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FORMATION OF THE LAYERED DEPOSITS IN THE VALLES MARINERIS, MARS

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Thick sequences of layered deposits are found in the Valles Marineris (1-3). They exhibit fine, nearly horizontal layering, and are present as isolated plateaus of what may have once been more extensive deposits. Individual sequences of layered deposits are as thick as 5 km. We have argued previously that the morphology of the deposits is most consistent with origin in standing bodies of water (3). The rhythmic nature of the layering, their lateral continuity, horizontality, great thickness, and stratigraphic relationships with other units in the canyons all appear most consistent with deposition in a quiet aqueous environment. If standing bodies of water existed for any significant period of time in the Valles Marineris, they were almost certainly ice-covered. Here, we examine in more detail the conditions necessary for the existence of ice-covered Martian paleolakes, and consider mechanisms for sediment deposition in them.

Groundwater has been very important in shaping the Martian surface. There is ample evidence that the Martian regolith is highly porous and permeable, and at one time contained large amounts of liquid water (4). If a large tectonic depression such as the Valles Marineris cut deep into an aquifer system in the martian regolith, it would be natural for the canyons to become partially filled with water. As long as the subsurface aquifer system remained charged, water in the lakes could be replenished readily by seepage from the canyon walls.

It is unlikely that the Martian atmosphere was thick enough to have sustained mean annual temperatures above freezing after the earliest epoch of Martian history. Any standing water bodies would be expected to have a perennial ice cover. Perennially ice-covered lakes presently exist in the Dry Valleys of Antarctica. There the mean annual temperature is also well below freezing, and the ice on the lakes has reached an equilibrium thickness (5). As ice is lost from the upper surface of the lake by ablation, new ice forms on the lower surface, releasing latent heat as it does. This heat is the dominant term in the energy balance equation that gives the equilibrium ice thickness. Water in the lake is replenished in Antarctica by surface flow; on Mars this could be accomplished by ground water seepage. The rate of ablation exerts a strong influence on the equilibrium ice thickness, and on Mars it is poorly known. Based on reasonable estimates of ablation rates, the equilibrium thickness of ice on Martian lakes under the present climate might be 65 to 650 m (5). The depth of possible lakes is very poorly constrained, and could have ranged from very shallow depths to more than 5 km deep.

There are three ways that sediment could enter an ice-covered lake: down through the ice cover, up from the lake bottom, or in from the lake margins. We now consider each of these possibilities in turn.

Four processes that could have transported sediment downward through an ice cover are considered: (a) solar energy warmed individual particles, allowing them to melt through the ice; (b) sediment worked its way downward through vertical melt channels; (c) a layer of sediment deposited on the ice was thick enough to cause the ice layer to founder, dumping the sediment into the lake; and (d) a layer of sediment deposited on the ice cover led to a Rayleigh-Taylor instability, and sediment diapirs penetrated downward through the ice layer.

Simple energy calculations show that solar warming is inadequate to melt moderate-sized grains downward through the 5-meter ice cover of typical Antarctic lakes (6). It is therefore expected to be wholly inadequate on Mars, where the surface temperature and solar flux are still lower, and the equilibrium ice thickness may be one to two orders of magnitude greater.

Migration through vertical melt channels appears to be the primary sedimentation mechanism in some Antarctic lakes (7). Melt channels form when the ice thickness is less than about 3 m. In order for this process to have operated on Mars, surface temperatures and ablation rates must have been high enough to thin the ice to only a few meters, and liquid water must have been stable at the surface for periods during the summer. Neither condition is likely to have been met, as there is no evidence that the Martian climate at the time of layer deposition was substantially warmer than it is at the present.

Foundering of the ice cover could have occurred if enough debris was loaded onto the ice surface so that the overall density of the ice-sediment layer became greater than that of the liquid below. As sediment accumulated on the ice surface, the ice layer would thicken continuously, since freezing at the lower surface of the ice would no longer balanced by ablation from the upper surface. We calculated, for a given thickness of the sediment layer to be dumped into the lake, how rapidly sediment must be piled onto the ice surface for foundering to occur. We take ice surface temperatures of 210 to 240 K, bulk sediment densities of 1.5 to 2.5 g cm^{-3}, and sediment layer thicknesses at foundering of 75 to 150 m (the thickness of a light layer and a light/dark couplet, respectively, measured in Candor Chasma). Sedimentation rates of 0.4 to 15 mm yr^{-1} are required, and will lead to foundering at ice thicknesses ranging from 0.5 to 2.8 km. A weakness of the foundering hypothesis is that the ice would not undergo substantial melting during the foundering event, and could subsequently reform as a continuous cover and continue to thicken. However, these calculations neglect the effect of a geothermal heat flow. If the geothermal heat flow had an Earth-like value, the equilibrium thickness of even a sediment-covered ice layer might be no more than $\sim$ 2 km. Foundering could then occur repeatedly, taking place each time the sediment thickness exceeded the critical value. For an equilibrium ice thickness of 2 km, continuous sedimentation and repetitive foundering with a bulk sediment density of 2.0 g cm^{-3} would produce a sequence of layers each 140 m thick.

