

COMPOSITIONAL CONTROLS ON THE FORMATION OF KAERSUTITE AMPHIBOLE IN SHERGOTTITE METEORITES. K.M. Pitman^{1,2} and A.H. Treiman³. ¹Dept. of Physics & Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA <pitman@baton.phys.lsu.edu>. ²Space Science Institute, Boulder, CO 80303, USA. ³Lunar and Planetary Institute, Houston, TX 77058, USA <treiman@lpi.usra.edu>.

Introduction: The shergottite basalts, meteorites of Martian origin, contain rare small grains (~10-100 μm diam.) of kaersutite, a Ca-amphibole rich in Al and Ti [1-3]. Kaersutites have been used to estimate the water content of shergottites and the Martian mantle [4]; however, questions remain about the original water content of the amphiboles [5] and if they formed from magma [6]. We investigated the petrographic settings of amphiboles in two shergottites and confirm that these amphiboles occur only in multiphase inclusions in pyroxene. In fact, kaersutite is found only in pigeonite. This suggests that the occurrence of amphibole is controlled in part by the composition of its host phase. Crystallization of host (cognate) pigeonite from a magmatic inclusion will enrich the remaining melt in Ca, Al, and Ti, supporting formation of kaersutite.

Samples and Methods: We identified kaersutite grains in thin sections of the shergottites Zagami (UNM 999) and EETA79001 (,443). Zagami and EETA79001 include several lithologies: UNM 999 is fine-grained [2], and EETA79001,443 represents the A lithology (relatively fine-grained and magnesian) [7]. Both samples contain ~70 % pyroxene grains. Zagami contains nearly equal proportions of augite (high-Ca) and pigeonite (low-Ca) [2], while EETA79001A has three times more pigeonite than augite [8]. In both shergottites, the pyroxene grains are larger (up to 0.5 mm across and 1 mm long) than plagioclase (maskelynite), oxides, sulfides, or Ca-phosphate grains.

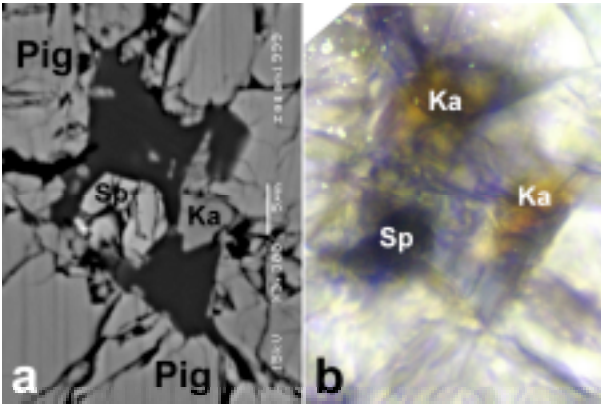


Figure 1. Typical amphibole-bearing magmatic inclusion in Zagami UNM 999. Both images of same inclusion, at same scale (bar is 5 μm.). Pig = pigeonite; Sp = hercynite spinel; Ka = kaersutite. [a] BSE. Darkest phase is aluminosilicate glass. Bright spots are Fe sulfide. [b] Optical, plane polarized light. Inclusion contains two amphibole grains, only one of which is accessible to BSE.

Thin sections were characterized optically at LPI, noting kaersutite by its color and pleochroism (Fig. 1b). Using SEM/BSE and EDS (JEOL JSM-5910LV at

Johnson Space Center), we mapped both sections, confirmed optical identifications of kaersutite, and qualitatively identified the kaersutites' host pyroxene and nearby phases (Fig. 1a). Quantitative chemical analyses were obtained by EMP/WDS (Cameca SX100 at JSC), using natural and synthetic standards. Chemical compositions of the kaersutite, other inclusion phases, and host pyroxenes are consistent with earlier results on these shergottites (Table 1, [1-3,7-9]).

