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# Formation of vesicles in asteroidal basaltic meteorites

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## Abstract

Rare asteroidal vesicular basalts have previously been thought to form in surficial lava flows with CO as the vesicle-forming gas. However, vesicular lava flows are unlikely on small, airless bodies such as asteroids. To unravel the origin of these rocks, we analyzed vesicle sizes and abundances for two angrites and two eucrites using high-resolution X-ray computed tomography and conducted numerical modeling of bubble formation in a dike of ascending magma. Modeling results indicate that thin (<30 cm wide) dikes are trapped at ~5 km depth where ~75 ppm of CO and $CO_2$ contribute equally to vesicle formation. Vesicular eucrites were metamorphosed in this deep-seated environment, the gas was lost, and they were excavated by impacts.

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*Keywords:* basalts; vesicles; asteroids; meteorites; volatiles

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## 1. Introduction

The almost ubiquitous exsolution of volatiles to form gas bubbles during magma ascent commonly produces vesicular basalts on Earth [1]. However, vesicles are quite rare in meteorites, reflecting differences in fundamental properties, including parent body size, the presence or absence of an atmosphere, and the volatile species and abundances present in the melts. Among basaltic meteorites, eucrites are the largest group, numbering more than 200, and include three unbrecciated, vesicular members (Ibitira, Pecora Escarpment (PCA) 91007, and Yamato 981651; [2,3]). Ibitira is the earliest-recovered and best known of the vesicular meteorites and large slices have recently been made available to museums. The angrite group contains fewer than 10 members, but includes the recently-recovered, multi-kilogram, vesicular samples D'Orbigny and Sahara 99555. The recent availability of these samples has renewed interest in the formation of vesicular asteroidal basalts.

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Theories for the origin of asteroidal vesicular basalts are primarily based on studies of Ibitira, which exhibits abundant, small vesicles set in a fine-grained, granoblastic matrix. Ibitira was suggested to have formed in a lava flow, by analogy with terrestrial vesicular lava flows, with CO as the dominant vesicle forming gas [4]. A lava flow origin is widely accepted [2,5,6], in part because the fine grain size suggests rapid cooling. It has been further suggested that vesicular lava flows were buried under subsequent flows and widespread crustal metamorphism produced the granoblastic texture [7]. Vapor-deposited minerals within the vesicles of Ibitira formed during later crustal metamorphism [8,9].

Eucrites like Ibitira offer promise for understanding asteroidal volcanic history, as a convincing link exists to a specific asteroid. Spectral and dynamical evidence suggest that eucrites (and the related howardites and diogenites) originated on asteroid 4 Vesta [10], providing constraints (e.g., crustal thickness, parent body size) on eucrite formation and ground truth for the DAWN mission which will visit this third largest asteroid in the next decade.

It is unlikely, however, that vesicular lava flows formed on the surface of 4 Vesta. While vesicular lava flows are common on Earth, owing to the near-surface exsolution of water, small parent body sizes and lack of an atmosphere limit their formation on asteroids. Near-surface volatile exsolution in ascending magmas on Earth often produces fire-fountaining, with partially-degassed magma clots falling back and coalescing to form vesiculated lava flows. A similar mechanism would operate on 4 Vesta, but the lack of an atmosphere to limit gas expansion means that magma fragmentation and consequent gas escape would be extremely efficient [11]. Exsolved gas bubbles might be retained near the base of a lava flow due to the weight of overlying lava, but the equivalent of terrestrial atmospheric pressure on 4 Vesta would require a ~130 m thick lava flow and flows of this thickness are unlikely to form on asteroids [11] given the low viscosity of these magmas. It is worth noting that vesicular basalts exist from the Moon, but the conditions of formation of these magmas differed from the asteroidal case. In particular, the dominant volatile was CO produced by a smelting reaction and the 6- to 7-fold higher gravity allows much thinner flows to retain bubbles. Formation of vesicular basalts as impact melts, as has been argued for lunar granulitic breccias and some terrestrial, vesicular impact melts, similarly requires an unreasonably thick melt sheet. Additionally, the low abundance of siderophile elements in Ibitira contrasts with elevated levels in lunar impact melts, introduced by the metal-rich meteoritic impactor [12], and argues against an impact origin for Ibitira.

