# VOLCANIC ASH (TEPHRA) DEPOSITION AS A MECHANISM FOR MELTING SNOW AND ICE IN A LATE NOACHIAN ICY HIGHLANDS CLIMATE.

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**Introduction**: Recent climate models for the Late Noachian [1,2] predict that: 1) the mean annual temperature (MAT) was ~225 K, 2) increased atmospheric density induced an adiabatic cooling effect that resulted in significant accumulation of snow and ice in the southern uplands (the Late Noachian Icy Highlands - LNIH - scenario [1-3]) and 3) temperatures >273 K did not occur for significant durations under a wide range of parameters. The presence of thick snow and ice deposits in the southern uplands, and these low MATs, are incompatible with the observed ensemble of liquid water-related features (valley networks and lakes [4-6]), all interpreted to indicate MAT >273 K and a warm and wet climate characterized by rainfall [7]. If these climate models are correct, how can they be reconciled with the geologic observations? Several mechanisms have been proposed to address this conundrum by way of transient or punctuated ice melting, surface runoff, and ponding in a LNIH climate scenario: 1) repeated summertime melting at the edges of the ice sheet [8], 2) punctuated melting events from impact crater/basin-induced heating [9-11], and 3) punctuated melting events from volcanism-induced heating [12-14]. Another generally unexplored component of the volcanic hypothesis is the potential role played by the widespread emplacement of tephra, and the effect that this might have in lowering the surface albedo, changing the glacial mass balance, and inducing heating and melting of ice. Here we review the effects of tephra emplacement on snow and ice on Earth and Mars, and explore its potential as a mechanism to help explain the geological evidence for the ensemble of observed fluvial and lacustrine features.

**Generation and dispersal of tephra:** Explosive eruptions on Earth and Mars involve the rise of magma and its degassing under progressively lower rock overburden pressure [15-17]; magma disruption occurs at ~75% gas bubble volume fraction. Low atmospheric pressure on Mars induces enhanced magma fragmentation into fine-grained tephra more commonly associated with viscous, silicic magmas on Earth and encourages the development of plinian eruption columns. These rise convectively into the atmosphere until reaching a neutral buoyancy height, at which point tephra disperse laterally, assisted by the prevailing wind regime. Larger particles will tend to settle out of the expanding eruption cloud proximal to the vent, and finer particles will be carried progressively farther away from the vent before they settle out of suspension and are deposited on the surface. The finest fraction resides in volcanic aerosols, and these can remain in the atmosphere for much longer duration and be distributed globally before settling out years to decades later [18].

**Effects of tephra emplacement on ice observed on Earth and Mars:** Tephra that is deposited on snow and ice will markedly lower the surface albedo, an effect that can result in significant heat absorption; additional absorbed heat then conducts through the tephra layer toward the underlying snow and ice and can have two further and contrasting effects [19]: 1) If the tephra is thin, heat is conducted into the snow and ice and can cause melting and sublimation. 2) If the deposited tephra is thick enough, it will act as an insulating layer, interrupting the glacial mass balance and protecting the snow and ice below from further direct solar-insolation-induced heating.

Terrestrial examples of the effects of tephra deposition on snow and ice can be summarized as follows: *Tephra thermal effects*: Typically, the distance travelled by the tephra in this depositional regime ensures that it will have cooled to ambient temperatures before deposition, and thus will not conduct magmatic heat into the snow and ice. *Albedo effects*: Particulate material tends to reduce the albedo above snow and ice [20-22]; tephra-related albedo decreases of up to 0.5 have been noted [23], with longer term effects being most important in the ablation zone. Mount St. Helens ash was used in controlled experiments carried out on a glacier surface [24]; initial applications reduced surface albedo of the natural snow of ~0.61 to values from 0.18-0.4, depending on the particle type and concentration. Dust mantling measurements on Himalayan glacial ice [25] showed that initial snow albedo averaging 0.39 was reduced to 0.15-0.22. *Tephra thickness effects*: On the basis of measurements of natural tephra deposition, combined with field simulations and with laboratory experiments and measurements, the general thickness of tephra that induces melting is in the mm to cm range on Earth. In one study, maximum ice ablation occurred under a tephra thickness of 0.25 mm [25]. *Tephra absorbed heat, ablation and melting effects*: A ~30% albedo decrease caused by tephra emplacement [24] increased melting by ~50% in comparison to the adjacent snow areas. Dust loading significantly increased glacial surface melting, by a factor of ~1.4 [25]. *Net effects on melting in terrestrial glacial environments*: In summary, deposition of thin layers of ash and dust onto snow and ice can serve to lower the albedo relative to the surrounding snow which can result in significant absorption of solar radiation and resulting changes in glacial mass balance, increasing ablation and melting. *Historical examples*: Evidence for enhanced ice sheet melting of the Fennoscandian Ice Sheet [26] driven by volcanic eruptions toward the end of the last deglaciation (~13,200–12,000 years ago) has been found in an extremely well-dated annual glacial varve chronology; this showed that abrupt ice melting events coincide with volcanogenic aerosol emissions recorded in Greenland ice cores. This correlation implied "enhanced ice sheet runoff primarily associated with albedo effects due to deposition of ash sourced from high-latitude volcanic eruptions." even though the climate was undergoing atmospheric cooling due to enhanced concentrations of atmospheric aerosols [26].

