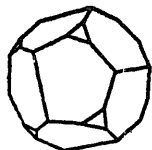


Hypersthene-ilmenite(/magnetite) symplectites in coronitic olivine-gabbronorites

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Symplectitic intergrowths of hypersthene (host) with ilmenite and minor magnetite (vermicules) in a gabbroic sill from the Precambrian of southwest Sweden occur as replacement products of olivine, and are thought to have formed simultaneously with the replacement of nearby crystals of ilmenite and Ti-magnetite by biotite and hornblende (and spinel). These interrelated replacement processes may have taken place during, or immediately after, the final stages of the magmatic crystallization, at temperatures of about 660-680°C, as part of the inherent metamorphism of the gabbroic rock. Another expression of this metamorphic imprint is the occurrence of two-tiered corona shells of hypersthene/hornblende (+spinel) at the interface of olivine and plagioclase crystals.

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Symplectitic intergrowths of pyroxene (host) with ilmenite and/or magnetite (vermicules) have been reported from many different rock types from a wide range of environments: kimberlites (e.g. Ringwood & Lovering 1970), deep-seated gabbroic rocks (e.g. Goode 1974; Van Lamoen 1979), shallow gabbroic bodies as the Skaergaard (e.g. Haselton & Nash 1975; Ambler & Ashley 1977), basaltic flows (e.g. Muir & Tilley 1957; Haggerty & Baker 1967) and a lunar basic breccia (Haselton & Nash 1975). Not surprisingly, a number of rather different petrogenetic models have been put forward to explain occurrences of such different settings. These models range from a pseudomorphic breakdown of an HP (>100 Kb) Ti-garnet to pseudomorphic breakdown of olivine by oxidation under surface conditions. Pyroxene-ilmenite/magnetite symplectites may be more widespread than commonly realized. Comparatively few petrologists examine their rocks by reflected light microscopy, the method most suited for identifying the intergrowths. In transmitted light, most of these intergrowths appear homogeneous and opaque, because of the high content of disseminated ilmenite/magnetite.

The present paper reports the results of a petrographic and micro-analytical investigation of such hypersthene-ilmenite (/magnetite) intergrowths (Fig. 1) in olivine-gabbronorites from southwest Sweden. These rocks represent the

central, massive part of one of the many, large, at places discordant, sheet-like basic bodies occurring within the gneisses which make up the bulk of the Precambrian basement of eastern Värmland. Similar basic intrusions, collectively known as *hyperites*, occur at many places in the Precambrian of southern Sweden and southern Norway, and have been described by Bugge (1922, 1943), Magnusson et al. (1958), Holtedahl & Dons (1960) and many others. Their intrusion age may be ca. 1550 m.y. (Mulder 1971; Welin et al. 1980). The quartzo-feldspathic country rocks give ages of 1700-1800 m.y. (Welin & Gorbatshev 1976; Welin & Kähr 1980). The deformation and recrystallization effects especially shown at the margins of the hyperite bodies may be of Grenvillian age (Magnusson 1929; Hjelmqvist 1934; Bugge 1943). The gabbroic rocks discussed here are not affected by this later metamorphic imprint.

Petrography

The olivine-gabbronorites containing the hypersthene-ilmenite (/magnetite) symplectitic intergrowths are medium-grained massive rocks with a dark grey colour. The rocks appear as isotropic aggregates of platy, somewhat lath-shaped plagioclase crystals, a few mm, locally up to 30 mm, in size.

In thin section the following minerals were found: amphibole, apatite, biotite, Ca-rich and Ca-poor pyroxene, garnet,

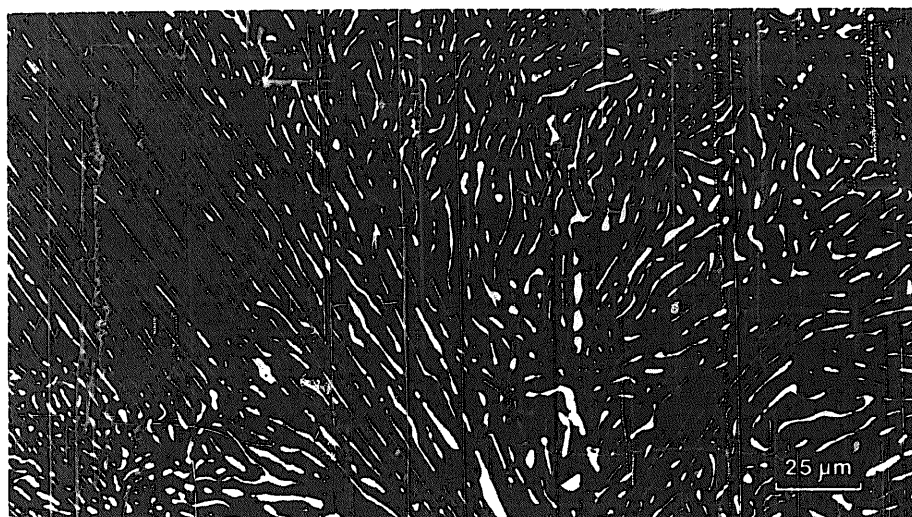


Fig. 1. Hypersthene-ilmenite(magnetite) symplectite, photomicrograph of polished section in reflected light. The dark matrix consists of hypersthene, the bright vermicular bodies of ilmenite, with a few exceptions where they are of magnetite. The two opaque phases cannot be discriminated in this picture.