The retention of vesicles in asteroidal basalts indicates formation at depth and the size and abundance of those vesicles offer important constraints for modeling the nature of the vesicle-forming gas, the physical conditions under which the vesicles formed, and, more broadly, the nature of crust formation on differentiated asteroids.

## 2. High-resolution X-ray computed tomography

To determine the sizes, shapes and three-dimensional distribution of vesicles in basaltic meteorites, we analyzed specimens of the vesicular eucrites Ibitira (two slices of the main mass) and PCA 91007 and the vesicular angrites D'Orbigny and Sahara 99555 at the University of Texas High-Resolution X-ray CT facility [13]. Meteorite samples, sources, catalog numbers, and masses used in this study were Pecora Escarpment 91007,0, Meteorite Working Group, 103.94 g; Ibitira, Smithsonian USNM 6860, 329.1 g; Ibitira, Field Museum FMNH Me 3211, 186.3 g; Sahara 99555, Naturhistorisches Museum, Vienna, 36.5 g; D'Orbigny, Smithsonian USNM 7069, 154.4 g. A summary of results is given in Table 1 and supplemental material is available online at http://www.ctlab.geo.utexas.edu/pubs/McCoy_KWBWD/mccoy_kwbwd.htm. Both slices of Ibitira exhibit a silicate matrix with abundant, small vesicles bounding a zone (probably part of a dike structure in three

Table 1
Summary of vesicle properties in eucrites and angrites

| | Ibitira USNM 6860 Low Res | Ibitira FMNH Me 3211 Low Res | Ibitira FMNH Me3211 High Res | PCA 91007 ,0 Low Res | D'Orbigny USNM 7069 Low Res | Sahara 99555 High Res |
|---|---|---|---|---|---|---|
| Sample volume ($cm^3$) | 104.1 | 54.8 | 58.8 | 34.5 | 48.5 | 11.5 |
| Vesicle volume % | 2.1 | 3.3 | 3.0 | 0.4 | 1.4 | 0.2 |
| Number of vesicles | 31081 | 12692 | 19205 | 787 | 101 | 8 |
| Vesicles/$cm^3$ | 298.57 | 231.44 | 326.56 | 22.81 | 2.08 | 0.70 |
| Max. vesicle volume ($mm^3$) | 14.1 | 488.5 | 489.7 | 4.0 | 87.7 | 5.6 |
| Min. vesicle volume ($mm^3$) | 0.0033 | 0.0038 | 0.0005 | 0.0100 | 0.0219 | 0.3038 |
| Median vesicle volume ($mm^3$) | 0.035 | 0.035 | 0.025 | 0.095 | 2.568 | 4.177 |

dimensions) largely depleted of small vesicles, but containing a few, very large vesicles (Fig. 1a,b). Ibitira contains ~200–300 vesicles/cm$^3$ measuring between 0.0033 and 489.7 mm$^3$ (median size=0.025–0.035 mm$^3$) and vesicles occupy 2–3 vol.%. PCA 91007 contains fewer vesicles (~23 vesicles/cm$^3$) of a relatively restricted size range (0.01–4.0 mm$^3$; median 0.095 mm$^3$), occupying ~0.4 vol.% of the rock. In contrast to Ibitira and PCA 91007, the angrite D'Orbigny contains a relatively low density of vesicles (~2.0 vesicles/cm$^3$), but these vesicles tend to be large (0.02–87.7 mm$^3$; median 2.6 mm$^3$) and occupy a fractional volume (~1.4 vol.%) roughly comparable to that of Ibitira vesicles. Vesicles in D'Orbigny are interspersed evenly throughout the rock (Fig. 1c), which also displays a diktytaxitic structure formed by late-stage melt migration and removal. Sahara 99555 displays vesicles of comparable size to those in D'Orbigny, although the small sample (volume 11.5 cm$^3$) contains relatively few vesicles.

