Recent Water Release in the Tharsis Region of Mars

PETER J. MOUGINIS-MARK
Planetary Geosciences Division, Hawaii Institute Geophysics, University of Hawaii, Honolulu, Hawaii 96822

Received January 28, 1988; revised July 17, 1989

Numerous channels have been identified in northwestern Tharsis, Mars, at the base of the Olympus Mons escarpment and to the west of Ceranuus Fossae. These channels are anastomosing in form, and have associated streamlined islands, indicating that they were most likely formed by flowing water. The preferred model for channel formation involves either the tectonic release of water from a deep groundwater system or, less likely, the intrusive heating of deep-seated ice lenses. Because the channels are carved in some of the youngest lava flows on Mars, it is believed that water or ice existed at certain places at equatorial latitudes until the recent (<1 byr B.P.) past.

INTRODUCTION

The interaction of magma with water and ground ice appears inescapable if the climatic regime of Mars during volcanic epochs was similar to its current state (cf. Soderblom and Wenner 1978, Hodges and Moore 1979, Allen 1979, 1980). Indeed, since the earliest investigations of the Mariner 9 data set (Sharp 1973a,b), it has been recognized that the interaction between volcanism and ground ice, and the subsequent generation of melt water, has probably been an important geologic process on Mars. Examples of this proposed interaction include the existence of pseudocraters (Frey et al. 1979, Allen 1980), tablemountains (Hodges and Moore 1979, Allen 1979), and several outflow channel systems close to volcanic constructs (Mouginis-Mark 1985, Squyres et al. 1987). Recently, Wilhelms and Baldwin (1989) have also explored the possible role played by igneous sills in the shaping of the Martian uplands and concluded that the nonconcentrated thermal source provided by intrusions might explain a number of otherwise puzzling phenomena in this area.

In the case of the channels to the west of Elysium Mons, intrusive activity radial to the summit of the volcano was inferred to be the most likely cause of late-stage heating of the ground ice (Mouginis-Mark 1985). For Dorsa and Harmakhis Valles (to the south of Hadriaca Patera), Squyres et al. (1987) attributed the formation of the channels to the emplacement of lava flows upon a layer of permafrost, with the release of melt water due to basal heating by the lavas and subsequent collapse of the overlying materials.

Most of the volcanic centers with associated melt water features are relatively old (Greeley and Spudis 1981, Neukum and Hiller 1981, Wilhelms and Baldwin 1989), placing the possible melt water release at a relatively early time in Martian history. Such an observation supports the idea that volatiles have been cold trapped at high latitudes over the history of the planet (Fanale et al. 1986). However, recent studies of small channels in the Mangala (Masursky et al. 1986) and Memnonia (Scott and Chapman, 1989) regions of Mars have shown that in certain instances small channels of probable fluvial origin could form at equatorial latitudes.

This paper describes several additional exceptions to this hypothesized global trend of geologically early volatile migration toward the poles and documents examples of water release that took place upon some of the youngest lava flows within northwestern...
Tharsis. The channels described here are located to the east of the Olympus Mons escarpment and to the west of Ceraunius Fossae, which are areas believed to comprise Java flows that may be several kilometers in total thickness (Scott and Tanaka 1981, Solomon and Head 1982). The materials at the base of the Olympus Mons escarpment have been mapped as a series of young lava flows by Scott et al. (1981; Unit Aop) and form a relatively smooth surface with a very low crater density (~90 craters >1 km diameter per 10 km²; Scott et al. 1981). These lava flows are interpreted to be the youngest sequence in the Tharsis region, formed by eruptions from faults and fissures in the plains to the east of Olympus Mons. Because of their location in a young volcanic area, the channels described here may have been formed by water released by intrusive events and, by virtue of their young age and near-equatorial location, are likely to be of importance for interpreting the recent distribution of volatiles on Mars.

NEW OBSERVATIONS

Analysis of Viking Orbiter images with 25–210 m/pixel resolution has revealed numerous channels (Fig. 1 and Table I) within

<table>
<thead>
<tr>
<th>Channel No.</th>
<th>Viking Pic. No.</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Resolution (m/pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>465S24</td>
<td>16°N</td>
<td>129°W</td>
<td>51</td>
</tr>
<tr>
<td>2</td>
<td>465S33-36</td>
<td>19°N</td>
<td>129°W</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>690A17-24</td>
<td>13°N</td>
<td>129°W</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>808A42, 71</td>
<td>13°N</td>
<td>129°W</td>
<td>137</td>
</tr>
<tr>
<td>5</td>
<td>808A35*</td>
<td>28°N</td>
<td>127°W</td>
<td>167</td>
</tr>
</tbody>
</table>

Note. * Due to limitations in image resolution, these frames were used to give only a tentative identification of fluid channels.

