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THE ORIGIN OF CHANNELS AND ASSOCIATED DEPOSITS IN THE ELYSIUM REGION OF MARS

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TABLE OF CONTENTS

Christiansen, E.H., 1984, Volcanic debris flows in the Elysium region of Mars: Geological Society of America Abstracts with Programs, v. 16, p. 470.

Christiansen, E.H., and Ryan, M.P., 1985, Volcanic debris flows in the Elysium region of Mars: NASA Technical Memorandum 87563, p. 239-241.

Christiansen, E. H., 1985, Geology of Hebrus Valles and Hephaestus Fossae, Mars: Evidence for basement control of fluvial patterns: Geological Society of America Abstracts with Programs, v. 17, p. 545

Christiansen, E.H., and Hopler, J.A., 1986, Geomorphic evidence for subsurface volatile reservoirs in the Elysium region of Mars: Lunar and Planetary Science XVII, p. 125-126.

Christiansen, E.H., and Hopler, J.A., 1987, Volatile reservoirs below the surface of the Elysium region of Mars: Geomorphic evidence: NASA Technical Memorandum 89810, p. 307-309.

Lahars in the Elysium Region of Mars

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ABSTRACT

Photogeological studies of the Elysium volcanic province, Mars, show that its sinuous channels are part of a large deposit which probably was emplaced as a series of huge volcanic debris flows or lahars. The suggestion is based on evidence that the "lahars" were: 1) gravity-driven mass flow deposits (lobate outlines, steep snouts, smooth medial channels and rough lateral deposits, the deposits narrow and widen in accord with topography, and they extend downslope); 2) wet (channeled surfaces, drainage features); and 3) associated with volcanism (the deposits and channels extend from a system of fractures which fed lava flows). It is conceivable that heat associated with magmatism melted ground ice below the Elysium volcanoes, formed a muddy slurry which issued out of regional fractures and spread over the adjoining plain.

INTRODUCTION

Perhaps the most fascinating result of the satellite missions to Mars was the discovery of numerous sinuous channels on its surface which resemble those produced by fluvial erosion on Earth (Baker, 1982; Mars Channel Working Group, 1983). The presence of the channels is taken as evidence that some fluid, generally believed to be water, flowed across the surface of Mars and formed the channels or valleys. The genesis of the channels by flowing water is somewhat perplexing in that liquid water is not stable at the present surface of Mars. This fact has led to a variety of hypotheses to explain the occurrence of liquid water at the surface including climate change, the outbreak of aquifers confined to depths at which liquid water is stable (greater than about 1 km, Carr, 1979), or to the melting of ground ice by magmatic heat (McCauley et al., 1972; Masursky et al., 1977). Another enigma is that most Martian channels do not appear to have associated deposits of sediments, even though the very existence of the channels is evidence that considerable erosion has occurred.

The purpose of this paper is to outline the evidence that the lobate channeled deposits in the Elysium volcanic province of Mars are lahars as initially suggested by Christiansen and Greeley (1981). The apparent source of the lahars lies beneath the Elysium volcanic province. This conclusion bears at once upon both of the problems outlined above and adds to the growing body of evidence for extensive sub-surface reservoirs of ice on Mars (Carr, 1986).

GEOLOGIC SETTING

The reputed lahars extend 1000 km from their sources, cover an area of 1 million km^2, and probably have a cumulative volume exceeding 100,000 km^3 (Fig. 1). The lahars occur on the steep northwestern slopes of a flexural dome in the Martian lithosphere (Hall et al., 1986). The topographic dome is approximately 2000 km across and stands 3 to 5 km above the surrounding plains. The dome is transected by northwest-trending fractures and graben, and capped by lavas which erupted from three shield volcanoes centered on the fracture system or from the fractures themselves. Elysium Mons is the largest of the shields and is most closely related to the channeled deposits described here; it rises 13 km above the dome and is about 600 km in diameter. More details about the geology of the Elysium volcanic province can be obtained in papers by Malin (1977), Mouginis-Mark et al. (1984) and Christiansen and Hopler (1987).

WHAT ARE LAHARS?

Lahar is the Indonesian name for a volcanic breccia transported by water. The term is used to describe flowing volcanic debris as well as the deposits formed by such flows. Fisher and Schminke (1984) have provided an excellent review of the nature of lahars. Summarizing from their work and references cited therein, lahars are:

1) mass flow deposits,
2) wet with water acting as a mobilizing agent, and
3) generated as the direct or indirect result of volcanism.

Using these criteria and the character of the Martian features as displayed in Figures 1 - 6, the Elysium channels and associated deposits can be interpreted as lahars.

LAHARS ARE MASS FLOW DEPOSITS

A wide variety of mass flow deposits exists (e.g., mud and debris flows, lava flows, pyroclastic flows, landslides or sturzstroms, and glaciers). All of these genetically diverse flows are produced by the gravity driven flow of viscous, non-newtonian fluids which possess significant yield strengths. As a consequence, their deposits are morphologically similar, especially on aerial photographs. For example, most mass flow deposits have steeply sloping lobate snouts and their margins are distinctly elevated above the surrounding plains. These features reflect their generally non-newtonian behavior and the simple fact that mass occupies a volume determined by the density and porosity of the material. In the case of debris flows, these deposits have marked lateral deposits which flank medial deposits created by plug-like flow of the central part of a debris tongue (Johnson, 1970). In plan view, most mass flow deposits consist of multiply digitate lobes of material that came to rest at slightly different times. In general, where slopes are steep (and velocities high) the deposits left by all types of mass flows are relatively thin and become thicker and broader on the gentle slopes of unconfined plains or piedmonts. In the case of lahars, the surface of the debris flows are quite smooth with gentle undulations resulting from differential compaction of the debris (Fisher and Schmincke, 1984; Siebert, 1984). In fact, the smoothness of lahar surfaces may be important for distinguishing them from volcanic debris avalanches which have extremely hummocky surfaces and display numerous hills and small mounds (Siebert, 1984).

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

The simple observation that the Elysium "lahars" are gravity-driven mass flow deposits can be made from the images returned by the Viking orbiters. Figure 2 shows a dramatic example of the morphology and definition of these flows. Snouts or flow fronts are well-defined, medial deposits (where not cut by later water flow) are developed inboard and are generally smooth. Shadow measurements in this vicinity indicate that the flow front is less than 100 m high. The multiple, overlapping nature of the debris lobes is seen in Figures 2 and 3. The flow deposits trend down the western flank of the Elysium dome, dropping approximately 5000 m over their 1000 km course. Much of the drop occurs in the first 100 km. Where the slopes are steep narrow chutes developed and at the break in slope at the base of the dome the deposit fans out abruptly to form a thin deposit less than 200 m thick (pre-existing impact craters protrude) that bury older lava plains (Fig. 4).

LAHARS ARE WET

By definition, lahars contain a significant proportion of water. Mud and debris flows are fluids in which water and solids form an intimate mixture which generally moves by laminar flow (Fisher and Schmincke, 1984). For example, the matrixes of three 1980 Mt. St. Helen lahars contained 22 to 36 volume percent water (Pierson, 1985). Beverage and Culbertson (1964) defined mudflow as containing less than 40 volume percent water and hyperconcentrated streams as containing 40 to 80 volume percent water. Using these definitions, Fisher and Schmincke (1984) point out that many terrestrial lahars may be hyperconcentrated streams instead of true mudflows. The viscous properties imparted by the included water dictate that on steep slopes debris flow velocities may be high enough to keep the entire mass in motion. In fact, lahars may erode channels on the steep flanks of volcanoes (Fisher and Schmincke, 1984). In general however, the basal contacts of lahars are non-erosional.

On Earth, this water separates from the granular matrix of the flow by downward infiltration of overridden materials, by upward expulsion of pore fluids onto the surface of the debris, and by evaporation (Fisher and Schmincke, 1984; Lawson, 1982). For example, Curry (1966) reported that water drained for 12 days from the base of an alpine mudflow in Colorado. Such de-watering may cause surface ponding of water and consequent smooth accumulations of sediment, branching sapping valleys, and even collapse pits (Singewald, 1928; Lawson, 1982; Kochel et al., 1985; and Higgins, 1984). These sapping and piping features are the best geomorphic evidence that debris flows are emplaced with a significant proportion of water. In addition, the emplacement of many terrestrial debris flows and lahars are followed by relatively underloaded flood waters (issuing from the same sources which created the debris flows) eroding earleir deposits to form runoff (in contrast to seepage) valleys (Johnson and Rodine, 1984).

That the Elysium flow deposits were wet is demonstrated by several lines of evidence. The most obvious indications of water are their channeled surfaces. The largest channels at Granicus Valles are near the source of the flows and were eroded during a late water-rich phase of the development of the flow deposits (Figure 4). These channels are gently sinuous, have streamlined features on their floors, and anastomose distributary patterns. Several investigators have concluded that they are fluvial channels (Malin, 1976; Mouginis-Mark et al., 1982), but their intimate association with the flow deposits (Fig. 1) was not noted until the initial stages of this investigation. These channels ultimately disappear by merging with smooth medial deposits. Approximately 75 km farther "down stream" stubby tributaries start up and merge with broad smooth-surfaced channels (Fig. 5). The reappearance of the channels suggests that they are seepage valleys formed as pore waters were expelled to the surface. Short reticulate systems of sinuous valleys (individually less than about 5 km long) cut the distal portions of the deposits are also interpreted as seepage features (Fig. 6). Both types of valleys have analogs in debris flows on Earth, as described above. The pitted nature of the lateral deposits (Fig. 3) of some of the channeled deposits may also be the result of de-watering--either by more active piping associated with downward draining or as a result of enhanced evaporation of the included water in coarse-grained marginal deposits. These irregular depressions developed from formerly smooth and more extensive lateral deposits. Distal channels are filled by dark flow materials resembling material remobilized by draining of the deposit (Fig. 6).

LAHARS ARE ASSOCIATED WITH VOLCANISM

Lahars may be produced as a direct consequence of eruption such as by the incorporation of ice, snow, groundwater, or stream water into pyroclastic flows or surges. Lahars not directly related to eruptions include those created by the mobilization of volcanic ash on the steep slopes of a volcano by torrential rains, the rapid melting of snow or ice, or by draining a crater lake.

The debris flows of the Elysium region are inextricably linked with volcanism. Lavas and debris flows formed late in the evolution of the volcanic province. The source of the Granicus lahars and channels (Fig. 4) is an elongate trough formed on the steep western flanks of the Elysium dome. Adjacent troughs to the north fed lava flows and lahars (Figs. 1 and 4). The lava sources and the lahar sources all trend WNW and are part of the regional fracture system which transects the Elysium dome (Fig. 1). Although most of the lahars are superposed on the voluminous fissure-fed lavas, locally they are older (Mouginis-Mark, 1985). These observations show the close temporal and spatial association of volcanism and lahar generation. The absence of large surface scars and the way in which debris flows and channels issue from fractures show that the debris and water must have sub-surface origins.

ORIGIN OF ELYSIUM LAHARS

The lahars of the western Elysium region appear to have been generated as a result of "parasitic" eruptions on the northwestern flanks of the Elysium dome. Mouginis-Mark (1985) and Christiansen and Hopler (1987) present independent evidence that volatile-rich deposits lie beneath at least the western part of the Elysium province. Elevated heat flow related to the development of the fissure-fed flank eruptions may have melted ground ice and liquefied sub-surface materials. Direct contact between magma and water is difficult to prove at this point, but may have generated abundant fine particles as well as superheated steam (Wohletz, 1986). The intersection of this slurry with the regional fracture-dike system led to the rapid and perhaps explosive expulsion of debris flows down the western slope of the province. Three separate groups of lahars have been identified (Fig. 1). Where slopes were steep, erosional troughs developed; where the slope was lower, the vast lobate deposits formed and were later cut by continued draining of water from the fractures and from the deposits themselves.

CONCLUSIONS

Lobate flow deposits with well-defined snouts, medial channels, and lateral deposits issue from a northwest-trending system of fractures that cut the Elysium dome. They extend 1000 km down the regional slope to the northwest and cover 1,000,000 km^2. Geomorphic evidence that these flows were wet debris flows and not lava or pyroclastic flows include the presence of: 1) apparently fluvial valleys on their surfaces; 2) seepage valleys; and 3) numerous irregular depressions representing dewatering of the deposits. The debris flows issue from the same set of fractures that fed extensive flank eruptions of Elysium Mons demonstrating their association with volcanism. Based on this evidence, I conclude that these channeled deposits are lahars resulting from the interaction of volcanism with a reservoir of volatiles buried in the Martian crust.

REFERENCES CITED

Baker, V. R., 1982, The channels of Mars: University of Texas Press, Austin, 198 p.

Beverage, J.P., and Culbertson, J.K., 1964, Hyperconcentrations of suspended sediment: Hydraulic Division American Society of Civil Engineers, v. HY6, p. 117-126.

Carr, M.H., 1986, Mars: A water-rich planet? Icarus, v. 68, p. 187-216.

____ 1979, Formation of Martian flood features by release of water from confined aquifers: Journal of Geophysical Research, v. 84, p. 2995-3007.

Christiansen, E.H., and Greeley, R., 1981, Mega-lahars(?) in the Elysium region, Mars [abs.]: Lunar and Planetary Science XII, p. 138-140.

Christiansen, E.H.,and Hopler, J.A., 1987, Geomorphic evidence for subsurface volatile reservoirs in the Elysium region of Mars: Submitted to Journal of Geophysical Research.

Curry, R.R., 1966, Observation of alpine mudflows in the Tenmile Range, central Colorado: Geological Society of America Bulletin, v. 77, p. 771-776.

Fisher, R.V., and Schmincke, H.U., 1984, Pyroclastic Rocks: Springer-Verlag, Berlin, 472 p.

Higgins, C.G., 1984, Piping and sapping: Development of landforms by groundwater outflow, in LaFleur, R.G., ed., Groundwater as a geomorphic agent: Allen and Unwin, London, p. 18-58.

Johnson, A.M., 1970, Physical processes in geology: Freeman and Cooper, San Francisco, 577 p.

Johnson, A.M., and Rodine, J.R., 1984, Debris flow, in, Brundsen, D., and Prior, D.B., eds., Slope instability: John Wiley and Sons, Chichester, U.K., p. 257-361.

Kochel, R.C., Howard, A.D., and McLane, C., 1985, Channel networks developed by groundwater sapping in fine-grained sediments: analogs to some Martian valleys, in, Woldengerg, M., ed., Models in geomorphology: Allen and Unwin, Boston, p. 313-341.

Lawson, D.E., 1982, Mobilization, movement, and deposition of active subaerial sediment flows, Matanuska Glacier, Alaska: Journal of Geology, v. 90, p. 279-300.

Malin, M.C., 1976, Age of Martian channels: Journal of Geophysical Research, v. 81, p. 4825-4845.

_____1977, Comparison of volcanic features of Elysium (Mars) and Tibesti (Earth): Geological Society of America Bulletin, v. 88, p. 908-919.

Mars Channel Working Group, 1983, Channels and valleys on Mars: Geological Society of America Bulletin, v. 94, p. 1035-1054.

Masursky, H., Boyce, J.M., Dial, A.L., Schaber, G.G., and Strobel, M.E., 1977, Classification and time of formation of Martian channels based on Viking data: Journal of Geophysical Research, v. 82, p. 4016-4038.

McCauley, J.F., Carr, M.H., Cutts, J.A., Hartmann, W.K., Masursky, H., Milton, D.J., Sharp, R.P., and Wilhelms, D.E., 1972, Preliminary Mariner 9 report on the geology of Mars: Icarus, v. 17, p. 287-327.

Mouginis-Mark, P.J., 1985, Volcano/ground ice interactions in Elysium Planitia, Mars: Icarus, v. 64, p. 265-284.

Mouginis-Mark, P.J., Wilson, L., Head, J.W., Brown, S.H., Hall, J.L., and Sullivan, K.D., 1984, Elysium Planitia, Mars: Regional geology, volcanology, and evidence for volcano-ground ice interactions: Earth, Moon and Planets, v. 30, p. 149-173.

Pierson, T.C., 1985, Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington: Geological Society of America Bulletin, v. 96, p. 1056-1069.

Siebert, L., 1984, Large volcanic debris avalanches: Characteristics of source areas, deposits and associated eruptions: Journal of Volcanology and Geothermal Resources, v. 22, p. 163-197.

Singewald, J.T., 1928, Mudflow as a geologic agent in semiarid mountains--Discussion: Geological Society of America Bulletin, v. 39, p. 480-483.

Wohletz, K.H., 1986, Explosive magma-water interactions: Thermodynamics, explosion mechanisms, and field studies: Bulletin of Volcanology, v. 48, p. 245-264.

