VESICULAR EUCRITES: WHERE AND HOW DID THEY FORM AND WHY ARE THEY SO RARE?

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Introduction: Vesicular basalts are notable for their rarity in the world's meteorite collections [1]. McCoy et al. [2] studied four such samples – the eucrites Ibitira and PCA 91007 and the angrites D'Orbigny and Sahara 99555 – performing computed tomographic scanning and simple vesicle rise time calculations in an effort to understand the conditions under which angrites and eucrites formed. Vesicles in angrites are large and evenly distributed, with calculated rise times of minutes requiring rapid cooling. In contrast, vesicles in eucrites are substantially smaller, leading to rise times of hours, and with a complex distribution suggesting coalescence.

A number of questions remain unanswered, including the relationship between vesicle-enriched and -depleted zones and the role of coalescence. On a broader scale, the formation location (lava flows vs. shallow dikes vs. deep intrusives), timing, and nature of the gas that formed the vesicles are all open questions [3]. In this abstract, we address these questions.

Results and Discussion: We conducted additional studies of Ibitira, including computed tomographic scanning of the Field Museum's specimen (FMNH Me 3211; 186.3 g) and BSE imaging across the vesicle-poor zone in the Smithsonian's sample (USNM 6860; 329.1 g). We performed numerical modeling to constrain emplacement depth, length scales for bubble growth, and the nature of the vesicle-producing gas.

Computed Tomography (CT). Although [1] argued for bubble coalescence in the formation of the vesicle-poor zone, clear evidence was lacking. Figure 1 is a 3D rendering constructed from CT data of the Field Museum's Ibitira specimen. The vesicle-depleted zone includes two very large vesicles (up to 488 mm^3) and overall, vesicles occupy ~3 vol.% of Ibitira. The presence of such large vesicles points to a clear role for bubble coalescence.

Backscattered Electron Imaging (BSE). To understand the relationship between the vesicle-enriched and –depleted zones, we constructed a BSE mosaic of an area (~1.2 by 3 cm) in the Smithsonian's Ibitira sample that included both these zones. We distinguished opaque phases, pyroxene, plagioclase, silica and vesicles. Apart from the expected difference in vesicle abundance (0.7 vs. 3.0 vol.%), the two zones differ in silica (12.5 vs. 17.8), but show little difference in plagioclase (33.6 vs. 31.6), pyroxene (43.3 vs. 40.7) or opaque (9.8 vs. 7.5) abundance. We conclude that the entire rock represents a single magma unit, rather than the vesicle-depleted zone being a distinct vein within the vesicle-rich host.

Computational Modeling. We have performed three sets of interrelated calculations. The first calculates the distance that veins of known width move through cold host rock before quenching. This is particularly relevant since the outer ~5 km of Vesta is a chilled zone that efficiently dissipates heat to space. Migration distances for dikes through this chilled zone are short, with a 2 cm wide vein migrating 18 μm (!) before quenching, while a 20 cm wide vein would migrate 178 m. Given these short migration distances, nucleation of bubbles must begin below this ~5 km cold zone in order to allow bubble growth.

The second set calculates the depth of bubble nucleation given the radius of the body (we used 260 km radius, appropriate to Vesta), density, volume fraction of vesicles, temperature (we used the liquidus temperature of basalt), and the gas of interest (CO_2 and H_2O). CO_2 bubbles nucleate below 5 km at concentrations in excess of 40 ppm. In contrast, water concentrations must reach nearly 4000 ppm for bubble nucleation to occur below 5 km, owing to the much greater solubility of H_2O in basaltic magmas. At these high concentrations, petrologic indicators of a wet magma should be apparent, strongly suggesting that water was not the volatile responsible. A caveat is that low concentrations of H_2O (<500 ppm) are possible for much wider veins at shallow depths, if Ibitira is an offshoot from a larger dike.

The final calculations model the growth of bubbles from nucleation (10 μm radius) to a final radius of 0.5 cm (the largest vesicles in Ibitira). Bubbles grow by diffusion of gas, decompression, and coalescence, and move upward both by rising through the magma and by movement of the magma within a dike. Figure 2 illustrates bubble growth in a 20 cm wide vein with different CO_2 concentrations. Constraints are the base of the chill zone (~5 km) and the crust (maximum of 25 km, [4]). Vesicles in Ibitira require movement of several km to grow, inconsistent with shallow, near-surface dikes or lava flows of modest dimensions. In addition, the atmospheric overburden pressure on Earth is absent from asteroids and gases would readily escape. Unless asteroidal lava flows are much thicker than expected (1 bar pressure occurs at the base of a 133 m thick flow), degassing would be extremely efficient. This suggests that, contrary to expectations [5], vesicular eucrites sample intrusives at depth, not surficial lava flows.

