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Frozen Martian lahars? Evaluation of morphology, degradation and geologic development in the Utopia–Elysium transition zone

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ABSTRACT

Regional coverage of high-resolution data from the CTX camera has permitted new, detailed morphologic analysis of the enigmatic Utopia–Elysium flows which dominate the transition zone between Elysium volcanic province and Utopia Planitia. Based on topographic and morphologic analysis of the Galaxias region, this study supports the lahar hypothesis put forth by previous works and suggests that the center and the margins of the outflow deposits have very diverse morphologies that can be explained by varying degrees of water drainage and freezing. Regular channel and flood plain deposits are found in the central part of the outflow deposits, whereas the marginal deposits are interpreted to contain significant amount of ice because of their distinct morphological properties (smooth, lobate flow-fronts with upward convex snouts, unusual crater morphologies, raised rim fractures and localized flow fronts indicating rheomorphism). Thus, this study suggest that, unlike terrestrial lahars, lahar emplacement under Martian conditions only drain in the central parts, whereas the water in the margins of the outflow deposit (~75% of the total outflow deposit in the Galaxias region) freezes up resulting in a double-layered deposit consisting of ice-rich core with an ice-poor surface layer.

It is here furthermore suggested that continued intrusive volcanic activity was highly affected by the presence of the ice-rich lahar deposits, generating ground-ice–volcano interactions resulting in a secondary suite of morphologies. These morphologies include seventeen ridges that are interpreted to be möberg ridges (due to their NW–SE orientation, distinct ridge–crests and association with fractures and linear ridges) and depressions with nested faults interpreted to be similar to terrestrial ice-cauldrons, which form by enhanced subglacial geothermal activity including subglacial volcanic eruptions. These sub-lahar intrusions caused significant volatile loss in the ice-rich core of the distal lahar deposit and resulted in remobilization, deflation, and retreat of the lahar deposits, explaining the raised rim fractures, enclosed depressions, and small isolated islands found in distal lahar deposits.

1. Introduction

Landforms resulting from ice–volcano or magma–H_2O interactions on Mars are of great interest because they reveal the presence of volatile-rich deposits in the past and thereby aid to constrain the distribution of water through Martian geologic history.

A variety of magma–H_2O interactions, including both intrusive and extrusive magmatic activity, have been proposed (e.g. Chapman, 1994; Gulick, 1998; Christiansen and Greeley, 1981; Russell and Head, 2003; Wilson and Head, 1994; Frey et al., 1979) and a comprehensive review of general environment and geological settings has concluded that magma–H_2O interactions on Mars have been widespread through space and time (Head and Wilson, 2002). Intrusive activity from plutons has been suggested to thin the cryosphere (Wilson and Head, 1994) and potentially result in groundwater sapping due to enhanced hydrothermal activity (Gulick, 1998: Gulick and Baker, 1990). Both dike (Wilson and Head, 2002; Russell and Head, 2003; Head et al., 2003) and sill (Wilson and Head, 1994; Wilson and Mouginis-Mark, 2003) intrusions have been proposed as mechanisms for generating major lahars in various regions such as Mangela Valles, Elysium Fossae, Cerberus Fossae and Athabasca Valles either by melting substantial amount of ground ice (Christiansen, 1989; Christiensen and Greeley, 1981: Christiansen and Hopler, 1986; Wilson and Mouginis-Mark, 2003; Tanaka et al., 1992) or by cracking the cryosphere allowing drainage of confined aquifers (Russell and Head, 2003; Wilson and Head, 2002; Head et al., 2003; Burr et al., 2002).

Volcanic edifices proposed to result from magma–H_2O interactions range from subglacially emplaced dikes (eg. Kadish et al., 2008; Pedersen et al., 2010; Shean et al., 2005) to subglacial

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volcanoes (eg. Chapman, 1994; Ghatan and Head, 2002; Chapman and Tanaka, 2001; Chapman et al., 2000; Kadish et al., 2008) such as möberg ridges (Chapman, 1994; Chapman et al., 2000) and tuyas (Chapman and Tanaka, 2001; Kadish et al., 2008). The formation of highland patera in Early Hesperian times has also been suggested to result from magma–H_2O interactions by explosive dispersal of ejecta due to magma–groundwater interactions forming low, broad volcanic edifices (Crown and Greeley, 1993; Greeley and Crown, 1990 and Greeley and Spudis, 1981). Other evidence for volcano–ice interactions includes rootless cones (e.g. Mouginis-Mark, 1985; Fagents and Thordarson, 2007; Frey and Jarosewich, 1982; Frey et al., 1979; Milkovich et al., 2006; Shean et al., 2005) and thermally distinct craters, which Morris and Mouginis-Mark (2006) interpreted to result from steam-generated explosions due to interaction between a hot mudflow and ground ice.

Hence, a plethora of volcano–ice interactions known from Earth have been suggested to occur on Mars, and the transition zone between the Elysium rise and Utopia Planitia has been commonly suggested to host a variety of these features (Chapman, 1994; Christiansen, 1989; Christiensen and Greeley, 1981: Christiansen and Hopler, 1986; Morris and Mouginis-Mark, 2006; Russell and Head, 2003; Wilson and Mouginis-Mark, 2003; Pedersen et al., 2010).