Two of the most intriguing channels identified are located within 20 km of the base of the Olympus Mons escarpment, at 13°N, 129°W and at 16°N 129°W. A small outflow channel (channel 1, Table I) is associated with an arcuate graben located at 16°N 129°W, which is ~15 km from the base of the escarpment (Fig. 2). This channel is ~85 km in length, is braided, and comprises three main segments, each with widths of 300–1,600 m. Numerous streamlined islands (Fig. 3), similar to the examples described by Baker and Kochel (1979) and by Kochel (1981), are found within a distance of 20 km from the open end of the graben, and a series of cataracts can also be seen. Atmospheric haze precludes the confident determination of depths for all the channel segments, but digital measurement of shadow lengths from the calibrated version of Viking image 468S33 indicates that the channel system is quite shallow. Five scarp heights were measured (see Fig. 3A), and gave an average depth of ~23 m.

This average depth permits an estimate of the channel volume to be derived. Measurements of all the segments of channel 1 give a surface area for the entire system of ~50 km². Assuming that all of the channels are the same depth (clearly only a generalization, since locally the cataracts and distribution identified in Fig. 3B appear to have very different depths), the volume of mate-
FIG. 1. Distribution map of the fluvial channels identified within northwestern Tharsis in this analysis, with the channel numbers keyed to Table 1. Where it can be confidently identified, each arrow indicates the direction of water flow. Random stipple areas mark the locations of Olympus Mons aureole deposits. The fractures associated with Tharsis doming are also shown.
Fig. 2. High resolution (24 m/pixel) view of the arcuate graben located 15 km from the Olympus Mons escarpment that has probably acted as a conduit for the released water that formed channel 1. Areas outlined denote locations of Figs. 3 and 4. Viking Orbiter frame 468S53. Image width is equivalent to ~23 km. North is to top left of image.
Fig. 3. (A) Computer enhancement of subsence from Viking image 468553 (see Fig. 2 for location). A 155 x 155 pixel high-pass filter, followed by a linear stretch from DN = 65 to 165 were applied to the data after removal of pixel drop outs. Arrows show the locations where shadow length measurements were made. Image width equivalent to 13.4 km. (B) Morphologic sketch of the braided portion of channel I (area is the same as Fig. 3A). Although the direction of flow cannot be persuasively identified, two features suggests that the flow direction was from the northeast to southwest (top to bottom of image). At 'A' the shape of the segments of the channel are more consistent with a merging flow than divergent flow. The area of cataracts (cross-hatched area to east of point 'A') appears to deepen toward the south, again supporting the idea of flow from the northeast. However, other landforms are either noninformative or could suggest flow toward the northeast: streamlined islands (dotted areas) do not show any preferred orientation or flow structures, while several sink holes ('S') could equally be interpreted as distributed source areas for water flowing northward. Barbs show drop in topography, dashed lines indicate areas where boundaries are only approximate. Note the variable channel depth (relatively shallow at 'x' and deep at 'y').
rial removed from channel 1 is \( \sim 1.15 \text{ km}^3 \). Taking Komar's (1980) estimates for the erosional efficiency of surface water flow on Mars, a minimum estimate for the volume of water released to create channel 1 would be \( \sim 3 \text{ km}^3 \) (erosion efficiency of 40%), while a more plausible volume estimate for the water released from channel 1 would be \( \sim 12 \text{ km}^3 \) (erosion efficiency of 10%).

Two alternative interpretations are possible for the origin of the water that is presumed to have carved channel 1, and as such have a bearing on the potential role of late-stage igneous activity producing this water release: (1) That the water was released from the graben, which acted as a point source; or (2) That there was a distributed set of sources for the water and that the graben acted as a major sink for the majority of the water. Unlike the Elysium Fossae
graben and Dao Vallis (Mouginis-Mark 1985; Squyres et al. 1987), no landforms indicative of large-volume water release at a source, such as chaotic terrain, can be found at the inferred source of channel 1 (Fig. 4). Nevertheless, the incision of cataracts on the channel floor which evidently became progressively deeper toward the south (Fig. 3), the streamlined shape of a major confluence within the braided channel ("A" in Fig. 3B), and the observation that flow toward the south is consistent with the flow directions of lava flows in this area (Mouginis-Mark et al. 1982) all suggest that the graben was the point source for the water.

The ultimate fate of the surface water is unclear, since many of the channel segments appear to braid into subdued deltas at their southern extents or may be covered by subsequent deposits at their distal ends. Several channel segments do, however, end in what appear to be sink holes or ponds (Fig. 3B), which could have allowed some of this water to have percolated back underground, or to have permitted evaporation from confined basins.

