INTRODUCTION

Analysis of the Mariner 9 and Viking Orbiter image data sets reveals a variety of volcanic landforms that formed over an extended period of Martian history (cf. Carr, 1973; Carr et al., 1977; Greeley and Spudis, 1981). In addition, the wide diversity of evidence for a large amount of subsurface ice contained within the Martian regolith (Lucchitta, 1981; Rossbacher and Judson, 1981) indicates that it is likely that there have been substantial volcano/ground ice interactions on Mars. While few clearly defined examples of such interactions have been identified, recognition of the resultant landforms would both add to our knowledge of climatic history (Fanale et al., 1985) and help to further characterize the styles of volcanic activity on Mars (Wilson et al., 1982). While it is evident that constructional activity was common, debate over the diversity of Martian volcanism has focused on the identification of possible pyroclastic materials and their implications for the range of magma chemistries (Francis and Wood, 1982). Explosively produced landforms could either be attributed to volatile-rich magmas or to the interaction between a depleted magma and a layer of near-surface volatiles. Possible evidence for pyroclastic activity was first recognized in Mariner 9 images (West, 1974; Peterson, 1978), but the likelihood of volcano/ground ice interactions (Allen, 1979, 1980; Frey and Jarosewich, 1982; Mouginis-Mark et al., 1982) has left the origin of this activity, and thus the original volatile content of the erupted magma, unresolved.

One of the most likely regions on Mars where such an interaction between volcanism and near-surface volatiles has taken place is Elysium Planitia (Mouginis-Mark et al., 1984). As part of a regional mapping program focused on this area, Mouginis-Mark et al. (1984) consolidated several
lines of evidence that support the extensive interaction between volcanic materials and a preexisting water table or layer of ground ice. Numerous landforms in western and northern Elysium Planitia were identified to support this hypothesis, including the existence of chaotic terrain (Carr and Schaber, 1977), probable megahar (or mudflow) deposits (Christiansen and Greeley, 1981), outflow channels with multiple levels and streamlined islands (Baker, 1982), an airfall deposit on the summit of Hecates Tholus (Mouginis-Mark et al., 1982), and diverse impact crater morphologies (Hale, 1983).

Based on theoretical considerations of Martian volcanic eruptions (Wilson and Head, 1983; Wilson et al., 1982), the interaction of ascending magma and subsurface volatiles should have produced landforms that differ significantly from other volcanic features on Mars in terms of their morphology, size, and albedo. For example, Wilson et al. (1982) calculated that strombolian eruptions would permit pyroclastic fragments larger than a few centimeters to collect near the vent, while clasts in the millimeter to centimeter range would be projected to a significant fraction of their vacuum ballistic range (up to about 2 km). Fragments in the submillimeter-size range would be carried into a convecting eruption cloud and widely dispersed. In the case of Vulcanian eruptions, the presence of subsurface ices or water may have made this style of activity quite common by increasing the possibility of chilling an intruded magma. Thus the magma would have a greater tendency to block the conduit, promoting intermittent explosive eruptions as the strength of this cap rock was exceeded by the increasing magma pressure within the rest of the conduit system. Small pyroclastic flows (nueces ardentes) should have been formed during this type of activity by the partial collapse of the eruption cloud.

In the case of effusive activity, Squyres and Moosman (1984) attempted to model the effect of a lava flow being emplaced upon a layer of ice-rich permafrost and inferred that several different processes could take place: (1) melting of ice to produce potentially large amounts of liquid water; (2) generation of steam that escapes into the atmosphere; and (3) hydrothermal alteration of basaltic glass to form palagonites. On the basis of the observational data presented below, it is believed that the first of these processes has operated within Elysium Planitia, while Earth-based spectra of Mars (Singer, 1982) support the third process elsewhere on Mars, because palagonites have spectral properties that provide a better fit to the spectra of Martian fines than other proposed mineral phases.

