

suggest that the twinning in the pyroxenes in the Apollo 12 rocks is probably a primary feature, associated with rapid growth, and this explanation is probably equally valid in explaining the twinning of the pigeonites in 14310. Evidence obtained by Ridley *et al.* (1972) suggests, however, that the phase of rapid growth of the pigeonites in 14310 did not extend beyond the initial stages of crystallization.

The optic properties determined for these pigeonites are: $b = \beta$, $2H\gamma = 27^\circ$ and $\gamma: [001] = 35^\circ$, but in both cases $2H$ could only be measured¹ on one set of twin units. Rotation of crystal (B) on the U-stage revealed the presence of a narrow discontinuous zone on its eastern margin, but $2H$ of this zone could not be determined.

Spot analyses of these crystals by electron probe yielded the results presented in table I.

TABLE I. *Results of spot analyses of pigeonites by electron probe*

	A1	A2	A3	B1	B2	B2a	B1a
SiO ₂	53.0	52.4	52.4	51.8	51.6	52.7	52.5
TiO ₂	0.65	0.79	0.84	0.86	0.78	0.51	0.87
Al ₂ O ₃	1.30	1.02	1.30	1.30	1.48	0.97	1.30
Fe as FeO	18.6	21.1	22.7	22.2	22.3	18.5	19.9
MgO	23.9	21.4	19.4	19.7	19.9	22.9	21.5
CaO	3.51	4.36	5.01	5.49	4.47	3.88	3.87
Total	100.96	101.07	101.65	101.35	100.53	99.46	99.94
Wo, mol. %	6.8	8.6	10.1	10.9	9.0	7.7	7.8
En	65.1	59.1	54.5	54.8	56.1	63.7	60.9
Fs	28.1	32.3	35.4	34.3	34.9	28.6	31.3

Apart from a slightly higher Wo content, these compositions are similar to those obtained for the pigeonite in sample 14310 by other investigators (e.g. Hollister *et al.*, 1972; Kushiro, 1972; Takeda and Ridley, 1972).

There is no appreciable variation in composition between the two sets of twin units in either crystal, the variation in Fe/Mg ratio being areal in character. Crystal (A) shows the usual slight increase in Fe/Mg ratio outward in both directions from the centre, whereas crystal (B) shows an outward *decrease* in this ratio, which is apparently unidirectional (fig. 1a).

Line scans of crystal (B) by electron probe (fig. 2) indicate, however, that the Fe/Mg ratio decreases outward in *both* directions from the centre, thus confirming the indication, given by the spot analyses, that this crystal shows reverse zoning. Reverse zoning of a multiple-twinned pigeonite grain in 14310 has also been observed by Hollister *et al.* (1972), who regard it as indicating a pre-melt history for this grain and, therefore, supporting their contention that 14310 contains pre-melt mineral fragments.

The line scans also confirm the presence of the narrow marginal zone observed on the U-stage and indicate that it is richer in Ca and Fe and poorer in Mg than the interior of the crystal. Its composition, Wo₁₈En₄₇Fs₃₅ (estimated from the results of

¹ Measured on a polished thin section, under a temporary cover slip mounted with Canada balsam, using U-stage segments of R.I. 1.649.

the line scans and spot analyses) is slightly more calcic and magnesian than that recorded by Ridley *et al.* (1972) for the rims of the pigeonites in 14310. If we accept their conclusions concerning the crystallization of the pyroxenes in 14310, the estimated Wo content of the pigeonite in thin section 110 is very close to the maximum value.