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FIGURE CAPTIONS

Figure 1. Geologic map of the Elysium region of Mars. Geologic units from youngest to oldest: lc - channeled lahars; ps - smooth plains; pm - modified plains; le - Elysium lava flows; pk - knobby plains; pmn - mottled northern plains. Channels shown by fine lines on lc. Open fractures and graben shown with line and ball symbol. Geographic features: AT - Albor Tholus; EM -Elysium Mons; GV-Granicus Valles; HT - Hecates Tholus; HV - Hrad Valles; VL2 - site of Viking Lander 2. Summit craters and outlines of the shield volcanoes are also shown. The scale is given for 20°N to 50°N for this Mercator projection.

Figure 2. The southern margin of the lahars associated with Granicus Valles are composed of broad multiple lobes with rough lateral deposits and smooth medial deposits. This mosaic is approximately 90 km across and is centered near 28.3° N, 224°W. north is toward the top of all of the Viking imagery shown here.

Figure 3. The rough pitted marginal deposits flank smooth medial deposits. This frame is centered near 36.7°N, 242°W. The frame is 100 km across.

Figure 4. The sinuous channels of Granicus Valles cross the surface of a lahar near its source trough (A). The channels are broadly sinuous, have streamlined features on their floors, and form an anastomose distributary pattern. The valleys become broader and shallower to the NW before they merge with the smooth surface of the sedimentary deposits. The northern margin (B) of the lahar buries older lava flows erupted from a fissure/trough source (C) like that

from which the channels and lahar issue. This mosaic is 280 km across and is centered near 28°N, 225°W.

Figure 5. Broad valleys with stubby tributaries (A) reappear about 450 km NW of the area shown in Fig. 4. These valleys probably represent seepage valleys and the wet lahars drained to the surface and "remobilized." This mosaic is 200 km across and is centered at 35.5°N, 231°W.

Figure 6. The margins of distal lobes of the Elysium lahars are dissected by closely spaced valleys like these. The valleys are interpreted to represent seepage of water confined in the sediment and consequent erosion. Dark smooth deposits shown at the bottom are intra-channel debris flows. The frame is 110 km across and is centered at 40°N, 247°W.

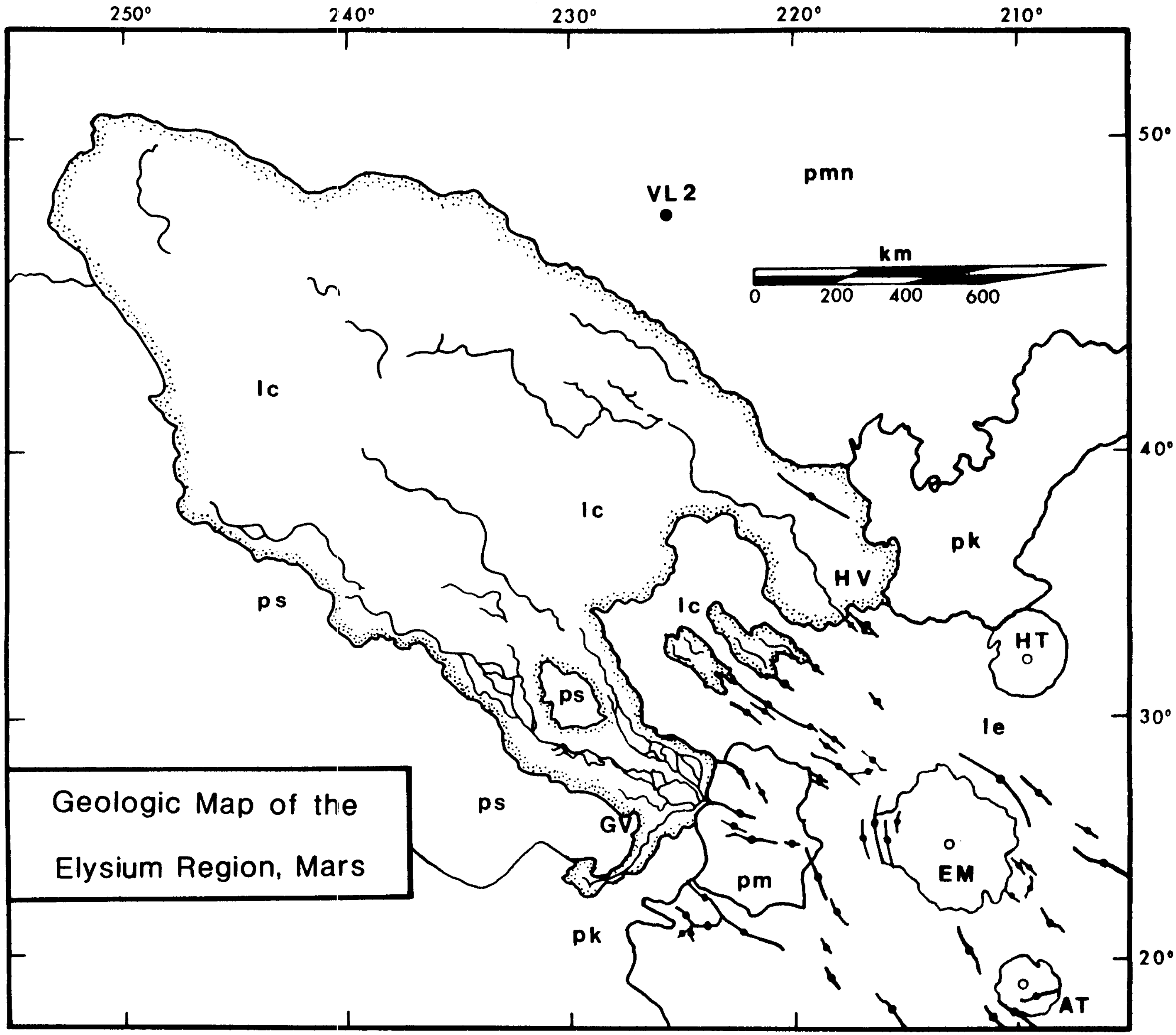
Geologic Map of the
Elysium Region, Mars
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Figure 1

Figure 2

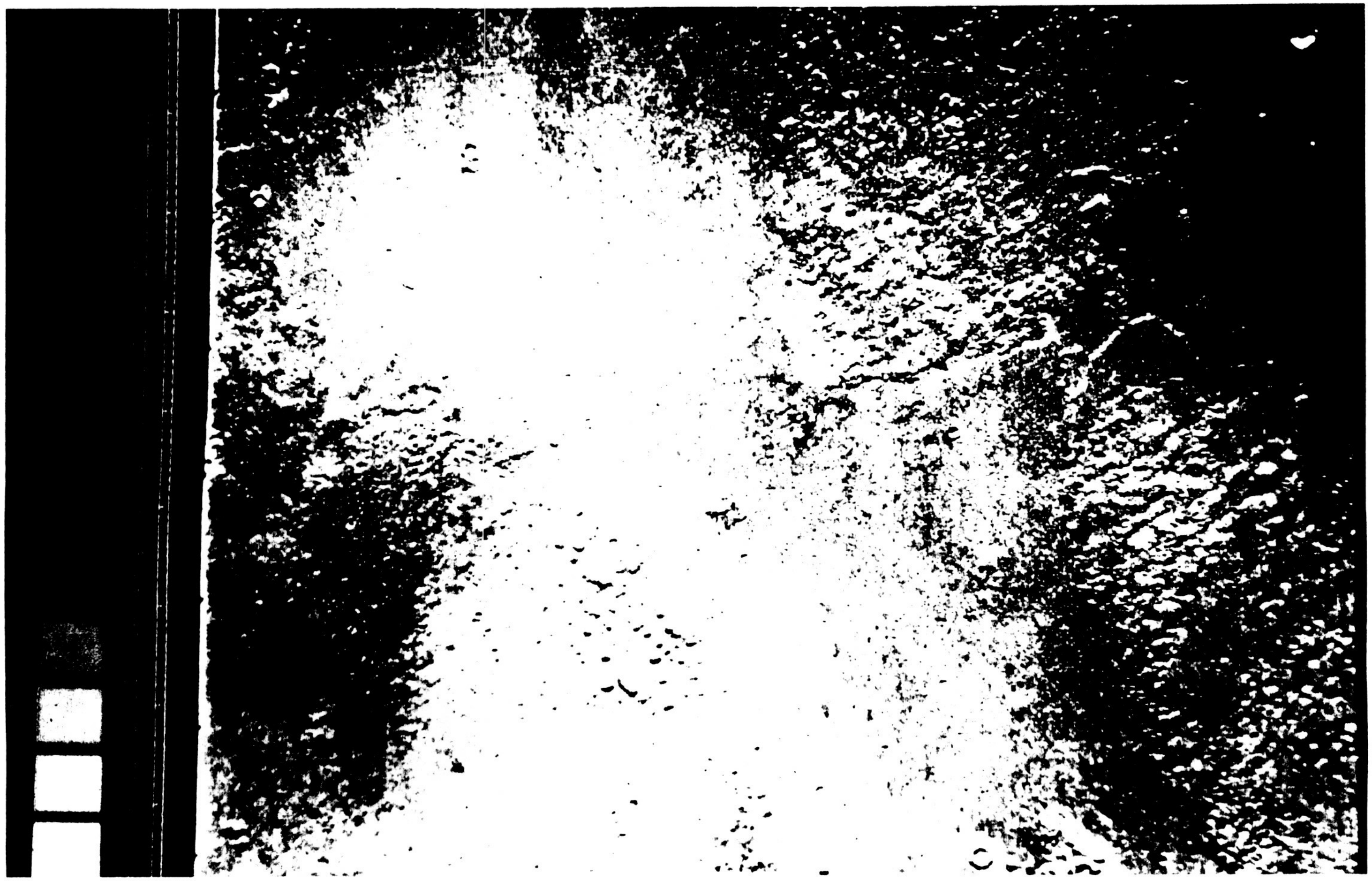

Figure 3

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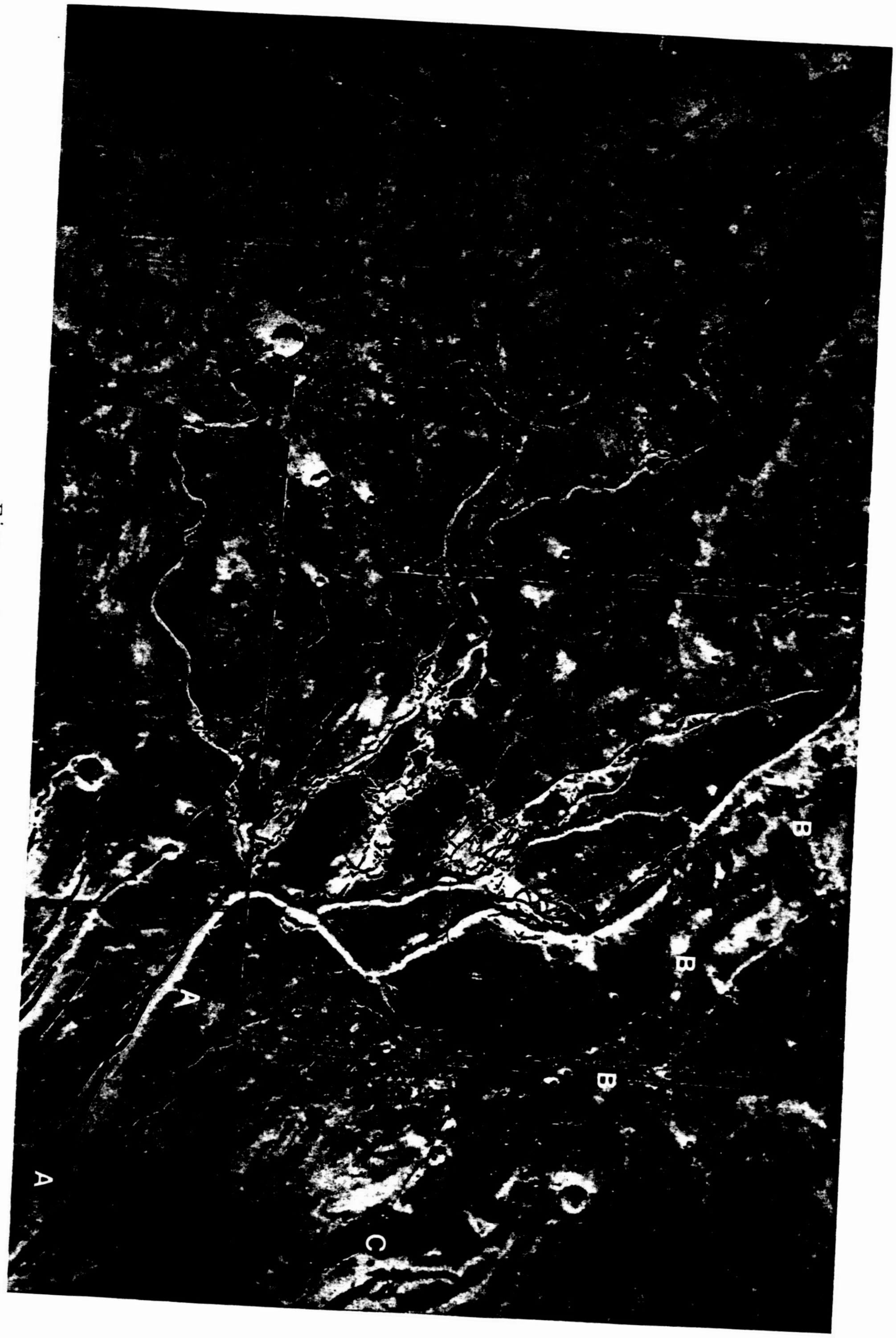

Figure 4

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Figure 5

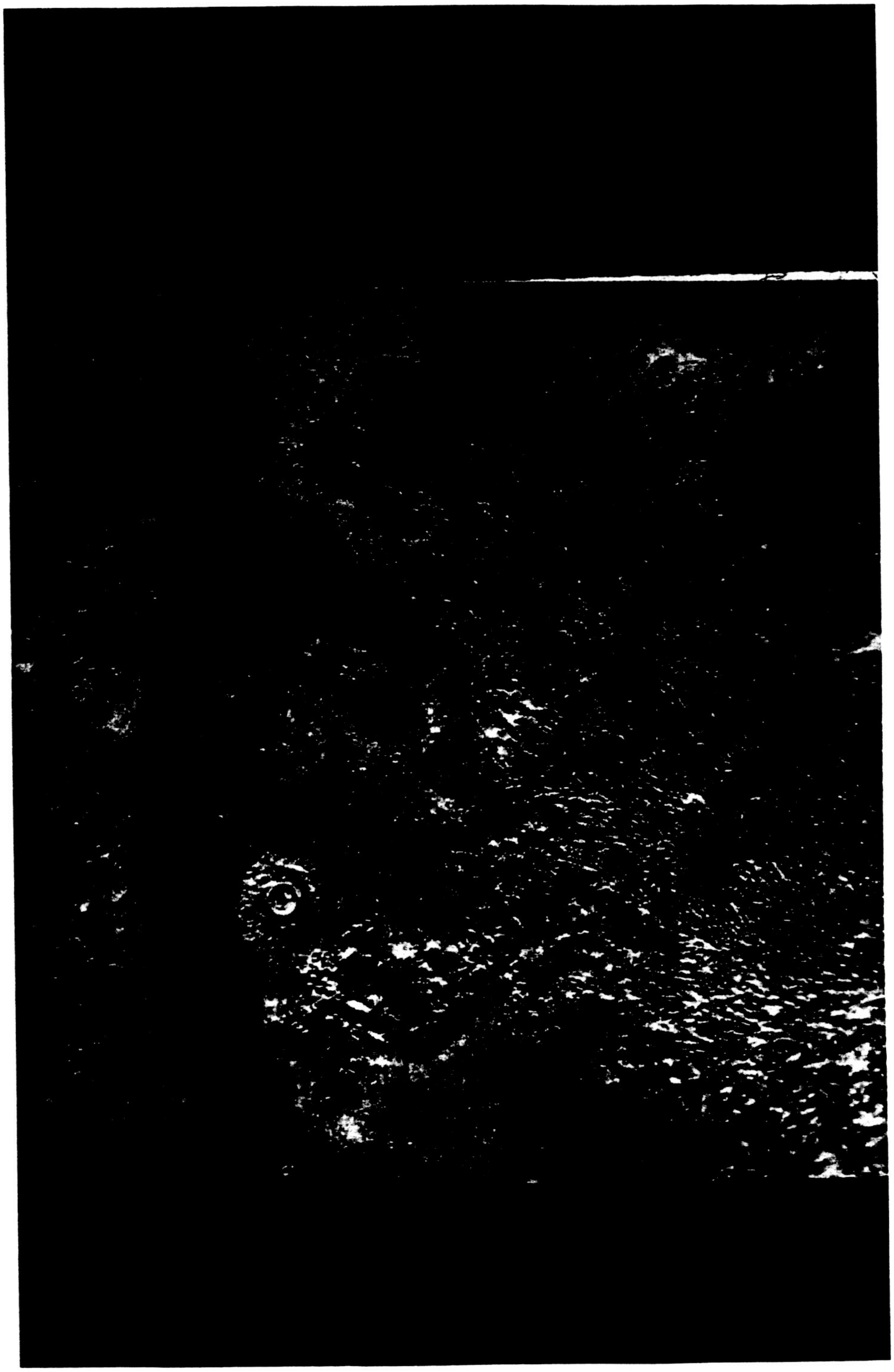

Figure 6

Geomorphic Evidence for Subsurface Volatile Reservoirs in the Elysium Region of Mars

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Abstract.