The objective of this paper is to document landforms in northwestern Elysium Planitia that have morphologies consistent with those predicted to form on the basis of numerical modeling of magma and lava interacting with volatiles within the regolith. It is hoped that constraints can be provided for interpreting the styles of volcanic activity and the distribution of near-surface volatiles on Mars. Such an investigation is not only pertinent to volcanological studies of Mars. Due to the relatively young age of volcanism within Elysium Planitia (2–3 × 10⁹ yr B.P.; Neukum and Hiller, 1981), and the near-equatorial location of the area (20–35°N), data pertaining to the occurrence of subsurface volatiles at this locality will also be relevant to numerical models of long-term global transport of regolith volatiles on Mars (cf. Clifford and Hillel 1983; Fanale et al., 1985). For example, the model of Fanale et al. (1985) predicted the depth to the ice interface as a function of latitude, time, and assumed soil properties. In their model, it was calculated that there would be a general recession of near-surface water from the equatorial regions of Mars that would have extended to a depth of 100–300 m over geological time. This analysis attempts to place further constraints on the vertical distribution of these volatiles at the time of volcanic activity by investigating the diversity of landforms within Elysium Planitia.
LANDFORMS ASSOCIATED WITH VOLCANO/GROUND ICE INTERACTIONS

Mouginis-Mark et al. (1984) have recently presented a revised interpretation of the diversity of landforms found within Elysium Planitia, based on an analysis of Viking Orbiter medium- and high-resolution images. Some additional interpretations of the specific landforms that they believed were associated with volcano/ground ice interactions follow, as well as descriptions of further corroborating features recognized here. The regional setting of the area under consideration is shown in Fig. 1.

MeltWater Deposits

A range of landforms are found primarily in the northern parts of Elysium Planitia that suggest that meltwater has been released from the regolith. Flows can be seen that are believed to be the products of meltwater release associated with the emplacement of lava flows on terrain containing ground ice, while morphological evidence suggests that ephemeral lakes once existed.

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Fig. 1. Photomosaic of Elysium Planitia, showing the three major volcanoes Hecates Tholus (HT), Elysium Mons (EM), and Albor Tholus (AT). The locations of Figs. 3, 4, A, B, 6, 7, 9, 12, and 13A, B are also shown. Mosaic of Viking Orbiter frames 844A13-22, 844A35-46, and 846A13-22. Width of image through summit of Elysium Mons (25°N) equivalent to 1070 km.
in certain catchment areas, and that possible mudflows or megalahar deposits are located here.

To the west of the volcano Hecates Tholus, a series of lava flows extends over 500 km from the summit of Elysium Mons (Fig. 2). Although local topography is rugged and image resolution is only 50 m/pixel, shadow length measurements suggest that these lava flows are approximately 100–150 m thick. From the models of Allen (1980) and Squyres and Moosman (1984), the interaction between such lava flows and preexisting ground ice should be visible at the resolution of available Viking Orbiter images; if subsidence of the lava flow has taken place as a result of melting ground ice, local negative-relief portions of the lava flow should be visible. Provided that meltwater channels or pseudocraters are larger than about 150 m [which is typically the case for possible pseudocraters identified by Frey and Jarosewich (1982)], the surface morphology of the lava flows could also provide evidence for the presence or absence of ground ice close to the surface. Examination of Viking images (Fig. 3) reveals that evidence for such interactions may exist; northward of the lava flows there is a second type of flow feature that has a more subdued relief and less lobate outline than the lava flows. This second type of flow, which may extend more than 50 km from the leading edge of the lava flows, is interpreted here to be a deposit associated with the deposition of sediments originally carried within meltwater released from the regolith during the emplacement of the lava flows. These flows are similar to the megalahar deposits proposed to exist in western Elysium Planitia by Christiansen and Greeley (1981) excepted that they grade smoothly into the distal ends of lava flows, rather than being related to source channels. However, like the megalahars of Christiansen and Greeley, these lobes may be the Martian equivalents of Icelandic jökulhlaups, where large volumes of sediment-laden meltwater are released when an eruption occurs beneath a glacier (cf. Rist, 1976). This comparison may not be strictly valid, however, since the meltwater on Mars is unlikely to have come from an overlying glacier, but rather from igneous intrusions into ground ice or to the emplacement of lava flows upon ice-rich ter-

