ELYSIUM PLANITIA, MARS: REGIONAL GEOLOGY, VOLCANOLOGY, AND EVIDENCE FOR VOLCANO-GROUND ICE INTERACTIONS

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Abstract. Geological mapping of Elysium Planitia has led to the recognition of five major surface units, in addition to the three volcanic constructs Elysium Mons, Hecates Tholus, and Albor Tholus. These units are interpreted to be both volcanic and sedimentary or erosional in origin. The volcano Elysium Mons is seen to have dominated constructional activity within the whole region, erupting lava flows which extend up to 600 km from the summit. A major vent system, covering an area in excess of 75 000 km^2, is identified within the Elysium Fossae area. Forty-one sinuous channels are visible within Elysium Planitia; these channels are thought to be analogous to lunar sinuous rilles and their formation in this region of Mars is attributed to unusually high regional topographic slopes (up to $\sim 1.7°$). Numerous circumferential graben are centered upon Elysium Mons. These graben, located at radial distances of 175, 205–225, and 330 km from the summit, evidently post-dated the emplacement of the Elysium Mons lava flows but pre-dated the eruption of extensive flood lavas to the west of the volcano. A great diversity of channel types is observed within Elysium Fossae. The occurrences of streamlined islands and multiple floor-levels within some channels suggests a fluvial origin. Conversely, the sinuosity and enlarged source craters of other channels suggests a volcanic origin. Impact crater morphology, the occurrence of chaotic terrain, probable pyroclastic deposits upon Hecates Tholus and fluvial channels all suggest extensive volcano-ground ice interactions within this area.

1. Introduction

The Elysium Planitia region is the second largest volcanic complex on Mars, superseded in size only by the Tharsis region. Mapping of Elysium from Mariner 9 images (Scott and Allingham, 1976; Malin, 1977) revealed that this volcanic region is centered at about 25° N, 212° W and consists of a broad dome which measures about 1700 x 2400 km in extent. Located atop this dome are the three volcanic constructs Hecates Tholus, Elysium Mons, and Albor Tholus (Figure 1).

Initial geological analysis of Viking Orbiter images has shown that Elysium possesses a more diverse volcanic history than that of Tharsis. In addition to numerous lava flow units, both volcanic and fluvial channels are observed (Christiansen and Greeley, 1981; Mouginis-Mark and Brown, 1981; Baker, 1982) as are probable large-scale pyroclastic

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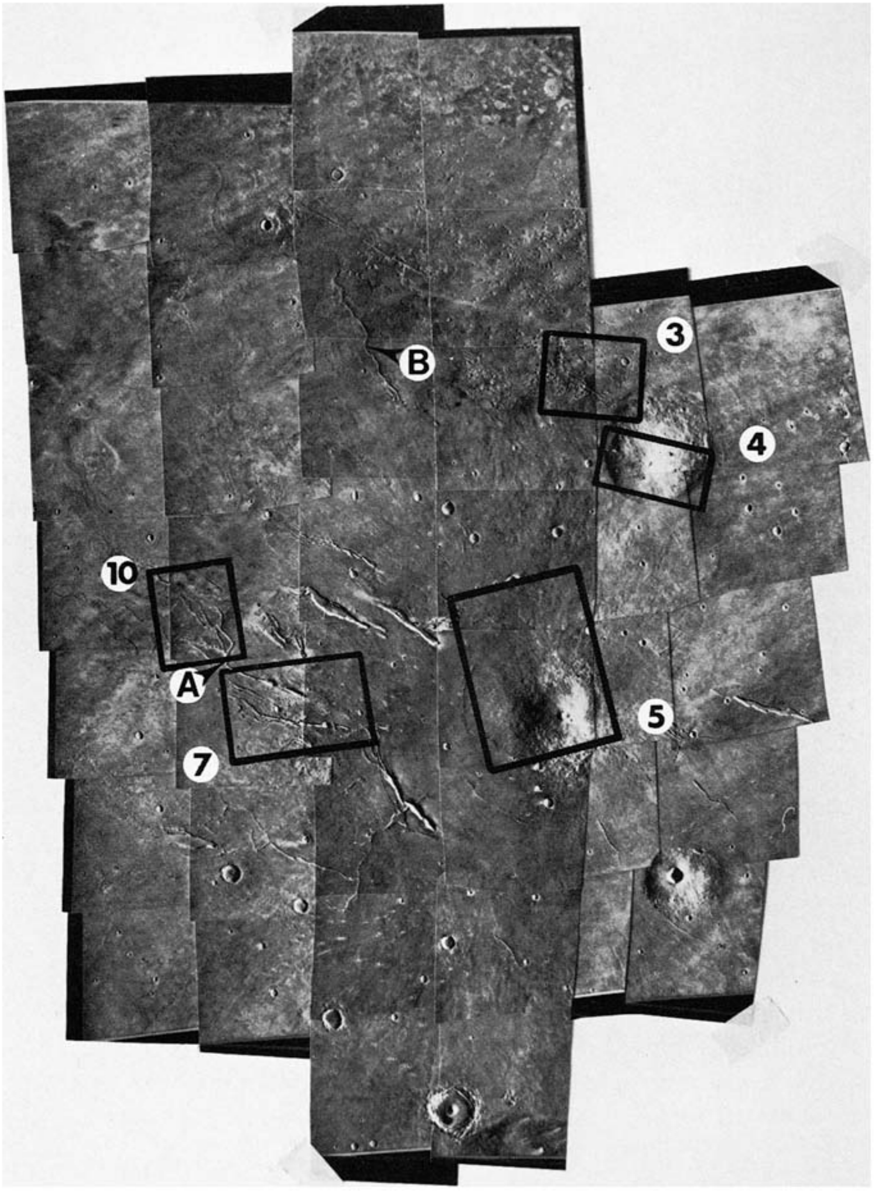

Fig. 1. Photomosaic of Elysium Planitia, showing the three principle volcanoes and Elysium Fossae. Outlined are the locations of Figures 3, 4, 5, 7, and 10. Measurements of channels 'A' and 'B' are presented in Figure 12. Mosaic compiled from Viking Orbiter frame numbers 844A13–22, 844A37–46, and 846A13–22. See Figure 2 for the locations of the volcanic constructs and the coordinates of this mosaic.

deposits near the summit of the volcano Hecates Tholus (Mouginis–Mark *et al.*, 1982a). Due to its size and relatively good state of preservation, Elysium represents a useful second example of a constructional volcanic province which can be compared to Tharsis in order to interpret further the volcano–tectonic evolution of Mars.

Any model for the origin and evolution of the Tharsis province should also be applicable to the Elysium region. Geophysical data indicate that a broad positive free-air gravity anomaly is associated with the observed topographic rise of Elysium Planitia (Sjogren, 1979), from which Solomon and Head (1982) concluded that it is unlikely that a thermal mechanism is responsible for the origin of the Elysium Dome. Based on the spacing of preserved graben around Elysium Mons, Comer *et al.* (1980) estimated the thickness of the elastic lithosphere beneath the volcanic constructs to be 50 ± 10 km. Results of gravity measurements derived by Bills and Ferrari (1978) suggest that the crust is thicker by 15–25 km beneath Elysium than below adjacent areas (compared to 35–50 km thicker beneath Tharsis than adjacent areas). Assuming an Airy model for crustal structure, crustal thickness has been determined as 30–100 km by Janle and Ropers (1982); they also calculated a minimum lithospheric thickness of 150 km assuming a Pratt model.

In addition to being an analogue to Tharsis in terms of its geophysical evolution, Elysium Planitia also represents a second example of an area in which large volcanoes have been constructed on Mars. Thus this area permits a further analysis of the spatial distribution of vents, their relative importance (in terms of magma volumes) and their temporal distribution. Furthermore, initial analysis of landforms on the perimeter of Elysium Planitia (Carr and Schaber, 1977; Christiansen and Greeley, 1981; Mouginis-Mark and Brown, 1980) has revealed several candidate examples of volcano–ground ice interactions. Such interactions have been proposed for several other regions of Mars (cf. Allen, 1979), but have not been recognized in such intimate association with geologically recent volcanism, such as Tharsis. A better understanding of the geology of Elysium Planitia will not only provide additional constraints on martian geophysical and volcanological problems, but may help to constrain the more recent volatile distribution within the upper crustal layers.

2. Surface Geological Units

The mapping from Viking Orbiter medium (150–250 m/pixel) and high (40–60 m/pixel) resolution images has identified five distinct surface units within Elysium Planitia in addition to the volcanic constructs (Figure 2):

Flood Lavas: This is the stratigraphically youngest unit within Elysium Planitia. Some lobate flow fronts are visible within this unit, but it is not possible to recognize complete flows, nor can the flow direction or vents be identified. The flood lavas are cut in a number of places by graben that are circumferential to Elysium Mons; it appears, however, that most of these graben are 'inherited' from the underlying topography (i.e., the graben have been buried by younger materials and have since been reactivated), due to their subdued appearance compared to other examples close-by, and to their lower frequency of occurrences.

