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MECA Special Session at LPSC XVII:

MARTIAN GEOMORPHOLOGY AND ITS RELATION TO SUBSURFACE VOLATILES

edited by
Stephen M. Clifford, Lisa A. Rossbacher, and James R. Zimbelman

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Contents

Introduction

During the course of the LPI Study Project "Mars: Evolution of its Climate and Atmosphere" (MECA), much attention was devoted to theoretical discussions of the martian volatile inventory, the planet's climatic and atmospheric evolution, and the interpretation of various remote sensing data sets (e.g., Viking IRTM and MAWD). Yet, during the first two years of the study, there was comparatively little discussion of what might be learned regarding the quantity and distribution of subsurface volatiles from an analysis of martian geomorphology. In an effort to address this oversight, a special session and evening panel discussion entitled "Martian Geomorphology and its Relation to Subsurface Volatiles" was held as part of the 17th Lunar and Planetary Science Conference.

In recent years, a long list of martian landforms has been compiled whose origins have been attributed to the presence of ground ice. Typically this association is based on a perceived resemblance to cold climate features found on Earth. Unfortunately, among other problems, it is not uncommon for the scale of these features to differ by several orders of magnitude from that of their terrestrial counterparts. The picture is further complicated by the numerous conjectures that have been made linking the dimensions and overall appearance of these landforms with such variables as regolith volatile content, physical state, and distribution with depth. Often these conclusions appear to be based on little more than an investigator's "gut feeling"; although, on occasion, a significant effort has been made to support a claim through detailed theoretical analyses and laboratory experiments.

Clearly, any effort to realistically constrain the quantity and distribution of volatiles based on an examination of orbital imagery must be preceded by an objective reassessment of our understanding of martian geomorphology. In particular: How confident are we of the identification of various martian landforms as indicators of subsurface volatiles? Are volatiles truly the best possible explanation for the origin of these features, or is it a bias that is now so deeply ingrained that the presumption is automatically made whenever any new and unusual landform is discovered?

To help address these and related questions, a panel discussion/debate highlighted the LPSC special session. The panelists included: Mike Carr, Fraser Fanale, Baerbel Lucchitta, Mike Malin, Pete Mouginis-Mark, Peter Schultz, Steve Squyres, and Jim Zimbelman. The moderators were Steve Clifford and Lisa Rossbacher.

The panel reviewed a number of morphologies that have been cited as potential indicators of subsurface volatiles; however, two in particular, rampart craters and terrain softening, were the focus of more in-depth discussion because of the popular attention they have received and the fact that their areal distributions are by far the most extensive of all the proposed indicators. The fluidized ejecta pattern that characterizes most rampart craters (Fig. 1) is thought to originate from an impact into a water or ice-rich crust; however, "terrain softening" does not represent a particular morphology, but a style of landform degradation. The term describes the rounded or subdued appearance frequently exhibited by topographic features poleward of 30° latitude (Fig. 2), a characteristic whose origin has been attributed to ice-enhanced creep.

The questions that follow are some of those considered by the panel:

Rampart craters:

(1) What is the basis for the association of rampart craters with subsurface volatiles?
(2) Is there any experimental evidence that supports the idea that the rampart crater ejecta morphology originates from an impact into a volatile-rich regolith? If so, how close were the experimental conditions (e.g., impact velocity, target and projectile strength, temperature, etc.) to those expected in an actual impact on Mars?
(3) Assuming a volatile origin, is there anything about the morphology of a rampart crater that is diagnostic of the specific volatile (i.e., CO_2 or H_2O), its original state in the regolith (chemically bound, physically adsorbed, ice, or a liquid), or the quantity that was entrained to produce the ejecta's characteristic fluidized appearance?

(4) What is the experimental or theoretical basis for calculating the depth to, or thickness of, a volatile-rich layer based on rampart crater onset or termination diameters?
(5) What other target or projectile properties are likely to influence crater morphology, and in what way?
(6) Rampart craters are alleged to form by an impact into a volatile-rich crust, yet, with the exception of a few isolated occurrences on Ganymede, no rampart craters are found on any of the icy satellites. How can this fact be reconciled with the popular model of rampart crater formation?
(7) In studies of the distribution of rampart craters, various subcategories of crater morphology have been defined and mapped. Unfortunately, few investigators have utilized the same classification system. Can such studies be correlated? For example, are there any clearly identifiable trends in crater morphology with latitude or terrain type that are common to all such studies?
(8) What obstacles prevent the adoption of a common system for the classification of martian crater morphology? Are there any reasons for not adopting such a common system of classification?
(9) Are there any alternative explanations for the origin of rampart craters that do not require the presence of volatiles? If so, on what evidence are they based? Are there any arguments against these alternatives?

Terrain softening:

(1) What is the basis for identifying H_2O ice as the agent responsible for this style of landform degradation?
(2) Is there any experimental evidence that supports this conclusion? What about terrestrial or other analogs?
(3) If terrain softening does indeed originate from ice-enhanced creep, are the mechanical properties of the martian crust implied by the dimensions and morphology of the affected terrain consistent with those expected of ice-mineral mixtures at ambient martian temperatures?
(4) Could the observations of subdued topographic relief at mid to high latitudes result from processes other than ice-enhanced creep (e.g., dust mantling, or atmospheric obscuration)?
(5) Would the analysis of crater diameter-frequency plots for the affected regions provide useful information to refute or support the ground ice hypothesis? Have any such studies been done?
(6) Because terrain softening is restricted almost exclusively to the latitudes poleward of 30°, it has been argued that ground ice must be absent from the regolith at equatorial latitudes. However, rampart craters are found throughout the supposedly dry equatorial band—even in the very youngest of terrains. How can this apparent contradiction be reconciled?

Future research:

(1) Is there any type of analysis of existing Viking or Mariner data that could shed additional light on the rampart crater or terrain softening questions? What about laboratory studies?
(2) Are there any diagnostic tests or observations that could be carried out by the instrument packages that have been proposed for the upcoming Mars Observer Mission?
(3) What types of instruments or experiments might be included in some future Mars mission to help determine the state, distribution, and total inventory of subsurface volatiles?

An overview of the special session and panel discussion is provided in the session summary by Jim Zimbelman. Lisa Rossbacher concludes the summary section with a critical review of our current understanding of martian geomorphology.

Stephen M. Clifford
Houston, Texas

Program

Monday, March 17, 1986
1:30 p.m.

Chairmen: S. Clifford and L. Rossbacher

Oral Presentations

Volatile inventory of Mars (invited)
R. O. Pepin

Small valley networks and the past and present distribution of subsurface volatiles, Aeolis Quadrangle, Mars
G. R. Brakenridge

Northern sinks on Mars?
B. K. Lucchitta, H. M. Ferguson, and C. Summers

Geomorphic evidence for subsurface volatile reservoirs in the Elysium Region of Mars
E. H. Christiansen and J. A. Hopler

Early changes in gradation styles and rates on Mars
P. H. Schultz and D. Britt

Ground patterns on Earth and Mars
L. A. Rossbacher

Spatial resolution and the geologic interpretation of martian morphology
J. R. Zimbelman

Implications for substrate volatile distributions on Mars from complex crater morphology and morphometry
W. S. Hale-Erlich

Morphologic variations of Martian rampart crater ejecta and their dependencies and implications
J. S. Kargel

Effects of elevation and plains thicknesses on martian crater ejecta morphologies for the ridged plains
V. M. Horner and R. Greeley

Pseudocraters as indicators of ground ice on Mars
H. Frey

The role of fluidization in the emplacement and alteration of the suevite impact melt deposit at the Ries Crater, West Germany
H. E. Newsom, G. Graup, T. Sewards, and K. Keil

Water-ice in the martian regolith: Experimental investigation of lithologic effects
J. L. Gooding

Poster Presentations

Morphology of large valleys on Hawaii: Implications for groundwater sapping and comparisons to martian valleys
R. C. Kochel and J. O. Piper

Presented by Title Only

Session Summaries

Overview of Afternoon and Evening Sessions

James R. Zimbelman

Two special sessions were held on Monday, March 17, 1986, at the 17th Lunar and Planetary Science Conference to investigate the topic "Martian Geomorphology and its Relation to Subsurface Volatiles." The afternoon session involved submitted papers on the topic (which appear in this volume) while the evening session centered around a panel discussion format. Both sessions served to emphasize that some fundamental issues regarding subsurface volatiles on Mars are still unresolved.

Bob Pepin opened the afternoon session with a comprehensive review of constraints on the volatile inventory of Mars. He used results from the analysis of gases in the Antarctic meteorite EETA 79001 (interpreted by several researchers to be a sample from Mars) to show that a considerable quantity of H_2O (tens to hundreds of meters deep planetwide) should be present within the surface of Mars. These results are consistent with earlier volatile inventory estimates and provide the theoretical basis for considering the influence of subsurface volatiles on surface morphology. The northern plains of Mars have several features that may be related to liquid and/or frozen water within the martian surface. Don Wilhelms, Ken Tanaka, and David Scott all noted that the knobby plains near Elysium Mons are the source of young channel systems and possible fluid lahars (mudflows). Eric Christiansen also reported on very large lahars west of Elysium Mons that may have included up to 10^4 km^3 of water. Polygonally fractured terrain in sedimentary deposits were described by Baerbel Lucchitta; these deposits appear to be related to the large outflow channels. There is a striking similarity in shape and scale between subkilometer-wide ridges present near the mouths of both the martian outflow channels and ice streams in Antarctica, leading Lucchitta to conclude that the martian waters may have partially frozen upon reaching the mouths of the channels. Heinz-Peter Jöns mapped features in the northern plains that he interpreted to be due to gelifluxion, or a periglacial origin of soil flow. Herb Frey noted that pseudocraters (subkilometer pitted mounds interpreted to result from the explosive interaction of lava and ice) could be sensitive indicators of near-surface ground ice. Numerous features appear to indicate the presence of subsurface volatiles but it is not clear to what extent these features are correlated with each other or with specific volatile distributions.

Channel networks in the highlands areas of Mars were examined as evidence of volatiles contained within the older, more heavily cratered terrains on Mars. Gary Brakenridge noted that better observational criteria are needed for distinguishing the diverse genetic mechanisms of valley networks on both Earth and Mars. He proposed hydrothermal systems associated with early impact events as an additional hypothesis to be considered. Peter Schultz reported on photogeologic analysis that indicates a substantial decrease in the gradation rate with time for Mars. This analysis indicates that the small valley networks are predominantly from early in the history of Mars when atmosphere-surface exchange of volatiles resulted in extensive gradation while more recent run-off channels are due principally to subsurface volatile loss. These results emphasize the need for careful consideration of the age of morphologic features in assessing their potential significance to volatile abundance.

Rampart craters continue to receive considerable attention but there is still no consensus on how best to interpret these features as volatile indicators. Wendy Hale-Erlich presented results on the analysis of complex craters where no strong latitudinal dependence was observed for either fluidized ejecta (ramparts) or craters with pitted central peaks, implying a uniform global distribution for any volatile associated with these features. In contrast, Jeff Kargel presented evidence that rampart crater lobateness (the ratio of observed ejecta perimeter to an equivalent area perimeter) changes from higher values at equatorial latitudes to lower values poleward of 35° latitude. Vicki Horner reported that changes in ejecta morphology with elevation in Lunae Planum may best be explained by variations in the plains' thickness. These results illustrate that several factors can contribute to rampart crater morphologies so that the real significance of volatiles to ejecta morphology remains unclear.

