MAGMATIC PROCESSES THAT PRODUCED LUNAR FIRE FOUNTAINS: EVIDENCE FROM VESICULAR RIMS ON PICRITIC GLASS BEADS.

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Introduction: The standing hypothesis for the formation of the lunar picritic glass beads is eruption in a volatile-driven fire fountain followed by degassing while suspended in a hot, turbulent vapor plume.

Reanalysis of the Apollo 15 A, B, and C green glass beads from slide 15426,72, led to the discovery of beads with small patches of highly vesicular green glass adhering to their rims (fig. 1). There are now three related compositional data sets for the lunar picritic glasses: the glass bead compositions themselves, the vesicular glass rims, and thin surface coatings on the beads, which may represent the gases that drove the fire fountain eruptions (*e.g.*, [1,2], *c.f.* [3]).

Methods: The beads and their rims were analyzed with a JEOL-JXA 733 Superprobe electron microscope at MIT. The interior of each glass bead was analyzed five times with a 10-micron beam spot size, using a 10 nA beam current and an accelerating voltage of 15 kV, for major oxide components. Rims were also analyzed five times when space permitted. During a separate analysis session we measured the trace elements Ni, S, Cl, Cu, Zn, and F, with five separate analyses of each sample, using a 10 micron spot size but a 200 nA beam current and counting times up to 300 seconds.

Results: We found four beads with partial vesicular rims: beads 80A, 84A, 155B, and 190B (all bead numbers are from Delano's notation). All the vesicular rims are extremely high in S (1000 to 2300 ppm) and contain as much as 420 ppm Ni. The S content in particular makes the rim compositions distinctive from the glass beads they adhere to. There is no detectable F, P_2O_5, Zn, or Cu in the vesicular rims, and Cl is near or below the detection limit (fig. 2). The beads themselves contain no F or Zn and low S, but one A subgroup contains notably high Cl. The rim glasses have different major and minor element compositions than the beads they are attached to, and they show no diffusion profiles with the interior bead. In contrast to the vesicular rims, the thin surface films on many beads are enriched in S, Cl, F, and Zn (*e.g.*, [4]).

Discussion: The vesicular rim glasses must have erupted simultaneously with the glass beads. Bead 80, in particular shows vesicles from the glass rim pressing into the glass of the bead itself (fig. 1). This process could only have happened while the central glass bead was still ductile.

The highest S content in the vesicular rims is 2300 ppm. An Apollo 15A green glass melt at 2.2 GPa is theoretically saturated with 2300 ppm sulfur [5]. We suggest that the vesicular rims degassed very little after eruption, based on their abundant vesicles and high sulfur content, and that their sulfur content is a direct indicator of origination depth. The Apollo 15 A glasses are multiply saturated at 2.2 GPa [6], so the sulfur in the vesicular rims is consistent with an origin at about the same depth as the group A glasses. The major element compositions of the rims also suggest a provenance similar to the A, B, and C green glass beads: melting from depleted magma ocean cumulates [6-8].

Since sulfur saturation increases with decreasing pressure (*e.g.*, [5]), sulfur cannot have driven magma from depth, as it would not degas as pressure decreased. Near or at the surface, sulfur would degas into the vacuum of space, and could thus have broken the magma into drops and created the spraying fire fountain, but it could not have pushed the magma through the crust. Chlorine may have played a larger role in driving the eruption, because its saturation limit decreases with pressure [9]. A deep driving force for eruption, however, may actually be unnecessary. Wieczorek *et al*. [10] suggested that buoyancy is the controlling factor in eruption. If the magma conduit is continuously connected to some depth, hydrostatic head may also drive eruption. When the magma reaches the vacuum, volatiles will degas, creating fire fountain eruptions.

Delano [7] had suggested that the surface films originated in an undifferentiated, volatile-rich reservoir near the green glass source at □ 400 km depth. The findings in this paper support that hypothesis and further suggest that at least a portion of the melted, volatile-rich source retained its separate composition throughout the eruption process, and ended as vesicular, glassy rims on the Apollo 15 glass beads.

Conclusions: The S in the rims indicates that the vesicular rim glasses did not linger in the vapor plume, degassing. Sulfur cannot have driven the eruptions from depth, because sulfur saturation increases with decreasing pressure. We suggest that the Apollo 15 glass beads were driven to erupt by buoyancy or hydrostatic head, possibly aided at depth by chlorine or fluorine degassing, and that degassing volatiles into the vacuum drove the final fire-fountaining eruption. The data from this study are consistent with either a heterogeneous lunar mantle at depth, or with the vesicular rim glasses originating in a primordial source beneath the bottom of the depleted magma ocean cumulates. They would therefore either support the hypothesis of heterogeneous mantle mixing after magma ocean crystallization, or the hypothesis of a magma ocean about 450 km deep.