ilmenite, K-feldspar, magnetite, olivine, plagioclase, pyrite, pyrrhotite, quartz, serpentine, spinel and zircon. The main magmatic paragenesis comprises plagioclase, Ca-rich and Ca-poor pyroxene and, in lesser amounts, olivine, ilmenite and Ti-magnetite. Late magmatic minerals – K-feldspar, more sodic plagioclase, quartz, biotite, hornblende, Ca-rich and Ca-poor pyroxene – were found filling the angular interstices between the earlier magmatic crystals. *Plagioclase* crystals, zoned, $An_{(60-65) (65-75) 60-55}$, idiomorphic to hypidiomorphic, $\Phi = 0.2-30$ mm, are in nesophitic to ophitic intergrowth with pyroxene crystals. Towards K-feldspar in the late magmatic interstices the plagioclase crystals may be supplied with a thin, inconstant rim of An_{45-40} . The pyroxene crystals are irregular in form, up to 2 cm in size and show a great variety of exsolutions. The *Ca-rich pyroxene*, augite, shows very regular and thin, 1–2 μ , (001) exsolution lamellae of Ca-poor pyroxene. Locally, very small amounts of light greenish augite occur in the late magmatic interstices. In most samples the main magmatic *Ca-poor pyroxene* crystallized as pigeonite, and consists now of a hypersthene matrix containing blebs and lamellae of augite in different orientations. Locally this exsolution process did not take place, preserving the homogeneous pyroxene phase (with the same bulk composition as matrix and exsolutions put together). In the more Mg-rich samples the magmatic phase is hypersthene instead of pigeonite. Very minor amounts of both early and late magmatic Ca-poor pyroxene are present. The magmatic *ilmenite* and *Ti-magnetite* crystals (ilmenite/magnetite ≈ 4) are in a subophitic type of intergrowth with the plagioclase crystals, or appear to be filling isolated interstices between the plagioclase crystals. Simple, magmatic intergrowths of ilmenite and Ti-magnetite crystals do occur. The magnetite shows exsolutions of ilmenite sheets parallel to {111}, and spinel lenses parallel to {100}. The ilmenite shows exsolutions of spinel sheets oriented parallel to {0001}. At the interface of ilmenite and magnetite crystals with plagioclase a reaction rim consisting of biotite and/or hornblende (plus some spinel) was found to be fairly consistently developed. Where both biotite and hornblende are present, the biotite is in a separate zone directly surrounding the ilmenite/magnetite. The *olivine* crystals, rather large, $\Phi = 0.5-2$ mm, locally in clusters of two or three crystals, are supplied with two-tiered reaction rims along the olivine/plagioclase interface: an inner orthopyroxene rim, towards the olivine, is surrounded by an outer one of hornblende-spinel symplectite. Garnet locally replaced the outer rim.

Hypersthene-ilmenite(magnetite) symplectites (Figs. 1 and 2) occur as irregular, bulbous bodies, and in some cases as irregular veins within olivine crystals. The symplectite bodies vary from 0.2 to 0.7 mm in diameter and consist of irregular vermicules of ilmenite, 1–5 μ wide and 20–200 μ long, set in a hypersthene matrix. A few vermicules were found to consist of magnetite. This magnetite phase does not show ilmenite exsolution. The opaque stringers form $30 \pm 2\%$ by volume of the symplectites, determined by point counting of enlarged photomicrographs. This high content of disseminated ilmenite and magnetite renders these intergrowths opaque in thin section. This hinders the determination of the hypersthene by optical means. Instead it was identified and analysed by microprobe and electron microscope. The latter apparatus, however, was used only in a semi-quantitative way to make rapid checks of the matrix composition at a large number of points. It was thus confirmed that all of the matrix is hypersthene, though of somewhat variable composition. Practically all symplectite bodies occur where olivine in the section can be seen to be in contact, or nearly so, with magmatic ilmenite or Ti-magnetite crystals. The exceptions to this rule are so few that they can readily be explained by assuming that the plane of section has just missed the oxide crystals. However, it is not uncommon to find contacts between olivine and ilmenite/magnetite crystals which are not supplied with symplectites. Commonly the symplectite bodies are separated from the magmatic ilmenite/magnetite crystals by a thin, irregular rim of hypersthene (Fig. 2 g), or, more rarely, of biotite, but direct contacts be-

