Porosity of Micrometeorites measured by Tomography.

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Introduction: Vesicles are common in stony micrometeorites (MMs) and probably form during atmospheric entry heating by the breakdown of gas-producing phases. For example, the decomposition of hydrated phases might liberate $H_2O(g)$ and the decomposition of sulfides might generate gaseous allotropes of sulfur.

In an effort to better understand the porosity of micrometeorites, and the phases that give rise to the vesicles, we tabulate the number and describe the appearance of vesicles in previously sectioned micrometeorites. We also map the internal structure of stony MMs using the technique of synchrotron computed microtomography (CMT). Classical sectioning shows a single cut through the MM at high resolution, but pertains to only a small volume of material. X-ray tomography gathers information at lower spatial resolution but for a much larger volume and allows one to study how vesicles and mineral phases connect in 3-dimensions as has been demonstrated for Type I sphrules [1] and unmelted micrometeorites [2].

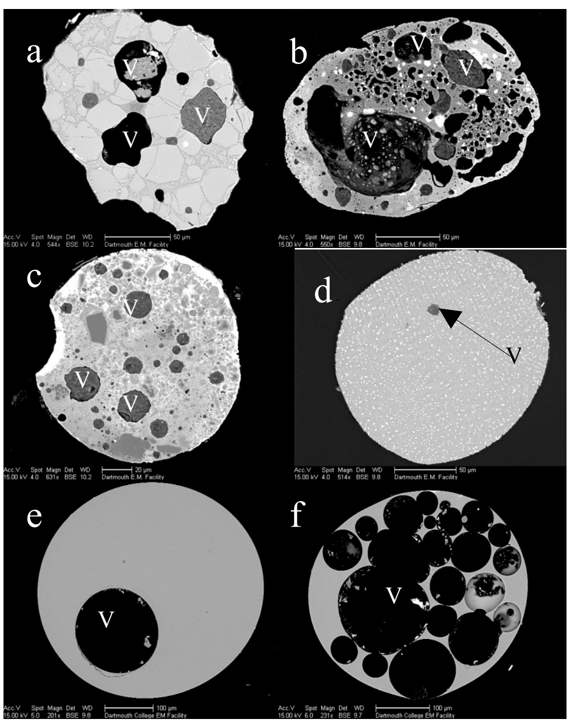

Fig. 1. Vesicles (V) in different classes of MMs. Only the largest vesicles are labeled for images a, b, c, and f.

Methods: We examined images of 614 previously sectioned micrometeorites from mounts containing a random sample from the South Pole Water Well [3]. We categorized the textural type [3] and counted the vesicles present in each one (Table 1). We also imaged 4 groups (3a&b and 4a&b) containing 100 micrometeorites by using the CMT technique at beam line X2B, Brookhaven National Laboratory. The apparatus on X2B has a spatial resolution of 4 µm voxel size. Silicate and voids are easily distinguished. Taken with [4], we have imaged 202 micrometeorites tomographically.

For the CMT scans the MMs were placed in a Tygon tube having a 1-mm internal diameter. Each sample had 20 to 30 MMs and filled a volume extending 2 to 3 mm along the length of the tube. We plugged the ends of the tubes with a glass and Cu sphere to serve as as references for setting the image brightness. From the x-ray data we constructed cross-sectional images of 4 µm slices, ~800 images per sample, or 25 slices for a 100-µm MM.

We outlined, by hand, the MM and the vesicle boundaries in the tomography slices and created a 3-D model of the micrometeorite using IMod, a freeware program. The model then allowed us to calculate the volume of each micrometeorite and its vesicles. We built models for 24 micrometeorites selected to represent the different classes of MM present.

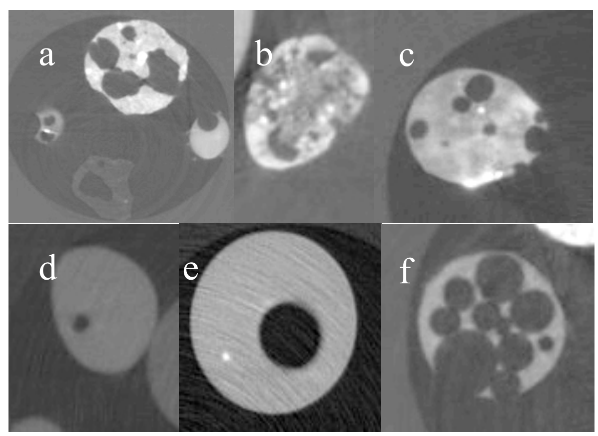

Fig. 2. CMT slices for a RGB (a), Scor (b) PO (c), BO (d), Glass (e) and vesiculated glass (f).

Results and discussion: About 25% of the 614 sectioned MMs contain vesicles (Table 1). All scoriaceous (by definition), >80% of the porphyritic (PO) and relict grain bearing (RGB), ~10% of the barred olivine (BO) and cryptocrystalline (CC), and ~30% of the glass micrometeorites contain vesicles. The appearance and the number density of vesicles differ among these classes (Fig. 1). Vesicles in relict grain bearing micrometeorites (includes coarse-grained umelted MM) are usually not round: instead, the shape of the vesicle follows the boundary of the surrounding phenocrysts (Fig. 1a). Scoriaceous MM have many elongated vesicles, some of which can be large relative to the size of the MM. Larger vesicles are often found near the surface of the scoriaceous MM and smaller vesicles in the interior (Fig. 1b). MMs with porphyritic textures have nearly spherical vesicles of various sizes (Fig. 1c). Barred olivine spherules have small round vesicles (1d), CC and glass spherules generally have spherical vesicles (Fig. 1e) and about 5% of the glass spherules are highly vesiculated (Fig. 1f).