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Fig. 2. Sketch map showing occurrences of chaos and lava flows (arrows) to the west of Hecates Tholus. Circles with inward facing barbs represent impact craters, cross-barbed lines indicate graben. Also shown are the locations of Figs. 3, 4A,B, and 7.
Fig. 3. Two types of flow features are recognizable to the west of Hecates Tholus. Lava flows from Elysium Mons (L) can be identified from the hummocky morphology of the compound flows, while deposits inferred here to be meltwater deposits (jokulhaups; J) are thinner and less lobate. Note that most of the jokulhaups appear from beneath the lava flows (see text for discussion). Visible on some of the isolated massifs are the remnants of lava flow lobes (A) indicating that at least some direct heating of the terrain that subsequently collapsed took place. The location of Fig. 8 is also shown. Mosaic of Viking Orbiter images 651A07-12, centered at 33°N, 215°W; image resolution is 52 m/pixel. The width of the image is equivalent to 115 km.

Allen (1980) argued that the limiting depth of an ice-rich layer at which pseudocraters would form would approximate to half the thickness of the overriding lava flow. If this assumption is valid, then the absence of pseudocraters on the surface of the 100- to 150-m-thick Elysium flows would imply that the ice-rich layer within the regolith was at a depth of at least 50–75 m. Were the ice to be replaced by liquid water, the heat needed to create the superheated steam was found by Allen (1980) to be only 7% less than for ice, implying that...
FIG. 4. (A) Several irregular depressions acted as collecting areas or lakes (L) for fluids derived from the jokulhaups. Erosional channels (C) and collapse pits (P) can also be seen. Rectangle shows the location of Fig. 5. Viking Orbiter image 651A06, centered at 33.71°N, 215.48°W, image resolution is 52 m/pixel. Image width is equivalent to 60 km. (B) Morphological sketch of the area shown in Fig. 4A. Cross-hatch areas are chaotic terrain, vertical lines denote jokulhaup deposits, and the dotted unit is a partially buried lava flow. White areas signify main catchment areas (ephemeral lakes?) and pathways for fluid flow, which are shown by arrows. Collapse features are shown by barbed lines. The boxed area gives location of Fig. 5.
the physical state of the volatile layer would not be a critical factor in the formation of pseudocraters. Such an estimate of the depth of the volatile layer is compatible with the model of Fanale et al. (1985) which predicts that the regolith was depleted of volatiles to a depth of 100–300 m at this latitude and time. As a word of caution, however, it is clear that the limiting factor in the estimate of volatile depth to produce pseudocraters lies in the estimate of lava flow thickness, which is recognized to be only approximate in this instance.

In addition to the sediment lobes immediately to the north of the lava flows, further lines of evidence support the idea that significant volumes of meltwater were released from the regolith during lava emplacement. Within the chaotic terrain to the north (Figs. 4A,B) are several topographic depressions of irregular shape that have a smooth surface texture, except for faint linear ridges (at a resolution of 50 m/pixel). At higher resolution (8 m/pixel; Figs. 5A,B), one set of these ridges is seen to be part of a distributary network not unlike a dissected river delta fan. This distributary network has at least two main discharge points, each of which measures 2 km in width, while the total length of the system extends for 25 km from the most likely source area (Figs. 4A,B). Rather than being ridges built by tectonism or constructional processes, these ridges are interpreted here to be the remnants of a former deltaic fan that has been dissected by subsequent fluvial activity. Carr (1983) has shown that it is possible that transient lakes once existed on the Martian surface, and the preferred model for explaining the observed features is one involving the existence of a temporary lake that occupied the irregular depression that forms the catchment area shown in Fig. 5B, with the deltaic fan created where the channel entered the lake. After drainage of the lake, subsequent meltwater-flow carved the distributary network into the deltaic fan. Ridges of sediment that are visible on the adjacent plain several kilometers beyond the discharge points indicate that meltwater release was a repetitive phenomenon in this area.