From Figure 2, we conclude that gas concentrations must have been ~50-200 ppm CO_2. Melting begins at depths corresponding to lower crustal or upper mantle and melts migrate into cooler zones, preventing runaway coalescence. Higher gas concentrations (e.g., 500 ppm) produce bubble growth well below the base of the crust and lack any mechanism for quenching the melt. At lower concentrations (<25 ppm), bubble nucleation begins within the 5 km chill zone. At concentrations <5 ppm, CO_2 is completely soluble in basaltic melt and bubbles will not nucleate. It is unlikely that any geochemical signature of these modest gas concentrations remains in sampled vesicular eucrites.

Our work suggests two possible explanations for the rarity of vesicular eucrites. Sampling of vesicular eucrites at depths on the order of ~5 km would require much greater excavation depths than sampling of near-surface, vesicle-free eucrites. This theory is supported by the lack of vesicles in most near-surface, brecciated eucrites, while the highly-metamorphosed, vesicle-rich Ibitira plausibly formed at considerable depth [4]. Impact provides a plausible means of exposing these deep-seated vesicular basalts on asteroids, in sharp contrast to Earth where only near-surface veins and dikes are accessible. An alternative theory is that eucrites formed from a protolith that was initially volatile poor and/or devolatilized during metamorphism prior to melting. In this model, only early formed melts incorporated sufficient volatiles (e.g., ~100 ppm CO_2 for Ibitira, ~50 ppm for PCA 91007) to produce vesiculation at depth. Later melts incorporated so few volatiles that bubble nucleation began either within the outer chilled zone or did not occur at all owing to the solubility of CO_2 in basaltic melts. This model would predict that vesicular basalts are among the oldest eucritic meteorites. The absence of ^{26}Mg excesses from decay of live ^{26}Al in Ibitira [6] might argue against this latter model.

References: [1] Wadhwa M. and Davis A.M. (1998) *LPSC XXIX* [2] McCoy T.J. et al. (2002) *LPSC XXXIII*, Abstract #1213. [3] Drake M.J. (2001) *MAPS* **36**, 501-513. [4] Yamaguchi A. et al. (1996) *Icarus* **124**, 97-112. [5] Mittlefehldt D.W. et al. (1998) *Planetary Materials*. [6] Hsu W. and Crozaz G. (1996) *GCA* **60**, 4571-4591.

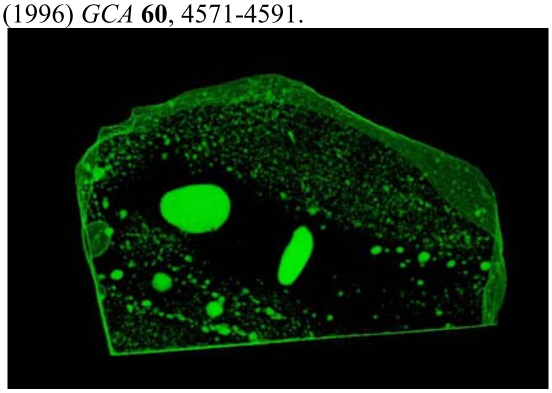

Figure 1. 3D rendering constructed from CT data. Vesicles are shown in green and the silicate host is semi-transparent. The two large vesicles in a zone otherwise swept free of vesicles are clear evidence for coalescence. Specimen is 8.4 cm along the edge.

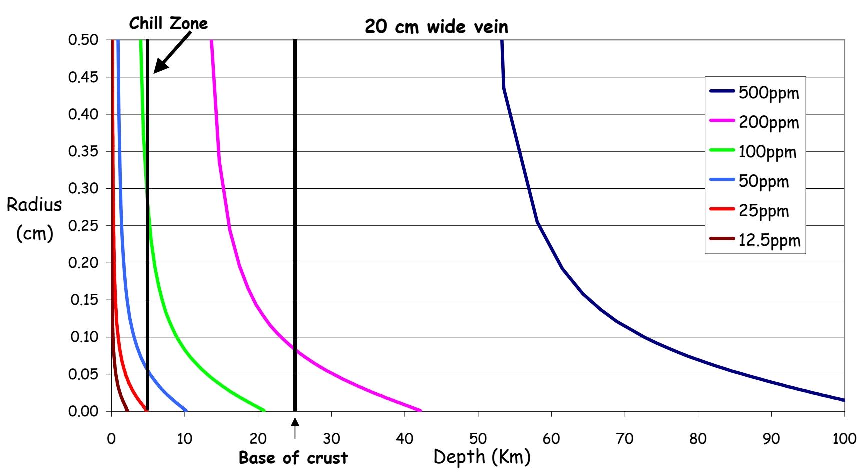

Figure 2. Depth vs. radius for growth of bubbles in a 20 cm wide vein with concentrations of CO_2 from 12.5-500 ppm. Concentrations from 50-200 ppm satisfy the constraints of melting in the lower crust or upper mantle and solidifying in the outer ~5 km chilled zone to prevent runaway coalescence.