ORIGIN AND ARRANGEMENT OF BOULDERS ON THE MARTIAN NORTHERN PLAINS: ASSESSMENT OF EMPLACEMENT AND MODIFICATION ENVIRONMENTS.
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Introduction: Recent observations of boulder-scale clasts in the northern plains of Mars, particularly in the Vastitas Borealis formation (VBF) [1], have renewed interest in understanding the origin and modification history of this hemisphere-spanning geomorphological unit. Mapping of the northern lowlands provides a broad stratigraphic history. Overlying Noachian basement, Hesperian ridged plains units and marginal outflow channel deposits are surfaced by the Vastitas Borealis formation (VBF) [2, 3]. Modification and resurfacing by aeolian and glacial processes, including dichotomy-boundary glaciation [4-6], latitude-dependent modification, and crater-infilling dominates the Amazonian history of the VBF [7-9]. Deconvolving modification of the VBF from primary depositional structures is essential to evaluating hypotheses regarding the presence of standing water in the northern plains of Mars during the Hesperian or Noachian [10-12]. Here we focus on HiRISE images [1, 13] of the northern plains to evaluate hypotheses for the origin and subsequent arrangement of boulder piles (basketball terrain [13]), lineated boulder piles (lineated basketball terrain), and crater-oriented boulder “halos” (Figure 1) [14, 15] in the VBF and surrounding units. We confine our analysis to 301 full-resolution HiRISE images, spanning latitudes 30-80°N, taken during orbits 001331 to 003595.

Boulder Origins: Mechanisms for the origin of boulder-sized clasts on the surface of Mars can be divided into processes which are hypogenetic (e.g., previously existing impact processes), syngenetic (e.g., outflow channel residue), or epigenetic (e.g., impact processing) with the emplacement of the VBF. We consider the latter two mechanisms.

Outflow Channel Residue. Flux rates of 10^9-10^{10} m^3/s have been calculated for peak Hesperian outflow flood events, which have been shown to drain into the northern plains [10, 16]. The VBF has been interpreted as a 100s of m thick sublimation residue of these flood events [16], suggesting that deposition of flood-carried boulders is possible. Such a syngenetic deposition of boulders is not consistent with the distribution of “boulder halos” (Figures 1-2), which are distributed between ~55-70°N in a circumpolar arrangement, and which is not spatially associated with outflow channels. This suggests that the boulders observed on the polewards portions of the VBF were not originally deposited by outflow flood events, although this does not preclude the distribution of finer particles across the VBF by outflow flood events [16].

Impact Processing. Impact-excavated boulders are common on the martian northern plains (e.g., VL2 Mie crater ejecta [17]). Boulders are commonly distributed in radial and discontinuously-concentric patterns in the northern plains boulder halos (Figure 1). This distribution has been interpreted as evidence that the boulders are proximal ejecta from buried impact craters [1, 14]. Small boulders (< 1 m) are commonly found in polygon troughs; large boulders are less well organized. Large boulders (> 4 m diameter) in boulder halos are commonly angular and tabular. Craters with well-formed boulder halos are commonly several hundreds of meters in diameter, suggesting that spallation fragments are gathered from tens of meters depth [18]. Polygonally patterned surface textures are largely uniform across boulder-halo craters, suggesting that the polygonally patterned VBF mantle covers the cratered surface relatively consistently. The presence of boulders overlying the crater-resurfacing VBF, coupled with the absence of secondary crater-like forms surrounding the boulders presents an apparent stratigraphic inconsistency: the boulders were generated by pre-VBF impacts, and are present overlying post-impact VBF. What process excavates and arranges VBF boulders? Are boulders excavated out of and deposited onto a surface that has lowered the boulders to their present configuration, or have the boulders been raised from their original stratigraphic level?

Boulder Arrangement: We evaluate three scenarios for boulder arrangement: a water-free end-member, a traditional liquid-water/active-layer end-member, and an intermediate, cold-desert processes scenario.

Water Free. In the complete absence water (solid or liquid), aeolian deflation, and the generation of a large-scale desert pavement, is the primary process for revealing boulders emplaced in the VBF. Such a process would require the complete planation of crater rims by aeolian erosion. Such a scenario could not explain the existence of lineated boulder piles.

Active Layer. The presence of a saturated active layer in cold environments on Earth both brings buried boulders to the surface and results in the sorting of rocky materials into geometric arrangements through the action of frost heave [19]. Active-layer conditions have been modeled for Mars on steep and warm slopes within the past 10 MY [20]; however, frost-heave can only be effective at bringing VBF boulders to the surface if the active layer penetrates several meters into the low-angle, resurfaced cratered unit (deep enough to access buried boulders at a variety of crater positions).

