CAN BOULDERS SUPPLY MATERIAL FOR PONDS ON THE ASTEROID 433 EROS?

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Introduction: "Ponds" are features on the asteroid 433 Eros that are thus far observed to be unique in the solar system [1, 2]. Morphologically, they are flat-floored [3] and often sharply embay the bounding depression in which they sit (Fig. 1), thus the description as ponds. Ponds appear to be smooth, indicating that the material is finer-grained than the best resolution of the NEAR-Shoemaker images (i.e., sub-cm) [2]. One of us (PCT) has constructed a database of 334 ponds [cf. 2]. While they can reach sizes of ~210 m across, the majority are < 60 m wide. Most ponds are found on the bulbous ends of the elongated asteroid [2, 4].

Color images indicate only relatively subtle differences to the rest of the surface, with ponds possessing somewhat bluer colors. These color characteristics can be attributed to 1) the presence of very fine-grained material (< 50 μm), 2) a lack of space-weathering of the pond material, or 3) a sorting process that separates silicate-rich pond material from the silicate-plus-metal composition of Eros [2]. Based on an observed spatial correlation between the location of most ponds and areas of the surface that experience prolonged durations of terminator passages, electrostatic levitation of a very fine-grained component of the regolith of Eros has been proposed to be crucial in the formation of ponds [2]. Modeling has demonstrated the plausibility of dust levitation on Eros [5] as a delivery mechanism of pond material to within a bounding depression, although seismic shaking [e.g., 3] has been invoked to flatten this material to the observed pond morphology.

Here, we propose an alternative delivery mechanism of material to form ponds: eroding boulders. Like the dust levitation scenario, we invoke seismic shaking to smooth the material into a pond.

Boulders and Ponds: Some boulders on Eros display what appear to be debris aprons (Fig. 1). Aprons observed around boulders within ponds have been interpreted as pile-up of pond material against local topography [2]. Alternatively, we suggest the aprons may be the result of boulders eroding in place. This observation necessitates a mechanism by which boulders can erode. Micrometeoroid erosion, however, is believed to be too slow [4]. We suggest thermal erosion caused by the large diurnal cycling of surface temperatures. S-type asteroids like Eros are likely the sources of ordinary chondrites, which are composed of silicate-rich chondrules of order 1 mm in size, held in a more metal-rich matrix. The likely disparate thermal properties between the chondrules and the matrix may produce stresses that can progressively disaggregate the surface of a boulder. If a boulder lies in a local depression, the eroded material may be trapped and serve as source material for a pond.

There is evidence that boulders and ponds are related. Large blocks on Eros (> 30 m across), inferred to be ejecta from the impact that created Shoemaker, are observed to lie in an equatorial band [6], their distribution in many ways similar to areas that show prolonged terminator passages [2]. Furthermore using a subset of the pond distribution selected to investigate the bounding depressions, histograms of the number of ponds in bins of pond width display a somewhat bimodal distribution (Fig. 2). The distribution appears to be largely lognormal, peaking in the 25-35 m bin, except for a smaller secondary peak centered at 85 m. We have tried various decompositions of the pond population to explain this bimodal distribution (e.g., high versus low latitudes, image resolution), not finding a consistent explanation except for an association with boulders: larger ponds tend to have boulders clearly visible within the bounding depressions (Fig. 2).

A New Mechanism: Based on our observations, we propose a new scenario for the formation of ponds. 1) A boulder is delivered to a local depression. 2) The boulder erodes in place. 3) Seismic shaking flattens the material into the pond morphology. Volume estimates of boulders are consistent with estimates of the volume of material in a pond; the ~90-m pond examined in [3] would require a single boulder 30-40 m across, of which there are several hundred examples on Eros.

This scenario may be consistent with the observed bimodal distribution: smaller ponds would require smaller boulders. The observation that the distribution of ponds without obvious associated boulders tend to be smaller may suggest that boulders in these ponds have already eroded sufficiently to be unobservable.

