

Magmatic processes that produced lunar fire fountains

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[1] Reanalysis of the Apollo 15 A, B, and C green glass beads from slide 15426,72, led to the discovery of patchy, highly vesicular glass rims adhering to beads. These rims are high in S and Ni and low in MgO, but otherwise compositionally similar to the green glasses. We find that these rims represent a unique melt composition that places constraints on lunar magmatic processes. Combining the compositional data for the vesicular glass rims with new minor element data for the green glass beads leads us to hypothesize that the vesicular rim fluid originated near the green glass source, at about 2.2 GPa. These findings support the theory of a heterogeneous lunar mantle, and suggest that sulfur did not drive the eruption from depth, but that degassing volatiles into the vacuum did drive the final fire fountain eruption. **INDEX TERMS:** 5455 Planetology: Solid Surface Planets: Origin and evolution; 6250 Planetology: Solar System Objects: Moon (1221); 8450 Volcanology: Planetary volcanism (5480); 8414 Volcanology: Eruption mechanisms; 8439 Volcanology: Physics and chemistry of magma bodies. **Citation:** Elkins-Tanton, L. T., N. Chatterjee, and T. L. Grove, Magmatic processes that produced lunar fire fountains, *Geophys. Res. Lett.*, 30(10), 1513, doi:10.1029/2003GL017082, 2003.

1. Introduction

[2] The Apollo 15 glasses were erupted onto the lunar surface at ~ 3.5 Ga [Meyer, 1975] in what most investigators agree was a gas-propelled fire fountain eruption [e.g., Ridley *et al.*, 1973; Heiken *et al.*, 1974; Delano, 1979, 1986]. In an attempt to better constrain the compositions of the green glasses, we have reanalyzed the Apollo 15 green glass beads from slide 15426,72 [Elkins-Tanton *et al.*, 2003]. This compositional information provides new insights into melting processes, source compositions and eruption mechanisms of the picritic glasses, and provides new constraints on the deep lunar interior at about 3.5 Ga. We found four thin, highly vesicular glass rims with compositions distinct from the interior of the beads. Thousands of analyses of green glasses have been published [e.g., Delano, 1979, 1986; Galbreath *et al.*, 1990; Steele *et al.*, 1992; Shearer and Papike, 1993; Shearer *et al.*, 1996; Elkins-Tanton *et al.*, 2003] and their compositions fall into discrete groups that show limited variability [Delano, 1979, 1986]. The vesicular rim compositions lie outside the well defined variations of each glass group, and their unique compositions provide important clues to the provenance of the Apollo 15 ultramafic glasses. Vesicles inside green

glass beads have been reported previously by a number of researchers [e.g., Delano and Lindsley, 1983]. In contrast, the vesicles in this study are tiny and confined to the 10–20 micron thick glass patches rimming the picritic glass beads. With the discovery of these vesicular glass rims, there are now three related lunar compositional data sets that shed light on petrogenesis and eruption conditions of the lunar picritic glasses: the glass bead compositions themselves, the vesicular glass rims, and thin surface coatings on the beads.

