GLASS-BEARING INCLUSIONS IN SHERGOTTY.

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Introduction

Glass-bearing inclusions have been extensively studied in all SNC meteorites (Shergottites, Nakhlites and Chassignites) as a key to deduce the composition of the melt from which these meteorites formed [e.g., 1-3]. In the classical model view, these inclusions are considered to represent a small volume of the co-existing magma that was trapped during growth of the host mineral. The assemblage of crystal and glass -in multiphase inclusions- are assumed to be the result of subsequent closed-system crystallization. The study of all types of glass-bearing inclusions (glassy and multiphase) in some of the SNC meteorites led [4] to suggest a non-classical scenario in which formation of these rocks was governed by low (sub-solidus) temperatures. In Shergotty, like in other basaltic shergottites, glass bearing inclusions are hosted by pyroxenes (augite and pigeonite), whitlockite and ulvospinel. Here we report results on major and trace element compositions of these inclusions in order to better understand the petrogenetic processes that were involved in the formation of this rock.

Samples and Results

The Shergotty thin sections A and B (NHM, Vienna) were studied by microscopic and micro-analytical techniques following standard procedures. Major element compositions were obtained with a SX100 CAMECA (University of Vienna) and trace element analyses were performed with a CAMECA IMS 3F ion microprobe (Washington University in St. Louis). The studied samples show two types of glass- bearing inclusions hosted by pyroxenes, whitlockite and ulvöspinel: Glassy inclusions (GIs) and Multiphase inclusions (MIs). The latter, consist of glass and micrometer sizes crystals of pyroxene, kaersutite, apatite, spinel and iron sulphide. Kaersutite-bearing inclusions are mainly observed in pigeonite, but can also occur in augite (Fig. 1).

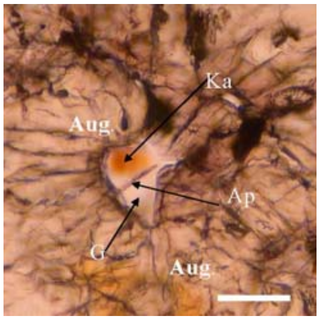


Figure 1: Optical plane polarized light image of a multiphase inclusion hosted by augite. Ka (Kaersutite), Ap (apatite), Aug (augite) and G (glass). Scale bar: 60 µm.

All glass-bearing inclusions trapped by augite and pigeonite have irregular shapes. Those hosted by whitlockite and ulvöspinel are usually rounded or ellipsoidal. Both types of inclusions (GIs and MIs) occur in the center and in the rim of pyroxenes and ulvospinel. In whitlockite they are mainly aligned at the centre of elongate crystals. Both GIs and MIs can be present in a single grain and have variable sizes, ranging from 10 to 50 µm and 30 to 100 µm, respectively.

Glasses from all inclusions are rich in SiO_2 and Al_2O_3 and poor in FeO, CaO and MgO, with variable contents of Na_2O and K_2O. The chemical compositions of GI hosted in the core and rim of pyroxenes, ulvöspinel and whitlockites are shown in Table 1.

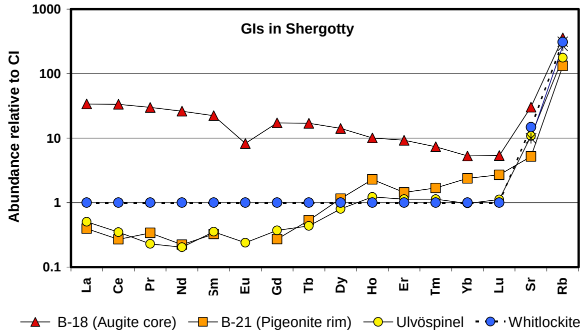
Table 1: Major chemical compostions of GIs in Shergotty

N	Pig. Core B-18 (3)	Pig. rim (3)	Aug. core (2)	Aug. rim B-21 (2)	W (6)	Usp (7)	Meso (2)
SiO2	69.0	74.8	70.8	69.5	75.0	80.0	74.9
TiO2	0.24	0.15	0.22	0.10	0.26	0.40	0.53
Al2O3	17.4	14.7	15.9	17.9	12.5	11.0	12.4
FeO	1.53	1.27	1.21	1.05	0.89	1.31	1.93
MnO	0.06	0.04	0.04	0.04	0.04	0.03	0.03
MgO	0.13	0.07	0.05	0.08	0.02	0.04	0.08
CaO	1.86	2.12	1.46	1.22	1.87	0.61	1.60
Na2O	2.76	3.89	2.41	3.01	1.15	1.81	1.75
K2O	6.49	2.82	6.30	7.17	5.35	4.30	6.11
P2O5	0.59	0.18	0.15	0.07	0.13	0.11	
Total	100.0	100.1	98.5	100.1	97.2	99.7	99.3

Reference: Pig.: Pigeonite; Aug.:Augite; W: Whitlockite; Usp: Ulvöspinel; Meso: mesostasis from [7].

SIMS analyses show that glasses from GIs and MIs have variable REE contents (Fig. 2). The GI B-18 is located in a pigeonite core. The glass in B18, has REE contents around 20 x CI and a fractionated, LREE enriched pattern (La/Lu:~7) with a negative Eu anomaly (8 x CI). Glasses from GIs trapped in an augite rim (B21) and in a ulvöspinel show similar abundances of REE, characterized by low LREE (~0.3 x CI) contents and HREE abundances around 1 x CI. Both glasses show a fractionated LREE depleted pattern (La/Lu: 0.15 for B21 and 0.5 for the GI in ulvöspinel; Fig. 2). In four GIs trapped by whitlockites we could not avoid some contamination by the surrounding phosphate. The REE contents based on the first five analysis cycles (after which the element signals are highly variable) were estimated to be around 1 x CI. All glasses have Sr contents around 10 x CI and high Rb abundances (~ 200 x CI) (Fig. 2).

