THERMAL AND IMPACT HISTORIES OF PYROXENES IN LUNAR EUCRITIC GABBROS AND EUCRITES. Hiroshi Takeda and Hiroshi Mori, Mineralogical Institute, Faculty of Science, University of Tokyo, Hongo, Tokyo 113, T. Ishii, Ocean Research Institute, Univ. of Tokyo, Minamidai, Nakano-ku, Tokyo 164, and M. Miyamoto, Dept. of Pure and Appl. Sci., College of General Education, Univ. of Tokyo, Komaba, Meguro-ku, Tokyo 153, Japan.

To obtain better understanding of processes responsible for the formation of ancient planetary crusts, we have been carrying out comparative studies on pyroxenes in pristine lunar crustal rocks and in a layered crust of the howardite parent body(1), which appears to have preserved a record of the most primitive differentiation events in our solar system associated with crust formation. We have reported a similarity in crystallization trends between the KREEP basalts and quickly cooled eucrites(2). However, lunar analogues of eucrite have been very rare. Because a pristine eucritic gabbro 61224,6 was discovered from Decartes by Marvin and Warren(2), we investigated exsolution, inversion and deformation textures of pyroxenes in samples 61224,36 and 61223,47 by single-crystal X-ray diffraction and electron microprobe techniques. For comparison, pyroxenes in eucritic analogues, Moore County, Juvinas, Yamato-74356 and in lunar KREEP-rich quartz-monzodiorite 15405,148 which contains pigeonites with similar textures and chemical compositions to those of common eucrites(4), have been reinvestigated by the above techniques and analytical transmission electron microscopic(TEM) techniques. Computer simulation(5) on cooling histories of these exsolved pigeonites has been performed with new lamellar widths obtained by TEM.

Thin section 61224,36 is one of 3 thin sections of rock 61224,6 supplied by Dr. U. Marvin, who also picked up small rock and pyroxene fragments (61223, 47) similar to 61224,6 from the original coarse fines. Pyroxene crystals were separated from 4 rock fragments of 61223,47, which consist of clear plagioclase and brown pyroxenes surrounded by pale green glasses, and from 15405, 148, and lunar norite/gabbro clasts, 15445,226, 15455,237, and 67035,33. The crystals were mounted along c^* or a^* and precession photographs of $h0l$, $0kl$ and $hk0$ nets were taken using Zr-filtered MoKα radiation. These crystals were then mounted with the l axis perpendicular to the plane of slide glass for electron microprobe analysis of their exsolved phases. The sources of eucritic pyroxenes and the TEM techniques are described in our accompanying paper(6).

As was described by Marvin and Warren(3), thin section and grain observation show that 61224 and 61223 have homogeneous, coarse-grained equal amounts of plagioclase, inverted pigeonite and augite, and minor shock-melted glass. The texture and pyroxene compositions are similar to some cumulate eucrites and are suggestive of a slowly cooled, plutonic rock. However, one of the characteristics of the lunar analogue in comparison with true eucrites is occurrence of augite. The fact can be explained by high proportions of the Wo components (13.6 mol.%) in the CIPW norm calculated from the bulk chemistry of (3). The augite coexists with pigeonite in a grain forming chains of subhedral crystals 0.5 to 3mm in size. The bulk chemical compositions of the pigeonite and augite in contact each other (Table 1 and Fig. 1) gave apparent crystallization temperature of 1100°C (±20°), which was obtained by a pigeonite-augite geothermometer of Ishii et al.(7), and is the same as that of the minimum stability field of the pigeonite. The augite exsolves lamellae of low-Ca pyroxenes about 6μm wide with about 30μm interval.

The exsolution texture of the inverted pigeonites is disturbed by shock events. Between thick augite lamellae (3-10μm in width) that was in common with (001) of the original pigeonite, there are several thinner lamellae.

PYROXENES IN LUNAR EUCRITIC GABBROS

Takeda, H. *et al.*

The widths of augite were measured on the oriented crystal section. The X-ray diffraction patterns of the inverted pigeonites show considerably misoriented spots of orthopyroxene due to shock effect and the presence of two augites with (100) and (001) in common. Faint spots of pigeonite with also (100) in common may have been produced by shock-induced transformation from orthopyroxene as was found in the Johnstown diogenite. Some lamellae and thin films of augite-pigeonite interface show high concentration of aluminum, which may be shock-melted glasses similar to those found at the pyroxene-plagioclase boundary(3). An indication of similar shock-melting in a submicroscopic scale was found in the 15405 pyroxene by TEM. The detailed description is given in our accompanying paper(6). The mean width of exsolved pyroxene measured by TEM is about 1μm. Shock melted glasses with Al-rich augite compositions were also found in 15445 and 15455, in which a primary orthopyroxene coexists with plagioclase.

The TEM studies on the eucritic pyroxenes did not show an evidence of strong shock effect as found in the above lunar pyroxenes(6). Some new findings include presence of abundant orthopyroxene-like stacking faults in pigeonite with (100) in common (Fig. 2), which has been predicted by our X-ray study(1). To obtain accurate widths of exsolved augite lamellae in eucritic pigeonites, the measurements were made of ion-thinned pyroxene foils exactly oriented with the (010) foil perpendicular to the electron beam by the TEM technique. Submicroscopic augite lamellae were found in the Moore County pigeonite (partly inverted) between the thick (50μm) lamellae, but no such two-generation lamellae were detected in Juvinas and Yamato-74356. The mean widths (μm) with maximum values in parentheses for eucritic pigeonites are: Moore County: 0.1 (0.3), Juvinas: 0.5 (0.8), and Yamato-74356: 0.2 (0.3) (Table 2). The compositions of the lamellae were examined by the analytical TEM(6).