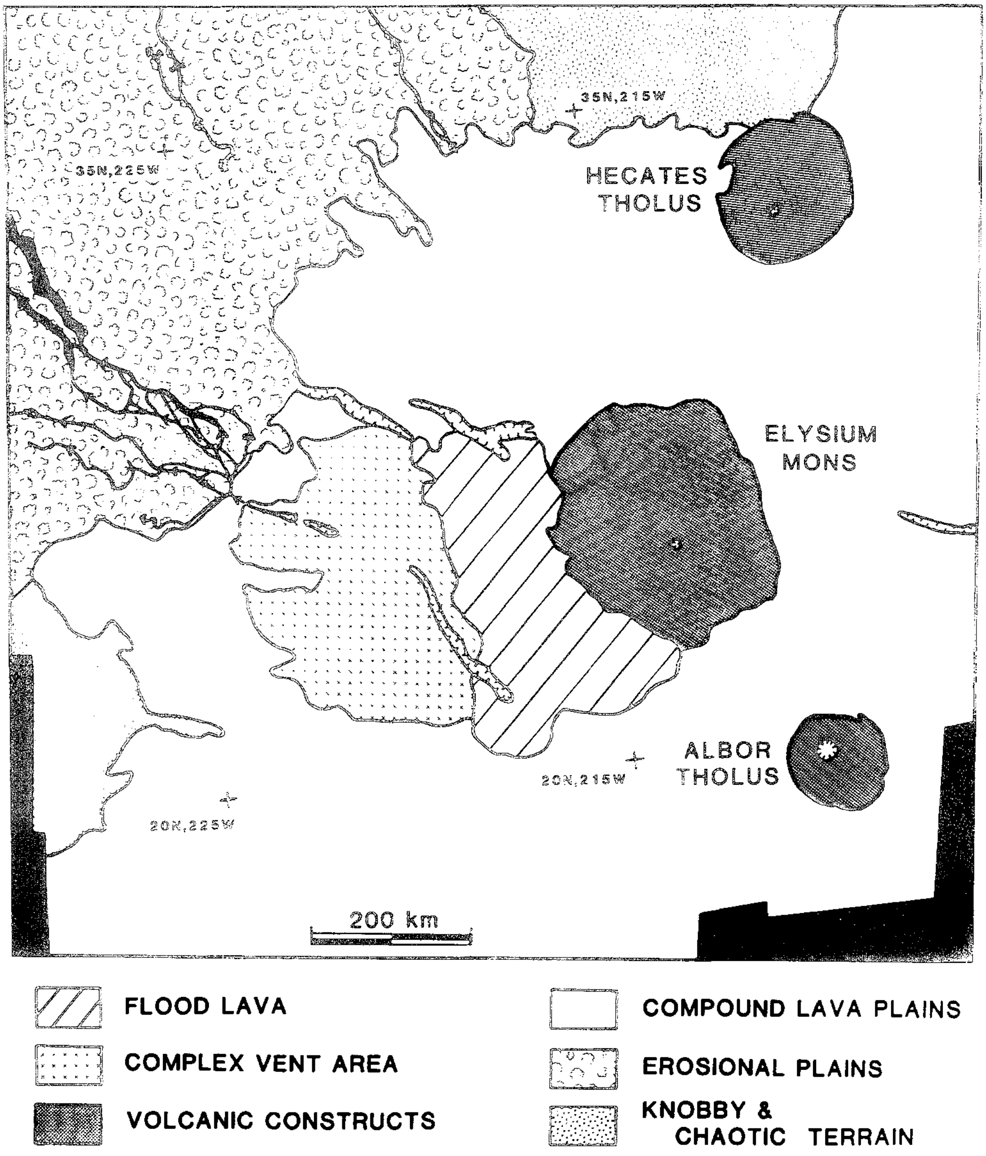

Fig. 2. Morphological map of surface units within Elysium Planitia. Graben are indicated by hatched outlines, while channels are shown by single lines with arrows depicting the direction of flow. Map prepared using Figure 1 as base map.

Complex Vent Area: Mouginis–Mark and Brown (1981) recognized that the area to the west of Elysium Mons contains many pit craters, source craters for channels and sinuous rilles, and is generally very hummocky with numerous dome-shaped features. This unit, which appears to have formed prior to the emplacement of the flood lavas, is considered in greater detail in the section on volcano morphology.

Compound Lava Plains: This is an areally very extensive unit, which almost surrounds Elysium Mons and extends as much as 800 km from the summit. The primary distinction between this unit and the *flood lavas* is the large number (more than 100) of individual flow lobes which can be detected in this unit. These lava flows are visible over much of this unit and it is likely that more than one phase of volcanism can be recognized here. On all flanks of Elysium Mons, but particularly to the north, these lava plains grade into the flows preserved on the lower and middle slopes of the volcano, indicating that much of the plains material has a strong affinity to the volcano. Flows from Elysium Mons that comprise part of the compound lava plains are responsible for the partial burial of both Albor and Hecates Tholi.

Erosional Plains: Christiansen and Greeley (1981) postulated this plains unit to the north and west of Elysium Fossae to be mega-lahar deposits, primarily because it has a channeled and hummocky surface and the occurrences of features morphologically similar to erosion and deposition products of terrestrial mudflows. While it is probable

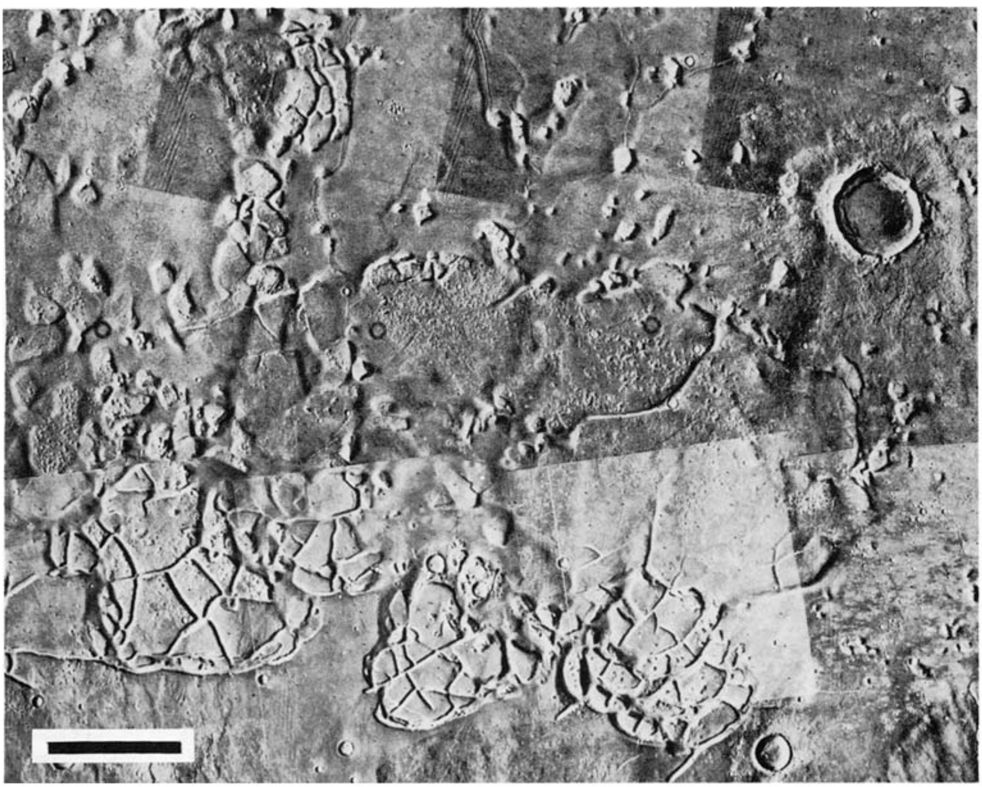

Fig. 3. To the north and west of Hecates Tholus is located an extensive area of knobby and chaotic terrain. The upland plains (bottom of this image) appear to have partly collapsed and have been eroded to produce isolated upland remnants over 10 km in size. Part of JPL mosaic 211–5274. Scale bar is 20 km.

that mudflow deposits do not exist at the distal ends of some of these channels (see the section below on channel morphology), we find insufficient evidence to support the interpretation that all of the unit mapped by Christiansen and Greeley is a sequence of lahar deposits. Etched and hummocky terrain is not always associated with the channels, nor does a channel lie 'upstream' from all the observed deposits.