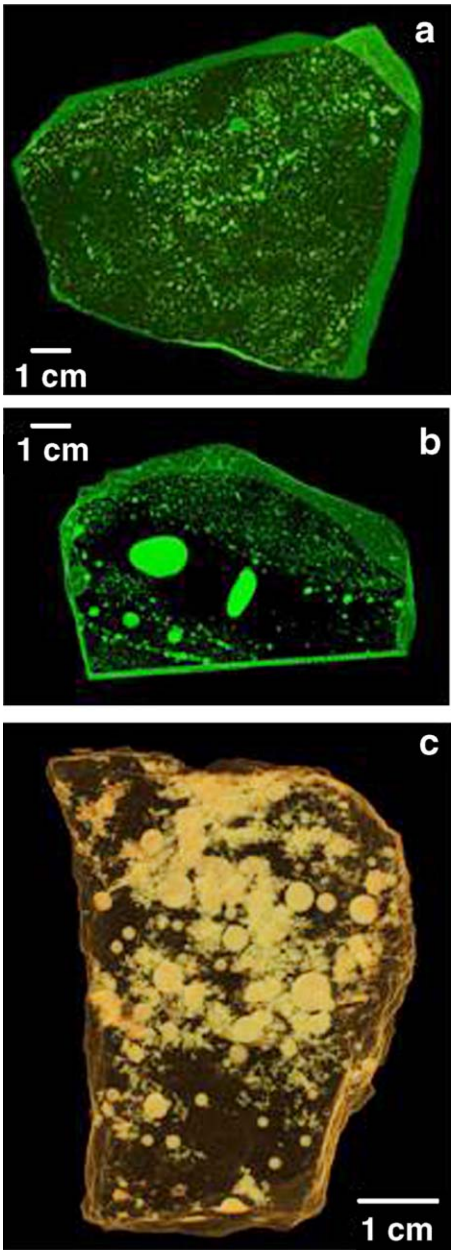

Fig. 1. Three-dimensional renderings of high-resolution X-ray computed tomography data for (a) Ibitira specimen USNM 6860. This specimen exhibits a zone depleted in vesicles cross-cutting a matrix enriched in small vesicles. (b) Ibitira specimen FMNH Me 3211. The same vesicle-depleted zone contains two very large vesicles, evidence that bubble coalescence played a significant role. (c) D'Orbigny USNM 7069. Large, spherical, early-formed vesicles occur interspersed with late-stage void space.

The zone in Ibitira depleted of small vesicles but containing some large vesicles (Fig. 1b) is of special interest and may provide clues to the formation of this rock. We considered the possibility that this zone is a separate magmatic unit intruded through the host. However, no distinct quenched margin exists. Ibitira was imaged using a low-vacuum scanning electron microscope (JEOL JEM-5800LV) with an attached Oxford Link ISIS-300 system. Modal abundances were derived from grayscale BSE images using grayscale binning in Adobe Photoshop™ and mapping of mineral abundances from composite backscattered electron images across this zone demonstrates no differences in plagioclase, pyroxene or opaque abundances. We conclude that Ibitira represents a single magmatic unit. This region of Ibitira exhibits a comparable vesicle volume (~3 vol.%) to the remainder of the rock, despite containing a low vesicle density (~1 vesicle/cm$^3$). Formation of a few large vesicles is consistent with run-away growth of a single gas bubble in a vertical dike system, where a growing bubble quickly overtakes smaller bubbles. We propose that this zone denotes a region of enhanced bubble coalescence. There are two critical requirements for this process. The first is that gas release is a continuing process, so that a range of bubble sizes is present, and the fact that gas production (by exsolution or chemical reaction) is pressure-dependent guarantees that this is satisfied. The second requirement is that the rise speed of the magma in the dike is not too great relative to the rise speed of the bubbles in the magma, to ensure that there is enough time during the rise of a given batch of magma for larger bubbles to overtake smaller ones [14,15]. This condition is maximized when the dike transferring the magma is narrow, offering a large resistance to the bulk flow of the magma but having little effect on the motion of gas bubbles. We implicitly assume that Ibitira does not represent the tip of the dike, where continued bubble motion after the dike had ceased propagating would lead to an unrepresentative distribution of gas bubbles.