The distribution and geomorphic character of small outflow channels, volcanic debris flows, and knobby terrains suggest that sizable reservoirs of volatile materials exist (or existed) near the surface of the Elysium volcanic province in the northern hemisphere of Mars. Several types and ages of terrains have developed as a result of the periodic loss of volatiles from these reservoirs.

The knobby terrains of this region appear to be the degraded surface expression of volatile-rich surficial materials. These vast plains are dotted with sparse mesas and knobs of an erosional origin. Minor parts of the knobby terrains are marked by water-related features. Consistent with these observations, we suggest erosion of material in these terrains involved the sublimation of ice from their near-surface portions.

New geologic mapping using Viking imagery further suggests that the knobby terrains extend beneath the Elysium dome and volcanoes. In this environment of steep topographic and thermal gradients the volatile reservoirs also lost water through the generation of small outflow channels (and associated chaotic terrain) and through the generation of a series of volcanic debris flows or lahars during the Early or Middle Amazonian Epochs.

The outflow channels (250 and 600 km long) cut the knobby plains, contain channel bedforms, branch down the regional slope,

and have surface breakout features. The geomorphic evidence suggests that the knobby plains were the source of the water released through the channels. Apparently the flow of fluids in one valley system, Hephaestus Fossae, was structurally controlled by the configuration of troughs buried beneath the knobby plains. The pattern of these valleys is like that of the troughs exposed in the polygonally fractured plains of Adamus Labyrinthus.

The lahars extend 1000 km down the regional slope on the northwest of the Elysium dome, have channeled surfaces, lobate margins, basal drainage channels, and "sublimation" pits on their margins. All this evidence suggests that these sedimentary deposits formed as gravity-driven wet debris flows. No surface scar is related to their source, which we therefore infer to be located in the subsurface and correlate it with a buried knobby plains unit.

A model consistent with these geomorphic observations is proposed which suggests that some 360,000 km^3 of water were periodically released during the evolution of the Elysium region of Mars. (This amounts to a globe encircling layer of about 2.5 m.) The evidence provided by these landforms reenforces the emerging notion that Mars is a volatile-rich planet.

Introduction

There is a continuing controversy about the volatile endowment of the planet Mars. This problem is essentially geochemical by nature [Anders and Owen, 1977; Pollack and Black, 1979; Wanke and Dreibus, 1985] and it will ultimately be resolved with a larger geochemical data base. In the meantime, geomorphic studies of the surface of Mars have assisted in ascertaining the nature of volatile reservoirs in the near-surface regions of the planet [e.g. Carr, 1986]. Since the return of the Mariner 9 images of Mars, numerous investigators have pointed to geomorphic evidence for the existence of large and small reservoirs of volatiles (principally water) near the surface of Mars. The spatial and temporal distribution as well as the size of these subsurface volatile reservoirs are important for understanding the bulk composition of Mars, as well as the evolution of its landforms, climate, volcanic eruption and meteorite impact styles, and, since water is critical for the development of silicic magmas, perhaps even crustal development.

A short list of these geomorphic indicators of subsurface volatiles [Rossbacher and Judson, 1981; Squyres, 1984] includes: outflow channels, valley networks, fretted terrain, thermokarst, lobate debris aprons and debris flows, rampart craters, patterned ground, volcanic table mountains, chaotic terrain [Sharp, 1973], knobby plains [Allen, 1979], and terrain softening [Squyres and Carr, 1986].

This paper presents the results of photogeological investigations of the Elysium volcanic province suggesting that it contains large volatile reservoirs beneath its surface. We begin by outlining the geology of the Elysium region and then summarize the evidence that three types of landforms are the result of the presence of volatile-rich materials near the surface of Mars. We find evidence for the presence of subsurface volatile reservoirs from: 1) vast expanses of knobby terrains around the margins of the Elysium province, 2) small outflow channels, and 3) large lahars. These landforms, which have thus far escaped systematic investigation, yield insight into the distribution and size of these reservoirs, how they interacted with the surface environment, and may provide further clues to resolving the history of martian volatiles.

In the subsequent discussions we have assumed that the most abundant volatile that can liquify and flow freely across the martian surface is water. We are certainly not alone in making this assumption and are justified by the cosmochemical abundance of water and by its well understood phase transformations.

Geology of Elysium Planitia

The eastern half of the northern hemisphere of Mars is dominated by the plains of the Elysium volcanic province. Elysium Planitia lies north of the scarp that separates the heavily cratered southern terra from the younger plains of the northern hemisphere. The distribution of surface geologic units and tectonic features in this region as determined by new photogeological mapping using Viking images is shown in Figure 1. This mapping builds on the base established by Scott and Allingham [1976] and Hiller [1979] using Mariner data. Unit descriptions are listed in Table 1.

The Elysium province is centered on a large topographic swell approximately 2000 km across that stands 3 to 5 km above the surrounding plains [U.S. Geological Survey, 1976]. It is the second largest volcanic province on Mars. There is little evidence to support the notion that the Elysium dome owes its topography entirely to constructional volcanism, as suggested by Solomon and Head [1982] for the Tharsis province. Instead, the topography probably reflects the configuration of a flexural uplift in the martian lithosphere [Hall et al., 1986]. Three large shield volcanoes cap the dome. Elysium Mons [Malin, 1977] is the largest (13 km high and 400 to 700 km across [Blasius and Cutts, 1981]). The plains surrounding Elysium Mons consist of fissure-fed, composite lava flows (unit pl). Most lavas flowed radially away from Elysium Mons even though the vents for many lie hundreds of kilometers away from the summit of the volcano and may be younger than the main construct [Neukum and Hiller, 1981]. Hecates Tholus is the second largest volcano in the region; it lies 500 km north of Elysium Mons and is about 6 km high and 160 to 175 km across [Mouginis-Mark et al., 1982]. Lava flows erupted from vents radial to Elysium Mons bury part of Hecates' flanks. Likewise, the northern parts of the third volcano, Albor Tholus (150 km across and 3 km high [Blasius and Cutts, 1981]), are buried by lavas from vents that are peripheral to Elysium Mons. Our stratigraphic studies are consistent with the crater counts of Tanaka and Scott [1987] in showing that Elysium Mons is younger than Hecates Tholus and Albor Tholus. Earlier crater counts suggested that Elysium Mons was the oldest of the three shields [Neukum and Hiller, 1981; Plescia and Saunders; 1979]. Furthermore, Neukum and Hiller [1981] suggest that the volcanic province formed 3.8 to 3.4 Ga (Model 1). However, from combined stratigraphic and crater studies Tanaka [1986] places the formation of the Elysium volcanic province in the Early Amazonian Epoch which using the Hartmann et al. [1981] crater density chronology extended from 1.8 to 0.7 billion years ago.

The Elysium dome is transected by a set of long subparallel fractures and graben, called Elysium Fossae, that trend west-northwest. The fractures appear to be the western extension of Cerberus Rupes, attributed by Hall et al. [1986] to quasi-global loading caused by the Tharsis rise. Plescia [1986] also suggests that Elysium Fossae, were produced by deformation of the lithosphere by the Tharsis load. The spatial coincidence of both fissure-fed and shield volcanoes with the western part of the fracture trend strongly suggests that the fractures served to localize the magmatism. Images of the western flanks of the Elysium dome show numerous lava flows issuing from these fractures and are direct evidence that the fractures served as the sources of, at least, late eruptions in the province.

The volcanic plains (unit pl) of Elysium Planitia are nearly surrounded by several types of knobby terrains (Figure 1) discussed in greater detail in subsequent sections of this paper. Cutting across these knobby terrains are several channels and sedimentary deposits. The knobby plains (unit pk) in the western part of the mapped area grade southward into a terrain of isolated to interconnected troughs interpreted as erosional valleys. Layered (sedimentary?) materials are exposed in the ragged margins of the plateaus formed between the depressions. We have mapped this unit as etched layered plateaus (ple). Because of the gradational contacts, the mounds and mesas of the knobby plains appear to be erosional remnants of this unit. To the north, the knobby plains are replaced at the surface by the plains of Adamus Labyrinthus which consist of polygonal troughs arranged in a fairly regular pattern [Pechmann, 1980; McGill, 1986]. Lucchitta et al. [1986] interpreted the fractured materials as sedimentary deposits which blanket an older cratered terrain. We suggest below that the southern exposures of the polygonal plains were exhumed as the overlying knobby plains unit was stripped away.

Geomorphic Evidence for Subsurface Volatiles

Based upon regional photo-geologic mapping, we describe knobby terrains, outflow channels, and volcanic debris flows from the Elysium region. The channels and debris flows have not previously been described in any detail. We develop the hypothesis that these features are evidence for the presence and extent of large reservoirs of volatile-rich material beneath the surface of this part of Mars.

Knobby Terrains

Knobby terrains in the Elysium province consist of relatively smooth surfaces with variable proportions of knobs and flat-topped mesas. Broadly similar knobby terrains of different ages form the surface of approximately 3,000,000 km^2 in the Elysium region. We have divided these into three knobby terrain units: knobby plains (pk), Nepenthes-type knobby terrains (pkn), and Orcus-type knobby terrains (pko). The latter types are named after the regions where they are best developed. Typical surface characteristics are shown in Figure 2. The Nepenthes Mensae region marks the highland/lowland transition zone southwest of Elysium Mons. The Orcus Patera region is about 1000 km west of Elysium Mons and is an equal distance north of the generally accepted location of the scarp that separates the highlands and lowlands of Mars.

The knobs and mesas of the knobby plains (pk, Figure 2) are widely and generally randomly distributed mounds rising above an otherwise smooth surface. Shadow measurements indicate the knobs range up to 100 m high. Stratigraphic relationships reveal that knobby plains are the degraded surface of a deposit which overlies the polygonally troughed terrain (unit pp) of Adamus Labyrinthus in the Amenthes quadrangle. The contact between the polygonal plains and the knobby plains is transitional (Figure 1). Isolated knobs and mesas dot the southern part of the polygonal plains and become abundant in the knobby plains. In addition, the troughs that outline the polygonal blocks become indistinct and disappear as the knobby plains are approached from the north. Fracture rings, interpreted by McGill [1985] to represent impact craters buried beneath pp units, are also visible in the knobby plains, but their topographic expressions are subdued. Other circular depressions are also found in the knobby plains as described below (Figure 5b). These appear to be buried craters as well. All of these relationships suggest that the knobby plains materials evolved from a stratigraphic unit that buries the polygonal plains. Moreover, this deposit apparently thins and disappears to the north toward Adamus Labyrinthus. The isolated mesas attest to the former extent of the knobby plains unit and provide clear evidence that the knobby plains unit has been partially stripped away to reveal the underlying polygonal plains. Thus, the apparent northward thinning of the knobby plains unit may be the result of enhanced erosion near its northern boundary rather than from original variations in thickness. In short, the knobby plains unit is a remnant of a once thicker and more extensive plains unit we call the knobby plains precursor. The southern extent of the buried polygonal plains is not known but it must extend as far south as Hephaestus Fossae.

The erosional development of the knobby plains is clearly displayed in southern Amenthes quadrangle. There, knobby plains have developed at the expense of an extensive plateau marked by irregular depressions and pits (ple, Figure 2b). Layering is visible in the walls of these ragged depressions. Erosional stripping of the knobby deposit in this region also exhumed large impact craters (Figure 2b).

North of the volcano Hecates Tholus, knobby plains of eastern Galaxias Mensae are buried by Elysium lava flows. To the west of the volcano, knobby plains are separated from the lava-covered uplands by a large area of chaotic terrain with small debris flows and even features interpreted as lake deposits [Mouginis-Mark, 1985]. He interprets these features as resulting from the melting of near surface ice as it was overridden by hot lava. (We included these features with the lahars in Figure 1.) Even farther north (about 45° N), the knobby plains disappear and reveal underlying polygonally troughed terrain like that found farther south in the Amenthes quadrangle (Figure 1).

On the western side of the Elysium dome (in the vicinity of the Hyblaeus trough) equidimensional patches of chaotic terrain too small to map on Figure 1 mark the transition between the knobby plains and the lava plains. As deduced from these stratigraphic relationships and its distribution around three sides of the Elysium volcanic province, the knobby plains underlie at least the western part of volcanic region. The knobby plains unit was apparently involved in the flexural bending that created the Elysium dome.

The knobby plains precursor appears to have developed in middle martian history. It overlies the polygonal plains of Adamus Labyrinthus which, according to McGill [1986], are post-Lunae Planum in age (Early Hesperian) and is in turn buried by Elysium lava flows and lahars (Early Amazonian). Age assignments are those of Tanaka [1986]. Clearly these knobby plains are not the result of the breakup of the heavily cratered southern highlands. They formed and were modified after the structural differentiation and erosion of the highland/lowland transition. The degradation of the knobby plains precursor appears to have occurred mostly before Elysium volcanism because vast tracts of smooth lava plains bury knobby plains.

Few geomorphic clues remain to tell us about the mechanism of erosion of the knobby plains. The plains are cut by two outflow channels noted above, and by other smaller sinuous channels (Figure 6). However, evidence for fluvial erosion is not extensive and the volume missing from the knobby plains precursor must have been either stripped away by eolian processes or it may represent the seepage or sublimation of water that had been sequestered in layered surficial deposits (earlier water-laid sediments, eolian deposits, regolith, or volcanic ash). The eolian hypothesis for the erosional history of the knobby plains cannot, by itself, account for this association. Likewise, no evidence of streamlined landforms like those produced by eolian erosion have been detected. As pointed out by Sharp [1973b] and reiterated by Carr [1986], eolian deflation eventually produces a coarse-grained deflation inhibiting layer. The spatial coincidence of the knobby plains with the water-related landforms described below (channels, chaotic terrain, and lahars) lends credence to the volatile-loss hypothesis. Diurnal or seasonal temperature variations may have driven sublimation of ice in a deposit earlier formed in equilibrium with the atmosphere.

Other types of knobby terrains border the province on the south and east. The Nepenthes and Orcus types of knobby terrains are broadly similar to each other and consist of rounded to sub-polygonal hills of similar size. These terrains are more rugged than the knobby plains (compare Figures 2b and 2c). The Nepenthes knobs are widely spaced (compared to those of the Orcus type) and have large areas of intervening smooth plains that partially bury older degraded craters defined by their protruding, knobby rims. The Nepenthes type of knobby terrain forms a zone between the densely cratered southern highlands and the relatively smooth and younger knobby plains of Elysium Planitia (Figure 2c). This zone is generally less than 300 km wide. Most knobs are less than 6 or 7 km across, but nearer the highland scarp some "knobs" are actually mesas up to 15 km across with rectilinear outlines. The knobs appear to be erosional remnants of cratered plateau materials produced by erosion and southward retreat of the highlands boundary [Hiller, 1979]. The low plains in the knobby terrain appear to be deposits of younger materials that are continuous with the etched plains (ple) and the knobby plains (pk) of the north.

The Orcus-type knobby terrain consists of closely spaced, generally conical mounds [Scott and Allingham, 1976] that are partially buried by plains units pr and ple (Figure 1). This knobby terrain is also embayed by the young channeled plains (pc) of the Cerberus region. In eastern Elysium Planitia, rugged upland areas of Orcus-type knobby terrain lie atop fault-bounded blocks (e.g., Phlegra Montes) that extend as far as 50°N. Like the Nepenthes knobs, these probably formed by erosional modification of a heavily cratered terrain, but they are found hundreds of kilometers north of the traditional highland/plains transition in the Aeolis quadrangle. Water-related features also mark the extent of these knobby materials. Such landforms include channeled plains and volcanic mudflows [Wilhelms, 1986]. Although stratigraphic relations show that the erosion of the Orcus-type knobby terrains occurred before the deposition and modification of the knobby plains precursor, we suggest that all of the knobby terrains owe their present morphology to the loss of volatiles once stored in near-surface reservoirs.

