Lahars in the Elysium region of Mars

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ABSTRACT

Photogeological studies of the Elysium volcanic province, Mars, show that its sinuous channels are part of a large deposit that was probably emplaced as a series of huge lahars. Some flows extend 1000 km from their sources. The deposits are thought to be lahars on the basis of evidence that they were (1) gravity-driven mass-flow deposits (lobate outlines, steep snouts, smooth medial channels, and rough lateral deposits; deposits narrow and widen in accord with topography, and extend downslope); (2) wet (channeled surfaces, draining features); and (3) associated with volcanism (the deposits and channels extend from a system of fractures which also fed lava flows). Heat associated with magmatism probably melted ground ice below the Elysium volcanoes and formed a muddy slurry that issued out of regional fractures and spread over the adjoining plain. The identification of these lahars adds to the evidence that Mars has a substantial volatile-element endowment.

INTRODUCTION

Perhaps the most fascinating result of the spacecraft missions to Mars was the discovery of numerous sinuous channels that resemble those produced by fluvial erosion on Earth (Baker, 1982; Mars Channel Working Group, 1983). The presence of the channels is taken as evidence that some fluid, generally believed to be water, flowed across the surface of Mars and formed the valleys. The genesis of the channels by flowing water is perplexing in that liquid water is not stable at the present surface of Mars. Various explanations for the occurrence of liquid water at the surface include climate change, the outbreak of aquifers confined to depths at which liquid water is stable (greater than about 1 km; Carr, 1979), and the melting of ground ice by magmatic heat (Masursky et al., 1977).

In this paper I outline the geomorphic evidence that lobate channelled deposits in the Elysium volcanic province of Mars are lahars, as initially suggested by Christiansen and Greeley (1981). The apparent source of the lahars lies beneath the Elysium volcanic province. This conclusion bears upon the “volcanic” origin of some channels and adds to the evidence for extensive subsurface reservoirs of volatiles on Mars (Carr, 1986).

GEOLOGIC SETTING

The reputed lahars extend 1000 km from their sources, cover an area of 1,000,000 km², and probably have a cumulative volume exceeding 100,000 km³ (Fig. 1). The deposits occur on the steep northwestern slopes of a flexural dome in the Martian lithosphere (Hall et al., 1986). The topographic dome is about 2000 km across and stands 3 to 5 km above the surrounding plains of the northern hemisphere. The dome is transected by northwest-trending fractures and grabens and is capped by lavas that erupted from these fractures and from three shield volcanoes centered on the fracture system. Elysium Mons is the largest of the shields and is closely related to the channelled deposits described here; it rises 13 km above the dome and is about 600 km in diameter. Details about the geology of the Elysium volcanic province are given by Malin (1977), Mougins-Mark et al. (1984), and Greeley and Guest (1987).

WHAT ARE LAHARS?

Lahar is the Indonesian name for a volcanic debris flow. Summarizing from Fisher and Schmincke (1984), lahars are (1) mass-flow...
deposits, (2) wet (water acts as a mobilizing agent), and (3) generated as the direct or indirect result of volcanism. Using these criteria, the Elysium channels and associated deposits are interpreted as lahars. The evidences against alternative modes of origin (stream erosion, debris avalanche, pyroclastic or lava flow) of these channelled, lobate deposits are also considered in this context.

Lahars Are Mass-Flow Deposits

Many types of genetically diverse mass-flow deposits exist (mud and debris flows, lava flows, pyroclastic flows, landslides, and glaciers). All are produced by the gravity-driven flow of viscous, non-Newtonian fluids that have significant yield strengths. As a consequence, their deposits are morphologically similar; steeply sloping lobate snouts and distinctly elevated margins reflect their generally non-Newtonian behavior. Debris flows have marked lateral deposits that flank medial deposits created by pluglike flow of the central part of a debris tongue (Johnson, 1970). In plan view, most mass-flow deposits consist of multiply digitate lobes of material that came to rest at slightly different times. In general, where slopes are steep (and velocities high) the deposits left by all types of mass flow are relatively thin, or absent, and become thicker and broader on the gentle slopes of unconfined plains. The surfaces of lahars are smooth and have gentle undulations resulting from differential compaction of the debris (Fisher and Schmincke, 1984; Siebert, 1984). The smoothness of lahar surfaces is important in distinguishing them from volcanic debris avalanches formed by sector collapse, which have hummocky surfaces and numerous hills (as much as 2 km across and 200 m high) and small mounds (Siebert, 1984).

