MAGMA DYNAMICS ON THE MOON: A COMPUTED TOMOGRAPHY INVESTIGATION OF APOLLO BASALT VESICULARITY.

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Introduction: The presence of vesicles in volcanic rocks can be used to investigate the potential location of a given sample within a lava flow, the emplacement mechanism of that sample (i.e. on the lunar surface), and the relative influence of volatiles on magma compositions [1]. Furthermore, the explosivity of a magma is tied to the amount of dissolved volatile components and the extent to which degassing has occurred. In addition, the coalescence of dissolved volatiles (present as bubbles and preserved as vesicles) works to enhance rock permeability, and may also enhance degassing, final emplacement style [3], and the type of eruption that occurs [e.g. 1]. The shape of resulting vesicles is tied to the collision rate of bubbles during magma evolution and deformation as a result of local stress(es) [4-6]. Investigating the vesicle content of Apollo basaltic samples can therefore be used to interrogate the dynamics of magma ascent and lava emplacement on the Moon.

Collectively, the physical parameters influencing the emplacement of lava flows on the lunar surface at a given time may be examined by investigating the shape of vesicles and the overall vesicularity of the rock [e.g. 2-3]. Both of these can be quantified in volcanic samples from any planetary body through computed tomography (CT) which permits nondestructive analysis in 3D. CT evaluates how X-rays are attenuated through a rotating sample [e.g. 7]. X-ray attenuation is a function of the elements present at a given point in the sample; atoms with high electron density return brighter grayscale values. Meanwhile, vesicles return a dark spot on a scan, which makes them relativley simple targets for analysis during post-processing. Individual vesicles can be used to create vesicle size distributions (VSDs), akin to crystal size distributions (CSDs) created from 2D observations [e.g. 8].

Methods: Samples investigated here included the basaltic samples 10057,19 (Apollo 11, high-Ti, relatively fine grained), 12043.0 (Apollo 12, low-Ti, relatively medium grained), and 15085,0 (Apollo 15, low-Ti, relatively coarse grained). Complete documentation of the analytical methodology may be found in [7, 9-11]. Once scans of the sample are generated (fig. 1), they are corrected for artifacts and are subsequently reassembled into 3D models. All steps are carried out with respect to voxels (volume elements) in the sample. Using Blob3D [10] the voxels are assembled into
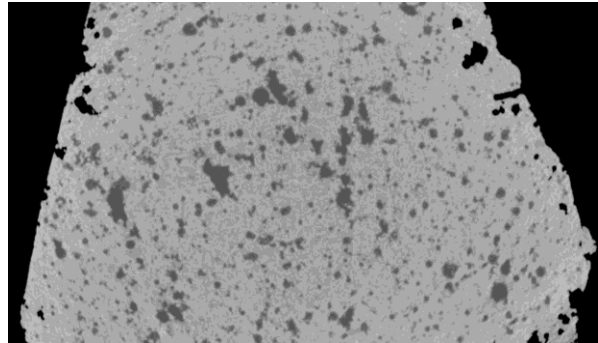

Fig. 1: Detail of one "slice" of sample 10057,19. This sample has a fine grained matrix, in which individual minerals are challenging to determine. The larger, dark gray vesicles are easy to distinguish in this sample. Black vesicles are ones that connect to the outside and were not assessed.

individual "blobs" (here, vesicles) from which characteristics of interest can be extracted. These characteristics include the length, width, height , volume, and orientation with respect to the sample. The size characteristics of each vesicle can be used to determine vesicle shape and volume, while the density of these vesicles may indicate the degree of degassing experienced by each respective magma, and therefore may inform the stage of eruption at which the sample erupted.

Results: Vesicles are easily distinguishable in all samples due to their low grayscale values (generally ~50 and below), giving the vesicles a dark appearance (fig. 1). This allows extraction of component characreiustics to be relativeley straight forward. From this, VSDs similar to [12] and the work done by [13] were obtained.

The VSDs sumamrized in fig. 2 can easily be compared to traditional CSDs. While it is of course acknowledged that vesicles develop due to different phenomena than crystals, they occupy a physical space within a magma, just like crystal populations do. A similar pattern emerges where there is a lower density of vesicles of larger size. As for the smaller vesicle sizes, their density is also very low. This however may be due to lack of successful separation and extraction of data at small volumes. Sample vesicularities were also calculated. Sample 10057,19 has a vesicularity of 7.24 %, 12043,0 has a vesicularity of 1.25 %, and 15085,0 has a vesicularity of 0.27 %.

