A LAVA SEA IN THE NORTHERN PLAINS OF MARS: CIRCUMPOLAR HESPERIAN OCEANS RECONSIDERED. 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]Atmospheric Sci., Box 351640, Univ. of Washington, Seattle WA 98195, [3]Geological & Planetary Sci., Caltech, Pasadena, CA 91125.

Introduction: A widespread hypothesis is that the N. Plains of Mars once lay beneath an ocean created by drainage of Hesperian-age outflow channels. Floodwater is hypothesized to have deposited ~10^2 m depth of sediments, forming the Vastitas Borealis Formation (VBF) [1]. However, putative VBF "shorelines"[2] are disputed [3, 4] and there is no spectral evidence for marine VBF evaporites [5]. Meter-scale boulders in areas where pooled water should have left fine sediments also beg explanation [6]. We present evidence that the VBF is rock produced by floods of lava, not water. Observations show that a ~10-20 m-deep regolith, which is rapidly smoothed by ice working, partially overlies ~100-200 m of VBF lava. If an ocean existed in the N. Plains, it was more ancient and any remants must lie below the VBF, possibly deeply.

Method: We used Mars Orbiter Camera (MOC) and HiRISE images to examine the morphology of small craters in the N. Plains. We considered diameter (*d*) ranges of 20-200 m, 200-2000 m, and *d* >2 km ("very small", "small", and "large" craters, respectively). We chose these size ranges because they form morphological classes indicative of subsurface geology at latitudes >60°N in the VBF. We also examined surface ages and modification features relevant to the history of the N. Plains.

How craters indicate the nature of the VBF: Very small craters (20< *d* <200 m) consist of pits with rock abundance on the rims no different from surrounding plains (Fig 1a). In contrast, small craters (200< *d* <2000 m) often appear only as dark boulder rings in an apparent rim and ejecta region (Fig 1b). Such craters are generally elevated with low relief from a few m to >60 m (Fig 1c,d). Large craters (*d* > 2 km) have distinct well-defined rim and floor structure, often with few boulders or blocks around the rim or in the nearby ejecta, and with large, relatively light-toned ejecta blankets (Fig 1d). More varied crater morphologies occur <60°N.

Consistent division of crater morphology at *d*~200 m in areas >60°N must indicate a change in subsurface composition at a crater depth of ~20 m. Very small craters (20< *d* <200 m) do not eject boulders or blocks, unlike small ones (200 < *d* < 2000 m). Thus, the upper ~20 m of the VBF evidently consists of an unconsolidated regolith (and ground-ice, given ubiquitous patterned ground). But at >20 m depth, "small" craters (200 < *d* < 2000 m) excavate a lower layer of competent rocky material that forms blocks and boulders. 'Blocks' (2-6 m) are found almost exclusively in small crater rims (200< *d* <2000 m). Across the plains, boulders (<2 m) are also common with an exponential increase at smaller sizes, consistent with break-down by impacts and thermal stress.

It is reasonable to suggest an igneous composition for the boulders and blocks. The requirement for a competent rock disfavors salt-cemented or ocean sediments. Farther south, *in situ* data show that soil-free boulders at the Pathfinder site are predominantly igneous with a composition consistent with orbital infrared spectra [*7*]. Vesiculated boulders at the Viking Lander 2 site also show a lava origin [*8*]. Although at different latitudes, the excavated VBF material that forms blocks and boulders is likely to be igneous also because orbital spectra for igneous mineralogy extends across the N. Plains. Possibly the break down of boulders terminates in mafic sand, as seen in Phoenix Lander microscopy [9], which would explain widespread basaltic spectral signatures.

Surface textures suggest that the VBF is made of layers consistent with lava flows. Images show benches of height comparable to one or two large boulders. Erosion in layers (Fig 1f) indicates that the VBF consists of multiple layers of competent material that range in thickness from a few meters to ~10 m.

Surface ages and VBF history: Surface ages from crater densities [10] indicate that "tiny" craters (*d* <20 m) formed or were eradicated within ~1 Ma, very small craters (20-200 m) formed or were eradicated on a timescale of ~10 Ma, while "small" craters (200-2000 m) formed or were eradicated on timescales of several hundred Myr. Thus, the accumulation of lava that formed the 100-200 m deep VBF happened before the formation of "small" craters.

Why the plains are smooth: The smoothness and flatness of the N. Plains have been attributed to ocean sediments, but the geomorphology discussed above suggests a role for large-scale inviscid lavas. Lava pooling in topographic lows between wrinkle ridges would have smoothed wrinkle ridge profiles, as observed [1]. There are also 3 other smoothing processes, as follows, that have probably been active for Gyrs:

1. Impact brecciation. "Tiny" craters (*d* <20m) have formed in recent impacts (Fig 2a) (also [*11*]). Tiny and very small impacts acting since the Hesperian must have disintegrated rock in the top few meters to produce fragments susceptible to wind deflation.