Laboratory and field analyses provide useful constraints on the processes inferred to be active on Mars. Craig Kochel and Jonathan Piper effectively demonstrated the processes active in groundwater sapping through laboratory experiments and field examination of large channels on the Hawaiian islands, strengthening the case for a sapping origin for certain martian channels. James Gooding demonstrated that basaltic regoliths might be significantly undercooled before freezing, increasing the potential distances for fluidized flows on Mars. Horton Newsom suggested that degassing pipes in the impact melt at Ries crater indicate fluidization of the deposit with volatiles from beneath the ejecta and similar phenomena might occur on Mars.

The question of scale must be considered in the interpretation of martian morphology. Lisa Rossbacher presented the results of a nearest-neighbor analysis of polygonal fractures on both Earth and Mars. She determined that, on both planets, the pattern of larger polygons is more random than the pattern of smaller polygons; this result favors a process-dependent model over an evolutionary model for polygon formation. The spatial resolution of the Viking images also influences the scale at which surface features can be interpreted. Jim Zimbelman showed an example from the Asheron Fossae region where 8 m/pixel images revealed an aeolian origin for features previously inferred to be related to subsurface volatiles from 57 m/pixel data. Most of the questions raised by the morphologic studies of Mars can only be effectively addressed through an examination of the highest resolution data available.

Participants in the evening panel discussion included Mike Malin, Mike Carr, Fraser Fanale, Baerbel Lucchitta, Peter Mouginis-Mark, Peter Schultz, Steve Squyres, and Jim Zimbelman; Steve Clifford and Lisa Rossbacher served as moderators. The introduction included brief presentations by panel members on specific landforms cited as indicators of subsurface volatiles and on guidelines for the interpretation of morphology from spacecraft images. Two features were singled out for more detailed examination, rampart craters and terrain softening, and about one-half of the session was alloted for their discussion.

Rampart craters have a distinctive ejecta morphology, often with a prominent ridge at the distal margin of the ejecta. When the panel was asked whether any feature of rampart crater morphology is truly diagnostic of the role of volatiles in the cratering process, no clear answer was presented. This highlights our present lack of understanding of the real details of the rampart cratering process and also points to an area for future work. Are there rampart craters on the icy moons of the Jovian planets? Baerbel Lucchitta showed some examples of possible rampart craters on Ganymede and noted that many more may be present but that the spatial resolution isn't quite sufficient to reveal details of the ejecta. Mike Carr made the interesting observation that the rampart ejecta morphology isn't seen for craters smaller than 3 km in diameter, with the cut-off size staying quite consistent planetwide. He suggested that this may be telling us something fundamental about the rampart crater formation process and should be investigated further. Several panel members also voiced concern that a consensus has not yet been reached regarding the classification and distribution of rampart craters.

Terrain softening is a style of landform degradation noted by Steve Squyres and Mike Carr and it is interpreted to be the result of subtle downslope movements by ice-rich soils. The strong latitudinal dependence of the degradation, only seen poleward of 30° latitude, is probably the strongest evidence that a volatile is involved in the degradation process. Can ice flow at these latitudes in the martian environment? Baèrbel Lucchitta showed some laboratory data that indicate that ice could flow but it would do so extremely slowly, arguing for considerable age for such features. Several examples were shown of the degraded terrain relief but, as with the rampart craters, there is still no conclusive morphologic evidence that a subsurface volatile is the degradation agent. Clearly, alternative hypotheses should be considered and tested against the volatile-dependent hypothesis.

Some specific recommendations were expressed at the conclusion of the panel discussion, including (1) a comprehensive analysis of rampart crater morphology and distribution, (2) a compilation of clearly labeled photographs with the best examples of all features proposed as indicators of subsurface volatiles, (3) detailed modeling of the flow states proposed for various landforms, including the rheology of the flowing materials, and (4) evaluation of the pressure and temperature conditions present during a cratering event in order to assess the significance of various volatiles present within the target and the ejecta.

Martian Geomorphology: A Critical Summary

Lisa A. Rossbacher

Water, water, everywhere

In the ten years since Viking arrived at Mars, the role of water in the planet's history has evolved from doubtful to possible to likely to a foregone conclusion. Immediately after the Viking landing, the notion of water ice on Mars was still regarded with skepticism and thinly disguised humor. Now, the situation is reversed; few argue about whether ice exists on Mars. The real questions today are where and how much.

Planetary geologists have spent considerable time and effort—and, at LPSC XVII, words—about ways in which geomorphology can be used to decipher the presence and role of subsurface volatiles on Mars. We have made some progress in sharing inventories and theories; we have far to go in consolidating and evaluating different ideas to reach some consensus.

Morphologic indicators

One example of an area in which communication hasn't worked is the use of crater morphologies as indications of subsurface volatiles. The first study of this offered a promising direction for research (Johansen, 1978), but it was plagued by inconsistent sampling, convoluted presentations of data, and a whimsical terminology. Too many people either accepted the latitudinal distribution of crater morphologies with few reservations or rejected the worth of the study altogether. Subsequent studies have concentrated on varying interpretations of specific types of crater ejecta, rather than overviews (Mouginis-Mark, 1979; Schultz and Gault, 1984). Despite many exhortations in the wilderness of martian crater studies, no full-scale reanalysis has been completed.

Of the other martian landforms used to infer the presence of subsurface ice, nearly all offer ambiguous answers. Flat-topped, steep-sided volcanic constructs, which bare a resemblance to Iceland's table mountains, are a promising indicator (Hodges and Moore, 1978; Allen, 1979), but their limited geographic distribution severely limits their usefulness. Mouginis-Mark (1985) has evaluated the range of landforms in Elysium Planitia that may reflect the interaction of ground ice and volcanic processes. Within that area, the locations of meltwater deposits, outflow channels, collapse features, and possible pseudocraters have a latitudinal variation. This distribution suggests subsurface ice either gets deeper or disappears between 35°N and 24°N.

Thermokarst, which appears as hummocky ground or closed, rimless depressions created by loss of ground ice, may be a good clue to the presence of subsurface volatiles (Theilig and Greeley, 1979; Rossbacher and Judson, 1980, 1981). Certainly these features have the advantage of a relatively wide geographic distribution (Rossbacher and Judson, 1981) and abundant terrestrial analogs (Gatto and Anderson, 1975). The major difficulty with these martian landforms is that a thermokarst origin is not a unique explanation; another possibility is volcanokarst formed by drainage of lava from beneath a solidified cover and subsequent collapse. A volcanic interpretation is supported by the proximity of many of the closed depressions to the Tharsis volcanoes, although this relationship might also reflect a local heat source that could contribute to melting.

Polygonally fractured ground on Mars may be related to subsurface volatiles (Carr and Schaber, 1977; Rossbacher and Judson, 1981; Lucchitta, 1983), but arguments have also been made for a volcanic (Morris and Underwood, 1978) or tectonic (Pechmann, 1980) origin. The terrestrial analogs that are closest to the martian landforms in size are desiccation fractures in arid regions (Willden and Mabey, 1961). Although most efforts have concentrated on periglacial analogs and thermal contraction processes, desiccation may be equally important. Recent evidence that "desiccation weathering" may be significant on the surface of Io supports this (Nash, 1986). McGill (1985) has suggested that the fractured martian plains may have resulted from the emplacement of a water-saturated overburden that settled, compacted, and dried out. This proposal helps explain the abundance of circular fractures that may indicate buried craters. A number of investigators are actively pursing this promising avenue of research. The effects of drying sediments may play a role in exhuming older landscapes on Mars (Rhodes, 1984). Exhumed topography and its relation to volatile history is another area that deserves further study.

The most recent entry in the morphologic indicators contest is not a landform but a style of landform modification. Terrain softening, as proposed by Squyres and Carr (1986), is caused by slow downslope creep of volatile-rich material. The proponents of this process have identified a latitudinal distribution, with no evidence of softening equatorward of 30° latitude and a significant amount of modification in mid-latitudes. The style of softening changes around 60°N and S. This distribution corresponds well with predicted unstable-ice areas (Smoluchowski, 1968; Fanale, 1976).

Combining the evidence

Inferences about subsurface volatiles are restricted by other factors besides the ambiguous interpretation of landform origins. Arvidson and others have warned about the problems of atmospheric obscuration and poor image quality for interpretation of geomorphology, geology, and crater-count ages. Zimbelman (1986) has illustrated some of these problems associated with image resolution. High resolution images may depict scenes that are drastically different from lower resolution frames, and features that appear periglacial at 300 m/pixel suddenly look aeolian at resolutions of 10 m/pixel.

Studies of martian geomorphology—particularly those related to the implications for subsurface volatiles—have remained too compartmentalized. This fact was evident from the special martian geomorphology session at LPSC XVII, but the discussions didn't solve the problem. The landform studies remain separate. We need to accept that no single morphologic indicator will answer all the questions about subsurface volatiles. Mike Malin has pointed out that, in a field founded on the principle of multiple working hypotheses, such consolidation of information has been surprisingly slow in coming.

Taken as a group, the variety of landforms discussed here could all contribute information to our understanding of Martian geomorphology. Different landforms offer different types of evidence, and we need to ask different questions of each. For example, thermokarst should give clues to volatile abundance, ejecta morphology to the depth of volatiles, patterned ground to volatile history, and terrain softening to more recent effects of the volatiles. Mouginis-Mark (1985) has done this for a group of landforms in Elysium Planitia. This approach needs to be extended over the entire planet.

Most importantly, we should then consider carefully whether this set of information is internally consistent. Morphologic evidence presented at LPSC XVII did not all point to the same distribution of subsurface volatiles on Mars. Where the data suggest conflicting interpretations, we need to reconsider some of the answers—and probably some of the questions as well.

Future efforts

The greatest immediate need is for a carefully designed study of the distribution of various types of ejecta morphology on Mars. These landforms are widespread, and they offer the most extensive data set for determining the characteristics of the surface and near-surface material on Mars. In the process, we should heed the warnings of Arvidson, Zimbelman, and others regarding the quality of the data we use. High resolution images are available for many areas; where they are available, we should be using them. The growing body of evidence that demonstrates the value of high resolution images also emphasizes the importance of acquiring more photographs. We are accumulating an enormous list of areas that need closer scrutiny. Future morphologic studies of Mars need additional high-resolution images. With a little luck and a lot of scientific support, the Mars Observer should provide this.

A remaining need is for investigators working with all the various morphologies to consolidate their results. The special session at LPSC XVII was a tentative start, but we are still talking at each other rather than with our colleagues.

Acknowledgments

The special session on "Martian Geomorphology and its Relation to Subsurface Volatiles" at Lunar and Planetary Science Conference XVII was possible only because of the hard work of Steve Clifford, who handled most of the premeeting organization and logistics. In the fading light of the Halley's Comet field trip, he deserves special commendation. Similarly, all the people who gave invited and contributed talks and who participated in the panel discussion offered important contributions to the issues being considered. My professional and personal thanks goes to all of them. Dallas Rhodes' review of this summary and Rosalie Thompson's typing and other assistance are gratefully acknowledged.

