An unusual clinopyroxene with complex lamellar intergrowths from an eclogite in the Sunndal-Grubse ultramafic mass, Almklovdalen, Nordfjord, Norway

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SUMMARY. Clinopyroxene crystals with complex lamellar intergrowths of orthopyroxene and garnet are described. The orthopyroxene lamellae are irrationally orientated within the clinopyroxene host although the optical relationships of these minerals are consistent with (100) exsolution in clino-pyroxene. The intergrowth is nevertheless considered to be the result of exsolution processes. Possible modes of origin are reviewed together with the general significance of exsolved pyroxenes in eclogite- and granulite-facies associations.

Field and petrographic description. Two specimens (6912 and 6095) of clinopyroxene-rich orthopyroxene eclogite were collected 450 metres ESE. of a small schoolhouse in the valley between Sunndal Vatn and Seternes Vatn, Almklovdalen (Lappin, 1966, fig. 5). They occur within the eclogitic layers of the Sunndal-Grubse mass, a large, essentially dunitic mass, which contains minor garnet-rich and clinopyroxene-rich eclogites as well as occasional garnet peridotites (Lappin 1966).

In these specimens large (maximum dimension 1 cm) platy crystals of a green, well-cleaved, lamellar clinopyroxene are set in a fine-grained greenish groundmass consisting of elongate (1 mm long) clinopyroxenes and subordinate amounts of still finer-grained garnet and orthopyroxene. Secondary amphibole is also present. The large clinopyroxenes have complex plucked boundaries suggestive of cataclasis, and internal dislocations along which minor recrystallization is seen. Their lamellae range from about 20 to 300 microns in width. They have a very varied appearance, best demonstrated by modal sketches drawn from microprobe X-ray images (fig. 1). They vary from straight or curved orthopyroxene plates inset with fairly regularly spaced garnets to lamellae with a complex interdigitation of garnet, ortho-, and clino-pyroxene, though again garnet seems to occur at the termination of, or at points of junction of, orthopyroxene lamellae.

Optical and geometrical relationships. The optical orientation of the orthopyroxene relative to the clinopyroxene host was determined with the universal stage as was the orientation of the lamellae themselves. The latter in particular presented peculiar

features in their overall spatial orientation, as shown by reference to the equally well developed {110}, {100}, and {010} cleavages in the host clinopyroxene, and by their curved form. In every case where the optic orientation of the orthopyroxene could be determined the relationship is as shown for two grains (fig. 2A, B): α orthopyroxene lies approximately parallel to β clinopyroxene; γ and α for clinopyroxene and β and γ
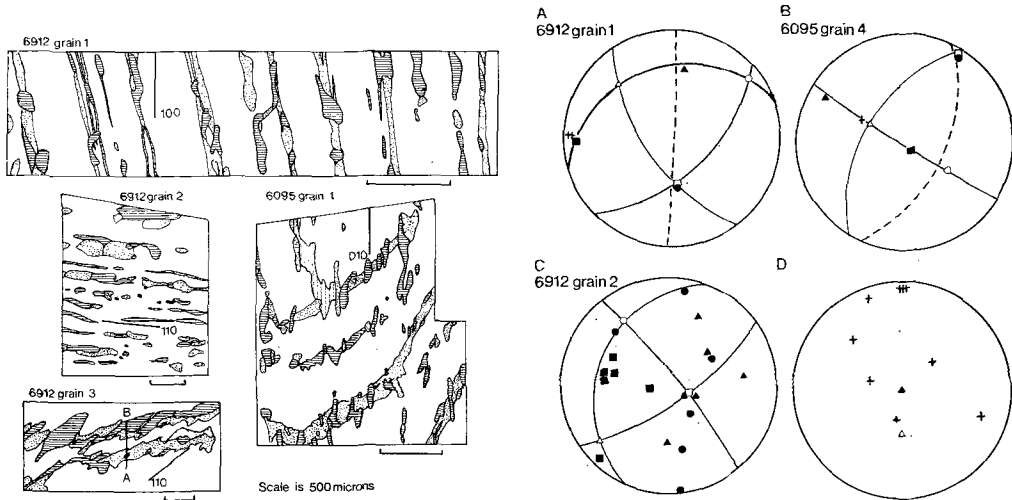
FIGS. 1 and 2: FIG. 1 (left). Drawings of X-ray microprobe images of various lamellar clinopyroxenes. Garnet, line ornament; orthopyroxene, dotted ornament; clinopyroxene, no ornament; amphibole, wavy ornament. The generalized trace of the dominant clinopyroxene cleavage is also shown. 6912, grain 1: Garnet occurs mainly at node points in orthopyroxene lamellae. 6912, grain 2: Coarser lamellae are recrystallized and most lamellae are apparently discontinuous; this is largely due to the presence of clinopyroxene or recrystallized clinopyroxene within the lamellae. 6912, grain 3: Complex interdigitation of garnet and orthopyroxene; local examples of step-edged lamellar interfaces. 6095, grain 1: Curved lamellae with spindle-like garnets though one lamella shows opposite relationships; there are dislocations parallel to trace of cleavage, within these garnet has recrystallized into an extremely elongate aggregate and clinoamphibole has also formed. FIG. 2 (right). The relationships between α, β, γ of clinopyroxene (open symbols) and α, β, γ of orthopyroxene (filled symbols) α, circle; β, square; γ, triangle. Trace of lamellae (dashed line) and pole to lamellae (cross) are also shown. A and B: Relationships in two grains. C: α, β, γ for recrystallized orthopyroxenes relative to α, β, γ of host clinopyroxene. D: Poles to lamellae for seven grains rotated so that γ orthopyroxene is vertical and γ clinopyroxene lies in appropriate relationship in b(010).