Knobby and Chaotic Terrain: The existence of collapsed terrain and isolated highland remnants was first described by Sharp (1973) from Mariner 9 images. He interpreted these materials to have formed by the undermining and collapse of the pre-existing upland surface, probably as the result of the melting of ground ice. Two outcrops of this unit are visible in the mapped area: the northernmost is the most pronounced, with polygonal remnants more than 10 km in diameter preserved in a transition zone more than 30 km in width (Figure 3). At this location, a sequence of Elysium Mons lavas comprises the upland unit to the west of Hecates Tholus, while the lowland unit grades into the northern plans of Utopia Planitia (Scott and Carr, 1978). There is no evidence of lava flows extending northward beyond, or over, this escarpment, indicating that collapse (possibly due to the melting of ground ice) occurred after the emplacement of the lava flows. In the southwestern portion of the study area, more subdued relief is seen at a second exposure of this knobby and chaotic material. Most of the upland remnants (presumed to originally be part of the compound lava plains) are fragmented into mesas less than 5 km wide and most of them are located at the distal end of a graben that has possibly been utilized as an outflow point for melt water.

3. Ages of Surface Units within Elysium Planitia

Detailed crater counts of several units within Elysium Planitia by Plescia and Saunders (1979) and Neukum and Hiller (1981) permit the relative ages of these units to be compared. Based on the number, N, of craters larger than 1 km diameter per 10^6 km^2, Plescia and Saunders (1979) found that Elysium Mons is the oldest construct ($N = 2350 \pm 153$), followed in decreasing age by Hecates Tholus ($N = 1800 \pm 351$) and Albor Tholus ($N = 1500 \pm 263$). These values imply that the summit of Elysium Mons is older than the summit of Hecates Tholus, although both Plescia and Saunders (1979) and Neukum and Hiller (1981) found evidence for resurfacing events on Hecates (consistent with the postulated air-fall deposits that mantle parts of Hecates; Mouginis-Mark *et al.*, 1982a).

Selective measurements of crater densities on both the Elysium shield ($N = 4800$) and adjacent lava plains ($N = 1200$–2900) by Neukum and Hiller (1981) indicate that flank activity occurred appreciably after the summit was constructed, but that the time of emplacement of these lavas spanned the period of formation of the knobby and chaotic terrain ($N = 2000$) to the northwest. Resurfacing of parts of the lower Elysium Mons shield is indicated by the slight excess of large relative to small craters compared to the average crater size distribution curve.

To the west of Elysium Mons, between the volcano and the Elysium Fossae vents, is located a series of circumferential graben, numerous lava flows that are subradial to the summit, and an extensive area of lava flows which we have mapped as 'flood lavas' on our terrain map (Figure 2). Without exception, all of these graben appear to post-date the individual lava flows where superposition relationships are clear. While it is possible that some of these flows have been fractured after being emplaced over narrow graben, no unequivocal morphological evidence exists to support this interpretation. Further evidence to support the idea that structural deformation post-dated most of the volcanic activity lies in the fact that no lava flows have been identified which originate at the graben (although a couple of 20 km-long sinuous channels do emanate from graben located on the lower flanks of Elysium Mons).

It does, however, appear that there was some evolution with time between volcanic and tectonic events preserved within Elysium Planitia. While all of the individually identifiable lava flows which comprise the *compound lava plains* unit pre-date tectonism, the flood lavas span a period in time when the fractures were forming. Several of the graben on the lower flanks of Elysium Mons terminate abruptly at their intersection with the flood lavas. Some of these graben appear to have been reactivated after flood lava emplacement, but it is apparent that this late-stage, highly effusive activity occurred after most of the circumferential fracturing (and Elysium Mons flank activity) occurred.

4. Volcano Geomorphology

The three volcanic constructs within Elysium Planitia, and the complex vent area adjacent to Elysium Fossae (Figure 2), present a very diverse range of volcano morphologies. As a result, it is pertinent to consider each volcano individually, in order to place the styles of volcanic activity into a temporal and spatial context.

Hecates Tholus: This is the northernmost of the three constructs, and is elliptical in plan with axis lengths 160 x 175 km. The volcano is centered at 32° N, 209° W, and Mariner 9 ultraviolet spectrometer altimetry estimates (Hord *et al.*, 1974) indicate that the volcano rises about 6 km above the surrounding plain. The summit of Hecates Tholus (Figure 4) is characterized by a nested caldera complex 11.3 x 9.1 km in extent; partial burial of the southern flanks has resulted in an apparent 30-km southward offset of the caldera from the preserved center of figure of the volcano.

Unlike the large Tharsis shields, which show ample evidence of lobate lava flows on their flanks, Hecates Tholus has no such flow features that are identifiable at an image resolution of 40 m per pixel (Mouginis-Mark *et al.*, 1982a). Instead, numerous sinuous channels radiate from the summit area of the volcano, except to the west of the caldera which shows indications of large-scale mantling. The subdued nature of the surface, and a paucity of impact craters at this location, suggest that this area of the volcano could be the best example of a recent large-scale air-fall deposit yet recognized on Mars (Mouginis-Mark *et al.*, 1982a).

Albor Tholus: A single volcanic caldera, measuring 35 x 30 km, characterizes the summit of this volcano, which has a preserved basal diameter of 160 x 150 km. Two independent measures of the height of the summit above the surrounding plains indicate that

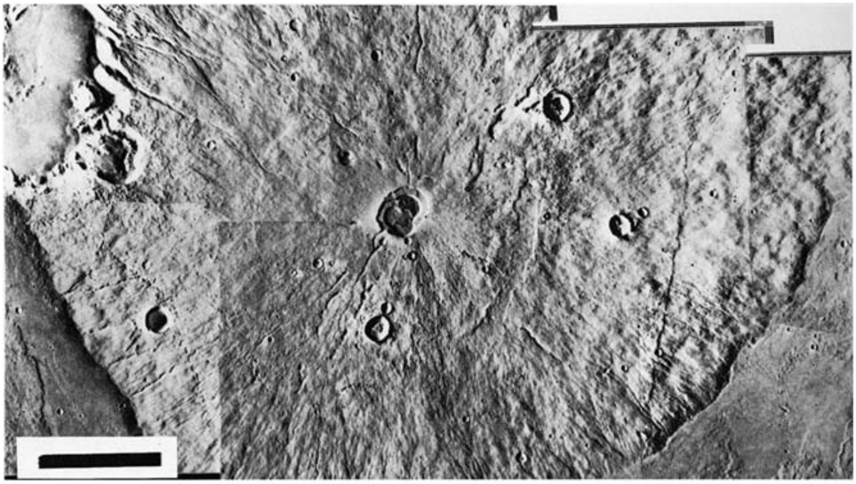

Fig. 4. Hecates Tholus is the northernmost of the three Elysium Planitia constructs. Mapping of the volcanoe's summit area identified a probable pyroclastic air-fall deposit and numerous fluvial channels (Mouginis-Mark *et al.*, 1982a). The southern flanks of this volcano have been partially buried by lava flows from Elysium Mons. Mosaic of Viking Orbiter frame numbers 651A15-23. Scale bar is 25 km.

Albor Tholus has between 3 km (Blasius and Cutts, 1981) and 5 km (Pike *et al.*, 1980) of relief. At an image resolution of 250 m per pixel, no lava flows are visible on the flanks; due to the absence of channels on the flanks, it is likely that this volcano was constructed by effusive rather than explosive activity (Reimers and Komar, 1979; Mouginis-Mark *et al.*, 1982a). Two graben, generally circumferential to Elysium Mons, cut the south-eastern flank of Albor at distances of 50 and 75 km from the summit. Overlap relationships show that the flanks of the volcano, particularly to the northwest, have been partially buried by lava flows from Elysium Mons.

Elysium Mons: Elysium Mons is the largest volcanic construct in Elysium Planitia (Figure 5), rising approximately 13 km above the surrounding plains (Pike *et al.*, 1980; Blasius and Cutts, 1981). Based on the identification of radial lava flows, Blasius and Cutts (1981) interpreted the volcano as having basal dimensions of 420 to 500 × 700 km, compared to the earlier (Mariner 9-based) value of 170 km determined by Malin (1977). Photogrammetric measurements by Blasius and Cutts (1981) gave an estimate of $4.4 \pm 0.2°$ for the mean flank slope, with maximum values of about 18°. Malin (1977) carried out the first detailed investigation of Elysium Mons, comparing its morphology to the superficially-similar African volcano Emi Koussi. Although only one episode of caldera collapse appears to have been responsible for producing the present caldera of Elysium Mons, Malin identified at least four discrete levels within the caldera using low-sun Mariner 9 B-frame images. This summit caldera is about 14.1 km in diameter and shows signs of enlargement by slumping on its northern wall. No lava flows are visible on

Fig. 5. North and west of the summit of Elysium Mons (summit caldera is arrowed), numerous lava flows and circumferential crater chains can be observed. The hummocky terrain and steep flank slopes (Pike *et al.*, 1980; Blasius and Cutts, 1981) suggest that Elysium Mons may be a composite cone. Viking Orbiter frames 541A43 and 44. Scale bar is 50 km.

