EVALUATION OF VOLCANO ICE INTERACTIONS AS A POTENTIAL GEOLOGIC PROCESS FOR THE FORMATION OF PHYLLOSILICATES ON MARS.

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Introduction: Phyllosilicates detected in Noachian-aged terrains on Mars [1,2], are a function of 1) the nature of the protolith (e.g., basalt, ash) and its susceptibility to alteration and weathering, 2) the water to rock ratio, 3) the temperature of the water to modulate reaction rates, and 4) the duration of exposure to liquid water in order to provide sufficient time for production of phyllosilicate minerals. Strata of Al-phyllosilicates overlaying Fe/Mg phyllosilicates have been observed throughout the Southern Highlands of Mars [3,4]. Weathering profiles on Earth with Al-phyllosilicates lying stratigraphically above Fe/Mg phyllosilicates have been identified as analogs for the Mars stratigraphy [5]. A continuously warm and wet climate for Noachian Mars [6] would provide all of the ingredients necessary for the production of these phyllosilicate sequences in the surface and very near-surface environment (e.g., high water to rock ratios for sufficient timescales) [6,7].

Early Mars climate models, however, have had great difficulty in producing a continuously 'warm and wet' Noachian Mars due to the faint young Sun and the absence of mechanisms to produce and sustain greenhouse gases in sufficient abundances [8]. This has given rise to another climate scenario for a "cold and icy" [8,9] Mars in which the liquid water needed to form the observed phyllosilicates would be present only transiently on the surface. This model predicts a surface environment, much like the current Mars climate, with mean annual surface temperatures (MAST) at 225 K, almost 50 K below the melting point of water.

There have been several formation theories for phyllosilicates on Mars including hydrothermal alteration [1], impact driven alteration [10], and predominately, leaching of parent material [11]. While the first two are reconcilable with a "cold and icy" climate, the leaching necessitates liquid water to be available at the surface.

Thus, several different hypotheses have been proposed which provide the conditions for temporarily stable liquid water in a cold and icy scenario. In one variation of the climate model, punctuated atmospheric heating by volcanism raises MAST above 273 K for decades to centuries [12]. This the spatial and temporal constraints seem insufficient to explain widespread phyllosilicate formation. In a second variation, impact events [13] cause punctuated atmospheric heating and rainfall; although the effects could result in higher atmospheric temperatures for decades to centuries, the duration is still geologically short. A third variation involves the cold and icy surface climate environment, and investigates the effects of extrusive Noachian and Early Hesperian volcanism. Massive flood basalt lava extrusions rapidly erupt onto and cover surface materials, including surface snow and ice deposits [14]. This process has two results: 1) Contact melting: initial contact of lava with snow and ice deposits places water into contact with the erupting basalt and nearby rocks as the hot meltwater drains. 2) Deferred melting: several kilometers of accumulated basalt deposits eventually raise the melting geotherm into the ice-cemented cryosphere and potentially up into buried glacial ice deposits, causing a period of deferred melting that may occur more than 10^4 years later. This would provide long-term sustained contact of warm meltwater with Noachian protolith.

The distribution of surface snow and ice should be widespread in the "cold and icy" climate model. First, the abundance of surface to near-surface snow and ice is likely to be significantly higher in the Noachian [15]. Secondly, spin-axis/orbital variations cause the redistribution of surface snow and ice into widespread and latitudinally extensive non-polar regions, as seen in the Amazonian (e.g., [16]). Thirdly, if the atmospheric pressure exceeds several tens to hundreds of millibars, an adiabatic cooling effect causes most of the snow and ice to migrate to the highlands, a situation known as the "icy highlands" model [9].

Here, we explore the lava-ice interaction mechanism [14] in a cold and icy Noachian Mars climate scenario [8,9] in order to assess whether this mechanism can provide the ingredients necessary to form the widespread Noachian phyllosilicate deposits [1,2].

Methods: Two main factors must be considered. The first of these is corresponding timescales. (1) The timescales over which the meltwater was produced must coincide with the time required for phyllosilicates formation. Two scenarios were considered: formation from basaltic parent material [10,17-18] or from pyroclastic parent material [10,17]. (2) The volume of water created by the melting must be consistent with the amount required for phyllosilicate formation.

To further investigate this as a candidate process, an Earth based analogue was considered in which volcano-ice interactions created the meltwater necessary to form phyllosilicate sequences. Iceland was chosen for its well documented mineralogy and volcano-ice interactions.