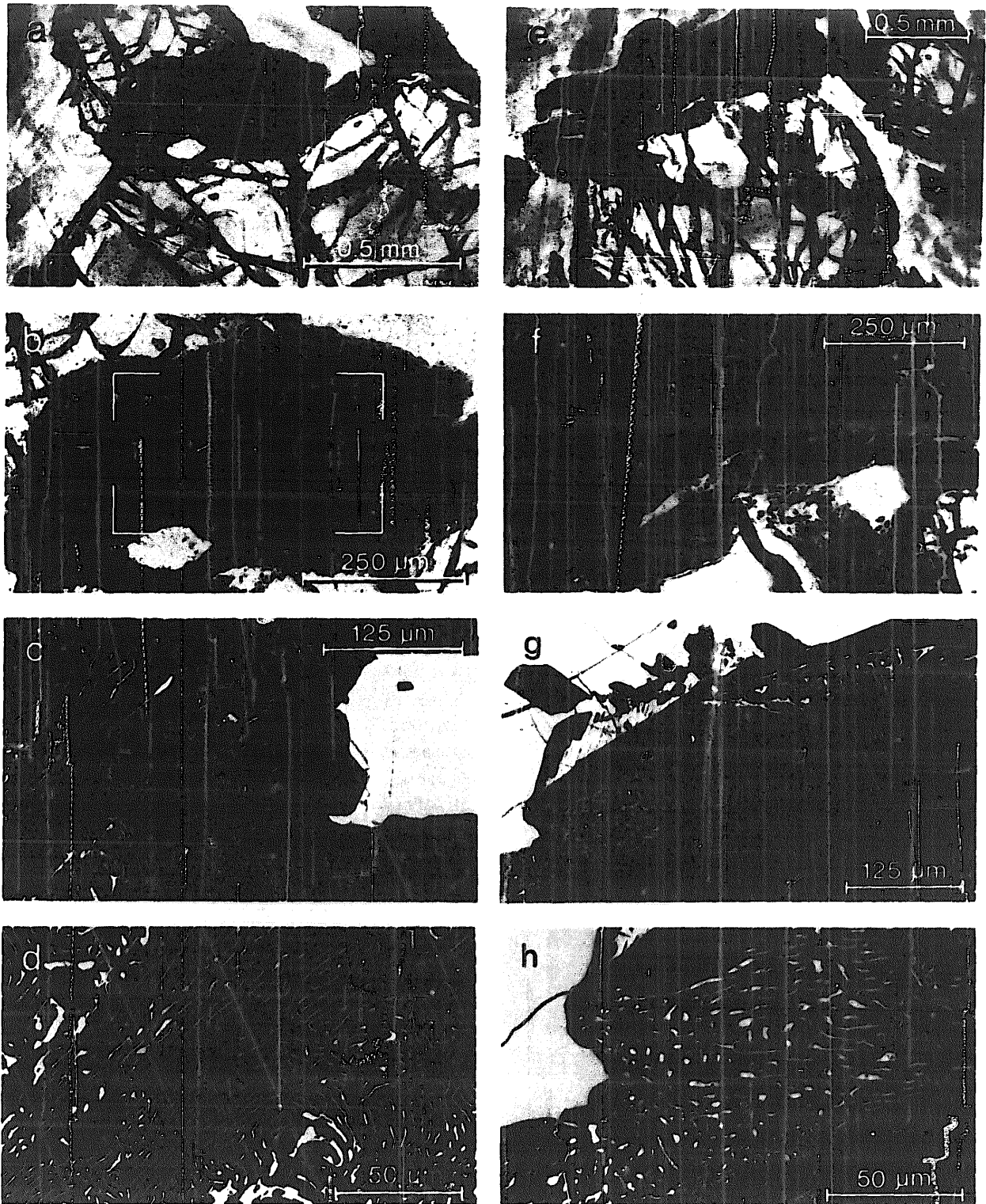


Fig. 2. Two occurrences of hypersthene-ilmenite(magnetite) symplectite, illustrated in two columns of photomicrographs. Figs. *a* and *e* are in transmitted light and show olivine crystals with adjacent opaque material. Figs. *b* and *f* present a close-up of the opaque material. Figs. *c* and *g* give a further enlargement in reflected light. Fig. *c* stresses that the 'opaque material' of the transmitted light pictures is inhomogeneous, consisting of hypersthene-ilmenite(magnetite) symplectite and a large ilmenite crystal. Fig. *g* shows the symplectite directly bordering on olivine (lower right hand corner), it is separated from the large ilmenite and Ti-magnetite crystals (left hand top) by a thin rim of hypersthene (without ilmenite/magnetite vermicules). Figs. *d* and *h* give a further close-up of the symplectites.

tween ilmenite/magnetite crystals and symplectite do occur.

