EVIDENCE FOR MAGMATICALLY DRIVEN CATASTROPHIC EROSION ON MARS.

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Introduction: We suggest here that the martian crust in many geologic settings has been extraordinarily susceptible to erosion induced by voluminous magmatic activity. First, examination of major volcanic terranes in highland settings with Mars Orbiter Laser Altimeter (MOLA) data reveal that such terranes lie in relatively low areas adjacent to lowland basins. Intrusion of extensive sills may have led to planation of vast highland areas and deposition into adjacent basins. Secondly, shallow dikes or small sills may have produced collapse depressions and in some cases huge lahars and mass flows at major volcanic complexes. We infer that the upper martian crust in these areas was largely made up of unconsolidated rocks rich in volatiles, perhaps dominated by CO_2, at the time of the associated igneous events.

Volcanism and Planation: We note three unusual yet similar highland volcanic plains, Syrtis Major, Hesperia, and Malea (south of Hellas Planitia) Plana. These areas (1) form wrinkled-ridged plains 1000 to 1500 km across, (2) have relative ages ranging from Late Noachian to Early Hesperian [1-3], (3) include large central volcanic structures (Nili, Meroe, Tyrrhena, Amphitrites, and Peneus Paterae), (4) occur on the rims of large, ancient impact basins (Hellas and Isidis), (5) have marginal erosional channels or chaotic terrain where they enter the basins, and (6) cover relatively low basin-rim areas largely devoid of rugged massifs that stand up to 2 to 4 km above surrounding terrain in adjacent rim areas.

The central vents associated with each high plain demonstrate that the outcrops are volcanic; most other highland plains on Mars of similar age do not include discernible volcanic vents. The vent structures, especially those with broad central depressions, also indicate relatively near-surface magma chambers, because the depressions probably formed by caldera collapse due to withdrawal from such chambers.

The coincidence between the volcanic plains on these basin rims, their relatively low topography, and the lack of rugged basin massifs protruding through much of the plains may be suggestive of a common origin. The volcanic rocks could have buried much of the preexisting landscape, but not the taller massifs that are common on other parts of the basin rims. Tectonic deformation may have caused relative lowering of parts of the rim. For example, the Hellas impact may have resulted in radial faults along which substantial vertical offsets occurred [2]. Although such processes may explain some amount of the lowering of the plains, it seems highly coincidental that these high plains also appear to be completely filled with volcanic rocks much younger than the impacts. Nor do the volcanic vents lie along any evident fault zones that might be related to basin deformation.

We therefore suggest that massive volcanism and (or) intrusion may have eroded these areas of basin-rim material, likely made up of uplifted crustal material and ejecta. As indicated by Clow [4], injection of magma into ice-rich ground would be expected to cause rapid melting and catastrophic breakouts. However, it seems difficult to imagine such wholesale erosion of terrains $\sim 10^6$ km^2 in area by the melting of water ice alone due to its high specific and latent heat capacity and limited volume (one unit of interstitial ice yields less than one unit of water). If the ices were in the form of clathrate and dry ice, the released CO_2 gas may have easily fluidized an unconsolidated or fragmented regolith. CO_2 has much lower specific and latent heats than water and each unit of dry ice can yield up to 500 units of CO_2 gas, leading to the generation of huge debris flows [5] that were deposited into adjacent basins. The eroded terrain may have resembled some of the broad martian outflow channels like Kasei and Simud Valles or the collapsed terrains associated with fretted valleys and knobby terrain near the crustal dichotomy where large scale collapse and volatile activity are also implicated [6]. Following this expulsion of volatiles from the crust, continued volcanic outpourings at each of these sites then buried the eroded plains with lava (Hesperia and Syrtis Major Plana) and perhaps pyroclastic flows (Malea Planum). Possible evidence for late-stage magma/ground-ice interaction at each of these sites includes outflow channels (Dao, Harmahkis, and Reull Valles) along the southern margin of Hesperia Planum [3], extensive breakup structures along the Syrtis Major Planum/Isidis Planitia contact [7], and widespread grooves where Malea Planum forms part of the inner rim of Hellas basin [2].