[3] Many researchers have analyzed the thin coatings on the outside of the glass beads for volatiles, and suggested that these volatiles represent the gases that drove the fire fountain eruptions [e.g., Meyer *et al.*, 1975; Goldberg *et al.*, 1976; Butler and Meyer, 1976; Wasson *et al.*, 1976; Chou *et al.*, 1978; Delano, 1979; Fogel and Rutherford, 1995]. Goldberg *et al.* [1976] found that the Apollo 15 green glass surface layer, about a tenth of a micron in thickness, contains up to 3000 ppm of fluorine, while typically lunar rocks contain only 50 to 100 ppm fluorine. Fluorine is thus a prime candidate for volatile propulsion during eruption. Analysis of other Apollo 15 beads showed that sulfur was the most common element in the surface coatings [e.g., Carusi *et al.*, 1972]. While orange glasses from Apollo 17 contain 420 to 750 ppm S, and Apollo 15 green glasses contain 100 to 500 ppm, mare basalts can contain up to 2700 ppm [e.g., Gibson and Moore, 1974; Delano *et al.*, 1994]. Butler and Meyer [1976] suggested that if the picritic glasses were primitive analogs of the basalts, then the picritic glasses must have lost S in the eruption process, thus identifying S as a possible driving force in eruption. Delano *et al.* [1994] investigated this hypothesis experimentally, and found that at 1300°C, 82 to 97% of sulfur was lost from an 80 μm green glass bead in 2 to 5 minutes. This suggests that the beads spent several minutes in a hot vapor plume after eruption and before cooling [see also Arndt *et al.*, 1984]. The standing hypothesis for the formation of the picritic glass beads is, then, eruption in a volatile-driven fire fountain, and continued degassing while suspended for several minutes in a hot, turbulent vapor plume. Degassing is followed by a falling from the plume into the cold near-vacuum of the lunar surface, and quenching quickly enough that many glass beads avoided growing crystals.

2. Experimental and Analytic Methods

[4] Analyses were performed on a JEOL-JXA 733 Superprobe electron microscope at MIT. The microprobe was calibrated with primary and secondary standards, including two anhydrous glasses that have been character-

Table 1. Compositions of Glass Beads and Vesicular Rims, With Microprobe Counting Errors and Minimum Detection Limits

Sample	Grp	N	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Mg#	NiO	S	Cl
Rim on bead 80	A	5	45.46	0.51	11.14	0.48	16.32	0.18	15.84	9.62	0.23	0.043	0.000	63.4	423	2317	194
Rim on bead 84	A	3	46.95	0.36	8.30	0.53	17.80	0.22	16.68	8.79	0.21	0.029	0.000	62.6	280	1768	32
Rim on bead 155	B	3	45.07	0.52	8.09	0.50	19.33	0.20	17.17	8.67	0.26	0.030	0.000	61.3	318	2129	144
Rim on bead 190	B	5	46.10	0.39	8.32	0.56	18.21	0.19	17.16	8.79	0.18	0.023	0.000	62.7	271	959	41
Bead 80	A	5	45.88	0.39	7.26	0.53	19.82	0.28	17.37	8.39	0.06	0.02	0.01	61.0	199	294	10
Bead 84	A	3	45.84	0.37	7.50	0.51	19.58	0.27	17.28	8.51	0.09	0.02	0.02	61.1	188	296	0
Bead 155	B	5	46.98	0.39	7.66	0.54	17.40	0.27	18.19	8.41	0.15	0.02	0.00	65.1	104	384	0
Bead 190	B	4	45.92	0.47	7.72	0.51	19.01	0.25	17.42	8.54	0.13	0.02	0.00	62.0	159	485	3
2- σ population errors			0.12	0.05	0.09	0.08	0.2	0.04	0.1	0.1	0.05-0.12	0.06	0.02		32-48	6	56
Min. detection limits			0.019	0.060	0.023	0.066	0.046	0.053	0.029	0.021	0.30	0.014	0.071		65	22	150

Notes: Reported values are averages of N analyses. Oxides in wt %, minor elements in ppm.

ized at the MIT lab. Both the anhydrous glass standards were reproduced within 1- σ error limits. Analysis of the green glasses themselves was further calibrated among sessions by comparing the repeated analysis of two specific glass beads. Each glass bead and rim 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 (see Table 1). During a separate analysis session we measured the trace elements Ni, S, Cl, Cu, Zn, and F. Again five separate analyses of each bead were done, with a 10 micron spot size but a 200 nA beam current and counting times up to 300 seconds. The CITZAF correction package of *Armstrong* [1995] was used to reduce the data and obtain quantitative analyses.