However, these features have never been analyzed as an interconnected system before, which this study shows is necessary to understand the closely linked, complex succession of volcano–ice interactions. Intriguingly, these results imply that Mars lahars, unlike terrestrial lahars, may freeze during emplacement producing ice-rich deposits. This suggests that (1) we must re-evaluate the emplacement characteristics of lahars under Martian conditions (2) a significant amount of the water generating the lahars is still present as ice in the lahar deposits and finally (3) the ice-rich lahar deposits hugely affected subsequent volcanic activity generating a secondary suite of ice–volcano interactions.

1.1. Terrestrial lahars

Lahar is defined as a general term for an event where a water–rock–debris mixture (different than a normal stream flow) flows rapidly from a volcano (Smith and Fritz, 1989). The term encompasses a continuum from debris flows to hyperconcentrated stream flows (Lavigne and Thouret, 2000). The definition was officially agreed upon at the International Penrose Conference, "Volcanic influences on terrestrial sedimentation" August 28–September 2, 1988 in Washington State, USA after problems regarding the misuse and misunderstanding of the Javanese word that was originally introduced by Scrivenor (1929) (Smith and Fritz, 1989).

Lahars can occur either during or after an eruption and require (A) abundant water and unconsolidated debris (B) steep slopes and (C) a triggering mechanism (Vallence, 2000; Lavigne and Thouret, 2000). Various triggering mechanisms that can generate lahars are edifice or flank collapse or sudden release of water (e.g., by rapid glacier melting, emptying of a crater lake, subglacial eruptions or heavy rainfall) (Vallence, 2000; Lavigne and Thouret, 2000; Mothes et al., 1998).

The flow dynamics of lahars are controlled by the ratio of liquid and solids as well as the properties of the solid fraction. The ratio of liquid and solids in the flow is dependent on (A) the erosion and bulking (incorporation of material) capabilities of the flow, (B) the segregation processes of the flow, (C) the downstream dilatation and (D) the depositional processes of the flow (Vallence, 2000). Lahars can therefore vary from being debris flows with sediment concentrations ≥50–60% by vol. to hyperconcentrated flows with 20–60% sediment by vol., but they often start out with a flood phase with ≤20% sediment by vol. (Lavigne and Thouret, 2000; Vallence and Scott, 1997).

The density and the grain size of the solid fraction affect the segregation processes in the flow. Particles less dense than the effective fluid density commonly collect at the surface forming a raft of material that appears to move en masse. The proportion of fine grained particles impacts the effective fluid density, which affects how easily particles settle or buoyantly rise. The fines can also potentially impact the cohesion of the flow (Vallence, 2000; Lavigne and Thouret, 2000). If the solid fraction is ≥40% by vol., kinetic sieving is the primary segregation process, controlled by particle percolation and squeeze expulsion rather than settling of particles. This process promotes large particles to collect at the surface and at the perimeter of the flow resulting in lateral grading (Vallence, 2000). Observations suggests that rapid changes in along-flow behavior can be attributed to a low fines content and an unsteady flow regime caused by rapid deposition and downstream changes in the channels morphology (gradient, channel cross section and roughness) (Thouret et al., 1998). Gradual incorporation of water at the front of the lahar and subsequent dilution of the flow can also affect the behavior of the lahar, but it is only important for lahars traversing along water bodies (such as active rivers) and only so long as the volume of the lahar is not significantly greater than the volume of the water body (Vallence, 2000). The depositional processes have been suggested to be either incremental, or abrupt "freezing", where the deposition occurs en masse, or as an intermediate process with alternating gradual accretion and fast, abrupt deposition (Vallence, 2000, Lavigne and Thouret, 2000).

In this way, the deposited volcanoclastic units produced by lahars can vary significantly from case to case as well as among the proximal, medial, and distal parts of each deposit, since lahars can change behavior downstream (see Fig. 1 to get an overview of relational and locational terms used in this article) (Table 1). Additionally, properties of lahars can vary temporally since the amount of unconsolidated debris available will change during continued lahar activity. A sustained lahar activity will therefore tend to transition into a normal flood since the available sediment will have been carried down slope in the earlier stages of the flow (Vallence, 2000).

Terrestrial lahar deposits vary from <100 m to 200 m in thickness. They can travel more than 300 km from the source and have volumes up to 3.8 km^3, as exemplified by the Chillos Valley Lahar from Cotopaxi volcano, Ecuador, and the Osceola mudflow from Mount Rainer, which are some of the biggest Holocene lahars known (Vallence, 2000; Vallence and Scott, 1997; Mothes et al., 1998).

Morphologically, the volcaniclastic units deposited by lahars often have channeled deposits in the center incising terraces of different elevations (eg. Thouret et al., 1998; Tanarro et al., 2010). The terraces are flanked by marginal levees and lobes, which together with arcute surface ridges reflect the unstable, surging nature of lahars. These marginal deposits often have steep, lobate snouts, which typically exhibit channels in the distal parts of the deposits due to the more watery, erosive, final waning stage of the lahar formation (Vallence, 2000, Major and Iverson, 1998). An overview of typical morphologies and stratigraphic relations for terrestrial lahars are summarized in Fig. 1 and in Table 1.

2. Geologic setting

The study area range from −1100 m to −4300 m in elevation and encompasses the northwestern part of the Elysium rise, the western part of Galaxias Chaos and the transition into Utopia Planitia (138°–145°E; 31°N–40°N) (Fig. 2). This study area contains