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# MINERALOGICAL STUDY OF STRIPED PYROXENE IN SYENITIC ROCKS OF SIVAMALAI, SOUTH INDIA

MIHIR K. BOSE, *Department of Geology,*
*Presidency College, Calcutta, India.*

## ABSTRACT

Striped pyroxene, hitherto unreported from the "Sivamalai Series" (Holland 1901) has been investigated. The bulk composition of the hypersolvus pyroxene corresponds to that of a ferroaugite that has exsolved Ca-poor phases on (001) and (100) of the host. Free hypersthene has also resulted from complete unmixing of the primary pyroxene. Optical- and X-ray characters of the calcic host correspond to that of a hedenbergite-rich phase. Microprobe scanning reveals the Ca-poor phase to be more enriched in manganese than the host. The Ca-poor pyroxene developed in two stages during a continuous history of unmixing of the hypersolvus phase.

## INTRODUCTION

The assemblage of alkali rocks at Sivamalai (11°02′:77°33′) in Madras State, was reported by Holland (1901). Petrography of the syenitic rocks has been described subsequently (Subramaniam 1949) but detailed mineralogical and geochemical investigations have been undertaken recently by the author and his coworkers. The present note embodies the results of investigations on newly found striped pyroxene in the constituent members of the "Sivamalai Series." The genetic implications of the pyroxene intergrowth are also discussed.

## MINERALOGY

The pyroxene, an unmixed ferroaugite, is the chief mafic silicate in some types of syenites which are apparently new members in the "Sivamalai Series" as named by Holland (1901). The striped pyroxene may coexist with fayalite-rich olivine. The syenites are in general hypersolvus; feldspar, the major constituent in the rocks, is a mesoperthite while subordinate albite in granules may occur in the interspaces of perthites. The clinopyroxene occurs in stout subhedral grains and shows oriented lamellae of orthopyroxene. The bulk composition of the pyroxene as determined from chemical analysis plots well within the ferroaugite field (Fig. 1). The optical characters of the clinopyroxene constituent in the intergrowth are comparable to those of common ferroaugite (Table 1) but somewhat deeper absorption color and higher $Z\wedge c$ value would indicate an appreciably high proportion of hedenbergite component in the phase. The optical characters of Sivamalai pyroxene when referred to standard determinative diagram (Hess 1949) would indicate a composition ($Wo_{44}En_{18}Fs_{38}$) very close to ferrosalite-hedenbergite field (Poldervaart and Hess 1951). Possibly some minor elements influence the optical

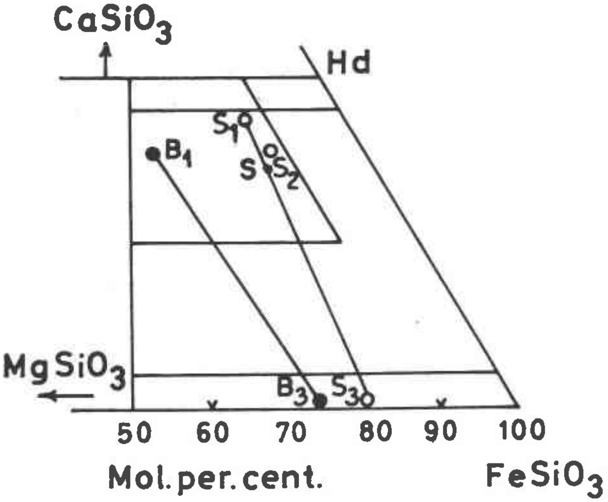

FIG. 1. Part of $CaSiO_3$-$MgSiO_3$-$FeSiO_3$ diagram to show the coexisting pyroxenes in Sivamalai syenite. $S_1$-ferroaugite; $S_3$-free hypersthene associated with ferroaugite; S-graphically estimated composition of the hypersolvus pyroxene; $S_2$-the analysed striped pyroxene (Table 2). $B_1-B_3$-the tie line for pyroxenes in iron rich diabase of Beaver Bay (Muir 1954).

properties of the pyroxene (and thus the deduced composition) but data are inadequate to determine if this is important. The *d* values for the characteristic X-ray reflections of the clinopyroxene phase (Table 2) are closer to those for hedenbergite than for augite, as compared with data furnished by Zwaan (1954). The $\Delta d(220-221)$ and $\Delta d(221-310)$ values when referred to determinative curves along the diopside-hedenbergite join (Zwaan 1954) suggest the proportion of $Di_{27}Dd_{73}$ in the