Other unusual landforms, also believed to be associated with the emplacement of sediments, can also be recognized within an area to the west of these catchment areas. Irregularly shaped depressions, concentric craters 1.0–1.5 km in diameter, crenulated terrain, and the exposed remnants of morphologically fresh lava flows can all be seen (Fig. 6). This area possesses a different morphology from that of the area to the east, in that a relatively thick layer of material appears to have been emplaced upon the preexisting terrain in the form of a low-viscosity flow. It is therefore possible that this material has a different origin than the sediments identified in Figs. 4A,B and 5A,B; the morphology of this western material appears more similar to the mudflow or megalahars previously identified by Christiansen and Greeley (1981). The irregular depressions within this mudflow deposit (arrowed in Fig. 6) vary in size from 0.5 to 7.0 km in width and may be as much as 30 km in length. In all cases they are relatively shallow depressions with hummocky floors that show a slight preferential orientation along their long axis. It is possible that these collapse features were either formed where the flow materials were emplaced over preexisting graben or by some other unknown mechanism. All the concentric craters, of which a total of nine can be seen, lack rims, and either have no interior structure or possess a small central mound. While no origin for these concentric craters can be unequivocally identified, they may be impact craters that have formed after the mudflow deposits had been emplaced [i.e., the concentric nature of these craters may be due to a similar target strength difference to the one responsible for concentric craters on the lunar mare; Quaide and Oberbeck (1968)]. Alternatively, the concentric craters could be pseudocraters created by the emplacement of a warm mudflow deposit upon a layer of ground ice,
FIG. 5. (A) At high resolution (8 m/pixel), ridges on the floor of the catchment areas are seen to be distributary networks, where it is inferred that sediments were deposited and eroded by meltwater (direction of flow was from the bottom left to the top of the field of view). Viking Orbiter frames 434B04 and 434B05, centered at 34.03°N, 215.95°W. (B) Sketch map of the distributary network shown in Fig. 5A. The catchment area floor (white unit) is likely to be a series of outwash deposits, with the largest sediment lobe denoted by crosses. The deltaic fan (black) has been dissected by several channels. Chaotic terrain (cross hatch) surrounds this area, and is also visible as a few partially buried massifs.
although this mechanism appears less likely due to the presence of central features (central peaks?) within the craters.

Chaotic Terrain and Collapse Features

Chaotic terrain was first interpreted by
Sharp (1973) to be an indicator of localized collapse following the removal of ground ice. Carr and Schaber (1977) recognized that the irregular area of collapsed terrain to the west of Hecates Tholus was quite likely to be the product of such a process. Examination of this area (Fig. 7) reveals that chaos formation has not progressed uniformly along the whole length of the boundary, but that it seems likely that lines of structural weakness have played an important role in this collapse process. A few examples can be identified where lava flows have been subsequently dissected by chaos (e.g., at “A” in Fig. 3), but in most cases the lava flows do not extend within 30–50 km of the area of collapse. Thus the relationship between the formation of the chaotic terrain and the emplacement of the lava flows upon regolith containing ground ice is unclear.

Debris features similar to those identified within the fretted terrain of Mars (Squyres, 1978; Lucchitta, 1984a) can be found within the chaos. Even on the top of isolated remnants, mass flow has produced a series of small ridges, suggestive of ground ice very close to the surface (Fig. 8). As with the fretted terrain, movement of ice-rich debris within the collapse features of the chaos appears to have taken place, although the lack of continuous ridges parallel to the valley walls argues against widespread horizontal transport of material by this process within Elysium.