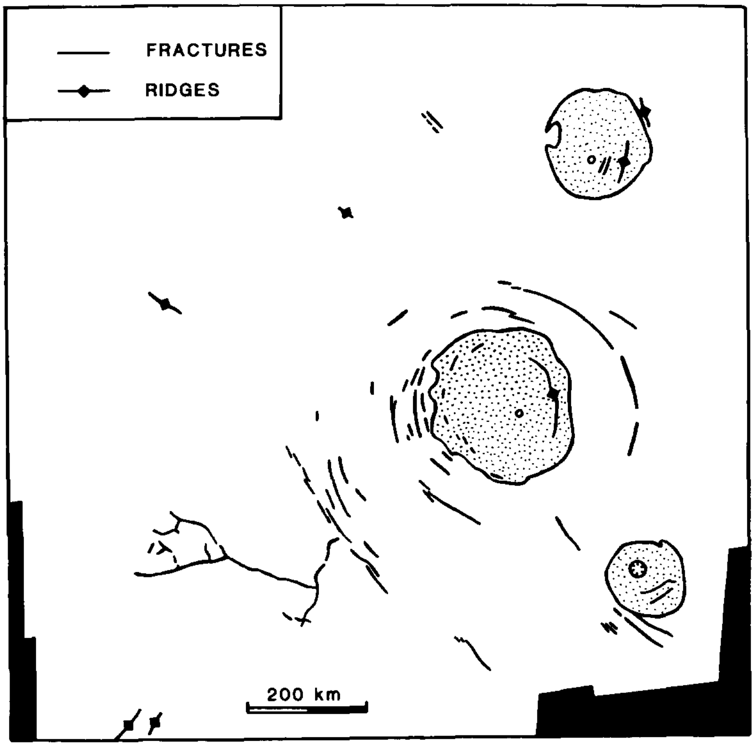

Fig. 6. Location map showing fractures and ridges within Elysium Planitia. Base-map is same as Figure 1.

the caldera floor in either Mariner 9 or Viking high-resolution images, consistent with the proposal that most martian volcanoes had lava lakes within their calderas (or were completely resurface) as part of their period of final summit activity (Mouginis–Mark, 1981).

The flanks of Elysium Mons show considerable variety in surface morphology (Figure (Figure 5). The eastern flanks are very subdued, with almost no lava flows recognizable at a resolution of 150 m per pixel. Indeed, it was this subdued morphology and apparently steeper flanks which led Malin (1977) to propose the Elysium Mons is a composite volcano with a blanketing of pyroclastic material on its flanks. A large, semicircumferential ridge is also found in this area to the east and north of the summit at a radial distance of 70 to 100 km. This feature has positive relief and is superficially similar to some mare ridges on the moon, suggesting that it is compressional in origin. Unlike mare ridges, this ridge is unusually narrow (about 1 km in width) and is virtually continuous for its entire 150 km length. A unique feature of Elysium Mons is an extensive set of circumferential extensional tectonic features centered on the volcano's summit (Figure 6). A major set of graben is located approximately 175 km west of the summit, with additional graben at 205 to 225 km to the south and northest. Also nearly circumferential to Elysium Mons

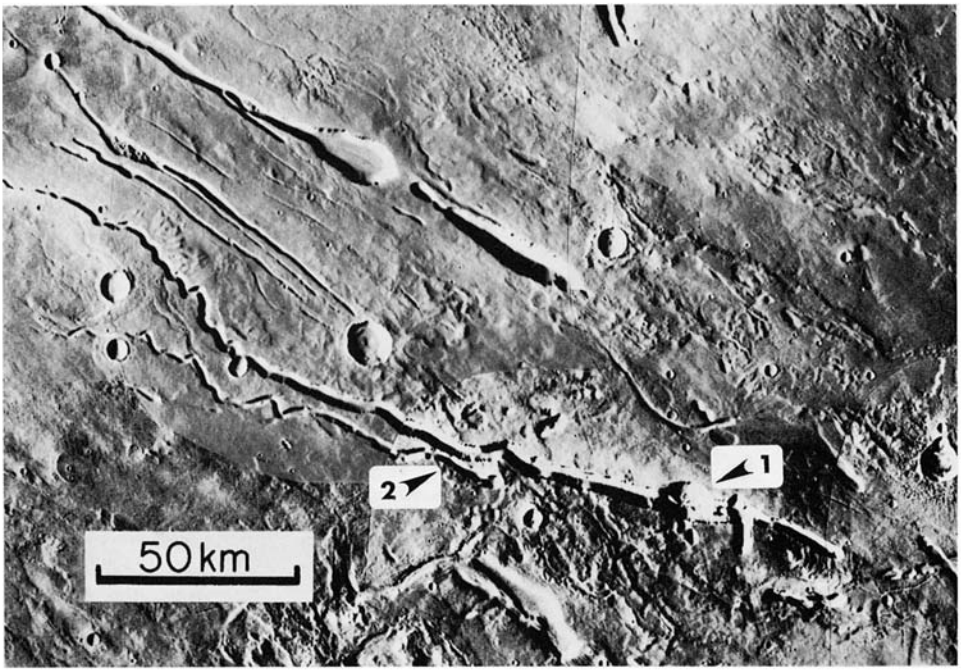

Fig. 7. Medium resolution (150 m per pixel) view of the complex vent area within Elysium Fossae. Morphometric data were collected on channels 1 and 2 (see Figure 12). Direction of flow in channels is from right to left. Mosaic of Viking Orbiter frames 541A35–40.

is a segment of Elysium Fossae (located toward the southwest at 22° N, 219° W). These graben are about 330 km from the summit and are up to 18 km in width.

Numerous small flank lava flows between 1.3 and 3.2 km in width and 25 to 60 km in length are observed on the upper northwestern slopes of Elysium Mons. Several crater chains and sinuous rilles are also located in this area and some extend right up to the caldera rim. At radial distances greater than 200 km, larger flows are observed. These flows typically have widths of 5 to 8 km and are about 50 to 100 km in length. Particularly to the north of the summit, the local relief of the flanks appears to be very hummocky at radial distances of 130 to 230 km, where many subdued subradial ridges 5 to 7 km in width have acted to pond some of these larger lava flows behind local obstacles.

Elysium Fossae Vents: While no large volcanic construct exists to the west of Elysium Mons, the area identified by our mapping as the 'complex vent area' (Figure 7) is considered by us to be a fourth volcanic center within Elysium Planitia. Measuring approximately 260 × 480 km in extent, this volcanic center is located 470 km west of Elysium Mons at 26° N, 220° W and is the source area for the channels comprising Elysium Fossae (Mouginis-Mark and Brown, 1981).

Prominent at this location are several large sinuous channels with enlarged source craters. In several respects, the area is morphologically-similar to the Aristarchus-Harbinger region of the moon (Zisk *et al.*, 1977), where numerous vents are located in hummocky terrain, show no strong structural control in their distribution, and are in close proximity to several dome-shaped features. In the case of the Elysium channels, a few examples display wide levees similar to those that flank the rille south of the lunar crater Euler (Schaber, 1978). Several irregularly-shaped domes are also present within Elysium that have crenulated surface textures reminescent of certain terrestrial rhyolite domes (Green and Short, 1971). While we do not propose that these Elysium domes are rhyolitic in composition, their morphology is unusual for Mars and most consistent with the extrusion of small volumes of magma.

Although Martian volcanoes illustrate a wide diversity of morphologies (cf. Wood, 1979; Greeley and Spudis, 1981), recognizable centers of volcanic activity on Mars are typically characterized by large constructs and multiple lava flows (Schaber *et al.*, 1978; Mouginis–Mark, 1981). The Elysium Fossae vent region differs from these other centers of martian volcanism in several respects:

(1) There is no prominent construct or volcano–tectonic depression associated with the source region.

(2) The numerous source vents for the sinuous channels are widely distributed over an area measuring more than 75 000 km^2 (Figure 2). Additional discrete sinuous channels also occur within 100 km of this complex, indicating that an areally extensive magma source region capable of erupting large volumes of lava was situated at this locality.

(3) The dome-shaped features at this location are morphologically different from possible martian cinder cones (Wood, 1979) and other landforms with proposed volcano–ground ice origins (Allen, 1979). Although lacking accompanying lava channels or flows, these domes are interpreted here to be volcanic in origin. Their size (20–30 km in basal diameter) and crenulated surface texture suggest that they were produced by low-volume and low-effusion rate eruptions rather than pyroclastic or phreatomagmatic activity.