TABLE 1. OPTICAL PROPERTIES OF FERROAUGITE

| 1 | 2 | 3 |
|---|---|---|
| $\beta=1.717\pm.002$ | 1.711 | 1.716 |
| $2V_z=57°$ | 50° | 52° |
| $Z\wedge c=46°$ | 39° | 45° |
| $X$ = Greenish gray<br>$Y$ = Greenish yellow<br>$Z$ = Green | Feebly pleachroic | Feebly pleochroic |

1. Ferroaugite in alkali syenite of Sivamalai, S. India.
2. Ferroaugite in iron rich diabase of Beaver Bay (Muir 1954).
3. Ferroaugite in syenite, Okonjeje complex. S. W. Africa (Simpson 1954).

TABLE 2. CHEMICAL ANALYSES OF PYROXENES

| | 1 | 2 | 1a | | | 2a | |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 46.73 | 48.86 | Si | 1.901 | 2.00 | 1.910 | 2.01 |
| $TiO_2$ | 0.46 | 0.93 | Al | 0.099 | | 0.070 | |
| $Al_2O_3$ | 2.91 | 1.51 | Al | 0.040 | 2.01 | — | |
| $Fe_2O_3$ | 2.74 | 2.26 | Ti | 0.014 | | 0.027 | 2.00 |
| FeO | 23.35 | 18.71 | $Fe^3$ | 0.083 | | 0.066 | |
| MnO | 0.82 | 0.38 | Mg | 0.239 | | 0.552 | |
| MgO | 3.92 | 9.48 | $Fe^2$ | 0.791 | | 0.612 | |
| CaO | 16.85 | 17.58 | Mn | 0.028 | | 0.012 | |
| $Na_2O$ | 0.78 | 0.24 | Ca | 0.735 | | 0.736 | |
| $K_2O$ | 0.45 | 0.00 | Na | 0.061 | | 0.018 | |
| $H_2O^+$ | 0.46 | 0.25 | K | 0.023 | | 0.000 | |
| $H_2O^-$ | | 0.06 | | | | | |
| | 99.47 | 100.26 | Percent cations | | | | |
| | | | Mg | 13.6 | | 27.9 | |
| | | | Fe | 44.8 | | 34.9 | |
| | | | Ca | 41.6 | | 37.2 | |

1. Chemical analysis of bulk striped pyroxene in syenite from Sivamalai; S. India.

2. Chemical analysis of ferroaugite in iron rich diabase, Beaver Bay, Minnesota (Muir 1954).

1a–2a. Atomic ratio on the basis of 6 oxygen atoms for pyroxenes in columns 1 and 2 respectively.

clinopyroxene phase. In optical and textural characters the Sivamalai pyroxene resembles closely the ferroaugite reported from Fe-rich diabase of Beaver Bay (Muir 1954) but the pyroxene reported here is richer in iron (FeO 24.05 and 23.35 percent in two analysed samples). The Siva-

TABLE 3. X-RAY DIFFRACTION DATA ON CLINOPYROXENE FROM SIVAMALAI[a]

| *hkl* | *d* (Å) | Relative Intensity | *hkl* | *d* (Å) | Relative Intensity |
|---|---|---|---|---|---|
| 021 | 3.348 | w | 222 | 2.209 | w |
| 220 | 3.265 | w | 112 | 2.180 | vw |
| 221 | 3.006 | vs | 331 | 2.148 | w |
| 310 | 2.984 | ms | 421 | 2.119 | mw |
| 311 | 2.907 | ms | 240 | 2.017 | mw |
| 131 | 2.581 | ms | 150 | 1.769 | w |
| 221 | 2.539 | vs | 531 | 1.628 | s |
| 400 | 2.261 | mw | | | |

[a] Powder diagram taken in Guinier camera with lead nitrate as internal standard (FeK = 1.93728).

malai ferroaugite also shows an appreciable amount of MnO (0.82 and 0.74 percent in two analysed samples) as commonly reported in ferroaugite (Deer *et al.*, 1963). Manganese is known to impart stability to $FeSiO_3$ (Yoder *et al.*, 1963, Lindsley 1965) and also invariably enters in the pigeonite structure (Deer *et al.*, 1963, p. 445); the latter may develop from a homogeneous calcic pyroxene during subsolvus cooling. The microprobe reveals that the Ca- poor phase is invariably richer in Mn than the calcic host.

