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CRYSTALLOGRAPHY AND MINERALOGY OF PYROXENES FROM FRA MAURO SOIL AND ROCK 14310. Hiroshi Takeda and W. I. Ridley, NASA Manned Spacecraft Center, Houston, TX 77058

Pyroxenes in Apollo 11 and 12 mare basalts are dominantly augite and pigeonite. Rare orthopyroxene, an indicator of non-mare rocks found in Apollo 12 coarse fines has been studied crystallographically (Meyer et al., 1971). In the Apollo 14 soil, orthopyroxene represents as much as 41% of all analyzed pyroxenes (Reid et al., 1971). The composition range in Mg/(Fe+Mg) is from .85 to .61. It is also found to be a common pyroxene in crystalline rock 14310 (Ridley et al., 1971).

The exsolution and overgrowth patterns of those orthopyroxenes, together with those of the coexisting pigeonites and augites were studied by single crystal x-ray diffraction methods to provide information on crystallization and cooling conditions. 12 pyroxene grains were separated from rock chip 14310,90. The crystals were mounted along c*, and precession photographs of $h0\bar{l}$ and $0k\bar{l}$ nets were taken using MoKα radiation with Zr filter. When the patterns were found to be complicated due to twinning or stacking faults, over-exposed $h0\bar{l}$ photographs with CuKα radiation using Ni filter were taken on the same crystals. Subsequently, each single crystal was studied by electron microprobe analysis.

Based on their chemical compositions, exsolution patterns, twinning and colors, these pyroxene grains can be classified into three major groups:

(1) Orthopyroxene (4 crystals), pale yellow or almost colorless but not transparent. The compositions are bronzitic ($Wo_4En_{80}Fs_{16}$). Neither exsolution of augite nor diffuse streaks along a*, indicative of the disordered orthopyroxene commonly found in meteorites (Pollack, 1968), have been detected within usual exposure time. A longer exposed photograph did show exsolution.

(2) Twinned magnesian pigeonite (5 crystals), has almost the same appearance as the orthopyroxenes, and is invariably twinned on (100) or $[001]_{180°}$. The intensities of twinned pair reflections vary from grain to grain indicating that twinning is not as fine as is found in twinned clinoenstatite transformed from protoenstatite. The class $\underline{b}$ reflections ($\underline{h+k}$ odd) of pigeonites are sharp. Exsolution of augite both on (100) and $(00\bar{1})$ is observed on longer exposed photographs. The intensities of the exsolved augites are proportional to the intensities of the host twin individuals (pigeonite). The β angle of pigeonite (Table 1) is the same as for a fully exsolved one, and the β angle of augites (106°23' for one exsolved on (100) and 106°12' for (001)) are not as large as rapidly cooled pyroxenes such as those of rock 12052 (Takeda,1971). In one of the twinned pigeonites ($Wo_8En_{71}Fs_{20}$) an orthopyroxene core (Wo_4En_{80}-Fs_{16}) is present with common (100). Another pigeonite without orthopyroxene is more iron-rich ($Wo_8En_{58}Fs_{34}$).

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(3) Colored intermediate pigeonite (3 crystals), the grains are pink to brownish, and more Fe-rich than the twinned pigeonites. All the grains we studied are untwinned. The diffraction patterns show predominant exsolution of augite on (001). The intensity ratio, pig./aug. is roughly 3/1. The lamellae or patches of augite ($Wo_{31}En_{32}Fs_{37}$) are barely detectable by electron microprobe in the matrices of pigeonites ($Wo_7En_{35}Fs_{58}$). The separation of the $\underline{a}^*$ axes of pigeonite and augite are close to the maximum values common for volcanic pigeonites. Both facts indicate relatively slow cooling. The class $\underline{b}$ reflections of pigeonite are sharp. Very weak diffuse streaks along $\underline{a}^*$ in some part of $\underline{h}02$ rows were observed on longer exposed photographs. One augite grain ($Wo_{29}En_{44}Fs_{27}$) has exsolved about equal amounts of pigeonite.