5. Distribution of Lava Flows

As part of the mapping project, 125 individual lava flows and 41 sinuous rilles were identified within Elysium Planitia (Figure 8). Unlike the Tharsis region, where several of the shield volcanoes have erupted lavas that cover the adjacent plains (Scott and Tanaka, 1981; Mouginis–Mark *et al.*, 1982b), examination of these Elysium lava flows demonstrates that Elysium Mons has dominated the formation of the most recent surface units: virtually all of the flows and rilles are aligned nearly radial to Elysium Mons. Both the southern flank of Hecates Tholus and the northern flank of Albor Tholus are partially buried by these flows. Individual flows extend to distances in excess of 600 km from the summit caldera. Maximum identifiable flow lengths are about 150 km, implying that either the flow morphology is very subdued close to the near-summit vents, that many of the lavas were erupted from vents at several hundred kilometers distance from Elysium Mons, or that later shorter flows covered the proximal areas.

There is some evidence from studies of terrestrial lava flows that the lengths of single

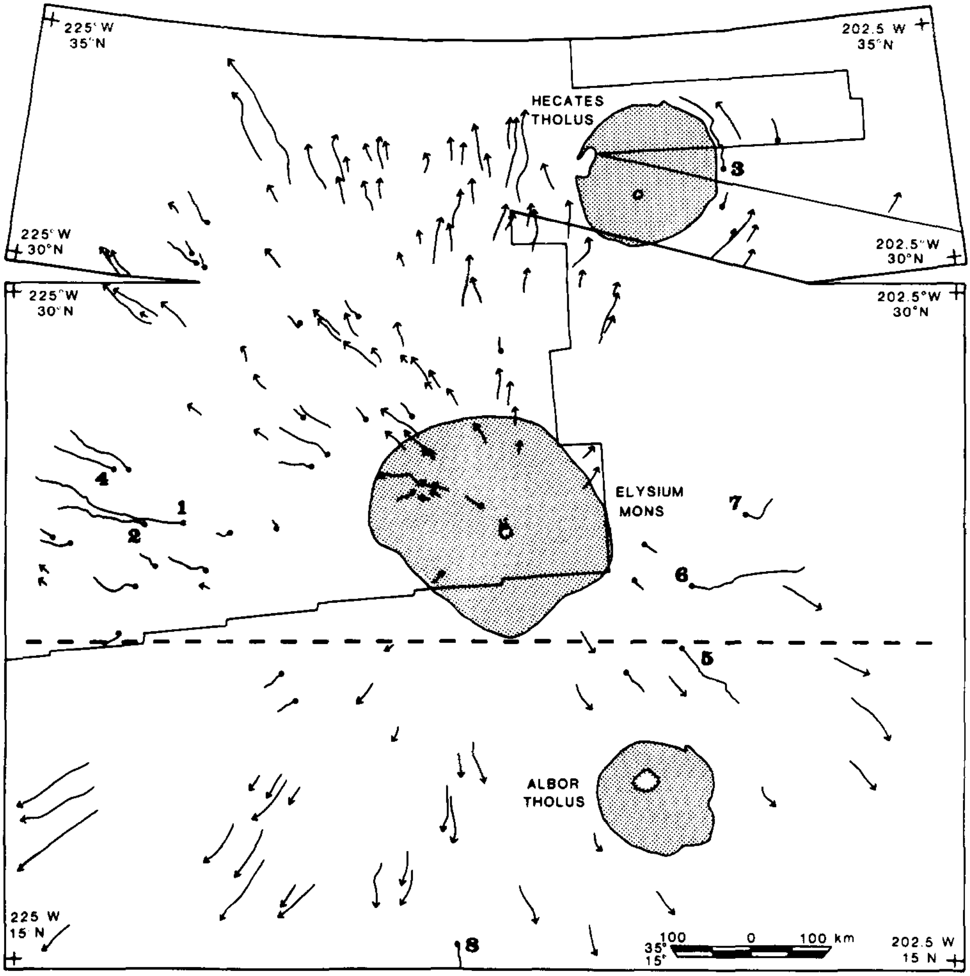

Fig. 8. Distribution map of all lava flows (arrows) and sinuous channels within Elysium Planitia. Evident from this map is the dominant role that flank activity from Elysium Mons has played in the construction of the surrounding lava plains. Map prepared using medium- and high-resolution images, with the U.S. Geological Survey photomosaics I-1386 and I-1398 as base maps. Dashed line shows the location of the radar ground track shown in Figure 9. Outline area in top left of diagram shows coverage of Viking Orbiter images with a resolution of 150 m per pixel or higher. Numbers refer to sinuous channels for which the mass eruption rates were calculated (see Table II).

flow lobes can be used as an indication of the eruption rates feeding the flows (Walker, 1973; Wadge, 1977, 1978), though there are a number of factors which complicate the relationship (Malin, 1980; Wilson and Head, 1983). Using an extrapolation of the data summarized by Malin (1980) we find that lava flow lengths in the range 150 to 600 km may imply eruption rates in the range 10^7 to 10^8 kg s^{-1}. In making these estimates we have ignored possible corrections for the differences between martian and terrestrial values of gravity and topographic slope on the grounds that such corrections are likely to be less than the currently unquantifiable consequences of differences in rheology between martian and terrestrial magmas (Wilson and Head, 1983). This range of eruption rates estimated for the Elysium Mons flows lies between estimates for quaternary basaltic eruptions on Earth (10^2 to 10^7 kg s^{-1}) and the basaltic eruptions which occurred near the end of the period of mare basin flooding on the Moon (10^6 to 10^9 kg s^{-1}; see Wilson and Head, 1983).

An unusual characteristic of the Elysium Planitia region is the high frequency of occurrence of sinuous channels (Figure 8). These channels are morphologically similar to lunar sinuous rilles. In the case of the Moon, it is thought that rille formation is due to thermal erosion of the pre-existing terrain by high effusion-rate lava flow (Hulme, 1973; Carr, 1974; Head and Wilson, 1981). Particularly in the cases where the rilles have enlarged source craters, the associated lava flows are thought to have been very turbulent, due in part to the influence of steep local slopes (Hulme and Fielder, 1977; Head and Wilson, 1981). In the case of the Elysium sinuous channels identified in Figure 7, it may also be the case that steeper than usual topographic gradients have promoted the formation of lava channels. A planet-wide search for martian channels with morphologies similar to lunar sinuous rilles (Mouginis–Mark and Wilson, 1982 unpublished data) indicated that virtually all such channels are located in areas where the local topographic slope is likely to be high. Unlike the lunar examples, very few martian sinuous lava channels are found on the volcanic plains (such as the ridged plains materials) and only a few are seen on the upper (steeper?) flanks of the Tharsis shields (Mouginis–Mark, 1981). Accordingly, the occurrence of more than 40 such channels within a radius of 600 km from Elysium Mons must indicate an unusual volcanic environment. The lengths of 37 of these Elysium rilles are summarized in Table I, and lie in the range 20 to 200 km. For comparison, the range of lengths of well defined lunar sinous rilles is about 40 to 140 km (Head and Wilson, 1981). Possible explanations for this unusual style of martian volcanism might have been high mass eruption rates, unusually wide source fissures, or the lack of constructional activity due to steep local slopes.

TABLE I

Length distribution of the 37 largest sinuous rilles in the Elysium area

Length range (km)	Number of Rilles
0– 20	0
21– 40	8
41– 60	8
61– 80	5
81–100	4
101–120	1
121–140	6
141–160	3
161–180	0
181–200	2

TABLE II

Lengths, mean widths and estimated mass eruption rates for eight sinuous rilles in the Elysium area. See text for explanation of mass eruption rate calculation. See Figure 8 for rille locations.

Rille number	Length (km)	Width (km)	Mass eruption rate ($kg\,s^{-1}$)
1	180	3.9	2.3×10^9
2	130	2.8	1.2×10^9
3	150	2.0	9.6×10^8
4	120	0.9	3.5×10^8
5	140	1.7	7.7×10^8
6	180	1.0	5.8×10^8
7	120	0.3	1.2×10^8
8	150	3.5	1.7×10^9

Hulme's (1973) model of sinuous rille formation as a result of thermal erosion of a substrate by a turbulent lava flow shows that the mass eruption rate, M, of the lava is proportional to the product of the length, X, and width, W, of the rille. The factor of proportionality is a function of the ratio of the eruption temperature to the solidus temperature of the lava, and its value has been determined for several lunar sinuous rilles by Head and Wilson (1981) who find that

$$M = (3.4 \pm 1.5) \times 10^6 XW,$$

where M is measured in $kg\,s^{-1}$ and X and W are given in km. This relationship has been used to find the values of M given in Table II for the eight large sinuous rilles in the Elysium area whose locations are indicated in Figure 8. There is an implicit assumption in the calculation that eruption- to solidus-temperature ratios for martian lavas were similar to those for lunar basalts.