A second series of small outflow channels (channel 2, Table I) has also been identified to the south of this first locality, within 120 km of the Olympus Mons escarpment at 13°N, 129°W. This set of channels also appears to originate from a fracture in the young lava flows surrounding Olympus Mons, and has produced a series of braided distributaries ~65 km in length. Furthermore, although image resolution does not permit detailed analysis, there are several additional graben to the east of Olympus Mons that appear from 150–220 m/pixel Viking images to be likely candidates for water outflow channels (Fig. 1). Channel 3 (Table I) which is associated with graben to the east of parts of the aureole material (at 20°N, 125°W) is the most likely candidate for a water channel in this area.

Despite the lack of Viking images comparable in resolution to those used to investigate channel 1, additional examples of probable fluid flow at some time after the eruption of the Aop lava flows in the Tharsis region (Scott et al. 1981) have also been studied here. Prorabed among the previously undocumented channels is a 400-km-long braided system (channel 4, Table I) to the west of Ceraunius Fossae that includes Olympica Fossae (Fig. 5). Viking Orbiter images with a resolution of 75–205 m/pixel reveal that in addition to the main channel, an anastomosing network of subdued channels ~20 km wide parallel Olympica Fossae for over 300 km. Both channel systems originate in a fracture located at 26°N, 111°W that is part of the complex of graben associated with Ceraunius Fossae.

For the main Olympica Fossae channel, the maximum width is ~4 km, and in several places the channel is divided into 3–5 subchannels. Streamlined islands also occur within Olympica Fossae, and the subdued channeling of the rim indicates that multiple episodes of bank overspill have taken place. Unfortunately, the low resolution and high sun angle of the Viking images precludes an estimate of the depth of Olympica Fossae.

The Olympica Fossae channel is but one of three subparallel channels that originate to the west of Ceraunius Fossae and flow in a generally west-southwest direction toward Olympus Mons (Fig. 1). Between Olympica Fossae and Halex Fossae, at 25°N, 122°W, additional channels can also be found that are a few hundred meters in width and ~450 km in length (channel 5, Table I). These channels appear to be preferentially located within an area of hummocky terrain that is different in morphology from the adjacent lava flows. Small channels (channels 6 and 7 in Table I) have also been found to the south and southwest of Olympica Fossae.

MODELS FOR WATER RELEASE

Although the surface flow of relatively small volumes (probably a few cubic kilometers) of water is evident from the Viking images, it is not immediately clear by what mechanism the original water or ice could have remained at this latitude and proximity...
to the Tharsis volcanoes until relatively recent times. Five possible models for the source of the subsurface volatiles have been investigated:

Model 1. Igneous activity supplied heat which modified shallow (top few hundred meters?) ice lenses which were relic from early Martian history. In this instance, water release at this latitude would mean that either the existing theoretical models for volatile migration on Mars (Fanale et al. 1986) require modification or that, for some unknown reason (such as unusually compact soils or the intercalated nature of the lava flows), the expected kinetics of ice withdrawal did not occur effectively in all equatorial sites.

Model 2. Igneous activity supplied heat which mobilized more deeply buried equatorial ice lenses which were relic from early Martian history. These lenses could originally have been at a shallow depth, but were subsequently more deeply buried (perhaps to more than a kilometer?) for most of their history and were exposed by the faulting associated with the graben in this area. In this instance, the general model for global volatile migration remains intact but also needs to be modified to consider local temporal variations of surficial geology due to the emplacement of younger lava flows and, possibly, aeolian materials.

Model 3. Relic ice lenses were heated by an igneous event, but these ice lenses were not truly remnants of the earliest Martian atmosphere (i.e., ice that was distributed randomly across the planet during the late heavy bombardment of Mars). Rather, these ice lenses could have originated from, say, volatile deposition following more recent volcanism when certain Tharsis volcanoes such as Alba Patera were probably erupting.
Fig. 5. Part of the middle reaches of Olympia Fossae (channel 4, Table 1), showing the main braided channel. Direction of water flow is from middle right to bottom left. Arrowed is a second, much more subdued channel system (channel 5, Table 1) that parallels Olympia Fossae for over 300 km. Viking Orbiter frame 39B47, centered at 25°N, 115°W. Image width equivalent to 80 km, large arrow points toward north.

Model 4. The release of ground water may have been unrelated to an igneous event, but took place within northwestern Tharsis due to tectonic deformation of the area due to loading of the surrounding plains by Olympus Mons. Deformation of the plains surrounding Elysium Mons has been investigated by Hall et al. (1986), and it is possible that loading of the adjacent plains by Olympus Mons and Alba Patera also led to fracturing of the adjacent surface materials. Model 4 also draws upon the model of Clifford (1987) in that the observed water could have been associated with the release of water transported over regional distances.

