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Almandine pseudomorphous after plagioclase in a metadolerite dyke from the Jotunheim, Norway

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SUMMARY. An undeformed metadolerite dyke cutting foliated pyroxene-granulite facies gneisses in the Jotunheim, Norway, has almandine rods replacing the cores of plagioclase laths, although garnet is generally absent from the enclosing gneisses, and is not present in reaction zones between peridotites and gneisses. Chemical analyses of the dyke and its garnet, plagioclase, and clinopyroxene are given. The presence of garnet in the dyke is attributed to the low mg ratio of the rock. The nature of the reaction leading to garnet pseudomorphous after plagioclase is discussed.

THE two-pyroxene–feldspar, granulite facies gneisses of the Jotunheim generally lack garnet (Battey and McRitchie, 1975). Garnet does, however, occur in amphibolites produced by retrograde metamorphism on shear planes cutting the granulites. The discovery of an undeformed dolerite dyke, in which almandine garnet, rich in the pyrope and grossular molecules, metasomatically replaces the cores of the plagioclase crystals, thus raises intriguing questions of the status of this garnet in the Jotunheim metamorphic history and the nature of the garnet-forming reaction.

The mountain Storegut lies 6.5 km NNW of Eidsbugarden in the Jotunheim district of central southern Norway (Map series AMS M711 sheet 1517 I, Tyin). On its SE flank, at about Grid Reference 605105, mineralogically layered pyroxene granulites of a pale feldspar-rich type (jotunites and mangerites) are cut by a metadolerite dyke 6.6 m wide, exposed over two lengths, each of about 15 m, about 90 m apart. It is terminated by a fault on the north and lost under snow to the south. The dyke is chilled at both margins and jointing oblique to the margin is seen in the western chilled edge. The eastern margin is against a 2-m-wide zone of the fine-grained basic gneiss with feldspathic streaks that run parallel to the dyke wall, while the western margin is directly against leucocratic gneiss. This asymmetry, coupled with differences in the degree of layering of the country rocks on either side, suggests that the dyke occupies a fault.

The centre of the dyke has 37.7 vol% clinopyroxene, 35.1% plagioclase (23.2% clear, 11.9% cloudy), 15.8% garnet, 9.1% ore, 5.2% biotite. The texture is ophitic (fig. 1) with plagioclase laths up to 2 × 1 mm, but mostly under 1.5 mm, randomly arranged and penetrating areas of granular pyroxene. The laths have some outgrowth of their margins and some of them, with their garnet cores, are slightly curved. Irregular areas of pyroxene up to 2 mm across are made of rounded anhedra about 100 μm across, with relics of larger grains up to 1 mm, crowded with opaque rod-like inclusions. The smaller grains are sometimes comparatively free of inclusions. The pyroxene appears to be entirely monoclinic with 2V ≈ 45°: it is not highly aluminous, but contains appreciable Na. Cuspate

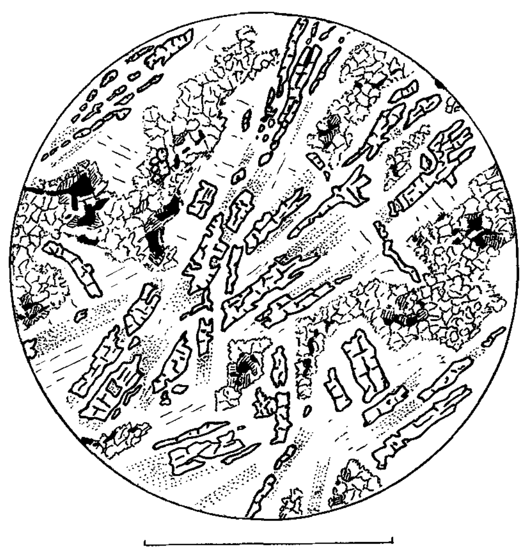

FIG. 1. Microscopic appearance of metadolerite, Storegut. Rods of garnet (heavy outlines) in partly clouded plagioclase (blank and dotted areas). Granular pyroxene (lighter outlines), with ilmenite (black) and biotite (closely lined).

blots of ilmenite up to 0.5 mm across occur in the pyroxene areas and it also forms crooked lines between pyroxene grains. Around the ore especially, and amongst the pyroxene generally, are flakes, 0.3 mm and downwards, of reddish-brown biotite. Accessory apatite occurs as stout crystals amongst the pyroxene.