orthopyroxene lie approximately within one plane and the angle between γ orthopyroxene and γ clinopyroxene averages 44°. This is of course the typical orientation for (100) exsolution in clinopyroxene as described by Poldervaart and Hess (1951).

In only one grain (fig. 2A), however, does the geometrical orientation of the lamellae approximate to {100} in the clinopyroxene host and even here the lamellae are set slightly transverse to, and feather into a {100} cleavage. In other grains, for example fig. 2B, the lamellae seem to have an irrational orientation relative to the c axis of the host grain (fig. 2C).

The orthopyroxene lamellae are more abundantly cleaved than the clinopyroxene host, for although they lack a typical prismatic cleavage they possess a strongly developed {001} cleavage. The lamellae sometimes have step-like interfaces against clinopyroxene and in these cases one edge is defined by this {001} cleavage whilst the other is a continuation of the {110} or {010} cleavage of the host grain. These cleavages curve when entering the lamellae and it is not certain, because of difficulties in measuring precise tilt within the lamellae, whether they are rational orthopyroxene cleavages. They do, however, share a common zone axis, [001] orthopyroxene.

Some coarser lamellae consist largely of mosaic zones of orthopyroxene and clino-pyroxene together with garnet. These suggest a later recrystallization of the lamellae. The orthopyroxenes of such zones tend to be elongate and eight sided. The optical orientation of six such orthopyroxenes is shown in fig. 2D; β for these grains tends to lie in the $\alpha\gamma$ plane of the clinopyroxene host, as for non-recrystallized grains, but α and γ seem to have fairly random orientations.

Spindle-like garnets (fig. 1) occur at fairly regular intervals within orthopyroxene lamellae and more occasionally garnet forms discrete lamellae parallel to the ortho-pyroxene lamellae. The garnets are elongate perpendicular to the {001} orthopyroxene cleavage, which can sometimes be traced through the garnets as a rough fracture. In the step-edged lamellae the garnets have a block-like shape defined by the two orthopyroxene cleavages. In some cases coarser, irregular-shaped garnets may indicate recrystallization as may smaller garnets tucked in beside recrystallized orthopyroxene.

Many of the groundmass garnets have spindle shapes whilst many groundmass orthopyroxenes lack a prismatic cleavage, suggesting that these minerals may be de-rived from the cataclastic breakdown of the lamellar phases. The plucked boundaries and internal dislocations of lamellar clinopyroxenes suggest that these minerals are porphyroclastic relicts with a finer-grained groundmass and thus that at one time these specimens consisted largely of lamellar clinopyroxenes.

The origin of the lamellae. An irrational geometrical orientation of orthopyroxene lamellae in a clinopyroxene host, and indeed the implied irrationality of the spindle and plate-like garnets (whose shapes seem to be dictated largely by orthopyroxene), have not been described, so far as the author is aware, in the literature. Orthopyroxene lamellae are commonly recognized by their geometric relationships and previous descriptions of garnet lamellae in clinopyroxene also emphasize their rationality. Thus Hentschel (1937) and Lovering and White (1969) describe lensoid garnets parallel to (100) clinopyroxene. Kuno (1969), on the other hand, notes garnet lamellae parallel to (100) and (010) whilst Saggerson (1968) describes garnet plates parallel to (001) clinopyroxene. There is obviously no unique exsolution plane for garnet within a clinopyroxene host.