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ABSTRACTS

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SMALL VALLEY NETWORKS AND THE PAST AND PRESENT DISTRIBUTION OF SUBSURFACE VOLATILES, AEOLIS QUADRANGLE, MARS; G.R. Brakenridge, Department of Geological Sciences, Wright State University, Dayton, OH 45435.

The small valley networks of Mars exhibit a variety of planimetric and cross-sectional morphologies. Like valleys on Earth, they may have formed through diverse genetic mechanisms, including floor and wall erosion from down-valley fluid flows, headward valley growth by spring sapping and head-wall collapse, and mass-wasting along fractures and faults. It is thus unlikely that the small valleys of Mars all have a single origin. In fact, one scientific outcome of continuing Martian geomorphic investigations may be the development of better observational criteria for separating valleys formed by different mechanisms on both Earth and Mars.

Several common classes of small Martian valleys appear, however, to have one unifying characteristic: the presence of subsurface volatiles, probably water and water ice, during their time of formation. Valley classes such as the sub-parallel slope ravines and the branching, flat-floored trunk valleys (1) are absent on (volatile-poor) Mercury and the Moon. Completed and in-progress geomorphic mapping in the Aeolis Quadrangle agrees with previous work (2) in suggesting a lithospheric, not atmospheric, source for fluids associated with valley development.

The valleys both transect, and are interrupted by, impact features at a variety of scales. It is not yet known whether valley development occurred throughout the Aeolis Quadrangle at closely similar times. Instead, it may be that individual valley networks are of different ages. However, a very widespread period of endogenetic volcanic activity (inter- and intracrater plains volcanism) postdates most slope ravines and the dissected landscapes they produced (3). Additional cratering, during the tail end of the Late Heavy Bombardment, postdates both valley development and plains volcanism. The apparent lack of young Martian valley networks indicates a change in either volatile abundance or the mechanisms for discharging volatiles at or near the surface.

In this respect, a past warmer or denser Martian atmosphere is often invoked as a prerequisite for small valley genesis. If true, this model implies that valley locations contain little or no information about modern subsurface volatile distribution, ca. 3.8 billion years later. However, another valley genesis model (1) does not require a more favorable atmospheric environment. Instead, hydrothermal systems associated with early impact events can explain valley growth through headward extension, down-valley fluid flow, and fracture-related mass wasting. Evidence in favor of this hypothesis includes the small scale global map of the Martian valleys shown in (4). Even at this scale, ca. 200 km wide and larger circular features that lack small valleys are conspicuous. They may represent relatively impermeable impact melt locations associated with old large impacts. Such craters were subsequently partially filled by flow volcanics, and scarred by younger impacts.

This model has different implications for the distribution of subcrustal volatiles through time and at present. If the source for the water and ice that helped mobilize valley development was lithospheric and not atmospheric, then valley location was controlled by: 1) the ancient regional distribution of subsurface volatiles during bombardment, 2) the location of conduits connecting these sources to the surface, as predicted by the structural geology of impact craters, and 3) the relative sizes of impact events: smaller impacts may not excavate beneath a volatile-poor, older impact melt.

Calculations of impact heat energies suggest that hot spring and other hydrothermal activity would be more constrained by volatile availability than by impact energies needed to melt and heat ice and water (1). A major uncertainty, but one susceptible to theoretical modeling, is whether valley development itself caused a significant net transfer of regolith water to the atmosphere. Did volatile abundances become progressively depleted during valley development, or was termination of valley genesis caused instead by a shut-down of release mechanisms? In the latter case, the subsurface abundance of volatiles may still be high.

Assuming a subsurface water origin, the development and location of conduits must exert the dominant control over local valley position. Discharge locations (valley heads) may be strongly affected by regional fracture systems as well as by the fractured and permeable zones surrounding individual impact structures. This is clearly true in quite different, and younger, geologic terrains, such as those in Thaumasia Fossae. There, small valleys are relatively uncratered, and exhibit spatial relationships to visible signs of volcanism and extensional faulting as well as to cratering. Impact events are not the only mechanism capable of melting permafrost, creating conduits, and promoting surface discharge or mass wasting. Thin volcanic flows in Thaumasia partially cover previously dissected surfaces, and have created there a geologic situation at least crudely similar to the more ancient and widespread inter- and intracrater plains volcanics and valleys of the heavily cratered terrains.

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GEOMORPHIC EVIDENCE FOR SUBSURFACE VOLATILE RESERVOIRS IN THE ELYSIUM REGION OF MARS

Eric H Christiansen and Jennifer A. Hopler, Department of Geology, University of Iowa, Iowa City, Iowa 52242.

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) beneath the surface of the planet. The spatial and temporal distribution of these subsurface volatile reservoirs is important for understanding the evolution of martian landforms, climate, and perhaps even large-scale tectonism.

The Elysium volcanic province contains a variety of evidence for the existence of large volatile reservoirs beneath the surface. Geomorphic study of these landforms yields insight into the distribution and size of these reservoirs and how they interact with the surface environment and will ultimately place constraints on the geometry, constitution, origin, time of formation, and temporal evolution of these important components of the martian crust. Three principal types of landforms appear to be related to subsurface volatile reservoirs in the Elysium region of Mars : 1) small outflow channels; 2) large lahars; and 3) vast expanses of knobby terranes around the margins of the Elysium dome.

Outflow Channels.

The most obvious expressions of the presence of a subsurface volatile reservoir in this region are two relatively small outflow channels--Hebrus Valles and Hephaestus Fossae (1). Located southwest of Elysium Mons, both channel systems arise and cut across a broad expanse of older plains dotted by irregular mesas and smaller knobs (knobby plains).

The anastomose Hebrus Valles system of channels is 250 km long and emerges full-strength from an elongate depression. The source depression is 10 km across and has narrow finger-like projections. Individual sinuous channels are less than 100 m deep and about 1 km wide; a braided reach is about 10 km wide. Streamlined bedforms are abundant in the middle reach. The channels become narrower and shallower downslope. Hebrus Valles terminate as a series of narrow distributaries. No sedimentary deposits are obviously related to the development of the channels. Hebrus Valles are similar to other small martian outflow channels and appear to result from fluvial erosion following the outbreak of a confined aquifer.

Hephaestus Fossae are a connected series of linear valley segments which branch and cross downslope but have high junction angles. Locally, the valley pattern is polygonal. Hephaestus Fossae are parallel to Hebrus Valles but are considerably deeper and longer (600 km). The rectilinear pattern of the valleys has suggested to some that the fossae are tectonic in origin. However, unlike graben systems, Hephaestus Fossae originate in an isolated depression very similar to the source of Hebrus Valles. At least two sinuous, apparently fluvial, channels also arise from this depression. It is suggested that like Hebrus Valles, Hephaestus Fossae are also of fluvial origin as a result of catastrophic flooding and draining of water from beneath the surface. Hephaestus Fossae channels appear to have cut through the knobby plains unit which overlies a polygonally fractured terrane like that exposed at the NW end of the fossae in Adamus Labyrinthus. Downcutting to, or subsurface flow at this pre-existing surface led to a channel pattern that was strongly controlled by the polygonal troughs buried beneath the younger knobby plains materials. Hebrus Valles channels did not excavate this deposit and hence show more typical outflow features.

Mega-lahars.

Photogeologic studies of the Elysium volcanic province provide specific examples of the importance of the interaction of volcanism and subsurface volatile reservoirs to produce distinctive landforms (2). Three sets of volcanic debris flows or lahars issue from the same northwest-trending system of fractures that localized the three major volcanic constructs in the Elysium province. These deposits are lobate in plan and have steep well-defined snouts. Evidence that these mass flow deposits were wet slurries and not lava or ash flows include: 1) the intimate association of channels with their surfaces--these channels are sinuous, form anastomose distributary patterns, and have streamlined features on their floors. These features are consistent with the flow of water across the deposits. 2) discrete channels issue from the base of the lobate masses suggesting draining of water from wet sediments; 3) short reticulate systems of sinuous valleys cut portions of the deposits' margins and look like seepage channels (3); and 4) numerous irregular depressions mark other areas of the flows and have clearly developed from a formerly smooth and more extensive deposit. These pits may be created by the removal of volatiles by sublimation or seepage.

We explain the presence of the lahars as the result of the melting of ground ice and liquefaction of subsurface materials. The development of the Elysium volcanoes is the most reasonable source of heat and is consistent with the stratigraphic evidence that lavas and lahars were nearly contemporaneous. The contact of magma with liquid water may have resulted in hydrovolcanic explosions which produce large quantities of easily mobilized fine-grained material (4). 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.

These sedimentary deposits extend nearly 1000 km down the regional slope to the northwest and cover 10^6 km^2. The deposits are less than 200 m thick near their sources and are probably much thinner on average. The total volume of the lahars may then be approximately 10^5 km^3. Taking a value of 30% water by volume--a figure typical of terrestrial lahars and non-volcanic debris flows (5)--implies that over 10^4 km^3 of water were involved.

Knobby Terranes.

Knobby terrane provinces consist of relatively smooth surfaces with variable proportions of knobs and flat-topped mesas. Broadly similar knobby terranes cover approximately 3 million km^2 in the Elysium region. The knobs and mesas appear to be erosional remnants of a formerly thicker deposit. The polygonally troughed terrane of Adamus Labyrinthus underlies the knobby terrane in the Amenthes quadrangle. In southern Amenthes quadrangle, the knobby plains have developed at the expense of an extensive plateau marked by irregular depressions and pits. Layering is visible in the walls of these ragged depressions. Erosional stripping of the knobby deposit has exhumed large impact craters. North of the volcano Hecates Tholus, knobby plains are developed at the expense of lava plains that partially bury the knobby plains (or its smooth undegraded precursor). Here, large lava-capped blocks give way to smaller mesas which grade northward into smaller knobs. Even farther north the knobby plains disappear and reveal underlying polygonally troughed terrane.

The knobby plains precursor appears to have developed in middle martian history. It overlies the polygonal plains of Adamus Labyrinthus which are post-Lunae Planum in age (6) and is in turn buried by Elysium lavas and lahars. The knobby plains are also cut by the two large outflow channels noted above and numerous small seepage channels on the western flanks of the Elysium dome. 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 sublimation of water that had been sequestered in the layered deposits. The spatial coincidence of the knobby plains with other water-related landforms lends credence to the latter hypothesis. The degradation of the knobby plains precursor appears to have occurred mostly before Elysium volcanism because vast tracts of smooth lava plains bury knobby terrane; but at least in the small region north of Hecates, knob development appears to have persisted until the later stages of Elysium volcanism. Assuming that most of the missing volume represents removal of volatiles, and ignoring the extent of the knobby plains that must underlie the Elysium volcanic province, the amount of water lost from this region may be approximately 10^5 km^3.

Implications for Sub-Surface Volatile Reservoirs at the Surface of Mars.

