METEORITIC EVIDENCE FOR THE MECHANISM OF POND FORMATION ON ASTEROID EROS.

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One of the many unexpected observations of asteroid 433 Eros by the NEAR mission was the many ponds of fine-grained (<1cm) materials [1&2]. These ponds are characteristically smooth and are found mainly within craters. Though level to a first approximation (and corresponding well to the gravitational equipotential field [3]), they can exhibit small, steep-walled, fault-like features, which suggests that the pond deposits can be indurated to some degree [2]. The ponds are distributed preferentially in low latitudes, near the ends of the elongated asteroid. These latitudes coincide with surfaces that spend the most time near Eros' terminator, as well as being the regions with the lowest surface gravity [1].

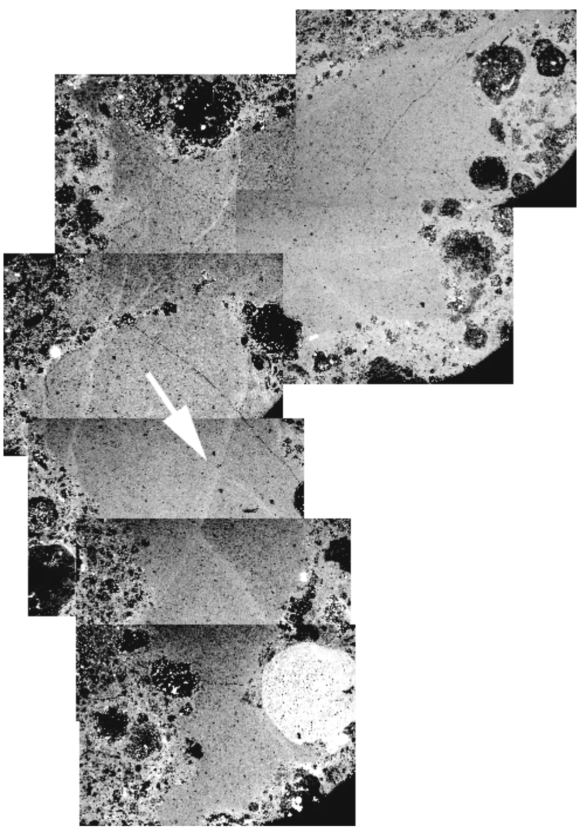

Fig. 1 BSE image of crossbeds (arrowed) in first Vigarano clast. "Up" is to the upper left. View ~1 cm across.

There have been two principal theories advanced to explain the ponds. Robinson et al. [4] proposed that electrostatic levitation of small grains played a major role in their formation. Others have supported the segregation and migration of fines by seismic shaking [1,2&5].

Do we have any meteoritic evidence of ponds on asteroids, and if so which of the proposed formation mechanisms does it support (if any)? There has been considerable work on the petrography and diversity of "dark clasts" present within chondrites and HED meteorites [6-9]. Some of the clasts found in CV chondrites, called "Type C" by Krot et al. [8], consist of uniformly fine-grained olivine. These clasts could have originated in fine-grained ponds, but their general lack of internal structures does not permit us to say much about the formation mechanism. Of greater interest is a single cm-sized clast located in the Vigarano CV chondrite [6&9]. While different groups came to completely different conclusions regarding its genesis, the most recent study [9] proposed that it represented a fluvial deposit. There appears, however, to be no evidence of aqueous alteration.

We have found a second example of this type of clast, in an ancient thin section at the Museum of Natural History (London). As revealed by SEM, microprobe and TEM analyses performed at JSC, these two Vigarano clasts consist nearly entirely of 5 micron- to submicron-sized grains of olivine Fo43-78, with a pronounced peak at Fo50. This is essentially the distribution of olivine compositions in Vigarano itself [8], and since most CVs have distinctive olivine distributions this fact suggests that the clasts are indigenous to the Vigarano host asteroid. Larger olivine grains up to a few 10s of µm are present, and most of these have normal zoning. The smallest grains are among the most iron-rich, having compositions as low as Fo43. Pyroxene, spinel, pentlandite and other accessory phases are present, and are well described by Tomeoka and Kojima [9]. The most distinctive feature of these clasts are numerous, closely-spaced, cross-bedded, arcuate bands. These bands are apparent in both reflected light and BSE images, because they contain a high proportion of the finest-grained, iron-rich olivine. We define each layer as a "bed", each of which contains within it a "band" with a high concentration of iron-rich olivine. Figure 1 shows a BSE image of the first-discovered Vigarano clast, with obvious arcuate, crossbedding. Figure 2 shows the second clast, where the bedding has a sinuous form, probably because the section was cut parallel to the beds, rather than normal to them as in the first (Fig.1) clast. Figure 3 shows a closeup BSE image of a band in the first clast. The entire clast consists of a porous aggregate of olivine grains; the pores in the arcuate bands are almost entirely filled with very fine-grained, iron-rich olivine [9]. From the sense of the crossbedding we can tell which way "up" was (a rare feature in meteorites!), and inspection of Figure 3 indicates that the relatively fine-grained bands are located at the *bottom* of each bed: the top of each iron-rich band is a transitional boundary, but the bottoms are very sharp. The bands have both sharp upper and lower boundaries in the second clast.