The lamellar clinopyroxenes are considered to form by exsolution processes because microprobe scans (fig. 3) suggest that both host and lamellar phases have uniform compositions and sharp interfaces, whilst modal analyses (made from modal sketches, fig. 1) show limited variations (4 lamellar clinopyroxenes range from 74·5 to 78·8 % clinopyroxene, 8·1 to 12·6 % orthopyroxene and 10·0 to 13·1 % garnet). Moreover,

Christian (1965, p. 322) in his general discussion of exsolution phenomena emphasizes that 'a coherent interface in the sense in which we use the term does not necessarily imply a rational interface'.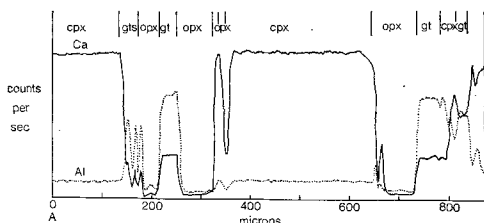 He does not describe an example of such exsolution though he offers the analogy of the irrational interfaces that can result from mechanical twinning. In the terminology used above the orthopyroxene/clinopyroxene interface (and probably also the garnet/clinopyroxene interface) would be described as semi-coherent (the optical data suggest limited but real misfit) and irrational.

FIG. 3. X-ray microprobe trace for Ca and Al across the complex lamellar zone in 6912, grain 2 (A–B, fig. 1). Cpx, clinopyroxene; opx, orthopyroxene; gt, garnet. Phases are of uniform composition within limits of resolution set by scan speed.

The coherent and semi-coherent interface with exsolved phases occurring as flat plates or ellipsoidal-shaped particles is such that the particle shape tends to minimize the strain energies of the transformation process and these particles, in rational orientation, minimize strain and surface energies (Yund and McCallister, 1970). The semi-coherent irrational interfaces of the Sunndal pyroxenes may thus be due to the diverging tendencies of strain and surface energies though this in no way explains why transformation conditions at Sunndal differ from those at Gilsberg, Austria (Hentschel, 1937). Here clinopyroxenes with rational lamellae of garnet occur in a very similar geological environment (clinopyroxene-rich rock within serpentinite).

In view of the importance of strain in exsolution processes the origin of the lamellae must be considered in terms of the complex stress/strain history of the Almklovdalen ultramafic masses (Lappin, 1967). Three possible processes for the formation of the lamellae can be considered.

Stress-controlled geometry of the lamellae. Two contrasting processes can be considered under this heading. Firstly, the lamellae may have formed within a tectonically-controlled plane or planes. Examination of lamellar clinopyroxenes within thin sections and hand specimens suggests that there is no tendency for any planar configuration. Secondly, the lamellae may be formed within individual grains as a response to localized resolved stresses. It must be noted, however, that known glide planes in clinopyroxenes, which are reflections of stress, are rational planes (Raleigh, 1967). Observed dislocations in the Sunndal clinopyroxenes are likewise rational, for they lie parallel to cleavages. This generation of dislocations cuts, causes rotation of, and local recrystallization within, the lamellae (fig. 1, 6095, grain 1).

The recrystallization of the host lamellar phase. A model for such a process can be suggested if it is assumed that clinopyroxenes with primary exsolution features—Gilsberg type with coherent(?) rational interfaces—are subjected to stress-controlled recrystallization. In such a process the optical orientation of the clinopyroxenes would

represent a compromise between older orientations and 'tectonic' controls whilst an overwhelming nucleation control may well be exerted by the host mineral upon the lamellar phases. This would tend to maintain the lattice continuity of the pyroxene chains. If diffusion processes are limited under such conditions the lamellae themselves might either retain their original geometrical orientations or rotate somewhat under stress (perhaps towards planes of maximum resolved shearing stress).

Hentschel (1937) has in fact attributed local, irrational garnet lamellae (coherent or incoherent?) in the Gilsberg clinopyroxenes to such a stress-induced recrystalliza-tion. The remarkable feature of these clinopyroxenes, however, is not the occasional irrational lamella but the rationality of most lamellae, despite intensive and spectacular internal folding. It is evident that lamellar clinopyroxenes can support considerable strain without recrystallization. Whilst the onset of such recrystallization processes will depend on temperature, pressure, and strain rate and will thus vary considerably, the limited recrystallization at Gilsberg places considerable constraints upon the applicability of the recrystallization hypothesis to the Sunndal clinopyroxenes.

