Exsolution of plagioclase from clinopyroxene in a pyroxenite from Jotunheimen, Norway

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SUMMARY. Petrography of an original websterite from Jotunheimen shows evidence of plagioclase exsolving from clinopyroxene to form both internal lamellae and also an intergranular symplectite with olivine and magnetite hercynite. The olivine is secondary, forming from both clinopyroxene and orthopyroxene. Microprobe chemical analyses are presented of all the phases mentioned. From the ratio of plagioclase to clinopyroxene the initial clinopyroxene probably formed at a depth greater than 35 km; if it crystallized at magmatic temperatures (1150 °C) the depth must have been about 70 km. Exsolution took place at a pressure less than 6 kb after upthrusting of the rock to shallower depths. The great depth of initial crystallization has important implications for the conditions of origin of the ultramafic component of this granulite facies terrain.

THIS study tries to set limits on the conditions of formation of one of the granulite facies rocks of the Jotunheim massif in Central Southern Norway. This massif is tectonically emplaced and nearly all its contacts are mechanical. In these circumstances mineral reactions provide the best clues to its history.

Griffin (1971a, b) has described reactions between olivine and plagioclase in anorthosites and at a peridotite-gneiss contact in the Jotun rocks and concludes that they cooled in the pressure range 7-10 kb during a 2-3 kb pressure increase (anorthosites) or isobarically (peridotite-gneiss pair), followed in each case by an abrupt decompression to pressures below 5 kb at temperatures of 750-800 °C.

The following account describes reactions taking place within an original websterite,[1] which have produced a plagioclase-olivine-spinel-orthopyroxene-clinopyroxene assemblage with coronas of plagioclase and olivine around magnetite-hercynite intergrowths and widespread olivine-plagioclase symplectite.

Occurrence. The rock comes from the second knoll eastwards from Galdhøpiggen, along the ridge to Keilhaus Topp, at an altitude of 2250 m. The ultramafic body at this point is enclosed in pale two-pyroxene-feldspar rock (jotunite and mangerite) of rather more felsic aspect than the average Jotunheim granulite facies rocks. In its isolation amidst more felsic rocks the ultramafic body is typical of many scores of such bodies in Jotunheimen. Contacts are not well seen, but may safely be inferred from other examples to be movement surfaces welded by recrystallization.

Description. The chemical composition of the rock and its minerals are given in Table I. Its texture is illustrated in fig. 1. The principal primary minerals are clinopyroxene, orthopyroxene, and magnetite. The clinopyroxene has a composition of $Ca_{47.5}Mg_{40}Fe_{12.5}$ and occurs in millimetre-sized plates with exsolution lamellae about 5 μm wide composed at least partly of plagioclase, An_{67} (Table I). Plagioclase lamellae in clinopyroxene have already been reported from Jotunheimen (Battey and McRitchie, 1975).

[1] i.e. websterite of Williams, not to be confused with websterite of Brongniart, an old name for aluminite.

The orthopyroxene is En_{71} and also occurs as millimetre-sized plates, with fine exsolved opaque rods, but without exsolved plagioclase lamellae. Magnetite is in numerous amoeboid crystals up to 1 mm across, many of which are surrounded by a clear collar of plagioclase, which confers a remarkable appearance on the thin section (fig. 1). It also forms grains down to micron size in the symplectite. The larger grains have exsolved lamellae of hercynite. Hercynite also forms marginal patches around magnetite grains, passing gradationally or sharply to magnetite across curving interfaces. Olivine, Fo_{61}, forms clusters of granules (fig. 2) along the margins of