The plagioclase has cores densely clouded with tiny specks of opaque material; and this clouding sometimes picks out original compositional zoning and extends as trails along twin composition planes. Outer clear zones are An_{22}, intermediate cloudy zones An_{36} (wt%) (Table I), and crystal cores An_{58} (by extinction angles).

TABLE I. *Chemical analyses*

	1	2	3	4	5	6
SiO_2	45.5	45.6	63.54	55.79	38.69	51.25
Al_2O_3	14.5	14.2	24.03	28.05	21.87	2.99
Fe_2O_3	4.6	6.8	—	—	—	—
FeO	12.4	9.5	0.20*	2.56*	27.47*	10.95*
MgO	5.01	4.86	—	—	5.18	11.92
CaO	8.58	8.48	4.56	6.75	7.02	21.04
Na_2O	2.93	4.12	8.99	6.94	—	0.99
K_2O	1.22	0.67	0.42	0.25	—	—
H_2O^+	0.45	1.04	—	—	—	—
H_2O^-	< 0.05	< 0.05	—	—	—	—
TiO_2	3.88	3.84	—	—	—	0.27
MnO	0.23	0.24	—	—	0.91	0.14
P_2O_5	0.57	0.58	—	—	—	—
Cr_2O_3	—	—	—	—	—	0.04
Sum	99.92	99.98	101.74	100.34	101.14	99.59

Norm				Or:Ab:An		Atoms to *n* oxygens		
q		—				*n*	12	24
or		7.2		2.2	1.1	Si	2.994	7.749
ab		24.6		76.0	58.7	Al	1.996	0.251 / 0.275
an		22.8		22.5	33.6	Fe*	1.773	1.379
di	wo	6.7	13.3			Mn	0.065	0.018
	en	3.3				Mg	0.599	2.704
	fs	3.3				Ca	0.580	3.411
hy	en	4.0	8.1			R^{2+}	3.017	Ti 0.027
	fs	4.1				—		Na
ol	fo	3.6	7.9			Alm 59		Ca 45.5
	fa	4.3				Py 20		Mg 36.1
mt		6.7				Gross 19		Fe 18.4
il		7.3				Spess 2		
ap		1.3						

1. Metadolerite (central part of dyke), Storegut.
2. Metadolerite (dyke margin), Storegut.
3. Plagioclase, unclouded, from metadolerite, Storegut.
4. Plagioclase, clouded, ditto.
5. Garnet, from metadolerite, Storegut. a_0 11.666 Å.
6. Clinopyroxene, ditto.

* Total iron as FeO. 1–2, anal. P. J. Oakley; 3–6, microprobe anals. W. Davison.

Garnet occurs mostly as axial rods in the cores of plagioclase laths (fig. 1) though there are some clusters of grains in pyroxene, mostly against feldspar. The relation to plagioclase is far stronger than to pyroxene and, to a close approximation, it can be said that garnet in this rock is pseudomorphously replacing plagioclase. The garnet is an almandine with a higher pyrope content than garnets of the almandine–amphibolite facies. The grossular content is also high, in the range characteristic of almandine from mafic granulites (Winkler, 1976, p. 263). If the garnet is taken to represent original plagioclase, the ratio of feldspar to pyroxene + feldspar (59.5%) is virtually the same as in a typical dolerite (e.g. Whin Sill, 59.2%, Harrison, 1968, Table 1). In the Storegut dyke some 31% (vol.) of the original plagioclase has been converted to garnet.

The rock from the chilled margin is a uniform mosaic of polygonal grains about 60 μm across of untwinned plagioclase, clinopyroxene, olive-brown hornblende, ore, and chlorite. There is a little foxy-red biotite and little clusters of sphene. Of garnet there is only a trace.

The rock analysis (Table I) shows a clear tholeiitic affinity, but the silica content is low compared with most basalts while the mg ratio, $MgO/(MgO + FeO + Fe_2O_3)$, of 0.23 is quite low, suggesting a well-differentiated magma. The high P_2O_5 supports this, but such a rock would normally have higher SiO_2 and lower TiO_2. The oxidation ratio, $Fe_2O_3/(Fe_2O_3 + FeO)$, is 0.27, close to that taken by Weigand and Ragland (1970) as typical of the diabase dykes of E North America, and there is no reason to suppose that the rock composition has been substantially changed by metasomatism. On an ACF plot the rock composition falls well within the triangle garnet–clinopyroxene–anorthite, so that at equilibrium with garnet present, and in the absence of significant amounts of a hydrous phase, hypersthene will not occur. However, the composition lies on the clinopyroxene side of the join of anorthite to the hornblende field. Consistent with this, in the dyke margin where hornblende enters (because water had access) only a trace of garnet appears. The centre of the dyke is in the clinopyroxene–almandine subfacies of Waard (1965*a*) and the margin in the hornblende–clinopyroxene–almandine subfacies.