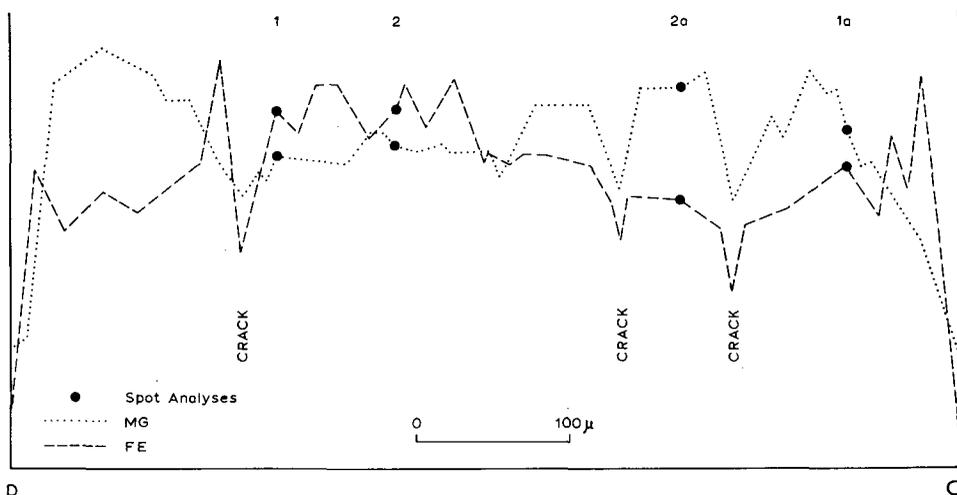


FIG. 2. Schematic representation of variation in Mg and Fe along electron probe traverse C-D (fig. 1a). Electron beam diameter $2-2\frac{1}{2}$ μm .

The evidence assembled above suggests that the multiple-twinned, reverse-zoned pigeonites have had an extremely complicated crystallization history. It appears that, after a short initial period of rapid growth, they crystallized more slowly, with slight normal zoning, for some considerable time. They were then, apparently, subjected to a marked change in environment, which resulted in a rather abrupt change to a more magnesian composition, followed by a lengthy period of gradual, progressive reverse zoning. These conditions persisted until the final stage of pigeonite crystallization, when a further change in environment caused a return to normal zoning. This zoning produced a rapid decrease in the Mg/Fe ratio and a marked increase in Ca content, the crystals eventually reaching a composition near the pigeonite/sub-calcic-augite boundary in the pyroxene quadrilateral.

A brief abstract of the results of this investigation has already been published (Drever *et al.*, 1972).

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Biotites in calc-alkaline intrusive rocks

FOLLOWING the initial work of Heinrich (1946), Foster (1960) examined the relationships between biotite compositions and generalized geological occurrences. She found that biotites from varieties of calc-alkaline intrusive rocks show considerable overlap when the *Y* site cations are plotted on triangular diagrams with (Al^{vi} , Fe^{3+} , Ti^{4+}), (Fe^{2+} , Mn^{2+}), and Mg^{2+} as apices, indicating that no simple correlation between biotite composition and host-rock types exists. However, Foster suggested that this overlap, in part, may be due to the loose usage of rock names such as 'granite'. The objects of this study are to revise Foster's diagram especially for intrusive calc-alkaline rocks using a rigorous rock classification and to test if the conclusions reached by the previous study are substantiated.

Analyses of biotites from calc-alkaline rocks were selected from the literature (sources quoted in the list of references) on the following criteria: a mode of the host rock was available; the rock was substantially free of metamorphism, weathering, and hydrothermal alteration. These criteria, especially the first, meant the rejection of many analyses; a total of 125 were finally selected. The analyses were divided into seven groups on the basis of host rock modes, following the classification of Streckeisen (1967): syenogranite (9), monzogranite (33), granodiorite (37), quartz diorite (21), monzonite (4), monzodiorite (11), and diorite (10). Cation abundances for each biotite were calculated to 44 anions (water and halogen free) using the computer program of Jackson *et al.* (1967).

The data are plotted on fig. 1a. It can be seen that the spread of analyses is similar to that found by Foster (1960, fig. 11), with no analyses in the phlogopite field but several being (Fe^{2+} , Mn^{2+})-rich. Fig. 1b shows the fields of biotite compositions from the various rock types. Biotites from monzonites, monzodiorites, and diorites (with the exception of one from the Guadalupe complex, which was ignored for the purposes of delineating the field) have similar, restricted compositions, which are Mg^{2+} -rich.