Table 1. Number and percentage of relict grain bearing (RGB), scoriaceous (Scor), porphyritic (PO), barred olivine (BO), cryptocrystalline (CC) and glass MMs that contain vesicles. Not all MMs are of these types.

Diameter (µm)	# MM	RGB	Scor	PO	BO	CC	Glass
> 250	124	4	1	6	56	22	27
% w Ves	**21**	**100**	**100**	**100**	**11**	**4**	**44**
106-250	376	39	11	54	158	48	47
% w Ves	**26**	**85**	**100**	**80**	**10**	**10**	**17**
53-106	114	9	2	14	1	0	2
% w Ves	**25**	**64**	**100**	**93**	**2**	**0**	**12**
Total	**614**	**52**	**14**	**74**	**215**	**70**	**76**

Fig. 2 shows the CMT counterpart of the the optical images in Fig. 1. As in Fig. 1, differences in the outlines of the MM and of vesicle shapes are readily seen in the CMT slices. Compositional information can also be gleaned from the slices. Regions of higher relative Fe content are brighter as seen, for example, in the rims of scoriaceous MMs (Fig. 1b and 2b). The dark areas (lower average atomic number) in Fig. 2c are probably relict Mg-rich olivines and the bright dot in Fig. 2e could be a Ni bead or platinum group nugget [1,5].

Although the CMT slices have lower resolution than SEM images (effectively 4 µm vs. 0.01 µm), the many slices available for each MM allows us to see how the distribution of phases and textures change in 3-D. For example, we can determine if vesicles are interconnected and if they are intact- not open to an outside surface. Fig. 3 shows an image of the model created for one of the 24 MMs. Comparing the volume of the MM with the volume calculated for voids yielded the porosity values shown in Fig. 4. Eight of the 24 MM were glass, two were Scor, three were PO and the remaining 11 were BO or CC. The glass spherules had porosities that ranged widely, from 0 to 63%. The Scor and PO MMs had porosities between 8 and 16%. Only one of the BO & CC had vesicles. The measured porosity and volume of the MM do not correlate (Fig. 4).

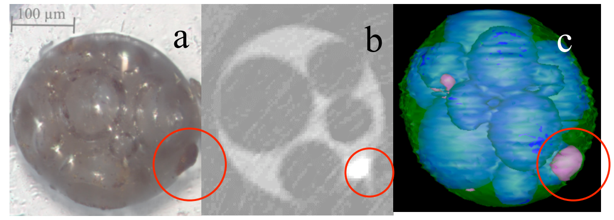

Fig. 3. Optical image (a), CMT slice (b) and meshed model (c) of highly vesiculated glass spherule, 50% porosity. The MM is similarly oriented in all three images- note circled metal bead. Second metal bead seen in model is not visible in other two images.

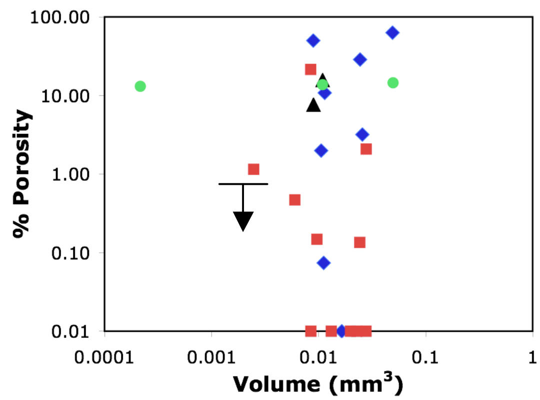

Fig. 4. Volume (mm^3) versus porosity for glass ◆ BO&CC ■, scoriaceous ▲ and porphyritic ● MMs. All estimated porosities below ~1% are upper limits.

Conclusions: Vesicles in MMs show up clearly in the CMT slices and IMod allowed us to calculate the percent volume of voids and phases of interest in the MMs. The shape and distribution of vesicles are tightly linked to specific textural types and provide an independent textural criterion for the classification of Scor, PO and glass MMs.

CMT shows that sulfides present in RGB, Scor and PO MMs abut vesicles. We infer that the breakdown of sulfides form the vesicles in these MM although the decomposition of other phases not seen today – hydrated silicates and carbonates – is not ruled out. Sulfides are generally not observed near vesicles in BO, CC and Glass MMs.

Tomography is a powerful tool for visualizing the 3-D distribution of metal beads, sulfides, and vesicles in MMs. It can also be used to screen for specific types of MMs or attributes, such as platinum group nuggets [5] or intact vesicles, without having to section the MM.

References: [1] Feng H. et al.(2005) M&PS 40, 195-206 [2] Tsuchiyama A. et al. (2004) M&PS 39, A107. [3] Taylor et al. (2000)) M&PS 35, 651-666. [4] Taylor et al. (2009), 40th LPSC Abstract 1692. [5] Brownlee et al. (1984) *Nature*, 309, 693-695.