TABLE I. *Chemical analyses*

	1	2	3	4	5	6	7	8	9
SiO_2	44.4	49.82	51.38	36.97	53.34	55.45	—	—	—
Al_2O_3	8.7	5.26	3.53	n.f.	29.36	25.62	1.27	—	60.78
Fe_2O_3	7.06	7.41*	18.17*	32.82*	0.53*	0.55*	87.06*	66.74	30.37*
FeO	11.2							26.99	
MgO	13.75	13.19	24.56	28.64	—	0.07	0.35	—	9.43
CaO	12.36	22.0	0.66	n.f.	12.83	10.19	—	—	—
Na_2O	1.27	0.79	—	n.f.	4.34	5.62	—	—	—
K_2O	0.14	—	—	—	—	—	—	—	—
H_2O+	0.27	—	—	—	—	—	—	—	—
TiO_2	1.18	0.61	0.11	n.f.	—	—	4.33	—	0.65
MnO	0.28	—	—	—	—	—	0.74	—	—
Sum	100.6†	99.08	98.41	98.43	100.40	97.50	—	100.42	101.23
					An mol% 76.8	An mol% 67	$FeAl_2O_4$ wt% 2.1		Fe_3O_4 wt% 9.9

Norm   Atoms to n oxygen

or	0.56	n	6	3	4
ab	10.48	Si	1.865	0.952	1.025
an	17.79	Al	0.135	0.048	—
di { wo	18.21	Y	2.00	1.00	—
en	12.10	Al	0.099	0.065	—
fs	4.75	Ti	0.018	0.002	—
hy { en	4.30	Ca	0.881	0.014	—
fs	1.72	Na	0.058	—	—
ol { fo	13.30	X	1.06	0.081	—
fa	4.28	Mg	0.742	0.683	1.191
mt	10.21	Fe*	0.231	0.282	0.759
il	2.28	W	0.97	0.965	1.95

1. Websterite, whole rock (anal. P. J. Oakley).
2. Clinopyroxene (av. of 6 anals.); Mg/(Mg + Fe*) 0.76.
3. Orthopyroxene (av. of 3 anals.); Mg/(Mg + Fe*) 0.71.
4. Olivine (av. of 4 anals.); Mg/(Mg + Fe*) 0.61.
5. Plagioclase of corona (av. of 6 anals.).
6. Plagioclase of lamellae in clinopyroxene (av. of 4 anals.).
7. Magnetite (av. of 4 anals.).
8. Ideal Fe_2O_3, FeO of col. 7: calc. sum.
9. Hercynite (av. of 4 anals.).

2–9. Microprobe analyses by W. Davidson.

n.f., not found.
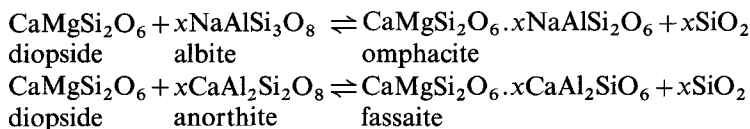FeO*, total iron as FeO.
† Including H_2O-, $< 0.05\%$.

both types of pyroxene grains, where they are against symplectite, and dispersed through the symplectite lanes. In composition it is much less magnesian than the primary olivine of other Jotunheim peridotites, which is Fo_{75-80}. Plagioclase, besides forming lamellae in the clinopyroxene, forms poikilitic plates of An_{77} enclosing magnetite as a clear rim, which extends to form the matrix of olivine and magnetite granules in symplectite lanes and patches that form some 25–30 vol.% of the rock. An idealized corona sequence is illustrated in fig. 2. Biotite occurs as scattered flakes, mostly small, but reaching 1 mm across, in the symplectite areas.