Implications for subsurface volatile reservoirs. Our ideas are not entirely original regarding volatile loss to form knobby terrains--they are in fact conservative compared to some others. Similar hypotheses invoking volatile loss for the origin of the knobby materials of the northern lowlands of Mars were proposed by Mutch et al. [1976] and Allen [1979]. Allen proposed that areas of knobby terrain in the northern lowlands represented the breakdown of an ice-rich layer that at one time formed the surface layer of parts of the northern plains. Allen preferred a glacial origin for the ice rather than ice in regolith mixed with other materials, and based on the heights of volcanic "table mountain" plateaus (locations shown in Figure 1), he estimated that the ice layer may have been 100 to 1000 m in thickness in the Elysium region.

We conclude that a more likely location for mid-latitude ice, however, is in the subsurface. We base that inference on the erosional nature of the knobby plains, the lack of evidence for regional glacial flow, and upon the landforms described in the following sections which require outbreaks of water from below the surface.

The distribution and ages of knobby terrains in the Elysium region suggest that water-rich materials have been produced and eroded episodically throughout the history of Mars. The Orcus and Nepenthes knobby terrains represent ancient (original?) crust that became degraded later in Mars history, after the decline in crater production rate. Our observations and suggested erosional evolution are in accord with the analytic model of Fanale et al. [1986] who proposed that the sublimation of ice from an ancient near surface ice-rich region in the crust would result in model dependent erosion amounting to the deflation of up to one hundred or so meters (decreasing with latitude and increasing with pore radius). However, we note that although the knobby terrains are extensively developed south of 40°N they extend to 50°N. Fanale et al. [1986] calculate that the northern limit to regolith ice-loss would be between 30 and 40°N. Moreover, it is difficult to understand the preferential production of knobby plains in the low northern hemisphere using a model based on an originally homogeneous planet-wide cryosphere [Fanale et al., 1986].

Knobby terrains like those in Nepenthes and near Orcus Patera must have once covered approximately 5,000,000 km2 of the region east of Elysium Mons. Assuming that the missing volume resulted from 50% stripping to an average depth of only 100 m, approximately 250,000 km3 of material was removed to create the rugged topography of these knobby terrains. (It should be noted that a commonly cited value for the global water abundance of Mars is equivalent to a planet encircling layer 100 m deep [e.g. Rossbacher and Judson, 1981]). If all of the lost material was water, a sizeable volatile reservoir once existed within the heavily cratered precursors of these knobby terrains.

The knobby plains of the Amenthes region attest to the generation of similar knobby erosional landforms later in the history of Mars. They formed in middle martian history and were subsequently degraded before Elysium volcanism. Fanale et al. [1986] calculate that a deposit consisting of 50% ice would be lowered by about 60 m over 2.7 Ga or 40 m over 1.8 Ga. These figures apply for the case of a "large" pore radius of 10 microns and at 20°N where the knobby plains are common.

Knobby plains surround the Elysium volcanic province in an arc that extends from the southwest margin to the northeast. We conclude that the knobby plains (or an undegraded equivalent like unit <u>ple</u>) extend beneath at least half of the province (Figures 1 and 3). Assuming that all of the missing volume represents removal of volatiles and including an approximation of the area that must underlie the Elysium volcanic province we can calculate the amount of water removed from this region. Taking 2,000,000 km^2 for the area of knobby plains losing an average of 50 m of water (estimated from mesa heights) over 50% of their extent suggests that the amount of water lost from this region approached 50,000 km^3. Given that our speculative model for the formation of the knobby plains is correct, the assumptions regarding their areal extent and depth of erosion are conservative. Furthermore, a substantial amount of water may still remain in the unit as evidenced by the water-related landforms that formed after the development of the knobs.

<u>Outflow Channels</u>

The least equivocal expressions of the presence of a subsurface volatile reservoir in the Elysium region are two relatively small outflow channels located southwest of Elysium Mons, Hebrus Valles and Hephaestus Fossae [Christiansen, 1985]. These channels have not been the subjects of previous investigation. Martian outflow channels generally lack the tributary systems of terrestrial rivers and start full-scale from local sources. Their sources are commonly marked by isolated depressions filled with a chaotic assemblage of wall slumps and polygonal blocks of upland surfaces and intervening valleys [Mars Channel Working Group--MCWG, 1983]. Catastrophic flooding by some fluid, probably water, is widely held to have been responsible for their generation [Baker, 1982]. The channels in the Elysium region arise in and cut across a broad expanse of older knobby plains (Figure 1). A third feature, informally called the Hyblaeus trough, has characteristics transitional between typical martian outflow channels and the debris flows described below. The Hyblaeus trough arises near the contact of the younger Elysium lava flows (unit pl) with the knobby plains. Channels were also identified southeast of Elysium Mons in the Cerberus region (Figure 1) by Wilhelms [1986] and Tanaka and Scott [1986]. These authors report the channels to be youngest channels on Mars. The young channels are not described further here.

Hebrus Valles. The northwest-trending Hebrus Valles system is 250 km long and begins in an elongate depression with narrow finger-like projections (Figure 4a, b). The channels emerge at their widest from this irregular depression that is about 10 km across. The interpreted source of the channel bears a resemblance to other areas of martian chaos which are commonly interpreted as collapse zones caused by the release of fluids; however, slumped debris at the base of scarps is not discernible at the resolution available (200 m/pixel). Individual channels are broadly sinuous and less than 1 km wide and, based on shadow measurements, they are less than about 100 m deep. The channels are diverted around the mounds of the knobby plains, and the overall trend of the channel system is down the regional slope. The channels bifurcate and rejoin along the length of the valley defining short links between vertices. Along most of its length, the Hebrus distributaries create a rejoining pattern in the sense used by Coleman [1976] to describe terrestrial distributary nets. Approximately 80 km from the source, the eastern branch of the channel disappears as it intersects a rimless circular depression (Figure 4a). Braided channels reappear on the north side of this sink, where they are narrower and shallower. This and other sub-circular depressions occur in the knobby plains and appear to be old impact craters buried by the material that makes up the knobby plains. A braided or anastomose reach of the western channel is about 10 km wide and extends for about 120 km (Figure 4b). The junction between the eastern and western branches is marked by a hanging valley. Streamlined islands or channel bars are abundant in the middle reaches of this segment of the channel (Figure 4b). Hebrus Valles terminate as a series of narrow distributaries (Figure 4c) where the channel network becomes mostly bifurcating instead of rejoining [Coleman, 1976]. As the number of channels increases, they become narrower, shallower, and eventually disappear downslope. Channel intersections, created by bifurcation and rejoining, define crude polygons in the distal portion of

Hebrus Valles just before they disappear. At the resolution available, only a few very narrow channels are seen to extend farther to the northwest. In contrast to the Granicus channels that also trend northwest down the flanks of the Elysium dome [Christiansen, 1984], no sedimentary deposits or contemporaneous volcanic activity are obviously related to the development of Hebrus Valles.

Hebrus Valles share many characteristics with martian outflow channels which are widely interpreted as having formed by fluvial erosion related to catastrophic flooding. These similarities include:

1) an isolated depression lies at the upslope termination of channels which emerge at their widest;

2) channel links become more numerous, narrower, and shallower down the regional slope;

3) channels branch and converge in the downslope direction;

4) the channels are broadly sinuous;

5) channels are diverted by topographic obstacles, and widen in topographic basins; and

6) streamlined features mark the channel floors.

Because of these similarities, we conclude that Hebrus Valles developed as the result of fluvial erosion following the outbreak or eruption of water that was confined within (or beneath) the materials of the knobby plains. Carr [1979] has used such a model to explain the generation of other outflow channels on Mars. Flow in the Hebrus system was initially confined to a few channels but subsequently flow became dispersed through a system of distributaries. Along the eastern branch, a temporary sink was created by a degraded impact crater that apparently filled with water and which then drained out to the northwest down the regional slope. Subsequently, flow became dominated by the western branch as evidence by the hanging valley at their junction.

We have attempted to quantify the channel pattern for Hebrus Valles by measuring the angle of bifurcation between converging and diverging channels in a downslope direction. Bifurcation angles scatter broadly with no well-defined mode (arithmetic mean $54^{\circ} + 17^{\circ}$ at 1 standard deviation; [Hopler and Christiansen, unpublished data, 1987]). Valley junctions in the extreme distal part of the system were excluded from these measurements because channel segments are linear and appear to have been structurally controlled (Figure 4c and see below). Similar measurements of terrestrial distributary nets are quite variable in that they include a wide range of bifurcation angles, are generally not normal populations, and often are not even unimodal [Morisawa, 1985]. The frequency distribution of bifurcation angles for the Hebrus system is thus indistinguishable from the whole range of topologies for terrestrial distributary systems. The results of this analysis are thus consistent with the generation of the Hebrus system by overland flow of a fluid. Moreover, these measurements differentiate the Hebrus Valles and Hephaestus Fossae system as described below.

Hephaestus Fossae. Hephaestus Fossae are a connected series of linear valley segments that bifurcate and rejoin downslope. The valley system is parallel to the Hebrus channels and also branches in the downslope direction (Figure 5a). The entire valley network is over 600 km long, considerably longer than the Hebrus system. Individual valley segments or links are less than 1.5 km across, about the same width as valleys in the Hebrus system, and up to 30 km long. Shadow measurements demonstrate that the Hephaestus valleys are deeper than Hebrus channels. In most places the shadows on available images extend across the entire floor of the valley and indicate depths that exceed 300 m. However, unlike the sinuous Hebrus valleys, Hephaestus valley segments are decidedly linear and have high junction angles. Changes in orientation of the links are not marked by broad curving bends typical of fluvial channels but instead by sharp angles. Throughout the valley system, these troughs outline polygonal blocks on the upland surface.

Hephaestus Fossae branch out from an isolated depression that is similar in size and shape to the source of Hebrus Valles (Figure 4b). The Hephaestus "source" lies only 60 km southwest of the source of Hebrus Valles and, like its counterpart, it occurs in the knobby plains. Moreover, two digitate projections merge with shallow, broadly sinuous channels that trend north (** in Figure 4b). These short channels are diverted by knobs and have streamlined bedforms that are similar in all respects to valleys of similar size in the Hebrus Valles system. One of these north-trending channels is left as a hanging valley on the wall of Hebrus Valles. In the distal part of the system, valley segments become discontinuous and in places appear beaded, as if they formed by coalescence of small pits (Figure 5b). Some of these distal valleys define crude concentric circles (Figure 5b). To the northwest, Hephaestus Fossae terminate near the gradational boundary between the younger knobby plains (pk) and underlying polygonal plains (pp) of Adamus Labyrinthus (Figure 1).

The linearity of the valley segments and their striking patterns led some investigators using Mariner 9 imagery to suggest that Hephaestus Fossae are tectonic features [e.g., Hiller, 1979; Schumm, 1974]. However, based on our observations and comparisons with Hebrus Valles, we conclude that Hephaestus Fossae are of fluvial/outflow origin. This conclusion is drawn from the following observations:

1) both Hephaestus Fossae and Hebrus Valles systems terminate upslope in nearly closed depressions (sources) that are similar in size and form,

2) at least two sinuous, apparently fluvial channels arise from the same depression that defines the source of Hephaestus Fossae,

3) the Hephaestus and Hebrus valley systems are parallel and both branch in the direction of the regional slope, demonstrating the importance of slope in the development of both valley systems,

4) the beaded valleys must have developed by the subsurface removal of material--piping or solution by moving groundwater and consequent collapse explain these landforms better than tectonism;

5) like distributary channels, but unlike most graben systems or other tectonic features, Hephaestus valleys branch from a single source, and finally

6) the Hebrus Valles system, which is clearly fluvial, and Hephaestus Fossae are closely associated in space, are developed in the save geologic unit, and are similar in age.

To account for the remarkable linearity of the valley segments, we propose that the orientations and lengths of channel segments were controlled by linear structures within or beneath the knobby plains unit (pk). Hephaestus Fossae valleys developed in this unit that overlies a fractured terrain (pp) like that exposed in the Adamus Labyrinthus region of Utopia Planitia. Fluvial downcutting to, or subsurface flow at the unconformity between pk and pp produced a channel pattern controlled by the orientation of the buried polygonal troughs. Groundwater piping and subsequent collapse at the surface seems to be the best explanation of the beaded valleys of Hephaestus. (Many terrestrial river systems have linear valley segments where erosion was guided by the patterns of pre-existing joints or faults in bedrock.) As indicated by the hanging valley described above, the Hebrus channels developed later than Hephaestus Fossae.

To test the hypothesis that the Hephaestus channel pattern was controlled by the orientation of troughs in a buried polygonal plains unit and to further contrast the Hebrus and Hephaestus valley patterns, bifurcation angles of Hephaestus valleys were compared with those for troughs in the polygonal plains of Adamus

Labyrinthus. Junction angles were measured along the entire length of Hephaestus Fossae and in an area of polygonal plains immediately northwest of the termination of the Fossae. Both sets of junction angles come from similar populations that are strongly unimodal with nearly normal distributions. Hephaestus Fossae bifurcation angles have an arithmetic mean of $91^{o} \pm 21^{o}$, whereas trough junction angles in Adamus Labyrinthus average $93^{o} \pm 25^{o}$ at one standard deviation [Hopler and Christiansen, unpublished data, 1987]. The similarity in bifurcation angles is consistent with basement control of the fluvial pattern for Hephaestus Fossae.

Consistent with an origin involving structural control of fluvial processes, the distal valleys of Hebrus Valles also form a polygonal pattern like Hephaestus Fossae and the troughs of the underlying polygonal plains (Figure 4c). The transition from typical distributary patterns to structurally controlled patterns occurs near the boundary between the knobby plains and the exhumed polygonal plains. In general, Hebrus Valles channels formed at the surface and must not have cut entirely through the knobby plains unit. Hence, they show channel patterns more typical of small outflow channels. Near Hebrus channel terminations, perhaps the overland flow rate became low and flow was instead dominated by groundwater movement. Consequently, polygonal valleys developed in the distal Hebrus system where the troughs of the buried fractured plains (pp) controlled subsurface flow directions and channel orientations. The contrasting valley patterns may have resulted from a lower original flow-rate for Hephaestus Fossae.

Early low-flow conditions may have allowed fluid flow to become concentrated at the pp-pk unconformity rather than breaking out to the surface as appears to have occurred at Hebrus.

Hyblaeus trough. Another previously undescribed feature apparently related to the eruption of water, or fluidized debris, occurs to the west of Hebrus Valles near the topographic break that defines the base of the Elysium dome (Figures 1 and 6). The informally named trough is located within an intersecting set of fractures or graben with no consistent orientations called Hyblaeus Fossae. Nonetheless, the orientations of several of the fossae and of the trough itself are parallel to other members of the northwest-trending Elysium Fossae. Hyblaeus trough is similar to outflow channels in that its upslope termination consists of a nearly closed trough-like feature with a smooth floor. Several mounds of debris mark the floor of the source. The trough is 100 km long and varies from 7 to 20 km wide and becomes shallower down slope. It has high steep walls where Elysium lava flows form the caprock on the adjacent plateau. The surrounding plateau shows no evidence of overland flow of a fluid. Farther west, this caprock disappears and the trough bifurcates into several channels that are shallow and sinuous (Figure 6). These relationships demonstrate that the source of the mobilizing fluid was below the capping lava flows. An area of chaos 20 km across marks the middle part of the channel system and is similar to, but smaller than, the large expanses of chaotic terrain at the head of many of the channels that flow into Chryse Planitia [Sharp, 1973]. At this location large blocks with angular perimeters are interspersed within the smooth-floored channels. The Hyblaeus channels terminate at least 300 km from their presumed source. Here in the knobby plains, a series of broad anastomose channels that are broad and shallow wend their way through a maze of knobs and large flat-topped mesas. Other areas of chaos with polygonal blocks and arcuate bounding escarpments occur to the south of Hyblaeus along the border of the Elysium province. They generally occur near the ends of Elysium lava flows as well.

We suggest that the Hyblaeus channels are also the result of the outbreak of a confined aquifer near the break in slope that defines the base of the Elysium dome. Pore-water pressure in the domed knobby plains unit may have built up beneath relatively impermeable capping lava flows. Areas of chaos on the chute or floor appear to be related to multiple outbreaks and collapse events that sustained the flow out of the trough in a northwestward direction. The poorly defined distal channels and the suggestion that some of the large blocks were carried out from the Hyblaeus trough show that the fluid involved was weakly erosive and had a high yield strength--features typical of debris flows. The debris flow model of Nummedal and Prior [1981] may therefore account for the concentrations of mounds in the distal reaches of the channels. We speculate that the Hyblaeus trough is transitional between fluvial channels such as Hebrus and the debris flows discussed in the next section. The source of the debris and of the water must have been the buried knobby plains.

