EXPLOSIVE VOLCANISM ON ASTEROIDS RE-VISITED: SIZES OF PYROCLASTS LOST OR RETAINED. Lionel Wilson1,2, Klaus Keil2 and Tim McCoy3. 1Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK (l.wilson@lancaster.ac.uk); 2Hawai‘i Institute of Geophysics and Planetology, University of Hawai‘i at Manoa, Honolulu, HI 96822, USA; 3Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560-0119, USA.

Background: When Wilson and Keil [1] proposed that explosive volcanism might have ejected the basalts produced by melting of the interior of the aubrite parent asteroid as sprays of pyroclasts, they assumed that the sizes of the pyroclasts would be in the range a few tens to several hundreds of microns. This assumption was based on measurements [2] of pyroclasts returned from the Moon by the Apollo missions. Lunar pyroclasts were formed when magma was disrupted by the growth of bubbles of CO generated by a smelting reaction [3, 4], and the size range measured is consistent with the theoretical prediction [5] that a size distribution of this kind to be expected whenever explosive eruptions occur on bodies without atmospheres. Bubbles forming in magmas by supersaturation or by chemical generation of a volatile phase nucleate with sizes of ~20 microns [6] and grow by decompression and additional gas diffusion. By the time that the bubbles are close packed, so that magma disruption occurs, the largest bubbles will have grown to at least mm size whereas the smallest will still be only tens of microns in size. Wilson and Keil [7] revised their earlier estimate on the basis that the volatile species in asteroids are not likely to be entirely dominated by CO and concluded that asteroid pyroclast sizes may have ranged from ~30 µm to 4 mm.

New analysis: Wilson et al. [8] reappraised the issue of the pyroclast size distributions to be expected on asteroids and found that the absence of an atmosphere is not the only important controlling factor; internal lithostatic pressure, a function of asteroid size and density, is also important. The internal pressures in chondritic asteroids greater than ~100 km in diameter are large enough that when silicate melting begins in the mantle, significant amounts of the volatiles incorporated into the asteroid at the time of its accretion can dissolve into the silicate melt. When the pressure decreases toward the external vacuum as this melt approaches the surface through veins and fractures (i.e., dikes), volatiles exsolve again as small (~20 micron) gas bubbles and expand to produce the pyroclast size distribution predicted by [5]. However, the pressures inside asteroids much less than 100 km in diameter are not large enough to cause significant amounts of the volatiles to dissolve into silicate melts, and so when mantle melting begins in small asteroids, primordial volatiles initially present as a free gas phase largely remain as such, and volatiles chemically or physically bound to minerals and liberated by dissociation also form a free gas phase. The resulting gas pockets can have a wide range of sizes. If they fill the widths of the veins and dikes through which the melts are rising, they break the liquid phase into discrete batches. These emerge through surface vents as liquid ribbons separated by gas, a process called "slug flow" [9, 10]. Hydrodynamic instabilities break these liquid ribbons into droplets with a range of sizes, mostly less than ~0.3 mm but possibly up to ~30 mm in diameter.

The pyroclast sizes just specified relate to silicate liquids. However, if the temperature in an asteroid mantle is high enough for significant silicate melting to take place, Fe,Ni-FeS liquids are also likely to have formed. These liquids will probably not migrate until the amount of silicate melting reaches at least ~20% [11], and so immiscible mixtures of the two liquids will begin to move together. The silicate liquids are generally less dense than the mantle minerals from which they form whereas Fe,Ni-FeS liquids will be denser than the host rocks, implying that if no other factors intervene the two liquids will migrate in opposite directions. However, trapped pockets or bubbles of gas within the Fe,Ni-FeS liquid can cause the bulk density of the mixture to be less than that of the mantle rocks [12], leading to upward migration of an immiscible mixture of the two liquids and the entrained gas bubbles and pockets. Fe,Ni-FeS liquids are very much less viscous than silicate liquids, and so if Fe,Ni-FeS liquids reach the surface in slug flow, most of the droplets into which they disrupt will be less than ~5 mm in diameter, and could be much smaller [8]. However, if a three-phase mixture of Fe,Ni-FeS liquid, silicate liquid and gas emerges, the higher viscosity of the silicate liquid may control the disruption process, and larger Fe,Ni-FeS liquid droplets may form.

