WHITE MARS: A GLOBAL EVOLUTION MODEL FOR MARS' SURFACE BASED ON CO_2.

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Introduction: A model is presented for the evolution of the Martian surface and atmosphere located in pressure and temperature conditions broadly around the triple point of carbon dioxide. Mars' surface features and evolution are shown to fit better than any model based on liquid water. The Amazonian outburst "floods" are reinterpreted as a new class of cold, gas-supported density flow analogous to Terrestrial pyroclastic surges and submarine turbidites, here termed Cryoclastic flows.

Studies of the present day surface of Mars demonstrate recurrent processes best explained by the presence of liquids at various times in its evolution. However, atmospheric models of Mars have great difficulty in achieving the stability criteria for liquid water [1]. This paradox is resolved here by modelling Mars' evolution with CO_2 as the active fluid, and demonstrating that many otherwise obscure features of the Planet can be explained by interactions of CO_2 around its solid / liquid / vapour triple point, rather than that of water. In particular, the early Noachian and Hesperian erosive valley features are shown to be due to local liquid CO_2 cycling driven by precipitation of CO_2 snow and rain within a moderately dense (~5 Bar) early atmosphere, locally warmed by impact heating and volcanism, whilst later Amazonian catastrophic outburst features are explained by largely solid subsurface deposits of CO_2 being released in self-sustaining collapse/flow events at the solid/vapour phase boundary with long-distance transport of the "flood" deposits sustained by internal release of CO_2 vapour. The closest terrestrial analogues to this process are Pyroclastic volcanic flows, submarine turbidity currents, or air-supported long-runout landslides and snow avalanches.

Pressure and Temperature on Mars:

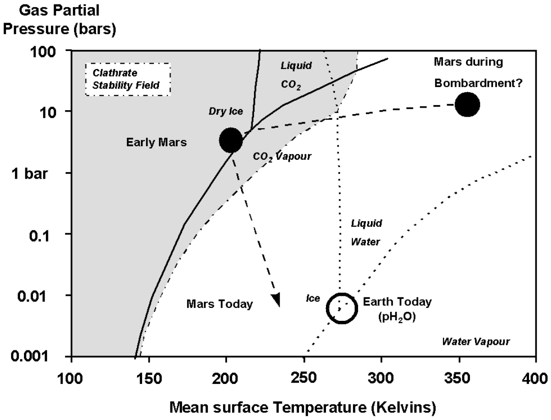

Fig. 1. Present and Past Martian P, T conditions compared to the phase diagram of the H_2O/CO_2 system (after Miller [2]). Early Mars is close to the CO_2 triple point just as Earth is now situated around the H_2O triple point.

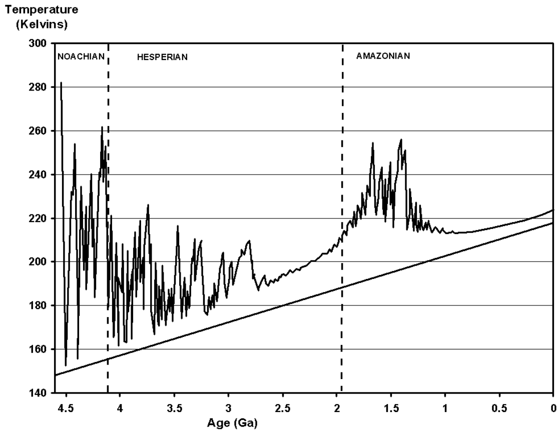

Fig. 2. A simulation of Mars' mean surface temperature through geological time based on a steadily warming sun and impact cratering into an icy regolith with repeated cycles of ephemeral atmospheric generation and collapse during the Noachian and early Hesperian.

This extends the model of Kasting [1] for early atmospheric collapse post-bombardment to one of repeated cycles of collapse during the closing phase of the bombardment itself. Mean temperatures do not reach the crucial 273 K required for liquid water at surface, suggesting that liquid water would have been a rare occurrence in local warm spots, at best. In the Amazonian, solar warming brings equatorial regions into unstable regimes where CO_2 ices in the regolith are prone to sublimation. Collapse events lead to the Amazonian outburst "floods" (actually resulting from gas-supported flows, not aqueous floods). Each collapse leads to temporary atmospheric support, but far below Noachian pressures. After the vulnerable terrain is consumed, the "floods" diminish and Mars evolves to the present thin, dry atmosphere.

