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ORIENTED MAGNETITE INCLUSIONS IN PYROXENES FROM THE GRENVILLE PROVINCE

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ABSTRACT

Oriented magnetite inclusions in primary pyroxene grains from two localities in the Grenville province, Renzy Lake (hornblende–granulite facies) and Umfraville (lower–middle almandine–amphibolite facies) have been investigated by petrographic and X-ray precession techniques. The magnetite inclusions are in the form of blades or flattened rods lying in the (010) plane. In augite they occur in two orientations designated "*Z*", inclined to the *Z* axis with "*Z*" Λ *Z* = 9°, and "*X*", inclined to the *X* axis with "*X*" Λ "*Z*" = 104°. Both dimensional orientations are associated with unique, specific crystallographic orientations. "*Z*" inclusions have $[\bar{1}10]_{mt}/\!/Y_{aug}$, $[111]_{mt}/\!/X^*_{aug}$, $[\bar{1}\bar{1}2]_{mt}/\!/Z_{aug}$, and the magnetite lattice is rotated 0.4° clockwise about the augite *Y* axis. "*X*" inclusions have $[\bar{1}10]_{mt}/\!/Y_{aug}$, $[\bar{1}\bar{1}1]_{mt}/\!/[\bar{1}01]^*_{aug}$, $[112]_{mt}/\!/[101]_{aug}$, and the magnetite lattice is rotated 1.9° anticlockwise about the augite *Y* axis. Orthopyroxenes have only "*Z*" inclusions, oriented parallel to the *Z* axis. The "*Z*" and "*X*" magnetite inclusions are, respectively, equivalent to "100" and "001" exsolved pigeonite lamellae in augite. The optimal-phase-boundary theory for pyroxene lamellae may be applied directly to a rationalization of the attitude and lattice rotation of the oriented magnetite inclusions, since the crystal structures of the two phases are related by common layers of close-packed oxygen atoms. The calculated inclination angles are very sensitive to ambient temperature. Excellent agreement is realized at about 600°C for both Renzy Lake and Umfraville augite. The magnetite inclusions were most likely precipitated as a breakdown or reaction product on metamorphic reheating to amphibolite-facies conditions. This hypothesis is consistent with the textural relations, mineral compositions and phase-boundary geothermometry.

Keywords: Grenville province, pyroxene, magnetite inclusions, geothermometry, optimal-phase-boundary theory, Umfraville, Renzy Lake.

SOMMAIRE

Nous avons étudié, pétrographiquement et aux rayons X, par précession, les inclusions de magnétite orientée dans les pyroxènes primaires de deux roches grenvilliennes, l'une du lac Renzy (facies granulite à hornblende), l'autre de Umfraville (facies amphibolite à almandine moyen inférieur). Les inclusions, en lames ou en bâtonnets aplatis, sont dans le plan (010) de l'augite, en deux orientations. Les unes ("*Z*") font un angle de 9° avec l'axe *Z*; les autres ("*X*") recroupent l'axe *X*, et "*X*" Λ "*Z*" = 104°. Dans les premières, $[\bar{1}10]_{mt}/\!/Y_{aug}$, $[111]_{mt}/\!/X^*_{aug}$, $[\bar{1}\bar{1}2]_{mt}/\!/Z_{aug}$, et le réseau de la magnétite est tourné de —0.4° (sens horlogique) autour de l'axe *Y* de l'augite. Les inclusions "*X*" montrent les relations $[\bar{1}10]_{mt}/\!/Y_{aug}$, $[\bar{1}\bar{1}1]_{mt}/\!/[110]^*_{aug}$, $[112]_{mt}/\!/[101]_{aug}$, et le réseau de la magnétite est tourné de +1.9° autour du même axe. Les orthopyroxènes possèdent seules les inclusions "*Z*", parallèles à l'axe *Z*. Les inclusions "*Z*" et "*X*" sont équivalentes aux lamelles d'exsolution "100" et "001" de pigeonite dans l'augite. La théorie de l'interface optimum entre ces deux pyroxènes peut expliquer l'orientation des inclusions et la rotation du réseau de la magnétite, vu que les deux structures cristallines en présence sont reliées par des couches d'atomes d'oxygène en empilement compact. Les relations angulaires calculées dépendent fortement de la température; à ~ 600°C l'accord est excellent pour les augites des deux localités. Les inclusions de magnétite ont très probablement été précipitées au cours d'un réchauffage de métamorphisme jusqu'aux conditions du facies amphibolite; cette hypothèse est compatible avec les relations texturales, les compositions minérales et la géothermométrie de l'interface.

(Traduit par la Rédaction)

Mots-clés: province Grenville, pyroxène, inclusions de magnétite, géothermométrie, théorie de l'interface optimum, Umfraville, lac Renzy.

INTRODUCTION

Pyroxenes in ultrabasic, basic and related rocks frequently contain oriented inclusions of both other pyroxenes (augite, hypersthene, pigeonite) and chemically unrelated phases such as magnetite, spinel, ilmenite, hematite, plagioclase and amphibole. A comprehensive survey of the relevant literature is given in Deer *et al.* (1977). Oriented magnetite inclusions characteristically occur as thin plates, blades or rods; Bown & Gay (1959) have recognized two distinct orientations of them in augite from Kragerö, Norway. In the first orientation, referred to as "*Z*" axis or "*Z*" below, the magnetite rods are elongate parallel to the augite *Z* axis and have the crystallographic orientation $(111)_{mt}//(100)_{aug}$, $[1\bar{1}0]_{mt}//Y_{aug}$. In the second orientation, referred to as "*X*" axis or "*X*" below, the rods are elongate parallel to the augite *X* axis with $(\bar{1}\bar{1}3)_{mt}//(001)_{aug}$, $[1\bar{1}0]_{mt}//Y_{aug}$. "*Z*" inclusions of magnetite and spinel occur in augite from the gabbro xenoliths in the basalts of Gough Island, South Atlantic (Le Maitre 1965), and "*X*" inclusions of spinel have been reported in a lunar augite (McCallum *et al.* 1975). Titanomagnetite inclusions in augite from the Kap Edvard Holm upper layered series (Elsdon 1971) and spinel in augite from the layered intrusions of the Giles complex, central Australia (Goode & Moore 1975) occur in both "*Z*" and "*X*" orientations. Naturally occurring oriented magnetite inclusions in orthopyroxene apparently have not been reported, but spinel inclusions in orthopyroxene are quite common (Moore 1968, White 1966, Le Maitre 1965).