The evidence provided by these landforms is internally consistent with the presence of a large relatively shallow volatile reservoir in the Elysium region of Mars. If the geologic features described above are reliable indicators of subsurface volatiles in this region, they imply that:

- the precursor of the knobby plains is an important volatile reservoir.
- volatile reservoirs lie relatively close to the surface.
- volatile reservoirs underlie millions of km^2 in this region.
- volatiles may be lost in a variety of ways from these reservoirs.
- volatiles were incorporated in an easily eroded surficial deposit in the middle history of Mars.

The ultimate origin of the water in this reservoir is uncertain, but the evidence is at least consistent with the polar wandering model described by Schultz (7). Otherwise, a model to explain the preferential entrapment of volatiles into one regions' surface materials is needed.

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ICE LENSES ON MARS

by François Costard+ and Audouin Dollfus*
* Observatoire de Paris, Section de Meudon, 92195 Meudon, FRANCE.
+ Laboratoire de Géographie Physique (Meudon-Bellevue).

With the dry periglacial-type climate of planet Mars, an underground permanent 1-3 Km thick permafrost extends all over the planet below the surface (1). Along cratered uplands and northern plain boundaries, chaotic terrains are observed, which were interpreted as thermokarst features (2). Thermokarsts are identified on Earth; they are produced by the melting of ground ice. This process of collapse is well developed in areas of segregation ice where ice lenses or wedges are produced (3). The purpose of the present work is to document the presence of ice lenses in the martian permafrost.

1 - In the Martian region Hydaspis Chaos, at 1°N and 29°W, several tens of ellipsoidal mounds are observed, with an average major axis of 7 km (fig. 1); we interpreted these features as ice lenses (4). Lucchitta suggested also the idea of ice lenses on Mars (5). On Earth, there are two kinds of ice lenses, the pingoes and the hydrolaccoliths; both are formed by segregation or injection of ice in a frozen ground (6).

a) Closed system pingoes in Mackenzie, for example, were grown by the cryostatic pressures of a frozen lake. Such a process cannot prevail on Mars as the planet stands presently, because the low atmospheric pressure of 6mb prevents the existence of water lakes. Advocated periodic climate variations might allow development of lakes but, if such was the case, pingoes would be observed widely over the planet, and not in specific areas.

b) Open system pingoes, also designated hydrolaccoliths, such as those in Alaska for example, have elongated shapes; they grow under artesian pressure, by the presence of a talik (unfrozen sediments within permafrost). In this case, the ground water close to the surface freezes and produces an ice core. This process is apparently more likely on Mars, an account of the morphology and location of the ellipsoidal mounds observed. The advocated presence of taliks is consistant with the formation of outflows from confined aquifers (7). Ice lenses on Mars are much larger in scale than for any terrestrial analogs, probably because the low gravity reduces the weights of the ice core and of the water under pressure.

2 - In the Pleistocene alluvial terraces of Central Yakutia, alas valley features are well developed and range from 2 to a few tens kilometer in length (8). The water is first trapped in flood plains, or frozen in lakes. Then, ice lenses and wedges are produced. Their subsequent melting contributes to the development of flat floored and steep sided depressions, called alas. Their coalescence produces a mature alas valley. On Mars, an alas like valley is observed at the month of the outflow Ares Vallis at 14°N and 28°N (fig. 2). This thermokarstic feature is about 200 km long and 100 km wide. Its floor has an alternation of fretted alluvial terraces with arcuate banks, and of flat circular depressions averaging 4 km in diameter. Narrow ridges are also observed, sometimes perpendicular to the valley. The widening of the floor at the very location of the alas valley implies a decrease of the flow surface velocity which facilitates the formation of an alluvial accumulation plain. In cold climate conditions, fluvial sediments are trapped as a frozen deposit with formation of ice segregation. Then, during a warmer climate episod, or by means of a geothermal heating, melting or sublimation of the ice in the lenses and wedges may produce extensive alas developments.

The analogy between Ares alas valley on Mars (fig. 2) and terrestrial counterparts such as Kokara in Siberia (fig. 3) is striking. However the

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martian feature is 20 times larger than the terrestrial analogs. The large number of circular depression in Ares does attest, for the majority of them, the presence of fossil ice lenses rather than impact structures. The presence of an alas valley on Mars and its fluviatil origin do support the formation of outflow channels as catastrophic floods (9) rather than glacial erosion.

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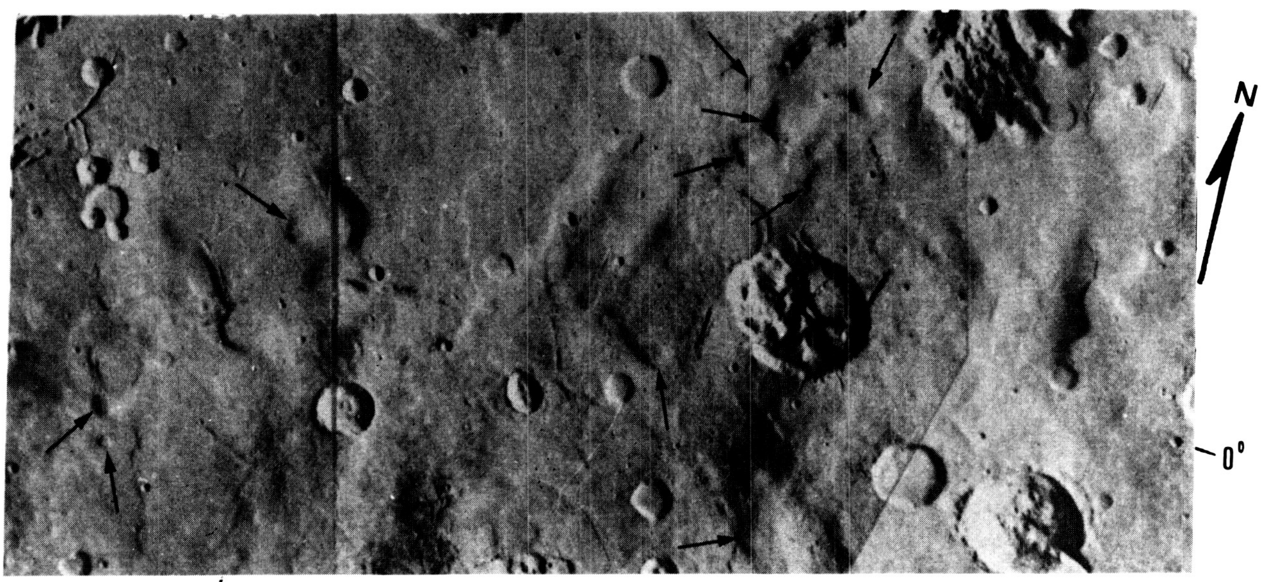

Fig 1 : ice lenses (Hydaspis Chaos)

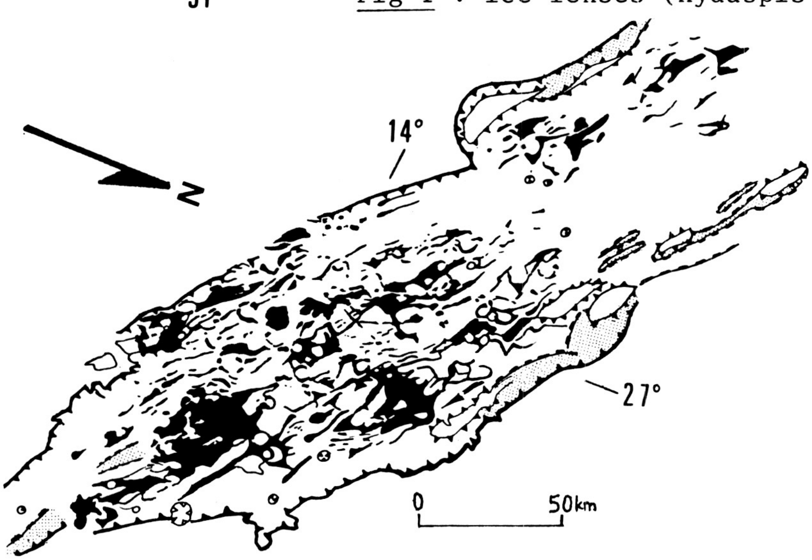

Fig. 2 : alas valley (Ares Vallis)

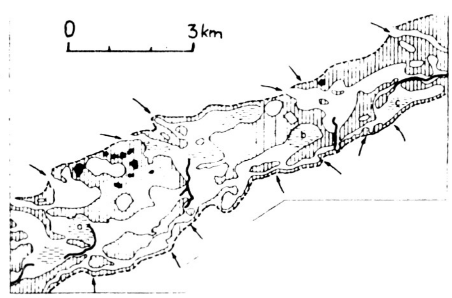

Fig. 3 : Mature alas valley of the river Kocara (after Soloviev)

PSEUDOCRATERS AS INDICATORS OF GROUND ICE ON MARS; Herbert Frey, Geophysics Branch, Goddard Space Flight Center, Greenbelt, MD 20771

In the search for reliable indicators of the past location of surface or near surface volatiles on Mars, pseudocraters (if they exist) would be of direct but limited use. We have previously suggested that the thousands of small (subkilometer) pitted cones which dot portions of the plains-forming units in northern Mars may be volcano-ice analogs of Icelandic pseudocraters (1,2), which on Earth form where lava flows over water or water-saturated ground (3). The steam explosion caused by this interaction is only marginally less efficient if (as is likely on Mars) ice is the volatile(4). Positive identification of martian pseudocraters would therefore be strong indication of past occurrence of ice at or near the surface of Mars.

The basis for suggesting that the small cones on Mars are pseudocraters includes: (a) small size, (b) abundant but patchy distribution on what appear to be volcanic plains, (c) presence of other features suggestive of surface or subsurface ice. (d) morphological similarities to Icelandic pseduocraters, and (e) the similarity in distribution of crater/cone diameter ratios to Icelandic pseudocraters(2). This last morphometric parameter may be the most important, since other possible small terrestrial volcanic analogs have very different crater/ cone diameter ratio distributions(2). In a survey of the available high resolution Viking Orbiter imagery, abundant fields of possible pseudocraters were found in SE Acidalia Planitia, S Utopia-Elysium, W Isidis Planitia and, perhaps, near Hellas (2,5,6). However, only a small fraction of the plains-forming units imaged at high resolution (range $\leq$ 2000 km) were found to contain the small cones: of some 12,200 images searched we found subkilometer cones with central pit on less than 350 (<3%). This low discovery rate, combined with the limited high resoluiton imagery, restrict martian pseudocraters as global indicators of surface or subsurface ice.

There are only minor morphological differences between the subkilometer cones found in Acidalia and those found in Utopia-Elysium-Isidis; more striking is the variation in background terrain on which the cones are found. In Acidalia the cones are found on smooth plains of both uniform and mottled appearance but also on widespread fractured and subdued fractured plains (2,7). The fractured plains are of interest because they may themselves be indicators of ground ice(8). All the plains-forming units on which cones have been found also contain rampart craters, but there are regional differences in the size distributions of these craters which may be interesting (see below). In Acidalia there are general trends in the dimensional and distributional characteristics of the cones which seem to depend on background terrain: the younger plains (which are smooth, not fractured) have a higher density of cones, but the average cone diameter is lower (<700 m) than on the fractured plains (>700 m). Cones on subdued fractured plains(9), which are under-populated in impact craters at the smallest diameters and have soft, incomplete or interrupted fracture patterns, have the largest mean diameters observed and also the highest percentage of widest central craters. Preferential obscuration of small cones and decrease in the observed cone base diameter due to blanketing by dust seems likely (7). This demonstrates another problem with using pseudocraters as indicators of ground ice on Mars: because of their small size they are easily removed or obscured by a variety of erosional processes.

