THE SOUTHERN UTOPIA HIGHLAND-LOWLAND BOUNDARY: BASIN STRUCTURAL CONTROLS ON AQUIFER DEVELOPMENT AND VOLATILE-DRIVEN RESURFACING.

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Introduction: Erosion and burial have obscured, removed, or otherwise modified many exposures of the globe-encircling highland-lowland boundary (HLB) scarp and its downslope plains. Southern Utopia Planitia, however, consists of uninterrupted HLB plains that are notably absent of the subduing, overprinting, and/or obliterating effects of regional-scale sedimentary, volcanic, or tectonic environments [1,2,3]. The landforms of southern Utopia HLB and their geologic, stratigraphic, and geomorphic associations are therefore critical to understanding the evolution of the HLB plains overall.

Building on regional mapping efforts [1] and topical studies [2,4-6], we detail the landform suites that dominate the southern margin of Utopia Planitia. Based on our observations and interpretations, we propose that the southern Utopia HLB plains units were derived from and within a structurally isolated, basin-marginal sedimentary sequence related to the Utopia multi-ring impact structure [2,7]. The HLB plains were deposited and resurfaced via volatile-related processes through the Hesperian and into the Early Amazonian.

Southern Utopia HLB Study Outline: The arcuate southern Utopia HLB scarp and band of plains materials lies between the southwestern base of the Elysium rise and the saddle that separates Utopia and Isidis Planitiae. We characterize landform suites in this region using planimetric configuration, albedo, texture, superposition, embayment relationships, relative density, and spatial associations of regional geological units, structures, and physiographic features. Primary datasets for the study included THEMIS infrared images, the MOLA dataset (463 m/px resolution) and the MDIM 2.1 and MOC WA mosaics (250 m/px). Supplemental datasets included THEMIS visible (19 m/px) and MOC NA (m/px) images and the Barlow global crater catalog [6].

Results: Four landform suites dominate the southern Utopia HLB plains: fractured plains, mounds, cones and associated materials, and cavi.

Fractured plains: We identify 32 isolated or coalesced, positive-relief features with sub-circular outlines and narrow, curvilinear fractures oriented radial and sub radial to a central uplift. Individual fractured plains exposures are 2 to 50 km in diameter and have average areal extents of ~500 km^2. The individual fractures are 500 to 800 m wide, and the uplifted regions are <50 m above the adjacent, unfractured plains. A direct relationship exists between fracture width and uplift height. Larger exposures of fractured plains have diffuse, knobby, and moated margins. Fractured plains are clustered at the base of the Elysium rise at <-3000 m elevation and are concentrated in the Utopia 1 unit of Tanaka et al. [1,4], with smaller exposures located in the Utopia 2 unit.

Mounds: We identify 82 features with circular, planimetric shapes and slightly convex, mesa-like surfaces. Mounds are 10 to 200 m high (50 m mean) and 1.5 to 12 km wide (4 km mean) and commonly contain small, pitted cones at their centers. Some mounds have lobate edges. Mounds are clustered north and northwest of Nepenthes Mensae from -2464 to -3434 m elevation (-2921 m mean), and are most commonly adjacent to complex wrinkle ridges. Mounds are easily differentiated from mesas and highland plateaus based on their high albedo, planimetric form, central pitted cones, and characteristic association with ridge features. Some small mounds, particularly those not associated with structural ridges, are located in shallow, circular depressions. Mounds occur entirely in the Utopia 1 unit [1,4].

Cones and associated materials: We identify 82 cone- and crescent-shaped features with smooth, sloping sides and wide, central pits. The cones are commonly <300 m high and have basal diameters between 4 and 10 km (6.4 km mean); pit diameters range between 50 and 70% of base diameters. The elevation of the interior pits are at or above the surrounding plains; larger cones contain higher elevation pits. We also identify 26 isolated or coalesced occurrences of high-albedo material with subdued, lobate margins associated with the cones, particularly those with a crescent form. These exposures have a mean area of ~260 km^2 and commonly form on the downslope margins of their related cones. Cones and associated materials are clustered northeast, north, and northwest of Amenthes Fossae, and occur entirely in the Utopia 1 unit.