Several other types of collapse features can also be recognized further south within Elysium Planitia. In many instances, such features take the form of linear troughs that have steep walls, smooth floors, and are open at the northwestern end (Fig. 9). These troughs, of which 22 major examples have been identified (Fig. 10), have lengths between 25–250 km, maximum widths between 4.5–25.0 km, and, from shadow-length measurements, are estimated to be 590–1040 m deep. Typically, troughs are orientated within 15° of radial to the summit.

Fig. 7. Chaotic terrain to the northwest of Hecates Tholus shows signs of structural control (along arrowed lines). Mosaic of Viking Orbiter frames 86A33-37, centered at 33°N, 212°W; image resolution is 38 m/pixel. The width of the image is equivalent to 65 km.
of Elysium Mons. Although there is some scatter in their spatial distribution, there appears to be a tendency for some clustering with respect to radial distance from Elysium Mons; most of the examples are located either at 240–270, 330–370, or 440–460 km from the volcano. Thus, while their origin is uncertain, it is likely that the troughs are related to the regional tectonics of Elysium Planitia (Sharp and Malin, 1975; Malin, 1976), with their precise location possibly controlled by concentric fractures associated with loading of the region by Elysium Mons (Hall et al., 1984). No single trough morphology exists, but a few frequently recurring features have been identified (Fig. 11A). In general, troughs have linear walls and smooth rims with little evidence of stratification within the wall. A few isolated blocks and surface markings
are seen on the floor, and these features are orientated parallel to the walls. In almost every case, the floor of the trough is smooth (at an image resolution of 150 m/pixel). At the proximal end (with respect to Elysium Mons), a small head tributary usually exists; no other gully is seen on the walls. Finally, the distal end of the trough is usually open, with a slight broadening in width compared to the rest of its length. In certain cases, material flowed out of the trough, as evidenced by the partial burial of lava flows located at the open ends of some troughs (Fig. 9). As discussed below, there appears to be a latitudinal variation in the occurrence of these troughs that display flow material at their distal ends; such features are only observed north of 24°N. Further south, troughs that exceed 600 m in depth still formed, but their interiors have not been modified by subsequent flows, nor do they widen at their distal ends. Such a situation is considered here to a possible result of the loss of volatiles from the regolith at this latitude, or the absence of a buried ice wedge at this location.
Quite often, these closed troughs align themselves with other troughs in a similar manner to a chain of pit craters, once more suggesting a tectonic influence in their mode of formation.

Outflow Channels

Mouginis-Mark et al. (1984) identified an area approximately 260 × 480 km in extent and located 470 km west of Elysium Mons which they interpreted to be a fourth volcanic center within Elysium Planitia. They gave this area the name Complex Vent Area due to the lack of a topographic construct and the occurrence of several large and small sinuous channels that have a morphology similar to lunar sinuous rilles. Most notable is the large braided channel system that is located at the western edge of this complex (Fig. 12). The main portion of this trough is a linear depression measuring 67 km in length and 2.7–3.6 km in width, with an enlarged collapse structure at its head that measures 22 × 11 km. No chaotic terrain within the trough, or other evidence for the collapse of the surrounding material, is associated with this structure, despite the fact that measurements of the sinuosity of the downstream outflow channels suggest that considerable quantities of meltwater were released here (Mouginis-Mark et al., 1984). Five main distributaries diverge from the end of the trough, and the existence of multiple stream levels within the largest outflow channels indicates that several different periods of outflow and erosion took place. Isolated areas of hummocky terrain, located primarily at points along the channel where rapid changes in flow direction occurred, are likely to be sedimentary deposits associated with the deposition of material entrained within the flow.