MARTIAN PSEUDOCRATERS AND ICE
Frey, H.

Pseudocraters do have one important contribution to make to the study of the distribution of volatiles in the martian crust. Because of the way they form, they indicate the presence of only surface (or very near surface) ice over which relatively thin lava flows have been emplaced. If the lava flow is too thick, cones will not form as the work required to lift the overlying molten rock becomes greater than that available from the explosion. Likewise, if the ice is buried too deeply beneath an insulating layer, the heat from the lava flow may dissipate before sufficient volatilization of the buried ice occurs(4). Therefore the size of pseudocraters and their spatial density depends on a combination of lava flow thickness and temperature, depth to the ice layer and fraction of ice in mixed layers (soil and ice). Dense concentrations are favored by relatively thin flows over abundant ice close to the surface; more widespread groupings may indicate variations in flow thickness and/or the depth to the (top of the) ice layer.

It would be interesting to compare the spatial density of possible martian pseudocraters with the size frequency distribution of rampart craters (10,11,12,13). Not only could such comparisons help to define the thickness of the ice layer(14), but comparison of rampart and non-rampart crater populations with a varying density of pseudocraters could place temporal constraints on the longevity of the ice-rich layer. For example: in Utopia Planitia where widely scattered small cones occur, rampart craters are rare for diameters < 3 km, but for D > 5 km almost all craters have this structure. Perhaps the small craters formed largely after the near-surface ice vanished. By contrast the rampart craters found in the fractured plains in Acidalia occur at very small diameters in the regions where small cones exist.

Despite the sampling problem, the latitudinal distribution of martian pseudocraters and its comparison with other ice-related features is of interest. In Acidalia Planitia most of the small cones lie at latitudes greater than 38°N, ranging up to 50°N. We find no convincing evidence for such features below ~35°N; however, there is very little high resolution imagery available. No small pitted ones are found in Chryse between 20 and 30°N, even though good imagery does exist (15,2). By contrast small cones are found as low as 10°N latitude in Isidis. These are unusual in their spatial distribution, however, being very densely grouped and often occuring in long chains(2). If these are also pseudocraters, then at the time they formed surface or near surface ice must have existed at this low latitude in eastern Mars.

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WATER-ICE IN THE MARTIAN REGOLITH: EXPERIMENTAL INVESTIGATION OF LITHOLOGIC EFFECTS.

J. L. Gooding, SN2/Planetary Materials Branch, NASA/Johnson Space Center, Houston, TX 77058 USA.

Introduction. Anderson [1] showed that, for clay-sized (< 2-μm) particles of kaolinite- and smectite-group minerals, ice-nucleation temperatures depend on both mineralogy and the water/mineral mass ratio. However, the median particle sizes in the Martian regolith are likely to be in the sand- to gravel-sized intervals [2] and crystalline phyllosilicates might not be very abundant [3]. Accordingly, new experiments were conducted to investigate the freezing and melting of water ice in a natural regolith that evolved in a Mars-like environment but without significant clay-mineral production.

Samples. Bulk sand and gravel material was collected from the upper 8-10 cm of Makanaka glacial-outwash debris near the summit of Mauna Kea, Hawaii. The outwash deposits represent glacial drift that was reworked by minor ouburst floods during the late Pleistocene [4]. Bulk samples were sieved and found to be composed mostly of lithic and mineral fragments derived from basalts, with moderate degrees of weathering [5]. As found previously by Ugolini [6], crystalline phyllosilicate weathering products were rare.

Thermal Analysis. Differential scanning calorimetry (DSC) was conducted with a full-range, Perkin-Elmer Model DSC2C under constant purge of dry carbon dioxide gas, using procedures described elsewhere [7,8]. Samples were held in aluminum containers, heated or cooled between 200 K and 300 K at 5 K/min, and temperatures of principal transitions were measured as defined in Fig. 1.

Results. For silt- and sand-sized fractions, with mass ratios of water/sample = 1, the onset of freezing occurred at 266-267 K whereas the onset of melting occurred at 272-273 K (Fig. 2). For comparison, pure water (in aluminum) undercooled to 256-257 K before onset of freezing. The onset of melting of pure water at 273.16 K served as a temperature calibration point. Therefore, the net effect of the substrate was to raise the freezing-onset temperature (by heterogeneous nucleation) but to lower the melting-onset temperature, relative to pure water. The temperature of melt initiation, defined as the first-inflection limit in the heat-flow curve during melting, was 271-272 K for pure water but was only 269-271 K for the water/sample mixtures. Although melting-onset and freezing-onset temperatures were approximately independent of water/sample ratio, the temperature of melt initiation covaried with water/sample ratio (Fig. 3). Because water-soluble salts were rare to absent in the Mauna Kea outwash soil, colligative-type freezing-point depression cannot explain the nonlinearity of the melting-initiation curve in Fig. 3.

Dependence on Heating and Cooling Rates. The effect of variations in the thermal-cycle rates remains to be investigated. Heating and cooling rates used in these experiments were similar to those used by Anderson [1] but are much greater than should ordinarily occur on Mars. For example, daytime surface heating and cooling rates during Martian summer at the Viking landing sites are on the order of $\leq$ 0.1 K/min [9, 10]. Because temperatures for most endoenthalpic transitions increase with increasing heating rate [11], it might be argued that Mars-like heating rates should lead to melting-initiation and melting-onset temperatures that are even lower than those in Figs. 2-3. For freezing phenomena, though, an inverse effect might occur, with slower Martian cooling rates producing freezing-onset temperatures that are higher than those in Figs. 2-3. However, fast cooling rates might apply to outburst floods and post-cratering emplacement of impact ejecta so that their freezing-onset temperatures might be similar to, or lower than, those suggested here.

Implications for Geomorphic Processes on Mars. Even in the absence of salts, temperatures at which freezing and melting of water occur in the Martian regolith should not be the same as those that apply to pure water. Although Anderson et al. [12] previously made that point for ultrafine-grained, clay-mineral substrates, it is clear that both comparable and contrasting effects occur in sandy "basaltic" regoliths that are poor in phyllosilicates. Fluvial and periglacial geomorphic processes should be affected because the temperature at which ice nucleates in a cold, wet regolith should be the temperature below which fluid flow yields to plastic flow, creep or fracture as the principal form of deformation. Experimental data suggest that wet "basaltic" regoliths that are cooled at moderate rates might remain unfrozen to temperatures of 266 K or lower, and might support fluidized mass movements at faster rates or along greater distances than might otherwise be expected.

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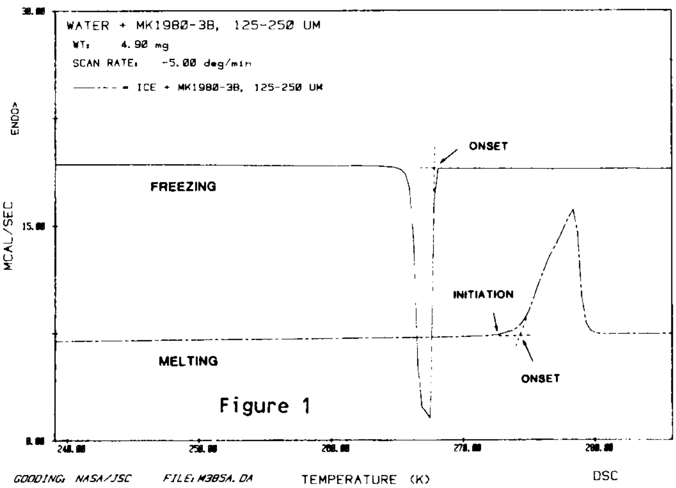

Figure 1

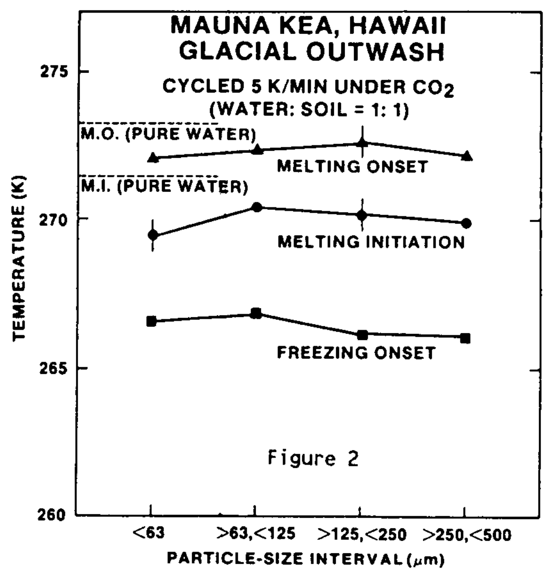

Figure 2

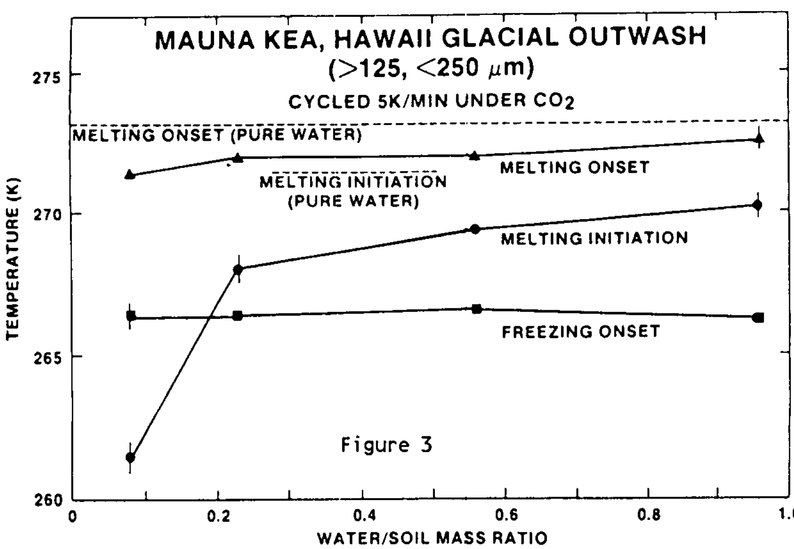

Figure 3

IMPLICATIONS FOR SUBSTRATE VOLATILE DISTRIBUTIONS ON MARS FROM COMPLEX CRATER MORPHOLOGY AND MORPHOMETRY. W. S. Hale-Erlich, Amoco Production Company, New Orleans, LA. 70150

The central structures found in complex impact craters on Mars include uplifts (central mountain peaks), depressions (floor pits), or a combination of these (peaks with summit pits) (1-3). The presence of depressions or pits as central structures, as well as fluidized ejecta deposits around these craters, have been attributed to interaction of the crater-forming process with a volatile component the martian substrate (4). Central structures in impact craters consist of materials from stratigraphic positions well below the target surface, and sampling depth increases with increasing crater rim diameter (6). Fluidized ejecta deposits may occur due to inclusion of volatiles in the primary ejecta cloud during crater excavation, and/or secondary entrainment of local near-surface volatiles during ejecta blanket deposition (4). Thus central structure morphology and morphometry, coupled with ejecta morphology, may provide the best estimate of variations in volatile content laterally and with depth in the martian substrate. Such variations in volatile content with latitude, substrate or terrain type (2,4) and depth (2,5) have been proposed. This contribution summarizes a study of all fresh complex impact craters for 75% of the martian surface to determine variations in these crater attributes with substrate (terrain), latitude and crater rim diameter (Drc). Data was collected for 2113 complex craters on all terrain types (7) and at most latitudes ($+90^{o}$ to -65^{o}).