Implications for subsurface volatiles. It is difficult to estimate the amount of water released to produce the three channel systems described here. A minimum value can be calculated by assuming the amount of water involved was equal to the amount of erosion (the volume of the valleys themselves). This conservative assumption leads to an estimate that over 1000 km^3 of water were released in these events. Perhaps more important than this gross estimate of the volume of water released, is the evidence the channel systems provide for the location of volatiles beneath the surface. In addition, their confinement to the knobby plains implies that this unit was the source of the volatiles--an inference consistent with the interpretation of the erosional modification of the knobby plains themselves.

Lahars

Many investigators have suggested on theoretical grounds that magma-ice interaction was important for the generation of the fluids that produced the martian channels [e.g., Masursky et al., 1977; McCauley et al., 1972; Soderblom and Wenner, 1978], but until recently there has been little geomorphic evidence to link volcanism and channel formation across most of Mars [Carr, 1979]. However, as originally implied by Malin [1976], photogeologic studies of the Elysium volcanic province provide a specific example of the importance of volcano-ice interaction to produce the channels of Hrad Valles, Galaxias Fossae, and Granicus Valles (Figure 1). Perhaps more importantly, these channels lie on the surface of large sedimentary deposits that we conclude are accumulations of volcanic debris flows or lahars that originated from subsurface volatile reservoirs. The only previous descriptions of these debris flows are found in short abstracts [Christiansen and Greeley, 1981; Christiansen, 1984]. In spite of some similarities with martian outflow channels of the sort just described, the association of this set of Elysium channels with volcanism and vast sedimentary deposits distinguishes them from other types of martian channels. Mouginis-Mark [1985] interpreted other much smaller areas in the Elysium region as melt water deposits, pseudocraters, and small channels related to the melting of ground ice overridden by lava flows. These landforms are in the Galaxias Mensae region (Figure 1) northwest of Hecates Tholus.

In the northwestern Elysium volcanic province, the earliest discernible volcanism directly related to Elysium Fossae (Figure 1) was the eruption of flood-type lavas that flowed to the northwest down the regional slope. Lava flows can be traced for 600 km away from their vents, perhaps implying low viscosities or high eruption rates [Walker, 1973]. In a sense these eruptions were parasitic. They formed late in the evolution of Elysium Mons and are displaced away from the main volcanic edifice along a structural trend. These relationships are typical of terrestrial parasitic eruptions. The usual martian problem of scale poses some problems for this interpretation because the eruptions originated about 300 km from the summit of Elysium Mons and created an accumulation of lavas that cover over 10,000 km^2. (For comparison, the basalts of the Snake River Plain cover approximately 50,000 km^2.) The greatest volume of these lavas erupted from two segments of the Elysium Fossae fracture system that were enlarged to troughs 4 to 10 km wide and 150 to 200 km long (Figure 7a). We concur with Mouginis-Mark et al. [1984] in likening these troughs to lunar rilles, and ascribe their origins to thermal and mechanical erosion accompanying high eruption rates from vents on a steep slope.

The Granicus and Hrad/Galaxias channels of particular interest here, issue from enlarged fractures that parallel those of volcanic origin described above, but situated to the south and north respectively. These troughs emerge just east of the boundary between the knobby plains and the lava flows of the Elysium province (Figure 1). The troughs are similar in morphology to those from which the lavas erupted and also formed on the steep western slopes of the Elysium dome. (In contrast, Mouginis-Mark et al. [1984] included the sources for the Granicus channels in their "complex vent area" implying a volcanic origin, but put the lava flows and their vents in an "erosional plains" unit that consists mostly of what we have called lahars.) Vast deposits (unit lc) with elevated margins and channeled surfaces spread out onto the adjacent plains (units pk and ps) from the mouths of these troughs (Figure 7a). The deposits extend down the regional slope toward the northwest and cover approximately 1,000,000 km^2. We regard these mass flow features as lahars. The lahars dropped about 5 km over their 1000 km course. Much of this drop in altitude occurs in the first 100 km [Downs et al., 1982] where the debris coursed through the narrow troughs of Elysium Fossae. These source troughs lack lava-flow features at their mouths. Instead, there are narrow sinuous channels that diverge from one another. We ascribe the present appearance of the troughs on the steep slopes to erosion resulting from the passage of fluidized debris and liquid water through a narrow fracture system. Erosion was enhanced on the steep slopes of the Elysium dome; presumably as a result of higher flow velocities and narrower flow paths. Deposition of debris was dominant where the slope was less steep in Elysium Planitia.

Near the sources of the lahars at Granicus Valles, the channeled deposits are smooth and thin (Figure 7a). Large portions of the rims of small craters protrude through the deposit indicating a thickness of significantly less than 200 m, using the crater diameter to rim height measurements of Lee [1984] and the smallest partially buried crater. At the mouths of the source troughs, the deposit spills over the flood lava plain described above obscuring the southern extent of the lava flows (Figure 7a). The southern margin of the lahar has multiple lobes with steep well-defined snouts like that shown in Figure 7b. At even greater distances, the debris flows cover the polygonally fractured plains that are typical of Utopia Planitia. In this area, the ejecta blankets of pre-existing craters are not completely buried. Proximal channels form a well-defined anastomose system of distributaries with wide lateral deposits. Locally, teardropshaped islands occur on the channel floors [Malin, 1976]. These streamlined features are evidence that liquid water flowed through these channels [Mouginis-Mark et al., 1984]. To the northwest, the channels are shallower and less distinct. Some channels disappear by merging with the surrounding debris plains. In their broad smooth appearance and lack of erosive downcutting, many "channels" are more like the central parts of debris flows [Johnson, 1970] than like channels produced by fluvial erosion. In some cases (e.g., Tinjar Vallis), broad shallow channels reappear farther along the same trends and have short tributaries similar to the seepage channels described by Higgins [1984]. Much of the distal lahars are dissected by narrow reticulate valleys that also resemble seepage or sapping valleys (Figure 7c). Some high-standing knobs and pre-existing craters that do not appear to have been buried are gullied by similar, but broader, systems of valleys. Also in the distal regions, the intrachannel regions are hummocky and irregular depressions are common. These depressions clearly developed from a formerly smooth and more extensive deposit (Figure 7a). These pits may be created by the removal of volatiles by sublimation or seepage. These observations suggest that these flow features were wet debris flows in which water separated from the granular matrix of the debris [Fisher and Schmincke, 1984] by percolation (creating fluvial seepage channels) and by evaporation (creating irregular depressions).

The second set of lahars, those associated with Hrad Valles and Galaxias Fossae, merge with the Granicus/Tinjar lahars to the south near the northern-most exposures of the flood-lava plain (Figure 1). These deposits have many of the same features as those related to Granicus Valles.

A third set of probable debris flows also issue from northwest-trending fractures and bury the central part of the lava plain (Figure 1). These flows are shorter (100 to 200 km) and have pitted, hummocky central areas, smooth lateral deposits, and steep lobate margins. Shallow sinuous channels issue from their bases and trend northwest across the flood lava plain. Other flow deposits, interpreted to be lava flows because they lack evidence for the removal of liquid water, emanate from this same set of fractures. The lavas appear to have formed contemporaneously with this set of lahars.

A summary of the evidence that these mass flow deposits were wet slurries and not "dry" lava or ash flows includes:

1) The distribution of channels is restricted to the topographically and geologically defined surfaces of lobate deposits. The channels are sinuous, form anastomose distributary patterns, and have streamlined features on their floors. (These characteristics are consistent with the flow of water across the deposits. Some of this water may have been derived by de-watering of the muddy deposits, but because many of the channels issue from and cut the source of the debris lobes much of the water appears to represent a late water-rich phase in the development of the lahar.)

2) Discrete channels issue from the base of the lobate masses

and cut their terminations suggesting drainage of water from wet sediments.

3) Short reticulate systems of sinuous valleys cut portions of the deposits' margins and have the form of seepage channels produced by dewatering.

4) Numerous irregular pits mark other areas of the flows and suggest that the removal of volatile material caused local collapse.

The geologic relations described above (lahars and lavas issue from the same fractures which cut older lavas) demonstrate that the debris flows formed amidst other volcanic activity in the Elysium region. This implies that the magmatism was important to the generation of the mobilizing liquid. Terrestrial lahars may be generated as the direct result of volcanism, as at Mount St. Helens [Pierson, 1985] or indirectly as the result of storms on the steep flanks of volcanoes. However, no upland scar is present from which all of the debris in the Elysium lahars could be derived. Thus we prefer to explain the origin of the lahars as the result of the melting of ground ice and liquefaction of subsurface materials. In this scenario, the magmatism associated with the development of the Elysium volcanoes is the source of heat for melting ground ice. A suggestion consistent with the stratigraphic evidence that lavas and lahars were nearly coeval. The knobby plains beneath the Elysium volcanic province were probably the source of water and debris. Perhaps, the contact of magma with liquid water resulted in hydrovolcanic explosions that produced large quantities of easily mobilized fine-grained material [Sheridan and Wohletz, 1983]. We believe that the intersection of this fluid reservoir with the regional fracture system led to the rapid expulsion of a muddy slurry down the steep western slope of the province. Our hypothesis is similar to the debris flow model described by Nummedal and Prior [1981] for the generation of the chaos and channels that surround Chryse basin in the western hemisphere of Mars. Important differences between our model and that proposed by Nummedal and Prior are found in the intimate spatial and temporal relationship of the debris flows with volcanism and in the obvious flow deposits associated with the channels that we describe. In regard to the latter point, Nummedal and Prior speculated that liquefaction mudflows on Mars attained such high velocities that they eroded the underlying terrain and were then deposited as thin blankets over large areas with little apparent relief to belie their existence in the depositional basin; in contrast, we postulate that the volcanic debris flows produced prominent deposits in the Elysium region.

Implications for subsurface volatiles. The Elysium lahars extend nearly 1000 km down the regional slope and cover 1,000,000 km^2. These sedimentary deposits are less than 200 m thick near their sources but are probably much thinner on average. The total volume of the lahars may then be approximately 100,000 km^3. Calculations using a value of 30% water by volume, a figure typical of terrestrial lahars and non-volcanic debris flows [Pierson, 1985], imply that over 10,000 km^3 of water derived from a subsurface reservoir were involved in the formation of the lahars. If water was drawn from the entire western half of the Elysium dome this corresponds to only about 3 m of buried water. (Accumulations of Cenozoic lahars in the central and northern Sierra Nevada of California may represent the upper limit for the volume of terrestrial deposits. These deposits covered in excess of 30,000 km^2 [Curtis, 1954], but they represent multiple sources and a range of ages.)

Conclusions

Studies of landforms related to the presence of subsurface volatile reservoirs will ultimately place constraints on the geometry, constitution, origin, time of formation, and temporal evolution of these important components of the martian crust. The evidence provided by such landforms in the Elysium region of Mars is internally consistent with the presence large, relatively shallow volatile reservoirs (Figure 2). If the geologic features described above (knobby terrains, channels, and lahars) are reliable indicators of subsurface volatiles in this region, they imply that these reservoirs underlie millions of km^2 in this region and that there were several episodes of incorporation and release of volatiles. Moreover, the episodic emplacement of volatile-rich deposits like the knobby plains will make it very difficult to detect latitudinal variations in the depth of subsurface ice of the sort modelled by Fanale et al. [1986].

The Orcus and Nepenthes type of knobby terrains are old and may represent the removal of volatiles incorporated in a thick megabreccia during the period of heavy bombardment. These materials lost their volatiles by sublimation before the knobby plains precursor formed and demonstrate that recycling of water in the near surface is a strong possibility.

The younger knobby plains unit is almost certainly a stratigraphic unit that formed in middle Martian history. The precursor of the knobby plains was apparently an easily eroded surficial deposit as well as a sink for an episode of volatile loss from elsewhere on the planet. Subsequently, volatiles escaped from this reservoir in a variety of ways (including outbreak of liquid water from confined aquifers on the flanks of the Elysium dome, melting of ice as a result of volcanism and incorporation of debris to form lahars, and sublimation or evaporation to the atmosphere).

The ultimate origin of the volatile-rich materials of the Elysium region is unclear. Moreover, it is unclear if the relationships described for the Elysium region are unique on Mars implying that only certain areas of Mars have near-surface volatile reservoirs. Alternatively, the distribution of volatiles in the northern plains could be more uniform and that the coincidences of steep topographic gradients and volcanism unique to Elysium caused the dramatic expressions of volatile-loss described here. In regard to the distribution of ice, the polar wandering model of Schultz [1986] is attractive because of its ability to explain what may be localized deposits of volatiles. Schultz suggests that volatiles became entrapped in near polar deposits during a period of true polar wandering associated with lithospheric mobility on Mars. The presumed path of the north pole crossed the Elysium region several times providing the opportunity for the preferential entrapment of volatiles is this region before they became stranded near the equator. This hypothesis has been rendered unlikely by the absence of normal faults or graben at the sites of the former rotation poles postulated by Schultz [Grimm and Solomon, 1986]. A more likely mechanism for the deposition of volatiles relies on the probability that the northern plains were lower than the southern highlands since very early in the history of Mars [Mutch et al., 1976; Carr, 1981]. Consequently, these plains could have been gravitational sinks for episodically released liquid water since that time. In much the same manner, the present poles are thermal sinks for atmospheric volatiles. Most of the large outflow channels empty into the northern plains. Accordingly the source of the volatiles may have been ice-rich deposits related to these outflow channels [cf. Lucchitta et al. 1986] or even earlier episodes of volatile redistribution.

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References

Allen, C. A., Volcano-ice interactions on Mars, Journal of Geophysical Research, 84, 8048-8059, 1979.

Anders, E., and T. Owen, Mars and Earth: Origin and abundance of volatiles, Science, 198, 453-465, 1977.

Baker, V. R., The channels of Mars, 198 pp., University of Texas Press, Austin, Texas, 1982.

Blasius, K. R., and J. A. Cutts, Topography of martian central volcanoes, Icarus, 45, 87-112, 1981.

Carr, M. H., Mars: A water-rich planet? Icarus, 68, 187-216, 1986.

Carr, M. H., The surface of Mars, 232 pp., Yale University Press, New Haven Conn., 1981.

Carr, M. H., Formation of martian flood features by release of water from confined aquifers, Journal of Geophysical Research, 84, 2995-3007, 1979.

Christiansen, E. H., Volcanic debris flows in the Elysium region of Mars (abstract), Geological Society of America Abstracts with Programs, 16, 470, 1984.

Christiansen, E. H., Geology of Hebrus Valles and Hephaestus Fossae, Mars: Evidence for basement control of fluvial patterns (abstract), Geological Society of America Abstracts with Programs, 17, 545, 1985.

Christiansen, E.H., and R. Greeley, Mega-lahars(?) in the Elysium region, Mars (abstract), Lunar and Planetary Science XII, 138-140, 1981.

Coleman, J. M., Deltas: Processes of deposition and models for exploration, 102 pp., Champaign, Ill., Cont. Educ. Pub, Co, 1976.

Curtis, G. H., Mode of origin of pyroclastic debris in the Mehrten Formation of the Sierra Nevada, California University Publications in Geological Sciences, 29, no. 9, 453-502, 1954.

Downs, G.S., P. J. Mouginis-Mark, S. H. Zisk, and T. W. Thompson, New radar-derived topography for the northern hemisphere of Mars, Journal of Geophysical Research, 87, 9747-9754, 1982.

Fanale, F. R., J. R. Salvail, A. P. Zent, and S. E. Postawko, Global distribution and migration of subsurface ice on Mars, Icarus, 67, 1-18, 1986.

Fisher, R. V., and H. U. Schmincke, Pyroclastic Rocks, 472 pp., Springer-Verlag, Berlin, 1984.

Grimm, R. E., and S. C. Solomon, Tectonic tests of proposed polar wander paths for Mars and the Moon, Icarus, 65, 110-121, 1986.

Hall, J.L., S.C. Solomon, and J. W. Head, Elysium region, Mars: Tests of lithospheric loading models for the formation of tectonic features, Journal of Geophysical Research, 91, 11,377-11,392, 1986.

Higgins, C. G., Piping and sapping: Development of landforms by groundwater outflow, in Groundwater as a geomorphic agent, edited by R. G. LaFleur, pp. 18-58, Allen and Unwin, London, 1984.

Hiller, K. H., Geologic map of the Amenthes Quadrangle of Mars, scale 1:5,000,000, Miscellaneous Investigations Map I-1110, U. S. Geological Survey, Reston, VA., 1979.

Johnson, A. M., Physical processes in geology, 577 pp., Freeman, Cooper, and Co., San Francisco, 1970.

