LATE HESPERIAN-EARLY AMAZONIAN VALLEY NETWORKS, INVERTED CHANNELS AND SULFATES ON THARSIS: THE CONFLUENCE OF EXPLOSIVE ERUPTIONS, SURFACE SNOW/ICE AND "ACID RAINS".

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Summary: Anomalously young Late Hesperian (LH)-Early Amazonian (EA) valley networks and inverted channels on the Tharsis rise in the vicinity of the Valles Marineris (VM) rim are associated with layered sulfates and opaline silica deposits. We present a combined geological process-climate evolution model that accounts for these anomalous temporal and mineralogical characteristics through a confluence of explosive volcanism, enhanced H_2O and S species release, atmospheric alteration of tephra, formation of "acid rains", deposition on predicted high-altitude snow/ice deposits, and immediate melting and runoff to form dendritic fluvial channels that empty into Valle Marineris. This model is fully consistent with a cold climate environment, accounts for the observed features, and requires no LH-EA mean atmospheric temperatures (MAT) >273 K; we interpret these features to be a "false positive" for 'warm and wet' climates extending into the Amazonian.

Introduction: Mars geological and climate history, as summarized in 2009 [1], consisted of an early period of basin formation, a Late Noachian warm/wet period characterized by surface precipitation, runoff and phyllosilicate weathering, a transition from a LN climate optimum toward the current hyperarid/hypothermal conditions (enhanced Hesperian volcanism and outflow channel formation, and sulfate deposition) to the Amazonian (cold and hyperarid, and dominated by polar deposits, glaciation and an anhydrous Fe-oxide weathering environment).

However, the acquisition of high-resolution image, thermal, VIS/NIR, and altimetry data revealed new evidence for landforms attributable to water precipitation and surface runoff in areas outside those traditionally associated with Late Noachian-Early Hesperian (LN-EH) southern upland valley networks. Particularly striking are the dendritic valley and inverted channel systems in the Tharsis rise, near the rim of Valles Marineris (VM) and dated to the Late Hesperian-Early Amazonian (LH-EA) [2-7]. The dendritic valleys are sinuous, extend over tens of km, show a high degree of branching, some inner channels, and they extend down local slope, all characteristics interpreted to represent rainfall precipitation and sustained fluid flow over geologically long periods of time. Collectively, these LH-EA fluvial landforms have been interpreted to indicate a much more extended period of warm conditions conducive to atmospheric precipitation, runoff and associated sustained hydrologic activity [2]. In more areally comprehensive studies, [3] showed that the fluvial landforms observed on the Valles Marineris plateau were characterized by branching valleys with 20-100 m deep V-shaped profiles typical of fluvial processes and that their incision occurred in a thin (<150 m) and weak, dark unit overlying the volcanic plains plateau substrate. The valley network 2D planforms show drainage densities requiring a minimum of thousands of years, but the 3D valley geometry shows limited incision and lack of concavity, suggesting a limited development in time (e.g., millions of years of evolution are unlikely). In addition, fluvial valleys are modified by aeolian processes, often leading to the formation of widespread inverted channels observed throughout the region. Furthermore [4], the widespread mantle associated with these fluvial channels and inverted ridges on the plateau was shown to consist of light-toned layered deposits (LLD); layered beds show variations in brightness, color, polygonal fracturing, and erosional properties. The strong inverted channels/light-toned layered deposit correlation suggested [4] an association with precipitation, fluvial-lacustrine processes, and surface water flow in the Tharsis VM region extending well into the Hesperian (3.7–3.0 Gyr).

Subsequent analysis [5] documented the 30–80 m thick light-toned layered deposits on the plateaus adjacent to Valles Marineris at five locations: all showed associated valleys and inverted channels and the associated beds display unique variations in brightness, color, mineralogy, and erosional properties (not typically observed in LLDs within adjacent VM); stratigraphic relations showed that fluvial activity occurred post-VM chasmata formation. Reflectance spectra reveal that these deposits contain Fe-sulfates and opaline silica, associations consistent with low-temperature, acidic aqueous alteration of basaltic materials. Weitz et al. [5] concluded that "although the source of water and sediment remains uncertain, the strong correlation between fluvial landforms and light-toned layered deposits argues for sustained precipitation, surface runoff, and fluvial deposition occurring during the Hesperian on the plateaus adjacent to Valles Marineris and along portions of chasmata walls."

The presence of H_2O- and SiOH-bearing phases [6], most consistent with opaline silica and glass altered to various degrees, and associated hydrated Fe sulfates, including H_3O-bearing jarosite, was further documented in the finely stratified deposits (LLD) exposed on the plains surrounding the VM canyon system and the VM floor. Milliken et al. [6] concluded that "The great lateral extent of the opaline- and Fe sulfate–bearing strata surrounding Valles Marineris, the interpreted mineralogy in its stratigraphic context, and the local and regional morphology are evidence for regionally extensive, acidic, low temperature aqueous alteration during the late Hesperian and possibly Amazonian."

