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The mineral assemblage of symplectites in lunar meteorite Asuka-881757

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Abstract: Asuka-881757 with a gabbro-like texture is from lunar mare. It is different from other known lunar mare basaltic meteorites. It is coarse-grained basalt with symplectite texture in mesostasis. It is composed mainly of pyroxene and maskelynite (An_{90}~An_{96}). Most ilmenites, troitites and some Fe-Ni metals are surrounded by symplectite. One of the symplectites consists of very fine-grained Fe-rich olivine (Fa_{93}) and silica phase in pyroxene host around troilite. However, the troilite and primary pyroxene did not react to form the symplectite. The coexisting fayalite, hedenbergitic pyroxene and silica phase suggest that they crystallized from the primary melt at a pressure lower than 1.15 GPa, indicating formation near the lunar surface.

1. Introduction

The symplectites in lunar rocks are reported by many investigators (*e.g.*, Bell *et al.*, 1975; Gooley *et al.*, 1974). Yanai and Kojima (1991) reported that symplectite is one of the most characteristic features of the Asuka-31 (official name: Asuka-881757). Asuka-881757 was studied by many investigators (Takeda *et al.*, 1992, 1993a,b; Koeberl *et al.*, 1993; Warren and Kallemeyn, 1993; Arai *et al.*, 1996). Takeda *et al.* (1992) suggested that the Asuka-881757 is not cumulate gabbro because of the abundance of mesostasis-like symplectites and the lack of detectable exsolution in pyroxene. It is classified as coarse-grained VLT basalt with symplectite texture in mesostasis (Takeda *et al.*, 1992).

Yanai and Kojima (1991) reported that symplectite is composed mainly of very fine-grained olivine, pyroxene, apatite, plagioclase, Fe-Ni metal and silica phase (quartz?). The olivine is Fe-rich, ranging from $Fa_{86.6}$ to $Fa_{94.6}$.

Bowen and Schairer (1935) reported that ferrosilite decomposed to fayalite and quartz at low pressure. Lindsley *et al.* (1964) determined that ferrosilite is stable at temperatures between 1150°C and 1400°C and 18 and 45 kbar, respectively. Ferrosilite has been synthesized by Akimoto *et al.* (1964, 1965) under pressure-temperature conditions ranging from 12 to 73 kbar and 620°C to 1270°C. They determined the equation for the boundary curve of fayalite + quartz = ferrosilite. Lindsley (1981) reported that at low pressure the low-Ca pyroxene decomposes to Hd_{ss} + fayalite + quartz, while the three-pyroxene assemblage orthoferrosilite-pigeonite-hedenbergite is on the $CaFeSi_2O_6$-$Fe_2Si_2O_6$ join at pressures above 1.15 GPa and below 2 GPa.

2. Petrography and mineralogy

Asuka-881757 is a coarse-grained and unbrecciated rock, consisting mainly of pyroxene (60%) and maskelynite (30%) with small amounts of ilmenite and troilite, and traces of olivine, apatite, silica phase and Ni-Fe metal. Most ilmenites, chromian ulvöspinels, troilites and some Fe-Ni metals are surrounded by symplectite. Symplectic intergrowths of olivine and pyroxene or silica phase occur commonly along pyroxene-maskelynite or pyroxene-pyroxene grain boundaries. The majority of symplectites was observed in the pyroxene side of the boundary of minerals.

Pyroxene occurs as subhedral crystals (3–5 mm in length) showing wavy extinction. Yanai and Kojima (1991) reported that the composition of the pyroxene is heterogeneous, ranging from $En_{7.8}$ to $En_{43.6}$, $Fs_{30.7}$ to $Fs_{68.2}$, $Wo_{11.6}$ to $Wo_{40.9}$. Plagioclase is completely maskelynitized (1–4 mm in length), and its composition ranges from An_{88} to An_{96}. Some symplectites are observed at the boundary of pyroxene and troilite or Fe metal. Olivine and silica phase are scattered 10–30 μm blebs in pyroxene. Backscattered electron (BSE) photograph shows the symplectite in Fig. 1.

The analyses of minerals in the symplectite were performed using energy dispersive X-ray spectrometer (EDS) (Oxford: Link-ISIS) at Joetsu University of Education. They are given in Table 1. The bulk chemical compositions of four symplectites are shown in Table 2. They are analyzed by EDS in a beam area of a 100 μm^2.

The chemical composition of fine-grained olivine is fayalitic (Fa_{93}) (Fig. 2).