Variations with Drc (Depth) - Central peak (Dcp) or pit (Dp) diameter and Drc were recorded for each crater. Statistical analyses defined power-law relations for Dcp/Drc (Figure 1) and Dp/Drc (Table 1). At Drc>60 km, Dcp is larger for a given crater diameter on Mars than on the Moon or Mercury. Pits (floor or pitted peaks) and fluidized ejecta deposits occur primarily where Drc = 20-55 km. At Drc>70 km, the Dcp/Drc relation is comparable to that for lunar and mercurian craters, ballistic ejecta types (4) predominate (Figures 2,3) and pits are extremely rare.

Regional Variations - Central peaks occur in 69% of the complex craters studied. They are the dominent central structure type on all terrains except Elysium lavas, although pits occur in some craters on all terrains. No consistant increase in pit frequency with latitude was found. Similarly, fluidized ejecta deposits are found at similar frequencies at all latitudes and on all terrain types. Central peaks occur in craters with fluidized as well as ballistic ejecta, as do pits.

Discussion - If the formation of pits and fluidized ejecta deposits requires the presence of substrate volatiles, the lack of strong dependances between the frequency of occurrance of these features with terrain or latitude argues for a global distribution of these volatiles. The predominince of pits as central structures, and fluidized ejecta deposits, at Drc<55-70 km suggests that these volatiles may be confined to depths sampled by craters within this diameter range, and the presence of relatively reduced central peak diameters, depth/diameter ratios (5), and a ballistic ejecta component for Drc> 60 km supports this hypothesis. This depth may be roughly constrained by present apparant crater depths (5,8) and terrestrial central uplift sampling depths (6) to between 2.5-6.5 km.

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FIGURE 1 : Dashed lines are

1 standard deviation

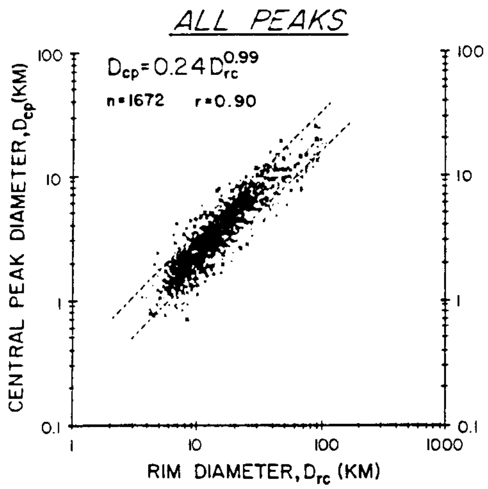

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Table 1: Morphometric relationships for craters on Mars (this study) and for the Moon and Mercury (data from Hale and Head [1979, 1980]).

Relation	Sample n	Slope (t)	Intercept (m)	Corr. Coeff.	Std. Dev.
Mars					
Floor diameter/Rim diameter	2220	1.09	0.47	0.98	0.05
Peak diameter/Rim diameter	1672	0.99	0.24	0.90	0.11
Fluidized ejecta.	1261	1.08	0.19	0.89	0.11
ballistic ejecta:	107	0.87	0.33	0.87	0.38
Pit diameter/Rim diameter	661	0.97	0.14	0.86	0.12
Floor pits:	441	1.01	0.14	0.92	0.09
Summit pits:	220	0.99	0.11	0.84	0.11
Peak ring diameter/Rim diameter	33	1.19	0.16	0.98	0.05
Moon/Mercury					
Peak diameter/Rim diameter	315	0.94	0.26	0.87	0.26

FIGURE 2

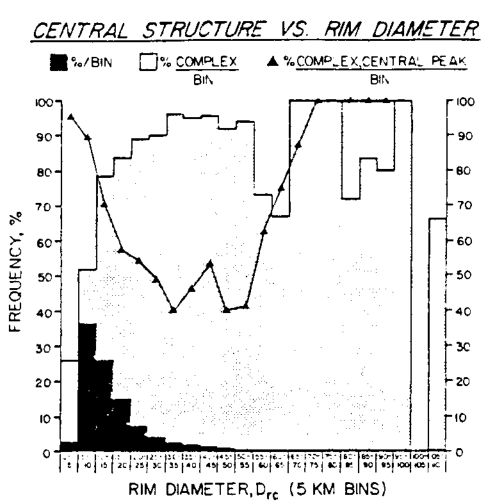
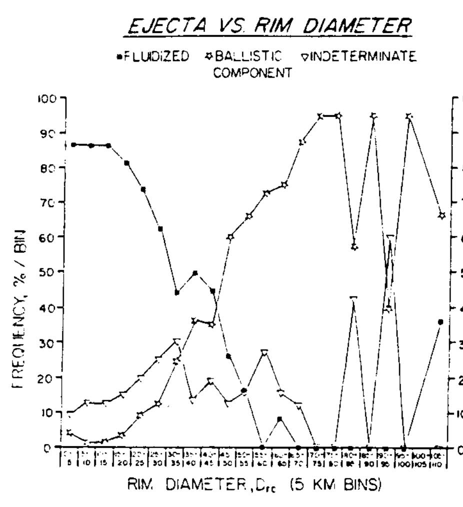


FIGURE 3



EFFECTS OF ELEVATION AND PLAINS THICKNESSES ON MARTIAN CRATER EJECTA MORPHOLOGIES FOR THE RIDGED PLAINS; V. M. Horner and R. Greeley, Dept. of Geology, Arizona State University, Tempe, AZ 85287

The effects of elevation and ridged plains thicknesses on martian crater ejecta morphologies have been investigated as part of a study of the relationship between crater ejecta characteristics and properties of planetary surfaces. This study incorporates several new supporting data sets: the 1:2M Viking photomosaics, Earth-based radar altimetry for the martian equatorial region (1) and preliminary Viking-based regional geologic maps (2,3). Early work involving a limited number of Viking frames indicated a decrease in ejecta extent and a shift towards lunar-like ejecta morphologies with increasing elevation (4). A later study, in which the revised elevation data were used (5), yielded no correlation between ejecta extent and elevation within the ridged plains, but no distinctions were made among ejecta morphologies. We show here a slight relationship between the distribution of ejecta morphologies and elevation, and a stronger relationship between the distribution of ejecta morphologies and ridged plains thicknesses.

367 fresh craters on the ridged plains unit were measured and classified from individual Viking frames used for the 1:2M photomosaics (resolution ~130-230 m/pxl). Mouginis-Mark's and Blasius and Cutts' ejecta classes were used to identify ejecta morphologies (4,6). An additional morphology was identified in this study: ejecta with one complete lobe around the crater and a partial outer lobe was designated as type SD (see fig. 1). Geologic unit, crater size, and latitude (0° to ±25°) were controlled in this study so that correlations between ejecta morphology and elevation could be more easily detected.

There appears to be a slight correlation of ejecta morphologies with elevation. For crater diameters (D_c) = 5-10 km, the single-lobed rampart type (SR) predominates at all elevations, but the percentage of both the partial outer-lobed (SD) and double-lobed (D) morphologies increases at high elevations. In addition, type SD ejecta is found more often than type D at high elevations. For D_c= 10-40 km, the only statistically significant change in ejecta morphologies with elevation is in the relative occurrence of ejecta types SD and D. At low elevations, type SD is found more often, yet at high elevations type D predominates. Regional studies within Lunae Planum show that the onset diameter for both ejecta types decrease with increasing elevation, and that within a given elevation range, the diameters of craters with SD ejecta are almost always < the diameters of craters with type D ejecta.

The change in ejecta morphologies with elevation may be best explained by a decrease in the thickness of Lunae Planum, where about half the data were obtained, with increasing elevation. For a given impact energy, increasingly complex ejecta morphologies would result from increasing atmospheric density (7). If differences in ejecta morphologies with elevation result mainly from changes in the degree of atmospheric drag effects, atmospheric density would have to increase with elevation to explain the current observations. It has also been suggested that double-lobed ejecta results from an impact into a target with a volatile-rich lower horizon (8). To explain the observations, the depth to this layer would have to decrease with elevation, and there is no *a priori* reason why this should occur at a given latitude. A third possibility is that our results mainly reflect a general decrease in the thickness of the Lunae Planum ridged plains with elevation. This is supported by a plot of our data with respect to thickness variations within Lunae Planum (9) and Hesperia Planum (10).

Figure 1 shows the relationship between ejecta morphology and ridged plains thicknesses. For three crater diameter intervals, ejecta morphologies become less complex as plains thickness increases. Simple ejecta morphologies dominate for large plains thicknesses and small crater sizes. For intermediate thicknesses and crater sizes, ejecta type SD predominates, progressing to types D and MR with increasing crater size and/or decreasing plains thicknesses. (The occurrence of type SS is mainly a function of latitude.) Factors which may affect the observed relationship include estimated errors in thickness contours (9,10), and the small number of usable rim heights in the study (9,10), so that local ponding or thinning of ridged plains material in some areas would be undetected.

It is also possible that changes in ejecta morphology with mapped ridged plains thicknesses represent changes in the abundance of subsurface volatiles. Different geologic units have different capacities for volatile storage; thus changes in the depth to the contact between the ridged plains and lower units may also represent changes in the depth to a transition in subsurface volatile content.