Model 5. For channels 1 and 2 the release of water may have come from a relic ice layer entrained within the basal materials that comprise the Olympus Mons escarpment. It has been hypothesized (Hodges and Moore 1979) that the basal layers of Olympus Mons may have had a subglacial origin, and that basal melting of ice may have promoted the gravity sliding that produced the Olympus Mons aureole materials (Lopes et al. 1982, Tanaka 1985). Water from this basal melting within Olympus Mons may thus have migrated to the surrounding terrain, where subsequent intrusions of faulting permitted the melt water to reach the surface.

Geomorphic analysis of the Viking image data permits these different models for ice storage and melt water release to be investigated. It is concluded (see below) that the most plausible models involve either heating of deep-seated ice lenses (Model 2), or release from a deep ground water system (Model 4), perhaps fed in the case of channels 1 and 2 by subsurface runoff from Olympus Mons (Model 5). Model 1 is believed to be unlikely because, were such shallow ice lenses still widely preserved on Mars, it is expected that the emplacement of the larger individual lava flows upon this terrain would also have been accompanied by the formation of pseudocraters or topographic depressions, or that the flows would have liberated sizable volumes of melt water at the surface (Allen 1980, Squyres et al. 1987); such phenomena are not seen even in the highest resolution Viking images of lava flows located within Tharsis (Scherer 1980, Thelig and Greeley 1986). Model 3 (recent deposition of volcanic fume) is also considered to be unlikely by virtue of the distance from the major vents on Olympus Mons (~350 km, and more than 25 km variation in elevation) and the very localized nature of these outflow channels. Were fume-charged ice lenses (i.e., ice deposits accumulated downwind of volcanoes erupting water-rich magmas) to be produced in this manner late in Martian history, it is believed that they would be more widespread and concentrated around the summits of the volcanoes rather than in specific locations at radial distances of several hundred kilometers.

In Model 2, a dike intrusion along a subsurface line of weakness, expressed at the surface as a graben, could be the cause of melt water generation and release at the surface. Alternatively, as is the case for certain other Martian channels (e.g., Mangala Vallis; Carr 1981), water release could be unrelated to igneous activity. It is thus possible that the loading of the Martian crust by Olympus Mons could have allowed water from depth (Model 4), or from subsurface runoff from Olympus Mons (Model 5), to reach the surface. Support for Models 2 and 4 also comes from the analysis of the other channel systems described here. In the case of Olympica Fossae (Fig. 5), water appears to have been released from graben in western Ceraunius Fossae, comparable to the source area for Mangala Vallis. Compared to channels 1 and 2, there is no direct equivalent to Model 5 (subsurface water flow off a volcanic construct) for Olympica Fossae. Either the channel systems have different origins or the released water that carved channels 1 and 2 did not originate from within the flanks of Olympus Mons.

Some consideration of the relative likeli-
hood of Model 2 and Model 4 is also possible. Although the geometry of Martian dikes and sills can only be inferred from terrestrial analogs (Knight et al. 1988), it is likely that the horizontal (and, possibly, the vertical) interface between a Martian dike/sill and subsurface ice lenses would be locally extensive. Such an interaction should thus release melt water over a large area of the surface from multiple sources. Since channel 1 appears to originate from a point source (Fig. 2), and Olympus Fossae are located almost 1500 km from Alba Patera (the nearest volcanic construct), an intrusive event is considered less likely as the cause of the melt water release (Model 2) than tectonic release of deep-seated water (Model 4). Image data do not permit Model 2 to be entirely ruled out, however, and the volume of water released at channel 1 (3–12 km$^2$) is well within the estimates of melt water release calculated by Squyres et al. (1987) for comparable volcanic–ground ice interactions south of Hadriaca Patera.

CONCLUSIONS

This analysis of fluvial channels demonstrates that water release took place in isolated areas within northwestern Tharsis until the relatively recent geologic past, and included episodes that postdate the emplacement of some of the youngest lava flows on the planet. While the origin and physical setting of the water remains unclear, the current observations lend additional constraints to our knowledge of the volatile history of Mars: (1) that ice lenses or deep-seated aquifers were probably preserved for extended periods of time at depths of perhaps a kilometer or more over much of the planet, including near-equatorial latitudes; (2) that in certain very specific localities geologic conditions were such that this water could be released to the surface even in geologically recent times; and (3) that while dike intrusions may have served as a catalyst for melt water release at the surface, there is no compelling reason to infer that intrusive events were a necessary component in this process. Thus Martian dikes hundreds of kilometers in horizontal extent need not be hypothesized to exist on the basis of the locations of water release within the Tharsis region.

ACKNOWLEDGMENTS

I thank Mark Robinson for making the shadow length measurements of channel 1 and for the preparation of Figs. 2–4, Cassandra Coombs, Fraser Fanale, and Susan Postawko for their comments on an early draft of this manuscript; and David Pieri and Peter Schultz who provided helpful discussions. This work was supported by NASA Grant NAGW-437 from the Planetary Geology Program. This is Hawaii Institute of Geophysics Contribution No. 2211.

REFERENCES