Lee, S.W., Wind streaks on Mars: Comparisons of production models with observations of bright streaks (abstract), NASA Technical Memorandum 86246, 155-157, 1984.

Lucchitta, B. K., H. M. Ferguson, and C. Summers, Sedimentary deposits in the northern lowland plains, Mars, Journal of Geophysical Research, v. 91, E166-E174, 1986.

Malin, M. C., Age of martian channels, Journal of Geophysical Research, 81, 4825-4845, 1976.

Malin, M. C., Comparison of volcanic features of Elysium (Mars) and Tibesti (Earth), Geological Society of America Bulletin, 88, 908-919, 1977.

Mars Channel Working Group, Channels and valleys on Mars, Geological Society of America Bulletin, 94, 1035-1054, 1983.

Masursky, H., J. M. Boyce, A. L. Dial, G. G. Schaber, and M. E. Strobell, Classification and time of formation of martian channels based on Viking data, Journal of Geophysical Research, 82, 4016-4038, 1977.

McCauley, J. F., M. H. Carr, J. A. Cutts, W. K. Hartmann, H. Masursky, D. J. Milton, R. P. Sharp, and D. E. Wilhelms, Preliminary Mariner 9 report on the geology of Mars, Icarus, 17, 287-327, 1972.

McGill, G. E., The giant polygons of Utopia, northern martian plains, Geophysical Research Letters, 13, 705-708, 1986.

Morisawa, M., Topologic properties of delta distributary networks, in Models in Geomorphology, edited by M. Woldenberg, pp. 239-268, Allen and Unwin, London, 1985.

Mouginis-Mark, P. J., Volcano/ground ice interactions in Elysium Planitia, Mars, Icarus, 64, 265-284, 1985.

Mouginis-Mark, P.J., L. Wilson, and J. W. Head, Explosive volcanism on Hecates Tholus, Mars: Investigation of eruption conditions, Journal of Geophysical Research, 87, p. 9890-9904, 1982.

Mouginis-Mark, P. J., L. Wilson, J. W. Head, S. H. Brown, J. L. Hall, and K. D. Sullivan, Elysium Planitia, Mars: Regional geology, volcanology, and evidence for volcano-ground ice interactions, Earth, Moon and Planets, 30, 149-173, 1984.

Mutch, T. A., R. E. Arvidson, J. W. Head, K. L. Jones, R. S. Saunders, The geology of Mars, 390 p., Princeton University Press, Princeton, 1976.

Neukum, G., and K. Hiller, Martian ages, Journal of Geophysical Research, 86, 3097-3121, 1981.

Nummedal, D., and D. B. Prior, Generation of martian chaos and channels by debris flows, Icarus, 45, 77-86, 1981.

Pechmann, J. C., The origin of polygonal troughs on the northern plains of Mars, Icarus, 42, 185-210, 1980.

Pierson, T. C., Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington, Geological Society of America Bulletin, 96, 1056-1069, 1985.

Plescia, J. B., Tectonics of the Elysium region of Mars (abstract), Lunar and Planetary Science XVII, 672-673, 1986.

Plescia, J. B., and R. S. Saunders, The chronology of the martian volcanoes, Proceedings of the Lunar and Planetary Science Conference 10th, 2841-2859, 1979.

Pollack, J. B., and D. C. Black, Implications of the gas compositional measurements of Pioneer Venus for the origin of planetary atmospheres, Science, 205, 56-59, 1979.

Rossbacher, L. A. and S. Judson, Ground ice on Mars: Inventory,distribution, and resulting landforms, Icarus, 45, 39-59, 1981.

Schultz, P. H., Polar wandering on Mars, Scientific American, 235, no. 6, 94-102, 1985.

Schumm, S. A., Structural origin of large martian channels, Icarus, 22, 371-384, 1974.

Scott, D. H., and J. W. Allingham, Geologic map of the Elysium quadrangle of Mars, scale 1:5,000,000, Miscellaneous Investigations Map I-935, U. S. Geological Survey, Reston, VA, 1976.

Sharp, R. P., Mars: Fretted and chaotic terrain, Journal of Geophysical Research, 78, 4073-4083, 1973a.

Sharp, R. P., Mars: Troughed terrain, Journal of Geophysical Research, 78, 4063-4072.

Sheridan, M. F., and K. H. Wohletz, Hydrovolcanism: Basic considerations and review, Journal of Volcanology and Geothermal Research, 17, 1-29, 1983.

Soderblom, L. A., and D. B. Wenner, Possible fossil H2O liquid-ice interfaces in the martian crust, Icarus, 34, 622-637, 1978.

Solomon, S. C., and J. W. Head, Evolution of the Tharsis province of Mars: The importance of heterogeneous lithospheric thickness and volcanic construction, Journal of Geophysical Research, 87, 9755-9774, 1982.

Squyres, S. W., The history of water on Mars, Annual Reviews of Earth and Planetary Science, 12, 83-106, 1984.

Squyres, S. W., and M. H. Carr, Geomorphic evidence for the distribution of ground ice on Mars, Science, 231, 249-252, 1986.

Tanaka, K. L., The stratigraphy of Mars, Journal of Geophysical Research, 91, E139-E158, 1986.

Tanaka, K. L., and D. H. Scott, The youngest channel system on Mars (abstract), Lunar and Planetary Science XVII, 865, 1986.

Tanaka, K. L., and D. H. Scott, Eruptive history of the Elysium volcanic province of Mars, NASA Technical Memorandum 89810, 333-335, 1987.

U.S. Geological Survey, Topographic map of Mars, Miscellaneous Investigation Series Map I-961, scale 1:25,000,000, Reston, VA., 1976.

Walker, G. P. L., Lengths of lava flows, Royal Society of London Philosophical Transactions, A-274, 107-118, 1973.

Wanke, H., and G. Dreibus, Volatiles on Mars (abstract), Lunar and Planetary Institute Technical Report 85-03, 90-92, 1985.

Wilhelms, D. E., Lava-ice interactions on Mars (abstract), Lunar and Planetary Science XVII, 946-947, 1986.

Figure Captions

Fig. 1. Generalized photogeologic map of the Elysium region of Mars. See Table 1 for description of map units and comments on stratigraphic relationships. Geographic features: EM - Elysium Mons, HT -Hecates Tholus, AT - Albor Tholus, CR - Cerberus Rupes, GV - Granicus Valles, HR -Hrad Valles, HF -Hephaestus Fossae, HV- Hebrus Valles, HT -Hyblaeus trough, GM -Galaxias Mensae, AL- Adamus Labyrinthus.

Fig. 2a. Knobby plains (pk) of the Amenthes quadrangle are marked by variable proportions of conical knobs and flat-topped mesas. The flat tops and nearly uniform elevation suggest that the knobs are the result of the degradation of a formerly extensive deposit. We suggest their morphology is the result of the loss of volatiles leaving only small high-standing remnants. The knobby plains are the source of other volatile-related features. This mosaic is centered near 22°N, 231°W and has a resolution of 190 m/pixel.

Fig. 2b. The knobby plains (pk) of southern Elysium Planitia grade into a terrain typified by isolated to interconnected depressions such as those shown here in unit ple. This mosaic is centered near 16°N, 238°W and has a resolution of 230 m/pixel.

Fig. 2c. Other types of knobby terrain such as this from the Nepenthes Mensae region (pkn) may have developed from portions of the ancient highlands by loss of volatiles creating this distinctive topography. This scene is centered near 12^{o}N, 249^{o}W.

Fig. 3. Three-dimensional model of Elysium Province showing a possible subsurface configuration for a volatile-rich horizon at the base of the volcanic pile. This block diagram shows the volcanoes Elysium Mons and Hecates Tholus and plains on the west side of the province. The vertical exaggeration is approximately 80 times; the distance along the face of the diagram is 1000 km. We relate the distribution and origin of many of the volatile release features to the presence of the knobby plains (shown with close stipple) and suggest that it underlies most of the Elysium province and was a source of water. High topographic and thermal gradients in the region led to the outbreak or release of water in a variety of ways which depended on the local environment. Lahars (open stipple), outflow channels, and the knobs of the plains are interpreted to be the result of volatile loss from this unit. Young fissure-fed lava flows that preceded the development of the lahars are shown with v pattern.

Fig. 4a. Outline map of Hebrus Valles showing the broadly sinuous form of the valleys, middle braided reach on the western branch, and the breakup of the valleys into a multitude of channels near their distal end. The channel pattern becomes polygonal near its termination. The stipled circular area on the eastern branch is a depression.

Fig. 4b. Detailed view of the sources of Hebrus Valles (to east) and Hephaestus Fossae (to west). Both valley systems have similar sources and arise in the knobby plains (pk) of Elysium Planitia. Streamlined bedforms and diversion of the channels around knobs are common in Hebrus Valles. Two broadly sinuous channels trend northward away from the source of Hephaestus Fossae (arrows). One valley was later occupied by flow from Hebrus and is left as a hanging valley on the south wall of Hebrus Valles (point A). Other valleys of Hephaestus Fossae have strong rectilinear patterns and outline polygonal blocks of knobby plains. Note that an older buried crater is present near the western margin of the image. This mosaic is centered near $18^{\circ}N$, $233^{\circ}W$. Image resolution is 190 m/pixel.

Fig. 4c. The distal portions of Hebrus Valles are marked by a typical system of anastomose distributaries to the south and a set of deeper rectilinear valleys to the north that form polygonal patterns. We suggest that the distal valley pattern is the result of structural control from an underlying unit as the knobby plains materials thin to the north. The scene is centered near 21.5°N, 234°W and has a resolution of 190 m/pixel.

Fig. 5a. Outline map of the valley system of Hephaestus Fossae. Linear valley segments branch down the northwest slope and define polygons on the upland surface. Some valleys are discontinuous. (The dark area in the middle of the map is an area where medium resolution Viking data are missing.)

Fig. 5b. The polygonal traces of the valleys of Hephaestus Fossae are interrupted near their distal ends by circular patterns (C) that are very similar to the fracture rings seen to the north in the polygonal plains (pp). They probably represent enhanced erosion along circular troughs developed over impact craters buried by the materials of the polygonal plains and later by knobby plains (pk) materials. In this part of the valley system, many valleys are discontinuous and have a beaded appearance (arrows) suggesting that collapse at the surface was initiated by the removal of material beneath the surface. This area is centered near 23°N, 240°W. The resolution of the image is 225 m/pixel.

Fig. 6. This erosional feature, informally called the Hyblaeus trough, has high bounding cliffs where it cuts Elysium lavas (pl), and then breaks up into discrete narrow channels as it

crosses onto the knobby plains (pk). Multiple patches of chaotic terrain with polygonal blocks and associated arcuate ridges developed on the channel floor and along the pl/pk boundary. We suggest that this feature resulted from the outbreak of water or wet debris mobilized from knobby plains materials buried by Elysium lavas. The mosaic is centered near 22.5°N, 227°W and has a resolution of 190 m/pixel.

Fig. 7a. The northern margin of the Granicus lahars (lc) buries lavas erupted from an enlarged trough on the steep northwestern slopes of the Elysium dome. Sinuous channels with numerous streamlined islands (A) transect the lahars suggesting that the fluid became more water-rich with time at this locality. The channels widen, become shallower, and disappear downslope (northwest) out of this mosaic. The source of these channels and the apparent source of the debris is a narrow trough with a slightly enlarged head (B). Other much smaller channels with tributary systems trend along the northern side of the source (C). The source lies in an area that we suggest is underlain by knobby plains at a relatively shallow depth. The mosaic is centered near 28.3°N, 224°W and has an image resolution of 150 m/pixel.

Fig. 7b. The southern margin of the lahars (lc) related to Granicus Valles is marked by broad multiple lobes. A striking example is marked with an arrow where it buries the smooth plains (ps). The channel (A) and wide margins (B) of these flow deposits are very well-defined. The resolution of these images is 80 m/pixel and they are centered near 32.5°N, 237°W.

Fig. 7c. The irregular depressions in this image are found on the flanks of a broad channel in the lahars (location shown in Figure 1). They have developed in what appears to have once been a continuous smooth deposit. Loss of mass from these sedimentary deposits may have occurred by evaporation, sublimation, or seepage of water into underlying units. Lower modification rates may be found in deposits that froze quickly or that were removed from communication with the atmosphere by variations in permeability of the deposit. The image is centered at 36.8°N, 242.4°W and has a resolution of 84 m/pixel.

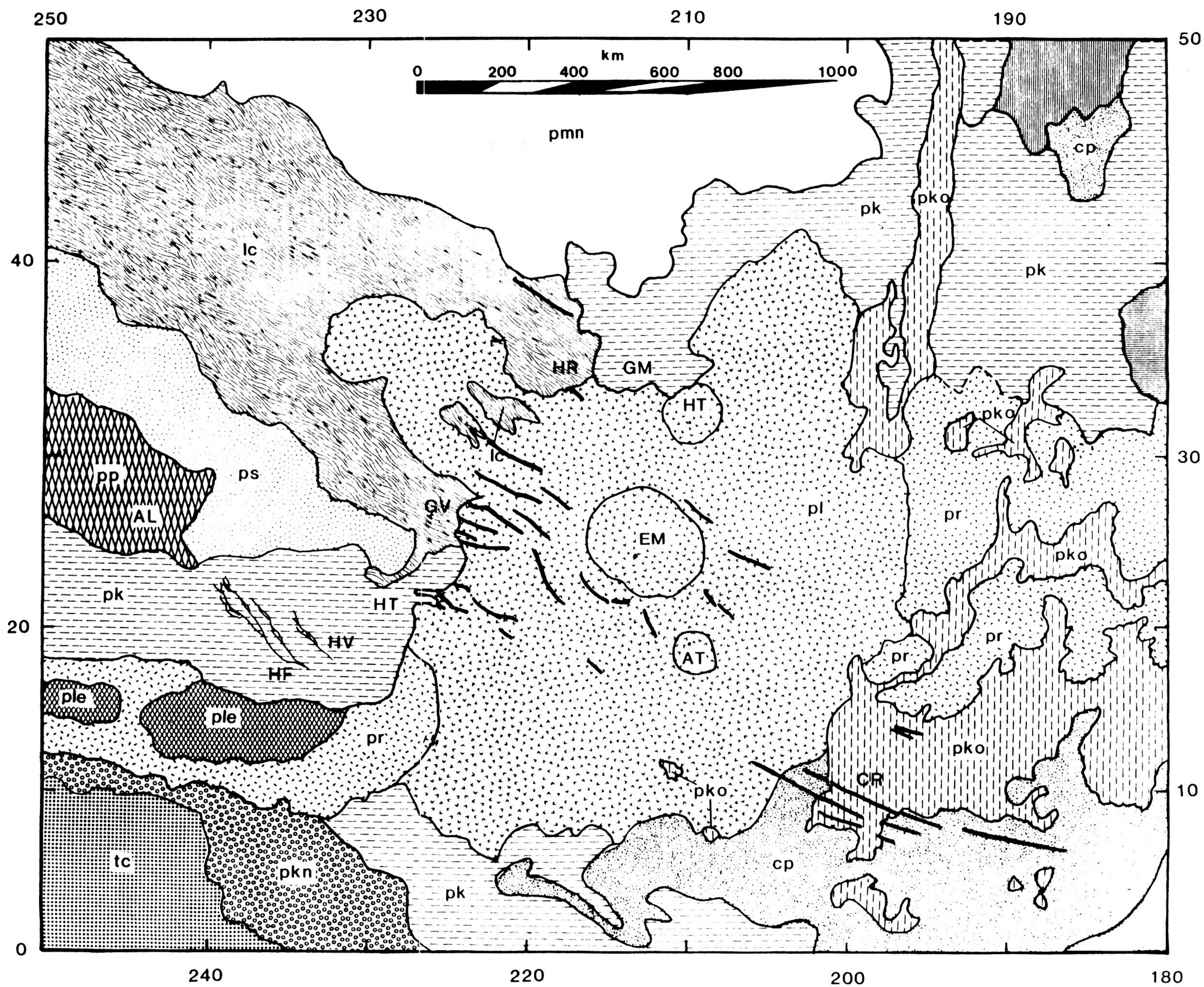
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Figure 1

