THE PRESERVATION AND GEOLOGIC EFFECTS OF EXOGENIC AND HYDRATED MATERIALS ON VESTA.

Brett W. Denevi[1], David T. Blewett[1], Debra L. Buczkowski[1], Maria Teresa Capria[2], Maria Cristina De Sanctis[2], Lucille Le Corre[3], Jian-Yang Li[3], Simone Marchi[4], Andreas Nathues[5], David P. O'Brien[3], Noah E. Petro[6], Thomas H. Prettyman[3], Frank Preusker[7], Vishnu Reddy[3], Christopher T. Russell[8], Jennifer E. C. Scully[8], Jessica M. Sunshine[9], Federico Tosi[2], David A. Williams[10]. [1]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD USA, [2]INAF, Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy, [3]Planetary Science Institute, Tucson, AZ, USA, [4]NASA Lunar Science Institute, Boulder, CO, USA, [5]Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany, [6]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [7]Deutsches Zentrum fur Luft- und Raumfahrt (DLR), Institute of Planetary Research, Berlin, Germany, [8]University of California, Los Angeles, CA, USA, [9]University of Maryland, College Park, MD, USA, [10]Arizona State University, Tempe, AZ, USA.

Introduction: In most respects Vesta resembles a typical airless body, where impact cratering, regolith mixing and downslope movement dominate its geology [e.g., 1,2]. However, Vesta appears to be unique among asteroids observed by spacecraft to date in the degree to which its geology has been influenced by exogenic materials. With the highest geometric albedo of any large rocky body (0.38) [3], Vesta is also striking because of the presence of heterogeneous deposits of dark material with geometric albedos as low as ~0.1 [4]. The majority of this low-reflectance material has been interpreted as exogenic in origin, the result of mixing with carbonaceous impactors [5–8]. Here we review the geologic consequences of the presence of hydrated minerals on an otherwise volatile-poor body, with an examination of how Vesta can inform our understanding of the effects of exogenic materials on other bodies.

Vesta's Pitted Terrain: From Dawn's highest resolution images of Vesta (pixel scales <20 m), clusters of closely spaced, irregular rimless pits (Fig. 1) were identified on several crater floors (Marcia, Cornelia, Licinia, and possibly Numisia) and, in one case, within crater ejecta (Marcia) [9]. The morphology of these pits is consistent with formation due to the rapid release of volatiles, triggered by heating from an impact event. Volatile escape is thought to erode the surface during escape, leaving coalescing pits that have a "soap-bubble"-like geometry [10]. The most prominent examples of the pitted terrain are associated with the 70-km impact crater, Marcia. Marcia formed within a broad region of low-albedo, high hydrogen [5] (Fig. 1), high OH- [8] and thick regolith [11]. It is the largest young impact crater on Vesta, with an estimated age of ~40-120 million years [9,12,13]. The pitted terrain at Marcia occurs within regions that show evidence for impact melt, suggesting substantial heating from an impact event that may have occurred at higher than average velocity [9,13]. Cornelia, which appears to be of comparable or younger age, shows similarly distinct pitted terrain within its floor, whereas such features at Licinia and Numisia are more degraded.

The pitted terrain may be closely tied to Vesta's dark material. Spectra of low-reflectance deposits indicate the presence of OH- and possibly H_2O [8], and Gamma Ray and Neutron Detector (GRaND) data find regions with over 400 µg/g H that correspond to areas of low albedo [5]. With low albedo and an average of 9 wt% H_2O bound within crystal lattices, carbonaceous chondrite meteorites are a likely source of this dark material [e.g., 14,15]. Heating from later impacts into carbonaceous-bearing regolith would result in devolatilization and the production of H_2O vapor. For H concentrations consistent with the GRaND results, calculations of the gas pressure of water vapor within regolith pore space show that it would be thousands of times higher than the overburden pressure of overlying soil; escaping water vapor would easily erode the soil to form the observed pits. Such devolatilization is consistent with the observation that while Marcia crater is located within a region of elevated hydrogen, its immediate surroundings are low in H [5] (Fig. 1).

Similar pitted terrain has been observed within numerous relatively young impact craters on Mars, and a conceptual model for its formation via degassing of a volatile-rich target surface [10,16] applies equally to Vesta. While ground ice was considered as a volatile source on Mars, the results for Vesta suggest that only hydrated minerals are required [9]. The observation that few craters contain pitted terrain at ice-rich high latitudes on Mars [16] may support a mineralogic origin for the volatiles responsible for the formation of pitted terrain on Mars as well.

Discussion: With abundant deposits of carbonaceous debris and the influence of these materials in creating impact-related landforms, Vesta's geology has been affected by exogenic materials to a degree not observed on other airless bodies studied to date. Given the long collisional history of the Solar System, the influence of exogenic materials on Vesta would seem to be a natural consequence; perhaps the real question is why are such effects not more commonly observed on other airless bodies? On the Moon and Mercury, hydrogen is thought to be largely in the form of water ice segregated within permanently shadowed regions near the poles or solar-wind implanted hydrogen whose main effect may be on the chemical space weathering of the surface. Exogenic materials are observed at low abundances within the lunar regolith (<2% in Apollo regolith samples [17]), but do not contribute to regional (or localized) variations in albedo or geology. Neither are such large effects of exogenic materials seen on other asteroids visited by spacecraft to date. This begs the question, has Vesta undergone some unique collisional history that resulted in unusually large exogenic effects on its surface? While this is possible, we instead suggest that a combination of factors resulted in a higher degree of preservation of exogenic materials on Vesta's surface.