Cold Desert Processes. In the Upland Stable Zone of the Antarctic Dry Valleys (ADV), boulders are sorted into Mars-like configurations by cold-desert processes dominated by sublimation in conditions lacking a wet active layer [21]. In Mullins and Beacon valleys, sublimation of buried glacier ice, coupled with aeolian deflation, brings boulder-sized rock-fall fragments to the ground surface [21, 22]. Enhanced sublimation at polygon troughs, particularly at polygon triple-junctions, leads to over-steepening of polygon margins and the eventual sorting of large boulders into polygon troughs and junctions under the influence of gravity [23-25]. The repeated activity of such sublimation-dominated processes may explain the lineated and stippled arrangement of basketball terrain reported by [13]. We also consider small-scale liquid water-related processes that are insufficient to generate a wet, seasonal active layer, as have been observed in Beacon Valley. Localized melting of snow on surficial dolerite boulders during peak summer conditions generates thin films of liquid water which accumulate under boulders [21, 23]. Thin-film water infiltrates to shallow depths, refreezes, and rapidly sublimates, depositing efflorescent salts beneath boulders [21, 23]. Localized, surficial, and short-lived water-freeze-heaving, possibly coupled with localized salt heaving, could bring boulder- and cobble-sized clasts to the surface and prevent burial by subsequent subaerial deposition [24]. The historical presence of thin water films in the VBF is suggested by the presence of silica-rich alteration rinds on surface materials [25].

Conclusions: Motivated by HiRISE observation of arranged boulders on the VBF, we evaluate a spectrum of origin and arrangement mechanisms characteristic of historical and present Mars environments, as well as terrestrial analog environments in the ADV. We find that syngenetic emplacement of boulders through impact excavation, coupled with hypogenetic, cold-desert processing, occurring in the absence of a deep active layer, may be sufficient to produce and position boulders on Mars in the configurations they are observed.

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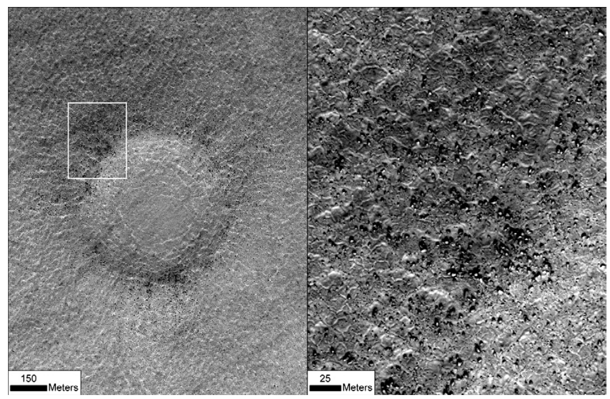

Figure 1. (Left) "Boulder halo" in northern plains of Mars (PSP_001477_2470). Crater is ~600 m in diameter, shows little topographic relief, and has an asymmetric distribution of radial and concentric boulders. (Right) Close-up view of boxed region. Boulders are concentrated in polygon troughs, and in polygon centers, suggesting arrangement by gravity-driven slumping, and persistence on low-slope polygon centers.

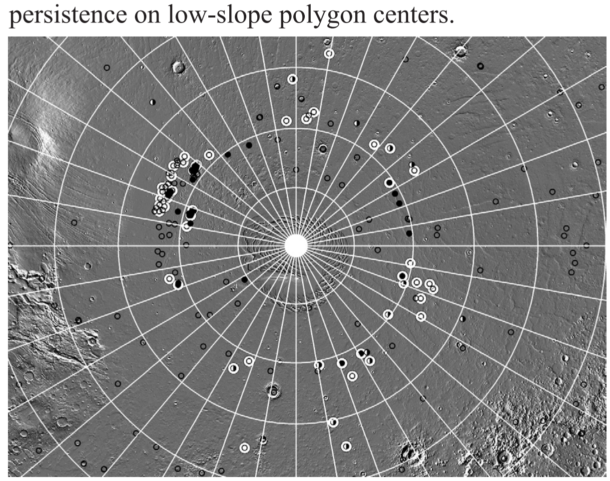

Figure 2. Polar-projection of martian northern hemisphere. White circles indicate boulder halos; black circles indicate basketball terrain; half-black circles indicate lineated basketball terrain; empty circles indicate survey images without these features.