Mineral chemistry

Mineral analyses were made with the Hitachi XMA-5B electron microprobe of the Institute of Mineralogy, Copenhagen University (analytical procedures given by Pedersen et al. 1975), and the TPD electron microprobe of the Vening Meinesz Laboratory, Utrecht University. Two samples were used (74Z59 and 75Z109) and the following crystals were analysed: – olivine, magmatic Ca-poor and Ca-rich pyroxenes, hypersthene from the coronas at the olivine/plagioclase interface and hypersthene and ilmenite from the symplectites. Analytical data are plotted in Fig. 3, and listed in Tables 1 and 2. A list of the complete analytical results is available from the authors.

Sample 74Z59 is more Fe-rich than 75Z109. In 74Z59 the analysed olivine crystals, while unzoned, have different compositions ranging from Fa_{47} to Fa_{52} , in 75Z109 from Fa_{39} to Fa_{43} .

The composition of the main magmatic Ca-poor pyroxene in sample 74Z59 has been determined in two ways. In crystal portions which are optically homogeneous, without exsolutions, by repeated point analysis, and in crystal portions showing exsolutions by a moving defocussed beam giving an integrated composition of matrix and exsolved augite. Both methods give very similar results with an average of $Wo_{9.3}En_{57.1}Fs_{33.6}$, which conforms very well to the compositions reported by Nwe (1976) for the Skaergaard gabbro (Fig. 3). In the more Mg-rich sample, 75Z109, the main magmatic Ca-poor pyroxene is orthopyroxene free of exsolutions and poorer in Ca ($Wo_{4.3}En_{66.7}Fs_{29.0}$) (see Fig. 3). This suggests that in the gabbroic rock discussed in the present paper the orthorhombic Ca-poor pyroxene crystallized up to somewhat Fe-richer compositions than in the Skaergaard magma. In sample 74Z59 the early and late Ca-poor pyroxene phases, present in very small amounts, have been analysed. The early phase is variable in composition and notably poor in Ca ($Wo_{1.5}$) and the late

phase is Ca-poor and Fe-rich ($Wo_3En_{56}Fs_{41}$) (see Fig. 3). The Ca-rich pyroxene composition has been determined with a moving defocussed beam giving a composition of approximately $Wo_{35.1}En_{44.3}Fs_{20.6}$ in sample 74Z59, and $Wo_{35.9}En_{45.0}Fs_{19.1}$ in 75Z109. These compositions are somewhat Ca-poorer than those reported by Nwe (1976) for the Skaergaard gabbro. The tie-line between the main magmatic Ca-rich and Ca-poor pyroxenes for sample 74Z59 conforms to those given by Nwe (1976), but that for sample 75Z109 is less steep (see Fig. 3).

The hypersthene in the coronas at the plagioclase/olivine interface is universally low in Ca ($Wo_{0.4-0.8}$) and shows an En/Fs ratio which is systematically lower than the Fo/Fa ratio of the olivine crystal which is replaced (see Table 1 and Fig. 3). In Fig. 4 this compositional relation is compared with those of other equilibrated olivine-orthopyroxene pairs reported by other authors.

The hypersthene in symplectitic intergrowth with ilmenite (magnetite) yields compositions similar to the corona hypersthene, though a few point analyses show rather high Ca content ($Wo_{1.9}$) (see Table 2 and Fig. 3). The ilmenite vermicules have been analysed by microprobe. The results (Table 2) show a relatively large content of SiO_2 , ranging from 0.78 to 1.11 wt. %, whereas published ilmenite compositions in gabbroic rocks show values ranging from 0.05 to 0.8 wt. % (see, for example, Deer et al. 1962 and Haggerty 1976). A feasible explanation for the high SiO_2 value is that the surrounding hypersthene has contributed to the analytical result. This is not surprising considering the small size of the ilmenite vermicules, and it would also explain the rather poor analytical totals, both for the ilmenite and the hypersthene. Repeated analyses have shown, however, that it is not possible to improve these results using the microprobe.

The Mg/Fe distribution between equilibrated ilmenite and pyroxene has been proposed as a geothermometer by Anderson et al. (1972). An improved calibration based on experimentally equilibrated mineral pairs was recently given by Bishop (1980). Three symplectitic ilmenite-hy-

Fig. 3. Compositional diagrams for olivine and various pyroxenes in two samples, 74Z59 (Figs. 3a, b,) and 75Z109 (Figs. 3c, d). Open symbols for olivine and orthopyroxene represent values for two sets of directly adjacent crystals, as illustrated in the schematical drawing of Fig. 3e. The hatched lines represent solidus and subsolidus pyroxene compositions, and the thin solid lines tie-lines between them, as given by Nwe (1976) for the early crystallization products of the Skaergaard magma. The heavy solid line represents the apparent pyroxene tie-line in the two samples studied here.