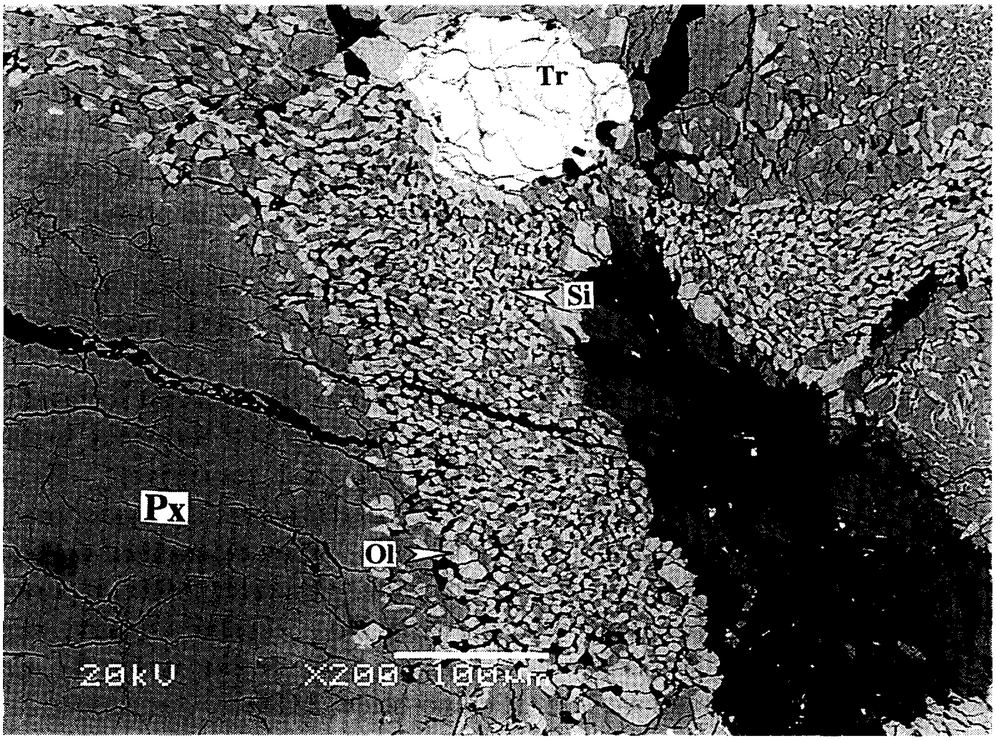

Fig. 1. Backscattered electron (BSE) image of symplectite in Asuka-881757. Troilite is surrounded by a symplectite halo. Symplectite is composed of olivine (Ol: light gray), pyroxene (Px: dark gray), silica phase (Si: black) and troilite (Tr: white).

Table 1. The chemical compositions of pyroxene, olivine, silica phase and maskelynite.

	Px near troilite	Px in symplectite	Px in symplectite	Px primary	Ol in symplectite	Silica phase in symplectite	Maskelynite
SiO_2	47.3	48.5	48.3	46.8	30.0	98.5	44.6
TiO_2	0.98	1.30	0.78	1.24	0.21	0.31	0.15
Al_2O_3	0.23	1.34	1.35	2.41	0.57	0.32	34.3
FeO	29.8	27.4	28.3	31.4	65.1	0.80	0.39
MnO	0.15	0.37	0.28	0.56	0.75	*	0.02
MgO	3.18	3.49	4.01	6.66	2.49	0.16	0.45
CaO	17.4	17.3	17.6	10.5	0.36	0.28	19.7
Na_2O	0.38	0.19	0.29	0.12	0.31	0.34	0.52
Total	99.42	99.89	100.91	99.69	99.79	100.71	100.13
oxygens	6	6	6	6	4	2	8
Atomic formulae							
Si	1.952	1.959	1.943	1.899	0.993	0.985	2.066
Al	0.011	0.064	0.064	0.115	0.022	0.004	1.872
Ti	0.030	0.040	0.024	0.038	0.005	0.002	0.005
Fe	1.030	0.927	0.951	1.065	1.803	0.007	0.015
Mn	0.005	0.013	0.010	0.019	0.021	*	0.001
Mg	0.196	0.210	0.240	0.403	0.123	0.002	0.031
Ca	0.771	0.750	0.759	0.455	0.013	0.003	0.978
Na	0.030	0.015	0.023	0.009	0.020	0.007	0.047
Total	4.028	3.978	4.014	4.003	3.000	1.010	5.016
Fe/(Fe+Mg)	0.840	0.815	0.798	0.725	0.936		An:95

* not detected

Olivine compositions from Asuka-881757 are tightly clustered and are much more Fe-rich than olivines from most lunar mare basalts (Fig. 2). The chemical composition of the pyroxene ranges from $Wo_{20.2}En_{17.0}Fs_{62.8}$ to $Wo_{37.5}En_{13.5}Fs_{49.1}$ (Fig. 3). Pyroxenes in symplectite are hedenbergitic as compared to host pyroxenes.