Lahars, like other gravity-driven mass flows, originate upslope, course down preexisting valleys or troughs, and terminate downslope. The passage of the debris stream is marked by a relatively thin accumulation of debris with a well-defined snout, smooth medial deposits, and rough coarse-grained lateral deposits. Terrestrial lahars are generally less than 5 m thick but range from less than 1 m to more than 200 m thick (Fisher and Schmincke, 1984).

The simple observation that the Elysium landforms described here are gravity-driven mass-flow deposits and not fluvial erosion channels can be made from Viking orbiter images. Figure 2 shows a remarkable example of the morphology and definition of the deposit and its margins revealing its similarity to some types of mass-flow deposits. Snouts or flow fronts are well defined; medial deposits (where not cut by later water flow) are developed inboard and are generally smooth, like debris flows but unlike volcanic debris avalanches. Also like typical lahars, multiple, overlapping lobes are prominent

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Figure 2. Southern margin of lahars associated with Granicus Valles is composed of broad multiple lobes like those shown here, with rough, pitted lateral deposits (l) and smooth medial deposits (m). Viking orbiter frames 612A48 and 612A50 show area about 90 km across. See Figure 1 for orientation of figures.

Figure 3. Sinuous channels of Granicus Valles cross surface of lahar near its source trough (A). Channels are broadly sinuous, have streamlined features on their floors, and form anastomosing distributary pattern. Valleys become broader and shallower to northwest before they merge with smooth surface of sedimentary deposits. Northern margin (B) of lahar buries older lava flows erupted from fissure/through source (C). Viking images 541A20, 541A22, 541A345, and 541A37. Area shown is 250 km across.
Shadow measurements here indicate that the flow front is less than 100 m high. The flow deposits trend down the western flank of the Elysium dome, dropping approximately 5000 m over the 1000 km course. Much of the drop occurs in the first 100 km (Downs et al., 1982). Where the slopes are steep, narrow chutes with no deposits developed; at the break in slope marking the base of the dome, the fan-like deposits less than 200 m thick (preexisting impact craters protrude) bury older lava plains (Fig. 3).

Lahars Are Wet
By definition, lahars are intimate mixtures of liquid water and solids. For example, the matrices of 1980 Mount St. Helens lahars contained 2 to 36 vol% water (Pierson, 1985). Although most lahars move by nonerosive laminar flow, those on steep slopes of volcanoes and with high proportions of water may erode narrow channels (Fisher and Schmincke, 1984).

On Earth, water separates from the granular matrix of debris flows by downward infiltration, by upward expulsion, and by evaporation (Lawson, 1982). Such dewatering may cause surface ponding of water and consequent smooth accumulations of sediment, branching sapping valleys, and even collapse pits (Singewald, 1928; Lawson, 1982, Kochel et al., 1985; and Higgins, 1984). These sapping and piping features are the best geomorphic evidence that debris flows are emplaced with a significant proportion of water. In addition, after the emplacement of many lahars, relatively underloaded flood waters (issuing from the same sources that created the debris flows) erode earlier deposits to form runoff (in contrast to seepage) valleys (Johnson and Rodine, 1984).

Several lines of evidence demonstrate that the Elysium flow deposits were wet. The most obvious indications of water are their channeled surfaces. Several investigators have concluded that the channels were caused by fluvial erosion (Malin, 1976; Mouginis-Mark et al., 1984); however, their intimate association with the flow deposits (Fig. 1) suggests a genetic connection with the deposits. The largest channels at Granicus Valles (Fig. 3) are near the source of the debris flows and appear to have been cut during a late water-rich phase of the development of the deposits. These channels are gently sinuous, have streamlined features on their floors, and have anastomosing distributary patterns. These valleys have analogs in the runoff channels associated with debris flows on Earth.