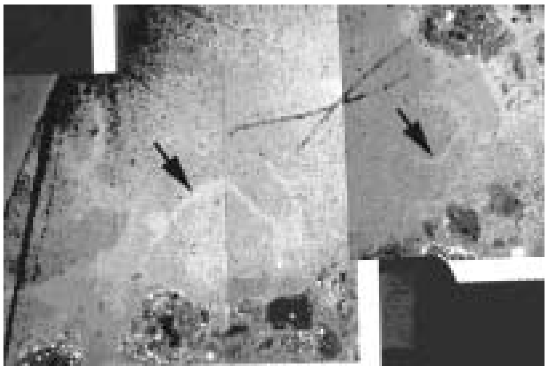

Fig 2 BSE image of sinuous-appearing bands (arrowed) in second Vigarano clast. View measures ~1 cm high.

Could these crossbeds have formed from either of the two processes suggested for Eros pond formation? Electrostatic levitation is a real phenomenon, serving to separate fines from among poorly-sorted regolith, and move it about the surface of an asteroid in hops [4,10-12]. However, it is not obvious how this mechanism would concentrate these fine-grained materials in discrete ponds, or if it could deposit materials in a size-sorted manner. By contrast, impact-induced seismic shaking can result in grain-size separation with fine-grained materials "percolating" through a coarse matrix to the bottom [13], which is exactly what we observe in the Vigarano clasts.

We propose the following scenario for the Vigarano clasts. (1) Some process separates fines from the bulk regolith material; this could well have involved electrostatic levitation, which could have separated the finest material from coarse accumulations. (2) An impact generates seismic shaking, forming one bed, with the finest grains percolating to the bottom of the bed. This presumably would be most effective at elongated portions of the asteroid, which is where ponds are observed on Eros. (3) Since each shaking episode should erase the layering from previous episodes, some process must periodically lithify the beds to some degree to preserve them. Later impacts can then cause degradation, but not total destruction of previously deposited beds. (4) Slumping, or impact-triggered motions, causes older beds to rotate, and subsequent beds can be deposited on an eroded, flat surface at an angle, creating the crossbeds.

We conclude that the Vigarano clasts formed in ponds that experienced seismic shaking. The Eros ponds may have formed the same way. There is a suggestion that the Eros pond surfaces are depleted in iron, based upon the gamma ray spectrum measured at the NEAR landing site [14]. This would be explained by percolation downward of iron-rich olivine and/or dense Fe-Ni sulfides. The latter phases are shown to be preferentially comminuted by multiple lab impacts into chondritic targets, being performed by authors MJC, FH and RVM.

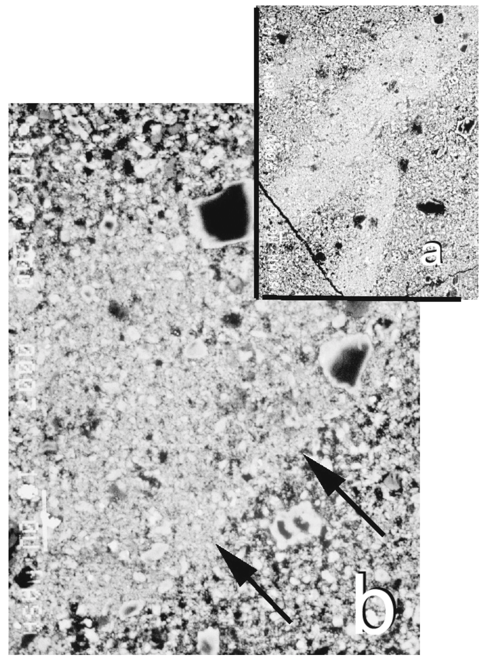

Fig 3 **a**: Higher magnification BSE image of crossbeds in first Vigarano clast. "Up" is to the upper left. View measures ~0.5mm across. **b**: Highest magnification BSE image of the bottom of one bed from the inset image. Iron-rich band stands out as bright; its lower boundary (arrowed) is sharp, while the upper boundary is gradational. Pore space is black: note the general lack of pores in the iron-rich band. View measure 100 μm across.

References:[1] Cheng et al. *MAPS*, submitted; [2] Veverka et al. (2001) *Science* **292**, 484-488; [3] Cheng et al. (2001) *Science* **292**, 488-491; [4] Robinson et al. (2001) *Nature* **413**, 396-400; [5] Asphaug et al. (2001) *LPSC XXXII*, 1808.pdf; [6] Johnson et al. (1990) *GCA* **54**, 819-831; [7] Kojima and Tomeoka (1996) *GCA* **60**, 2651-2666; [8] Krot et al. (1995) *Meteoritics* **30**, 748-775; [9] Tomeoka and Kojima (1998) *MAPS* **33**, 519-525; [10] Criswell (1972) Proc. 3rd LSC, 2671-2680; [11] Bibhas and Criswell (1977) *JGR* **82**, 999-1004; [12] Lee (1996) *Icarus* **124**, 181-194; [13] Horz and Schaal (1981) *Icarus* **46**, 337-353; [14] Evans et al. (2001) *MAPS*, in press.