MARTIAN GLACIAL MORPHOLOGY, GEOMORPHOLOGY, AND ATMOSPHERIC METHANE
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Introduction: We have earlier proposed [1] that methane clathrate hydrate in martian glacial ice could be responsible for both current martian atmospheric methane and for signs of past martian glacial melt. We further explore this idea, and compare it to the similar hypothesis of Prieto-Ballesteros, et al. [2].

Background: The presence of methane in the martian atmosphere [3-5] is intriguing, because methane’s photochemical stability on Mars is short [3], and nearly all terrestrial methane is biogenic. The mixing ratio is highest in water-rich areas, but varies greatly, suggesting that it is released from highly localized sources [4]. The existence of geomorphology resembling terrestrial glacial meltwater features is also puzzling, as martian surface temperatures, atmospheric pressure, gravity, and geothermal heat flux suggest that martian glaciers since the Noachian should be cold-based [6-7], even during periods of warm climate [1].

Methane release loci: Data from the Planetary Fourier Spectrometer (PFS) show highly variable mixing ratios, implying localized sources [4]. Allen et al. [8] seek correlations between methane and geologic structures. Work by McMenamin and McGill [1] and Prieto-Ballesteros, et al. [2] suggests that the correlation will be with remnant glacial features, such as those demonstrated by Head, et al. [9]. Prieto-Ballesteros et al. [2] propose that methane is released from cryospheric hydrates destabilized by the retreat of sublimating glaciers. As seen in Figure 1, this is minor compared to the amount destabilized within the remnant glacier itself. A glacial or cryospheric reservoir of methane does not constrain the ultimate source of the methane, which could be produced by microbe or abiotic geological processes.

Meltwater sources: The most likely sources of subglacial meltwater are local geothermal activity (limited to certain times and places), increased basal temperature due to the insulating properties of dust or gas hydrates, or lowered melting point due to inclusion of salts, gases, or gas hydrates [1]. Catastrophic dissociation of cryospheric gas hydrates may have caused chaos terrain and outflow channels [10,11].

Why methane hydrate: The fact that methane hydrate can explain both geomorphological features and atmospheric chemistry makes it an elegant solution to both problems. Carbon dioxide hydrate, which may also exist on Mars, would form where the CO₂-rich atmosphere interacts with ice, i.e., at the surface, and probably only near the poles [11,12]; concentrations of CO₂ hydrate are unlikely [10]. Methane hydrate formation, whether due to microbes or geologic processes, can occur within the hydrate stability zone (HSZ). In the HSZ, hydrates form spontaneously if the appropriate molecules are present, though the presence of salts inhibits them. Max and Clifford [10, 13] showed that a HSZ should begin at ~15 m below the surface of bare, ice-saturated regolith. Extrapolating from their results and assuming a glacial ice density of ~910 kg m⁻³ [14], methane hydrate should be stable beneath a mere ~38.5 m of glacial ice [1].

Methane hydrate dissociates below the melting point of water ice, and increases greatly in volume

![Figure 1: Cross section of the edge of sublimating ice, showing how hydrate dissociation releases methane to the atmosphere. Sublimation lowers the surface of the ice, destabilizing methane hydrate in the upper part of the HSZ. Methane, and possibly some water, escape to the atmosphere through fissures in the ice. Note the relative volumes of HSZ within the glacier and within the regolith that are destabilized by sublimation of the glacial ice.](image-url)
Associated meltwater can be extremely briny, because eutectic melting of a gas hydrate greatly amplifies salinity [17]. Dissociation is endothermic, drawing heat from its surroundings, and the increase in salinity may be enough to produce liquid water. The kinetic energy associated with the phase change can explain the existence of supposed rock drumlins [18] and other subglacial features [19,20].

**Glacial vs. cryospheric methane hydrate:** The Prieto-Ballesteros et al. model [2] is completely compatible with the current hypothesis, but does not explain glacial meltwater morphology, and cannot provide as much atmospheric methane per year. Evidence of volatile-rich mantles, rock glaciers, and debris-covered stagnant ice on Mars is widespread [e.g., 21], and as the ice in these reservoirs sublimes, it does so on all surfaces, not just at the toe, as implied by Prieto-Ballesteros et al. [2]. This exposes a much greater volume of clathrate to instability, and provides a much greater surface area for its release to the atmosphere, as shown in Figure 1.

**Methane clathrate in the cryosphere:** The evidence of sporadic contemporary flowing water or water-lubricated debris in gullies [22] may be explained by destabilization of cryospheric gas hydrates, which burst from their underground pockets and explosively release briny and/or gas-charged water. Rootless cones could also be caused by eruptions of dissociating hydrates. If gas hydrate deposits were present when the northern lowlands were covered by an ocean, we might find pockmarks similar to those associated with submarine methane release on Earth.

Maars proposed in the northern Arabia Terra region are significantly larger than those on earth. Carruthers & McGill [24] suggested that this might be related to the depth at which the magma-ice interaction occurs. Additionally, it may be due to the presence of methane hydrate, which appears to be a factor in the largest terrestrial maars [25].

**Methane clathrate in glaciers:** Gas hydrates have far less thermal conductivity than water ice, so if present in large amounts, they would increase geothermal warming of the base of the ice, but also buffer it from the effects of changing climate, particularly if distributed uniformly through the ice, resulting in more stable, long-lived glaciers. A similar effect would be obtained by significant quantities of dust embedded in the ice.) In fact, the remnant glaciers on Mars may have last experienced accumulation tens to hundreds of millions of years ago [9].

The high viscosity of gas hydrates (about 50x that of water ice) would retard internal deformation and flow of a uniformly hydrate-rich glacier, though dissociation near the base (from geothermal heating) might counteract that effect. Compared to water ice at a given pressure, methane hydrate is slightly less dense [18], so in an active glacier pockets of hydrate would behave like low-density rocks. Hydrate layers might deform and break apart as a glacier flows. If intact hydrate layers remain in a stagnant sublimating glacier or mantle, dissociation would increase pore pressure, creating a lubricating layer along which the overlying ice could slide. Finally, the low dielectric constant of methane hydrate suggests that layers may be detectable from orbit. In fact, layers with low dielectric constant have been found in martian ice [26]. Whether they are methane hydrate is open to speculation.

Northern Arabia Terra clearly contains a large amount of volatiles, and lineaed valley fill has been interpreted as evidence of glacial sublimation. Mantles here cling to the poleward-facing valley walls, as observed elsewhere [27], and some appear to have detached and slid downhill along a lubricating layer. This may be the result of a layer of methane hydrate destabilized by sublimation of the ice above.

**Detecting methane hydrate:** Even on Earth, detecting methane hydrate remotely is an uncertain venture. Thorough coverage by the PFS may reveal ephemeral methane releases associated with locations of volatile-rich mantles and glacial remnants. Thermal data may reveal transient cold spots on volatile-rich mantles and glacial remnants, if the debris layers that insulate them are not too thick for the thermal signature to be detected. These observations should be given priority in investigations of martian methane.

**References:**