Implications: These new results imply that the situation described by [1], in which the pyroclasts produced on an asteroid of a given size would either all be retained on the surface or all be ejected into space with more than escape velocity, is an over-simplification. We now see that there will always be a critical pyroclast size that marks a boundary: pyroclasts smaller than the critical size will be able to escape completely from the asteroid, but pyroclasts larger than the critical size will fall back onto the surface. A corollary is that the size range of clasts in pyroclastic deposits ac-
cumulate on asteroid surfaces will be very much coarser than the size range of the droplets that escape. This assertion is reinforced by the finding [13] of an unusual ~20 mm-sized clast in the Larkman Nunatak 04316 aubrite meteorite. The clast consists of a quench-textured Fe,Ni-FeS clast of a type previously unknown from aubrites joined by an igneous contact to a silicate vitrophyre composed of enstatite-forsterite-diopside-glass. McCoy and Gale [13] interpreted this as a likely product of pyroclastic volcanism. The factors controlling the critical pyroclast size are the asteroid diameter, the mean molecular weight of the volatile phase, and the mass fraction of the erupted fluid that consists of the volatiles. Using the methods of [8] we have calculated the way in which the critical size varies with these parameters for pyroclasts of any given density.

Figure 1 shows the results when the mean molecular mass of the volatile phase is 40 kg kmol$^{-1}$, the value adopted by [8] as a likely average of values corresponding to volatiles likely to be present in a range of compositions of parent asteroids, and the pyroclast density is 3000 kg m$^{-3}$, appropriate for silicate melt. The graph can be used for other pyroclast densities by noting that, to a good approximation, the critical droplet size for a given asteroid diameter and melt volatile content is inversely proportional to the droplet density. Other volatile molecular weights, $m$, can be treated by noting that the asteroid diameter $D$ at which a given size pyroclast has a speed equal to the escape speed is $D = K (n/m)^{1/2}$, where $K = 16.3$ km when $n$, the melt volatile content, is in ppm and $m$ is in kg kmol$^{-1}$.

Results: Fig. 1 shows that only a small amount of gas is needed to eject very large pyroclasts from small asteroids, but a very large amount of gas is needed to eject even small pyroclasts from large asteroids. At their intersections with the abscissa, where they become nearly vertical, the curves define the minimum gas mass fraction that must be present in the melt to allow any, even the smallest, of the pyroclasts to be ejected from an asteroid of a given size, and these values are consistent with those originally proposed by [1].

The size distribution of the pyroclasts is shown to be critically important. The vertical broken line in Fig. 1 is the asymptote to the 500 ppm gas curve and crosses the abscissa at an asteroid diameter of ~56 km. Thus, on an asteroid with this size, all pyroclasts, irrespective of their size, will be retained on the surface if the gas mass fraction, $n_m$ is 500 ppm or less. However, the broken line crosses the curve for $n_m = 1000$ ppm at a pyroclast size of ~15 mm; thus on this 56 km diameter asteroid all pyroclasts will be lost into space if the melt contains 1000 ppm gas unless their diameter is greater than 15 mm. Finally, the broken line crosses the curve for $n_m = 2000$ ppm at a clast size of 400 mm: if 2000 ppm gas is available in erupted melts on an asteroid 56 km in diameter, only pyroclasts larger than 0.4 m in diameter can avoid being lost.

Conclusions: If pyroclasts are identified on the surface of a given asteroid, either directly by spacecraft missions or by their recognition in meteorites, their sizes will give information on the conditions in the eruptions that formed them. If the asteroid size is known, or can be estimated indirectly, the size of the largest pyroclast gives a maximum estimate of the gas mass fraction involved in the eruption.