Intrusion, Collapse, and Lahars: Volcanic landscapes on Mars are replete with structurally controlled depressions [e.g., 8-10]. Many of these depressions are partly to wholly confined. In some cases they are breached by channels or are coalesced with other smaller depressions to form larger ones.

At Elysium, Ceraunius, and Tempe/Mareotis Fossae, linear enclosed and open troughs have formed along the same fracture systems that have controlled vent locations for the extrusion of shield and plains lavas and the construction of small edifices [8-12]. These troughs typically extend for several tens of kilometers or more in length and several kilometers or more in width. Flow deposits and channels extending for tens to hundreds of kilometers from the Elysium and Ceraunius troughs have been interpreted to be lahars or jökullhaups [12-14]. Similar associations but with smaller depressions include pits within rifts in the Thaumasia highlands [15] and pit chains within young grabens on Alba Patera [14]. All these depressions formed along fracture systems that likely served as conduits for dike intrusion. As in the case for the proposed, broad sills, other near-surface intrusions may have led to catastrophic erosion. For closed depressions, compaction, removal of volatiles, and erosion of clastic material in the subsurface may account for the required volume losses.

Perhaps the most dramatic example of magmatically induced erosion is the Valles Marineris/Noctis Labyrinthus. This huge system of mostly interconnected canyons ~3000 km in length cuts a topographic rise likely made up of a thick sequence of volcanic flows [16]. Within the canyons, layered deposits may consist of volcanic tuffs [17], including hyaloclastites formed by sub-ice volcanism [18]. Thick dikes may account for some of the proposed tectonic extension of the Valles Marineris system and perhaps catastrophic flood discharges [19]. In the non-structurally controlled canyons and chaotic terrain east of Valles Marineris, evidence exists for the generation of debris flows [20-21] and possible volcanic mantles [18]. We associate these events and propose that intrusions and volcanic eruptions in the Valles Marineris region led to the formation of catastrophic debris flows. We further suggest that they were charged by CO_2 to account for their ability to travel thousands of kilometers to the northern plains [5, 22]. Other potentially major examples of volcano-ice interactions on Mars include possible buried outflow channels on the northwestern flank of Tharsis [23], fretted channels and terrain [24], and knobby terrains in both highland and lowland regions.

Discussion: If our models for magmatically driven subsurface erosion are correct, magmatism was a leading cause of surface and subsurface erosion on Mars. The planation model is more conjectural, because other explanations for the observed volcanic/topographic associations cannot be ruled out. A better case can be made for the proposed dike-related erosion at some volcanic centers, because of the preservation of the related erosional and depositional features. In other cases, such as Valles Marineris, the geologic history is complex, and other formational mechanisms are possible.

Overall, we feel that the evidence is sufficiently compelling to suggest that magmatically induced catastrophic erosion has been a major yet under-appreciated geologic process on Mars. On Earth, volcanism at times results in huge erosional devastation with the assistance of large amounts of water, but not in the subsurface. Although Mars has a subfreezing and desiccating surface environment, the apparent vigor of its surficial and underground magmatically driven erosion indicates different fundamental geologic behaviors between the two planets.

One explanation may be that martian crustal rocks are generally more friable. This could happen if these rocks remain unconsolidated and uncemented [5, 25] or are subjected to intense and deep mechanical and chemical weathering. Another possibility is that the crust is CO_2 dominated, leading to near-surface clathrate and dry ice and potential subsurface CO_2 "liquifers" [5, 20, 26]. Volcanic heating might then lead to dissociation of clathrate, releasing gaseous CO_2 as well as melting of water ice. Heating of dry ice or subsurface liquid CO_2 would also lead to extensive production of gaseous CO_2. Carbonated water and gaseous CO_2 might provide a highly efficient means of lubricating such disturbed material, leading to catastrophic debris flows capable of transport across the surface or through subsurface conduits.

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