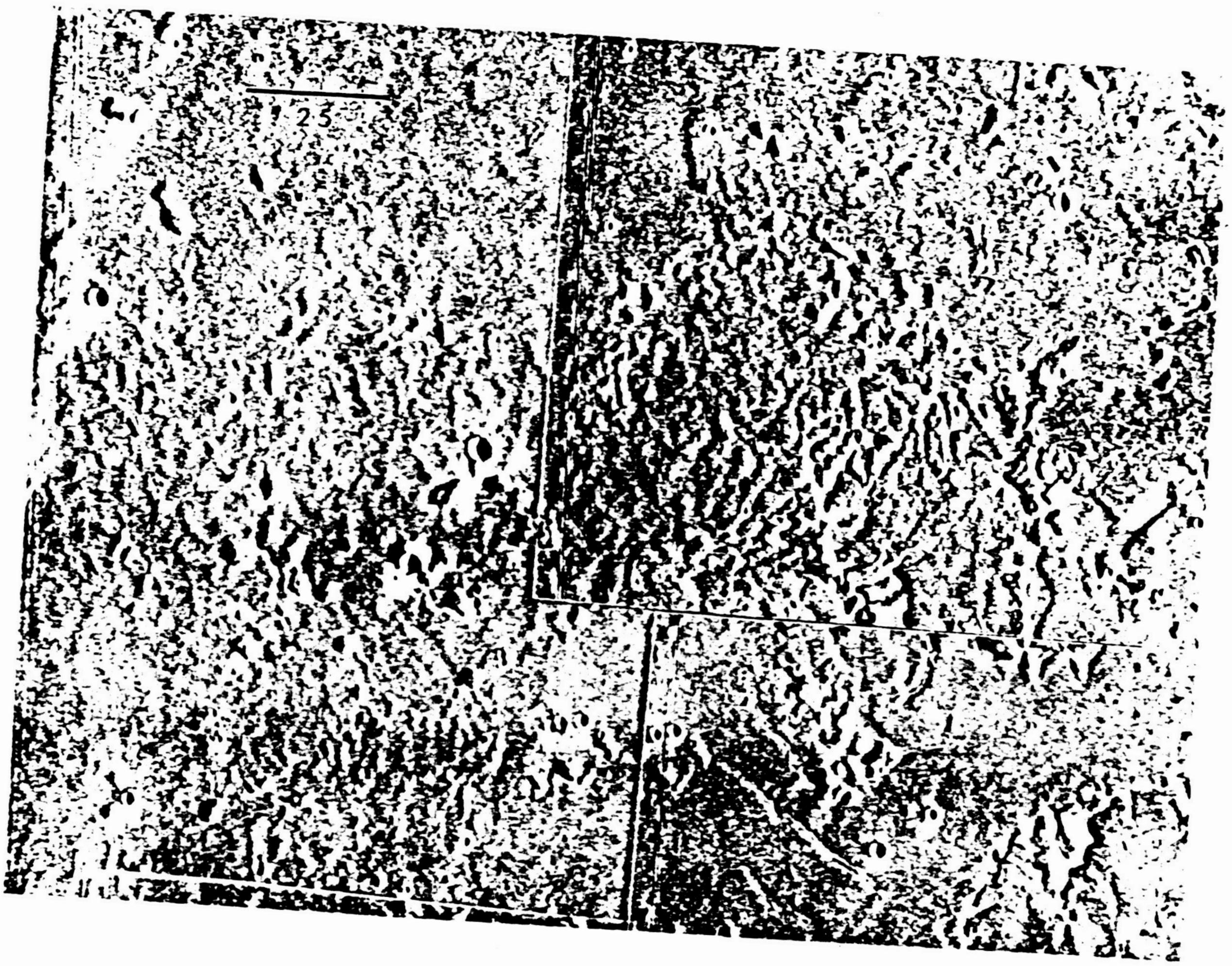

FIG 2a

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OF POOR QUALITY

FIG 2b

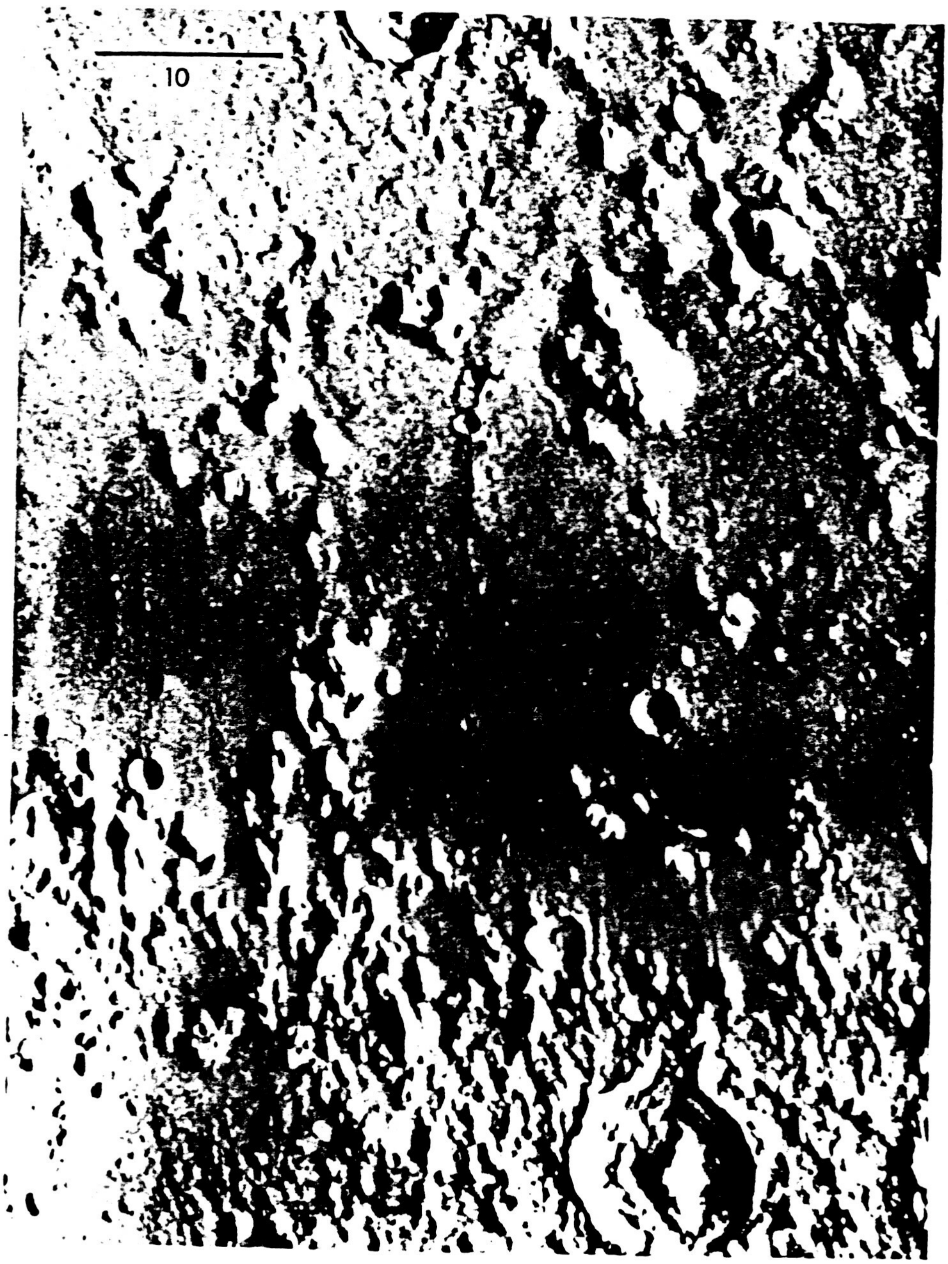


FIG 2C

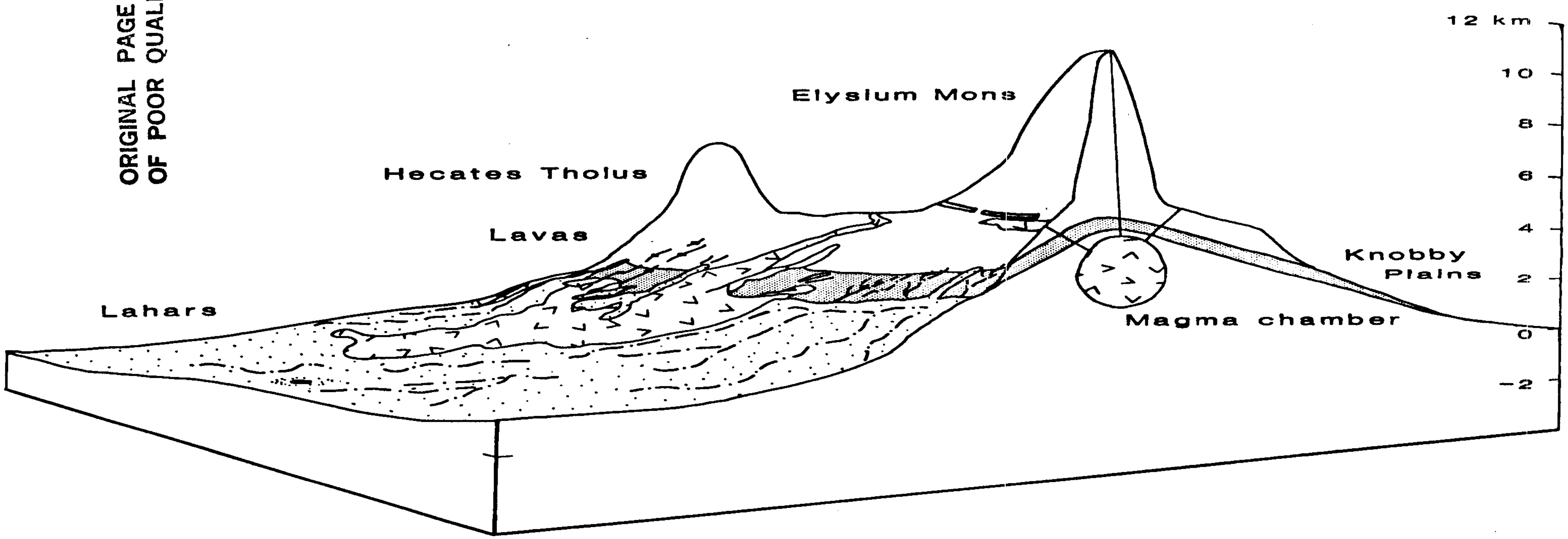

12 km
10
8
6
4
2
0
−2
Elysium Mons
Hecates Tholus
Lavas
Lahars
Knobby Plains
Magma chamber