## 3. Modeling vesicle growth

### 3.1. Methods

To explore the mechanism by which Ibitira and other vesicular eucrites formed, we undertook numerical modeling of bubble formation in a dike of ascending magma using the methods described in [14,15]. Several input parameters were necessary. We modeled bubble formation from $CO_2$, CO and $H_2O$, as these are often the dominant gases forming vesicles in terrestrial basalts and all three are likely to be present during the formation of eucrites [4]. Given the proposed link between eucrites and Vesta, we calculated bubble growth and magma movement on a body 260 km in radius [16] and calculated the surface gravity for a spherical body with a bulk density of 3700 kg/m$^3$ (an average of density estimates ranging from 3500–3800 kg/m$^3$ [16]). We also used constraints from the thermal and crustal structure of Vesta. Vesta, like all asteroids, would have a cold outer shell extending to a characteristic depth of ~5 km that dissipates heat at the surface as quickly as it absorbs heat from the interior [17]. Thus, any ascending magma must penetrate this cold, outer shell. Inferences from eucrite cooling rates and the depth of the south polar basin on Vesta that penetrates the basaltic crust suggest a crustal thickness of 10–25 km [10]. We initially modeled a dike width of 20 cm, which is approximately twice the size of the Ibitira meteorite. Given that wall rock is not present in the specimen, the width of the dike can only be constrained between this value (which accommodates ~80% mass loss from ablation during atmospheric entry) to that which would penetrate the crust (~50 cm) and lead to gas loss. Thermal stability calculations [14,18] indicate that a dike of 20 cm width would penetrate ~110 m into the cold, outer shell. The physical properties of the melt are additional input parameters. The bulk composition of Ibitira [19] was input to the MELTS [20,21] program to calculate a liquidus temperature (1185 °C at a depth of 60 km) and into formulations of [22] to calculate the viscosity (16.1 Pa s) and density (2840 kg/m$^3$) of the melt. We note that the relatively low abundance of bubbles in the magma would not substantially change its bulk viscosity. Magma rise velocity through the vertical dike was calculated using the formulation of [14] and yielded 0.014 m/s. Our calculations used experimental gas solubility data from [23]. For $CO_2$ and $H_2O$, bubbles 10 μm in radius [24] nucleate when gas reaches saturation. We assumed no supersaturation pressure. For CO, formation occurs as a result of the pressure-dependent smelting reaction $FeO+C=Fe+CO$ which, depending on the oxygen fugacity [25,26], should be operating freely by the time the pressure has decreased to 15 MPa. Once nucleated, bubbles grow as a result of decompression as they rise toward the surface, diffusion of gas into the growing bubbles, and coalescence of bubbles [27]. We assumed that bubble coalescence occurs whenever bubbles of differing sizes come into geometric contact during their independent buoyant rise through the magma, itself ascending buoyantly through the dike. We calculated bubble growth as a function of depth until the largest bubbles reach the maximum size of vesicles in Ibitira (~5 mm radius) or reach the surface of the body.

## 4. Results

In terrestrial systems, water is the dominant vesicle-forming gas, with terrestrial basalts containing 0.2–6 wt.% $H_2O$ [1]. In contrast, basaltic meteorites formed from very dry melts [4]. $H_2O$ is highly soluble in basaltic magmas and abundances of <1000 ppm (Fig. 2a) nucleate and grow bubbles only in magmas within 1.5 km of the surface of an asteroid. Concentrations of $H_2O$ in the magma have to exceed 3000 ppm to nucleate bubbles below the 5 km chill zone. This abundance is inconsistent with the amount of $H_2O$ thought to be present in eucrites [4] and with the presence of iron metal within them.

While $H_2O$ may be the dominant vesicle-forming gas in terrestrial systems, in asteroidal basalts, vesicle formation likely occurred by exsolution of a mixed CO–$CO_2$ gas. At an $fO_2$ of iron–wüstite and liquidus temperature of Ibitira, the equilibrium gas would contain 76% CO and 24% $CO_2$ [28]. Calculations for each of these species independently provide some measure of which dominated vesicle formation.

$CO_2$ is dissolved in the silicate melt and exsolves once it reaches saturation. Our calculations indicate that concentrations in excess of ~200 ppm grow bubbles at a depth below the basaltic crust, while magmas with $CO_2$ concentrations below ~75 ppm quench within the outer cold zone before bubbles reached the size of those in Ibitira (Fig. 2b). A concentration of ~75–100 ppm nucleates bubbles at ~20–30 km and they would reach the maximum size of those in Ibitira within the base of the cold, outer shell, where cooling would stop the process of bubble growth and magma ascent. A similar gas concentration (~75–100 ppm) is required for a 50 cm wide dike, with the magma rising faster through the dike (0.088 m/s) but being emplaced closer to the

