GROUNDWATER RECHARGE IN AN EPOCH OF CLIMAX LAKES IN THE VALLES MARINERIS, MARS.

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Introduction: Liquid water was once abundant near the surface of Mars, at least for limited times. Evidence for this includes valley networks, outflow channels [1], shorelines and deposits in craters [2], and a possible sea in Argyre [3], which overflowed to become a source for Ares Vallis. Ice-covered lakes may have existed in the Valles Marineris (VM) [1,4]. There is also evidence for a northern ocean [5] based on similar elevations of channel termini, the extreme smoothness of the northern plains, possible subaqueous alteration of basalts [6], and polygonal ground possibly formed by ice wedging [1].

Outflow channels formed from Late Noachian to Amazonian, with a peak in the Hesperian [3]. The fate of the waters that carved the channels is no longer a mystery. Although a large volume was lost to space [7], a large inventory remains in the polar caps and layered terrains, as rich ground ice poleward of ~60° latitude [8], and probably also as groundwater [3]. The smooth northern plains could be a frozen "ocean", veneered with debris [9]. The detection of rich ground ice at high latitudes was a key finding of the Odyssey mission, and confirmed long-standing predictions [1]. A key question remains: Where did the water come from that filled the canyon lakes and carved the enormous channels?

Polar Basal Recharge: Pressure-induced recharge may have occurred at the base of the polar caps. This model assumes a globally connected aquifer system that conducted water from the poles toward the equator [3]. Groundwater gradually accumulated in confined aquifers until it was catastrophically released to form the outflow channels. Basal recharge is probably not active today [3]. *Carr* [10] shows that polar recharge is unlikely to have helped form post-Noachian valleys and channels at elevations higher than the base of the south polar layered terrains (~1500 m). We build on the basal recharge model to consider additional recharge sources that would have helped support high-standing lakes in the VM. Two things are needed to permit groundwater recharge at low latitudes: local water-ice reservoirs, and sources of heat.

Ice Accumulation at Low Latitudes: Surface and ground ice may have been plentiful during the Late Noachian, setting the stage for igneous melting in the Hesperian. *Jakosky & Carr* [11] explored ways in which ice might accumulate at low latitudes during times of very high obliquity. At other times, during epochs of widespread volcanism, particulate and gaseous emissions may have catalytically aided the precipitation of water as snow at low latitudes. We recommend this line of inquiry as a promising research area. Atmospheric water vapor, along with that released by volcanism, would condense, freeze, and precipitate downwind from calderas and extruded flood basalts. The likelihood of precipitation is high in the presence of a nearly saturated atmosphere, and because it would *coincide* with the occurrence of volcanism, heat from intrusions and extruded lavas would be available to melt ground and surface ice.

In the present epoch, ground ice is unstable at low latitudes, leading to gradual diffusive loss over geologic time. However, substantial amounts can be maintained at low latitudes if water vapor re-condenses as it diffuses upward [12]. Stratigraphic variations in diffusive properties of the upper crust will control the distribution of ground ice [13]. This can result in equilibrium depths for ground ice that are shallower or deeper than predicted for homogeneous crust. During major episodes of volcanism, precipitation could accumulate as ice deposits at rates that outstrip sublimation, especially if the ice became mixed with layers of dust or ash.

Volcano-Ice Interactions: Extensive evidence of volcanically generated water has been documented for Mars [1]. The evidence includes channels on volcano slopes, features resembling table mountains, outflow channels starting at volcanoes, fluvial features emerging from beneath lava flows, and evidence of subglacial melting [14] in the south polar region. Icelandic jökulhlaups provide Earth analogs of catastrophic floods produced by sub-ice volcanism. The recent discovery [15] of very young outflow channels associated with youthful (~10 Ma) volcanic terrain suggests that igneous activity may be essential to produce the large amounts of surface water needed for flooding. Intrusion of magma into the cryosphere, forming sills or dikes, would efficiently transfer the available heat into phase changes of water and could potentially release large amounts of meltwater [16]. This idea is further explored by [17] and [18], who suggest that the intrusion of massive dikes could generate extensive graben systems within and near Tharsis that could melt large volumes of ground ice and provide a water source for

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catastrophic floods. This manner of water release avoids the difficulty of conducting recharge from the surface through a cryosphere to an underlying aquifer.

Squyres et al. [16] conclude that the eruption of lava over frozen ground would release only small amounts of water liquid and vapor because much of the heat would be lost to the atmosphere. We note that much larger water releases would be possible if flood basalts overran surface ice deposits, not just ice-saturated regolith. The ability of this meltwater to also infiltrate the surface would depend on conditions within the cryosphere.

Groundwater Pathways: Beneath the cryosphere, highly permeable basalts would efficiently transport meltwaters north and east from recharge areas to the canyons. The Hesperian structural complex of Noctis Labyrinthis (10°S, 100°W) provided a network of surface and underground pathways that enhanced drainage from elevated terrain in central Tharsis. Groundwater flowed easterly into the ancestral VM canyons.

Canyon Lakes: Many of the outflow channels that emptied into Chryse Planitia discharged from canyons where water could have been stored in ice-covered lakes, even at the equator. Thin (~1-m) deposits of dust or ash on ice covers would stabilize sublimation rates at ~10^{-5} cm yr^{-1} [1]. Water could have gradually accumulated in the canyons until climax levels were achieved. Rising lake levels would increase pressures in confined aquifers to the north, favoring catastrophic release. Kasei Valles floods began in Echus Chasma; Shalbatana and Ravi Valles were hydraulically linked to Ganges Chasma [19]; and flows from Simud-Tiu Valles emerged from the main canyons of VM. The water that filled the lakes probably came from several sources, including groundwater already present in Noachian strata beneath the cryosphere. Water may also have been recharged at the poles and transported through a global aquifer system [3], but lake elevations >1500 m [10] would probably have required recharge from volcano-ice interactions.

Estimated Water Volumes: The present-day VM canyons have a volume of ~4.5×10^6 km^3 [1]. Of this, we estimate <1.5×10^6 km^3 lie above 1500 m. If canyons were interconnected, lake levels would have been limited to the rim elevations of ~0 m or less in low-lying chaos basins of eastern VM. If the juncture between Coprates Chasma and Capri Chasma had been closed, lake levels to the west would still have been limited by the ~1720 m overflow elevation of the canyon rim at 16.08°S, 56.33°W. Much higher lakes may have been possible in ancestral western canyons (e.g., Candor and Ophir) if they had been fully enclosed.

We now estimate recharge rates needed to fill canyon lakes above the 1500 m elevation. Groundwater outflows from the canyons are assumed to be minimal if the crust north and east of VM was saturated with ice and water. Based on current topography, the VM drainage basin west of 70°W (Thaumasia and E. Tharsis) covers an area of ~5.5×10^6 km^2. Virtually all of this region is veneered with Hesperian volcanics [20] (given that Amazonian lavas cover Hesperian rocks). A water depth of 270 m over the recharge area is equivalent to 1.5×10^6 km^3. This volume would be produced by a spatially averaged recharge rate of ~0.3 mm yr^{-1} per million years. We believe this rate was attainable for active volcanic regions. Recharge probably occurred episodically throughout the Hesperian, in response to both intrusive and extrusive volcanism. The many basalt flows that comprise the major geologic units may each have induced small recharge events.

Conclusion: Episodic volcanism in areas west and south of VM could have produced meltwater equivalent to many VM volumes during Hesperian time (>10^9 yr). Very small recharge rates would have sufficed.

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