Fig. 3

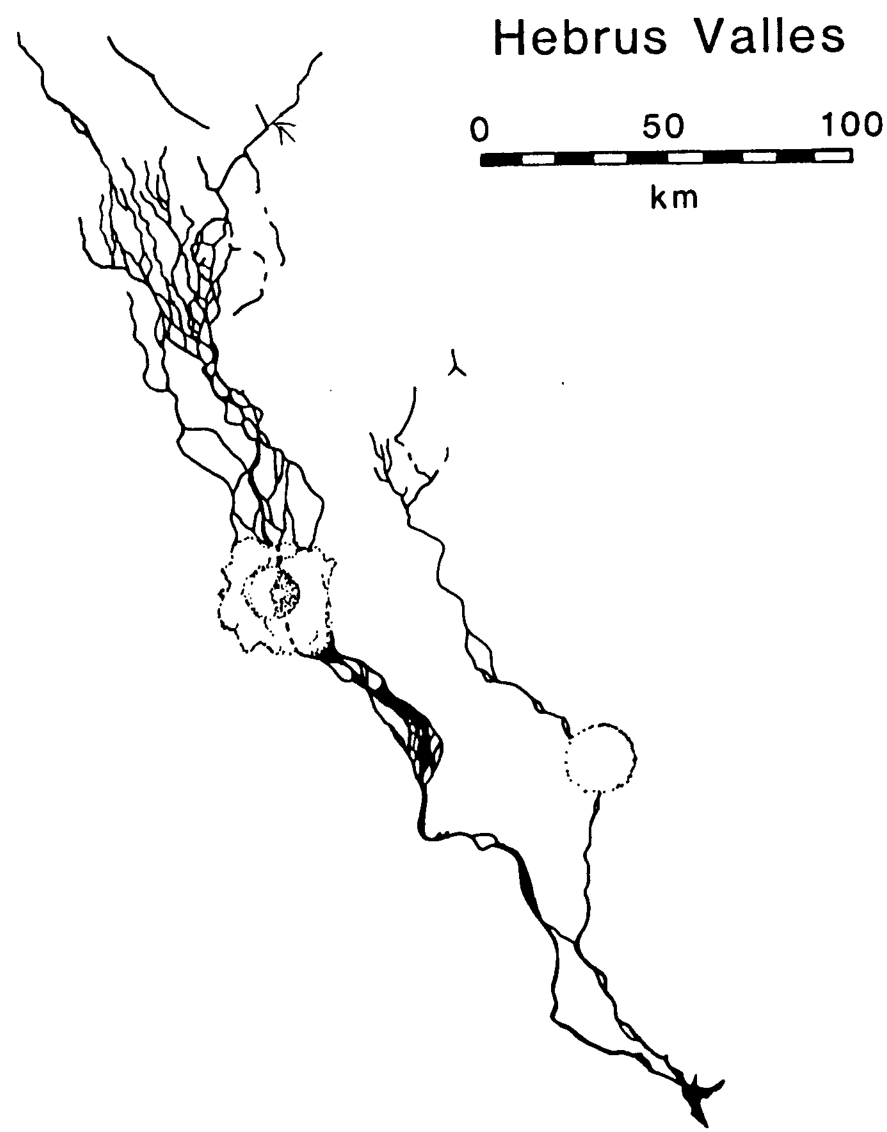


Fig. 4a

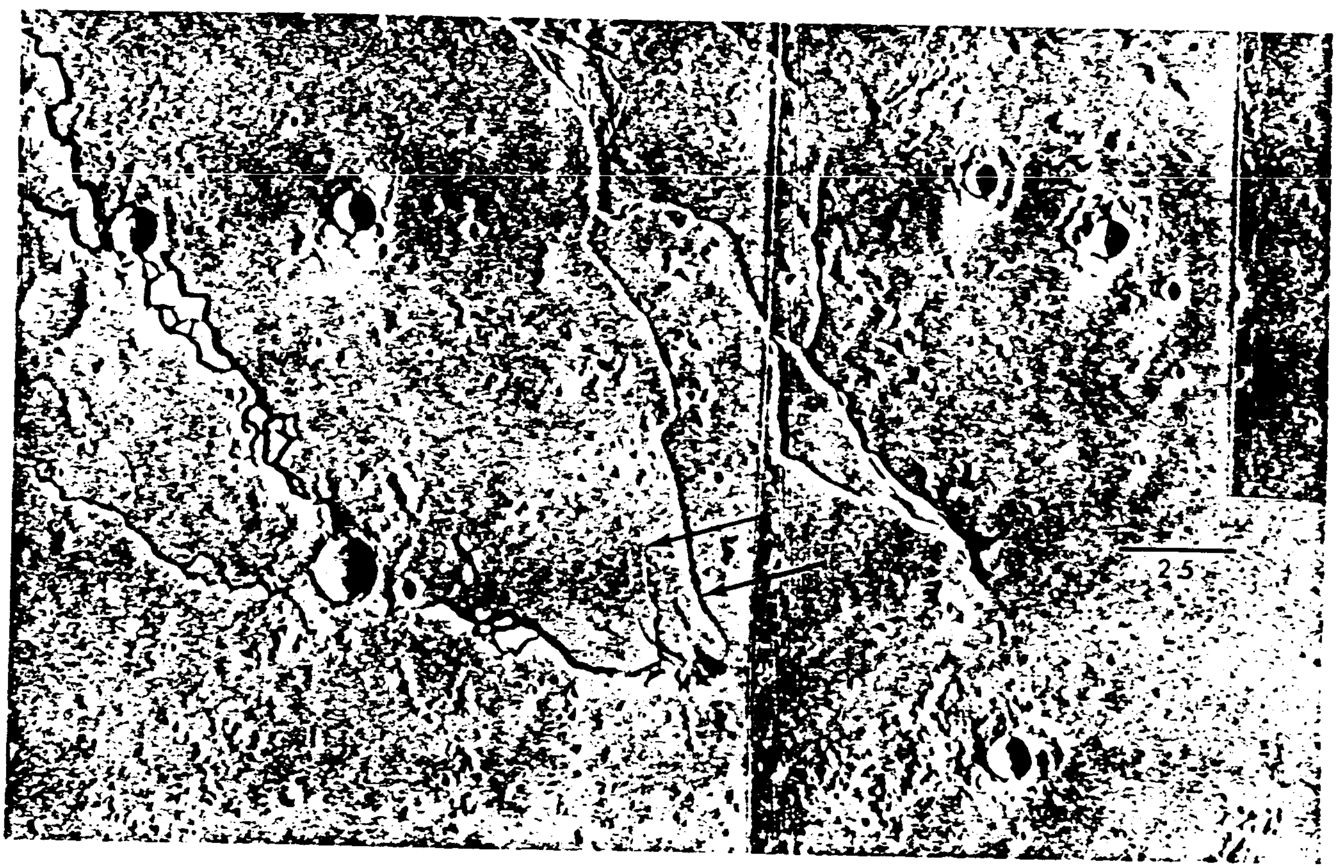


Fig 4b

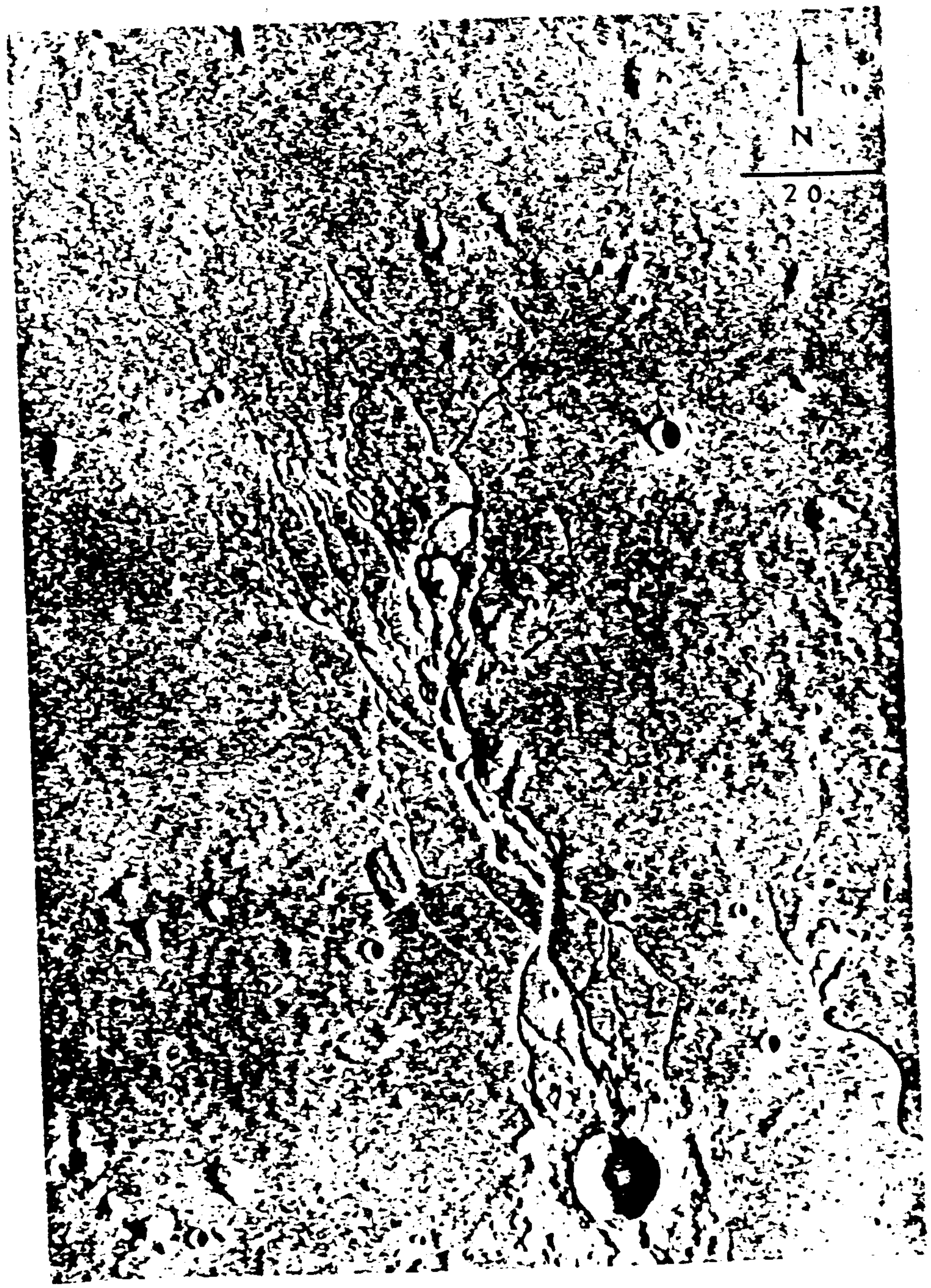
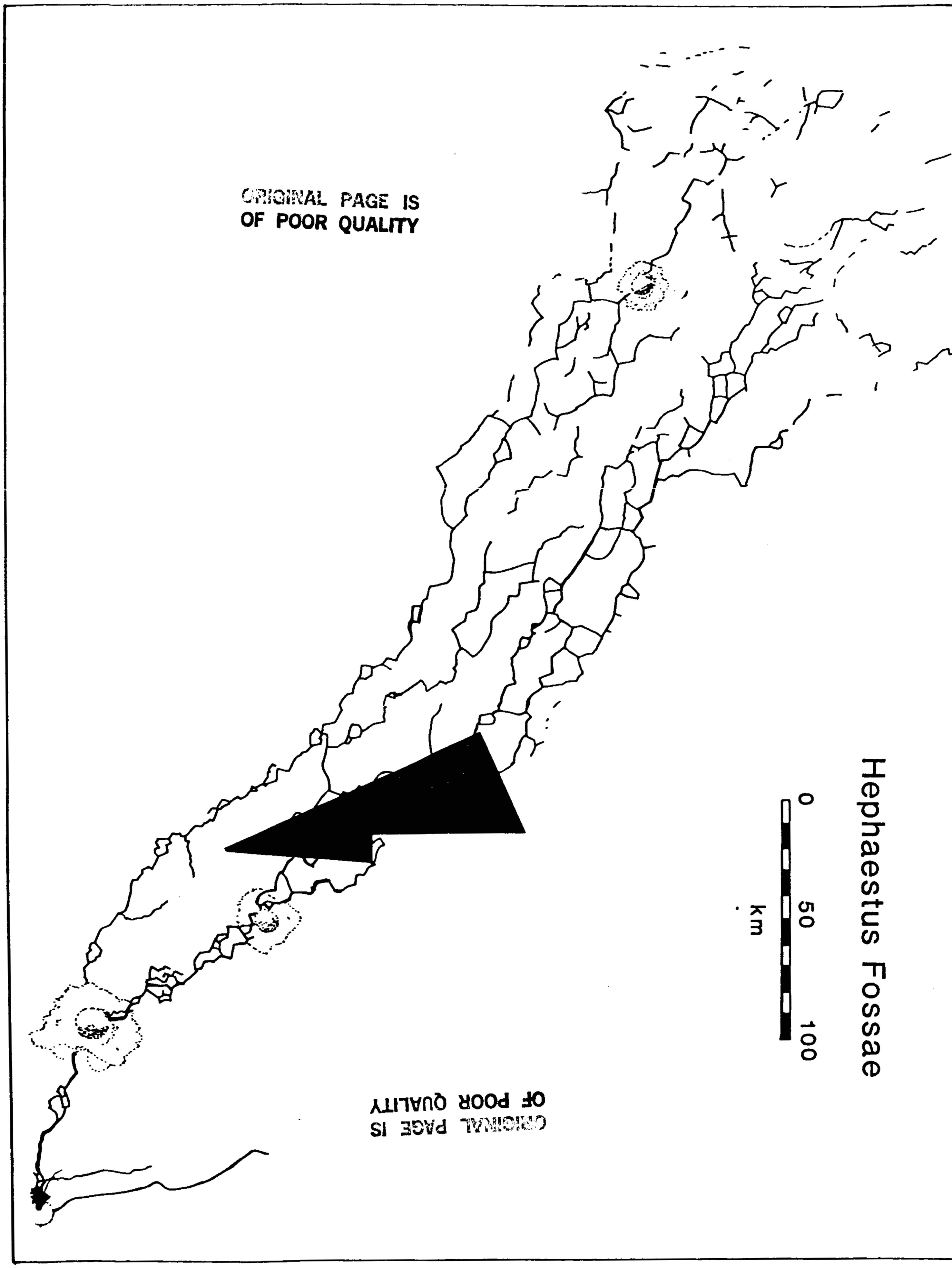


Fig 4c



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OF POOR QUALITY

Fig 5a

Fig 5b

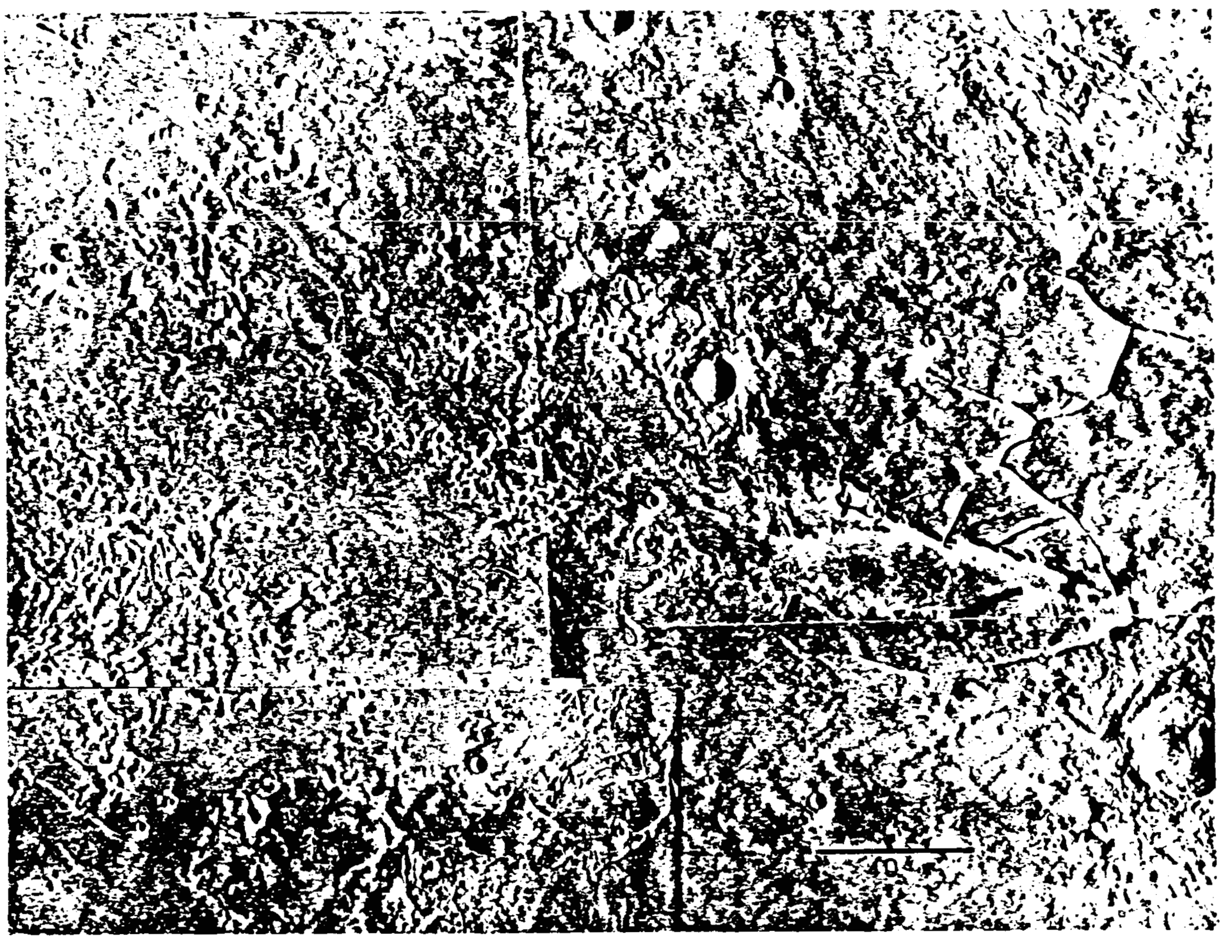

Fig. 6

Fig 7a

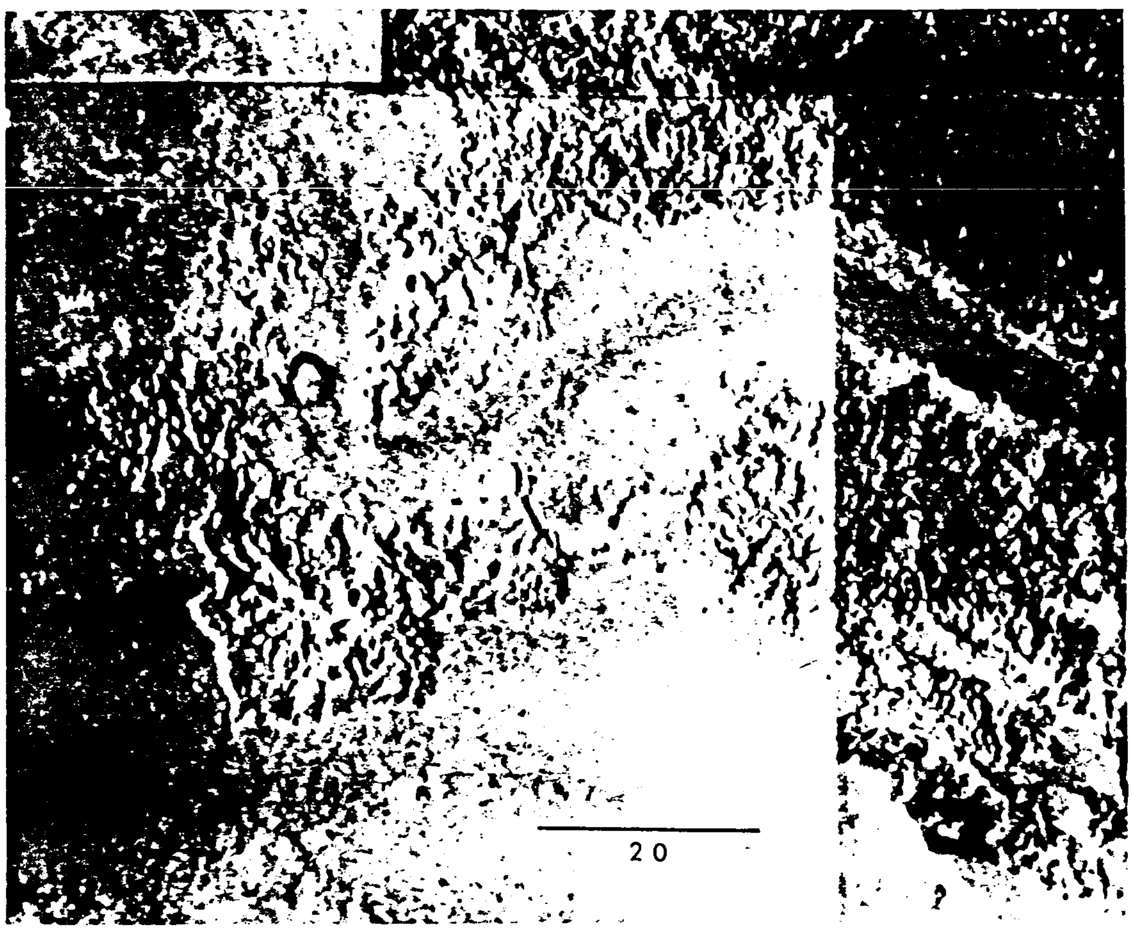

Fig. 7b

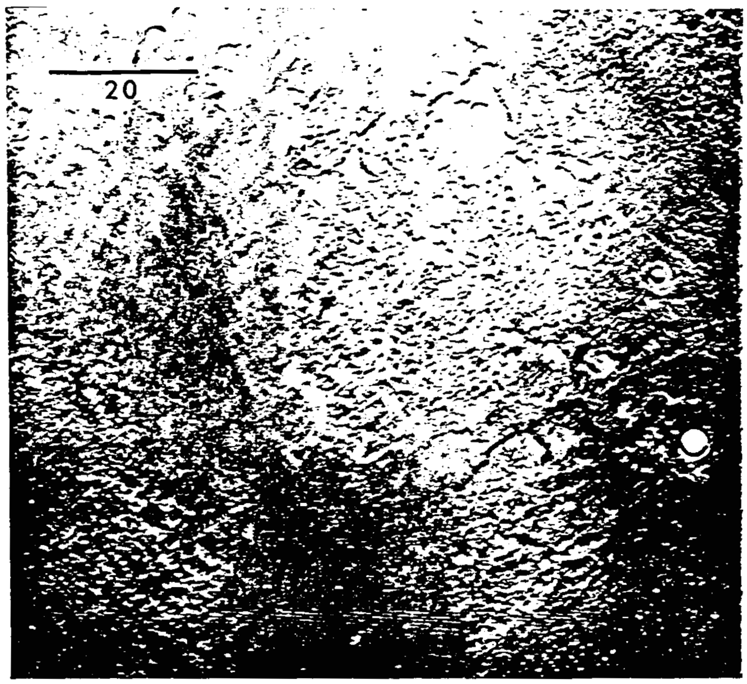

Fig. 7c