This paper reports on oriented magnetite inclusions in pyroxenes from two localities within the Grenville province, Renzy Lake (western Québec) and Umfraville (eastern Ontario). In particular, it is shown that inclusions in "*Z*" and "*X*" orientations in augite are actually only subparallel to the *Z* and *X* axes, respectively, and this permits a crystal-chemical analysis analogous to that for exsolution lamellae of pyroxene (Robinson *et al.* 1971, 1977, Jaffe *et al.* 1975). Pyroxenes from Renzy Lake have been studied previously by Johnson (1972) and Paul (1976). The present work is an extension of the thesis study of Bilcox (1979).

Pyroxenes from Renzy Lake

The Renzy Lake ultramafic complex in Hainaut Township, western Québec, is a small, sill-like body enclosed by paragneiss. It consists essentially of layered peridotite–pyroxenite enclosed by a hornblende–peridotite border zone, and has been metamorphosed to the hornblende–granulite facies (Johnson 1972).

Oriented magnetite inclusions are present in grains of augite (diopside), orthopyroxene (bronzite) and hornblende. The present study is restricted to pyroxene phases: magnetite inclusions are less well developed in hornblende, and the crystallographic and dimensional orientation relationships appear equivalent to those for augite described below. Both augite and orthopyroxene occur in two generations of crystallization: as large, irregular grains, which are evidently primary (magmatic) in origin, and as recrystallized equant polygonal grains, which are clearly metamorphic in origin. Magnetite inclusions are densely distributed in the central areas of the primary grains. Inclusion-free margins tend to be quite narrow, especially in poikilitic orthopyroxene grains, but do vary appreciably in width from grain to grain and rock to rock. Recrystallized pyroxene grains are relatively free of inclusions. The pyroxenes exhibit incipient alteration to amphibole. In particular, primary augite grains contain ragged lamellar patches of hornblende. Intergranular grains and randomly oriented inclusion blebs of magnetite are scattered throughout the rock specimens examined in the present study and

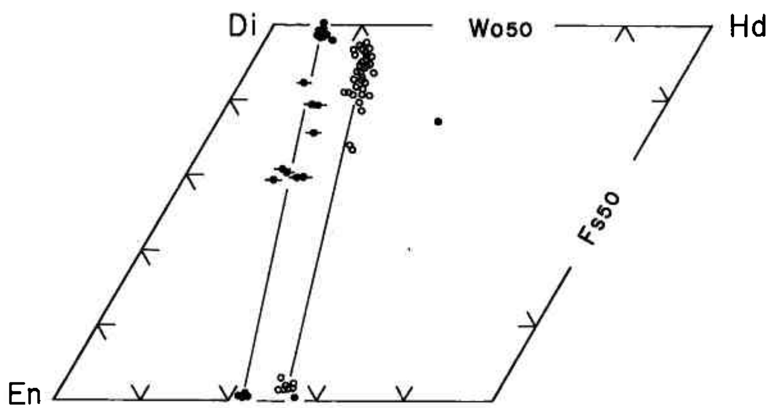

FIG. 1. Electron-microprobe spot analyses of coexisting pyroxenes from Renzy Lake hornblende peridotite (closed circles), and Umfraville olivine gabbro (open circles). Spot analyses of Renzy Lake augite (diopside) from areas with partial hornblende replacement and Renzy Lake hornblende are indicated with horizontal bar. Iron is reported as total Fe.

appear to be present to the extent of 2 to 5 modal %.

The Renzy Lake pyroxenes examined in the present study all come from hornblende peridotites. Electron-microprobe analysis (Fig. 1) suggest approximate compositions of $En_{45}Fs_{6}Wo_{49}$ for augite and $En_{78}Fs_{21.5}Wo_{0.5}$ for orthopyroxene. Both the mean value for $K_{D Mg.Fe}$ (2.17) and the Ca contents of the coexisting pyroxenes are typical of granulite-facies rocks (Fleet 1974b). Evidently, the Renzy Lake ultramafic rocks have been thoroughly equilibrated chemically even though they have a relict igneous texture. Augite and orthopyroxene grains are fairly homogeneous and lack any systematic compositional variation between the inclusion-rich cores and clear margins. A few microprobe spot analyses are displaced toward ferrosilite composition (Fig. 1) and clearly represent contamination by magnetite inclusions. However, the present data do not exhibit bimodal distributions and thus do not yield even a qualitative impression of the amount of iron associated with the