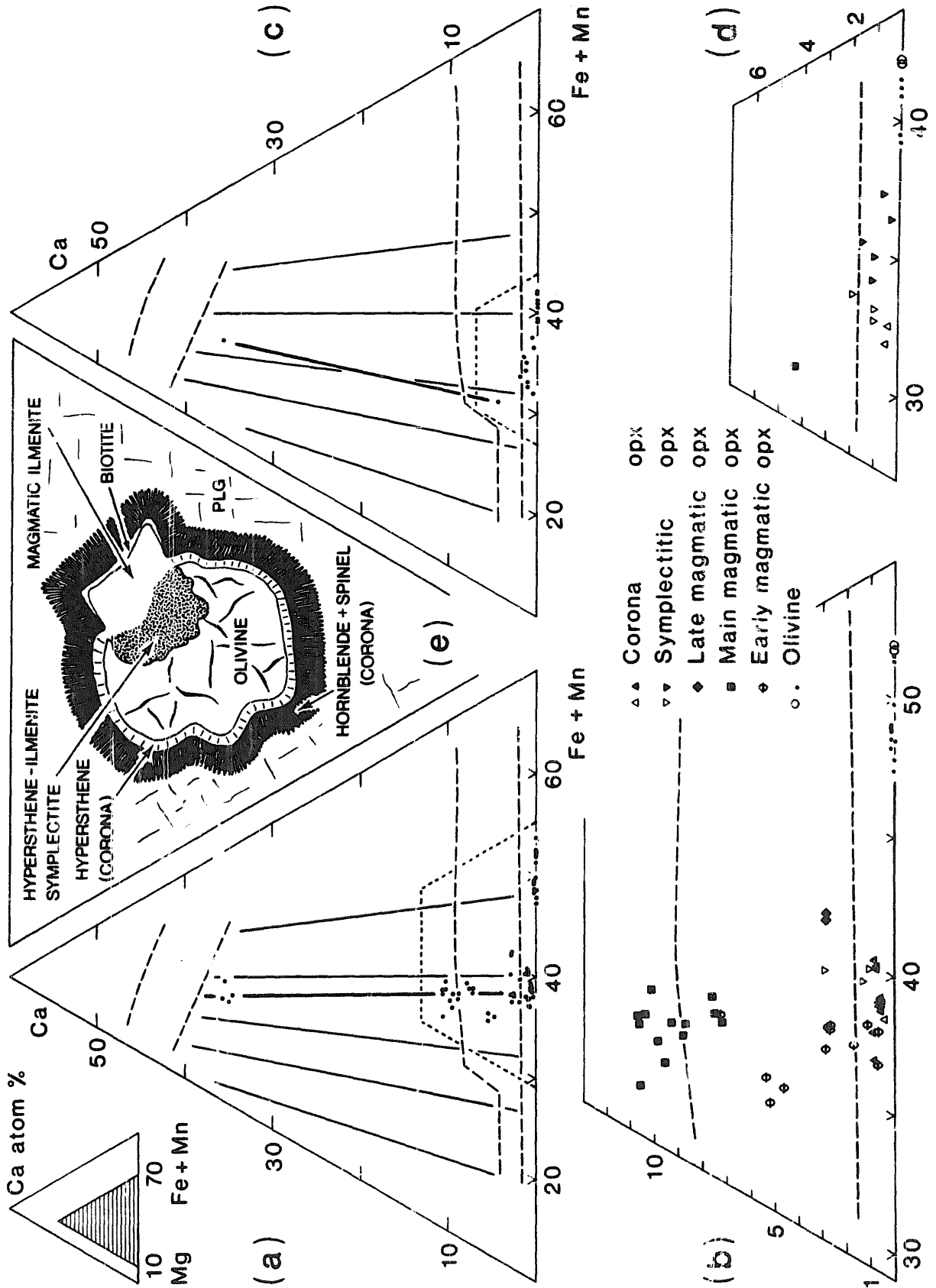


Table 1. Chemical composition of five pairs of olivine and directly adjacent corona orthopyroxene. Pairs 1–4 are from sample 74Z59 and 5 is from 75Z109 (see Fig. 4).

	1		2		3		4		5	
	ol.	opx	ol.	opx	ol.	opx	ol.	opx	ol.	opx
SiO ₂	33.86	52.99	34.46	52.37	34.47	52.07	34.49	51.83	35.68	53.09
TiO ₂	.03	.04	.02	.06	.07	.02	.06	.02	.02	.02
Al ₂ O ₃	.05	.81	.03	.57	.03	.63	.03	.74	.09	1.12
FeO*	43.18	23.96	42.82	24.13	42.63	24.05	41.85	23.63	36.02	20.34
MnO	.56	.52	.50	.45	.46	.44	.47	.44	.48	.42
MgO	22.71	21.76	21.21	20.39	22.42	21.52	22.38	21.06	28.13	24.52
CaO	.00	.24	.04	.33	.03	.27	.02	.32	.02	.24
Na ₂ O	.09	.05	.17	.17	.00	.06	.06	.02	.11	.04
K ₂ O	–	–	.03	.05	.03	.05	.03	.04	–	–
Total	100.48	100.37	99.28	98.52	100.14	99.11	99.39	98.10	100.55	99.79
Si	5.875	7.915	6.033	7.988	5.968	7.897	5.999	7.928	5.938	7.845
Ti	.004	.004	.002	.007	.010	.002	.007	.002	.003	.002
Al	.010	.143	.006	.103	.006	.113	.006	.133	.018	.195
Fe ²⁺	6.266	2.993	6.270	3.077	6.172	3.051	6.088	3.023	5.013	2.514
Mn	.082	.066	.074	.058	.067	.057	.069	.057	.068	.053
Mg	5.872	4.844	5.536	4.638	5.788	4.866	5.805	4.803	6.977	5.400
Ca	.000	.038	.008	.054	.005	.045	.004	.052	.004	.038
Na	.030	.014	.057	.051	.000	.018	.021	.005	.035	.011
K	–	–	.008	.009	.008	.009	.006	.008	–	–

