ATMOSPHERIC AND HYDROLOGICAL CYCLES ON MARS RELATED TO THARSIS SUPERPLUME.

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Introduction.

Throughout the recorded history of Mars, liquid water has shaped its landscape into a number of distinct morphologic types, including prominent features such as the circum-Chryse and the northwestern slope valleys outflow channel systems, and the extremely flat northern plains topography at the distal reaches of these outflow channel systems. Paleotopographic reconstructions of the Tharsis magmatic complex in the western hemisphere of Mars have revealed the existence of an enormous Noachian drainage basin/aquifer system in eastern Tharsis. The basin is proposed to source the magmatic-triggered outburst floods that sculpted the outflow channel systems, entrained boulders, rock, and sediment during passage, and ponded to form sequentially through time various hypothesized oceans, seas, and lakes. These events, which are largely the result of major pulses of Tharsis Superplume activity, generate volatile elements enough to saturate the atmosphere and to cause temporary (~tens of thousands of years) climatic/environmental excursions from prevailing cold and dry desert conditions (Baker *et al*., 2001). Other climatic-change contributors may include magmatic-driven activity at Elysium rise, especially during the Hesperian and Amazonian Periods (e.g., Skinner and Tanaka, 2001). As the volatile and water supply of the Noachian Tharsis basin/aquifer system is thought to have dwindled over time with each endogenic-driven flood event, water bodies inundating the northern plains and atmospheric thicknesses are expected to be progressively smaller with time. Thus, liquid water on the northern plains of Mars could have developed a great Noachian-Early Hesperian ocean, a secondary and reduced Late Hesperian sea, and a number of widely distributed minor lakes through Amazonian time, even in almost contemporary epochs; all related to denser atmospheric conditions and more clement periods.

Tharsis-triggererd atmospheric and oceanic cycles on Mars.

Basing on the ideas of episodic greenhouse atmosphere and water stability on the lowlands of Mars (Baker *et al.,* 1991), a conceptual scheme for atmospheric gases and water evolution can be proposed. We follow paleotopographic reconstructions of the Tharsis magmatic complex (recently referred to as Superplume; Baker *et al*., 2002) in the western hemisphere of Mars, which have revealed the existence of an enormous Noachian drainage basin/aquifer system in eastern Tharsis. The basin is proposed to source the magmatic-triggered outburst floods that sculpted the circum-Chryse and NSVs outflow channel systems (Dohm, *et al*., 2001b), entrained boulders, rock, and sediment during passage, and ponded to form sequentially through time various hypothesized oceans, seas, and lakes in the northern plains (e.g., McGill, 1985; Jöns, 1986; Parker *et al*., 1987, 1993; Baker *et al*., 1991; Scott *et al*., 1995; Head *et al*., 1999) and glaciers and rock glaciers and lacustrine environments such as in the southern hemisphere (Kargel and Strom, 1992; Cabrol and Grin, 1999; Head and Pratt, 2001; Baker, 2001) .

Our model would include a continuous Middle Noachian to Early Hesperian first greenhouse and oceanic epoch; the main water body would cover the lowlands (best portrayed by the north-south crustal dichotomy or Contact 1 of Parker *et al*., 1987, 1993 and Head *et al*., 1999; see Fairén and de Pablo, 2002) or about 1/3 of the planet's surface area for at least 500 m.y. This primitive ocean would have been maintained by two alternative but non mutually excluding processes (perhaps cooperative): [1] by the early continuous development of the Tharsis Magmatic Complex (stages 1-3, see Anderson, *et al*., 2001; Dohm, *et al*., 2001b); and/or [2] by a process of carbonate recycling in a primitive plate tectonic regime (e.g.: Condie, 1989; Sleep, 1994; Dohm, *et al*., 2002). In any case, at its earlier stages, both martian atmosphere and hydrosphere should have been protected by a planetary magnetosphere due to the activity of an inner planetary magnetic dynamo. A cold and dry intermediate period followed the first oceanic epoch, perhaps related to a transient pause of the Tharsis development and/or to the definitive cessation of plate tectonism. Renewed activity at the Tharsis Superplume resulted in the formation of Late Hesperian ocean, which would have extended over the deeper areas in the lowlands inset within the boundary of the first great ocean (Contact 2); the source of water, which enhanced the pre-existing circum-Chryse outflow channels and released CO_2 and other volatiles into the atmosphere, stems from significant effusive volcanic activity at Tharsis (stage 4, see Dohm, *et al*., 2001b). This Late Hesperian water body may have diminished into smaller seas and/or lakes. –During the Amazonian Period, renewed activity at Tharsis (Dohm *et al*., 2001b) and Elysium (Skinner and Tanaka, 2001; Pounders, *et al*., 2002) resulted in brief excursions from the prevailing cold and dry climatic conditions to form minor seas or lakes.