It is clear from the presence of exsolution lamellae that the plagioclase is exsolving from the clinopyroxene. The poikiloblastic texture of the symplectite demonstrates that the plagioclase is a diablastic product of a reaction producing it and an iron-rich olivine and probably some magnetite granules. The plagioclase is produced from the clinopyroxene and the olivine from both pyroxenes.
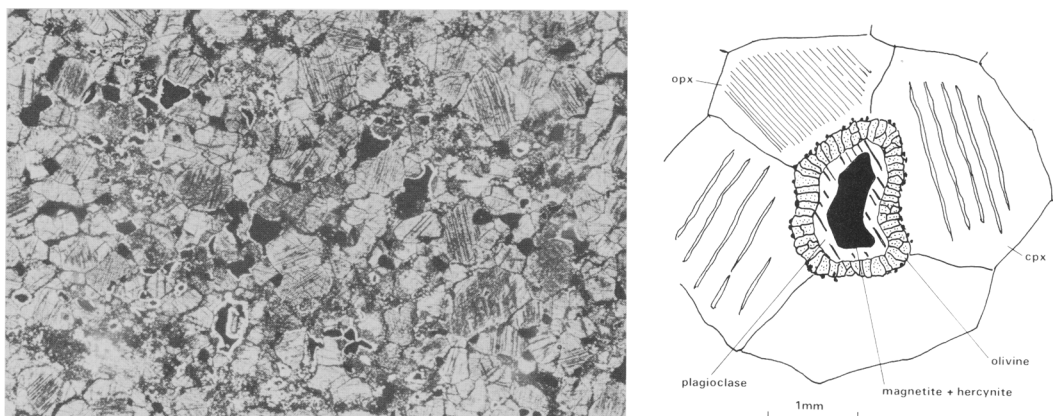
FIGS. 1 and 2: FIG. 1 (*left*). General texture of websterite showing pyroxene plates, with exsolution lamellae in clinopyroxene, collars of plagioclase around oxide minerals, and symplectite lanes. Short side of field is 10 mm. FIG. 2 (*right*). Idealized sequence of corona minerals.

Experimental data. Clinopyroxene dissolves plagioclase at high pressures, and we have here a case of such a high-pressure clinopyroxene discharging, at lower pressures, the plagioclase that it dissolved when it crystallized at depth. The reactions concerned are:

$$CaMgSi_2O_6 + xNaAlSi_3O_8 \rightleftharpoons CaMgSi_2O_6.xNaAlSi_2O_6 + xSiO_2$$
diopside   albite   omphacite
$$CaMgSi_2O_6 + xCaAl_2Si_2O_8 \rightleftharpoons CaMgSi_2O_6.xCaAl_2SiO_6 + xSiO_2$$
diopside   anorthite   fassaite

The amount of plagioclase that will dissolve in clinopyroxene depends upon the pressure. In the present case, all the plagioclase appears to have come out of the clinopyroxene. The question therefore is, how much pressure is required to put it back?

In the equations describing the reactions it will be noticed that when solution occurs SiO_2 is released. In fact, in experiments producing the solution of plagioclase in clinopyroxene the by-product SiO_2 has not been directly observed. Study of the pyroxene produced suggests that, in these experiments, the silica is at least partly taken up into the pyroxene structure as well, the pyroxene being then non-stoichiometric (Mao, 1971; Wood, 1976).

In the present case, however, when exsolution occurred silica was contributed to form the plagioclase by the formation of olivine from pyroxene. As has been seen, the new olivine is clearly secondary both in texture and in its composition.

Much experimental work has been done on the amount of plagioclase dissolved in diopside at various pressures (Kushiro, 1965, 1969; Kushiro and Schairer, 1970; Mao 1971; Bell and Mao, 1971). The diagram by Kushiro (1969) shows the amounts of An_{50} that will dissolve in diopside

at 1150 °C at different pressures, and this provides a basis for an estimate of the pressure at which the Jotunheim websterite formed (fig. 3).

Discussion. Before trying to put the plagioclase back into the clinopyroxene, however, we must establish the amounts of the different minerals. Because point-counting is very unreliable in a rock like this, which is full of symplectite, the mineral proportions are best obtained by calculation. We start with the C.I.P.W. weight % norm.