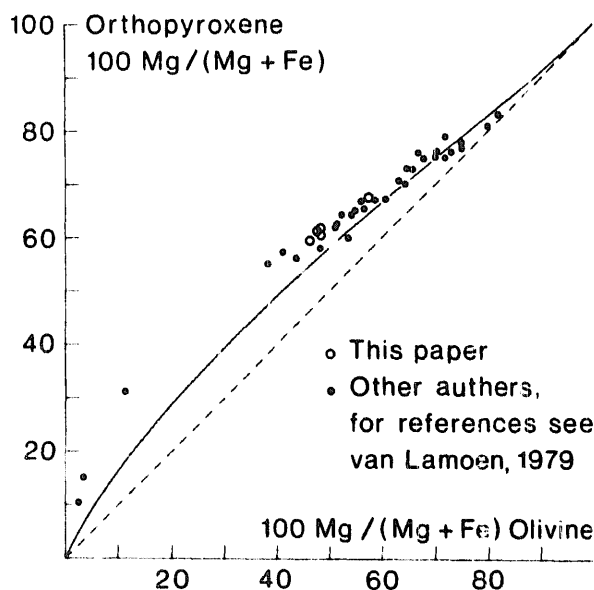


Fig. 4. A Mg/Fe partitioning diagram for equilibrated olivine and orthopyroxene. The diagram shows five directly adjacent olivine and hypersthene pairs from this study (Table 1), and a number of determinations by other authors (for references see Van Lamoen 1979, Fig. 6). The curved solid line represents the best fit curve – $\log \left(\frac{X_{Fe}}{X_{Mg}} \right)_{ol} = 0.1630 + 1.1128 \log \left(\frac{X_{Fe}}{X_{Mg}} \right)_{opx}$ – for the experimental partitioning values at 900°C, $P_{fluid} = 0.5$ Kb and $f_{O_2} \equiv$ QFM buffer, determined by Medaris (1969).

persthene pairs have been introduced to the equation given by this author. In making these calculations one might consider a number of limiting cases depending on whether (1) all iron is taken as FeO or whether a stoichiometrically fitting FeO/Fe₂O₃ ratio is calculated, and (2) whether MgO (and FeO) in the ilmenite are corrected for matrix contamination or not (see Table 2). The resulting temperatures vary from 623°C to 713°C at 2 Kb. In trying to restrict that range, one might argue (1) that calculating a FeO/Fe₂O₃ ratio for microprobe results is a reasonable procedure, thus preferring model (c) and (d) of Table 2. One might further argue that although the high SiO₂ content indicates a matrix contamination, the ilmenite might have had a SiO₂ content of its own of say 0.2 to 0.4. This would reduce the matrix effect and suggest temperatures of 660–680°C, which we regard as the most feasible temperature estimate for the formation of the symplectites.

Interpretation and discussion

The modes of origin suggested for pyroxene-ilmenite/magnetite symplectites from occur-

Table 2. Geothermometry based on three ilmenite/hypersthene pairs from the symplectitic intergrowths.

	1		2		3	
	ilm	opx	ilm	opx	ilm	opx
SiO ₂	.78	52.69	.84	52.59	.93	53.67
TiO ₂	47.66	.16	49.17	.13	47.36	.22
Al ₂ O ₃	.06	1.08	.40	1.12	.21	1.81
Cr ₂ O ₃	-	-	-	-	-	-
NiO	-	-	-	-	-	-
FeO*	44.98	21.07	44.45	21.52	45.51	20.67
MnO	.57	.21	.80	.23	.72	.49
MgO	1.68	23.06	1.72	22.77	1.89	24.16
CaO	-	.56	-	.43	-	.52
Na ₂ O	-	-	-	-	-	.02
Total	95.73	98.83	97.38	98.79	96.62	101.50

(a) FeO*, no matrix contamination

$\ln K_D$	3.3777	3.3085	3.3349
Fe/(Fe + Mg) ^{ilm}	.9376	.9355	.9311
T, 2Kb	675°C	694°C	684°C