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A

B

C

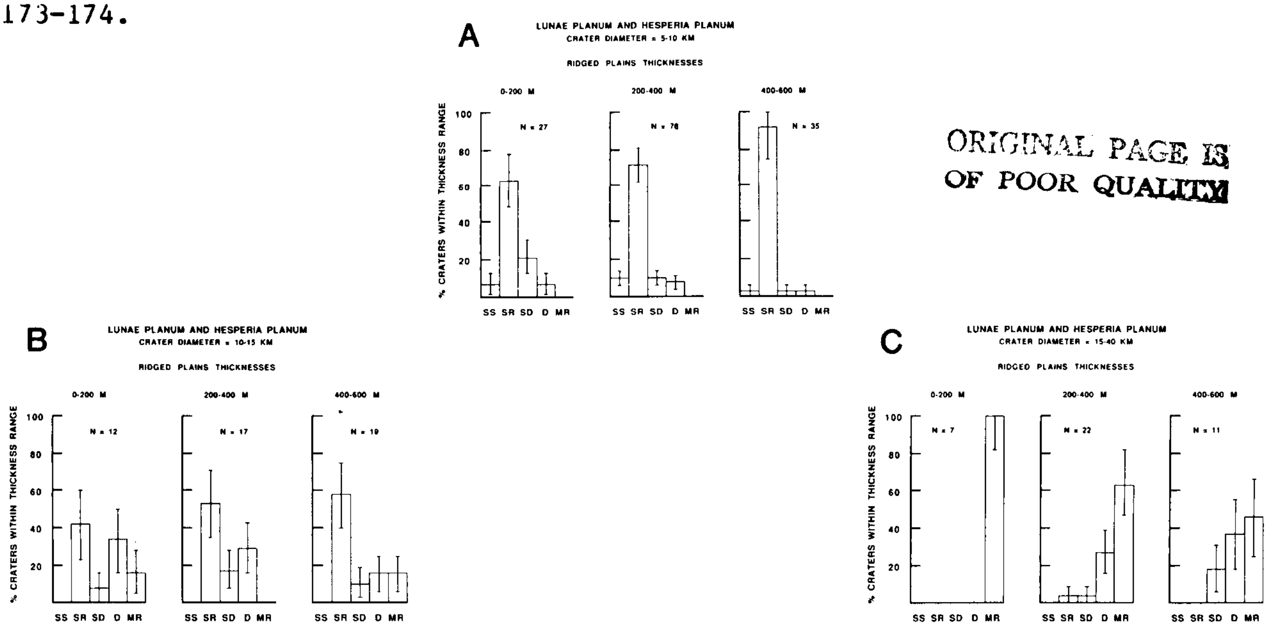

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Fig. 1 - The relationship between ejecta morphology and ridged plains thicknesses for Lunae Planum and Hesperia Planum, for A) D_c= 5-10 km, B) D_c= 10-15 km, and C) D_c= 15-40 km. SS= single-lobed, scarped terminus, SR= single-lobed, rampart terminus, SD= full inner lobe, partial outer lobe, D= two complete lobes, MR= multilobate. Thicknesses taken from (9,10).

ARCUATE GROUND UNDULATIONS, GELIFLUXION - LIKE FEATURES AND "FRONT TORI" IN THE NORTHERN LOWLANDS ON MARS - WHAT DO THEY INDICATE?

H.-P Jons, Geol. Institut, TU, 3392 Clausthal, W. Germany

An analysis of the relief of the Northern Lowlands on Mars led to the discovery of numerous relief elements which occur exclusively in this area. Among these features are polygons (?desiccation cracks;?settlement cracks) which are widely distributed between 20^{0} and 60^{0} lat. This area has been interpreted as a very large sedimentary basin (1,2). Its southern boundary is indicated by a narrow zone (up to ca. 150km wide) of unique morphologic features which form three sub - zones:

a) a sub - zone of arcuate ground undulations;
b) a sub - zone of tongue-shaped mud flows(?) or gelifluxion - like features together with
c) "front tori" (see Fig. 1).

Detailed investigations led to the result that these zones can be traced around the whole planet within the Northern Lowlands, with the exception of two larger gaps. (One gap is situated in the vicinity of the Lyot impact which is obviously younger than the last outflow event(s) and the other one is situated north of the Elysium volcanoes.) Moreover, these features (including the polygons) can be traced back into the mouth area and into the channels of the large outflow channels Ares-, Tiu-, Simud-, Maruth Vallis. This spatial distribution permits the assumption that during the last (catastrophic?) outflow event(s) a huge amount of aqueous slurry was released by these valleys into the Northern Lowlands where it probably formed a shallow circumpolar mud ocean. After its emplacement this material soon froze and/ or desiccated which resulted in the origin of the polygons. The southern "shoreline" of the proposed mud ocean is probably indicated by the set of special features which has been described above.

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ARCUATE GROUND UNDULATIONS

Jons, H.-P.

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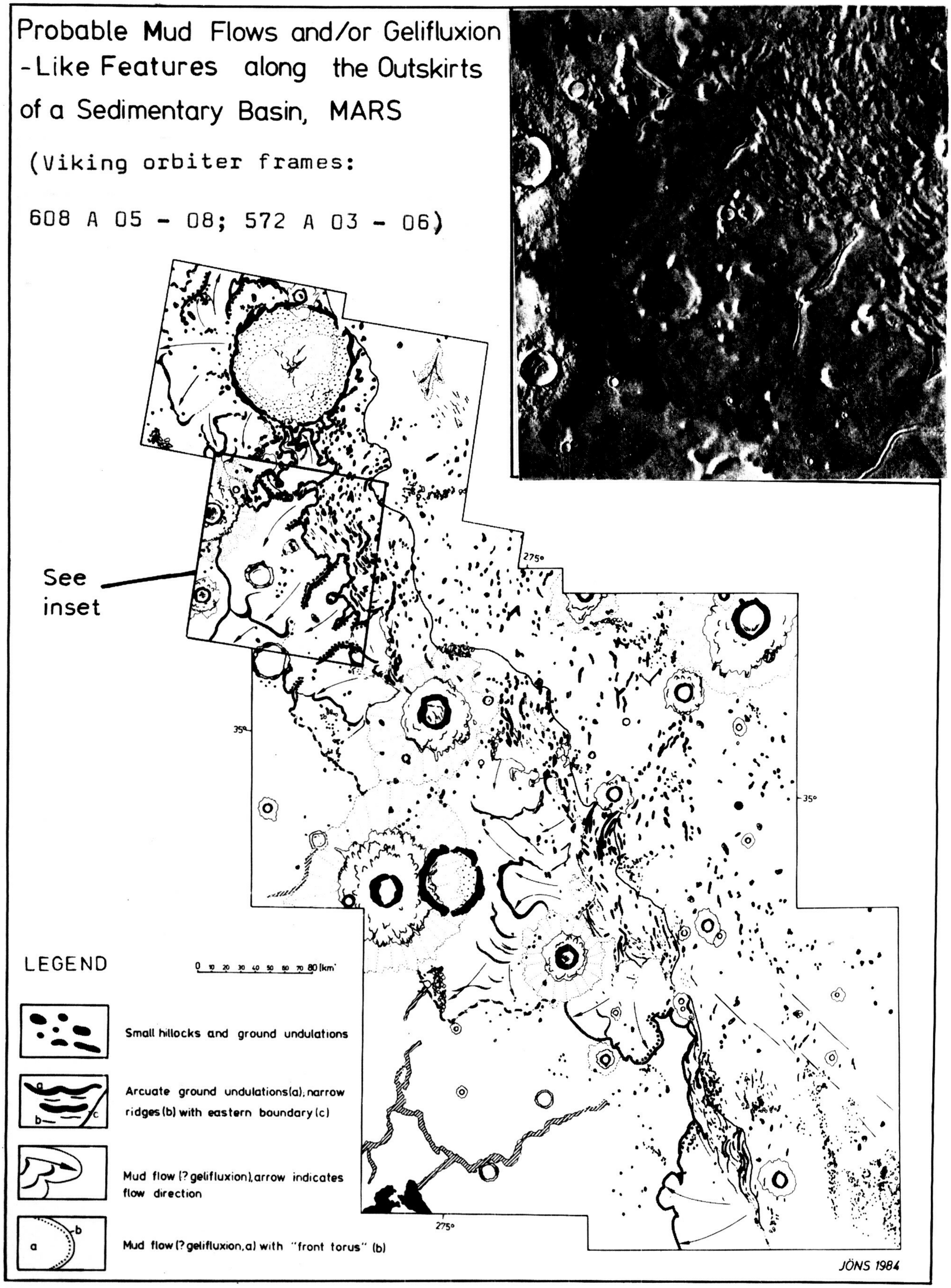

MORPHOLOGIC VARIATIONS OF MARTIAN RAMPART CRATER EJECTA AND THEIR DEPENDENCIES AND IMPLICATIONS; J.S. Kargel, Dept. of Planetary Sciences, Univ. of Arizona, Tucson, Arizona 85721

Johansen[1] reports observations indicating that the morphology of Martian rampart crater ejecta varies considerably with latitude. She finds that Martian rampart craters can generally be classified into two major descriptive types. The predominantly low latitude "water-type" ejecta morphology typically includes a sharp ejecta flow-front ridge and a highly crenulated, lobate flow-front perimeter; the higher latitude "icy-type" ejecta morphology lacks a sharp distal ridge and has a more circular perimeter. On the other hand, Mouginis-Mark[2] concludes that no correlation of rampart ejecta morphology with latitude exists if one excludes his "type 6" pedestal craters[3]. These contrary conclusions are each based on global surveys of Martian rampart craters using two different qualitative ejecta morphology classifications. This study is intended to approach this controversy in a more quantitative way.

The presence or absence of a distal ridge on an ejecta flow is the most distinguishing feature of the "icy" and "water" types of rampart ejecta, but this feature is difficult to quantify. The lobateness of the perimeter is more easily quantified. Here, lobateness is defined as Γ = (ejecta flow front perimeter)/(4π(flow area))$^{\frac{1}{2}}$. Note that Γ is similar to the H employed by Woronow and Mutch[4]. $\Gamma = 1$ for a circular ejecta flow front, with no upper limit for more circular ejecta. Few craters have Γ greater than 1.6. Similarly shaped ejecta blankets of different sizes have identical values of Γ.

In this study, Γ, crater size, latitude, longitude, elevation[5], and geologic unit[6] were determined for 538 rampart craters using 1:2 million scale USGS photomosaics. The geographic distribution of analyzed craters is shown in Figure 1. The chief selection criterion required a minimum of about 90% of an ejecta perimeter to be well delineated and uneroded; this criterion was relaxed somewhat at high latitudes, where poor image quality and extensive erosion and mantling reduce the sample size. This rigid criterion automatically introduces a sharp bias against the cratered highlands. No craters were rejected on the basis of circumstances such as oblique impact, diversion of the flow around obstacles, or local inclination of the surface. For multi-lobed craters, only the most complete and visually prominent lobe was analyzed.

Figure 2 shows that for low latitudes Γ depends strongly on crater size. High latitude craters show a similar though less clear size dependency. The size dependency of Γ for all craters taken together is about 0.025 per kilometer of crater diameter. This size dependence could be due entirely to a sensitively stress-dependent (and therefore scale-dependent) rheology of the flows, or to the dynamics of the excavation process; but perhaps also involved is the possibility that larger craters penetrate deeper into a water-rich layer that may underly an ice-rich permafrost[8]. Large craters may tap into abundant water, yielding highly fluid ejecta, whereas small craters may tap only into permafrost; these small impacts may melt and vaporize only a small fraction of the cold ice, yielding more viscous ejecta.

Figures 3a, b, and c quantitatively confirm Johansen's[1], and Blasius' et al.[7] observations that ejecta morphology varies with latitude, with the apparently lower viscosity, highly lobate "water-type" flows occuring generally at low latitudes, and the apparently higher viscosity, more nearly circular "icy-type" ejecta occurring at mid and high latitudes; the transition from more lobate to less lobate is gradational in the vicinity of ± 20° to ± 35°, consistent with Johansen's[1] findings. Narrow crater size bins are employed in Figure 3 and Table 1; then crater size is eliminated entirely as a free parameter by normalizing each data point to a common crater diameter using the 0.25/km size dependence. This latitudinal dependence can best be interpreted as indicating an ice-bearing permafrost layer that thickens towards high latitudes, underlain by a water-bearing layer that is more accessible to impacting objects at low latitudes. This observation also argues against long-term deviations from the present rotational axis[9] during Amazonian or Hesperian times, unless these deviations were smaller than about 20°.