In the norm ab + an totals 28·3 wt % and diopside 35·06 wt % so that plag/(plag + di) = 44·7 %. From Kushiro's diagram it is seen that this amount of plagioclase could not be accepted into diopside at 1150 °C.
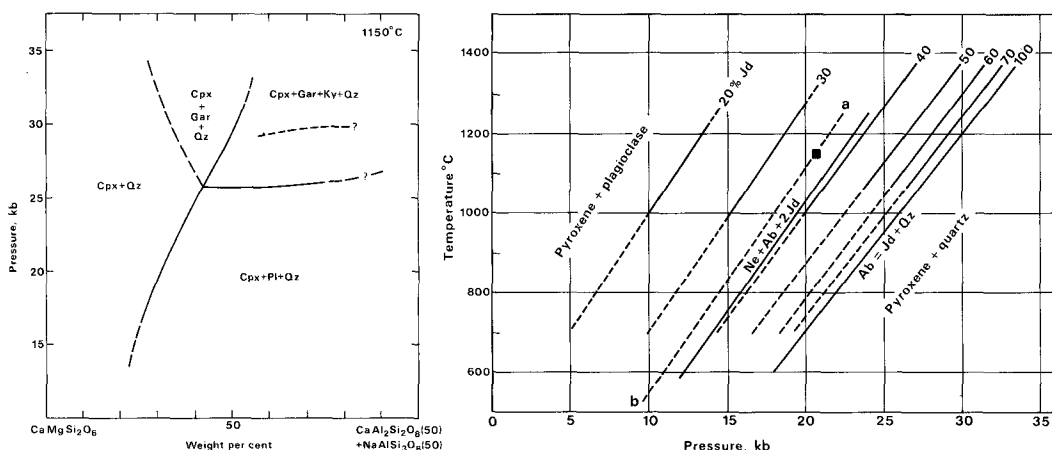
FIGS. 3 and 4: FIG. 3 (*left*). Solubility of plagioclase (An$_{50}$) in diopside at 1150 °C (after Kushiro, 1969). FIG. 4 (*right*). Content of the jadeite molecule retained in diopside at different temperatures and pressures. Lines numbered 20–100 represent increasing percentages of jadeite. (After Kushiro, 1969.) The line a–b is explained in the text.

But, as the olivine now present in the rock is derived from the pyroxene, some of the normative olivine must be made into diopside to restore this to its original amount, and this will make the plagioclase solution more dilute. If we suppose that half the normative olivine belongs in diopside, we obtain 48 wt % diopside. (If all the olivine were put into diopside we obtain the figure of 61 wt % diopside; but that would clearly be wrong since some of the olivine is seen by the textural relations to come from orthopyroxene.)

Moreover, some of the Al_2O_3 in the normative plagioclase is really in hercynite ($FeAl_2O_4$). Say one-fifth of the magnetite is hercynite (a generous estimate). If the anorthite is reduced by an appropriate amount, this leaves 24·9 wt % plagioclase, and provides a little more diopside, which now totals 49·4 wt %. The ratio plag/(plag + di) then becomes 33·5 wt %. If all olivine is put in diopside (see note above) this result would be 28·7 wt %. This we reject, but would accept an estimate of plag/(plag + di) = 32 wt %.

Kushiro's experiments show that, at 1150 °C a pressure of 21 kb would be needed to dissolve 32 wt % of An$_{50}$ in diopside. This pressure is equivalent to a depth of some 70 km, well below the base of the crust. At higher temperatures a higher pressure would be needed to maintain the solution. Thus, if the rock formed at magmatic temperatures it must have done so within the mantle, a conclusion that is important in considering its relations with the rest of the granulite facies rocks.

On the other hand, this rock may have equilibrated at a lower temperature. Kushiro's experiments on dissolving An_{50} in diopside do not explore lower temperatures; but his experiments on dissolving albite in diopside to give omphacite yielded a set of straight-line curves of temperature against pressure required to dissolve various amounts of jadeite. It is reasonable to assume a similar slope for such a curve in the case of An_{50} dissolved in diopside. Plotting the point derived above, at 1150 °C and 21 kb, and extrapolating to lower temperature, say to 500 °C, which may be expected at the base of the crust, we find that a pressure of 10 kb will suffice to squeeze 32 wt % of An_{50} into diopside (line a–b in fig. 4). This is consistent with the pressure to be expected at the base of the crust. Thus, provided the temperature is as low as 500 °C, the diopside might take up 32 % of plagioclase at the base of the crust, or, if it had taken it in at greater depth and higher temperature, it would still be able to contain it at the base of the crust.