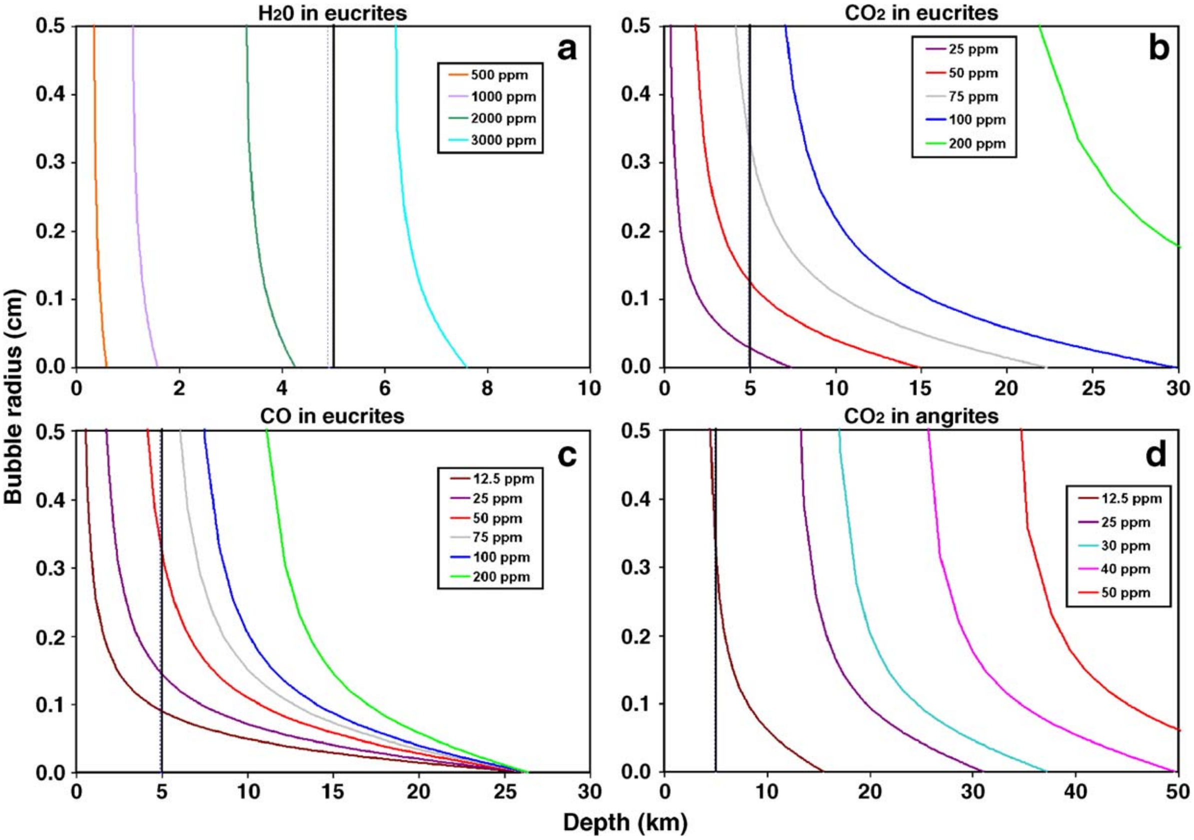

Fig. 2. Bubble radius (cm) vs. depth in the asteroid (km) for bubbles growing in an ascending, 20 cm wide dike. The solid vertical line represents the approximate base of the cold, outer shell on a differentiating asteroid and the dotted vertical line (overlapping the solid line in b,c,d) represents the penetration depth for a 20 cm wide dike. (a) $H_2O$ in eucrites. Exsolution occurs only near the surface. Deep-seated vesicle formation would require unrealistically high $H_2O$ concentrations. (b) $CO_2$ in eucrites. Gas concentration of ~75–100 ppm could produce eucrite vesicles. (c) CO in eucrites. Bubble formation occurs at the pressure-dependent onset of smelting. A gas concentration of ~50–75 ppm is required to produce eucrite vesicles, suggesting that CO and $CO_2$ contribute equally to vesicle formation. (d) $CO_2$ in angrites. The smaller inferred parent body size for angrites and fluid magma composition requires miniscule gas abundances to produce large vesicles.

surface (~500 m depth). Thus, the inferred gas concentration is relatively insensitive to the dike width used in the calculation.