(b) FeO*, maximal matrix contamination

$\ln K_D$	3.5970	3.5370	3.5756
Fe/(Fe + Mg) ^{ilm}	.9493	.9480	.9450
T, 2Kb	623°C	637°C	626°C

(c) FeO/Fe₂O₃ calculated, no matrix contamination

$\ln K_D$	3.2668	3.2369	3.2215
Fe/(Fe + Mg) ^{ilm}	.9308	.9310	.9217
T, 2Kb	704°C	713°C	713°C

(d) FeO/Fe₂O₃ calculated, maximal matrix contamination

$\ln K_D$	3.4853	3.4649	3.4612
Fe/(Fe + Mg) ^{ilm}	.9436	.9443	.9374
T, 2Kb	649°C	655°C	652°C

Pair 1 is from sample 74Z59, and pairs 2 and 3 from 75Z109. The temperatures are calculated with the help of the empirical equation given by Bishop (1980):

$$T(^{\circ}\text{C}) = \frac{1646 + 1634 \left[\frac{\text{Fe}^{2+}}{\text{Fe}^{2+} + \text{Mg}} \right]_{\text{ilm}} + 0.0124P}{\ln K_D} - 273,$$

where $K_D = (\text{Mg}/\text{Fe})^{\text{opx}}/(\text{Mg}/\text{Fe})^{\text{ilm}}$, and P is in bars. Four limiting cases are tested:

- All iron is ferrous, and analytical MgO (and FeO) values for ilmenite are real, not influenced by matrix contamination.
- All iron is ferrous, and MgO (and FeO) values for ilmenite suffer from maximum matrix contamination (all SiO₂ stems from the surrounding hypersthene).
- FeO/Fe₂O₃ calculated (based on a stoichiometric formula), no matrix contamination.
- FeO/Fe₂O₃ calculated, maximal matrix contamination.

rences quite different from the one presented in this paper will not be elaborated upon, as they clearly do not apply. For example, the clinopyroxene-ilmenite and orthopyroxene-ilmenite xenoliths in kimberlites are interpreted as converted HP (> 100 Kb) garnet (Ringwood & Lovering 1970), exsolved HP (> 40 Kb) pyroxene (Dawson & Reid 1970; Ringwood & Major 1968), or products of equilibrium, eutectic crystallization (MacGregor & Wittkopp 1970) in the Low-Velocity Zone (Boyd & Nixon 1973). We

will restrict our literature comparisons to those symplectites found in basic, mainly gabbroic rocks, conforming to the occurrence discussed here.

For orthopyroxene-magnetite symplectites, texturally similar to the symplectites discussed here, some authors have suggested an origin by oxidation of the olivine that is replaced. It is essential for this model that the symplectitic orthopyroxene is considerably more Mg-rich than the original olivine, as is illustrated by the

ideal replacement reaction for Fa_{50} olivine: $3Fe_2SiO_4 + 3Mg_2SiO_4 + O_2 \rightarrow 2Fe_3O_4 + 6MgSiO_3$. Haggerty & Baker (1967) reported such enstatite-magnetite intergrowths from subaerial basalt flows and from laboratory experiments in which olivine is heated in air. For more deep-seated environments proof of this oxidation process appears rather weak. Muir & Tilley (1957), who are often quoted as the originators of the oxidation hypothesis, found the intergrowths in 'thoroughly metamorphosed' picrite basalt; however, the replacive orthopyroxene ($Fs_{2.4}$) was shown to be more Fe-rich than the magmatic olivine (Fa_{20}). In appreciation of this, these authors rightly concluded that the oxidation reaction does not suffice to explain the replacement of the olivine. Goode (1974) proposed the oxidation model for orthopyroxene-magnetite symplectites in gabbroic rocks intrusive into granulite facies gneisses of the Musgrave Block, Central Australia, though clear evidence for the much more Mg-rich composition of the replacive orthopyroxene was not given. A somewhat different oxidation model was given by Haselton & Nash (1975) for hypersthene-ilmenite/magnetite symplectites from the lower parts of the Skaergaard intrusion. It was claimed that these intergrowths were formed by oxidation of Ti-magnetite inclusions in magmatic orthopyroxene. The origin of these Ti-magnetite inclusions was left unexplained.

The symplectitic intergrowths discussed in the present paper can hardly be explained by the oxidation model. Not only do they feature ilmenite, with magnetite only present in traces, but also the orthopyroxene composition, though slightly Mg-richer than the olivine (cf. Table 1, Fig. 3), is too Fe-rich to comply with the model (cf. quantitative calculations by Ambler & Ashley 1977:171).