Petrography and Mineral Chemistry: Kaersutite has been reported only in multi-mineral inclusions in pyroxenes, with variable proportions of silica-rich glass, hercynite spinel, a Ca-phosphate mineral, magnetite, ilmenite, and an iron sulfide. We concur that these inclusions are magmatic, i.e., remnants of magma droplets trapped in growing phenocrysts. We did not note kaersutite anywhere in Zagami or EETA79001A except in these inclusions in pyroxene.

Table 1. Chemical Compositions

	EETA79001 ,443			EETA	
	host pigeonite (anal. 51)	inclusion kaers. (anal.52)	inclusion glass (anal. 27)	augite [7]	79001A magma [8,9]
SiO ₂	52.87	36.40	74.41	52.1	49.4
TiO ₂	0.14	10.11	0.21	0.26	2.0
Al ₂ O ₃	0.70	14.48	17.66	1.5	7.4
Cr ₂ O ₃	0.41	0.37	0.05	0.62	0.3
FeO	17.84	15.97	1.42	15.0	18.1
MnO	0.56	0.28	0.09	0.52	0.56
MgO	21.47	7.48	0.46	17.6	12.2
CaO	4.95	10.90	2.03	11.8	9.2
Na ₂ O	0.07	2.03	0.69	0.2	0.8
K ₂ O	0.01	0.11	2.23	0.0	0.07
Sum	99.02	98.13	98.95	99.6	100.03

Analyses by EMP; augite from [7]. EETA79001A magma is recalculated from groundmass composition Eg of [8]. Estimates: of Cr₂O₃ from data in [8], of K₂O from [9]

We investigated 16 kaersutite-bearing magmatic inclusions in the shergottite thin sections. All of these kaersutite-bearing inclusions were in pigeonite pyroxene (Table 1). One of the kaersutite-bearing inclusions in Zagami also contained an augite crystal, abutting the glass and other inclusion phases but otherwise completely surrounded by pigeonite.

Table 2. Numbers of kaersutite grains by host pyroxene.

	Pigeonite	Pigeonite (w/ augite)	Augite	Total
Zagami	7	1	0	8
EETA79001	8	0	0	8

The absence of kaersutite-bearing inclusions in augite is not an artifact of sampling or of inclusion entrapment. We obtained element maps of selected areas in Zagami that included kaersutite-bearing pigeonites to ensure that our examination had included augite grains. In the maps, we found sub-equal proportions of pigeonite and augite (vis. [2]). The augites contain kaersutite-free multiphase inclusions, similar to the kaersutite-bearing inclusions in pigeonite. Thus, it appears that kaersutite really does not occur in magmatic inclusions in augite.

Chemical Modeling: Using a possible parental magma composition for Zagami UNM 999 [13], we attempted to model formation of amphibole in the shergottites using the MELTS model of basalt phase equilibria [10]. Our effort was not successful.

The MELTS model permits crystallization of amphibole only under unusual conditions. With the chosen parent magma, amphibole did not appear on the liquidus at low or high pressure (to 2 kbar) and at anhydrous to hydrous conditions (2.0 wt%, [4,11]). Amphibole appeared as a liquidus phase only when all other solids are suppressed. MELTS is capable of predicting equilibrium crystallization of amphibole crystallization for suitable bulk compositions, e.g. camptonite [12].

Several factors may contribute to the inability of MELTS to model formation of shergottite amphiboles. First, the amphibole in MELTS (an average hornblende) may not be an appropriate thermochemical substitute for the kaersutites in shergottites. Second, MELTS is designed for equilibrium processes, and crystallization of the magmatic inclusions is clearly at disequilibrium (e.g., absence of plagioclase, near absence of augite in inclusions in pigeonite). Finally, the MELTS database may not include the highly calcic, aluminous, and titanian liquids likely in the melt inclusions in pigeonite.

