EMPLACEMENT OF A DEBRIS OCEAN ON MARS BY REGIONAL-SCALE COLLAPSE AND FLOW AT THE CRUSTAL DICHOTOMY.

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Introduction: The question of what predated the catastrophic outburst floods is an intriguing one, especially with the recent recognition that the bulk of the sedimentary fill of the northern plains may have been emplaced in a single genetically-related series of dense mudflows over a relatively short timescale [1,2]. These rates do not seem credible for normal erosional processes so if the timescale is valid then it requires exotic, planetwide mechanisms for terrain breakdown.

An integration of topographic and morphologic data from the Chryse and Cydonia regions of Mars permits preliminary models of the terrain breakdown processes that could sustain flow rates as large as required by the isostatic data. Some interesting speculation as to transport and depositional processes is included.

Before the "floods": The catastrophic outburst floods of Mars are so large and have had such a dramatic erosive and depositional effect on Mars' surface that it is hard to discern evidence for prior processes. Nonetheless that evidence is available in terms of regional topographic gradients of both depositional surfaces and erosional remnants.

The northern lowlands: A thick sedimentary cover of ~2 km conceals a buried terrain that was extensively cratered. The sediments cover 1/6 of the entire planet and represent a volume of ~5 x 10^7 km^3.

A variety of mechanisms have been proposed for the source of the sediment, but most of them are fairly conventional and require many millions (or hundreds of millions) of years to achieve such gradation. Recent work [1, 2] has shown that the deposits do not appear to have had this much leisure. The emplacement timescale for the flows is literally of the order of 10^3 to 10^5 years, since post-depositional isostatic deformation caused by the load of the sediment sheet has depressed and uplifted its former margin – the contact identified as a possible shoreline [3]. Further work on this shoreline has shown that it does not exhibit the expected features [4] and is instead a lobate positive-relief feature encroaching on the surrounding terrains in many places. It appears to have flowed outwards as often as inwards. Therefore, its origin is posited as a giant mudflow [1, 2].

Scarp retreat: Large areas of Mars downslope of the present-day dichotomy scarp are littered with remnant knobs, and distinctive valleys – the fretted terrains, eat back into the scarp. Collectively they appear to represent ~ 1000 km of scarp retreat in a planet-encircling belt. Profile analysis suggests that the missing volume represents a wedge 4 km thick at the present day scarp and tapering to zero over the 1000km width of the belt of fretted and knobbed terrain. Extending this in a girdle planetwide, we come up with ~5 x 10^7 km^3 –the volume of the sediments.

Erosion rates: Average retreat rates of 10 to 1000m per year are required. The lower end of this scale is compatible with short-term erosive cycles on Earth - for instance storm erosion of marine cliffs or sideways channel cutting by meandering streams. The higher end of the scale requires more rapid mechanisms. In any case, with limited water availability and slow recycling on Mars, such erosion rates are simply not credible.

Alternative Mechanisms: Recent developments in Mars surface processes suggest that the outburst floods were not conventional fluvial outbursts but may instead have been CO2 vapour-supported density flows generated by the eruption of subsurface liquid CO2 from collapsing chaos zones [3]. Calculations of the rate of chaos development show that explosive disintegration due to liquid CO_2 outbursts can achieve local retreat rates of several km per *hour*, so an episodic or uneven collapse by processes such as this could easily achieve the desired retreat rates.

It has been hypothesised that the fretted and knobby terrains are the result of regional-scale flows akin to the outburst "floods" but limited water availability and the problems with recycling that water volume multiple times always made this difficult to accept. Now, if we substitute CO2 for water the equation becomes easier. The CO2 only ever has to move once from source to destination, since subsurface liquid CO2 expands many hundreds of times in its conversion to high pressure vapour.

The equatorial regions of Mars merely need to have reasonable (5%) saturation with liquid carbon dioxide, and the rest follows. But how could large regions of Mars be saturated with liquid carbon dioxide? There are two basic mechanisms, an inheritance or an infiltration.

