TRACKING THE PROCESS OF VOLATILE RELEASE FROM THE LUNAR HIGHLAND BRECCIA METEORITE NORTHWEST AFRICA 2996 USING VESICLE SIZE DISTRIBUTIONS.

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Introduction: Vesicles are frozen records of degassing processes in magmas. Textural studies of vesicles in pyroclasts and lava flows are commonly used to understand processes of gas exsolution that drive terrestrial magmatism [1]. In this study we apply the same techniques to further understand volatile escape from lunar materials.

Relative rates of bubble nucleation and growth control primary vesicle textures, which can later be modified by vesicle coalescence, deformation, or volatile escape. By measuring characteristics of vesicle populations such as size, spatial pattern, number density, and shape we can determine the physical processes by which volatiles escape from a melt. For example, these characteristics can tell us if growth and nucleation of vesicles in a melt occurred as a single event or in multiple stages, whether vesiculation occurred continuously or accelerated through time, and if bubbles coalesced, collapsed, or underwent Ostwald ripening [2, 3].

Vesicle textures in lunar materials provides a window into understanding the role of volatiles in the evolution of lunar materials. This is particularly important since recent studies show that the moon is wetter than previously thought [e.g., 4, 5, 6, 7]. Volatiles (e.g., H_2O, S, F, Cl, Na, CO_2) exist at the surface and in the interior of the Moon. Solar-implanted volatile elements at the surface may supply gases (and produce vesicles) in impact-generated materials [8]. In contrast, volatile elements from the interior are expected to supply gases to volcanic-generated products like pyroclasts or basalt flows.

The goal of this project is to quantify the vesicle textures and glass compositions in lunar meteorite Northwest Africa 2996 to better understand the process of volatile release from the matrix melt during meteorite formation, and to compare the vesicularity with other lunar materials. We studied a polished thin section of NWA 2996, TAL-1*, loaned from the Northern Arizona University collection by Dr. T. Bunch. It is a feldspathic regolith breccia that contains large clasts of anorthosite, mafic-rich clasts, and impact melt breccias with minor evolved lithologies basalt, glass beads [9, 10, 11], and an extensive glassy matrix that is dense in some areas but is highly vesicular in >50% of the thin section.

Methods: We used vesicle size distribution theory [12] to quantify the vesicle textures in NWA 2996. SEM backscattered mosaic images (Fig. 1a) were acquired at the Johnson Space Center using a JEOL 7600F field-emission SEM. All images were simplified (Fig. 1b) using *Adobe Photoshop* and *ImageJ* following the methods of Shea et al. [2], whereby each phase (vesicles, matrix glass, and minerals) was assigned a single grayscale value.

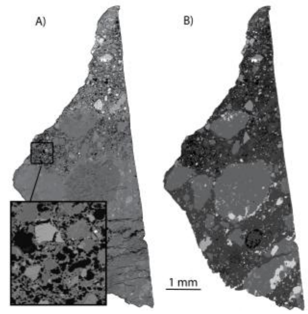

Figure 1: (A) SEM backscattered image of NWA 2996, Tal-1*. (B) Digitally simplified image. Black = vesicles; dark gray = matrix glass; medium gray = plagioclase; light grays = olivine, orthopyroxene, clinopyroxene; white = chromite.

The simplified image was imported into the Matlab-based program Fast Object Analysis and Measurement System (FOAMS) [2]. We used FOAMS to calculate and tabulate vesicle size and shape parameters (e.g., number of vesicles, diameter, area, perimeter, aspect ratio, etc.) as well as the 2-D vesicle number density, N_a (number of vesicles of a given size per unit area). FOAMS employs a stereological conversion [13] to convert N_a to a statistically more accurate 3-D vesicle number, N_v (number of vesicles of a given size per unit volume).

Geochemical compositions of matrix glass, dense glassy clasts, and glass beads were determined using a Cameca SX100 electron microprobe at the Johnson Space Center. The sample was analyzed with a 15 keV accelerating potential, 10 nA beam current, and a 10 µm spot size, using natural and synthetic standards.