Results and Discussion: The amount of time and water needed to create these clays are intertwined in dependence and can also vary dramatically depending on a number of factors including pH, ion content, rate of water availability, temperature, and starting material. Since Al-phyllosilicates require a higher water to rock ratio and/or a longer timespan to form than the Fe/Mg phyllosilicates we investigate the conditions required to create the Al-phyllosilicates [19].

On Earth, in humid climates (rainfall rates ~1.5m/yr.), formation over ~8,000-9,000 years [20] have been estimated for the weathering of rhyolitic volcanic ash/glass to halloysite. However, it has been shown that the residence time of water required for aqueous alteration of basaltic volcanic glass is appreciably less than for rhyolitic glass [21]. Due to lower surface area and porosity, basaltic rock as a parent material takes longer to form appreciable amounts of clays than volcanic ash under the same conditions.

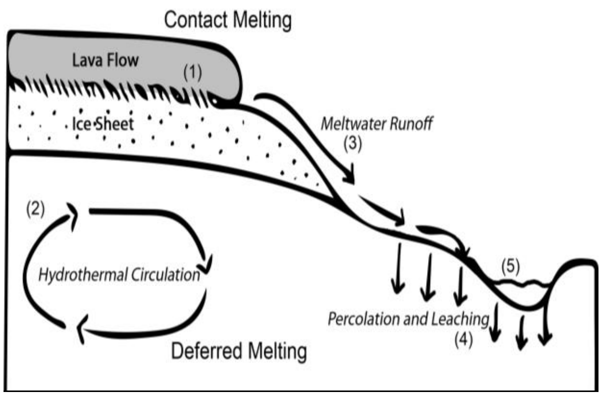

Fig. 1: Potential alteration from lava-ice interaction meltwater. (1) Contact between lava flow and ice sheet creates quenched glass. (2) Deferred melting of the cryosphere leads to shallow subsurface hydrothermal circulation. (3) Meltwater unable to percolate through the ice sheet runs off over the surface. (4) Runoff percolates into and leaches ash/rock layers downslope of the lava flow altering to products such as the phyllosilicate sequences. (5) Excess runoff settles in topographic lows where leaching and percolation continue.

Deferred melting creates a maximum of 15 mm of cryosphere melted/yr. [14]. This slow melting rate would not produce the amount of water required to alter the surrounding minerals in an appropriate time span without inducing hydrothermal circulation (**Fig. 1**). This would not produce layered phyllosilicate sequences, but instead, mineral assemblages including smectites and chlorite, potentially with prehnite (which indicates higher temperature alteration).

The first lava flow over an ice layer provides the most melting [14]. Either a thick lava flow or several successive smaller flows would be able to produce the melting rates and residence times necessary to leach either pyroclastics or basaltic rock. Successive lava flows would be ideal to create alternate periods of wetting and drying to assure formation of Al-phyllosilicates rather than amorphous silica [19].

Iceland's cold and climate with abundant volcano-ice interactions producing meltwater is an excellent analog. Here, meltwater can be stored to create glacially associated lakes, released to form fluvial systems, or as flooding [22]. Both Al-phyllosilicates and Fe/Mg smectites have occur in these setting [23]. They have been associated in part with glacial fluvial features [22]. Subsurface hydrothermal alteration has been found to correspond with volcano-ice geomorphology and produce mineral assemblages of smectites, mixed layered clays, kaolinite, zeolites, and quartz [24].

Conclusions: Based on results from laboratory experiments [21] and field observations [20], the timescales and water budgets generated by volcano-ice interactions are sufficient to leach and transform pyroclastics and volcanic glass. Although the time scales are less constrained (thousands-tens of thousands of years), the leaching of basaltic crustal rock should likely be able to conclude during contact melting given a sufficiently thick lava flow, or successive lava flows over the ice sheet. Thus, leaching of protoliths may still be the formation mechanism for some of the phyllosilicates observed on Mars given a "cold and icy" scenario.

Earth-based analogues in Iceland show alteration to phyllosilicates [23]; however whether this alteration is associated with volcano-ice interactions on the surface has not been well document. Subsurface hydrothermal alteration to phyllosilicates does occur as a result of volcano-ice interactions there [24].

Volcano-ice interactions are a strong potential candidate for creating the meltwater necessary for the leaching of parent material to form the phyllosilicate weathering sequences observed. Further work is necessary in assessing mineral deposits downslope of geomorphic indicators of volcano-ice interactions on Mars.

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