If, on the other hand, such a recrystallization process did occur within the Sunndal clinopyroxenes it must be an early one in terms of the tectonic history of the ultramafic masses. The stages of fabric development in these masses (Lappin, 1967) would allow for such an early recrystallization, for it seems reasonable to suggest that these large, porphyroclastic lamellar clinopyroxenes represent a stage equivalent to the early, large, porphyroclastic olivines in the ultramafic masses. A crystallization event, now represented solely as a chromite-defined lineation or foliation, predated these olivines.

The lamellae as primary exsolution features. Yund and McCallister (1968) suggest that clinopyroxene exsolves by discontinuous decomposition. In this process the ex-solved region or duplex cell forms behind an incoherent, often grain-boundary-con-trolled, interface, which sweeps across a grain. It seems possible that the geometrical orientation of lamellae might be dictated by the interface and hence be irrational whilst the mechanism demands that the lamellar interface be incoherent or semi-coherent (as is the clinopyroxene/orthopyroxene interface) (Yund and McCallister, 1970). Whilst such a mechanism seems viable one must ask why irrational lamellae are not more commonly recognized?

It is not possible to choose between the recrystallization and primary exsolution hypotheses because, on the one hand, the complexity of later events in the Almklov-dalen masses limits the understanding of earlier ones, and on the other hand more detailed optical and X-ray studies of lamellar pyroxenes from other environments are still required.

Whichever hypothesis is accepted, however, the mode of occurrence of garnet requires comment. The shape of garnets seems to be controlled by orthopyroxene cleavages and many garnets seem to occur only at node points in orthopyroxene lamellae. This suggests a two-stage exsolution process with the initial development of tschermakitic orthopyroxene lamellae and the later nucleation of garnet.

Such a two-stage process can be accommodated within both hypotheses. Thus the duplex cell mechanism is one of rapid growth when the exsolved phase(s) do not

necessarily have an equilibrium composition. In this case the initial growth of the cell could be followed by a slower process of localized diffusion and equilibration when garnet might grow. Recrystallization processes often tend to minimize entropy changes and thus again tschermakitic orthopyroxene lamellae might form, followed by a later nucleation of garnet. The great difficulties in nucleating this mineral relative to pyroxenes in high P, T experiments on basic rock compositions offer some support for these arguments.

The significance of exsolved pyroxenes in eclogite facies associations. Exsolved pyroxenes are known from four eclogite facies associations:

Inclusions in alkali basalts; Hawaii (Kuno, 1969; Beeson and Jackson, 1970), Kenya (Saggerson, 1968).

Inclusions in kimberlite; South Africa (Williams, 1932).

Layers and lenses in ultramafic rocks; Gilsberg, Austria (Hentschel, 1937); Sunndal, Almklovdalen, Norway.

Lenses and layers in gneisses and schists of greenschist, amphibolite, and granulite facies; Stadlandet, Norway (Lappin, unpublished data); Glenelg, Scotland (Sanders 1971).

Exsolved clinopyroxenes are not known, so far as the author is aware, from the fifth association: Lenses in glaucophane schist (and related facies) rocks.

The eclogites from this last association are significantly different from those of the other associations in other respects. Thus they have more limited ranges of bulk and mineral chemistry (Coleman *et al.*, 1965) and also different garnet/clinopyroxene distribution functions (Banno, 1970). It is suggested that they formed either under different conditions of equilibration or by different processes from the eclogites of other associations.

The environment in which the eclogites of the first two associations occur can be categorized as igneous whilst that of the third and fourth is orogenic. Granulite-facies rocks containing pyroxenes, garnet, and spinel in exsolution intergrowths can be similarly categorized. Thus samples from the Delegate pipe, Australia, (Lovering and White, 1969) are granulites from an igneous environment, whilst those from Beni Bouchera, Morocco (Kornprobst, 1969), and Bois de Feuilles, France (Lasnier, 1972), represent granulite facies rocks from orogenic environments.