Some authors have interpreted orthopyroxene-magnetite symplectites in gabbroic rocks as magmatic features. McSween & Nystrom (1979) proposed that the symplectites formed by a reaction between residual melt and magmatic orthopyroxene, thus not involving the olivine, which is present in their rocks, in the formation of the symplectites. This distinguishes this hypothesis from all the others; the evidence for it does not seem quite convincing (cf. discussion by Ambler & Ashley 1980 and McSween 1980). Ambler & Ashley (1977) concluded that orthopyroxene-magnetite symplectites from gabbroic rocks from the Wateranga intrusion, Queensland, Australia, represent eutectic-like intergrowths formed by

co-precipitation of orthopyroxene and magnetite at dispersed locations in a crystal mush where olivine was reacting with residual melt. This hypothesis is mainly based on (1) the presence of brown pargasitic hornblende which is considered as magmatic, and which was seen replacing the symplectites, and (2) the occurrence of ilmenite exsolution lamellae in the symplectitic magnetite indicating the HT character of the symplectite formation. These features are not present in the rocks discussed here, and the symplectites are not related texturally to the late magmatic interstitial fillings. Therefore, it is concluded that this hypothesis is not applicable to the symplectites discussed here.

Van Lamoen (1979) has interpreted orthopyroxene-magnetite symplectites in gabbroic rocks from SW Finland as having been formed by metamorphic replacement of olivine in close relationship to the formation of the inner pyroxene shell in the coronas at the olivine/plagioclase interface. It was suggested that the Fe for the magnetite mainly comes from the olivine, the main chemical exchange consisting of an expulsion of Mg; the following reaction was suggested: olivine + fluid (0.06 Al + 0.03 Ti) \rightarrow 1.03 orthopyroxene + 0.21 magnetite + fluid (0.44 Mg). This author claimed that the occurrence of the symplectites within the olivine would be restricted to zones directly bordering upon adjacent crystals of opaque oxides. It was suggested that this textural setting would have prevented the exchange of Fe, Mg and Si which took place at the olivine/plagioclase interface, and which there led to the formation of the two-tiered coronas. This model cannot be used for the symplectites discussed here because an external source for the Ti is needed. However, the proposed genetical setting of the symplectites as post-magmatic, metamorphic products seems to fit our occurrence.

In the symplectites described in the present paper all hypersthene-ilmenite symplectites occur within olivine crystals, as bulbous bodies or replacement veins. This indicates that the symplectites were formed by replacement of the olivine. The consistent juxtaposition of, on the one hand, magmatic ilmenite and Ti-magnetite crystals that are marginally replaced by biotite and hornblende (and some spinel) and, on the other hand, hypersthene-ilmenite/(magnetite) symplectites within olivine crystals, indicates that these two replacement processes are interrelated. The temperature estimate of about 660–680°C given above for the formation of the sym-

plectites would suggest that this process is contemporaneous with the crystallization of the granitic interstitial residual melt, or slightly later. Compare for example Winkler (1979), who suggested final crystallization temperatures of about 670°C at $P_{H_2O} = 2$ Kb for the Q-Ab-Or system. The analytical results on the hypersthene in the symplectitic intergrowths are in agreement with this conclusion. This hypersthene composition is similar to that of the coronas' hypersthene which is of clearly metamorphic origin, while some spot analyses give a rather high Ca content ($Wo_{1.9}$) making for compositions tending towards the late magmatic Ca-poor pyroxene (see Fig. 3).

These textural and compositional features suggest that the magmatic ilmenite and Ti-magnetite have reacted with a fluid phase rich in K and Si, during or immediately after the latest stages of the magmatic crystallization. This reaction probably involved plagioclase and produced biotite and hornblende (and spinel). The Ti set free by this process reacted through the fluid phase with the olivine and was redeposited as ilmenite, according to a reaction such as: olivine + Ti-rich fluid \rightarrow hypersthene + ilmenite + fluid.

This interpretation explains the symplectites as replacement features resulting from the inherent metamorphism, i.e. the metamorphism which takes place in the PT-regime which represents the cooling of the magmatic mass (cf. Zeck 1971). These metamorphic processes may start during the final stages of the magmatic crystallization. At that point the rock is mechanically rigid with small pockets of granitic melt remaining between the main phase crystallization products. The aqueous fluid phase active in this process may be juvenile, formed internally within the rock, or meteoric brought in by a Taylor convection (Zeck & Wallin 1980). The more predominant effect of this metamorphic imprint is the formation of the well developed two-tiered coronas around the olivine crystals at the contact with plagioclase, formed by a reaction such as: olivine + plagioclase + fluid \rightarrow orthopyroxene + hornblende + spinel + fluid (cf. Törnebohm 1877; Griffin & Heier 1971, 1973; Van Lamoen 1979). It seems uncertain, though, whether the formation of the coronas and the symplectites occurred simultaneously, as was concluded by Van Lamoen (1979). Goode (1974) presented evidence that symplectite formation post-dates the formation of the double-tiered orthopyroxene/hornblende coronas at the olivine/plagioclase interface. Also Frodesen (1968), in his

study of the Hiåsen gabbro (hyperite) in S Norway, concluded that the replacement of olivine by 'granular aggregates of orthopyroxene with large amounts of iron ore' post-dates the corona formation.

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