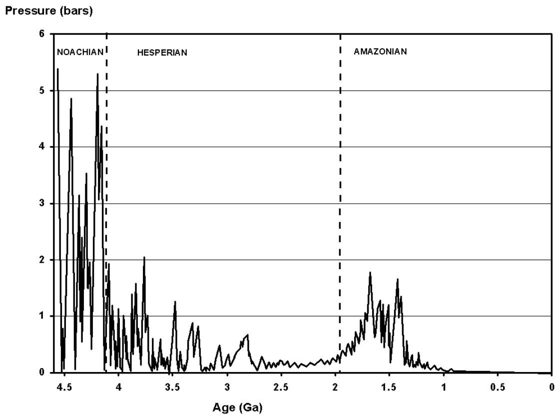

Fig. 3. Mean atmospheric pressure within the same simulation. Note that during Noachian times, occasional occurrences of P>5 bars occurs, permitting liquid CO_2 at surface. Liquid CO_2 would be a common occurrence during these times, except in local hot spots where it would be too volatile. CO_2 cycles would consist of rain in the periphery of hotspots, draining through river systems into local warm lakes that evaporated strongly and resupplied the rain.

Ice and Layering: The ubiquitous layering of Mars (craters cutting into layered terrain, and themselves filled with layered deposits), calls for a new insight. Standard sedimentary models of the layering cannot explain the infill of large closed craters and basins, without coexisting degradation of their margins, or breaching of their rims by major sediment transport systems. Volcanic explanations fail due to a lack of sufficient vents or fissures and dearth of flow morphologies. An ignimbrite origin is possible but again, vents and calderas on sufficient scale are clearly lacking. Instead, an interaction between impact sheets and episodic atmospheric collapse and icy layering leads to a thick layered regolith of rocky and icy layers. On early Mars, water ice is a refractory crustal component and is spread with other lithic fragments in the impact sheet. CO_2 is the active atmospheric volatile.

Noachian fluid erosion by liquid CO_2: In local areas, atmospheric cycles involving solid and vapour CO_2 ephemerally include a liquid CO_2 phase and lead to fluid erosion of the Noachian valley systems by liquid CO_2.

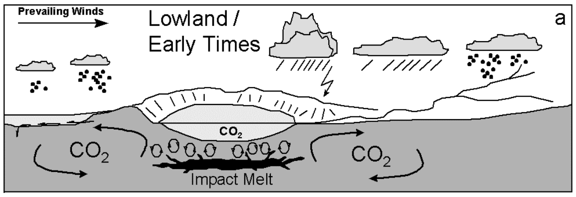

Fig. 4. The surface of White Mars in the Noachian. Local CO_2 cycling in the vicinity of warm craters leads to erosion and valley networks. Elsewhere an icy carapace protects the surface from the climate.

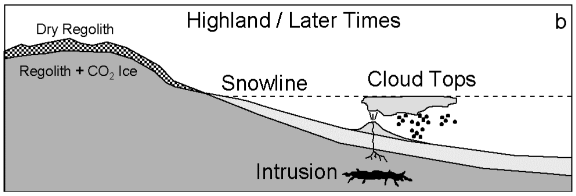

Fig. 5. At later times, liquid CO_2 disappears and a cold iceworld sets in. Eventually, atmospheric pressure decreases enough for solid CO_2 to sublimate away entirely at high altitude.

Outburst "Floods": The origin of Martian outburst "floods" in zones of chaos is entirely natural and obvious now that we understand that the terrain is largely layered ices and rock debris. Collapse of the terrain on weak volatile-rich layers is encouraged by steep local slopes such as craters or canyon walls, and fault scarps. Tectonic activity and volcanic swelling encourage slippage as does the global warming of surface temperatures into the Amazonian. Lambert & Chamberlain [3,4] introduced this style of collapse but concentrated on shallow instability. Instead, we now see that the instability extends to considerable depth and involves coherent collapse and slippage of km-scale regolith blocks.

The initial collapse leads to a partially-liquefied slurry of regolith blocks, loose fragments of rock and ice, and liquid CO_2 as the lubricant. As this heads downslope it loses integrity and transforms into a chaotic avalanche of blocks and fragments, lubricated by CO_2 vapour, and transforms finally into a true density flow. This is capable of travelling downslope for hundreds to thousands of km, and transporting large boulders and fragments within the debris cloud.

