DOES THE VASTITAS BOREALIS FORMATION CONTAIN OCEANIC OR VOLCANIC DEPOSITS? D. C. Catling[1], C. B. Leovy[2], S. E. Wood[1], M. D. Day[3], [1]Earth & Space Sciences/ Astrobiology Program, Box 351310, Univ. of Washington, Seattle WA 98195 (dcatling@uw.edu), [2]Deceased, formerly at the Univ. of Washington, Seattle WA 98195, [3]Geological & Planetary Sci., Caltech, Pasadena, CA 91125.

Introduction: The Vastitas Borealis Formation (VBF) is a late Hesperian geomorphic unit covering much of the northern lowlands of Mars [1]. A predominant hypothesis is that it consists of sediments deposited from an ocean that formed from floodwaters released from outflow channels [2]. The possibility of such an ocean is important because it bears on the potential habitability of ancient Mars. The VBF is also linked to putative ocean shorelines. Alleged ocean stands have inner ("Deuteronilus"), middle ("Arabia") and outer ("Meridiani") shorelines [3]. Much of the inner "shoreline" goes around the edge of the VBF.

However, several lines of evidence challenge the hypothesis that the VBF consists of ocean sediments. Spectral signatures for evaporites expected from an ocean are absent [4]. Instead, spectra indicate a basaltic surface modified by minor weathering [4, 5]. Images also show meter-scale boulders where water should have pooled to leave fine sediments [6]. In Amazonis Planitia, the low loss tangent of VBF material (0.005-0.012) from Shallow Radar (SHARAD) data is consistent either with porous sediments or with material similar to lunar basalts [7]. Furthermore, the imaginary parts of the permittivity values for the Amazonis VBF from SHARAD radar data are "too high to represent an ice-rich terrain", such that the VBF is a closer match to "terrains such as low-loss basaltic lava" [8]. The latter contrasts with an interpretation of MARSIS/Mars Express radar data used to map the average dielectric constant at 3-5 MHz to a depth of 60-80 m [9]. It has been argued that the low average dielectric constant in the VBF indicates ocean remnants and excludes volcanic materials [9].

The most direct way that the VBF is sampled is by impacts that have punched into the VBF in the past and ejected VBF material. We have surveyed the relevant impact craters. As we have noted previously, such small craters excavate dark blocks and boulders when the VBF is penetrated [10].

Method: We examined the morphology of craters of a sufficiently small size that the impacts that made them punched above, into, or through the VBF. Thus, such craters are compositional probes above, within and below the VBF. We examined High Resolution Imaging Science Experiment (HiRISE) images (down to ~0.3 m/pixel) from NASA's Mars Reconnaissance Orbiter of the VBF unit down to ~40°N latitude.

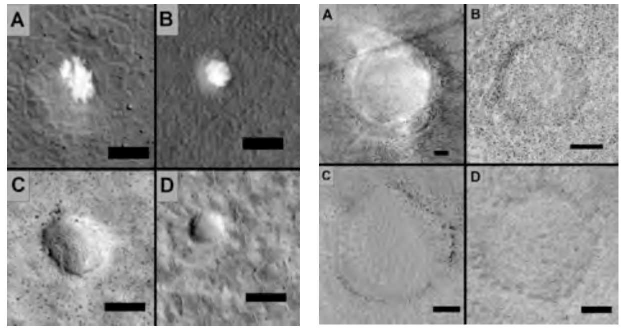

Fig. 1. **Left panel**: Type I craters penetrate shallow regolith without ejecting boulders (scale bar = 20 m). (A-D: ESP_016731_2360 (centered 55.5°N, 131°E), PSP_010415_2525 (72.2°N, 118.6°E), ESP_017777_2350 (54.7°N, 14.2°E), TRA_000856_2500 (69.8°N, 85.8°E)). **Right panel:** Type II craters penetrate a subsurface layer that produces ejecta of boulder and blocks. Increasing crater degradation is shown from A-D (scale bar = 100 m) (A-D: PSP_001380_2520 (71.7°N, 189.9°E), PSP_001474_2520 (71.6°N, 145.4°E), ESP_017777_2350 (54.7°N, 14.2°E), PSP_001501_2280 (47.7°N, 134.3°E)).

Results: *Three groups of small crater morphology*. Small crater morphology is found to divide up into three groups (I, II, III) with approximate diameter (*d*) ranges of 0-200 m, ~200-2000 m, and *d* >2 km. Type I craters (0-200 m) are pits with rock abundance on the rims no different from surrounding plains (**Fig. 1, left panel**). In contrast, Type IIa (200-2000 m) craters have dark boulders and blocks that define the crater rim. Some in this size range are highly degraded and flat, which we call Type IIb, but together Type IIa and IIb are a single diameter range. **Fig. 1 (right)** shows a range of degradation states of Type II craters from having a rim (A), to rings of boulders (B, C) where the rim used to be, to a state where all that is left of a crater rim is a faint ring of different tone (D). The degradation likely results from periglacial processes. If such circular structures were not degraded impact craters, an entire crater population of this size range would be missing. Finally, Type III craters (*d* > 2 km) have well-defined rim and floor structure, often with few boulders or blocks around the rim or in nearby ejecta, and with relatively light-toned ejecta blankets that is distinct from surrounding terrain. **Fig. 2** shows the statistics from 440 impact craters identified in HiRISE images on the VBF. We classified each crater according to its morphology. The morphological classes are a function of diameter and form 3 size-dependent groupings of Types I, II and III.

