THE NOACHIAN-HESPERIAN TRANSITION ON MARS: GEOLOGICAL EVIDENCE FOR A PUNCTUATED PHASE OF GLOBAL VOLCANISM AS A KEY DRIVER IN CLIMATE AND ATMOSPHERIC EVOLUTION.

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Summary: A peak volcanic flux centered in the early Hesperian erupted sufficient sulfur to cause short-term warming of the atmosphere, leading to basal melting of the south polar cap, formation of lower latitude valley networks and open-basin lakes, and a transition to sulfur-dominated weathering. The aftermath included dehydration, global cooling, change in weathering style and permanent reorganization of the hydrologic cycle to horizontally stratified in the Amazonian.

Introduction: The transition from the Noachian to the Hesperian periods of Mars history [1, 2] is known to involve changes in many characteristics of the planet including: *geological* (e.g., decrease in cratering flux [3] and valley network formation [4-6], changes in distribution, rates [1], and styles [7] of volcanism and tectonism [8]); *mineralogical* (e.g., changes in mineralogy and weathering/alteration style from phyllosilicates to sulfates [9]); and *climatological*/*glaciological* (e.g., [10]; change in the south circumpolar cap [11]). Here we assess the role of one specific observed phase, the emplacement of early Hesperian volcanic deposits [1, 2], as a dominant factor in the Noachian-Hesperian transition and in the evolution of the atmosphere.

Early Hesperian Volcanism: Geological mapping [1] (Fig. 1) and chronology [3] have led to an outline of the major phases of the history of Mars [1, 2] (Fig. 2). Using areas covered by units and their thickness, volumes have been calculated and time scales assessed to estimate the fluxes represented by volcanic processes, showing that there was a peak in the volcanic flux in the early Hesperian [1], before a continuing downward trend to the present. What are the geologic units associated with this peak? 1) *Flood-basalt-like plains volcanism*: The most prominent unit emplaced was Hesperian Ridged Plains (Hr) occurring within and outside craters throughout the uplands plateau area and in some lowland plains regions. Hr was interpreted [1] to be extensive lava flows erupted with low viscosity from many sources at high rates. Another significant concentration of Hr is in the Tharsis region of Mars, a huge broad 10 km-high dome (Fig. 1). The southeast (Thaumasia) and eastern (Hesperia Planum) parts of Tharsis are clearly formed of Hr, as are other portions on the flanks and surrounding Tharsis, that underlie the younger Amazonian-aged lavas [1]. Altimetry data revealed that extensive deposits of Hr underlie the Vastitas Borealis Formation in the northern lowlands, and Utopia, Isidis and Hellas basins [12]; recognition of these deposits increased the area of Mars volcanically resurfaced during the early Hesperian to ~30%. Using average thicknesses, the volume of Hr was estimated to be ~3.3 x 10^7 km^3. Effusion rates comparable to those of terrestrial flood basalts (10^5-10^6 m^3/s) were estimated from narrow 600-700 km-long dike-like ridges closely associated with Hr [13]. 2) *Central source complexes*: Central source regions (paterae) also characterize Hesperian volcanism (e.g., Hadriaca, Tyrrhena, Apollinaris, and Alba Paterae and Syrtis Major) [14-16]. These low-lying edifices and associated plains complexes are widely interpreted to have a significant explosive/pyroclastic component [17-19]. 3) *Plinian eruptions and regional pyroclastic deposits*: Fine-grained mantling units, interpreted to be related to pyroclastic airfalls erupted from the centers of volcanism or other now-buried vents, are widespread [1]. Analysis of the ascent of magma to produce plinian eruptions [20, 21] and assessment of atmospheric general circulation models [22] shows that erupted gases were voluminous and tephra deposits widespread. 4) *Subsurface dike emplacement*: Documentation of long, wide, eroded dikes associated with Hr [13], as well as huge radial graben systems surrounding Tharsis (interpreted to be radial dike swarms, surface manifestations of magma-filled cracks formed by the radial intrusion of dikes from central mantle-fed reservoirs [23]), adds a volumetrically very significant component to the volume of gases emplaced during this period [24].