Discussion: The vesicularities of the samples appear to match the profiles that would likely be predicted by CSD analysis. In these basalts, vesicularity increases with decreasing grain size, interpreted to be due to the movement of vesicles closer to the surface and a faster rate of cooling. Alternatively, the more vesiculated sample (10057,19) may also be one that formed during greater magma degassing, while the others formed at later stages of the eruption or from a magma that contained higher dissolved volatile components to begin with [e.g. 1, 3].

The distributions shown in fig. 2 all appear to stabilize above vesicle volumes of ~0.1 mm^3, and suggest that the samples may contain greater amounts of relatively medium sized vesicles over larger and smaller bubbles, particularly in samples 10057,19 and 15085,0. This may be due to the coalescence of bubbles into larger bubbles [3]. With added shear, bubble coalescence would be promoted, resulting in elongation [3], but there is no evidence for such behavior here. Based on the acquired scans (e.g. fig 1), there is no visual evidence for elongation, and the orientation distribution of these vesicles appears random [11], suggesting there was little to no preservation of a flow fabric, and therefore insufficient shear stress to affect vesicle coalescence (as preserved).

Overall, CT continues to be proven as a powerful computational technique which may be used to evaluate the distribution of various components in valuable samples. This study will continue to evaluate the potential of CT in providing data on the petrophysical characteristics of the Apollo basalt suite by analyzing other components within samples. This will include evaluation of crystal populations such as pyroxene, plagioclase feldspar, and ilmenite [11]. Future work will also include *in-situ* chemical analysis of the minerals in associated thin sections of the basalts studied here as distinct crystal cargoes are investigated.

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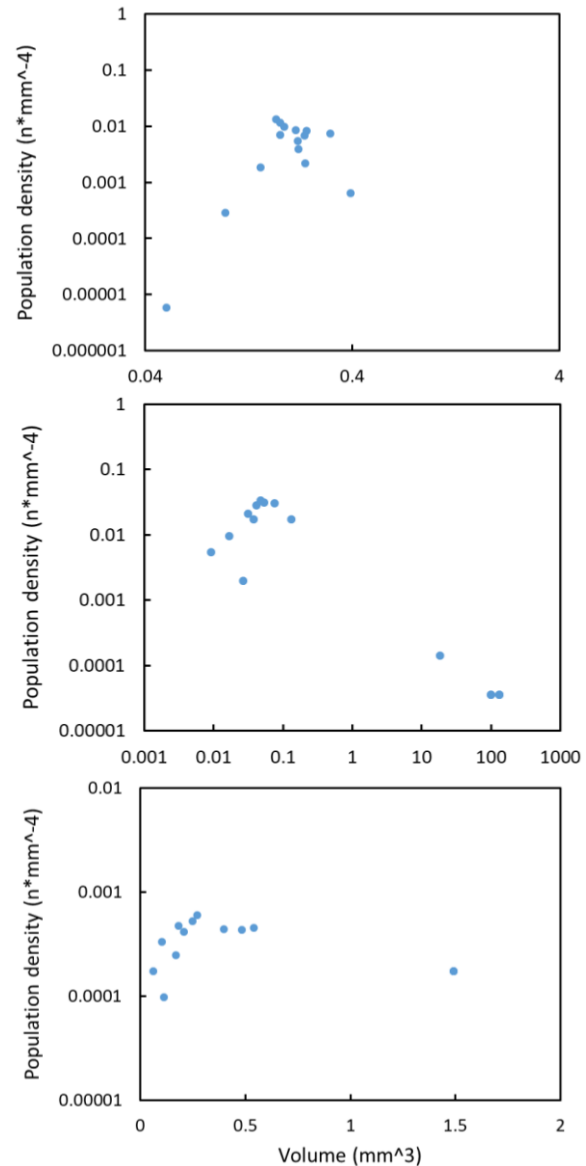

Fig. 2: VSDs for the discussed samples. Top is 10057,19, middle is 12043,0, and bottom is 15085,0. The samples appear to follow a trend of decreasing population density with increasing size, which is expected as more time may be needed to establish larger vesicles. Large vesicles will also have higher buoyancy and may be removed from the system more effectively. Observed variation in population density at smaller vesicle volumes could be due to difficulty of observation, inefficiency of the separation of small vesicles from the rest of rock, or a primary feature.