In most of these eclogite- and granulite-facies rocks pyroxenes with exsolved garnets are found only in pyroxene-rich rocks. Exsolution is not seen in other possible phases (garnet, spinel, olivine) or, in significant degree, in rocks with large modal amounts of such phases. For example the only exsolved samples found in a detailed examination of a classic area for eclogite facies rocks (Eskola, 1921), the Stadlandet and Alm-klovdalen areas of the Basal gneiss region of W. Norway, are the Sunndal clino-pyroxenes, described here, and orthopyroxene with exsolved garnet from an eclogite lens in gneiss at Sandviknaes, Stadlandet (Lappin, 1966, fig. 1). Both samples consist of about 75 % host and 25 % exsolved phases and occur in rocks with similar proportions of these phases.

Exsolved pyroxenes have not been found in more typical eclogites (garnet ≈ clino-

pyroxene±quartz±kyanite), orthopyroxene eclogite (garnet ≈ clinopyroxene+ orthopyroxene), or garnet peridotites (olivine > garnet ≈ clinopyroxene+ortho-pyroxene). This might suggest either a different history for exsolved samples, even though they are interlayered with rocks that do not show exsolution, or a modal, and hence bulk chemical, control on the exsolution process.

The observations made by Brett (1964) on exsolution processes in ores seem relevant in this context. He suggests that systems having a limited degree of supersaturation with respect to a possible exsolved phase can unmix coherently, whilst systems with higher degrees of supersaturation are characterized by incoherent exsolution and grain-boundary growth of exsolved phases. The latter process would not be recognized texturally as an exsolution process.

The pyroxenes, of the minerals involved in eclogite/granulite facies exsolution pro-cesses, have the greatest range of temperature/pressure-dependent solid solution particularly with respect to tschermakite (potential garnet) (O'Hara and Yoder, 1967). The only variation in garnet compositions as a function of temperature and pressure is likely to be in Fe/Mg ratios and such a variation can be accommodated by exchange reactions with other phases. Thus the eclogite/granulite facies samples that might show exsolution should consist largely of pyroxene (often pyroxenites) with a limited degree of supersaturation with respect to garnet (tschermakite) and other com-ponents, perhaps 30 % maximum. Samples with a greater degree of supersaturation would exsolve through incoherent exsolution and grain boundary growth. Many such samples (almost all typical eclogite facies rocks) would have primary garnets associated with complex pyroxene(s) and these could act as nucleation centres for grain boundary processes.

Exsolution textures in pyroxenes are generally interpreted in terms of the cooling history of the rock concerned. For example the igneous environment eclogite and granulite facies associations of Hawaii (Beeson and Jackson, 1970) and Delegate, Australia (Lovering and White, 1969) have been interpreted in terms of isobaric cooling at different pressures. It would seem reasonable to interpret the Norwegian exsolved pyroxenes in terms of a general reaction, which, however, might not be isobaric:

complex pyroxene (high T, high P) → pyroxene(s)+garnet (lower T, high P).
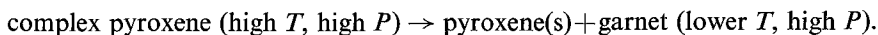
If the very limited occurrence of exsolution textures is due only to the chemical controls of supersaturation then the temperature–pressure estimates for this reaction is one to which all genetically associated rocks have been subject.

This observation is important with respect to the eclogite facies rocks from Nor-wegian orogenic environments (the third and fourth associations, above). Opinions on the origins of these rocks are divided between workers (O'Hara and Mercy, 1963; Lappin, 1966; Carswell, 1968) who regard these eclogites as tectonically controlled and introduced materials of lower-crust, upper-mantle origin with an early high temperature–pressure, possible igneous history. Other workers (Bryhni et al., 1970) recognize the influence of tectonism but argue that the eclogitic rocks are formed from pre-existing mafic/ultramafic rocks under the conditions of metamorphism

obtaining in adjacent amphibolite–facies gneisses. Special additional controls are provided by the outflow of water due to partial melting in nearby, vapour-deficient gneisses.

The temperatures and minimum pressures inferred for the pre-exsolution stage of the Sunndal clinopyroxenes are 1100 ± 50 °C and 20–22 kilobars (Lappin, in preparation). Such conditions are beyond the possible range of temperatures and pressures of amphibolite–facies metamorphism. The exsolved pyroxenes of association 3 must be seen as part of a complex temperature–pressure history for the rocks concerned. The occurrence of exsolved pyroxenes in two classic areas of eclogite-facies rocks within gneisses (Stadlandet (Eskola, 1921) and Glenelg (Alderman, 1936)) strongly suggests that some, if not all, of these rocks had a complex temperature–pressure history.

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