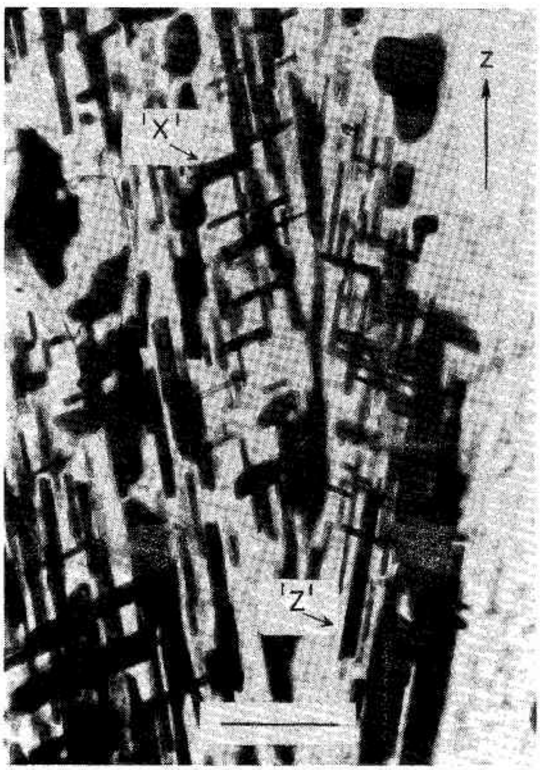

FIG. 2. Optical micrograph of "Z" and "X" magnetite inclusions in twinned Renzy Lake augite (diopside). Plane-polarized light. Scale bar is 25 mμ.

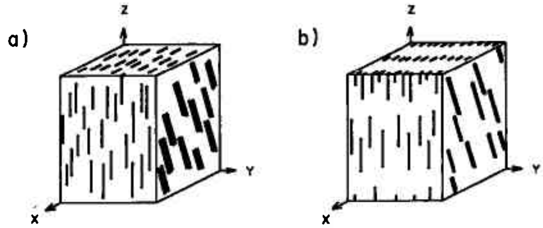

FIG. 3. Schematic distribution of "Z" magnetite inclusions in augite from (a) Renzy Lake peridotite, (b) Umfraville olivine gabbro.

magnetite phase. Several analyses within inclusion-rich cores of augite grains are displaced along the augite-orthopyroxene tie-line toward low-Ca compositions; this trend simply represents contamination by hornblende replacing augite (Fig. 1).

Augite grains have oriented magnetite inclusions in both "Z" and "X" orientations, although the former are larger and more numerous (Fig. 2). The inclusions are blade-like in shape, with maximum flattening in the (010) plane (Fig. 3a). Maximum dimensions are about 5 x 0.3 x 80 mμ for "Z" inclusions and 30 x 0.3 x 5 mμ for "X" inclusions; however, the apparent size of inclusions varies over about one order of magnitude (Fig. 2).

The extremely thin, blade-like nature of the inclusions can give a completely misleading impression of the relative proportions of inclusions to host crystal. In particular, augite in (010) section may be completely occluded by magnetite inclusions. However, sections cut normal to (010) suggest maximum areal densities of less than 10%, a figure that is consistent with the apparent relative intensities of magnetite and augite reflections on X-ray-diffraction precession photographs.

Although the inclusions lie in the (010) plane, "Z" inclusions are actually systematically inclined to the Z axis of augite, and "X" inclusions are likewise inclined to the augite X axis, as indicated in Figures 2, 3a and 4. Inclination angles in (010) section are "Z" $\Lambda\, Z_{aug}$ $= 8$ to $9.5°$ and "X" Λ "Z" $= 102$ to $106°$; both sets of inclusions are rotated anticlockwise about the $+Y$ axis of augite. The respective inclination angles are essentially constant, both from grain to grain and from rock to rock. They are also independent of location within the host grain and inclusion size. The reported variations in inclination angle are thought to be due to observational error. Because of their stubby and somewhat irregular appearance and sporadic distribution, the attitude of "X" in-

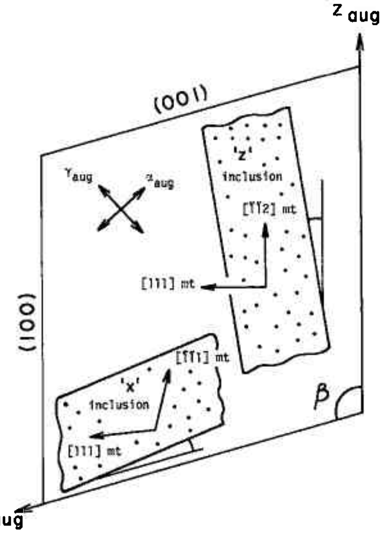

FIG. 4. Dimensional and crystallographic orientation of "Z" and "X" magnetite inclusions in augite.

clusions is particularly difficult to measure. However, most observations do fall close to the mean values of "Z" Λ Z_{aug} = 8.9° and "X" Λ "Z" = 103.4°.

Single-crystal X-ray-diffraction precession study of grain fragments of inclusion-bearing augite removed from specially prepared thin sections reveals two preferred crystallographic orientations of magnetite inclusions. The first has $[\bar{1}10]_{mt}/\!/Y_{aug}$, $[111]_{mt}/\!/X^{*}_{aug}$, $[\bar{1}\bar{1}2]_{mt}/\!/Z_{aug}$; on the basis of the correspondence of relative intensity of reflections and relative modal proportion in the X-rayed fragments, it is associated exclusively with "Z" inclusions. The second orientation has $[\bar{1}10]_{mt}/\!/Y_{aug}$, $[111]_{mt}\,\Lambda\,X^{*}_{aug} = 5°$, $[\bar{1}\bar{1}1]_{mt}\,\Lambda\,[\bar{1}01]^{*}_{aug} \sim 2°$ and is associated with "X" inclusions. These two crystallographic orientation relationships, then, are equivalent to those reported earlier by Bown & Gay (1959). Precession photographs of Renzy Lake augite also contain weak reflections of hornblende, confirming the thin-section observation of an amphibole alteration product.

Primary orthopyroxene grains in Renzy Lake rocks have only "Z"-oriented magnetite inclusions. These are essentially similar in appearance and distribution to the "Z" inclusions in augite, except that they are oriented parallel to the pyroxene Z axis. Single-crystal-precession study confirmed the expected preferred crystallographic orientation, $[\bar{1}10]_{mt}/\!/Y_{opx}$, $[111]_{mt}/\!/X_{opx}$, $[\bar{1}\bar{1}2]_{mt}/\!/Z_{opx}$.