In summary, early Hesperian volcanism was characterized by the resurfacing of >30% of the planet and involved flood-basalt-like effusion rates and plinian eruptions emplacing large quantities of gases and tephra

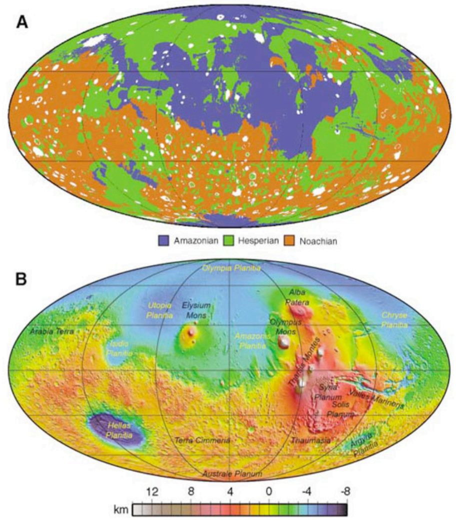

Fig. 1. Ages of surface units (a) and topography (b) of Mars [33,34].

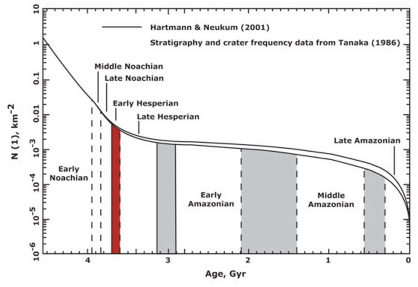

Fig. 2. Mars cratering chronology [3].

into the atmosphere, and large-scale intrusion of voluminous dikes in the crust, all during a geologically very short period of time (Early Hesperian is thought to have had a duration of ~100 million years; Fig. 2).

Estimates of Flux and Input into the Atmosphere: What effect would this peak of early Hesperian volcanic and magmatic activity have on the atmosphere? Analysis of the composition of samples of Hr by the Spirit rover in Gusev crater [24-26], and modeling of its behavior during melting and eruption, show that significant sulfur volatiles would be released into the atmosphere by eruption of magmas with Hr composition [24]. Geologic data show that a significant portion would be delivered directly into the atmosphere by plinian [21] and flood-basalt [13] eruptions and that vast quantities would continue to be added by degassing of the feeder dikes [23, 24]. Is the flux of magma sufficient to cause changes in the atmosphere from such eruptions? In previous work [27], Tharsis was estimated to contain 3 x 10^8 km^3 of solidified magma largely emplaced by the end of the Noachian; averaged over the entire Noachian, this flux was thought to be insufficient to have caused significant warming, due the low averaged input rate (Fig. 2) and the relatively rapid decay of sulfur species in the atmosphere [24]. However, as described above, a significant part of Tharsis was resurfaced during the early Hesperian [1, 2], particularly by Hr (Fig. 1), perhaps to depths of several km. The additive volume of volatiles associated with 1) Hr flood basalts, 2) central paterae eruptions, 3) direct plinian eruptions into the atmosphere, and 4) massive intrusive dike complexes, suggest that sufficient volumes of SO_2 and H_2S would be degassed into the atmosphere in a short enough time period (Fig. 2) to cause greenhouse warming [24, 28] for a sustained period or during multiple phases.

Role of Hesperian Volcanism in Global Climate Change: A very plausible case can be made for the presence, in the late Noachian, of an ~50 to 500 mbar CO_2 atmosphere [24, 29]. Typical conditions in this setting would be extremely cold polar temperatures and mean annual equatorial temperatures below freezing. What effect would the peak of volcanic activity have on this atmosphere and the evolution of the climate? Johnson et al. [24] investigated the effect of sulfur volatile influxes on background atmospheres of 50 to 500 mbar CO_2 with varying abundances of water and sulfur volatiles. They found that sulfur volatile influxes alone could have caused greenhouse warming by up to 25 K above that caused by CO_2 alone; surface temperatures could have been raised above the freezing point for brines and transient liquid water in equatorial and mid-latitude regions.