Although the values of W for the rilles in Table II are expected to be only estimates (due to the lack of high resolution images), we note that M is expected to be approximately proportional to $X^{3/2}$ for magmas with the properties of Bingham plastics (see Wilson and Head, 1983). The constant of proportionality evaluated from the eight pairs of values of M and W in Table II is such that

$$M = (5.3 \pm 3.1) \times 10^5 X^{1.5},$$

where M is given in $kg\,s^{-1}$ and X in km. This implies that the shortest rilles in Table I, with $X = 20$ km, were formed by eruptions with effusion rates of $(5 \pm 3) \times 10^7\,kg\,s^{-1}$. Such effusion rates are very close to the value of about $3 \times 10^7\,kg\,s^{-1}$ at which lava flows are expected to become turbulent under most planetary surface conditions (Wilson and Head, 1983). These results, although based on numerical values which have large uncertainties, are at least internally consistent with the proposal that the rilles were formed by turbulent lava flows.

While few detailed measurements of the topography of the Elysium Dome have been made (but see Blasius and Cutts [1981] for a low-resolution photogrammetrically-derived

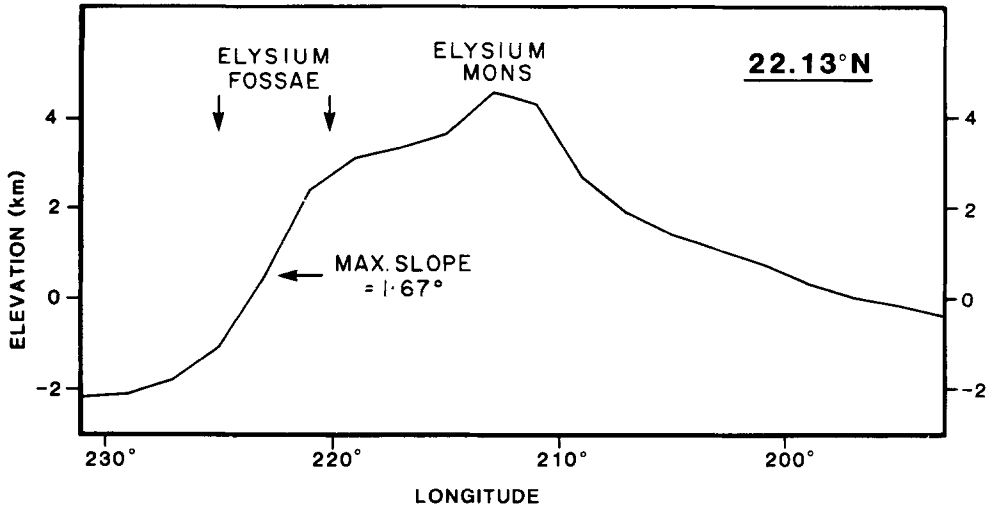

Fig. 9. Topography of southern Elysium Planitia at 22.13° N, as measured by Earth-based radar (Downs *et al.*, 1982). Ground track of data is shown in Figure 8.

topographic map of the southeastern part of the Dome), some Earth-based radar topography data have been acquired for the southern portion of the Dome at 22.13°N (Downs *et al.*, 1982). A comparison of this topographic profile (Figure 9) and the locations of the channels shows that the source vents for these channels are probably situated on regional slopes of at least 1.7°. While no slope measurements are aligned along the flow directions of the lava, this regional slope covers a horizontal distance of more than 300 km, and, together with the much steeper slopes close to the volcano's summit (Blasius and Cutts, 1981), may have been sufficient to promote unusually turbulent lava flows and the preferential formation of sinuous rilles. For comparison, regional slopes within the Tharsis region have been found to be no greater than 0.75° ± 0.03°, with typical values less than 0.3° (Mouginis-Mark *et al.*, 1982b).

6. Channel Origin

A wide diversity of channels is visible within Elysium Planitia, both on the flanks of Elysium Mons and within Elysium Fossae. The majority of the channels close to the volcano summit are interpreted here to be lava channels, due to their sinuous appearance, their enlarged source craters and an intimate association with lava flows. However, such a characterization is probably not permissable for many of the Elysium Fossae channels, which show both braided outlines and probable sedimentary features at their distal ends (Christiansen and Greeley, 1981).

Viking Orbiter images reveal that several of the Elysium Fossae channels contain

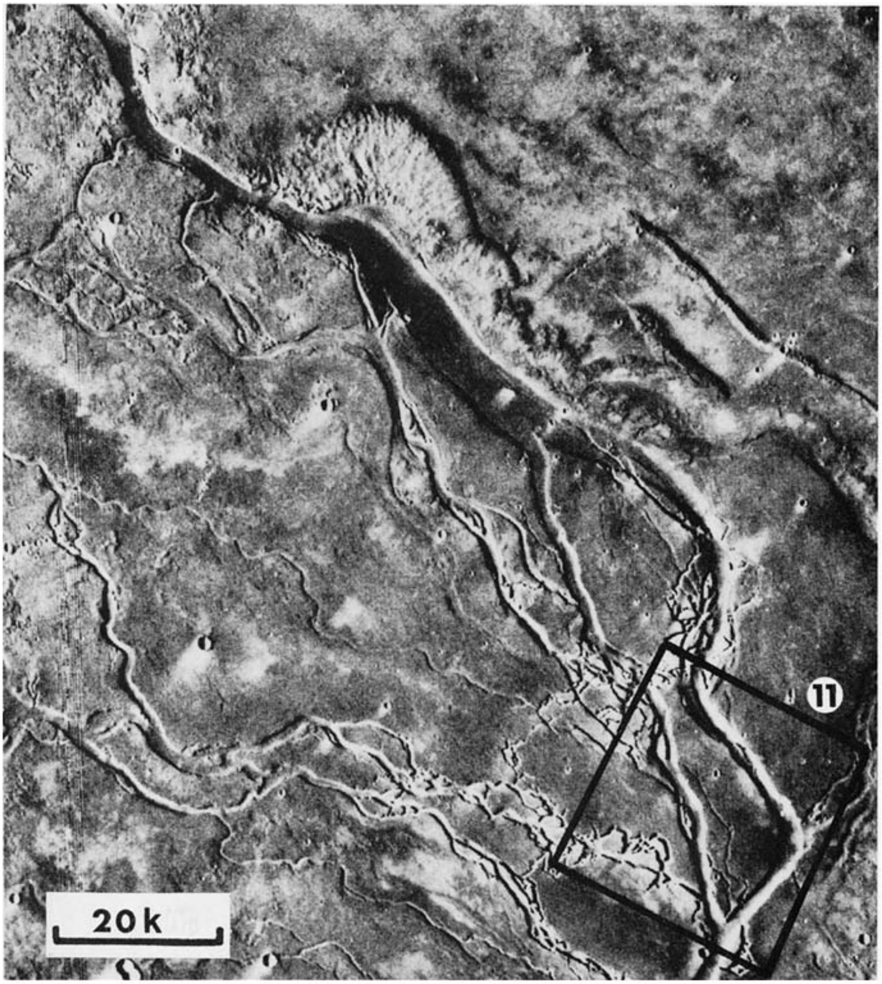

Fig. 10. View of probable fluvial channels within Elysium Fossae. Numerous braided channels suggest more than one episode of fluvial activity. Area shown in Figure 11 is outlined. Viking Orbiter frame 541A20, image resolution 153 m per pixel.

features that are also characteristics of the outflow channels surrounding Chryse Planitia (Baker, 1982). In particular, the existence of braided channels (Figure 10), different levels of channel floor at the same locality (Figure 11) and the occurrence of streamlined islands within these channels (Figure 11) suggests a fluvial, rather than volcanic, origin. In order to test for possible fluvial channels, morphometric measurements were made on the sinuosity and width of four of the largest channels (identified in Figures 1 and 7) and the length versus width of the streamlined islands.