PYROXENES FROM UMFRAVILLE

The Umfraville gabbro is the largest basic intrusion in the Hastings basin, eastern Ontario, having a maximum exposed dimension of about 10 km (Lumbers 1969). The gabbro body consists of peridotite, pyroxenite, olivine gabbro, diorite and anorthosite. It is surrounded by metasedimentary rocks and intruded by syenite and minor pyroxene monzonite. The grade of metamorphism of the local metasedimentary rocks varies from greenschist- to lower–middle almandine–amphibolite facies, but the gabbro body itself appears to have been emplaced late in the Grenville orogeny or actually after the culmination of the regional metamorphism (Lumbers 1969). Certainly, the rock textures in thin section are typically igneous. However, the rocks have undergone a certain amount of deformation, as indicated by subgrain development in plagioclase and some recrystallization of plagioclase and pyroxene. Also, exsolution of pyroxene phases in rocks containing both augite and orthopyroxene is limited to (100) orthopyroxene lamellae in augite. This observation and the incipient development of corona structure suggest a protracted period of subsolidus annealing and chemical re-equilibration. Intergranular and bleb-like magnetite are present to the extent of 2 to 5 modal %. One rock examined has the assemblage augite–orthopyroxene–magnetite–apatite, in which interstitial magnetite appears to be substituting for plagioclase feldspar and may, in fact, have been introduced through a replacement process.

Pyroxene grains in the basic and ultrabasic rocks are dusted with fine magnetite inclusions. In certain of the more gabbroic rocks, the magnetite inclusions are coarser in grain size, elongate and oriented and hence are more suitable for investigation by the techniques of the present study. Finely dusted magnetite inclusions extend more or less to the pyroxene grain-boundaries, but the more coarsely oriented inclusions tend to be concentrated in grain interiors, leaving fairly broad, clear margins. Augite grains also contain lamellae and blebs of orthopyroxene. These are more concentrated in grain interiors, and their distribution presumably reflects a primary enrichment of Ca toward the grain margins. Orthopyroxene also occurs as scattered, small, round grains with sparsely distributed magnetite inclusions in the grain interiors.

Electron-microprobe analysis of pyroxenes in the olivine gabbro (Fig. 1) suggests approximate compositions of $En_{43}Fs_{13}Wo_{44}$ for augite and $En_{72}Fs_{26}Wo_2$ for orthopyroxene. The mean value for $K_{DMg.Fe}$ (1.23) compares with 1.86 for charnockites, 1.49 for the Bushveld intrusion and 1.33 for the Skaergaard intrusion (Fleet 1974a), and is therefore typical for a small, high-level mafic intrusion. Both $K_{DMg.Fe}$ data and Ca contents confirm the petrographic observation that the Umfraville intrusive rocks have not been subjected to high-grade metamorphic conditions. The augite compositional data do show some dispersion along the augite–orthopyroxene tie-line, which is generally consistent with the trend of Ca enrichment toward grain margins. However, no analyses are anomalously high in total iron, and this simply confirms the estimated low modal proportions of magnetite inclusions in these pyroxenes.

Augite grains have oriented magnetite inclusions in both "Z" and "X" orientations (Fig. 5). However, the latter are subordinate in importance and much less abundant than in the Renzy Lake augite. The inclusions are rod-like in shape, with maximum dimensions of about 2 x 0.3 x 60 mμ for "Z" inclusions and 20 x 0.3 x 2 mμ for "X" inclusions and with maximum flattening in the (010) plane. The distribution of the inclusions is controlled by the (100) orthopyroxene lamellae, as indicated in Figure 3b; this contrasts markedly with the random distribution of magnetite inclusions in the Renzy Lake pyroxenes (Fig. 3a). The inclusions do not transect the orthopyroxene lamellae but they clearly postdate them, since they are restricted to interlamellar areas and align to form bands of inclusions in the (001) section and in most oblique sections.

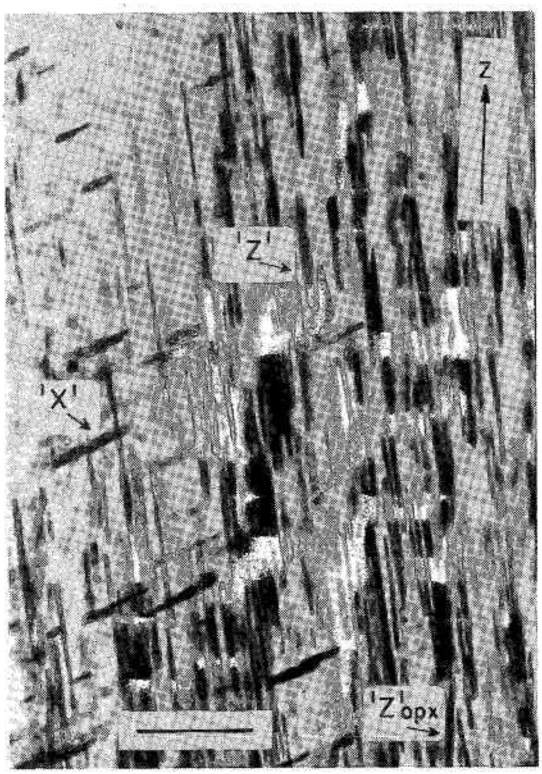

FIG. 5. Optical micrograph of "Z" and "X" magnetite inclusions in Umfraville augite. "Z"$_{opx}$ is "Z" inclusion within orthopyroxene lamella. Plane-polarized light. Scale bar is 25 mμ.