The possibility that the twinned Mg-rich pigeonite is twinned clinoenstatite inverted from protoenstatite can be ruled out by the fact that the composition of pigeonite is more Fe-rich and Ca-rich than the bronzite and the coarser twin individuals are sometimes observed optically. The diffuse streak along $\underline{a}^*$ found in clinoenstatite was not observed in the Mg-rich pigeonite. The compositional relation of core bronzite to twinned pigeonite and lack of exsolution of augite also excludes the possibility of the bronzite being an inverted pigeonite.

According to composition-temperature relations of pyroxenes (for example, Kuno, 1966), orthopyroxene separates from the magma in the earlier stages, and when it reaches the ortho- to high clino-pyroxene inversion boundaries (ca 1200°C) its place is taken by pigeonite which crystallizes continuously. The pattern for a twinned pigeonite with orthopyroxene having common (100) is similar to that obtained on an orthopyroxene heated up to the stability field of pigeonite by Ross et al. (priv. comm.). The monoclinic pigeonite growing on or in the orthopyroxene may have one of twin orientations, thus producing the twinning.

The diffuse streaks observed in the intermediate pigeonites, have been reported neither in terrestrial nor in pigeonites from mare basalts. Similar diffuse streaks have been found in pigeonites coexisting with secondary orthopyroxene from some eucrites or eucritic portions of some mesosiderites. The intensities of the streaks are stronger where the strong reflections of orthopyroxene are present in reciprocal space, e.g. between 102 and 202; and $\overline{2}02$ and $\overline{3}02$. Those streaks thus indicate the presence of stacking faults.

Cation distribution in M1 and M2 sites and the crystal structures of orthopyroxenes, one separated from a glass matrix breccia fragment (12033,97) and the other from an Apollo 14 crystalline rock (14310,90) and of magnesian pigeonite have been refined using intensity data measured by a Picker automated single crystal counter diffractometer The crystal data are given in Table 1. Due to small size of the orthopyroxene crystals only 389(A-12) and 866(A-14) reflections were observable, for which preliminary least-squares refinement resulted in R-values of 0.060 and 0.056 respectively.

The site populations and mean M-O bond distances for the A-12 orthopyroxene from KREEP material are: M1(.91Mg+.09Fe)2.097Å, M2(.06Ca+.50Mg+.44Fe)2.204Å; and for A-14 orthopyroxenes: M1(0.88Mg+0.07Fe+0.05 others)2.083Å, M2(0.09Ca+

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0.52Mg+0.39Fe+0.003 Mn)2.200Å. The temperature estimated from the distribution isotherms (Virgo and Hafner, 1969; Saxena and Ghose, 1971) is about 600°-700°. The temperatures were similar to those found in orthopyroxenes from volcanic rocks. The aluminum content of the orthopyroxene of rock 14310 used for structural work is not as high as those of 14310 orthopyroxenes. The structural features found in an aluminan bronzite formed at high pressure (Takeda, 1971) were not noticeable in the 14310 orthopyroxene.

The crystallographic features of the pyroxenes from Fra Mauro basalts are distinct from those of Apollo 11 and 12 mare pyroxenes and thus should be useful in characterizing such rocks and their crystallization trends. The non-mare pyroxenes reveal cooling rates fairly slower than many of the mare pyroxenes. Some similarities between these pyroxenes and some achondritic pyroxenes as discussed above will provide useful information in deducing the thermal history of parent bodies of these meteorite groups.

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TABLE 1. Cell dimensions and chemical compositions of orthopyroxene (Opx), pigeonite (Pig) and augite (Aug).

Sample	a, Å	b, Å	c, Å	β, deg.	Wo-En-Fs
12033,97 Opx	18.302(6)	8.884(2)	5.212(7)	---	3-68-29 *
14310,90 Opx	18.301(3)	8.869(2)	5.215(1)	---	5-72-23 *
14310,90 Pig	9.673(3)	8.896(2)	5.228(3)	108.65(4)	8-62-30 *
14310,90 Pig	9.715(1)	8.963(1)	5.239(1)	108.64(2)	7-41-52
14310,90 Aug	9.713(2)	8.964(3)	5.266(2)	105.93(2)	43-27-30

* microprobe analysis by A. M. Reid.