of garnet may have occurred in association with such a complete redistribution at a later reaction stage, locally related to recrystallization. Thus, the commonly observed weak Ca-zoning of eclogite garnets may be interpreted as a relict growth zoning controlled by an earlier subassemblage with plagioclase + spinel. The final re-equilibration can be described by a P–T-related continuous exchange: $(Fe,Mg)Ca_{-1}$ Gnt = $(Fe,Mg)Ca_{-1}Cpx$. The accompanying Mg/Fe increase in garnet would either result from a continuous $MgFe_{-1}$ exchange between garnet and clinopyroxene, but could also have been influenced by an extension of the local system to include equilibrium with phlogopite (complete breakdown of olivine).

Implications for P–T-time interpretations

Mineral inclusions and zoning within the host mineral (garnet) can be used to deduce P–T-time development during metamorphism, i.e. for a time interval corresponding to the garnet growth (cf. Tracy et al., 1976; Thompson et al., 1977; Krogh, 1982; Spear and Selverstone, 1983). Such applications must be built upon spatial models for the garnet growth (e.g. by overgrowth of successive layers around the core) and for the zoning mechanisms (diffusional vs. growth zoning; Tracy, 1982).

In the present case, pseudomorphic replacement of plagioclase by garnet and the assemblages recorded in transient stages may be used to deduce the growth mechanism and local controls on the composition at earlier stages. It is suggested that the weak zoning of Ca even in the completely reacted rocks is a relict after local equilibria between garnet and Ca and Al phases that later disappeared completely. Here, the zoning is also modified by homogenization due to diffusion in late growth stages. A consequence of the replacement type is that central parts of the garnets or garnet domains are not necessarily older than rim domains, and that central and marginal inclusions of omphacite grains in garnet can have formed simultaneously late in the reaction history by the final consumption of the plagioclase host.

Comparisons with related coronite occurrences

The total transformation to eclogite is not compatible with a single-stage model of cooling from igneous temperatures as suggested for coronites elsewhere in the WGR (Griffin and Råheim, 1973). The possibility of multistage reaction models should, however, be examined. Unfortunately, the relatively high degree of reaction even in the coronites presented here, means that there is no way to study the initial reaction stages.

The mineral replacements which have been described with garnet gradually replacing plagioclase, omphacite replacing olivine and augite, and a transient stage with orthopyroxene coronas have been observed in several occurrences, and have also been described by Griffin and Råheim (1973). They observed coronas of orthopyroxene and symplectitic clinopyroxene/spinel intergrowths, interpreted as the earliest reaction stage between olivine and plagioclase, and found that garnet had started to nucleate in a second stage at the contact between the early layers (Griffin and Råheim, 1973, p. 32 and Griffin and Heier, 1973, pp. 316–17).

When compared with the reaction sequence observed in the Flemsøy gabbro and with the recent available data on timing of the gabbro/dolerite intrusions and the eclogite metamorphism, a tempting interpretation is that the first corona stage of Griffin and Råheim (1973), corresponding to the reaction Ol + Pl = En + Di + Spl (see Griffin and Heier, 1973), might be attributed to cooling following the intrusion, while the garnet-forming reactions occurred during the much younger eclogite-forming event. Another observation of

garnet nucleation within a pre-existing corona (Opx, Cpx, Amp) has been observed in the Grøtshornet gabbro (20 km east of Flemsøy). This gabbro has been very little affected by the metamorphism (Table I); only *c.* 0.1 mm coronas occur between olivine and plagioclase, and it has not been altered by spinel growth *within* plagioclase as recorded in the Flemsøy gabbro. The absence of the 2-pyroxene (+Spl or Amp) corona stage in the Flemsøy gabbro could mean that it has been obliterated completely by the later reactions, for instance by replacement of an early diopside/spinel corona by garnet and omphacite, while orthopyroxene persisted and continued to grow in the advanced coronites. Alternatively, the Flemsøy gabbro had a different early cooling history.

In the present rocks, the presence of an original pre-metamorphic corona stage cannot be proven or disproven; it is particularly debatable whether some of the orthopyroxene could have formed during early cooling. The important point is, however, that there is evidence for extensive growth of the corona minerals orthopyroxene and garnet (and transient spinel in plagioclase) during a separate metamorphic event which was 800 Ma after the intrusion (Mørk and Mearns, 1986), and thus that coronas need not always be the product of igneous or deuteric reactions.

The pseudomorphic replacements of plagioclase by garnet and Al-rich phases has also been observed in metabasites of totally different compositions from the WGR, ranging from leuco-gabbro norite to Mg- and Ca-rich olivine websterite (Kvamsøy; Mørk, 1985b). Although different bulk compositions (and also the possibility of variations in the local fluid-deformation-*P*-*T*-time development) have led to different assemblages in the mafic subsystems, the general development in the felsic subsystems suggests a common mechanism for garnet growth and the development of Ca zoning in garnet.

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