The "Z" and "X" magnetite inclusions are inclined to the augite Z and X axes, respectively, as indicated in Figures 5, 3b and 4. Inclination angles in (010) section are "Z" Λ Z_{aug} = 8 to 10°, and "X" Λ "Z" = 103 to 104°; both sets of inclusions are rotated anticlockwise about the $+Y$ axis of augite. As in the Renzy Lake augite, the respective inclination angles are essentially constant. The mean values, used in the optimal-phase-boundary analysis below, are "Z" Λ Z_{aug} = 8.5°, and "X" Λ "Z" = 103.8°. A few "Z" inclusions are actually parallel to the Z axis; careful observation shows that these are within the lamellar areas and have developed from hypersthene.

X-ray-precession analysis confirmed the first crystallographic orientation observed for the Renzy Lake augite, namely, $[\bar{1}10]_{mt} // Y_{aug}$, $[111]_{mt} // X^*_{aug}$, $[\bar{1}12]_{mt} // Z_{aug}$. This is associated with magnetite present as "Z" inclusions. Reflections of magnetite in "X" inclusions were not observed, which is quite consistent with the minor development of this orientation in the Umfraville augite.

Orthopyroxene grains have "Z"-oriented magnetite inclusions only, aligned parallel to the pyroxene Z axis. Inclusion development is less extensive than in the coexisting augite grains and, of course, the inclusions are randomly distributed.

DISCUSSION

Optical and X-ray diffraction studies of the Renzy Lake and Umfraville pyroxenes essentially confirm the overall impression gathered from review of the literature data on oriented magnetite inclusions in pyroxenes. Magnetite inclusions in augite are in the form of blebs or flattened rods lying in the (010) plane of augite, and occur in two orientations, designated earlier as "Z" and "X", as reported by Bown & Gay (1959). In both Grenville province localities, "Z" inclusions are much more numerous than "X" inclusions; this seems consistent with the unequal development of the two orientations in other localities.

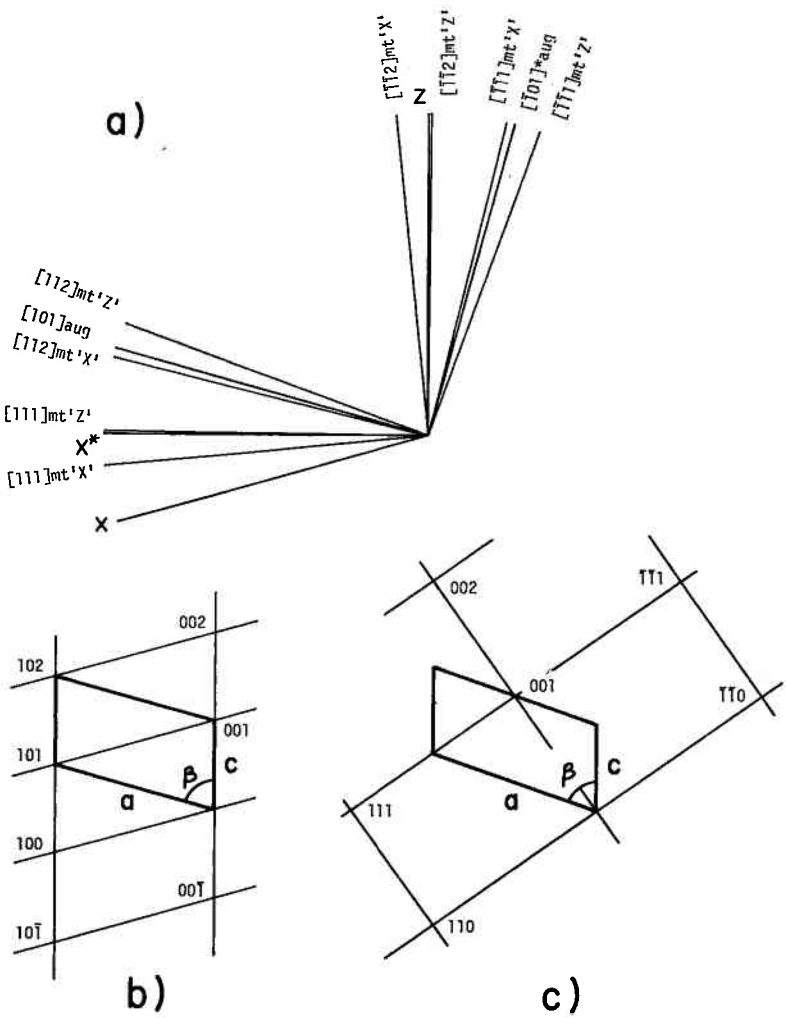

FIG. 6. (a) Crystallographic orientation relationships of "*Z*" and "*X*" inclusions in *X*, *Z* plane of augite. (b) Projection of alternative unit cell for augite relative to conventional-space lattice. (c) Projection of equivalent monoclinic cell for magnetite relative to conventional-space cubic lattice.

Both dimensional orientations are associated with unique, specific crystallographic orientation relationships, as reported by Bown & Gay: for "*Z*" inclusions, $[\bar{1}10]_{mt}//Y_{aug}$, $[111]_{mt}//X^{*}_{aug}$, $[\bar{1}\bar{1}2]_{mt}//Z_{aug}$, and for "*X*" inclusions, $[\bar{1}10]_{mt}//Y_{aug}$, $[111]_{mt}\,\Lambda\,X^{*}_{aug} = 5°$, $[\bar{1}\bar{1}1]_{mt}\,\Lambda\,[\bar{1}01]^{*}_{aug} \sim 2°$ (Fig. 6). In orthopyroxene, magnetite inclusions only occur elongate parallel to the orthopyroxene *Z* axis and have the crystallographic orientation relation $[\bar{1}10]_{mt}//Y_{opx}$, $[111]_{mt}//X_{opx}$, $[\bar{1}\bar{1}2]_{mt}//Z_{opx}$ which, with X_{opx} parallel to X^{*}_{opx}, is readily seen to be equivalent to that for "*Z*" inclusions in augite. This dimensional (and associated crystallographic) orientation has been reported previously for spinel inclusions in orthopyroxene. However, a second magnetite orientation, with inclusion blades parallel to $(100)_{opx}$ (White 1966), or with $[100]_{mt}//Y_{opx}$ (Le Maitre 1965), was not observed.