To the northwest, the sinuous channels disappear by merging with smooth medial deposits. About 75 km farther "downstream," stubby tributaries start up and merge to form broad smooth-surfaced channels (Fig. 4). The reappearance of these branched channels suggests that they are seepage valleys formed as pore waters were expelled to the surface; the presence of tributaries is inconsistent with an explanation involving incomplete burial of channels by younger deposits. Short reticulate systems of sinuous valleys (individually less than about 5 km long) cut the distal parts of the deposits and are similar to seepage channels on terrestrial lahars (Fig. 5). The pitted nature of the channeled landforms (Fig. 2) may be the result of dewatering of coarse-grained marginal deposits—either by more active piping associated with downward draining, or as a result of enhanced evaporation of the included water. Distal channels are filled by dark flow materials resembling...
material remobilized by draining of the deposit (Fig. 5). The geomorphic evidence for the presence of liquid water in the deposits argues against an interpretation of the lobate features as dry lava or ash flows.

**Lahars Are Associated with Volcanism**

Lahars may be related to eruptions directly (by incorporation of ice, snow, ground water, or stream water into pyroclastic flows or surges) or indirectly (by mobilization of volcanic materials on the slopes of volcanoes by torrential rains, by rapid melting of snow or ice, or by draining of a crater lake).

Debris flows of the Elysium region are apparently linked with volcanism. Regional mapping shows that lavas and debris flows formed late in the evolution of the volcanic province. The source of the Granicus lahars and channels (Fig. 3) is an elongate trough formed on the steep western flanks of the Elysium dome. Adjacent troughs to the north fed lava flows (with no evidence of associated channels or surface drainage features) and lahars (Figs. 1 and 3). The lava sources and the lahar sources all trend west-northwest and are part of the regional fracture system that transects the Elysium dome and apparently localized the volcanoes (Fig. 1). Although most of the lahars are younger than the voluminous fissure-fed lavas, locally they are older (cf. Mougins-Mark, 1985). These observations show the close spatial and temporal association of volcanism and lahar generation.

The estimated volume of the lahars is 10 to 100 times greater than that of troughs from which they emanate. In contrast, for volcanic avalanche deposits, source scar and deposit volume are equal. When this fact is combined with the photogeologic evidence that the debris flows and channels issue from fractures, it is probable that both debris and water came from below the surface of the volcanic province.

**ORIGIN OF ELYSIUM LAHARS**

The lahars of the western Elysium region appear to have been generated as a result of parastic eruptions on the northwestern flanks of the Elysium dome (Fig. 1). Mougins-Mark (1985) and Christiansen and Hopler (1986) have presented independent evidence that volcanic-ice deposits lie beneath at least the western part of the Elysium province. Elevated heat flow related to the development of the fissure-fed flow eruptions may have melted ground ice and mobilized subsurface materials. Squires et al. (1987) showed that intrusions into ice-rich permafrost should produce large amounts of liquid water; they calculated that the thickness of a liquid water layer produced by melting related to a sill intruded in permafrost with 25% ground ice would be comparable to or greater than the thickness of the sill itself. Direct contact between magma and water is difficult to prove at this point, but it may have generated abundant fine palagonitic particles as well as superheated steam (Wohletz, 1986). The intersection of a mixture of fine particles and water with the regional fracture system may have led to the rapid and perhaps explosive expulsion of debris flows down the western slope of the province. Where slopes were steep near the source, erosional troughs developed; where the slope was gentler on the plains northwest of Elysium, the vast lobate deposits formed and were later cut by continued draining of water from the fractures and from the deposits.

**CONCLUSIONS**

Lobate deposits with well-defined snouts, medial channels, and lateral deposits issue from a northwest-trending system of fractures that cut the Elysium dome. They extend 1000 km down the regional slope to the northwest and cover 1000,000 km². Geomorphic evidence that these channeled deposits were debris flows and not the results of stream erosion, dry avalanches, lava flows, or pyroclastic flows includes the presence of (1) discernible deposits with apparently fluvial runoff valleys on their surfaces; (2) seepage valleys; and (3) numerous irregular depressions representing dewatering of the deposits. The debris flows issued from the same set of fractures that fed extensive flank eruptions of Elysium Mons, suggesting their association with volcanism. On the basis of this evidence, these channeled deposits are best interpreted as lahars resulting from the interaction of volcanism with a reservoir of volatiles (probably water) buried in the Martian crust.

**REFERENCES CITED**


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