3. Discussion

Ferrosilite is not stable at low pressure, and it is stable at high pressure. Lindsley *et al.* (1964) showed by experiment that ferrosilite is stable at temperatures between 1150°C and 1400°C and 18 and 45 kbar, respectively (Fig. 4). Akimoto *et al.* (1964,

Table 2. The bulk compositions of symplectites.

	1	2	3	4
SiO_2	51.7	45.3	49.2	46.8
TiO_2	0.24	0.83	*	0.77
Al_2O_3	0.12	0.63	*	0.81
FeO	39.1	31.8	37.1	32.3
MnO	0.28	0.42	0.23	0.39
MgO	2.15	2.81	1.86	3.21
CaO	4.02	9.41	4.88	8.71
Na_2O	0.13	*	0.22	0.08
K_2O	0.13	0.06	0.02	0.20
Total	97.87	91.26	93.51	93.27
	Atomic	formulae	6 oxygens	
Si	2.144	2.025	2.141	2.036
Al	0.006	0.033	*	0.041
Ti	0.007	0.028	*	0.025
Fe	1.358	1.188	1.352	1.178
Mn	0.010	0.016	0.008	0.014
Mg	0.133	0.187	0.121	0.208
Ca	0.179	0.451	0.228	0.406
Na	0.010	*	0.019	0.007
K	0.007	0.003	0.001	0.011
Total	3.854	3.931	3.870	3.926
Fe/(Fe+Mg)	0.911	0.864	0.918	0.850

* not detected

1965) reported the boundary curve for the reaction: $1/2(Fe_2SiO_4)+1/2SiO_2=FeSiO_3$ under pressure-temperature conditions ranging from 12 to 73 kbar and 620°C to 1270 °C. The equation for the curve is:

$$P_{\mathrm{kbars}}=2.7+0.014\mathrm{T}\ (^\circ\mathrm{C}). \qquad (1)$$

The presence of troilite in Asuka-881757 indicates that after troilite crystallization the rock was not heated above the melting temperature 1200°C of troilite (Kullerud, 1967). The maximum pressure estimated by the eq. (1) is about 2 GPa in subsolidus. Thus, the coexistence of fayalite and silica phase indicates that the pressure of crystaliza-

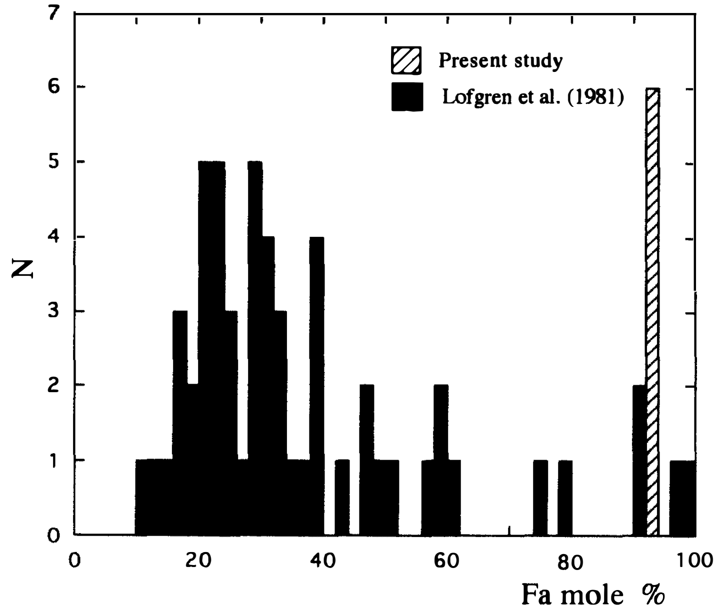

Fig. 2. Chemical compositions of olivine from lunar samples and lunar meteorite Asuka-881757. Filled blocks are olivines from the lunar basalts reported by Lofgren et al. (1981). Hatched blocks with an oblique line are olivines from lunar meteorite Aska-881757 in the present study.

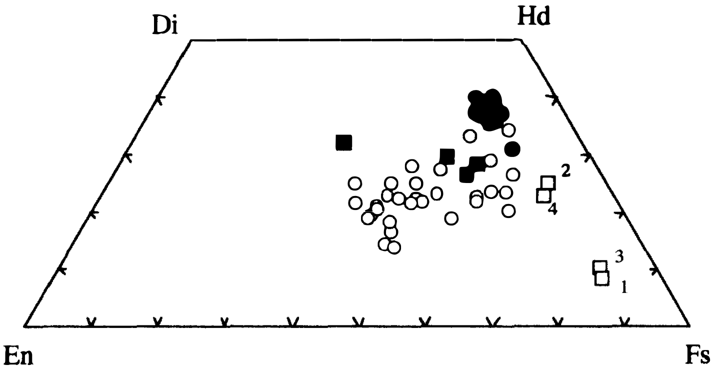

Fig. 3. Pyroxene compositions of Asuka-881757. Open circles are pyroxenes from rim of primary grain, and solid circles are pyroxenes in symplectites. Open squares are the bulk compositions of the symplectites. Solid squires indicate pyroxene rim. Numbers are the same as in Table 2.

tion of fayalite and silica phase is below 2 GPa. Lindsley (1981) reported that at low pressure the low-Ca pyroxene decomposes to Hd_{ss} + fayalite + quartz on the $CaFeSi_2O_6$-$Fei_2Si_2O_6$ join at pressures below 1.15 GPa.