Figure 2



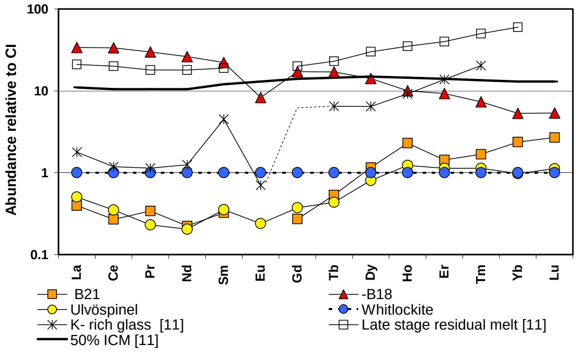
Discussion

The Shergotty achondrite is a member of the SNC meteorites, which are believed to originate from Mars [e.g. 5]. Of all SNC meteorites recognized up to date, shergottites are the most abundant group. They are commonly divided into three types: Basaltic, Lherzolitic and Olivine-phyritic [6]. The Shergotty meteorite belongs to the basaltic type. It is a cumulate rock consisting mainly of pyroxenes (augite and pigeonite), maskelynite, and minor (~ 2 %) ilmenite, titanomagnetite (ulvöspinel) and phosphates [e.g.,7]. Pyroxene crystals are zoned with respect to major (e.g., Mg-rich cores and Fe-rich rims), minor and trace element contents [7-8]. The trace and minor element trends in pyroxenes suggest that shergottites formed by progressive (closed-system) fractional crystallization [8].

Kaersutite-bearing inclusions: Of all the mineral phases found in Shergotty, the amphiboles (kaersutite) have been very useful for estimating, among others, the water content of shergottites [9] as well as for determining the composition of the magma that would favor amphibole formation [10]. Accordingly, the occurrence of kaersutite restricted to MIs hosted in pigeonite of Zagami and EETA 79001A led to the suggestion that, in the presence of Ca-rich minerals, shergottite melts will not evolve to allow formation of kaersutite [10]. In our studied samples, kaersutite was only observed inside multiphase inclusions in pyroxenes, in agreement with previous results [10]. However, although pigeonite in Shegotty is the main host mineral of kaersutite-bearing inclusions, we have observed at least one inclusion hosted in augite (Fig 1). This observation shows that kaersutite can also form in MIs that are hosted by a Ca-rich mineral. The previous conclusion -based on the study of Zagami and EETA 79001A [10]- cannot be extended to Shergotty.

Chemical compositions of glasses: Normative calculation of glasses from GIs and MIs indicate that they are dominated by Q-Or-Ab, with little An and a small (from 1.3 to 2.7%) pyroxene (ferrosilite) component. Projected onto the plane Orthoclase (Or)-Albite (Ab)-Anortite (An), the GI compositions fall onto the trend defined by the mesostasis in Shergotty [7]. Thus, GIs could represent small amounts of a late-stage residual liquid trapped by pyroxenes or during crystallization of late phases (e.g., whitlockite and ulvöspinel). However, although these liquids /melts have major element compositions akin to those of late melts [7], none of the GIs have trace element contents that resemble those of the K-rich glasses (mesostasis), the late-stage interstitial melt [11], or the calculated 50% intercumulus melt (ICM) (at this melt proportions the homogeneous pyroxenes cores and some rims, as well as some plagioclase would be cumulus) [11] (Fig. 3).

Figure 3



The rare-earth element contents in glasses from GIs are highly variable and reveal that -at the late stage of Shergotty crystallization- there are still some unresolved problems. Our study of GIs leave some open questions: why do GIs trapped in the core and rim of pyroxenes -with similar major element compositions (compare B21 and B18, Table 1)- show LREEs abundances that differ by up to two orders of magnitude, with patterns revealing opposite (B18: La/Lu:~7; B21: La/Lu: 0.15) fractionations (Fig. 3)? Why do liquids with different major element compositions trapped in an augite rim (B21) or during ulvóspinel formation (Usp, see Table 1) show similar fractionated LREE depleted patterns (Fig. 2)?

References: [1] Floran R. J. et al. (1978) *Geochim. Cosmochim. Acta* 42, 1213-1229; [2] Harvey R. P. and McSween H. Y (1992) *Earth Planet. Sci. Lett.* 111, 467-482; [3] Stockstill K. R. et al. (2005) *Meteoritics &Planet. Sci.* 40, 377-396; [4] Varela M.E. et al. (2000) *Meteoritics & Planet. Sci.* 35, 39-52; [5] McSween H. Y.(1994) *Meteoritics* 29, 757-779; [6] Goodrich C. A. (2002) *Meteoritics & Planet. Sci*. 37, B31–B3; [7] Stolper E. and McSween H. Y. (1979) *Geochim. Cosmochim. Acta* 43, 1475–1498; [8] Wadhwa M. et al (1994) *Geochim. Cosmich. Acta* 58, 4213-4229; [9] McSween H. Y. and Harvey R. P. (1993) *Science* 259, 1890; [10] Pitman K. M. and Treiman A. H. (2004) *LPSC,* Abstract # 1177; [11] Lundberg L. et al (1998) *Geochim. Cosmich. Acta* 52, 2147-2163.