Cavi: We identify 113 isolated or coalesced depressions (cavi) with gently to steeply sloping, scalloped or knobby margins. Some cavi have narrow marginal fractures. Cavi are variable in areal extent, ranging from 10 to >7000 km^2 (~600 km^2 mean). The southern exposures are >300 m deep and have smooth, gently sloping margins, while the northern exposures are only tens of meters deep and are lined with knob fields. Cavi floors notably lack jostled blocks, fractures, or hummocks. Cones (and associated materials) and mounds are common on the southern, higher elevation margin of many cavi. Cavi line the Utopia 1-2 geologic contact [1,4-5] and occur in close proximity to the other three landform suites. The surfaces immediately downslope of the cavi (in Utopia 2 unit) are some of the smoothest on the planet [5,8].

Discussion: We interpret the landform suites as follows: Fractured plains are dilationally cracked, uplifted surfaces [9], mounds and cones and associated materials are sedimentary-volcanic vents and flows [10], and cavi are subsidence features [10-12]. These observations and interpretations lead us to two conclusions: (1) the studied features formed by volatile accumulation, pressurization, and extrusion, and (2) regional subsurface conditions permitted these processes to occur.

Volatile-driven processes: Volatiles likely accumulated in southern Utopia as the result of regional groundwater flow [13] driven by atmospheric condensation/precipitation onto the HLB plains, the adjacent highlands, and/or the Elysium volcanic construct [e.g., 14]. Cryospheric pumping related to Elysium volcanic activity may also have supplied volatiles to the region [14-15]. Pressurization of accumulated volatiles may have been caused (1) hydraulically, through slow recharge into an aquifer overlying a vertical and/or horizontal groundwater flow impediment (e.g., low-permeability basement) and/or (2) hydrostatically, from climate and/or geothermal-related permafrost growth/contraction or aquifer compaction. Differences in the surface manifestation of subsurface pressures (e.g., cracks, cones, or mounds) may reflect differences in aquifer thickness, amount of volatiles, or mobilization mechanisms. For example, cones and flows may represent active, continuous mud eruptions from a thick substrate during tectonic or seismic events [11]. Conversely, pancake-like mounds may represent passive, short-lived eruptions from a thin substrate during horizontal compaction of the subsurface [10]. The removal of pressurized fluids through mud volcanism probably caused the compaction of the volatile-depleted substrate and the subsidence of the surface into pits and cavi [11-12].

Southern Utopia basin-ring aquifer: We delineate the Utopia multi-ring impact structure by extrapolating a boundary through arcuate saddles that separate the Utopia basin from the Borealis and Isidis basins (see Fig. 7 [4]). Using the $D \bullet 2^{1/2}$ "spacing rule" (D=diameter) [15], we calculate potential basin rings with diameters of 1200, 2470, 3500, and 5000 km. The original Utopia multi-ring structure likely consisted of deep-seated, circumferential, normal faults bounding stable and unstable crustal regions and buried by impact materials (e.g., fall-out, breccias, and melts) [7,16]. Topographic and structural rings were subsequently eroded and buried [2,7]. An idealized cross-section of the multi-ring structure across the southern Utopia HLB includes normally offset crustal blocks bounding a southward dipping regional "half-graben" overlain by a northward thinning sedimentary sequence [7]. The volatile-driven landform suites and their distributions are consistent with the accumulation of a sedimentary wedge between the 2470 and 3500 km rings. The inner 2470-km ring is coincident with lowland knobs and small ring-fractures identified by McGill [2] and likely reflect the structural boundary overlain by thin, compacted, sedimentary deposits. North of the 2470-km ring, lowland sediments likely thicken, as evidenced by the abrupt decrease in knobby terrains and the onset of giant polygonal fractures [2]. The outer, 3500-km ring is roughly coincident with the HLB scarp and associated highland knobs and mesas and forms the outer structural boundary for the sedimentary sequence. The 100-200 km band of knobs in the vicinity of both rings may reflect the damage zone associated with the ancient normal faults formed during impact [7].

Conclusions: We propose that the southern Utopia HLB plains formed through the erosion of the Utopia multi-ring structure. Eroded materials accumulated between the 2470 and 3500 km rings, burying the regional half-graben with a wedge-shaped sedimentary sequence. These materials were likely porous and were deposited above a fractured, crystalline basement. The result was a high-permeability sedimentary aquifer overlying low-permeability basement rocks. Volatiles accumulated in this aquifer were hydraulically and/or hydrostatically pressurized and extruded onto the surface as mud slurries via sedimentary volcanism. The volatile-depleted reservoir subsequently collapsed, resulting in material compaction and smoothing.

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