THE ORIGIN OF PERVASIVE LAYERING ON EARLY MARS THROUGH IMPACT/ATMOSPHERE FEEDBACK MECHANISMS.

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Introduction: The Noachian of Mars is a poorly understood epoch when ongoing major bombardment was actively modifying the planetary surface. Dating from this time there is evidence of active erosion of landforms, of deposition of thick layered terrains [1, 2], and of the formation of the Dendritic Valley Networks. These are probably all linked to the state of the early atmosphere.

Conventional models of a warm and wet early Mars suggest that this was a time of persistence of a ~0.5 to 2 bar CO_2 atmosphere, and that liquid water is responsible for most of the features we see.

An alternative model is that the planet was an iceworld at this time, poorly warmed by the Faint Young Sun, and that any thick atmosphere was transient and ephemeral, associated with the heat pulse of major impacts. The layering of early Mars cannot be treated in isolation from the impacts. Some of the layers will be impact ejecta while others will be dusty or icy layers related to atmospheric blooms and collapses. The role of CO_2 is a key to this process with its phase transition between high albedo ice and greenhouse gas offering a very highly geared positive feedback system.

Distribution: Layering on Early Mars is not merely a local effect of some isolated crater basins. It is a planet-wide phenomenon involving mobilisation and layering of essentially the entire uppermost 10 km of regolith.

Some authors prefer a volcanic explanation of the layers [e.g. 3], despite the lack of volcanic vents and fissures, and despite the obvious low strength of the layered materials. Poorly-welded pyroclastic ashes are a very real candidate, rather than stronger lava flows, but on Earth such extensive deposits are invariably associated with eruptive complexes containing complex cones and calderas.

Other authors invoke planet-wide sediment transport systems, yet the evidence of the distributory valley networks is exclusively of local to sub-regional networks of limited extent.

Airfall: One of the primary characteristics of the layered fill of craters and basins is that in many instances the host crater lacks any obvious inflow and/or outflow channel as would be expected for a normally-connected fluvio-lacustrine system [2]. Although a few craters do have valleys leading in or out, these are very much the exception rather than the rule. As a consequence, authors often refer to airfall as a possible origin of much of the layered material [2]. This airfall may be aeolian, pyroclastic, or impact ejecta.

Erosion: Noachian crater rims planetwide are subdued, and the craters contain thick laminated fill, but generally in larger volumes than the amount of locally available eroded rim material. Again, an airfall origin for much of the crater fill is required.

Timing: Younger craters expose layering within older craters, and younger craters likewise, comprising a “Chinese box” system where layers endlessly nest within layers. Clearly, whatever process was responsible for this layering must have been coaeval with the impacts that formed the craters. Perhaps it was even associated with the cratering process itself? To understand this, we first have to review conditions on early Mars.

The climate of early Mars: The simplest and most reliable atmospheric models for early Mars predict that, in the absence of any major heat input, the planet would be even colder and drier than it is now [4]. We expect an atmosphere of less than 1 millibar of CO_2, and polar caps and permafrost extending to much lower latitudes than at present.

In these circumstances, although internal processes such as volcanism could have led to flows at surface, all aeolian processes would be reduced to a fraction of that on modern Mars and fluvial processes would be quite impossible. This is the “background” scenario for Mars: cold and still conditions, waiting for something to happen.

Impacts: Any major impact into a cryogenic world such as posited here for early Mars is going to have two main effects. Material will be ejected from the impact site and deposited in a broad ejecta mantle. For the largest-scale craters this mantle will extend planetwide. In a simple mass budget calculation, the layered material filling each and every crater is approximately balanced by the sum of the ejecta from those craters. Only young craters are underfilled. Much of the “airfall” layering on Mars may therefore represent layers of ejecta from large and small impacts.

The composition of ejected material will match the existing regolith – rocky debris from previous impacts and ices trapped between the rock grains. Some of this ice is likely to survive both the initial impact and secondary processes without melting [5], especially the relatively refractory water ice and/or clathrate component. Ejecta, whether rocky or icy, will be emplaced on a ballistic timescale of minutes to hours.

Secondly, a significant fraction of the ice in the impact zone and in the re-entry/ secondary impact zone will be melted/vaporised. This material will join the atmosphere and may be a significant augmentation to the ambient atmospheric pressure. Ultimately, this material is destined to re-freeze and rejoin the polar caps and permafrost but the timescale and process by which it does is vital to the evolution of the planet.