Tharsis superplume activity.

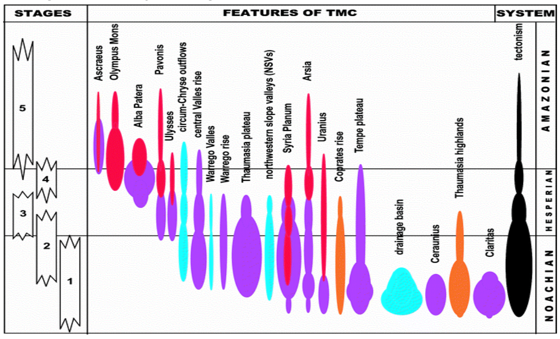
In our model, the Tharsis Magmatic Complex (TMC)/Superplume development, which includes pulses of magmatic-driven hydrological activity, directly influences the evolution of subsurface and surface water as observed in geological and paleohydrological records (Figures 1-4). This model highlights Tharsis-triggered flood inundations and their direct impact on shaping the northern plains, as well as making possible the existence of fossil and/or extant life. Figure 1 reflects Stage information of Anderson *et al.* (2001) and Dohm, *et al.* (2001b,c).

Noachian to Early Hesperian (Stages 1-3): First great ocean.

Incipient development of the Tharsis magmatic complex during the Middle Noachian (Dohm *et al*., 2001b; Anderson *et al*., 2001) to possibly the Early Hesperian

(Stages 1-3 of Dohm *et al.*, 2001b) (Figure 1) resulted in the first inundation, an ocean that would have covered the northern plains (approximately 1/3 of the total surface area of Mars, see figure 2).

Figure 1: Major stages in TMC development.



Dohm, *et al.* (2001b) show evidence that collectively indicate that the Tharsis magmatic complex began to form sometime around the Middle Noachian with significant pulses of magmatic-driven activity during Stages 1-3, including the growth Arsia, Syria Planum, and central Valles Marineris rises, which are interpreted to be centers of magmatic-driven tectonism, volcanism, dike emplacement, local hydrothermal activity, and associated NSVs and circum-Chryse outflow channel activity. The development of Thaumasia plateau and the emplacement of intercrater materials, which are interpreted to be the result of phreatomagmatic explosions such as in the Valles Marineris region where magma/water/water-ice interactions have been proposed (Chapman *et al.*, 2001), and older wrinkle ridged materials interpreted to represent deformd lava plains (Dohm *et al.*, 2001c), may have also been influential on outflow channel activity and related flood inundations during Stages 1-3 (Dohm *et al.*, 2001a-c).

Mars may have had a magnetic field during the first pulse of TMC activity, since one of the oldest and most dominant Noachian centers of activity, Claritas rise (Anderson *et al.*, 2001), spatially corresponds with a magnetic anomaly (Acuña *et al.*, 1999). In addition, plate tectonism may have been in operation during the Early Noachian into the Middle Noachian contributing to the formation of the northern plains (Fairén *et al.*, Icarus—in press; Baker *et al.*, 2002). If at least the first pulse of TMC magmatism accompanied plate tectonism, then the northern lowlands' landscape could have resulted from seafloor spreading (lasting from about 4.4 - 4.3 to approximately 3.8 – 3.7 Gy; Sleep, 1994); and possible carbonate recycling would have accounted to the reinjection of large amounts of CO_2 into the atmosphere, as it happens in Earth (Fairén *et al.*, 2002). Therefore, until at least Middle Noachian, the Martian atmosphere could have been much thicker than at present, capable of sustaining a considerable and long-standing liquid water-mass. Without the magnetic field protection during the Late Noachian (Stage 2), the atmospheric erosion rate would have increased. Surface water stability, however, could have been possible during hundreds of million of years (Lundin, 2001). Subducted hydrous material of the lithosphere could have represented an ample supply of water for later Tharsis volcanism, and its water release to subsequent seas and/or lakes (Baker *et al.*, 2002, Nature—in press). At the end of this stage (~Middle Noachian), plate tectonism ceased, some time following the termination of the planetary dynamo (Baker, *et al.*, 2002; Fairén, *et al.*, 2002). Also, if Mars really passed through a plate tectonic phase, its termination would have contributed to a break-up of the atmospheric equilibrium between adding and retiring carbonates; the result would be thinner, dryer and colder atmospheric conditions. The ocean would thus have been ice-covered during Late Noachian (Parker, *et al.*, 1993).