3. Results

[5] The individual glass beads vary in diameter from about 50 to 350 microns. Almost all the glass beads analyzed are homogeneous, contain no crystals, and have no radial compositional variations (detailed transects were taken to confirm this). Four beads from the groups A and B reanalyzed from slide 15426,72 have partial vesicular rims: 80A, 84A, 155B, and 190B (numbers from Delano's notation; see Figure 1). None of the group C glasses observed in this slide have rims, but there are far fewer group C beads. All the rims are high in S (1000 to 2300 ppm) and contain as much as 420 ppm Ni (Table 1). The S content in particular makes the rim compositions distinctive from the glass beads they adhere to. There is no detectable F, P₂O₅, Zn, or Cu in the vesicular rims, and Cl is near or below the detection limit (Figure 2).

4. Discussion

[6] The vesicular rims are compositionally distinct from the bead interiors, and show no diffusion profiles with the interiors. The rims are also compositionally distinct from the surface films; the lack of detectable F, P₂O₅, Zn, or Cu in the vesicular glass rims is of particular interest because the thin surface films are notably rich in S, Cl, F, and Zn [e.g., *Butler and Meyer*, 1976]. The vesicular rim glasses are enriched in S and Ni. The beads themselves, like the rims, contain no F or Zn and low S, but one A subgroup contains notably high Cl (see Tables 1 and 2). There is no scatter in Cl content between the low and high groups. Since all the group A glasses are likely to have undergone similar amounts of degassing, based on S contents, the different Cl contents likely reflect different source compositions. We also analyzed surrounding soil components to rule out

contamination, and found there is no compositional relationship between rims and soil materials, nor between the glass trends themselves and soil materials. For a comparison of the compositions of the glass beads, the vesicular rims, and the surface films, see Table 2.

[7] The physical relationships between the vesicular rims and the glass beads they adhere to indicate that the vesicular rim glasses erupted simultaneously with the glass beads. Bead 80, in particular, shows vesicles from the rim pressing into the bead itself; in Figure 1 the compositional boundary

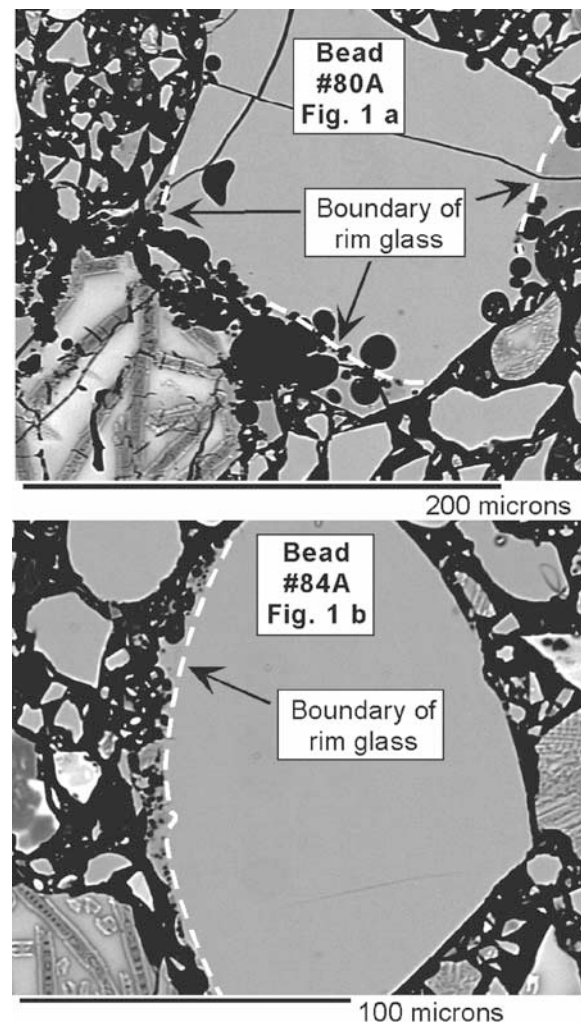


Figure 1. Homogeneous vesicular rims on beads 80A and 84A.

