VOLATILE-DRIVEN, DEFORMATIONAL AND RESURFACING ORIGIN FOR THE VASTITAS BOREALIS FORMATION ON MARS. K. L. Tanaka and J. A. Skinner, Jr., U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff AZ, 86001, USA, ktanaka@usgs.gov.

Introduction: The Vastitas Borealis Formation (VBF) makes up one of the largest map units on Mars, covering 17.6 x 10^6 km^2, or about 12% of the surface [1]. The VBF was mapped initially on the basis of its distinctive morphologic and albedo characteristics and its occurrence in the northern plains below the martian highland/lowland boundary (HLB) and boundary plains [2]. However, the origin of the VBF has proved to be controversial, owing to its many perplexing features.

Volcanic, tectonic, glacial, periglacial, and sedimentary related processes have been ascribed to various landforms encompassed by the unit [1-10 and references therein]. Mapping of putative shoreline features also followed in part the VBF contact [3]. Recently, Mars Orbiter Camera (MOC) narrow-angle (NA) images and Mar Orbiter Laser Altimeter (MOLA) topographic data have been used to study the unit [e.g., 4-5]. Perhaps receiving the most attention has been the marine sediment origin, because the VBF margin occurs mostly within a rather limited elevation range. Alternatively, we have suggested that the VBF resulted from volatile-driven reworking of earlier rocks [1]. Here, we examine distinct types of surface morphology within and surrounding the VBF and how they may bear on understanding of the origin of the VBF. These descriptions are generalizations, and cursory examination of the Mars Odyssey THEMIS images released in January 2003 reveals many complexities and variations in the expression of the VBF landforms.

VBF marginal morphologies: The margin of VBF can be mapped in most lower latitude areas (<40-50°N) by a slight increase in kilometer-scale roughness in MOLA data [1] relative to that of boundary plains material. In Viking visible wavelength and, better yet, in THEMIS daytime infrared images (DIR), two types of VBF marginal morphologies apparently produce the observed roughness: thumbprint ridges and sinuous trough-and-ridge systems.

Thumbprint ridges. These systems of concentric, arcuate ridges occur along the VBF margin and throughout most of Isidis Planitia (see map in [6]). Examination of MOC and THEMIS images show that they are more extensive than previously recognized; also, the pitted cones making up the ridges (where resolvable) appear to decrease in relief with increasing latitude, making them more difficult to detect [1]. The thumbprint ridges and inter-ridge plains form distinctive terrain having discreet margins, contrasting in albedo and thermal inertia with adjacent materials. In Deuteronilus, thumbprint terrain fills the lower troughs of the extensive fretted channels of that region [3]. The thumbprint terrain rises onto the trough margins across local relief of tens to >100 m.

In northwestern Utopia and Deuteronilus, the pitted cones have higher albedo than the surrounding plains. In Isidis, the associated plains are brighter in THEMIS DIR images than the boundary plains surface. The thumbprint terrain margin in places has a remarkably regular, lobate form and in some cases no discernible relief, mimicking the radii of curvature of nearby thumbprint ridges. In southern Utopia, inlier knobs of presumably older plains material are sparsely scattered within the terrain. Highly degraded craters are barely discernible within the thumbprint terrain, in many cases forming ring fracture systems, whereas degraded craters in boundary plains material preserve low rims and shallow, smooth floors.

Sinuous trough networks. Bounding much of the VBF are two types of sinuous trough-and-ridge networks: raised and inset. Both types have troughs roughly a kilometer or more in width, tens of kilometers in length, and tens of meters deep with a medial ridge usually too narrow and low to detect in MOLA data, but sharply defined in MOC NA and THEMIS DIR images. Raised trough networks form abrupt VBF margins a few tens of meters high in southern and northwestern Utopia and northeast of Alba Patera. Inset troughs occur in Acidalia, Arcadia, and Isidis Planitiae and include marginal scarps with concentric ridges respectively similar in form and relief to the troughs and medial ridges. Rarely, these ridges occur in multiple, closely spaced parallel or en echelon sets. Some ridges connect and rise onto knobs jutting above the plains. [8]

VBF interior morphologies: Where not buried by younger basin fill material, polygonal troughs form a distinctly rough surface in MOLA slope data in the lowest part of Utopia basin, in parts of Acidalia Planitia, and in the lower part of Borealis (north polar) basin surrounding Planum Boreum. Most polygonal troughs occur well within the VBF away from its margins. Viking and THEMIS images of the Utopia and Acidalia examples show the surface to include networks of narrow graben-like troughs. Some narrow, raised grooves occur with the troughs and have flows issuing from them [8]. Inlier knobs of older highland and plains materials are rare to absent. Pitted cones are sparse but appear larger than those associated with thumbprint ridges and tend to occur along troughs [8]. Between the polygonal troughs and marginal thumbprint ridges and sinuous trough terrain, the VBF surface appears to include a varying mix-

ture of subdued polygonal troughs and fractures, smooth plains, and patches of pitted domes.