P–T significance of the garnet

During progade metamorphism garnet appears first in basic rocks in amphibolites of low mg ratio, low oxidation ratio, and high MnO (Leake, 1972).

This is the first garnet isograd. The second garnet isograd is where the reaction opx + an → ga + cpx + qz takes place in the granulite facies (Waard, 1965*b*; 1967). Green and Ringwood (1967) have studied this reaction experimentally and find that it occurs first, with increasing *P–T*, in iron-rich and undersaturated basalts, while the more calcic the plagioclase, the more readily it reacts.

The mineralogy of the Storegut dyke shows that we are dealing with the second garnet isograd, and the preservation of ophitic texture and the pseudomorphous habit of the garnet show that the garnet was formed during slow cooling from the intrusion temperature, amidst hot country rocks, rather than by a prograde advance from lower facies. The rock is iron-rich (mg = 0.23) and undersaturated so that garnet will form at a relatively low pressure within the granulite facies.

TABLE II. *Atoms in the space of 25 unit cells of plagioclase (16 775 Å³)*

	Plagioclase, An_{60}	Garnet
O	800	1014.34
Si	240	253.58
Al	160	169.06
Fe	—	152.30
Mg	—	51.45
Ca	60	49.82
Na	40	—
Total	1300	1650.55

In the surrounding rocks garnet has not formed in the granulite facies except as a thin pellicle around iron-ore grains, in a few rocks where iron activity was high. At reaction zones between peridotites and feldspathic granulites (Griffin, 1971), where the low pressure to intermediate pressure granulite facies boundary reaction ol + plag → opx + cpx + spinel has taken place, the succeeding reaction, on further cooling at the same pressure, would be expected to be opx + an → ga + cpx + spinel, but this has not occurred. Griffin suggests that there was uplift and a sudden drop in pressure after the first reaction, which would preclude the second. The Storegut dyke must have been injected, and its garnet must have crystallized, before the pressure fell from a value (about 8 kb) between that needed for garnet formation in rocks of mg ≈ 0.25 and that required in rocks of mg ≈ 0.5 or more.

The garnet-forming reaction

It is assumed that the dyke crystallized initially to the normative mineral assemblage. There has been very little deformation to assist reaction. The pseudomorphous texture shows that diffusion on the 0.25-mm scale has been the main process. Table II shows that the change has been a large influx of Fe, Mg, and O into the plagioclase, and minor outward movement of Na, leading to a great increase in atoms per unit volume. In this process Ca, Al, and Si in plagioclase have been immobile, while Fe, Mg, and O have been the active ions in terms of movement. Nucleation of new phases, shown by the clouding, is closely related to original plagioclase zoning and twin composition planes, suggesting little disturbance of the plagioclase lattice during the build-up of new constituents.

The garnet-forming process must have involved outward migration of Fe, Mg, and O from olivine and pyroxene areas, though initially without lattice breakdown, since these minerals are stable to higher grades in the absence of plagioclase. This movement would be governed by the high temperature. When these ions (with their differing sizes) reached central regions of plagioclase crystals, they were taken up and incorporated in a new garnet lattice dictated by the load on the plagioclase lattice. Then a diffusion gradient would be set up and the flow of ions would lead to decomposition of the olivine and hypersthene. Garnet is not such a space-saving way of storing Fe and Mg as either olivine or hypersthene. The economy of space arises from incorporating the constituents of plagioclase. The matter may be expressed by saying that the calcic plagioclase exploits the thermal wandering of the ferromagnesian ions and captures them, to lighten the load it is carrying, by recrystallizing as garnet.

Various rather complex multistage reactions with pyroxenic intermediate products have been proposed between olivine and anorthite and enstatite and anorthite (e.g. Kushiro and Yoder, 1966). Though it cannot be proved that the clouding in the plagioclase does not include these intermediates, the pseudomorphous relationship suggests a single stage recrystallization of plagioclase into garnet.

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