The most important contribution of the present study is the observation that the oriented "*Z*" and "*X*" magnetite inclusions in augite are not parallel to the respective pyroxene crystallographic *Z* and *X* axes, but lie on irrational directions in the *X*, *Z* plane. As will be shown below, this phenomenon is a consequence of the monoclinic symmetry of the augite lattice and thus should be a characteristic feature of all oriented magnetite inclusions in clinopyroxenes. The magnetite–augite relationship is directly analogous to that for clinopyroxene exsolution lamellae in clinopyroxene (pigeonite in augite or augite in pigeonite: Robinson *et al.* 1971). As is now well known, these lamellae are not parallel to (100) and (001) planes as was previously supposed, but actually lie on irrational yet precisely defined planes parallel to the monoclinic *Y* axis. Although the magnetite inclusions in question have the general appearance of linear features, even perhaps planar in (010), they are in all other respects equivalent to the clinopyroxene lamellae. Thus, "*Z*" inclusions are equivalent to "100" lamellae, and "*X*" inclusions are equivalent to "001" lamellae.

Application of optimal-phase-boundary theory

The optimal-phase-boundary theory of Bollmann & Nissen (1968) has been adapted with remarkable success to a study of the attitude of pyroxene exsolution lamellae (Robinson *et al.* 1971, Jaffe *et al.* 1975). When a second phase nucleates within a host phase (through phase segregation), crystallographic orientation and crystal shape are primarily controlled by the structural similarity of the two phases. However, phase-boundary attitude is much more de-

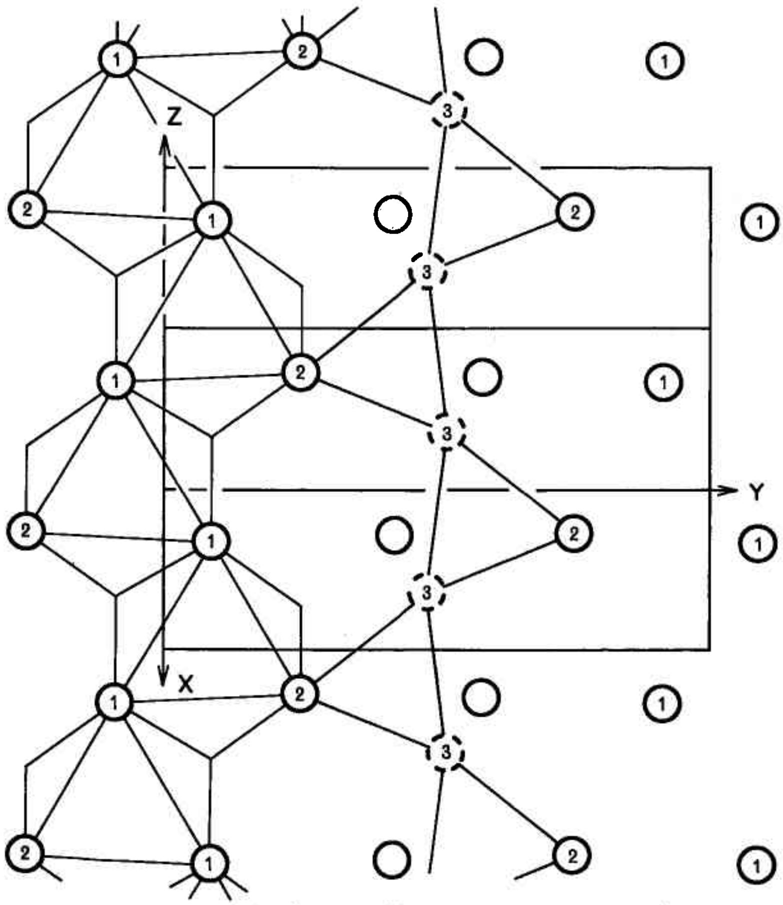

FIG. 7. Oxygen atoms in plane parallel to (100) at $x = 5/8$ in structure of diopside, showing *Z* axis arrays of close-packed 01 and 02 atoms associated with $M(1)O_6$ octahedra (outlined) and the development of two-dimensional close-packed array of oxygen atoms by complete *S* rotation of SiO_4 tetrahedral bases (outlined) about 02 (diopside positional parameters taken from Clark *et al.* 1969).

TABLE 1. ESTIMATED ROOM-TEMPERATURE LATTICE PARAMETERS FOR MAGNETITE AND AUGITE

	a	b	c	β
Magnetite- equivalent monoclinic cell[1]	10.283Å	8.905Å	5.142Å	70.53°
Augite- Renzy Lake peridotite- conventional unit cell[2]	9.761	8.938	5.249	105.75
- alternative unit cell	9.747	8.938	5.249	74.54
Augite- Umfraville gabbro- conventional unit cell[3]	9.763	8.940	5.245	105.9
- alternative unit cell	9.735	8.940	5.245	74.69

1. a_{cubic}=8.396Å; a=6d_{224}; b=3$d_{\bar{2}20}$; c=3$d_{\bar{2}\bar{2}4}$; β=180-[111]∧[$\bar{1}\bar{1}$1]
2. estimated from Turnock et al. (1973, Fig. 2) for En45Fs6Wo49
3. " " " " " " " " for En43Fs13Wo44

pendent on the dimensional fit of the two corresponding space lattices. It is invariably defined by a surface of minimum lattice-strain that is parallel to the plane passing through points where both lattices best match.