Inheritance: Early Mars was probably an iceworld with temperatures low enough for solid CO2 permafrost over much of its surface. It is also speculated that Mars' spin axis may have evolved with time, so that the warmest part of Mars may not have been the modern equator. By either mechanism, thick deposits of layered CO2 ices and regolith can be built up from early processes on Mars [5].

As the faint young Sun warmed, the surface and subsurface of Mars would gradually warm and much of the CO2 would melt (under subsurface confining pressure it need not vaporise). Thus extensive liquifers of CO2 could have been inherited.

Infiltration: Even if they were not inherited, a subsurface CO2 transport could operate over billions of years to saturate the regolith with mobile CO2. Water transport is often invoked for aquifer recharge [e.g. 6]. CO2 has lower viscosity, higher vapour pressure, and generally moves easier in the subsurface.

Consequences: Whatever mechanism led to the charge of the equatorial subsurface with liquid CO2, this is clearly not a very stable situation. As the planet warmed and tectonism progressed, many small breakouts would have occurred, each sourcing a small outburst "flood" – a CO2 density flow. These would tend to eat back into higher ground until the local pocket of CO2 was exhausted, or more resistant rock stopped the collapse.

With time, however, the collapses would have become more common and more significant, as the planet warmed and the regolith became more unstable. Eventually, a major CO2 liquifer would have been uncovered and a runaway collapse process began.

Elsewhere, we discuss how an erupting chaos zone is an unstoppable, and runaway process until the "fuel" is exhausted [7]. Furthermore, it is partially self-accelerating since large volumes of CO2 added to the atmosphere would raise global temperatures and lead to further ground warming (albeit on a time scale of 10^4 years or more). The total CO2 inventory associated with the mud ocean at 5% saturation equates to 1 bar of atmospheric pressure, but this would not be present at one instant.

Collapse would continue eating into the most unstable slopes – the crustal dichotomy, and thick layered terrains. The warmer atmosphere would lead to surficial mantle softening and slumping – a process common in fretted terrain. It is possible that warming *might* have permitted liquid water to flow in some specific sites at this time.

Initiation Sites: With such pervasive terrain collapse and bodily transport of debris, the initial site where collapse started is unlikely to have survived, however analogues exist across Mars in the numerous chaos zones. These have an evolutionary spectrum from small isolated blobs a few kilometres across to whole terrains hundreds of km across with extensive collapse and mass wasting. It is envisaged that collapse of the crustal dichotomy on Mars began as one or more small chaos zones, eating back into an extensive regional CO_2 liquifer. Collapse was prolonged and explosive, leading to the production of voluminous debris tongues of slurried regolith and associated mobile flows of vapour-supported density flows (CO_2 outbursts).

Scenario: As the dichotomy collapsed, the slurries would have poured into the northern lowlands, filling and covering pre-existing cratered terrain and emplacing thick deposits on a very rapid timescale. Outgassing from trapped volatile CO_2 would produce mud volcanoes [8, 9] and phreatic cones [10] as CO_2 escaped to surface and blasted loose debris upwards.

The northern plains would have been an extensive, mobile "sea" of fluidised debris – a "Mud Ocean" [1]. Its surface would have been wreathed in clouds of escaping CO_2 from fumaroles, fissures, and vents. The margin of the Mud Ocean would have been like the flow front of an aa lava – advancing in a bulldozer-like carpet, burying and engulfing the surrounding terrain, and steaming from the escape of CO_2. The speed of advance would have been, like lava flows, very variable and a function of fluid supply behind the flow front. Long stillstands and episodes of slow creep would alternate with short intervals of hundreds of metres per day, or more.

Discussion: By invoking a self-consistent CO2 outburst model for the collapse of the crustal dichotomy and fill of the northern plains we have developed an interesting scenario where very large terrains were modified in a very short geologic timeframe. Further work is required to validate terrain ages and check how possible this scenario is.

This scenario does not preclude liquid water, but makes it a very minor accessory to the main agent – CO2.

The outburst "floods" also appear to have occurred within the same short time window, since their floors are involved in the same isostatic ring uplift. This places them firmly as late stage or waning flows of a relatively small scale within the overall terrain collapse episode.

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