Styles of Volcanism

The landforms described in the previous section indicate that considerable amounts of volatiles existed within northwestern Elysium Planitia at the time of volcanic ac-
Fig. 12. To the west of the Complex Vent Area is a large set of outflow channels that are believed to be the products of meltwater release from the troughs to the east. Direction of flow was from right to left in this image. Multiple channel levels and streamlined islands indicate that fluid flow was a repetitive phenomenon. Mosaic of Viking Orbiter frames 649A11-18, centered at 28°N, 225°W; image resolution is 38 m/pixel.

Fig. 13. (A) To the west of Elysium Mons is an area that Mouginis-Mark et al. (1984) called the Complex Vent Area, because there are many sinuous channels, old lava flows, and hummocky terrain that exist here. Despite the lack of a volcanic construct, it is believed that this area represents a fourth volcanic center within Elysium Planitia. Mosaic of Viking Orbiter frames 541A36-41; image resolution is 150 m/pixel. The width of the image is equivalent to 265 km. (B) Sketch map of the Complex Vent Area (Fig. 13A) showing locations of sinuous channels (that are interpreted here to be volcanic in origin and unmodified by fluvial activity; source of channel marked by solid circle), hummocky terrain (cross hatch), and preserved lava flow fronts (barbed lines).
It is unclear what the exact role of igneous activity was in the formation of the troughs. If near-surface intrusions were the cause of the ground-ice melting, some form of deformation feature, or signs of explosive activity, would be expected. No depressions that are likely to be the products of regional subsidence can be seen, and there is no morphological evidence (in the form of small pyroclastic flows) to support the occurrence of strombolian or vulcanian eruptions in this area although the model of Wilson et al. (1982) predicts them to occur in such a situation. Similarly, no obvious areas of mantled terrain exist in this area that are comparable to the airfall deposit on the summit of Hecates Tholus (Mouginis-Mark et al., 1982). The possibility does exist that a thin, very extensive pyroclastic deposit mantles much of the area, particularly within the Complex Vent Area. Such a deposit would be difficult to identify in this area, due to the rugged character of the topography (Figs. 13A,B). However, if this were the case, some surface manifestation of magma chamber collapse, in the form of a volcano-tectonic depression, should be visible in the available images. No such depression can be identified within this area, arguing against large-scale explosive (plinian) eruptions. Based on analogy with other Martian volcanoes (Wood, 1984), it would therefore appear reasonable to speculate that the magma chamber associated with the Complex Vent Area was either of smaller size or at an appreciably greater depth than was typical for most Martian volcanoes. Two principle types of terrain are nevertheless recognizable within the Complex Vent Area (Fig. 13B); an older unit comprises hummocky terrain within which a number of small sinuous channels originate, while smoother, topographically lower material embays this hummocky terrain. Due to the recognition of a few isolated flow fronts within this unit, this smooth material is interpreted to be a sequence of thin lava flows.

Extrusives

Squyres and Moosman (1984) predicted that lava flows emplaced upon ground ice could produce large volumes of meltwater and promote the formation of pseudocraters. Analysis of the lava flows north of Elysium Mons (Fig. 3) shows that at least the first of these processes has operated in this area. It is evident, however, that the volatile-rich regolith has not significantly affected the emplacement or morphology of the lava flows; there is no obvious deformation of the flow surface, nor are there landforms comparable to those believed to be associated with phreatomagmatic activity elsewhere on Mars (Allen, 1980; Frey and Jarosewich, 1982). Pseudocraters are not widely distributed within Elysium Planitia (indeed, the only candidate examples are north of 34°N; Fig. 6), and there is no evidence to suggest that the flows possess the negative topography indicative of large-scale subsidence of hot lava as the underlying ground ice was heated, releasing the meltwater.

