SHOCK FORMATION OF KAERSUTITE IN MARTIAN METEORITES: AN EXPERIMENTAL STUDY.

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Introduction: Magmatic inclusions in Martian meteorites contain some hydrous minerals such as kaersutites [*e.g.*, 1-2]. The characteristic of Martian kaersutites is their water-poor [3] and Ti-rich (~10 wt%) compositions. The presence of kaersutite gives evidence that Martian parent magma contained water. In fact, several attempts have been performed to estimate the water content in Martian magmas and mantle [*e.g.*, 4]. Thus, it is important to reveal the crystallization process of kaersutite for understanding the Martian magma water content. However, no one has been successful in explaining crystallization process of Martian kaersutites because of difficulty in explaining crystallization of Ti-rich kaersutite. Johnson *et al*. [2] studied a partially crystallized magmatic inclusion in Chassigny and suggested that low TiO_2 content in synthetic kaersutite was due to ilmenite crystallization prior to kaersutite in the experiments. We suggested that Ti-rich kaersutites in Martian meteorites is a shock origin rather than a primary phase crystallized at depth [5]. In order to explore this hypothesis, we have performed shock experiments on analogous mixture of magmatic inclusions in Martian meteorites.

Observation of magmatic inclusion: We performed a detailed observation of kaersutite-bearing magmatic inclusions in Zagami (Fig. 1) and LEW 88516 (lherzolite) Martian meteorites. The size of magmatic inclusions is usually 100-200 µm in diameter, but their shapes are irregular. They are surrounded by radiation cracks in many cases. Kaersutite-bearing magmatic inclusions in Zagami and LEW 88516 usually occur only within cumulus pyroxene. Kaersutite coexists with Al-Ti diopside, Si-rich glass, and hercynite spinel. One of the most important observations is that kaersutite almost always has contact with both Al-Ti diopside and Si-rich glass. The size of kaersutites is up to 20 µm long. Olivine in LEW88516 also conrains a similar inclusion, but they do not contain kaersutites. The magmatic inclusions within olivine instead contain ilmenite and Fe-Ti oxides. Their bulk compositions are similar to those of magmatic inclusions containing kaersutite.

Shock experiment: The shock-recovery experiments were performed using a single stage 30 mm-bore propellant gun to generate shock waves by hypervelocity impact at the National Institute for Materials Science. The detailed experimental procedure is similar to Sekine *et al*. [6]. Starting materials were mixed powders (<30 µm) in the same mass of augite ($En_{28.5}Fs_{43}Wo_{28.5}$), albite ($Ab_{100}$), ilmenite and Ti-magnetite (Usp_{54}). So far we have performed two runs that gave the shock pressures of about 38 and 50 GPa, respectively. The peak pressure is estimated by the impedance match method using the measured impact velocity. The sample container and flyer are stainless steel 304.

Results of shock experiment: In the recovered experiment sample (starting material: augite, albite, ilmenite and Ti-magnetite) shocked at 50 GPa (Fig. 2), many Ti-magnetite grains melted, but a few of the large grains with some bubbles remained. About half of ilmenite grains remained. New phases with some bubbles (clearly absent in the starting material) were observed (Fig. 2). The new phases are observed between augite, albite, ilmenite and Ti-magnetite. Their compositions are similar to those of Martian kaersutites in magmatic inclusions (Table 1). The petrology of kaersutite-bearing magmatic inclusions in Martian meteorites is also consistent with this experimental result (Fig. 2). TiO_2 contents of these kaersutite-like phases are from 6 to 18 wt%.

In the sample (starting material: augite, albite, and ilmenite) shocked at 38 GPa, similar kaersutite-like phases are present in small areas. Their TiO_2 contents range from 6 to 12 wt%.

The only compositional difference between kaersutite-like phases produced in shocked samples and Martian kaersutites is Al abundance (Table 1). Al_2O_3 contents (7-8 wt%) of kaersutite-like phases (from both shots at 50 GPa and 38 GPa) are lower than those of Martian kaersutites (13-14 wt%). This is probably because augite used in the experiment has a lower Al_2O_3 content (Al_2O_3 = ~3 wt%) than Al-Ti diopside (Al_2O_3 = 8-10 wt%) coexisting with Martian kaersutites in magmatic inclusions.