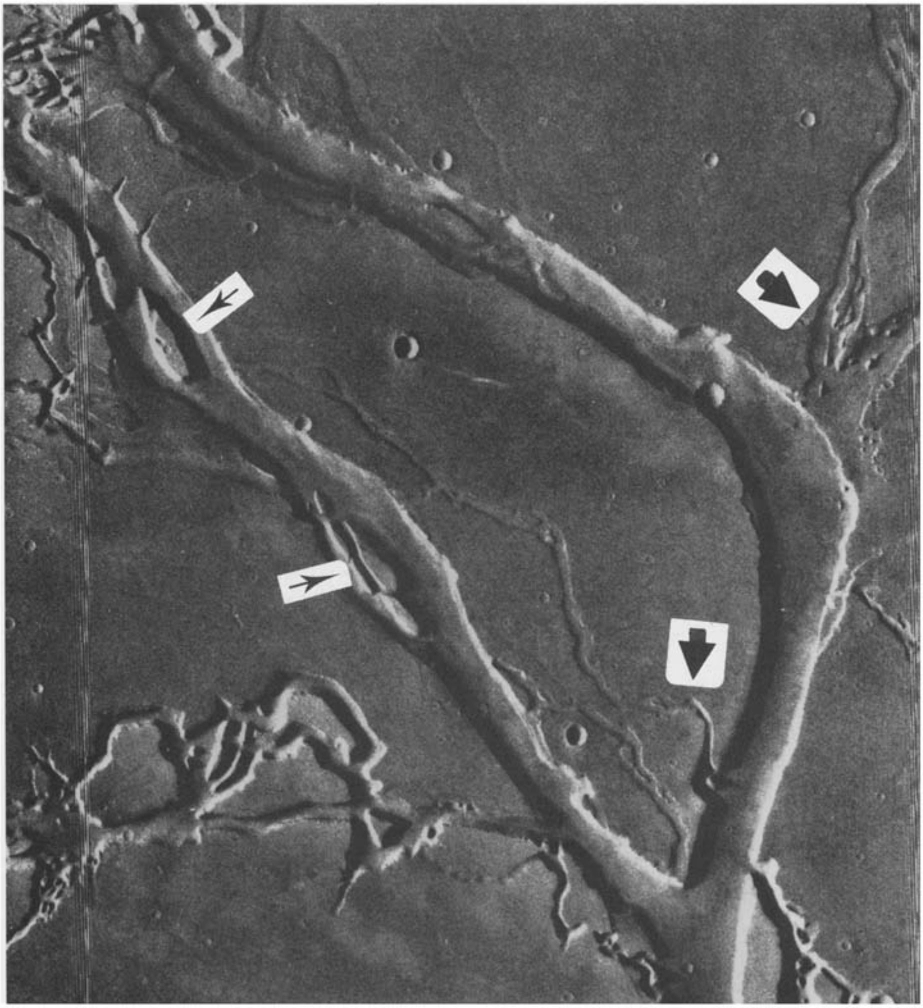

Fig. 11. High resolution (37 m per pixel) view of part of the channel system shown in Figure 10. Arrowed are several streamlined islands which were measured for comparison with similar examples within Kasei Vallis (Figure 13). Also shown (thick arrows) are the remnants of former channel floors, which suggest that multiple periods of channel formation took place. Viking Orbiter frame number 649A18. Width of image is 40 km.

An investigation of meandering terrestrial rivers by Leopold and Wolman (1957) showed that bank full width (W) is related to wavelength (λ) by the following relationship

$$\lambda = KW^{1.1}, \tag{1}$$

where $K = 7.32$ when λ and W are expressed in meters. Yalin (1972) found that when the largest turbulent eddies in a channel are perturbed or reordered by irregularities of the channel, bankfull width is related to wavelength as follows:

$$\lambda = 2\pi W. \quad (2)$$

Measurements were made on four separate channels within Elysium Planitia, in order to distinguish between fluvial and volcanic channels on the basis of the relationships expressed by Equations (1) and (2). Channels with shapes which have obvious structural control, such as an *en echelon* pattern, were excluded from this analysis. It is apparent from the data (Figure 12) that those channels which possess streamlined islands and multiple floor levels fall above the line deduced by Yalin (1972), whereas data for the channels with enlarged source craters fall below the line.

Baker (1979) described a mechanism by which streamlined landforms may have been created on Mars by catastrophic outflow of released melt water. He found that when the length of the streamlined landforms is plotted versus planimetric form area, a general

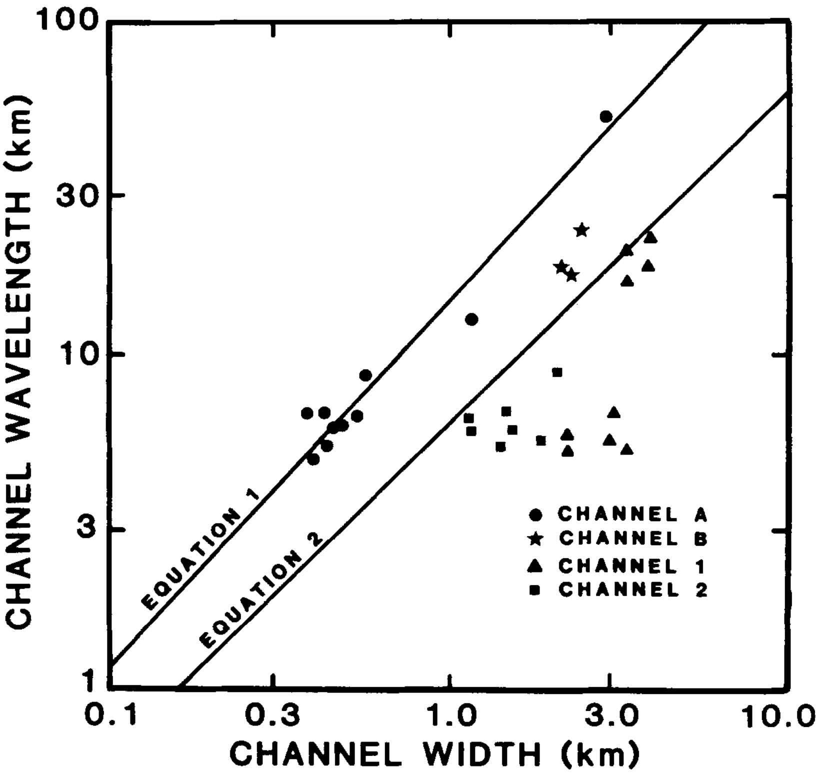

Fig. 12. Plot of width versus wavelength for four channels identified in Figure 1 (Channels A and B) and Figure 8 (Channels 1 and 2). Equation (1) is after Leopold and Wolman (1957), Equation (2) after Yalin (1972).

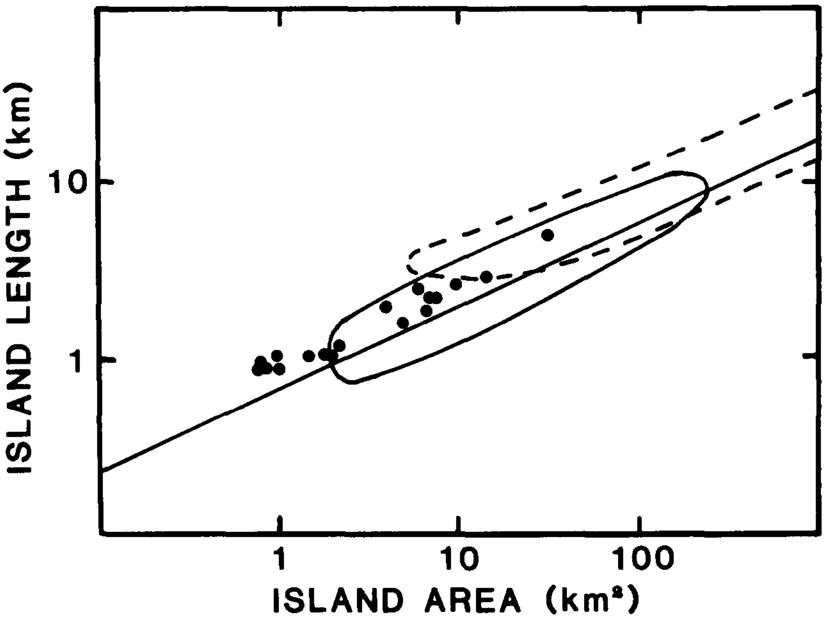

Fig. 13. Plot of area versus length for streamlined islands within Channel A. Dashed outline is for similar landforms within Kasei and Maja Valles, solid outline is for the Channeled Scablands in Washington (Baker, 1979). Straight line is a general model for these features (Baker, 1979).

correlation exists for both Martian outflow channels and examples located in the Channeled Scabland of Washington. One of the Elysium Fossae channels has an abundance of streamlined forms with the characteristic lemniscate shape (Figure 11). These features are in general smaller than other martian examples located within Kasei Vallis or Maja Vallis, but nevertheless appear to have a similar origin. Eighteen sets of measurements on those islands with the most distinct boundaries were made of the Elysium examples, and their dimensions compared to the observations of Baker (1979) (Figure 13).

Evident from Figure 13 is the close correlation between the Elysium channels and other Martian examples. Both data sets appear to be part of a continuum of landforms that differ only in absolute size. This implies that if Baker (1979) correctly interpreted the mode of formation of the Martian streamlined islands as being fluvial in nature, then a similar origin may be valid for some of the Elysium Fossae examples. Thus it appears from measurements of channel sinuosity (Figure 12) and streamlined island shape (Figure 13) that two different populations of channels exist within Elysium Planitia. Some channels, particularly those close to the volcanic craters, are likely to be volcanic in origin and are analogous to lunar sinuous rilles, while those channels in western Elysium Planitia are primarily fluvial in origin. It is likely, however, that at least some of these channels have been influenced by both volcanic and fluvial processes as volcano–ground ice interactions liberated large volumes of melt water. Additional evidence to support this hypothetical interaction is presented below.