2. Cryoturbation. At >60°N up to the polar dune fields, the surface is patterned at scales of 3-5 m and 20 m, similar to scales around the Phoenix site [12]. Monotonous patterning can be attributed to ground ice across the entire northern VBF [13]. Smoothing of features ~2 km diameter indicates that cryoturbation has swept across the plains probably many times since the Hesperian. However, crater morphology suggests that the near-surface ice is <10-20 m deep. At <60°N, patterning becomes less consistent or absent, supporting the idea that equilibrium surface ice extends down to ~60°N today, but extended farther during the past.

3. Wind deflation. Wind streaks, dust devil tracks, and barchan dunes show a role for wind in mobilizing material created by tiny impactors and cryoturbation. Surprisingly, boulders are often aligned in the predominant wind direction, as verified by wind streaks, barchan dunes, or rare wind tails behind obstacles (PSP_001375_2485). Boulders accumulate in piles that appear to suppress cryoturbation. At >75°N, boulder lines and barchan dunes dominate, with very few wind streaks and no dust devil tracks. Within 55-60°N, dust devil tracks dominate and there are very few boulder lines, with no barchan dunes or wind streaks. Predominant WSW-ENE winds in the VBF broadly agree with general circulation models, which also suggest that wind deflation shifted material from the N. Plains into dunes near the N. ice cap [14]. We find no evidence for eolian or fluvial sedimentation except for localized wind deposition in southern Vastitas Borealis. The lack of bedforms at the Phoenix site (68°N) provides ground-truth to our observations.

Conclusion. The stratigraphy of the N. Plains inferred from crater morphology suggests that an ocean of lava, not water, formed the VBF. This would require relatively inviscid lava from volcanoes or fossae. Support for such lavas comes lava flow morphology [15, 16] and *in situ* Gusev data where inferred viscosities down to 2.3 Pa.s [17] are comparable to lunar lavas [18] (roughly like motor oil at room temperature). We hypothesize that inviscid lava once filled the Vastitas Borealis basin. Post-Hesperian impact brecciation, ice-working, and wind deflation has smoothed the plains on smaller scales, explaining what we see today without recourse to an elusive, late-Hesperian water ocean.

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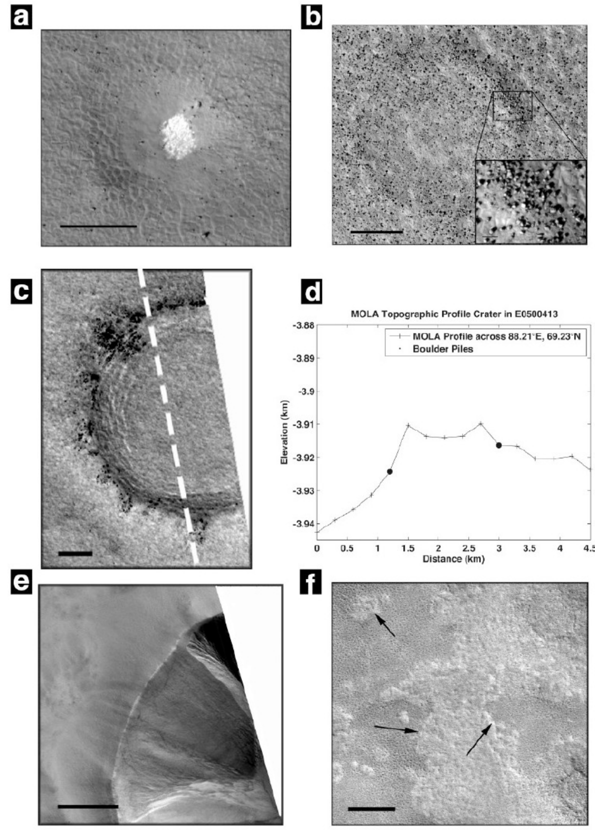

Fig.1: **a.** “very small” crater (PSP_001497_2480). **b.** “small” crater (PSP_010415_2525) **c.** “small” crater with MOLA track (E0500413). **d.** profile of track in c. **e.** “large” crater (R2300337). **f.** thin layer erosion (PSP_001972_2485). (Scalebars: a: 50m, b: 100m, 10m inset c: 200 m, e: 1 km, f: 500 m).

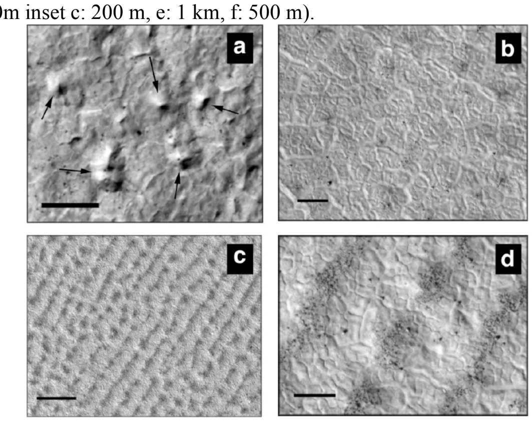

Fig.2: **a.** “Tiny” craters undergoing cryoturbation (PSP_001496_2485). **b**. 3-5 m, 20m polygons (PSP_001467_2490). **c**. aligned boulders (PSP_010415_2525). **d**. zoom of c. (Scalebars: a, b,d 20m. c, 100 m).