In pyroxenes, the surfaces of minimum lattice-strain are parallel to the Y axis and hence, are defined by coincidence vectors of the corresponding $h0l$ plane lattices (Robinson *et al.* 1977). Inclination angles and associated lattice rotations required to attain coincidence may be calculated from the a, c and β lattice parameters of the two related phases (see, for example, Robinson *et al.* 1971, Table 3; Jaffe *et al.* 1975, Table 4). Separate solutions arise for each of the structural constraints $Z_{lam}/\!/Z_{host}$ and $X_{lam}/\!/X_{host}$, corresponding to "100" and "001" lamellae, respectively.

The requisite crystallographic correspondence between magnetite and augite is not immediately apparent, but may be deduced through analysis of the crystallographic orientation relationships of both "Z" and "X" inclusions. "Z" inclusions have $(111)_{mt}/\!/(100)_{aug}$ and $[\bar{1}\bar{1}2]_{mt}/\!/Z_{aug}$, which aligns planar arrays of close-packed oxygen atoms in both structures. The ideal $C2/c$ clinopyroxene structure has layers of close-packed oxygen atoms parallel to (100) at $x = 1/8, 3/8, 5/8, 7/8$. The structure of augite (or diopside) is considerably distorted from this ideal configuration, so that the ideal two-dimensional arrays degenerate to essentially one-dimensional strips of 01 and 02 atoms parallel to the Z axis (Fig. 7). However, the close-packed strips may be broadened by slight displacements of the 03 atoms (Fig. 7) which, incidentally, are equivalent to complete S rotations of the SiO_4 tetrahedral bases about 02 (Thompson 1970, Papike *et al.* 1973). Clearly, the close-packed oxygens are the bridging element between the two structures, and their distribution adequately explains the restricted development of magnetite inclusions as rods subparallel to the Z axis rather than as "100" lamellae. The related lattice dimensions are $3d_{\bar{2}20mt} \sim b_{aug}$ and $3d_{\bar{2}\bar{2}4mt} \sim c_{aug}$ (Table 1, Fig. 6). Therefore, $[\bar{1}\bar{1}2]$ must be a principal axis of the magnetite plane lattice in the X,Z plane of augite, and the vector $3d_{\bar{2}\bar{2}4}$ becomes the c dimension of the equivalent monoclinic cell for magnetite (Table 1, Fig. 6).

The equivalent orientation for "X" inclusions is $[\bar{1}10]_{mt}/\!/Y_{aug}$, $[\bar{1}\bar{1}1]_{mt}/\!/[\bar{1}01]^*_{aug}$, $[112]_{mt}/\!/[101]_{aug}$ (Fig. 6). This orientation places $(\bar{1}\bar{1}1)_{mt}$ parallel to $(\bar{1}01)_{aug}$ which, once again, is parallel to close-packed oxygen-atom layers in the ideal $C2/c$ clinopyroxene structure. The related lattice dimensions are $3d_{\bar{2}20mt} = b_{aug}$ and $6d_{224mt} = t_{101aug}$ (where t_{101aug} is a vector of the real-space lattice), and the vector $6d_{224mt}$ becomes the X axis of the equivalent monoclinic cell (Table 1, Fig. 6). The parameters a, b and c of the equivalent monoclinic cell for magnetite are now defined, and β is simply (180–[111] Λ [$\bar{1}\bar{1}$1])° (Table 1, Fig. 6). Close inspection of X-ray-precession photographs reveals that both the "Z" and "X" magnetite lattices are slightly rotated relative to the host augite lattice about the common Y axis, as anticipated from the previous studies on pyroxenes. The rotations are about 0.40° clockwise for the "Z" lattice and about 1.85° anticlockwise for the "X" lattice (Fig. 6, Table 2).

In the calculation of magnetite–augite phase boundaries, the monoclinic magnetite cell must be compared not with the conventional unit cell of augite but with the alternative unit cell defined by the real-space lattice vectors t_{101}, t_{010}, t_{001} (Table 1, Fig. 6). Phase-boundary attitudes may then be computed directly from the equations of Robinson *et al.* (1977, Appendix). Calculated data for the strain-free, room-temperature lattice parameters in Table 1 are compared with the observed data for Renzy Lake and Umfraville augite in Table 2. Magnetite lattice parameters in Table 1 are derived from the cubic lattice parameter for pure Fe_3O_4 (a 8.396 Å, JCPDS Powder Diffraction File 19-629), which compares favorably with

TABLE 2. INCLINATION ANGLES AND LATTICE ROTATIONS OF MAGNETITE INCLUSIONS

	'Z'∧Z	'X'∧'Z'	'Z' Lattice Rotation	'X' Lattice Rotation
Renzy Lake- observed	8.9°	103.4°	+0.40°	-1.85°
- calculated[1]	11.7	98.5	+0.37	-1.70
Umfraville- observed	8.5	103.8	n.d.	----
- calculated[1]	11.0	99.1	+0.36	-1.69

1. from room-temperature strain-free lattice parameter data, Table 1.

the value of $a = 8.400(7)$ Å obtained by the measurement of uncalibrated precession photographs of complex augite–magnetite grains from Renzy Lake. Augite cell parameters are estimated from the cell-parameter plots of Turnock *et al.* (1973). The agreement between calculated and observed inclination angles and lattice rotations is quite consistent with the premise of optimal-phase-boundary control on the attitude of the magnetite inclusions. Discrepancies between the observed and calculated data are attributed very largely to the differential thermal expansion of the magnetite and augite lattices. High-temperature cell parameters have been estimated from published thermal-expansion data for magnetite (Clark 1966, Table 6-5) and from temperature coefficients deduced from Robinson *et al.* (1977, Fig. 9) for augite. Magnetite inclinations calculated from these data for the Renzy Lake augite composition vary markedly with temperature (Fig. 8). The mean values of "*Z*" Λ *Z* and "*X*" Λ "*Z*" for Renzy Lake augite are equivalent to temperatures of 580 and 586°C, respectively. Equivalent temperatures (from separate, unpublished calibration curves) for Umfraville augite are 560 and 587°C, respectively.