7. Volcano/Ground Ice Interactions

The interaction of volcanism and subsurface ice or water on Mars has been postulated on a number of occasions (cf. Allen, 1979; Hodges and Moore, 1979; Frey and Jarosewich, 1982). Such a hypothesis has been supported by the recognition of possible table-mountains and pseudocraters. In the Elysium Planitia region, additional morphological evidence exists to suggest that ground ice once existed at this locality. Previous investigators have drawn attention to the fluvial-like channels within Elysium Fossae (Christiansen and Greeley, 1981; Baker, 1982), the possible ground ice origin of the Knobby and Chaotic terrain (Figure 3; Sharp, 1973; Carr and Schaber, 1977) and the possible explosive eruptions of Hecates Tholus as a consequence of near-surface voltatiles (Mouginis–Mark *et al.*, 1982a). To this list of supportive landforms should be added the numerous impact craters within Elysium Planitia, which show a surprising variability in ejecta morphology and interior features over this area.

Since the return of the first Viking Orbiter images, a recurrent view in the interpretation of martian impact craters has been the probable role of subsurface volatiles in controlling crater and ejecta morphology: the lobate ejecta deposits that surround many craters in the diameter range 5–30 km might be the products of target volatiles becoming incorporated with the ejecta during its emplacement (cf. Carr *et al.*, 1977; Mouginis–Mark, 1979). Similarly, the diversity of central structures (Wood *et al.*, 1978; Hale, 1983) and crater depths (Cintala and Mouginis–Mark, 1980) may also indicate variations in target materials and/or volatile content.

Analysis of the fresh impact craters within Elysium and elsewhere on Mars by Hale (1983) revealed that an unusually high frequency of occurrence of craters with central pits is associated with the Elysium region. We have extended this morphological analysis of the Elysium impact craters in order to search for spatial variations in ejecta type. We show in Figure 14 the locations of impact craters having the characteristic types of ejecta deposit; our results indicate that a regional trend exists for ejecta morphology within Elysium Planitia. In general terms, Mouginis–Mark (1979) recognized three different types of ejecta morphology, which were attributed to variations in target properties and voltatile content. Typically, martian impact craters possess either a single or a double lobate deposit surrounding the parent crater. In areas with a lower volatile content, however, radial or 'lunar-like' ejecta deposits were formed, while in volatile-rich targets, very extensive (highly fluidized) ejecta deposits were created. Within Elysium Planitia, south of 24° N, all the craters of all sizes have the typical lobate ejecta deposits that are characteristic of most martian craters (Mouginis–Mark, 1979). Between 24° N - 34° N there is a transition zone, where craters smaller than about 10 km diameter have lobate ejecta deposits and craters larger than 10 km have a radial ejecta morphology. This size association is not completely consistent, however, since additional craters smaller than 10 km diameter that have radial ejecta morphologies are also seen toward the northern portion of this area. There also appears to be little systematic correlation between ejecta morphology and the type of central structure. North of the boundary between the lavas from

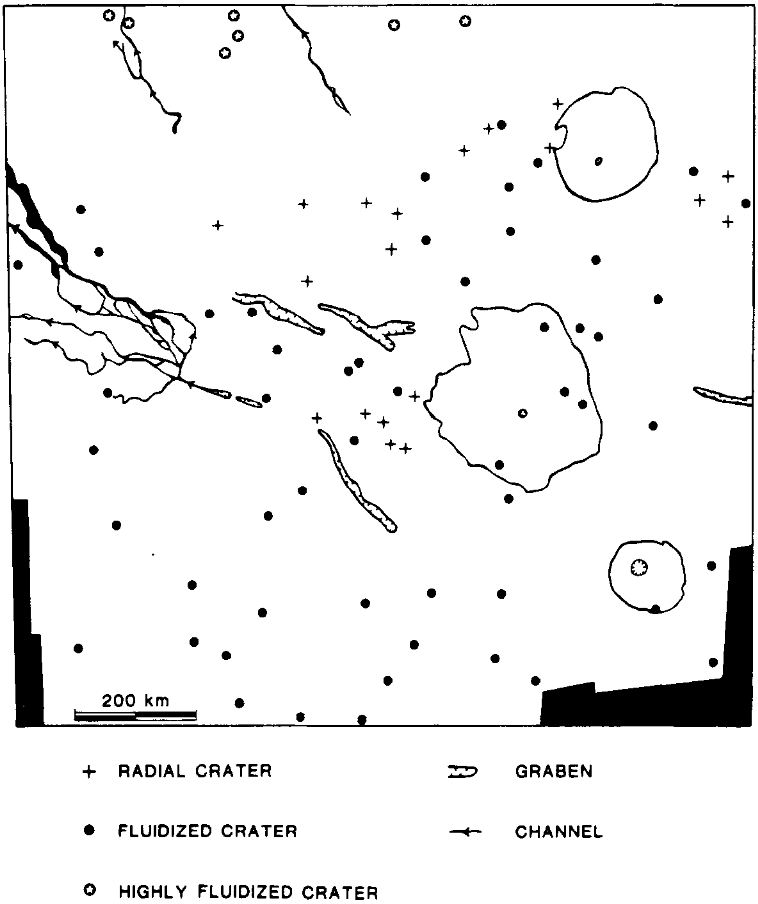

Fig. 14. Distribution of impact crater ejecta morphology within Elysium Planitia. Three main types of ejecta can be identified: radial, fluidized and highly fluidized. These different morphologies are thought to be a product of the variable volatile content of the targets at the time of crater formation (Mouginis-Mark, 1979). Base map same as Figure 1.

Elysium Mons and the Knobby and Chaotic unit (Figure 2), the character of the ejecta deposits changes once again. North of 34°N, the ejecta is very extensive, traveling to greater radial distances than for craters of comparable size within central Elysium Planitia.

These variations of impact crater morphology suggests that since the time of formation of the major surface units mapped in Figure 2, a spatially or temporally varying amount of volatiles has existed within Elysium Planitia. No obvious correlation has been observed between crater morphology and crater location relative to the position of the lava flow units, nor does the crater's proximity to Elysium Mons appear to be important. If the current view is adopted for the mode of formation of the different crater morphologies (i.e., target volatiles are primarily responsible for the formation of both the lobate ejecta deposits and the central pits; Carr *et al.*, 1977; Wood *et al.*, 1978), then the crater distribution shown in Figure 14 would suggest that most volatiles were located in the Knobby and Chaotic unit. Within Southern Elysium Planitia, the characteristic lobate ejecta deposits would suggest a volatile distribution similar to that in many other areas of Mars. To the north and west of Elysium Mons, the radial-textured ejecta morphology would suggest a lower than usual target volatile content: the cause of this asymmetry is not known, but it could be due to, for example, thermal effects from Elysium Mons driving-off the volatiles, unusually impervious lava flows acting as cap-rock, the subsurface escape of volatiles toward the north because of the nearby escarpment (Figure 3), or some other unknown reason.

8. Summary of Observations

The geology of Elysium Planitia is shown from this analysis to be appreciably more diverse than was intially believed from Mariner data (Scott and Allingham, 1976; Malin, 1977). Elysium Mons evidently dominated the constructional phase of volcanic activity as it is now preserved in this area, with flank lava flows extending to radial distances in excess of 600 km from the summit area. A second major system of vents has been located within Elysium Fossae, but this area represents a different style of volcanism with numerous isolated vents and little constructional activity. The preserved remnants of both Hecates and Albor Tholi have not contributed to the formation of the surrounding lava plains; the flanks of both these volcanoes are partially buried by Elysium Mons lavas, which evidently post-date large-scale activity on the tholi.

A large number of channels exist within Elysium Planitia that are morphologically similar to lunar sinuous rilles. We consider that most of these martian channels are volcanic in origin, and that they are preferentially located in this area due to unusually steep local slopes. In addition to lava channels, several water-carved channels appear to exist within Elysium Fossae, as evidenced by numerous streamlined islands within the channels and multiple stream levels at several localities. We agree with the hypothesis of Christiansen and Greeley (1981) that lahar deposits probably extend westwards from some of these fluvial channels, but are uncertain as to their areal extent. Based on the occurrence of knobby and chaotic terrain, the diversity of impact crater morphologies and the probable explosive history of Hecates Tholus, it is likely that extensive volcano–ground ice interactions have occurred over this area. It is unclear just how important the link between ground ice and volcanism may have been within Elysium Planitia, but it is evident that the volcanic style has been much more diverse within Elysium than within Tharsis. Because of this diversity, several volcanic landforms within Elysium may provide useful insights into volcanism which occurred within the southern cratered terrain of Mars earlier in the planet's history: Tyrrhena Patera, for example, has been described as the product of extensive phreatomagmatic eruptions (Greeley and Spudis, 1981), but has been so heavily eroded that its original morphology can no longer be determined. The need therefore exists to more fully investigate the extent and importance of these interactions between ground ice and volcanism, plus a more complete investigation of volcanism within Elysium Planitia, and will form the basis of a future analysis.

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