The first of these factors is impact velocity, which plays a large role in the degree of preservation of impactors. The high average impact velocities for the Moon (19 km/s) and even higher velocities for Mercury (43 km/s) [18] result in efficient vaporization of the impactor such that little original material is preserved and any volatiles are lost. In contrast, impact velocities on Vesta are closer to 5 km/s on average, and hydrated clasts observed within HED meteorites confirm that impacts at main-belt velocities do not always lead to devolatilization of the impactor [e.g., 19]. Moreover, the structures of the carbonaceous chondrites clasts in howardites are consistent with a "gentle deposition" on the Vesta surface.

But why do asteroids like Eros, Lutetia, Itokawa, and Steins show little evidence for the influence of exogenic materials? One factor may be the high albedo of Vesta, and models and samples that show it has a dearth of endogenic volatiles, both of which allow for the easier detection and identification of carbonaceous material as exogenic. Another important factor may be the size and structure of the body, which could enhance or inhibit preservation of exogenic materials. Whereas a large, differentiated asteroid like Vesta can preserve a heterogeneous regolith, smaller bodies with no core are more likely to be disrupted or homogenized by seismic shaking, and the ejecta of a single impact can affect the entire surface [20]. These asteroids may also be fragments of larger bodies and thus not preserve the early regolith, whereas the degree of exogenic material on Vesta's surface could indicate that it records the ancient delivery and mixing of exogenic material that was common throughout the Solar System [5,8] (e.g., the "late veneer").

We conclude that the largest coherent rocky bodies within the asteroid belt should show the effects of such exogenic material. Further, on asteroids with abundant hydrated minerals, whether exogenic or native, pitted terrain will also form at locations of high-velocity impacts, and will be preserved at the most recent of these sites. Impact cratering can thus result in not only devolatilization of impactors and target materials at high velocity, but the delivery, exposure, and redistribution of hydrated materials at lower degrees of shock.

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References: [1] Jaumann R. et al., *Science* 336, 687–690 (2012). [2] Williams D. A. et al., *Planet. Space Sci.* (2013), doi:10.1016/j.pss.2013.06.017. [3] Li J.-Y. et al., *Icarus* 226, 1252–1274 (2013). [4] Reddy V. et al., *Science* 336, 700–704 (2012). [5] Prettyman T. H. et al., *Science* 338, 242–246 (2012). [6] Reddy V. et al., *Icarus* 221, 544–559 (2012). [7] McCord T. B. et al., *Nature* 491, 83–86 (2012). [8] De Sanctis M. C. et al., *ApJ* 758, L36 (2012). [9] Denevi B. W. et al., *Science* 338, 246–249 (2012). [10] Boyce, J. M. et al., *Icarus* 221, 262–275 (2012). [11] Denevi B. W. et al., *EPSC*, EPSC2012–813 (2012). [12] Marchi S. et al., *Planet. Space Sci.*, in press (2013). [13] Williams D. A. et al., *Icarus*, submitted (2013). [14] Rubin, A. E. et al., *Geochem. Cosmochim. Acta* 71, 2361–2382 (2007). [15] Cloutis, E. A. et al., *Icarus* 216, 309–346 (2011). [16] Tornabene L. L. et al., *Icarus* 220, 348–368 (2012). [17] McKay D. S. et al., in *Lunar Sourcebook*, Heiken, Vaniman, French, Eds. (Cambridge Univ. Press, Cambridge, 1991), 285–356. [18] Le Feuvre, M., M. A. Wieczorek, *Icarus* 197, 291–306 (2008). [19] Zolensky, M. E. et al., *Met. Planet. Sci.* 31, 518–537 (1996). [20] Thomas, P. C. et al., *Nature* 413, 394–396 (2001).

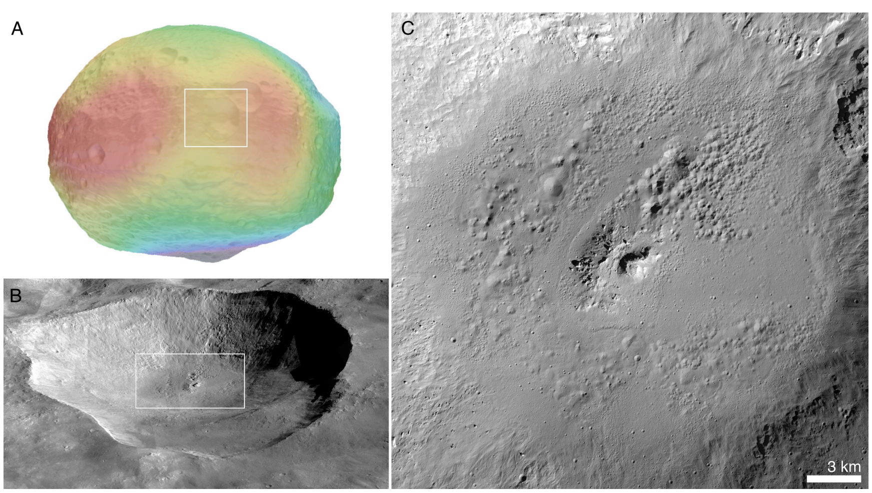

Fig. 1. A) Shape model of Vesta showing the location of Marcia crater (box). Colors shows H content [5] scaled from 0–400 μg/g. B) Synthetic perspective view of Marcia crater, location of C) shown in white box. C) Type example of pitted terrain on the floor of Marcia crater.