When compared to today's conditions, water and gases released during such Tharsis Superplume activity could have resulted in thicker post-heavy-bombardment atmospheric conditions. The first inundation originated from a highly productive aquifer system (Figure 1), and may have occurred when environmental conditions were more clement; the oceanic environment of the initial Oceanus Borealis may have persisted from the Middle Noachian to Early Hesperian related to episodic, pulsating Tharsis superplume activity. For example, an amount of ~$3x10^8$ km^3 of magmas has been proposed as the total release of Tharsis rise at Noachian time, and their volatile content would have produced the equivalent of 1.5-bar CO_2 and a global layer of water of 120 m thickness (Phillips, *et al.*, 2001). Water could so have extended over the lowlands during hundreds of millions of years (e.g., Clifford and Parker, 2001), while rainfall retired CO_2 from atmosphere and Tharsis reposed.

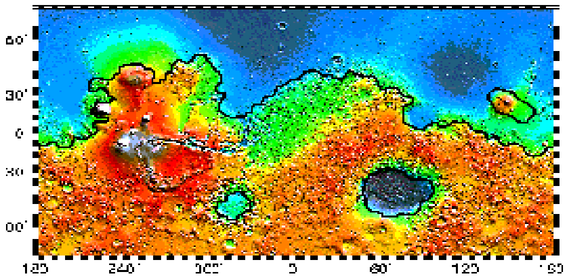


Figure 2: Possible shoreline profile of the first great martian ocean.

This initial inundation is best approximated by Contact 1 (Parker *et al.*, 1993). This primitive ocean would have been maintained by two alternative but non mutually excluding processes (perhaps cooperative): (1) continuous development of the Tharsis Magmatic Complex (stages 1-3, see Anderson, *et al.*, 2001; Dohm, *et al.*, 2001b), and/or (2) carbonate recycling in a primitive plate tectonic regime (e.g.: Condie, 1989; Sleep, 1994; Baker et al., 2002; Dohm, *et al.*, 2002; Fairén *et al.*, Icarus—in press). In any case, at its earlier stages, both the Martian atmosphere and hydrosphere should have been protected by a planetary magnetosphere due to the activity of an inner planetary magnetic dynamo.

An Early Hesperian pulse of Tharsis activity, which includes further development of the Arsia, Syria Planum, central Valles Marineris rises and Thaumasia plateau, may have triggered more flood waters to the northern plains adding to the potentially already existing northern plains ocean and/or ice body/ground ice. As the new floodwaters washed over the northern plains, the additional heat may have melted the upper layers of ice and the gradients created would allow the melt water to cycle into the hydrologic system (Baker *et al.*, 1991; Dohm *et al.*, 2001a). This third major pulse of TMC activity may have contributed enough CO_2 and other volatiles to the atmosphere to induce a short-lived (approximately tens of thousands of years; Baker *et al.*, 1991; Baker *et al*, Nature—in press) climatological perturbation.

Late Hesperian (Stage 4): The last Martian ocean. A dry period may have followed the Early Hesperian inundation as a result of a transient pause of the Tharsis development. The first clear discontinuity in TMC development is observed between stages 3 and 4 when Thaumasia Plateau was definitively established (Figure 1). Subsequently, a significant pulse of Late Hesperian volcanism within the Tharsis magmatic complex triggered yet more floodwaters that incised Chryse and other circum-Chryse outflow channels (e.g., Milton, 1974; Baker and Milton, 1974; Scott and Tanaka, 1986; Rotto and Tanaka, 1995; Scott *et al*., 1995; Nelson and Greeley, 1999) and Mangala Valles (e.g., Scott and Tanaka, 1986; Craddock and Greeley, 1994; Scott *et al*., 1995) and ponded in the northern plains to form a sea in the deeper recesses in the lowlands (Contact 2), inset within Contact 1 (figure 3). The water, CO_2, and other volatiles released during this stage of significant Tharsis-related effusive volcanic activity (stage 4, see Dohm, *et al*., 2001b) may have produced a greenhouse atmosphere. Thus, this new pulse of Tharsis magmatism may have been linked to the origin of the secondary, inset and transient ocean during the Late Hesperian (the tie proposed for Contact 2—Clifford and Parker, 2001). In its later stages, it is also possible that this hemispheric water-mass turned into a mud ocean (Tanaka and Banerdt, 2000) or froze (Carr, 1996), or progressively diminished into small seas or lakes.

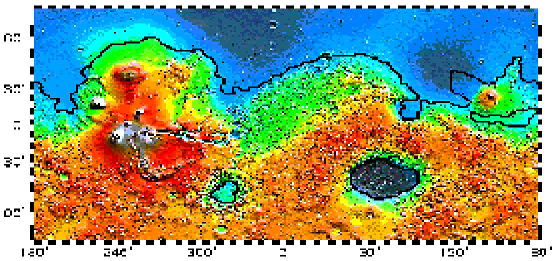


Figure 3: Possible shoreline profile of the secondary and lower martian ocean.