References: [1] Meyer Jr. C. *et al*. (1975) *LPS VI,* 1673–1699. [2] Goldberg R.H. *et al*. (1975) *LPS VI*, 2189–2200. [3] Fogel R.A., M.J. Rutherford (1995) *GCA 59*, 201-215. [4] Butler P., C. Meyer (1976) *LPS VII*, 1561-1581. [5] Holzheid A., T.L. Grove (2002) *Am. Min*. *87*. [6] Elkins Tanton L.T. *et al*. (2003) Accepted by *Meteoritics*. [7] Delano J.W. (1979) *LPS X*, 275-300. [8] Delano J.W. (1986) LPS XVII, D201–D213. [9] Webster J.D. *et al*. (1999) *GCA. 63*, 729-738. [10] Wieczorek M.A. *et al*. (2001) *EPSL. 185*, 71-83.

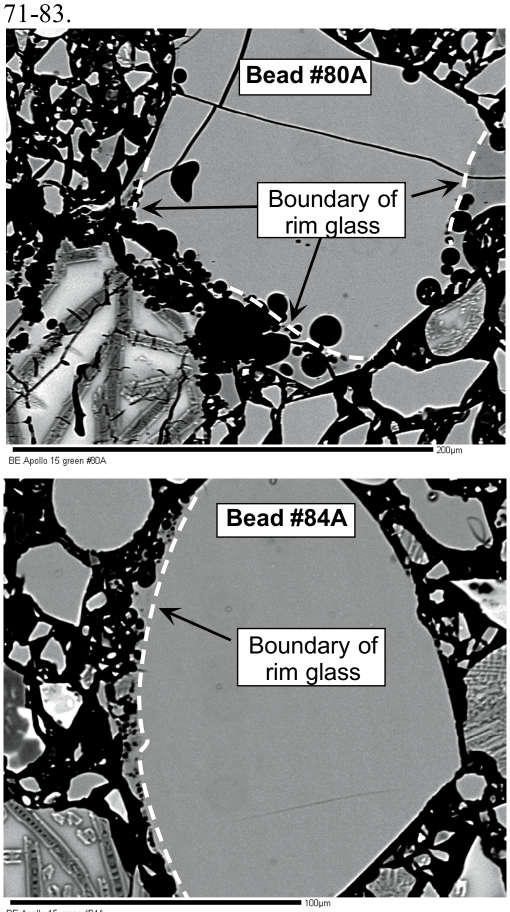

Figure 1: Backscattered-electron micrograph of Apollo 15 green picritic beads 80A and 84A, showing homogeneous vesicular partial rims.

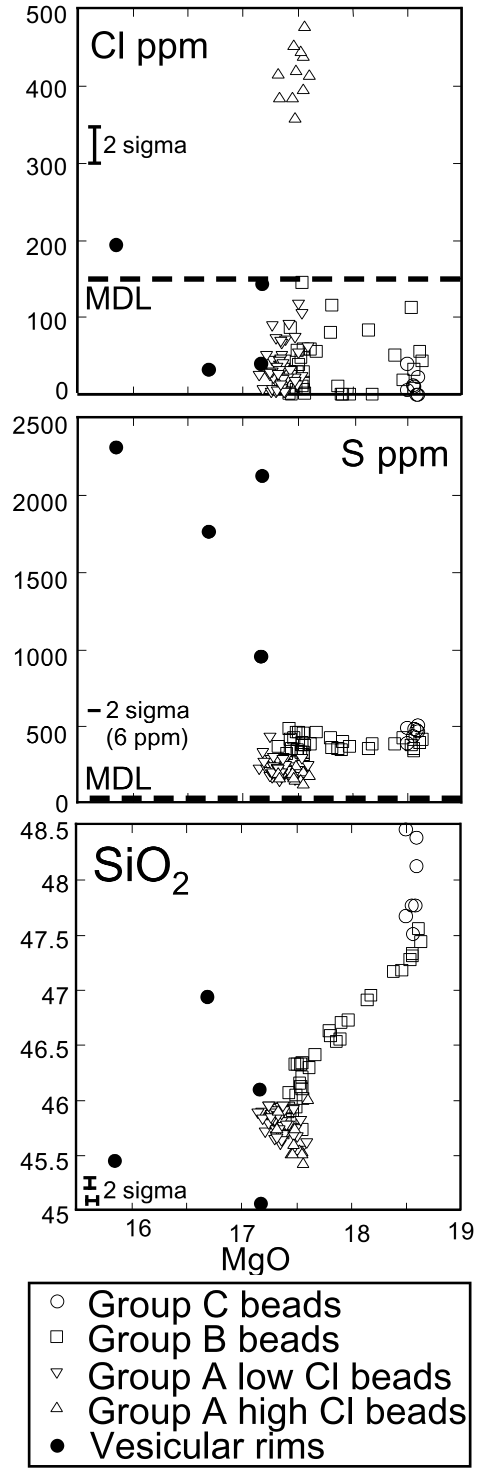

Figure 2: Compositional variation diagrams of Apollo 15 glasses and vesicular rims. MDL = Minimum detection limit. 2 σ population errors are shown with bars. All graphs are vs. MgO in wt%.