The observed inclination angles correspond, then, in both Renzy Lake and Umfraville augites to an optimal (or ideal) dimensional fit between magnetite and augite at a temperature close to 600°C. The observed inclination angles reflect the attitude of the interface between the magnetite nuclei and the augite host, and are not likely to be modified by subsequent annealing and additional crystal growth at a different temperature. Hence, inclusion attitude is a "fossil" record of the actual temperature of phase separation. In both Renzy Lake and Umfraville augite the separation of magnetite inclusions commenced at about 600°C.

Origin of magnetite inclusions

The textural evidence presented earlier strongly suggests that the magnetite inclusions in pyroxenes of the Renzy Lake and Umfraville intrusive rocks developed after crystallization of the primary phases. In fact, in Umfraville augite the inclusions clearly postdate exsolution of orthopyroxene. Furthermore, their overall spatial distribution and the apparent control of the optimal-phase-boundary theory on inclusion attitude are consistent with precipitation by homogeneous nucleation.

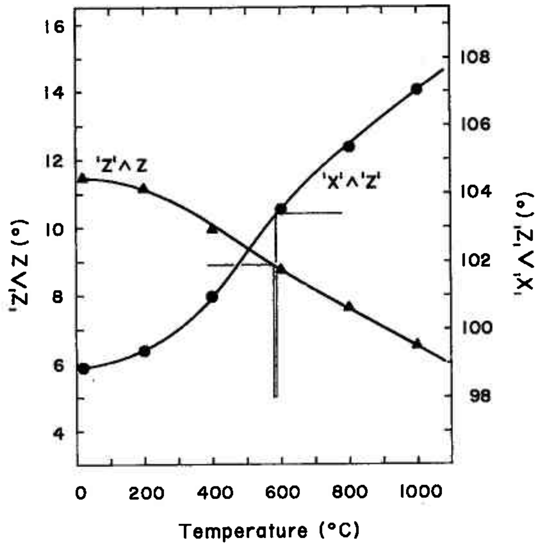

FIG. 8. Variation of calculated inclination angles of "*Z*" and "*X*" magnetite inclusions with temperature for Renzy Lake augite. Temperatures equivalent to mean observed data ("*Z*" Λ Z = 8.9°, "*X*" Λ "*Z*" = 103.4°) are indicated by ruled lines.

Application of the optimal-phase-boundary theory in the previous section indicates nucleation temperatures close to 600°C for the precipitation of magnetite inclusions in the two localities studied. The confidence limits of these temperature estimates are unknown. Possible error may be anticipated from measurement of inclination angles, estimation of lattice parameters, extrapolation of room-temperature cell parameters to high temperatures (and the compensating effect of pressure) and even estimation of the original augite composition. However, ±50°C would seem to be quite generous. The general concordance of the temperature estimates for Renzy Lake and Umfraville inclusions is probably not without significance, and further study may reveal that magnetite inclusions in pyroxenes, which are not too different in Mg/(Mg + Fe) ratio, may develop within a rather restricted temperature range.

Thus, the magnetite inclusions formed during the subsolidus history of the Renzy Lake and Umfraville rocks, following the essentially complete crystallization of all the magmatic constituents. However, unlike pyroxene lamellae in pyroxenes, they probably do not represent exsolution from a complex high-temperature solid solution. That hypothesis would be inconsistent with the presence of inclusions in both augite and coexisting orthopyroxene and with their sporadic development from one rock to another, especially in the Renzy Lake locality, where many hornblende peridotites are completely devoid of oriented magnetite inclusions.

However, magnetite is readily precipitated when pyroxenes are heated under laboratory conditions (Le Maitre 1965, P. Gay *pers. comm.*); we conclude, then, that the oriented magnetite inclusions are most likely a breakdown or reaction product formed during metamorphic reheating to middle amphibolite-facies conditions. This hypothesis is consistent with the apparent metamorphic history of the two rock bodies investigated. On subsequent prograde metamorphism to granulite-facies conditions, the complex pyroxene–magnetite grains should be recrystallized to discrete pyroxene and magnetite grains, and this appears to have occurred to a large extent at Renzy Lake. The zonal distribution of the magnetite inclusions within the pyroxene grains is probably a reflection of a primary chemical zonation, presumably to Ca-rich margins in augite and Ca-poor margins in orthopyroxene. For the Renzy Lake pyroxenes, this affords yet another indication that the magnetite inclusions were precipitated before the onset of granulite-facies metamorphism, since they predate chemical homogenization of the pyroxenes.

The precise nature of the reaction mechanism is not understood at the present time. This aspect is complicated by the apparent absence (or, at least, the undetected presence) of a consistently occurring second inclusion phase, as suggested by the combination of the following possible reactions:

$$\underset{\text{Ca } Fe^{3+}\text{-Tschermaks "molecule"}}{3[CaO.Fe_2O_3.SiO_2]}$$

$$\rightarrow \underset{\text{magnetite}}{2[FeO.Fe_2O_3]} + \underset{\text{wollastonite}}{3[CaO.SiO_2]} + \tfrac{1}{2}\, O_2,$$

and

$$\underset{\text{hedenbergite}}{3[CaO.FeO.2SiO_2} + \tfrac{1}{2}\, O_2$$

$$\rightarrow \underset{\text{magnetite}}{FeO.Fe_2O_3} + \underset{\text{wollastonite}}{3[CaO.SiO_2]} + \underset{\text{quartz}}{3SiO_2}.$$

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