In addition, if plate tectonism really occurred, its definitive standstill would result later in a massive heat accumulation in precise locations under the Martian crust. So, significant volcanic activity would be expected in Tharsis just after the cold and dry transient episode; such Late Hesperian activity is recorded in the early development of the giant shield volcanoes, Olympus Mons, Alba Patera and the Tharsis Montes during Satge 4 TMC development (Dohm, *et al.,* 2001b). The absence of such pre-Tharsis (pre-stagnant lid regime; Sleep, 1994) centralized volcanic giants suggests that the planetary interior's heat dissipation was more distributed such as during a pre-Tharsis Superplume plate tectonic phase (Early into Middle Noachian). But note that plate tectonism is not essential for the ideas stated here, because Martian hydrological cycles would have been driven by magmatic and tectonic activity at the Tharsis Magmatic Complex, and perhaps other vent areas such as at Elysium rise and major dislocations in the Martian lithosphere/crust (e.g., Hellas impact-induced dislocations, which magmas used as conduits to reach the Martian surface to form Hadriaca Patera).

Amazonian (Stage 5): Temporary lacustrine environments.

Finally, generally cold and dry desert conditions during the Amazonian were punctuated by small outflow releases such as at and near Mangala Valles and the channels systems that debouch into Utopia basin from the northwestern flank of Elysium rise, Hrad, Apsus, Tinjar, and Granicus Valles (Greeley and Guest, 1987; Skinner and Tanaka, 2001) to form a number of minor transient seas or lakes (figure 4). Various isolated pulses of Tharsis magmatism are document for the Amazonian Period (e.g., Scott and Tanaka, 1986; Greeley and Guest, 1987; Anderson *et al*., 2001), including the continuous growth of Olympus Mons, Alba Patera and the Tharsis Montes shield volcanoes. Late-stage Elysium Mons activity during the Amazonian (Skinner and Tanaka, 2001; Pounders, *et al*., 2002) also may have contributed to release carbonates and water into atmosphere.

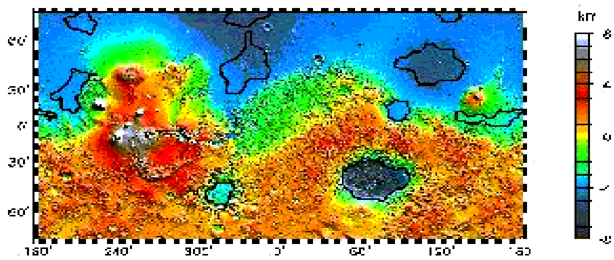


Figure 4: Amazonian paleolake shorelines on the martian lowlands.

Nevertheless, the long-term decline in planetary heat flow and sequestering CO_2 in carbonates and the progressive trapping of H_2O into clays in the cryosphere would have greatly depleted the original inventory of groundwater. This could well explain the apparent decline in outflow channel activity observed during the Amazonian. Floods and water bodies are also expected to be progressively smaller with time due to a dwindling water Noachian water supply (e.g., Noachian basin/aquifer system) due to insufficient recharge after each endogenic-driven event, and so offering less water to be mobilized from subsurface reservoirs through time.

Equally, a great water loss between each period is expected, as result of: Mars' reduced mass, whose gravity would be unable to hold a thick atmosphere (Baker *et al*., 1991). Water dissociation and exospheric hydrogen escape resulted once the original magnetic field protection against the solar wind was lost (e.g., Lundin, 2001). The released oxygen may have contributed to the oxidation of the regolith -hydrolysis of silicate minerals and formation of carbonate minerals. In addition, impact events are believed to have contributed to atmospheric erosion or thermal escape during the period of heavy bombardment.

But short duration episodes of higher heat flux to the surface are argued to be superimposed on the long-term gradual decline in mantle heat flux (Baker, 1999), in order to well explain the diverse evidence that collectively point towards environmental change, such as Thasis-triggered climatic excursions from the typical cold and dry desert conditions. This is what the MEGAOUTFLO hypothesis predicts (Baker, 1999; Baker, *et al*., 2000). In fact, it is possible that substantial remnants of the floodwaters that inundated the northern lowlands during Noachian and Hesperian ages could remain beneath thin mantles of Amazonian dust and volcanic flow and airborne materials.

The shorelines marking the major inundation phases would be subdued/modified because of subsequent floods, as well as from pervasive Amazonian wind modification.

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