These new data of the exsolution lamellae were employed to calculate cooling rates and depths of burial where the exsolution was developed by the same computer program used for our previous studies(5). Atomic diffusion coefficient(D) for the above simulation is $D=4.5\times10^{-19}cm^2/sec$ at 1125°C with activation energy of 28kcal/mol. Cooling rate of -0.2°C/year for exsolution lamella of 0.5μm in width to develope from 1100° to 850°C, and depth of 0.2km was obtained for Juvinas and -0.2°C/month and 70m for the Yamato-74356 pigeonite. For Juvinas, to see the minimum depth of burial, D of a magnitude of order larger was employed. The use of larger D can be justified by the fact that the diffusion of Ca will be faster for such Fe-rich composition. The results show that the cooling rate was reduced to -0.5°C/year and such cooling rates require rather shallow burial(100m). Therefore the meteorite need not have been subjected to extended subsolidus annealing proposed previously (2). Simple application of the program to the lunar 61223,47 pigeonite for the thickness of the hot lunar crust of 200km, instead of R= 250km for the spherical howardite parent body gave the depth of burial from 2 to 8km. The depth is comparable to that estimated for the cumulate eucrites(5).

In conclusion, in spite of similarities in their bulk chemistries, mineral assemblages, depths of burial in the crust, and crystallization temperatures(c.a.1100°C) between lunar and meteoritic eucrites, there are some differences in their pyroxene assemblages and exsolution, inversion textures, which can be attributed to bulk chemistry of the lunar ones. The largest difference lies in that the lunar analogues experienced much higher degree of shock events than the meteoritic eucrites. The chemistry and exsolution texture of the 15405 pigeonite are more close to those of common eucrites.

PYROXENES IN LUNAR EUCRITIC GABBROS

Takeda, H. *et al.*

Table 1. Chemical compositions of selected pyroxenes in lunar eucritic gabbros.

	L61224,36			L61223,47		
	Pig. Bulk	Aug. Bulk	Glass	Pig. Bulk	Opx. Host	Aug. Lam.
SiO_2	51.4	50.5	49.3	52.6	52.2	49.2
Al_2O_3	1.48	2.17	15.06	1.61	0.49	7.08
TiO_2	0.55	0.98	0.44	0.49	0.44	0.97
Cr_2O_3	0.41	0.68	0.20	0.38	0.33	0.24
FeO	21.3	13.07	12.48	18.05	20.6	17.32
MnO	0.24	0.25	0.13	0.30	0.30	0.21
MgO	22.1	15.92	9.06	21.2	22.2	13.59
CaO	3.18	16.88	11.74	3.76	1.63	10.34
Na_2O	0.14	0.15	0.84	0.11	0.00	0.07
Total	100.80	100.60	99.25	98.50	98.19	99.02

Table 2. Cooling histories of eucritic pigeonites.

Width (μm)	Initial Ca Mol%	Cooling rates	Burial depth
Juvinas(R=250km)			
0.5	8.01	-0.2°C/y	0.2km
0.5	4.55	-0.3/10y	0.6
6.88*	8.01	$-0.4/10^2$y	1.7
Yamato-74356			
0.2	7.41	-0.2/month	.07
Moore County			
54.6	10.1	$-0.2/10^2$y	9.1
L61223,47(d=200km)			
5.0	7.90	$-0.2/10^3$y	8.4

* old value.

We thank National Institute of Polar Research for the meteorite sample, Dr. M. Prinz for Moore County, and Prof. C.B. Moore for Juvinas.

References:

(1) Takeda H. (1979) *Icarus* 40, 455-470.
(2) Takeda H., Miyamoto M., Duke M. B. and Ishii T. (1978) *Proc. Lunar Planet. Sci. Conf. 9th*, p. 1157-1171.
(3) Marvin U. B. and Warren P. H. (1980) *Lunar and Planetary Science XI*, p. 671-673, Lunar and Planetary Institute, Houston.
(4) Ryder G. (1976) *Earth Planet. Sci. Lett.* 29, 255-268.
(5) Miyamoto M. and Takeda H. (1977) *Geochem. J.* 11, 161-169.
(6) Mori H., Takeda H. and Sadanaga R. (1981) *Lunar and Planetary Science XII.* (this volume), Lunar and Planetary Institute, Houston.
(7) Ishii T., Takeda H. and Yanai K. (1979) *Mineral. J.* 9, 460-481.

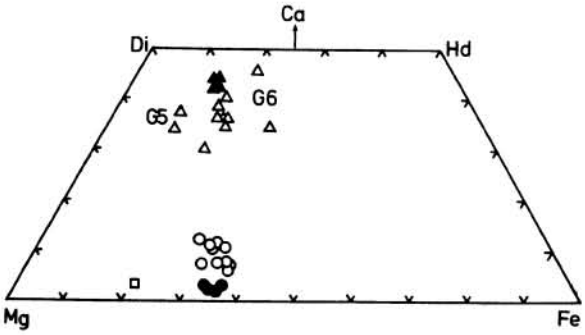

Fig. 1. Pyroxene quadrilateral plots of bulk chemical compositions of augite(open triangle) and pigeonite(open circle), and exsolved pair of orthopyroxene(solid circle) and augite (solid triangle) of lunar eucritic gabbro 61224,36 (G6: green glass), and those of orthopyroxene(squre) and glass(G5) of lunar norite clast 15445,226.

Fig. 2. Electron micrograph of the Juvinas pigeonite (right). Width is 2μm. Note thick (001) augite lamellae and fine vertical stacking faults of orthopyroxene slab parallel to (100).