Even if foundering did not take place, it is likely that a thick layer of sediment that accumulated on the ice surface would penetrate the ice by a Rayleigh-Taylor instability. The configuration of dense sediment over less dense ice would favor diapiric upwelling of the ice and sinking of the sediment. We consider the flow to be dominated by the rheology of the ice, and take an upper sediment layer of 75 to 150 m thick. For an ice temperature near freezing, the instability will grow in tens of years. For a temperature of 210 K, the growth time is of the order of 10^4 yr. Therefore, if a sediment layer thick enough to form one of the observed layers accumulated on an ice cover, it would probably penetrate it rapidly.

The limiting factor for sediment deposition by foundering or a Rayleigh-Taylor instability is the ability to accumulate substantial amounts of sediment on the ice surface. Global dust storms could conceivably be the source for the sediment, but there are significant problems with this hypothesis. The present Martian climate produces net deposition of dust at the poles, and this process would have had to be somehow reversed. Furthermore, sediment would have also presumably accumulated on the surrounding uplands as well as in the Valles Marineris. None is presently observed there. This difficulty could be overcome if there were repeated periods of deposition and erosion near the equator. Sediment built up on the uplands would be swept away during erosional episodes, while debris deposited on the ice would be trapped by foundering or a Rayleigh-Taylor instability, and preserved. Without a clearly plausible mechanism for massive, repeated sedimentation at low latitudes, however, origin of the deposits by downward migration through an ice cover remains speculative at best.

Volcanic material that originated beneath the lake might also be a source for the layered deposits. There are several arguments against formation of the deposits by subaerial volcanism. One would expect that accumulations of ash-fall debris would be widespread, yet there are no layered deposits on the uplands surrounding the Valles Marineris. The nature of the layering also does not support an ash-flow origin. Typical large terrestrial ash-flows form aprons of individual flows that taper away from central vents. Smaller and more abundant flows would produce irregular layering. In addition to there being no identifiable volcanic calderas, the layered deposits are characterized by fairly uniform layer thicknesses that extend laterally for at least many ten's of kilometers. These arguments would be largely eliminated if the volcanism were subaqueous. Volcanic constructs may have been destroyed by slumping of material off cones as they were forming, or masked by floating pumice that eventually became water-logged and sank to the lake floor. Volcanic eruptions in water also would more evenly distribute effusive material. Even at fairly great depths, it seems that explosive volcanism could occur on Mars. On Earth, eruptions change from effusive to explosive activity, due to magma vesiculation, at water depths of 300 m for basaltic magma (8), and 500 m for silicic magma (9). The corresponding water depths for explosive eruptions on Mars are about 800 m and 1300 m, respectively. Although there is no direct evidence for it, the process of subaqueous volcanism is an attractive mechanism for explaining some aspects of the layered deposits.

Finally, the nearby canyon walls are an obvious source of sediment for the layered deposits. It is likely that the Valles Marineris formed as tectonic grabens that were substantially enlarged by removal of interstitial ground ice and collapse of the canyon walls. In a lacustrine environment, sediment would have been transported from the canyon walls into the deeper portions of the canyons by gravity flows, and deposited in nearly horizontal layers. This mechanism presents some geometric complications, and may not be able to account for all of the deposits. The material from the the collapsing canyon wall is sufficient to only partially fill the depressions that formed, yet the present deposits rise nearly to the level of the canyon rims in places. This problem could be alleviated if plateaus of layered deposits had cores of undisturbed canyon wall material, or if material were also added by volcanic eruptions or sediment transport downward through the ice.

We conclude that there are several geologically feasible mechanisms that could have led to formation of thick deposits in ice-covered paleolakes in the Valles Marineris. Present data are insufficient to choose conclusively among the various possibilities. Several types of data from the Mars Observer mission will be useful in further characterizing the deposits and clarifying the process of their origin. They should be considered important targets for a future Mars sample return mission.

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