Correlated geological activity: Is there geological evidence (Fig. 1) for events that might be linked to the predicted levels [24] of sulfur-related greenhouse warming? 1) Valley networks (VN), accepted as evidence for the flow of liquid water on Mars, generally ceased forming near the Noachian-Hesperian boundary [4] and may have peaked in their formation at that time. Open-basin lakes (OBL) [5] linked with VN are often embayed by Hr, placing their formation in close association. 2) Bibring et al. [9] proposed that the mineralogy of surface alteration generally correlates with time (Noachian-phyllosilicates, Hesperian-sulfates); they envisioned that late Noachian-Hesperian volcanic outpourings and associated volatile release could have emplaced sulfur that rapidly oxidized to produce H_2SO_4 and created multiple acidic surface environments conducive to extended sulfate deposition. This period was followed by a decrease in the abundance of liquid water, lowering of surface temperatures, and a dominance of Amazonian weathering styles. 3) Basal melting of the south-circumpolar ice sheet (Dorsa Argentea Formation; DAF; [11]) near the Noachian-Hesperian boundary [30], suggests that the temperature of the atmosphere was raised by ~25-50 °C [31] during this period, sufficient to cause basal melting and esker formation, but not enough to cause top-down ice cap melting.

An Integrated Geological Scenario for the Noachian-Hesperian Transition and Implications for the Evolution of Climate: Peak Hr-related volcanism centered in the early Hesperian is interpreted to have caused sufficient global warming of a 50-500 mbar CO_2 atmosphere during a period of the order of 100 Ma, to create elevated surface temperatures in the mid-latitudes and equatorial regions of Mars. This resulted in melting of snow and ice deposits to form valley networks and open basin lakes [4,5]; mean annual temperatures at the South Pole were elevated sufficiently to cause basal, but not top-down, melting [31]. During this period, acidic aqueous surface environments produced extensive sulfate deposits [9, 32]. Water was removed from the atmosphere and surface environments by percolation into the water table, incorporation into precipitated minerals and, toward the end, freezing into a growing cryosphere. The aftermath of this phase involved dehydration, global cooling, a change in weathering style and permanent reorganization of the hydrologic cycle into a global horizontally stratified configuration, all of which defined the Amazonian.

References: 1. K. Tanaka et al., *Mars*, Arizona, 11, 1992; R. Craddock and R. Greeley, Icarus, 204, 512, 2009; 2. M. Carr and J. Head, *EPSL* 294, 185, 2010; 3. W. Hartmann and G. Neukum, *SSR*, 96, 165, 2004; 4. C. Fassett and J. Head, *Icarus* 195, 61, 2008; 5. C. Fassett and J. Head, *Icarus* 198, 37, 2008; 6. B. Hynek et al., *JGR* 115, E09008, 2010; 7. R. Greeley and P. Spudis, *RGSP* 19, 13, 1981; 8. T. Watters, *JGR* 98, 17049, 1993; 9. J.-P. Bibring et al., *Science* 31, 400, 2006; 10. F. Fanale et al., *Mars*, Arizona, 32, 1992; 11. J. Head and S. Pratt, *JGR* 106, 12275, 2001; 12. J. Head et al., *JGR* 107, 5003, 2002; 13. J. Head et al., *Geology* 34, 285, 2006; 14. M. Robinson et al., *Icarus* 104, 301, 1993; 15. M. Ivanov and J. Head, *JGR* 111, E09003, 2006; 16. H. Hiesinger and J. Head, *JGR* 109, 1004, 2004; 17. R. Greeley and D. Crown, *JGR* 95, 7133, 1990; 18. D. Crown and R. Greeley, *JGR* 98, 3431, 1993; 19. T. Gregg and M. Farley, *JVGR* 155, 81, 2006; 20. L. Wilson and J. Head, *RG* 32, 221 1994; 21. L. Wilson and J. Head, *JVGR* 163, 83, 2007; 22. L. Kerber et al., *LPSC 41* 1006, 2010; 23. L. Wilson and J. Head, *JGR* 107, 2002; 24. S. Johnson et al., *JGR* 113, E08005, 2008. 25. R. Gellert et al., *Science* 305, 829, 2004; 26. H. McSween et al., *JGR* 111, EO2S10, 2006; 27. R. Phillips et al., *Science* 291,2587, 2001; 28. A. Halevy et al., *Science* 318, 1903, 2007; 29. F. Forget et al., *DPS*, 2010; 30. A. Kress et al., *LPSC* 40, 2009; 31. J. Fastook et al., *LPSC* 42, 2011; 32. A. Gendrin et al., *Science* 307, 1587, 2005; 33. S. Solomon et al., *Science* 307, 1214, 2005; 34. J. Head, http://www.largeigneous provinces. org/06july.html, 2006.