Results and Discussion: The calculated bulk vesicularity of TAL-1* is ~9.4%, but currently there are no other quantitative reports of vesicularity in lunar feldspathic breccias with which to compare. However, the bulk "porosity" of many lunar materials have been reported and represent a maximum estimate for vesicularity, as these measurements include porosity due to vesicles and cracks. Feldspathic breccias range in bulk porosity from <1% to 36%, while impact melt breccias (basaltic and feldspathic) range from 2% to 28% [14, 15]. In the context of bulk vesicularity, NWA 2996 is moderately vesicular. However, gas that created the vesicles exsolved from the shock-melted matrix and not from entrained clasts, so considering a corrected "matrix-only" vesicularity of 20% indicates that NWA 2996 is moderate-to-highly vesicular relative to other feldspathic and impact melt breccias (Fig. 2). Vesicles in NWA 2996 document degassing of volatiles that are likely derived from shock melted rock and lunar surface volatiles. For comparison, we also report values of vesicularity that we measured for the most highly vesicular Apollo basalts (samples 15016, 15556), which derived their volatiles from the Moon's interior.

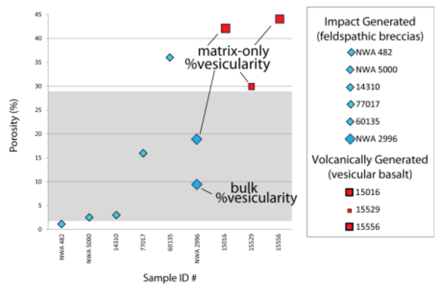

Figure 2: Vesicularity measurements (this study, large symbols) compared to porosity of lunar products (small symbols [14, 15, 16]).

The dominant aspect ratio of the vesicle population is ~0.6, which indicates that many vesicles were deformed after growth. This likely occurred during welding of the breccia.

A histogram of vesicle sizes shows the vesicle population to be a single-mode Gaussian distribution. This indicates that nucleation and growth of bubbles occurred in a single pulse, as expected for a single shock metamorphic event. A slight negative skew in the distribution indicates that Ostwald ripening occurred [2, 3].

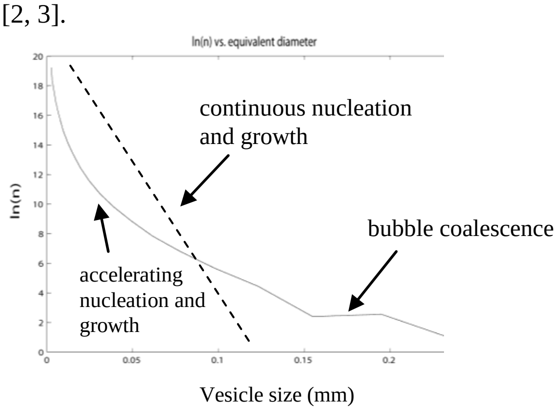

Figure 3: Vesicle size distribution of NWA 2996 (solid line).

The vesicle size distribution for NWA 2996 can be represented as a population density function [16, 17], where n is the volumetric number density of vesicles per vesicle size class. A plot of ln (n) vs. vesicle size (Fig. 3) has a slope of $-1/G\tau$ and an intercept of n^o (G is the mean bubble growth rate, τ is the timescale of nucleation and growth, and n^o is the volumetric number density of bubble nuclei). The vesicle size distribution for NWA 2996 is concave up for smaller vesicles, signifying accelerating nucleation and growth of bubbles. For comparison, a linear distribution would indicate a constant rate of nucleation and growth (dashed line). The abrupt change in slope from ~0.15 to 0.2 mm shows that the product $G\tau$ changes, which is likely the result of large bubble coalescence.

Microprobe analyses show both the matrix glass and dense glass clasts are compositionally similar to three lithologies represented in NWA 2996 clasts: anorthosite, mafic-rich clasts, and basalts. Glass bead compositions represent shocked anorthosite. The target lithologies that generated these glasses are anhydrous, however, the relatively high matrix vesicularity indicates volatiles existed. This implies that the target site for NWA 2996 may have been volatile-rich, supplying the gases needed to generate vesicles. However, we cannot test this hypothesis until there are more data on vesicle size distributions and volatile contents in feldspathic breccia samples from mature lunar regolith.

Conclusion: NWA 2996 has a moderate-to-high vesicularity compared to the porosity of other lunar feldspathic breccias, but is less vesicular than the most vesicular lunar basalts. Vesicles nucleated and grew in a single, accelerating pulse, and experienced Ostwald ripening, bubble coalescence, and post-formation deformation. Glass compositions indicate that vesicles formed by shock melting of nominally anhydrous lithologies, implying that addition of surface volatiles are likely required to explain the matrix vesicularity.

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