## 5. Implications

Carbon monoxide was the dominant volatile [4] in eucrites, but, in contrast to $CO_2$, its nucleation is pressure dependent. CO nucleates relatively deep (~26 km) and concentrations of CO of ~50–75 ppm are needed to grow bubbles to the size of those in Ibitira below the 5 km chill zone (Fig. 2c). The process of vesicle growth is then arrested as the magma chills upon entering this zone. The similarity in gas concentrations needed to form vesicles (~75 ppm) suggests that CO and $CO_2$ contribute equally to vesicle formation, even though CO is by far the dominant volatile in the melt. This conclusion appears to be valid whether eucrites formed early during partial melting of a largely undifferentiated body or late as a result of fractional crystallization of a magma ocean on a fully-differentiated parent body [29]. In either case, the bulk density of the asteroid is the primary variable, as the gravity and pressure are the primary constraints on bubble growth and velocity.

Our modeling points to deep formation of bubbles from a mixed CO–$CO_2$ gas. Does this conclusion hold for other asteroid vesicular basalts or if vesicular eucrites did not originate on Vesta? Recent work found that Ibitira differed in $\Delta^{17}O$ [30] and pyroxene Fe/Mn ratio [31] from other eucrites and may sample a separate parent body. Additional basaltic asteroids have also been identified [32], including 17 Thetis, whose average semi-major axis at 2.47 AU is close to the meteorite-delivering 3:1 resonance in the asteroid belt. While the link between eucrites and Vesta seems strong, we cannot rule out Ibitira and/or most eucrites originating on a body like Thetis. We have tested the sensitivity of our model to these assumptions by modeling bubble growth in the angrites.

Our angrite calculations mimicked those of the eucrites, with a few important differences. The parent asteroid of the angrites is currently unknown, although 3628 Boznemcova has been postulated as a possible parent body and has a derived radius of 8 km [33]. We assumed a radius of 50 km, given that most asteroids in the range of a few to tens of kilometers are collisional fragments of larger parent asteroids. This smaller size is also consistent with other basaltic asteroids that could be eucrite parent asteroids. The angrites have a liquidus temperature of ~1155 °C but, owing to their $SiO_2$-poor compositions [34], are eight times more fluid (2.06 Pa s) than eucrites. We present the calculation only for $CO_2$, owing to the higher $CO_2$/CO ratio in the oxidized (IW+1) angrites compared to the reduced eucrites. In contrast to our earlier calculations, the smaller parent body size results in deeper bubble nucleation, with magmas containing greater than 40 ppm of $CO_2$ nucleating bubbles in excess of 10 μm at the center of the asteroid. Vanishingly small concentrations of ~12.5 ppm are needed to nucleate and grow bubbles within 20 km of the surface and reach 0.5 cm within the base of the cold, outer shell. The fluid nature of the angrite melt leads to efficient bubble coalescence, explaining the fact that angrites contain far fewer, but larger, vesicles than observed in eucrites. These calculations confirm that nucleation of vesicles would occur at even greater depths in smaller asteroids and that bubble growth is sensitive to magma viscosity.

Finally, we speculate about why vesicular basalts among meteorites are so rare while such basalts are relatively common on Earth. The likely answer is that vesicular basalts on asteroids require formation at depth and this may have been a relatively rare phenomenon. Most asteroidal basalt samples likely crystallized at or near the surface [11], with conduits greater than 0.5 m in width providing a ready pathway for magma degassing. As such, only those dikes that were relatively small and trapped at depth preserved the evidence for vesicle formation. The intrusion of these small dikes into cold country rock provided a mechanism for rapid cooling of the magma. On 4 Vesta, the dikes that formed eucrites may have been trapped at significant depths, providing an ideal location for metamorphism to explain the fine-grained, granoblastic texture of Ibitira. In contrast, the angrites, which exhibit evidence of relatively rapid cooling [34], may have been emplaced in dikes closer to the surface. A long period of metamorphism in Ibitira almost certainly erased any signature of the minute amounts of gas that formed the vesicles. These deep-seated dikes were later excavated by impacts, perhaps one of which liberated the small, basaltic vestoid asteroids from the south polar basin on Vesta. This impact excavation allows us to examine deep-seated igneous assemblages in differentiated asteroids in a way not possible on Earth, where extensive weathering that erodes volcanic edifices also alters the fine textures produced at such depths.

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