As a consequence, we predict that the pond material is composed of liberated chondrules and matrix, which naturally satisfies the requirement based on images that the material be sub-cm in size. In addition, the color characteristics of ponds would, under this scenario, result from the lack of space weathering on material recently liberated from a boulder interior, seismic sorting of the silicate-rich chondrules from the denser, more metal-rich matrix, or some combination.

Influence of Local Slope and Elevation: The proposed scenario is suggestive, but it does not naturally explain the pond distribution. Like the ponds, large boulders (> 30 m across) are concentrated equatorially [2, 6]. There are, however, > 33,000 boulders of sizes down to 1 m that are more evenly distributed across the surface. To further understand the origin of ponds, we explore their relationships to local slope and elevation. Ponds are typically located on low slopes and at higher elevations. The low slopes ensure that pond materials do not escape the bounding depressions during seismic shaking. The presence of a thick layer of regolith may inhibit the formation and retention of ponds by submerging the bounding depressions in which ponds occur. Therefore, the presence of ponds at higher elevations may be due to a lack of regolith in these regions, because successive seismic shaking events could have enabled downslope migration of loose, mobile regolith.

Discussion and Future Tests: We have proposed a mechanism by which there exists a causal relationship between boulders and ponds on Eros. A boulder, if caught within a bounding depression on locally low slopes, may supply the pond material. Like the electrostatic levitation model, this model invokes seismic shaking to flatten the material to the pond morphology. To test these models will require mm-scale imagery, to distinguish whether the pond material is mm-sized or finer. We do recognize the possibility of a hybrid model, where both mechanisms are important. In addition, any model must eventually explain the relative dearth of ponds. There are large areas on Eros that witness prolonged terminator passages, and there are > 33,000 boulders. Yet, there exist only ~300 identified ponds. The disparity of these numbers suggests the process that creates ponds is relatively inefficient, any destructive mechanism is relatively efficient, or both.

Thus, other tests are currently possible. Seismic shaking experiments [e.g., 7] may reveal the conditions under which the pond morphology can be created and possibly destroyed, and may elucidate the mechanical properties of the materials that form both the ponds and the bounding depressions. Furthermore, thermal cycling experiments on ordinary chondrites can more firmly establish the plausibility of the thermal erosion mechanism we have proposed; we further note that this process is a previously unrecognized mechanism for generating regolith on S-type asteroids.

References: [1] Veverka J. et al. (2001) *Science, 292*, 484-488. [2] Robinson M. S. et al. (2001) *Nature, 413*, 396-400. [3] Cheng A. F. et al. (2002) *Meteoritics & Planet. Sci., 37*, 1095-1105. [4] Robinson M. S. et al. (2002) *Meteoritics & Planet. Sci., 37*, 1651-1684. [5] Colwell J. E. et al. (2004) *Icarus, 175*, 159-169. [6] Thomas P. C. et al. (2001) *Nature, 413*, 394-396. [7] Izenberg N. R. and Barnouin-Jha O. S. (2006) *LPS XXXVII*, Abstract #2017.

Figure 1. Portion of NEAR-Shoemaker MSI image at MET 156087851. This pond, ~90 m wide, has a boulder with a debris apron sampled by an NLR track [3].

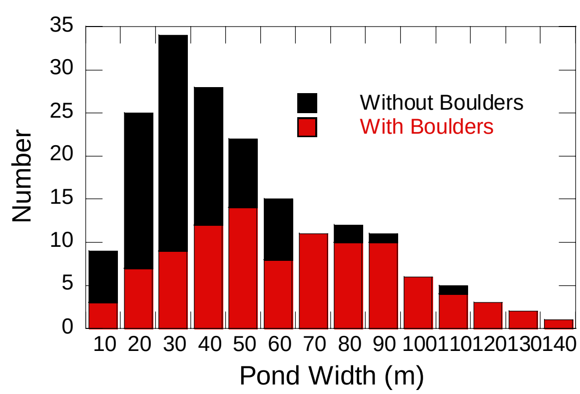

Figure 2. Histogram of number of ponds within bins of pond width 10 m wide and centered on the indicated value, using a 184-member subset of the pond population. Ponds with associated boulders are in red, while ponds without boulders are in black; the total bar height is a sum of the two.