Intergrowth of the two pyroxene phases on various scales was clearly depicted by Ca-distribution patterns from the electron microprobe. The pyroxene plates reveal larger areas of somewhat uniform and relatively higher Ca distribution, with much thinner zones of remarkably low Ca content (Fig. 2) corresponding to fine lamellae of a Ca-poor pyroxene phase. Calcium content of the exsolved pyroxene, however, varies with the width of the lamellae, indicating various stages of diffusion of Ca into the host structure. The distribution of Mn across the pyroxene grains appears to be somewhat irregular, although the Ca-poor phase is invariably richer in Mn than the host. In this respect the distribution of Fe is sympathetic with that of Mn and the exsolved phase is distinctly richer in Fe.

A notable textural feature in the ferroaugite from Sivamalai is the development of two sets of hypersthene lamellae oriented parallel to (001) and (100) of the host. When the intergrowth is coarse enough the average thickness of the lamellae oriented on (001) is 0.027 mm (as measured on 010 section of the host). The other set consists of very fine, closely spaced sheets, distributed about 5 subindividuals per mm. The hypersthene lamallae parallel to (001), as observed on (100) sections of augite, show feeble pleachroism and moderate birefringence (0.019); they are invariably coarser than the lamellae on (100) of the host (Hess 1960). The coarser development of lamellae was obviously favoured by easy migration of ions across the (001) plane at relatively higher temperature while the finer lamellae on (100) are products of limited diffusion at a lower temperature.

An interesting textural feature associated with the pyroxene, is the development of hypersthene blebs and granules localized at the borders of the ferroaugite. Such free hypersthene in the rock occurs invariably in close spatial association with ferroaugite. The later in such cases shows a fewer number of relatively thick hypersthene lamellae. These observations hint to a possible origin of discrete hypersthene through complete unmixing during subsolvus cooling. The optic axial angle ($2V_x = 78°$) and birefringence (0.020) for marginal hypersthene indicate a composition of $En_{20}Fs_{80}$. The compositions of the coexisting pyroxenes in the

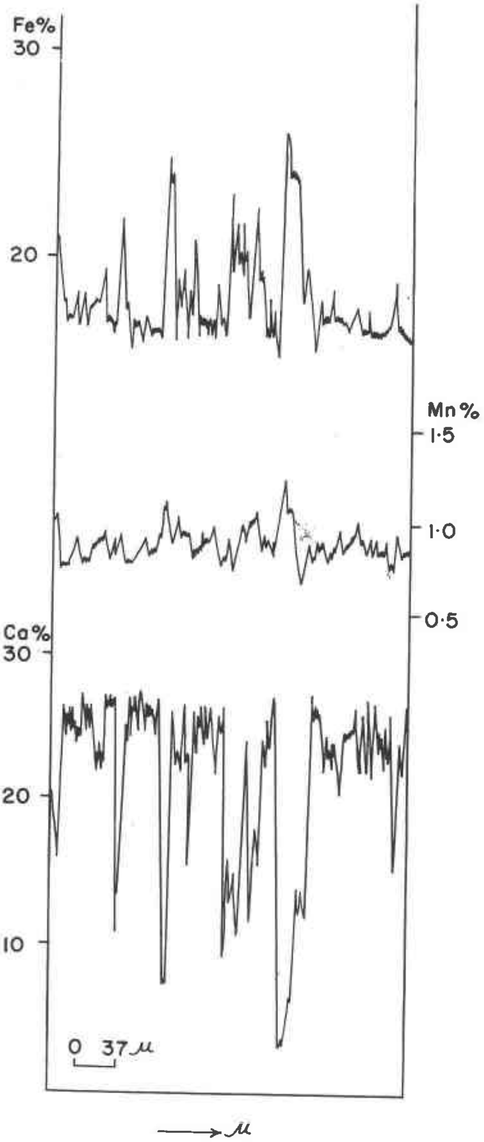

FIG. 2. Microprobe scan of pyroxene showing the distribution of Ca, Fe and Mn. Note the relative concentration of Fe and Mn in the Ca-poor phase compared to the host.

rock is shown (Fig. 1) in the manner suggested by Hess (1941). The relative proportion of the two pyroxenes in such coarse intergrowth was determined by careful drawing of the grains with prism camera lucida on graph paper and an approximate composition of the primary pyroxene is indicated on the tie line (Fig. 1). The composition of the hypersolvus pyroxene deduced graphically plots close to that determined from chemical analysis of the related sample.