Degree of shock pressure: Shock pressures experienced by Martian meteorites have been estimated by several studies. The Shergotty meteorite experienced higher pressures than 29 ±1 GPa [7] and ~40 GPa [8]. Chassigny experienced similar degree of shock (~35 GPa) [9]. In contrast, Nakhla experienced lower shock degree of ~20 GPa [10]. The discovery of new high-pressure polymorphs of SiO_2 in Shergotty indicates that Shergotty was shocked as high as from 45 GPa up to 95 GPa in local places [8]. Due to the presence of minute minerals in the magmatic inclusion (the diameter is 50 to 100 µm), the pressure would have induced reaction among these minerals. Thus, it would be possible that magmatic inclusions in shergottites (and probably Chassigny) experienced shock pressure of ~50 GPa. Thus, difference in the shock pressure estimated among different types of Martian meteorites could explain the reason why only shergottites and Chassigny contain kaersutites, although nakhlites (without kaersutite) contain similar magmatic inclusions. The degree of shock for nakhlites (~20 GPa) would not be enough to cause the reaction of augite, albite, ilmenite and Ti-magnetite. Therefore, kaersutite could not be produced in nakhlites. The reason of the absence of kaersutites in the magmatic inclusions within olivine is unclear. One possible explanation is that the temperature inclease of olivine is lower than pyroxene [11] and the peak temperature was not enough to react the minerals.

The following is a hypothetical crystallization process of Martian kaersutite in magmatic inclusions. Al-Ti diopside, Ti-magnetite, ilmenite and Si-rich glass were primary phases in magmatic inclusion. Due to the impact event on Mars (probably the ejection event from Mars), magmatic inclusions in Martian meteorites have suffered a shock pressure of ~50 GPa. Increase of the pressure and temperature by shock would partly melt these minerals in magmatic inclusions. Ilmenite and Ti-magnetite could not crystallize because a release of the shock pressure would bring about rapid decrease of the temperature. Kaersutites could crystallize in the magmatic inclusion as temperature decreased.

Water content of Martian magma: Martian kaersutites in magmatic inclusions contain small amounts of water (0.1-0.2 wt%) [3]. Mysen et al. [13] estimated the water content of Martian magma based on the analytical result of water content in Martian kaersutites in conjunction with the crystal chemical model of kaersutites. They estimated that water contents in Martian magma and mantle were 1-35 ppm. Such a low water content is different from the results of [13] (~1.8 wt%) estimated from pyroxene crystallization experiment and spacecraft observations [*e.g.*, 14]. Dann *et al.* [13] suggested that oxidation and dehydrogenation of kaersutite may have occurred during ascent of magma or as a result of shock. However, these presumptions are unlikely because water contents of kaersutites are invariable during transport from the Earth's mantle to the surface [15]. Shock experiments of amphibole up to 30 GPa also did not show clear change [16].

Thus, shock formation of kaersutites can explain low water and high Ti contents of Martian kaersutites and does not conflict with the models of "water-rich" Martian magma and mantle [14].

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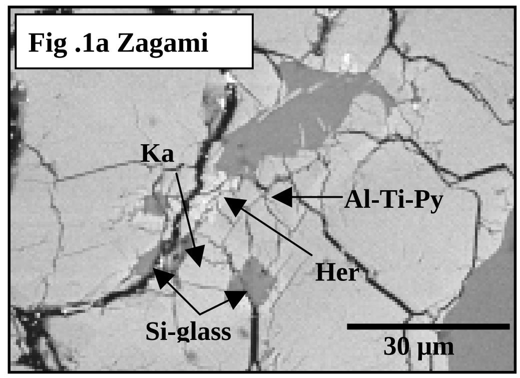

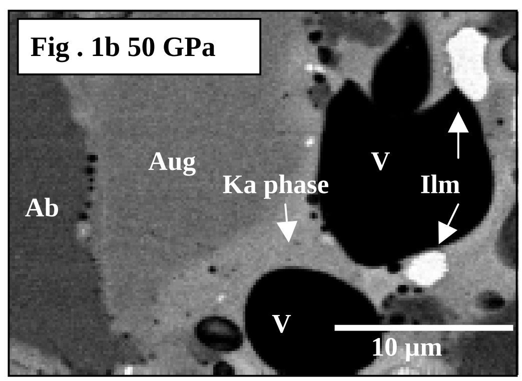

Fig. 1 a) Backscattered lectron image of a magmatic inclusion in pyroxene of Zagami. Kaersutite: ka. Al-Ti-rich pyroxene: Al-Ti-py. Hercynite: her.
b) Run product at 50 GPa. kaerstutite-like phase: Ka phase. Augite: Aug. Albite: Ab. Ilmenite: Ilm. Vesicle: V.

Table1 Chemical compositions of kaersutite-like phase and Martian kaersutites

	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
Ka-phase	41.19	10.55	7.41	0.00	17.18	0.16	7.59	10.47	1.53	0.19	96.26
Zagami	36.97	8.83	14.18	0.44	17.95	0.29	6.58	10.71	2.39	0.12	98.45
LEW88516	36.98	10.31	15.61	0.38	14.27	0.30	8.93	11.04	1.36	0.47	99.63

Ka-like phase: Ka-phase.