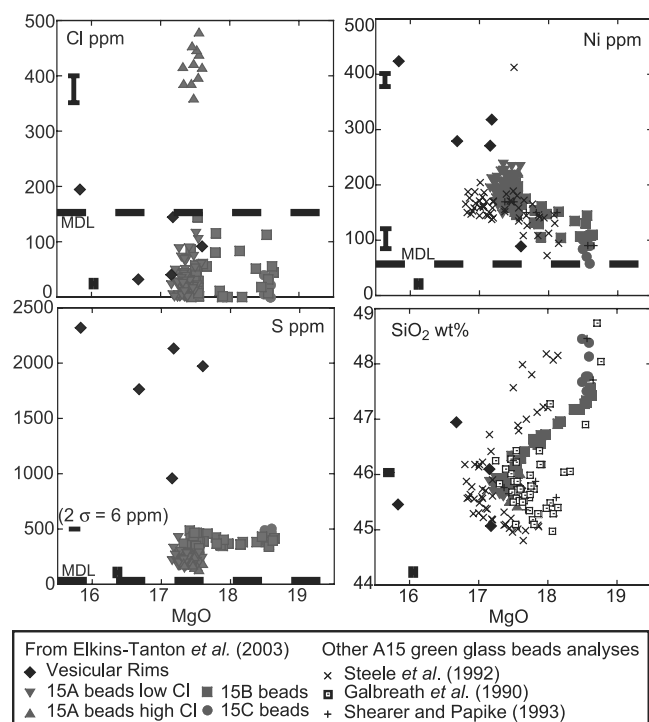


Figure 2. Compositional variations of Apollo 15 glasses and rims. Data: *Elkins-Tanton et al.*, 2003; *Steele et al.*, 1992; *Shearer and Papike*, 1993; and *Galbreath et al.*, 1990. Major elements in wt%, minor elements as ppm. MDL = minimum detection limit. Bars: 2σ population errors.

is marked as a dotted line, and the vesicles in some cases cross this line. This process could only have happened while the central glass bead was still ductile. These vesicular rims are consistent with the observations of *Agrill et al.* [1973] and *Heiken et al.* [1974], that smaller beads of green glass adhered to the outside of larger beads while still molten and in the process of eruption [see also *Delano*, 1993]. Since the materials are compositionally distinct, and were still ductile when they adhered to each other, we must conclude that the rims are a separate glass composition that adhered to the larger beads during their eruption process. This result is important evidence for multiple compositions of green glass erupting simultaneously.

[8] The highest S content in the vesicular rims is 2300 ppm. Following the parameterization of *Holzheid and Grove* [2002], it can be shown that an Apollo 15A green glass melt at 2.2 GPa is saturated with 2300 ppm sulfur. Sulfur saturation, however, increases with decreasing pressure. Therefore, a green glass with 2300 ppm sulfur could have originated either at 2.2 GPa, or at a shallower level

with a higher sulfur content, subsequently degassing sulfur into the vacuum. Based upon their abundant vesicles and high sulfur content in comparison with other green glass material, however, we suggest that the vesicular rims underwent little degassing after eruption, and that their sulfur content is a direct indicator of origination at about 2.2 GPa.

[9] The Apollo 15 A glasses are also multiply saturated at 2.2 GPa [*Elkins-Tanton et al.*, 2003], indicating that this is the depth of melt segregation. The sulfur content of the vesicular rims is therefore consistent with their origin close to the same depth as the group A green glasses. The major element compositions of the vesicular rims are similar, but distinct from those of the green glasses groups A, B, and C. This suggests a similar provenance of the rims to the groups A, B, and C, that is, melting from depleted magma ocean cumulates, with the possibility of some primordial, undifferentiated lunar material included [*Delano*, 1979, 1986; *Elkins-Tanton et al.*, 2003]. The difference in major element compositions also indicates that none of the analyzed green glasses themselves represent devolatilized rim glass. The high Ni contents, which fall roughly on the same trend defined by the group A glasses (Figure 2), also indicate a similar origin for the vesicular rim glasses as the group A glasses.