Striped pyroxene having the intergrowth on a finer scale, was separated from crushed rock by means of heavy liquid, and a pure pyroxene fraction was obtained by repeated cleaning of the silicates in a Frantz Isodynamic Separator. The pyroxene was analysed by X-ray fluorescence and atomic absorption spectrography. The chemical analysis and the calculated ratios of the metal atoms are presented in Table 2 along with chemical data for the Beaver Bay pyroxene for a comparison. Atomic percentages of Ca, Mg and $Fe^{2+}$ for the Sivamalai pyroxene correspond with those for common ferroaugite but the concentration of other constituents *e.g.*, Ti, Mn, and alkalies are higher than those noımally assumed to be present in pyroxene (Deer *et al.*, 1963, p. 132). However, there may be a general tendency for enrichment in Na and Mn in pyroxenes with increasing amount of iron in the composition. The composition of the hypersolvus pyroxene determined from the chemical analysis is plotted in Figure 1.

## DISCUSSION

The composition of pyroxene in alakli-basaltic magma is normally considered to be restricted close to the Di-Hd join (Wilkinson 1956). This characteristic, when extended in the late liquids, is very likely impressed by the nature of reaction behaviour of the early mafic phases in alkali magmas. In the alkali syenites of Sivamalai, the composition of the pyroxene may indicate an apparent deviation from the expected trend and may reflect extended solid solution of Ca-rich pyroxenes at higher water pressure (Yoder *et al.*, 1963). I have recently observed similar pyroxene intergrowths in syenitic rock from the alkali igneous province of Oslo; this will be described elsewhere. Though clinopyroxenes in alkali rocks are normally not expected to coexist with a Ca-poor phase, the present observations indicates a possibility of such coexistence, at least through textural evolution of a homogeneous pyroxene.

The possible nature of the pyroxene solvus in the system Di-En-Fs-Hd was depicted by Barth (1951) more than a decade ago. The solvus crest as shown by Barth (1951) slopes progressively towards the Hd-Fs join and the present observation attests to its extension well within the ferroaugite field. The crestal temperature of the solvus on Hd-Fs join is considered to be 950°C (Deer *et al.*, 1963). Such Fe-rich pyroxenes as discussed here are expected to develop from late liquids at lower temperature (and possibly at higher volatile pressure) compared to the magnesian types. The relative shift in positions between the temperature minimum and solvus crest for progressively Fe-rich compositions of pyroxenes as suggested by Muir (1954) may be imposed by migration of the solvus towards the En-Fs join at higher water pressure (Yoder *et al.*, 1963). Thus in the Fe-rich region of the pyroxene quadrilateral (*e.g.*, in the ferroaugite field) a single pyroxene phase may develop, which may unmix subsequently during slow subsolvus cooling as observed in Beaver Bay and Sivamalai rocks. During the subsolidus cooling, the pyroxene in the hypersolvus syenite of Sivamalai first exsolved the pigeonite (subsequently inverted to hypersthene) lamellae on (001) of the host and diffusion (aided by slow cooling in presence of adequate water) favoured the segregation of the Ca-poor pyroxene component towards the margin of the host. This post magmatic history of slow cooling is also corroborated by the textural evolution of the perthites. During such gradual fall of temperature, the two pyroxene phases may have been in equilibrium and the partition of elements (particularly Fe, Mg, and Mn amongst major elements) between the two was attained as demanded by the prevailing physical environment. With further lowering of temperature (below the pigeonite-hypersthene inversion temperature) another set of hypersthene lamellae exsolved out on (100) of the host but their development was limited due to restricted diffusion of Ca at lower temperature. Since the ferroaugite and coarse hypersthene have resulted from slow cooling process, the tie line between the two phases may reflect the normal behaviour of coexisting igneous pyroxene (Hess 1941). A more recent review on pyroxene relations by Brown (1961) modifies but does not disprove this concept that Fe and Mg in coexisting pyroxenes in equilibrium, maintain a definite relation which may find expression through the slope of the tie line. However, the exact value of the distribution factor for Fe and Mg in such pyroxenes may be influenced by the prevailing physical conditions.

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