Discussion: We find that in the shergottites (at least in Zagami and EETA 79001A), kaersutite amphibole occurs only in multiphase magmatic (i.e., melt) inclusions in pigeonite. None were found in augite pyroxene, and none have been reported elsewhere in the shergottites, e.g., as phenocrysts, in the mesostasis [2], or in melt inclusions, feldspar or Ca-phosphate [2,13].

The restriction of kaersutite to inclusions in pigeonite suggests that the magmas in them are different from magmas elsewhere in the shergottites: the bulk magma (i.e., mesostasis) and the magma trapped in

melt inclusions in other minerals. One can consider differences in the volatile contents of the melts (i.e., H₂O, Cl, F) and differences in non-volatile components.

It has been inferred that the kaersutite in the shergottites implies water-rich magmas (i.e., 2% H₂O by weight) and water loss during ascent to the Martian surface [4,11,14]. The inclusions in pigeonite could have been trapped while the magma was still wet, and inclusions in other phases were trapped after water loss. However, the core pigeonites and augites appear to be contemporaneous [2,13,15], and kaersutite can grow with little water [16,17].

Kaersutite formation should be favored in bulk melt compositions rich in Ca, Al, and Ti. Magma included in pigeonite will evolve to these enrichments – pigeonite contains less of these elements than the magma, Table 1. Magma included in augite will not become enriched Ca, because augite contains more CaO than the magma (Table 1), and mesostasis magma will have its Ca and Al content buffered by plagioclase. Thus, our results suggest that the non-volatile composition of magma plays a crucial role in permitting the formation of amphibole. In the presence of minerals rich in Ca and/or Al, shergottite melt will not evolve to permit formation of kaersutite. Our results do not refute the importance of water (or other volatiles) in kaersutite formation but imply that other factors are also crucial.

Acknowledgments: This work was performed during a LPI Graduate Fellowship to KMP. Meteorite samples were loaned by the Institute of Meteoritics, University of New Mexico. C. Schwandt, G. Robinson, and L. Le (all Lockheed@JSC) supported SEM and EMP analyses. Thanks to G. Byerly (LSU) for discussions regarding MELTS calculations. KMP is supported by SSI. AHT acknowledges support from NASA Cosmochemistry Grant NAGW-12184.

References: [1] Treiman A.H. (1985) *Meteoritics* **20**, 229. [2] McCoy T.J. et al. (1992) *Geochim. Cosmochim. Acta* **56**, 3571. [3] Treiman A.H. (1998) *Meteoritics* **33**, A156. [4] McSween H.Y.Jr. & Harvey R.P. (1993) *Science* **259**, 1890. [5] Popp R.K. et al. (1995) *Amer. Mineral.* **80**, 1347. [6] Monkawa A. et al. (2003) *Lunar Planet. Sci.* **XXXIV**, Abstr. #1534. [7] McSween H.Y.Jr. & Jarosewich E. (1983) *Geochim. Cosmochim. Acta* **47**, 1501. [8] Schwandt C.S. et al. (2001) *Lunar Planet. Sci.* **XXXII**, abstr. #1913. LPI. [9] Longhi J. & Pan V. (1989) PLPSC 19th, 451. [10] Ghiorso M.S. et al. (1995) *Contrib. Mineral. Petrol.* **119**, 197. [11] Dann J.C. et al. (2001) *MaPS* **36**, 793. [12] Rock, N.M.S. (1991) *Lamprophyres*, p. 80, Blackie and Son Ltd, Glasgow. [13] Stolper E.M. & McSween H.Y.Jr. (1979) *Geochim. Cosmochim. Acta* **47**, 1475. [14] Lentz R.C.F. et al. (2001) *Geochim. Cosmochim. Acta* **65**, 4551. [15] Hale V. et al. (1999) *Geochim. Cosmochim. Acta* **63**, 1459. [16] Popp R.K. et al. (1995) *Amer. Mineral.* **80**, 534. [17] Mysen B.O. et al. (1998) *Amer. Mineral.* **83**, 942.