There is some evidence, however, that the lava flows may have been cooling more rapidly here than in other areas of Mars, perhaps as a consequence of basal chilling from the underlying strata. Evident in Fig. 3 is the compound nature of the flows; rather than a single flow unit being present, it appears that each lava flow advanced in a stochastic manner. Although this could be a product of the local (unknown) topography at the scale of the flows, these flows do possess an unusually high number of lobe fronts on the surface of the main flow, which has resulted in a step-like morphology. This flow morphology occurs at distances in excess of 100 km from the vent area, and appears to be associated with individual flow units, possibly indicating that an unusually rapid increase in viscosity may have taken place at the leading edge of the flow. This in turn may have been due to changes in the mass eruption rate of the lava or due to basal cooling by the melt-
water. Each of these two mechanisms have been observed in the field on Earth, with a sequence of flow budding and over-riding due to variations in effusion rate seen during the development of a compound lava field on Mount Etna (Pinkerton and Sparks, 1976), while cooling by water may have been responsible for the diversion of lava flows during the 1973 eruption of Heimaey (Jonsson and Matthiasson, 1974).

**DISCUSSION**

Many morphological features argue in favor of significant amounts of ground ice existing within western Elysium Planitia at the time of volcanic activity. Pseudocraters, meltwater deposits, collapse troughs, chaotic terrain, and outflow channels can all be found at different latitudes. The occurrence of these features suggests that a latitudinal distribution of volatiles existed, possibly in a similar manner to the predictions of Fanale et al. (1985). At the northernmost latitudes (32°–35°), ground ice may have been within 50 m or so of the surface, permitting the formation of pseudocraters and horizontal mass movement within the chaotic terrain. At 30°–32°, insufficient volatiles were located close to the surface to permit pseudocraters to form, although the emplacement of relatively thick lava flows was able to liberate large volumes of meltwater to create jokulhlaup-like deposits. From 30°N–25°N stable trough walls may indicate that the volatiles were absent from the top few hundred meters of the crust. However, some of these troughs have acted as the source areas for considerable volumes of water, implying that the trough floors intersected the volatile layer at this latitude. The most productive example of a trough with an outflow channel has its source located at 26°N. South of 24°N, troughs were still formed (presumably by regional tectonism; Carr, 1981; Hall et al., 1984), but there is little evidence of meltwater discharge.

These “dry” troughs are estimated to be at least 600 m deep (i.e., are of comparable depth to the ones seen further north) and may therefore provide morphological clues to the distribution of volatiles on Mars. Fanale et al. (1985) calculated the rate of volatile loss from the Martian regolith as a function of depth for different regolith pore sizes. Over the age of Mars, the migration of water from the equator to the poles, coupled with the finite volume of water and the geothermal gradient of Mars, would have combined to produce a wedge of ground ice that progressively thins and increases in depth toward the equator. If the water inventory on Mars were unlimited, then the model of Fanale et al. (1985) would be inconsistent with the above observations, since ice would still be present at depths in excess of 600 m for any soil parameters. However, if the initial average global depth of water-rich soil (say, 50% by volume) is limited to values between 50 and 150 m, then solutions consistent with the morphological observations presented here and the model of Fanale et al. can be found (Fig. 14). These assumptions regarding the initial depth are not unreasonable since they correspond to a global layer of water 25–75 m in thickness; a range which is intermediate among cosmochemically derived global water abundances (McElroy et al., 1977; Pollack and Black, 1979; Wanke and Dreibus, 1984). A comparison between the ice distribution thus derived and the distribution of observed landforms suggestive of ground ice within Elysium Planitia (Fig. 14) shows that 1.8 byr ago (approximating to the age of the Elysium lava flows; Neukum and Hiller, 1981) the ice wedge would have been approximately 30 m thick at 35°N (if it was assumed that the ice wedge is 100% ice, greater thicknesses would result from varying amounts of interstitial ice). This ice wedge would have been encountered at a depth of 40 m if the average pore diameter was 1 μm. This same ice wedge would have completely disappeared at 25°N for the same set of regolith conditions. Alternatively, if the pore diameter was 10 μm, the ice wedge at 35°N would have been only a
few meters in thickness and would have been at a depth of about 145 m. As with the 1-μm particle size, no ground ice would have been encountered at about 25°N with an average particle size of 10 μm after 2.7 byr of Martian history. No absolute depth estimate is possible from these models, however, since the volatile distribution considered by Fanale et al. (1985) would likely be a relic of early Martian history, and it is clear that several hundred meters of young (1.8-byr-old) lava flows have been emplaced on top of the older material. Thus the models of Fanale et al. only predict that a thin layer of ground ice would be encountered within Elysium Planitia at the time of volcanism and extensional tectonism, and that this layer thins toward the equator in a manner consistent (but not exclusively so) with the observed distribution of “wet” and “dry” troughs. Unfortunately, determining the actual depth of occurrence of this ice wedge at the time of graben formation within Elysium is considered beyond the currently available data. Other morphological evidence, based on the investigation of landslides within Valles Marineris (Lucchitta, 1984b), does support this interpretation of deeply buried ice or water existing at depth close to the equator in recent Martian history, as do impact crater morphologies within Elysium Planitia (Hale, 1983). It is therefore concluded that the volatile layer within western Elysium Planitia displayed an increase in depth of burial beneath the surface (at the time of volcanic activity) from less than 50 m to perhaps more than 600 m over a latitudinal range of 11° from 35°N to 24°N. Interestingly, this latitudinal range for the transition from ground ice affecting landforms to one where landforms are unaffected is very similar to the one ob-
served by Squyres and Carr (1984) to be associated with a variety of landforms distributed planetwide, suggesting that the two independent sets of observations are both describing the same phenomenon.