Takeda *et al.* (1992) found the evidence of rapid growth and cooling of zoned pyroxene in Asuka-881757. Takeda *et al.* (1993a) suggested on the basis of the microtextures of pyroxene that Asuka-881757 cooled more slowly than samples near the surface of a lava flow, but more rapidly than those crystallized near the surface in disequilibrium growth condition of true plutonic gabbroes. Arai *et al.* (1996) concluded on the basis of chemical variations of chromian ulvöspinel that it may have crystallized from a residue at the last stage of crystallization. They suggested that Asuka-881757 was cooled more slowly than typical mare basalts, probably near the

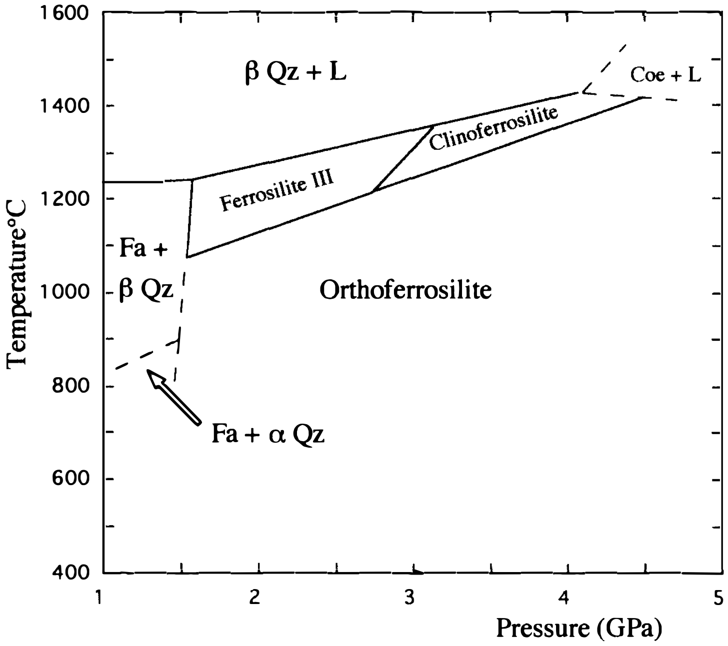

Fig. 4. Stability relations of ferrosilite (after Lindsley et al., 1964)

center of an uncommonly thick lava flow. The assemblage Fe-rich olivine (fayalite)-silica phase in the symplectite also indicates that the symplectite formed at low pressure.

Si contents of four symplectites are higher than 2 of stoichiometric pyroxene. The fact shows that the symplectite is not formed by the chemical reaction of troilite and pyroxene. If the troilite and primary pyroxene reacted to form the symplectite, Si content of symplectite is lower than that of the primary pyroxene by Fe supplied from troilite.

The chemical compositions of the symplectites and pyroxene are similar except for the SiO_2 content. The chemical compositions of four symplectites are plotted in Fig. 3. The symplectite 1 around troilite is plotted near the corner of Fs. Fe-rich low Ca pyroxene decomposes into fayalite, hedenbergite and silica phase at low pressure (Lindsley, 1981, 1983). Symplectite formed at the boundary of pyroxene and other minerals, and it is observed at the rim of pyroxene. Takeda *et al.* (1993b) reported that pyroxene approaching the mesostasis display the trend towards hedenbergitic composition. As shown in Fig. 3, pyroxene in the symplectite has hedenbergitic composition. For example the bulk composition of symplectite 1 is plotted near Fe-rich low Ca pyroxene. At low pressure fayalite and silica phase are stable on the ferrosilite-like bulk composition. As FeO content of pyroxene increase at the last stage of crystallization, Fe-rich pigeonitic pyroxene is not stable at low pressure. Fe-rich pigeonitic pyroxene decomposed to hedenbergitic pyroxene, fayalite, and silica phase as symplectitec texture. A majority of symplectites occurs at rim of pyroxene. Alternatively the residual liquid composition is so Fe-enriched that pyroxene crystallization was replaced by crystallization of silica and fayalite. The presence of minor amounts of feldspar and apatite in some symplectites supports this hypothesis.

In conclusion, the coexisting fayalite, hedenbergitic pyroxene and silica phase suggest that they crystallized at pressure lower than 1.15 GPa, indicating formation near the lunar surface.

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