Under conditions of very low partial pressure of water vapour there is no clear restriction on the temperature of initial formation of the pyroxene. It is conceivable that, given time, the pyroxene could grow at the temperature of about 500 °C imagined to exist at the base of present-day crust of 'normal' thickness. If, however, a higher temperature is deemed necessary for pyroxene growth the pressure must have been higher to maintain the plagioclase components in solution in the pyroxene, and a thicker crust must be postulated, or the pyroxenite must be derived from the mantle. If we conclude that the pyroxenite is of mantle origin, this clearly has important implications for the relation of the ultramafic bodies in the Jotunheim to the enclosing felsic two-pyroxene gneisses.

Whatever may be the correct conclusion about the depth of initial crystallization, the subsequent history clearly involves partial re-equilibration under conditions of the plagioclase + pyroxene side of the curve a–b in fig. 4, so that partial exsolution of the plagioclase from the pyroxene took place. This occurred at a pressure low enough for olivine and plagioclase to coexist. This appearance of olivine on decompression is a new feature of the Jotunheimen coronas. Earlier descriptions (Griffin, 1971b; Battey, 1960) deal with olivine and plagioclase reacting to give orthopyroxene, clinopyroxene, and spinel under the higher-grade conditions. Now we have the reverse reaction, which sets an upper limit of perhaps 6 or 7 kb pressure for the decompression reactions. The content of Al^{3+} in the magnetite and of Fe^{3+} in the hercynite, though not in exact mutual accord on Turnock and Eugster's solvus (1962), suggest a temperature of below 525 °C for their exsolution. Incidentally, it is clearly shown that when magnetite exsolves hercynite, Ti partitions strongly into the magnetite and Mg into the hercynite (Table I).

The re-equilibration at reduced pressure was only partial, as witnessed by the fact that the remaining clinopyroxene contains 5·4 wt % Al_2O_3 and the orthopyroxene 3·5 %.

The evidence for an episode of decompression, with temperatures permitting re-crystallization, in the history of the Jotunheim supports Griffin's (1971b) conclusions. The possibility, now introduced, that the ultramafic rocks have their origin in the mantle, would not accord with earlier postulates (Dietrichson, 1958; Battey and McRitchie, 1975) that they developed by crystal settling from a gabbroic magma.

Morse (1975) describes plagioclase lamellae, $An_{43.5}$ to $Ån_{92}$, from orthopyroxene megacrysts in anorthosite from the Nain Complex of Labrador, and Emslie (1975) furnishes data on occurrences of lamellae ranging from $An_{55.8}$ (mol) to $An_{91.6}$ in both clinopyroxene and orthopyroxene of sixteen examples from Labrador, Quebec, and the Rogaland Complex in southern Norway. Morse thinks it most probable that rapid growth of the Nain megacrysts led to the metastable incorporation of the plagioclase component, which exsolved on later annealing. Emslie, on the other hand, argues for an origin of the megacrysts in the mantle, with

subsequent exsolution as a result of decompression when they were injected into the upper levels of the crust. Emslie's conclusion that decompression is the cause of the exsolution seems consonant with the evidence of the smaller crystals from Jotunheimen. The depth of their origin remains dependent upon assumptions about the temperature at which they grew.

Finally, perhaps the most conspicuous feature of the rock described above, the concentration of inclusion-free plagioclase as a clear pellicle around magnetite grains, is not explained in terms of the mineral reactions discussed. The same textural feature was noted in reaction zones between peridotite bodies and feldspathic gneisses (Battey, 1960) without any explanation being found. The occurrence, within some clinopyroxene grains, of rounded plagioclase areas with a central cluster of magnetite granules may indicate that some magnetite is a product of pyroxene recrystallization accompanying exsolution of plagioclase. Morse (1975), noting the invariable presence of magnetite grains along with plagioclase lamellae in the hypersthenes he describes, concluded that the plagioclase exsolved by a coupled redox reaction in which the production of magnetite released silica to provide that necessary for the plagioclase. In the rock here described, however, it seems implausible to suppose that the large magnetite–hercynite blots, which have only relatively narrow plagioclase rims, are produced as a direct consequence of the exsolution, and these magnetites are therefore regarded as primary in the same sense that the pyroxenes are primary. The rims of plagioclase around them must presumably be attributed to a preference of the exsolved plagioclase to nucleate on magnetite, or at magnetite–pyroxene interfaces.

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