[10] The green glass beads all have sulfur contents below 500 ppm, that is, well below saturation levels for their depths of origin [*Elkins-Tanton et al.*, 2003]. The glasses may then have degassed their sulfur after eruption [*Butler and Meyer*, 1976; *Delano et al.*, 1994]. Interestingly, the S contents of the erupted green glass beads increases with decreasing depth of origin: the C group, which is multiply saturated at 260 km depth, has the highest S content, while the A group, multiply saturated at 440 km depth, has the lowest S content [*Elkins-Tanton et al.*, 2003]. This trend is consistent with variations in S saturation values, which increase with decreasing pressure. Thus the green glasses seem to have degassed the majority of their sulfur but retained the relative sulfur compositional trends.

[11] As stated above, sulfur saturation increases with decreasing pressure [e.g., *Holzheid and Grove*, 2002], and therefore sulfur cannot have driven magma from depth, as it would not degas as pressure decreased. At some point 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, though it could not have pushed the magma up through the crust. Chlorine, however, may have played a larger role in driving the eruption. *Webster et al.* [1999] showed that Cl saturation in andesites decreases with pressure. If the magmas contained more Cl originally, the Cl may have degassed during magma ascent, helping to drive the eruption.

[12] A deep driving force for eruption may be unnecessary, however. *Wieczorek et al.* [2001] determined the relative buoyancy of liquid mare basalts and lunar crustal

Table 2. Comparison of Glass Beads, Vesicular Rims, and Surface Films

Material	S	F	Cl	Zn	Ni
A15 green glass beads	100–500	nd	nd or 400–500	nd	50–240
A15 green glass beads that have vesicular rims	300–500	nd	nd	nd	100–200
Vesicular rim material from this study	950–2300	nd	nd or ~200	nd	270–420
Surface films on A15 beads	340	20–3000	>6	38	nd

Note: All elements in ppm. Bead and rim data from this paper. Surface film data from *Butler and Meyer* [1976], *Goldberg et al.* [1976], and *Delano et al.* [1994].

compositions, and suggested that buoyancy is the controlling factor in eruption; in areas where the crust has been removed by giant impact, or in cases when the magma erupts at super-liquidus temperatures, the erupting magma is positively buoyant during the entirety of ascent to the surface. If the magma conduit or network is continuously connected to some depth, hydrostatic head may further drive eruption. Then, when the magma reaches the surface, volatiles will degas into the vacuum, creating the fire fountain eruptions, and plating onto the glass beads as surface films.

[13] Delano [1979] had suggested that the elements present in surface films originated in an undifferentiated, volatile-rich reservoir near the green glass source at ≥ 400 km depth. The findings here that the vesicular rims and glass beads represent melts from compositionally distinct sources, and that the vesicular rims may have originated at depths as great as the glasses themselves, support Delano's 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.

5. Conclusion

[14] Four of the glass beads from groups A and B have small patchy vesicular rims. The S content in the vesicular rim glasses indicates a provenance for some of the vesicular rims at a maximum of 2.2 GPa, the same depth as the group A glasses. Their size, texture, and composition are consistent with being mantle melts from a source similar to but distinct from the green glass source, at about the same depth as the group A glasses. Therefore there was either a heterogeneous lunar mantle at about 450 km depth, or with the vesicular rim glasses originating in a primordial source beneath the bottom of the depleted magma ocean cumulates. They therefore support either the hypothesis of a magma ocean about 450 km deep, or the hypothesis of heterogeneous mantle mixing after magma ocean crystallization.

[15] The S in the rims indicates that the vesicular rim glasses did not linger in the vapor plume, degassing. The rarity of the vesicular rims and their high S content both suggest that most of the fire fountain propellant was in a vapor phase. Sulfur cannot have driven the eruptions from depth, because sulfur saturation increases with decreasing pressure. We suggest, therefore, 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.

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