In summary, could the presence of these extensive valley network/inverted channel systems, their associated LLDs and the mineralogic evidence for regionally extensive, acidic, low temperature aqueous alteration be related to an extension of warm and wet (MAT >273 K) ambient conditions, rainfall, aqueous alteration and runoff extending from the Noachian into the Late Noachian and Amazonian [7]? In this scenario, the presence of sulfates and opaline silica is interpreted to be related to the alteration of underlying basaltic bedrock making up the EH Tharsis plains veneer. However, among the conundra are: 1) the apparently short time of fluvial activity [3], 2) the lack of an erosional source region for the LLD sediments, 3) the difficulty in maintaining an ambient warm and wet >273 K climate into the Amazonian [8], 4) the close association of the array of unusual features in the LLD, 5) the huge volume of ILD sulfates and the lack of a complementary sufficiently large and long-lasting sulfur/amorphous silica alteration source environment, and 6) the superposition of the LLD and fluvial channels on top of the plains, not emerging as groundwater altered by long residence in a geothermally warm subsurface basaltic substrate [9].

An Alternate Hypothesis: Here we recap the Hesperian geological history and climate conditions in the Tharsis region in order to provide a framework to search for plausible interpretations of these anomalously young fluvial features and unusual associated sulfate-opaline silica LLDs, that might resolve some of these conundra, and not require the presence of a highly anomalous warm and wet climate in the LH and into the Amazonian. In the LH, Tharsis is the highest region on Mars [10], has recently been resurfaced by EH regional volcanic plains (e.g., Lunae Planum) [10], VM has tectonically opened and deepened [10], the ambient climate is thought to be well below 273 K on the basis of Tharsis' extreme altitude [8], as well as geological evidence [11-13], and Tharsis is interpreted to be a depocenter for snow and ice (a third pole) [8] prior to the time that Mars' global temperatures becomes primarily latitude-dependent due to P_{atm} decay [14]. Tharsis Montes/Alba Patera central volcanic eruptions continue [10] and explosive eruptions are common [15]; the low P_{atm} associated with Tharsis' altitudes optimizes H_2O and sulfur species gas release, bubble growth and magma disruption [16], all favoring plinian co-eruption and dispersal of hot, fine-grained ash, SO_2, and H_2O [17]. Can these combined characteristics provide a mechanism to account for the unusual nature and timing [2-7] of the anomalous LN-EH fluvial features and LLDs?

We now describe an eight-stage model to compare with observations: 1) The low P_{atm} of the high-altitude Tharsis environment favors co-eruption and dispersal of SO_2, H_2O and hot fine-grained tephra [17]; consequent admixture of tephra water and sulfur creates acid species that can precipitate in a variety of forms [18-19] and fall to the surface to create deposits of sulfur-rich, fine-grained layered mantle containing altered opaline silica-rich ash. 2) Interactions of the precipitates and predicted surface snow and ice deposits overlying the EH volcanic plains cause immediate and rapid surface melting and production of meltwater composed of a sulfur-rich acid solution with a depressed melting temperature [19]. 3) Meltwater generated by this ash-acid precipitation process immediately begins to collect on the ice deposits and flow down regional slopes toward local lows, creating dendritic networks of channels, eroded into existing layered snow/ice and altered ash deposits from previous events. 4) Sulfur-rich meltwater streams and altered ash sediments empty into VM, drain to the floor, and pond to form layered sulfate deposits; evaporated water vapor returns to regional cold traps. 5) Acid precipitation events are largely governed by plinian eruption durations, plume dispersal patterns [20], and eruption intermittencies; resulting fluvial events are largely governed by the distribution and thickness of surface snow/ice, and local/regional drainage pathways. 6) The relatively fixed volcanic sources [10], and longevity of the regional Tharsis cold trap [8], suggest that these processes can occur episodically over long geological periods; fluvial networks, once formed, are likely to be reactivated. 7) Tharsis plinian activity continues intermittently throughout the LH-EA, perhaps accounting for the voluminous and thick accumulations of Interior Layered Deposits (ILD) on the VM floor [23]. 8) Amazonian loss of Tharsis surface ice to the poles [14], assisted by eolian activity, serves to remove the LLD and expose inverted channels, revealing the entire array of fluvial features and deposits observed today.

Synthesis: This model provides a plausible, testable explanation for the combination of fluvial features observed in the LLD that might otherwise seem to require a warm and wet ambient Late Hesperian-Early Amazonian climate with MAT >273 K. In the context of the hypothesis presented here, the LH-EA fluvial activity represents a "false-positive" [22] for a late stage "warm and wet" Mars climate.

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