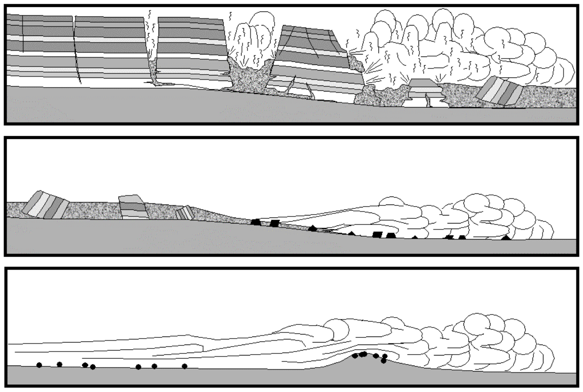

Fig. 6. Generation of icy regolith slurries from collapse of layered terrain leads to flow transition into cold gas-supported density flows that form the Amazonian outburst "flood" channels and their associated topographic and textural enigmas. Surrounding areas receive additional airfall of fine debris, blanketing small craters and adding to the uppermost layers/

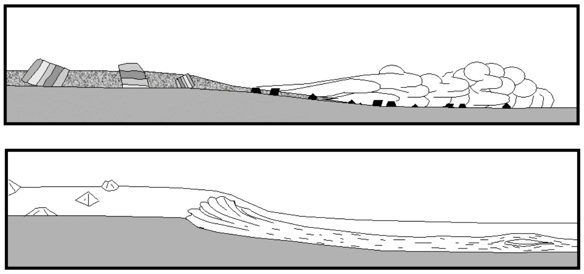

Fig. 7. Comparison of density flow in motion and the resulting morphology and texture after flow ceases. Note stranded blocks with pyramidal or mesa forms, and minor local slumping. Transition zones between flow regimes are preserved as surface chutes leading from flat plains to incised channels.

Terrestrial Analogues:

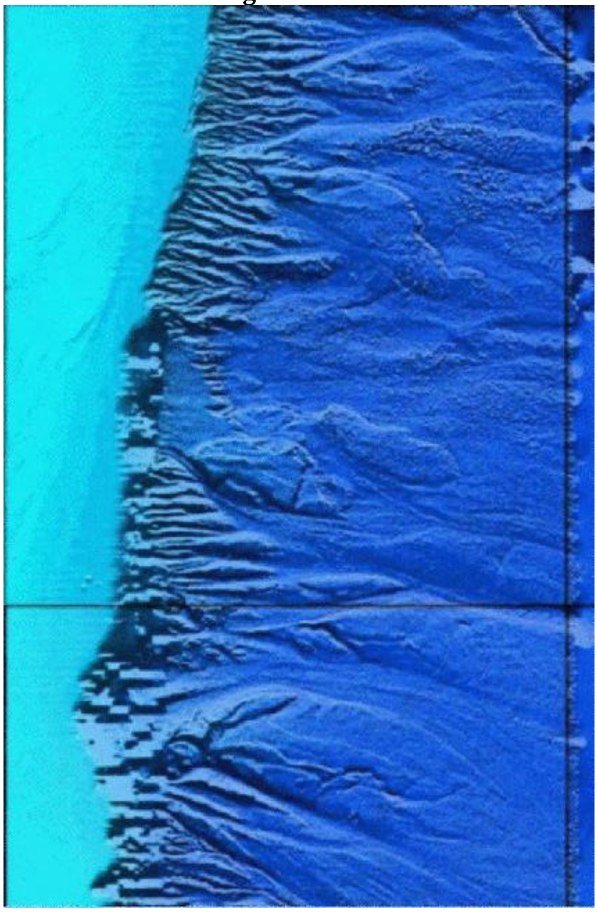

Fig. 8. Terrestrial turbidite channels off the Atlantic margin of USA. Note the broad, flat-bottomed channels with relatively low banks and flow-parallel striations. These channels weave gently and define pointy-ended ovoid and teardrop shaped islands. This entire erosion/transport/depositional system is in water depths of 0.5 to 5 km and has never been emergent subaerially.

The morphology of the Amazonian outburst “flood” channels on Mars are unusual compared to all subaerial terrestrial analogues. To date, the best morphological link is with submarine density flows (turbidites) [5]. The reason why this analogue holds is that the Martian flows were also fluidised density flows.