Origin of VBF features involving ground volatiles: As mentioned earlier, the VBF landforms have a wide variety of proposed origins. Because (1) tectonic and resurfacing processes involving ground ice (and perhaps other subsurface volatile phases and compositions including liquid water, steam, and carbon dioxide) can be invoked for all of the common VBF morphologies and (2) the basin setting of the VBF suggests prolonged capture of ground water and clastic, fine-grained sediment prior to its formation [e.g., 1, 9], it seems reasonable to formulate mechanisms of VBF landform origin involving near-surface, volatile-rich material.

First, we note that boundary plains material between the HLB and the VBF displays extensive degradation. Surrounding the VBF, boundary plains material (unit Hb_2) appears to result from collapse and resurfacing of older boundary plains material (unit Hb_1) [1]. Degraded craters in the boundary plains have subtle rims and shallow floors. Apparently, a terrain softening process relaxed crater features. In addition, knobs with benches rise above the surrounding plains. In some cases, the knobs occur in patches surrounded by broad, shallow depressions. Those relations are suggestive of modest, local uplift of pre-existing knobby plains followed by collapse that produced the benches and depressions. This process may involve migration and injection of water, slurry, and/or icy material into areas where the cryosphere is relatively elevated, perhaps due to the effects of topography, material thermal conductivity, or local magmatic intrusion. Because similar knobs with benches and subtle crater and contractional ridge forms occur within VBF, it appears that the boundary plains resurfacing occurred throughout the expanse of VBF prior to development of VBF. This pre-VBF activity seems to have significantly subdued landforms hundreds of meters in relief and to have formed and enlarged isolated knobs.

Apparently, modification of plains bounding the VBF occurred during two stages of activity: (1) the Late Noachian/Early Hesperian and (2) the Late Hesperian, as indicated by the crater densities of the VBF bounding plains materials in Utopia Planitia [1]. Also, local mud volcanoes and flows and spring discharges onto the boundary plains may have developed in association with the second resurfacing stage.

VBF features typically show relief of tens of meters and, thus, contributed only moderately to landform destruction. Fields of scattered knobs extending from the boundary plains into the VBF appear slightly modified by post-Hb_2 degradation. Some knobs appear to have subdued bounding scarps, and some subtle wrinkle ridges and associated crenulations disappear where they enter the VBF from the bounding plains. Thus much of the plains contraction may have ceased during the Late Hesperian prior to VBF formation at the end of the Hesperian and into the earliest Amazonian.

Characteristic VBF features may have developed from further modification of a fairly homogeneous ice- and water-rich, loosely consolidated fine-grained material. Where this material is especially thick, such as in low-lying regions of the plains and infilled craters and channels, its gradual desiccation could have produced the polygonal troughs of the VBF. [10]. Discharges of water- and steam-charged clastic material may have produced the pitted cones and apparent fissure-fed flows as mud volcano emissions along trough-bounding faults [8]. Along the margins of most of the VBF and throughout the VBF in Isidis basin, water and/or CO_2 at shallow depths may have been prevalent. Perhaps induced by seismic shaking from impacts that led to liquefaction of water-saturated fines, the plains material deformed along arcuate zones that developed into the troughed and ridged morphologies. Discharges along these arcs may have been gas dominated leading to mud volcano cones without associated flows. This process may have been pervasive throughout thumbprint terrain, leading to its resurfacing by fine-grained material that accounts for the apparent low thermal-inertia of the ridged material in THEMIS DIR images. Modest plastic flow and local uplift, perhaps involving the subsurface movement of slurry, may have resulted in the suite of sinuous trough features.

Future work: We will continue to document and map VBF features and test and refine our interpretations as relevant new MOC NA and THEMIS and other Mars Odyssey data are released. In addition, we will further our examination of the adjacent plains and cratered highland materials surrounding the VBF to provide a better understanding of the VBF's geologic context and possible interplay with regional and local tectonism, volcanism, outflow-channel dissection, and other activity. We will also study the effects of later modification of the VBF evident in latitudes above 40-50°N. [e.g., 7].

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