Ephemeral atmospheres: In the case of a small impact, the atmospheric increment will be truly ephemeral and will begin to freeze-out immediately onto the cold planetary surface, and in particular in the polar cold traps. On a scale of hours to months, the atmosphere will restabilise and effectively an ice-rich layer will have been deposited on top of a rock-rich layer of ejecta.

Over time, with many small impacts, multiple overlapping local ejecta sheets will be deposited, and each will be capped by a thin frost/ice layer recording the collapse of the ephemeral atmosphere.

Large impacts: The energy associated with a large impact corresponds to many years of steady solar heating, delivered to the planet on a timescale of seconds. This energy is partitioned in various ways, but ultimately will be distributed as heat in the atmosphere, in the ejecta sheet, and in the core of the crater. These will all proceed to cool, with the majority of the heat escaping via the atmosphere and radiating to space.

During this phase, sufficient heat energy can be cycled through the atmosphere to significantly augment the atmospheric heat budget. Early Mars had a likely insolation of only 70% that of modern Mars, due to the faint young Sun [6]. However if the scale of impact-related heating is sufficient, this can be augmented back to and beyond the present level. A large enough impact would have the effect of bringing Mars into the region of a stable thick CO_2 atmosphere.

Atmospheric dynamics: Clearly, these are going to be complex and depend crucially on the size and location of any recent impact features, and their cooling history. However we can paint some useful scenarios:

Polar impacts: These will be particularly effective since a large near-polar impact will access rich permafrost deposits and polar ice to inject into a thick atmosphere. Additionally, the hot impact crater will effectively annul or seriously reduce the cold trapping potential of that one pole for a timescale of many years, decades, or centuries. Mars' atmosphere will then experience strongly asymmetric summer/winter cycles until the hot crater is subdued by encroaching ice.

In the "hot" half of the cycle the non-impacted pole will be oriented sunwards and boil off, and the impacted pole will remain warm by impact heating and resist condensation. Therefore a relatively thick atmosphere will develop. In the cold half of the cycle, the impacted pole is illuminated and doubly warmed, while the cold pole experiences condensation as on modern Mars.

This will be a time of extensive aeolian activity with a strong bipolar cyclicity. Episodes of very active aeolian transport in the "hot" season will alternate over the Martian year with quieter episodes in the "cold" season. These are ideal conditions to produce thick deposits of rhythmically layered sediments in topographic lows such as older (cool) impact craters.

Major impacts: Wherever it may occur, a truly major impact will have a significant effect on the atmosphere. This may be sufficient to raise the atmospheric pressure to the full limit of available volatiles, which on early Mars may be several bars of CO_2 [e.g. 7]. In these circumstances, and with the additional greenhouse effect of a thick CO_2 atmosphere, two things will happen. Liquid water may become stable in equatorial regions, permitting rain, rivers, lakes and rapid erosion, and liquid CO_2 may even become stable in polar regions (if the global inventory exceeds 5.1 bars CO_2). Therefore a polar CO_2 rain cycle also becomes possible. In the most extreme case, one could speculate that the northern lowlands could form the bed of a small CO_2 ocean, containing the excess atmospheric CO_2.

Discussion: Whether the local erosive agent is liquid water or liquid CO_2, in the brief interludes on early Mars following major impacts, the atmosphere will be temporarily very energetic and prone to seasonal cyclicity. In these circumstances, very rapid erosion of the loose regolith will occur. This is the likely time of crater rim degradation, crater fill, and the formation of layered deposits in local basins.

Layered deposits of Noachian age are intrinsically linked to crater formation processes and the very large amounts of ejecta match neatly with the large amounts of layered fill. This is no coincidence, and the atmospheric consequences of major impacts are probably responsible for the details of the layering.

References: [1] Nedell S.S. et al. 1987 *Icarus 70*, 409-441 [2] Malin M.C. & Edgett K.S. (2000) *Science 290*, 1927-1937 [3] McEwen A. S. et al. (1999) *Nature 397*, 584-586. [4] Hoffman, N. (2001) *This Conference*, Abstract 1286 [5] Boyce J.M. & Roddy D.J. (1996) *AAS-DPS XXVIII proc.* 145-146 [6] Gough D.O. (1981*) Solar Phys. 74,* 21-34 [7] Pepin, R.B. (1992) *LPI Workshop On The Evolution Of The Martian Atmosphere*