The styles of volcanic activity should, according to theory (Allen, 1980; Wilson et al., 1982; Squyres and Moosmen, 1984), have been affected by this volatile layer. Effusive eruptions that produced lava flows in excess of 200 km in length were the most common form of activity in this area, and well preserved examples of interaction between these lavas and the underlying volatiles can be seen. Nevertheless, the lava flows have undergone little surface modification due to collapse, and the expected formation of pseudocraters did not occur. However, effusive volcanism within northern Elysium may not have been totally unaffected by the underlying ground ice. While the development of a step morphology on some of the lava flows may have been the result of changes in the volume of magma erupted during a single eruption, it is also possible that this morphology may be the product of basal cooling of the flows due to meltwater release from the regolith. The identification of erosion channels cut into possible deltaic fans in topographic lows with smooth surfaces provides morphological evidence for the former existence of ephemeral lakes, as predicted by the models of Carr (1983). Presumably the formation of these lakes, and the repetitive inflow of water into the catchment areas, was due to the release of meltwater during or immediately after volcanic activity.

An absence of evidence for vulcanian eruptions, which should have produced pyroclastic flows had the volatiles chilled the ascending magma close to the surface, provides evidence for the absence of near-surface volatiles close to the volcanic vents. Similarly, the lack of large mantled areas comparable to the one identified on Hecates Tholus argues against plinian explosive eruptions occurring in this area. This analysis has also confirmed the unusual character of the Elysium Complex Vent Area; no evidence has been found of cinder cones, pyroclastic flows, or airfall deposits within this area. The lack of constructional features and the relatively small size of individual flows indicate that an unusual magma reservoir probably existed here, producing small volumes of magma over a large area of western Elysium Planitia. Thus the cause of the diversity in volcanic landforms within Elysium Planitia remains enigmatic. Were signs of geologically recent explosive activity associated with near-surface volatiles to be found anywhere on Mars, western Elysium should be the area where they are observed. Because these signs do not exist, this analysis lends supportive evidence for a juvenile source for the magma volatiles within Elysium Planitia, and as such appears to favor a similar magma chemistry for explosive eruptions such as the one previously identified for Hecates Tholus.

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