**Late Noachian/Early Hesperian: A period of peak volcanism and tephra emplacement:** Volcanism is a prominent process in the Late Noachian and Early Hesperian (LN-EH) history of Mars [27,28], resurfacing over 30% of the surface [29] through flood-basalt style effusive volcanism [30]. Associated explosive eruptions commonly occurred throughout this period [31-34], spreading layers of tephra regionally and globally (Fig. 1) from numerous and widespread explosive source vents [33], potentially including "supervolcanoes" [35]. Analysis of sensitivity of plume behavior and tephra dispersal to variations in atmospheric pressure [33] shows that higher pressures allow plumes to convect to greater altitudes, and dispersal to focus in narrower latitudinal bands; final lateral distance traveled depends on the volcano location and season and can either increase or decrease with higher pressure but typically exceeds 1000 km [33]. In summary, voluminous explosive volcanism and widespread tephra deposition occurs at a time and locations (Fig. 1) coincident with geologic evidence for Late Noachian-Early Hesperian enhanced fluvial erosion, valley networks and open/closed basin lakes.

**Effects of tephra deposition on snow and ice on Mars:** A detailed treatment of the effects of the deposition of tephra on snow and ice in the current/Amazonian climate regime on Mars [19] showed significant effects from the emplacement of thin layers of tephra, enhancing ablation in equatorial and mid-latitude regions. The analysis also revealed the possibility of *deferred* melting, in which tephra layers of the same thickness emplaced at higher latitudes served to insulate the underlying snow and ice; over longer time periods, however, as obliquity changes brought this region into warmer regimes, significant deferred ablation could readily take place. This study also showed that under the atmospheric pressure of the Amazonian climate, sublimation was favored over melting. However, in the increased atmospheric pressure thought to characterize the Late Noachian/Early Hesperian climate (hundreds of millibars to a bar [36]), melting would have dominated over sublimation. Initial analyses suggest that although amounts of diurnal meltwater production may be relatively small, the additive effect, coupled with potential volcanically-induced global MAT increases (perhaps to 243K [14]), may provide substantial meltwater.

**Conclusions:** We find that under Late Noachiam Icy Highlands conditions [1-3], explosive volcanism and tephra emplacement [19] can: 1) emplace deposits of tephra with thicknesses sufficient to cause short-term regional melting of surface snow and ice deposits, producing potentially significant volumes of meltwater, and 2) produce layers of tephra that initially protect the underlying snow and ice, but result in deferred heating and melting as changing obliquity brings the deposits into a warmer climate regime. We conclude that explosive volcanism, and the distribution of tephra onto snow and ice deposits, represents a "cold-climate melting mechanism" that should be considered among the candidates for generation of meltwater in further testing the Late Noachian Icy Highlands climate model. Widespread distribution and deposition of fine-grained silicate material resulting from modest to large-sized impact cratering events [37] are predicted to cause similar effects.

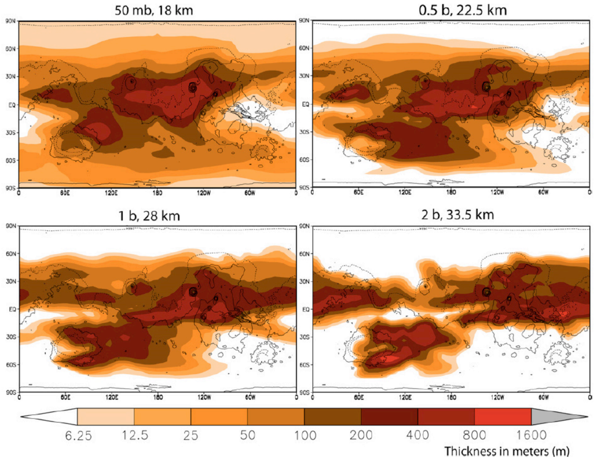

**Fig. 1.** Combined ash distribution patterns for all of the major volcanic centers on Mars, assuming each erupted 1.4 $10^6$ km$^3$ of ash during their lifetimes. Band of ash-covered latitudes becomes narrower with increasing atmospheric pressure. [33]

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