Another type of density flow on Earth is the volcanic pyroclastic flows and surges. These are subaerial gas-supported flows of huge speed and energy that emerge either directly from an eruptive vent, from the collapse of an eruptive column, or from an avalanche of unstable fresh hot lava. It is this latter analogue that we turn to in explaining the transition from a collapsing sector of chaotic terrain, progressing through an incoherent avalanche and becoming a fully fluidised gas-supported density flow. On Earth the pressure support comes from volatiles in the hot magma, and from the expansion of entrained air. Due to the high temperatures and low volatile content, this is initially explosive, but short lived on Earth. On Mars, due to large volume % of ices in the layered regolith, the support can continue for a long time, although the expansion pressure is much lower so the process is not explosive.

Note that I am not suggesting that the outburst “floods” on Mars are volcanic. Instead, I am invoking transport analogues from equivalent gas-supported volcanic flows, as I also do from terrestrial submarine turbidites where water is the fluid phase. The flow conditions on Mars would have been cold (<250 K), hence my description of them as “Cryoclastic” flows. Of course, as viewed on Mars they would have been warmer than the local surface, due to their origin from regolith originally buried by several km, and transport towards the cooler northern plains. They would have been volatile-rich and very steamy as they outgassed rather like the Valley of Ten Thousand Smokes. A variety of post-depositional modifications would have occurred as they settled and degassed - leading to the polygonal terrains seen in outwash plains and a variety of mantling deposits as surface layers slumped or crept downhill.

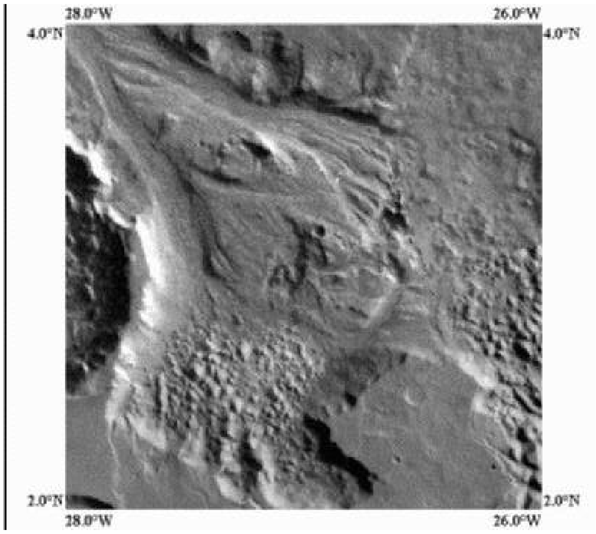

Fig. 9. An analogous view of Martian outflow channels showing the same broad, flat-bottomed striated channels, and pointed islands.

Fig. 10. A subaerial pyroclastic channel sourced from Unzen volcano, Japan. The flow cuts across cultivated land.

Surface textures and deposits: Density flow deposits depend on the grain sizes involved in the flows. Ignimbrite plains result when largely fine-grained material is dumped over a wide area. Rocky surfaces result from coarser grained flows.

Fig. 11. Surface boulders deposited by a pyroclastic flow from the Soufriere hills volcano, Martinique. Note the striking similarity in scale and appearance to the rock-strewn surface around the Pathfinder Lander site.

During evolution of the flow, it may separate into distinct high and low density flows with different particle sizes, velocities, and flow behaviour depending on details of its flow history, the local slope and roughness of the ground, and the degree of lateral confinement. Low density flows can ascend considerable hills (>1 km), and travel long distances across flat plains, generally in wide and unconfined flow fronts. High density flows can be strongly erosive and travel in confined channels downslope. It is these confined flows that define the Martian outflow channels.

Fig. 12. A surface deposit at the margin of a pyroclastic flow from Mount St Helens. Note the uniform blocky debris at the surface, looking like crushed rock dumped from trucks. Much of Mars' surface will consist of rocky plains like this, often with a surficial coating of fine airfall debris from other nearby flows. The dust of Mars is the fine debris from the flows, being slowly reworked in the present thin atmosphere.

References: [1] Kasting J.F. (1991) *Icarus*, **94**, 1-13. [2] Miller S. L. (1974) In *Natural gases in marine sediments* (I. R. Kaplan, Ed.) 151-177. Plenum Press, N.Y. [3] Lambert R. St J. and Chamberlain V. E. (1978) *Icarus*, **34**, 568-580. [4] Lambert R. St. J. and Chamberlain V. E. (1992) Abstract - NASA *MSATTMA Workshop.* [5] Kornar P. D. (1979) *Icarus* **37**, 156-181.