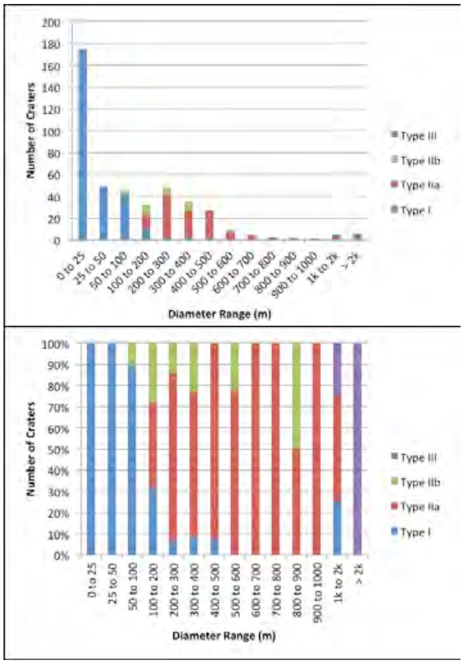

Fig.2. Crater morphology variation with diameter. (See text).

Implications for the VBF. Impacts penetrated to a depth that is roughly 0.1 times the crater diameter. So the simplest explanation of why there are 3 crater morphologies is that they indicate three different materials at increasing depth. Impacts that made the Type I craters (~0-200 m) penetrated into material that extends to a maximum depth of ~20 m. We interpret this material as unconsolidated regolith because the craters that formed are pits with rock abundance on the rims similar to that on the surrounding plains. The impacts that excavated 200-2000 m Type II craters penetrated farther, between depths of ~20-200 m, which is the VBF layer. The material ejected from this depth range forms dark boulders and blocks. 'Blocks' (2-6 m) are found almost exclusively on small crater rims whereas across the plains there are mainly boulders (<2 m), which exponentially increase in abundance with smaller size, suggesting gradual disintegration. Finally, impacts that created craters larger than 2 km diameter penetrated below ~200 m depth and encountered a compositional change from a rocky VBF above to more friable material below. The subsurface stratification boundary depths (~20 m and ~200 m) that we deduce from crater morphology are close to those found in Amazonis VBF from SHARAD data [7].

Conclusions: *Small impact geomorphology suggests igneous VBF material*. Impacts that have penetrated the VBF in the northern plain ubiquitously eject dark blocks and boulders. Elsewhere on Mars, such boulders are interpreted as igneous, which is proven by *in situ* data at landing sites. The probable ejection of such material does not support the idea that the VBF consists solely of marine sediments. Instead, we conclude that that the VBF contains mostly volcanics. However, the VBF generally sits beneath a shallow regolith of ~20 depth and above another layer of more friable material. Our interpretation is consistent with radar data which suggests that the VBF materials (in Amazonis, at least) are unconsolidated volcanics [8].

What about MARSIS radar? The global mapping of the average dielectric constant (for 3-5 MHz) to a depth of 60-80 m has a clear north-south dichotomy [9]. The idea that the low average dielectric constant in the VBF of 4.5±1 indicates oceanic sediments because basalts should be ~9 [9] has important caveats. First, our small impact crater geomorphology indicates that the VBF is usually covered with ~20 m of unconsolidated regolith while SHARAD data in Amazonis suggests that the same regolith layer extends 30-50 m from the surface and overlies the VBF [7]. Thus, a dielectric constant that is an average to 60-80 m depth has a large contribution from unconsolidated surface regolith even at low latitudes. Moreover, the shallow regolith at low latitudes was ice-filled in the recent geologic past during obliquity cycles [11] and so is probably very porous. Second, the MARSIS-derived low dielectric constant can be explained by 35% porosity of volcanic materials [9]. We note that vesiculated lavas have primary porosities that range 5-50% [12]. Great secondary porosity is expected on Mars from fractures in an impacted landscape. Because sand (25-50%) and silt (35-50%) porosities overlap those of porous lavas, inferred porosity is ambiguous for discriminating sedimentary from volcanic lithology.

We conclude that HiRISE images favor the hypothesis that VBF ejecta are igneous. However, the boulders are too localized to determine their composition from orbital spectra within large orbital footprint areas. Their composition could be determined in the future from lander or higher spatial resolution orbital data, which we anticipate will verify our interpretation.

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