Contrary to the observations of Mouginis-Mark[2], Γ is not dependent on elevation. That observation was probably due to the inclusion of generally low-elevation pedestal craters in the data set[3].

Table 1 suggests that there is little or no geologic control on Γ. When high latitude and low latitude craters are considered separately, terrains of greatly varying age and characteristics possess craters with similar values of Γ. This tentative result suggests a roughly constant Martian climate through Amazonian and into Hesperian times, and roughly uniform volatile contents of diverse geological materials. However, initial indications are that modest excursions of the climate might be revealed by more detailed geologic and morphologic analysis.

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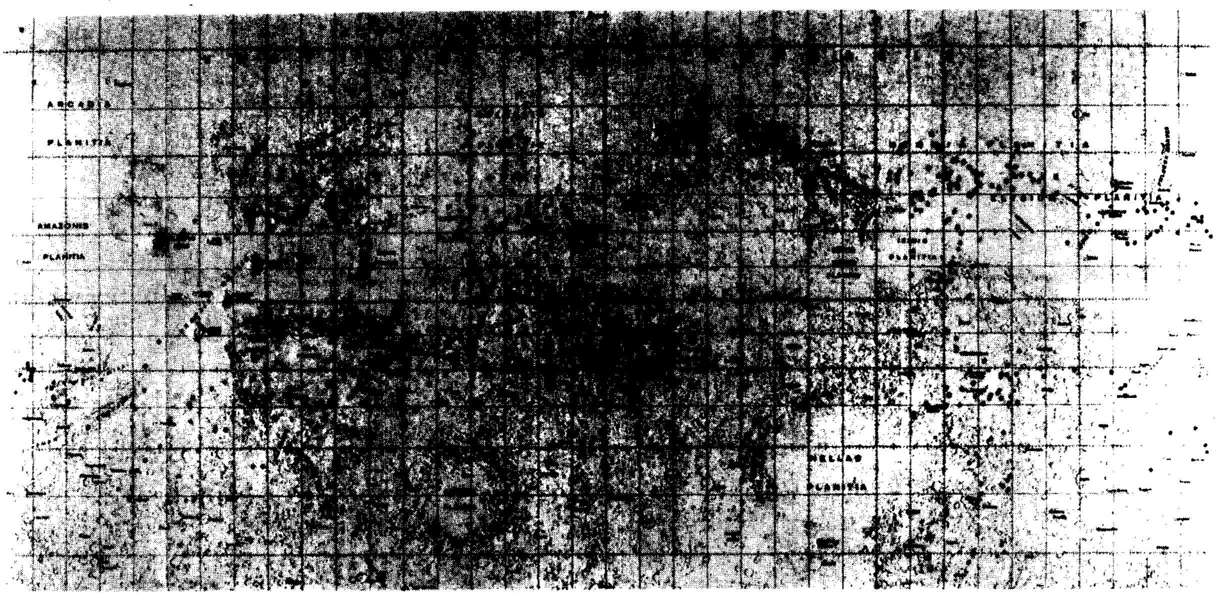

Figure 1. Locations of analyzed craters, except for those at latitudes $> \pm 65^{\circ}$.

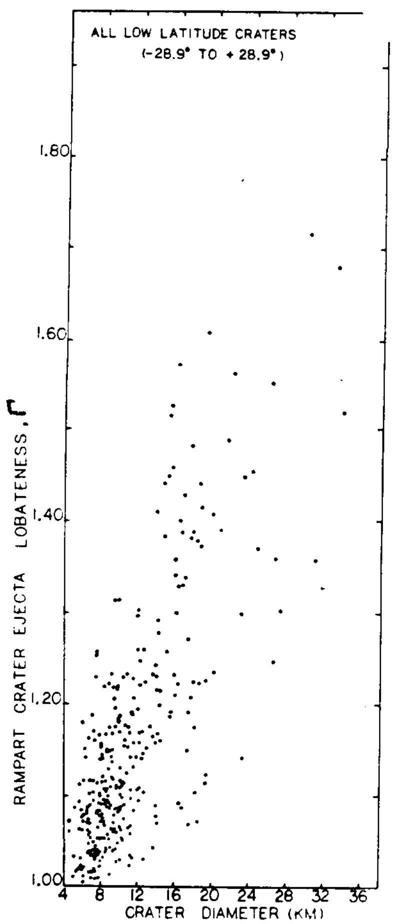

Figure 2. Size dependence of ejecta lobateness. Error in $\Gamma \pm .03$.

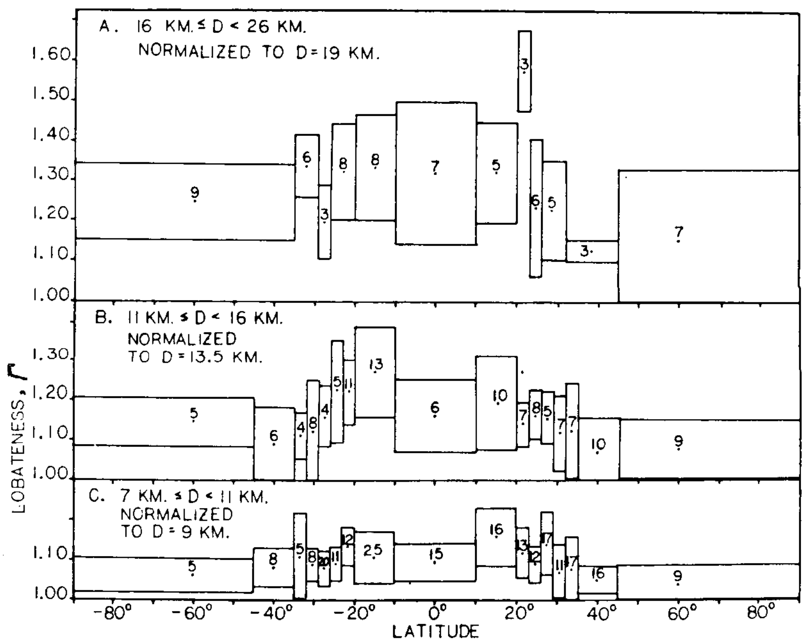

Figure 3. Latitudinal dependence of ejecta lobateness. Boxes give 1σ dispersion (not error) of Γ and width of latitude bins. Also given are numbers of samples and mean Γ (dots). Normalizations discussed in text.

Table 1. A comparison of the lobateness of crater ejecta on various terrains for craters with 10 km $\leq D < 20$ km. Also given are numbers of samples and 1σ natural dispersions (not error) of Γ.

	Cratered terrains, Nhc + Nplc	Mottled Plains, Npm	Ridged Plains, Hprg	Rolling Plains, Hpr	Amazonian Plains, Apt, Apc, Aps
High Latitude ($\geq \pm 30^{\circ}$)	$1.130 \pm .078$ (N=25)	$1.118 \pm .127$ (N=20)	$1.121 \pm .095$ (N=16)	$1.102 \pm .080$ (N=7)	$1.132 \pm .095$ (N=25)
Low Latitude ($< \pm 30^{\circ}$)	$1.174 \pm .113$ (N=23)	No Npm; not applicable	$1.205 \pm .094$ (N=52)	$1.163 \pm .100$ (N=7)	$1.205 \pm .111$ (N=46)

MORPHOLOGY OF LARGE VALLEYS ON HAWAII: IMPLICATIONS FOR GROUNDWATER SAPPING AND COMPARISONS TO MARTIAN VALLEYS

R. Craig Kochel and Jonathan O. Piper, Department of Geology, Southern Illinois University, Carbondale, Illinois 62901

Stream channels draining the windward slopes of the islands of Hawaii, Maui, and Molokai display greatly variable degrees of dissection relative to their leeward counterparts. Leeward slopes are slightly dissected with numerous high density channel networks developed in parallel arrangement. Windward channels are dominated by deeply dissected valleys having broad U-shaped cross-sections and amphitheater headward terminations (Fig. 1). It is unlikely that the asymmetry of rainfall-runoff between opposite sides of these volcanoes can account for these differences alone, especially since dissected valleys occur on windward slopes as well. Groundwater sapping processes are suspected to play a major role in explaining the morphology observed in deep Hawaiian valleys. The contribution of groundwater to the formation of large Hawaiian valleys was discussed by early workers (1, 2). They noted the apparent coincidence of dike swarms with headward terminations of large valleys and suggested that once surface runoff incision proceeded to depth where it intersected perched dike water, the influx of groundwater caused dramatic increases in the rate of valley enlargement.

Evidence supporting the importance of sapping comes from a combination of studies of imagery and topographic maps, field observations, and laboratory experiments. Drainage basins were outlined on 7.5' topographic maps from which morphometric measurements were made. Table 1 summarizes the trends of these studies. Principal components analysis of the morphometric data showed that valleys could be distinctly separated on the basis of morphometry (i.e., Fig. 2 shows first principal component).

Field reconnaisance of several valleys verified the significance of groundwater discharge into the large valleys. Valleys appear to be retreating headwardly by plunge pool erosion at valley-head waterfalls combined with basal sapping and associated mass wasting of headwalls. Plunge pool erosion appears to have been minor. Large discharge springs occur at the base of valley heads, even in valleys without waterfalls or where falls were diverted by upstream irrigation tunnels. Piracy of groundwater flow has played a major role in the development of these sapping valleys, much as it does in the evolution of surface runoff networks.

Finally, experimental studies of groundwater sapping processes in unconsolidated sediments (3) provide useful analogs to the Hawaiian channels. The effect of a sudden increase in groundwater contribution to a channel system was mimicked with the use of stratigraphic variations in sediments of varying hydraulic condivity. Surface channels were established on a smooth slope by groundwater sapping through the sediments from a headward reservoir. A more permeable and porous medium was put in the headward area of the slope which was progressively tapped as sapping channels cut headwardly. The rate of channel widening and extension increased significantly after the headward aquifer was tapped. These experiments and others in progress lend support to the model of increased dissection in the Hawaiian valleys caused when channels incised to the level of perched dike waters near the volcano summits. Widening of the headward portions of the large valleys on Kohala (Fig. 1.) by subsurface piracy is similar to the valley head widening that occurred in experimental runs at the level of the major aquifer. The

Hawaiian and experimental valleys bear many morphologic and morphometric similarities to valleys along the slopes of Valles Matineris on Mars, also thought to have been influenced by sapping processes.

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(3) Kochel, R.C., Howard, A.D., and McLane, C., 1985: in Woldenberg, M.J., ed., Models in Geomorphology, New York, Allen and Unwin, p. 313-341.

TABLE 1. COMPARISON OF RUNOFF-DOMINATED AND SAPPING-DOMINATED VALLEYS ON KOHALA VOLCANO

CHARACTERISTIC	RUNOFF-DOMINATED	SAPPING-DOMINATED
Basin shape (K)	extremely elongate	light-bulb shaped
Head terminations	tapered, gradual	amphitheater, abrupt
Trend of channel segments	uniform	variable
Downstream tributaries	frequent	rare
Local relief (R2)	low	high
Drainage density (TDD)	high	low-canyons high-plateaus
Drainage symmetry	symmetrical	asymmetrical low down-dip
Canyon area/basin area (BCR)	low	high
Junction angle (MJA)	lower	higher

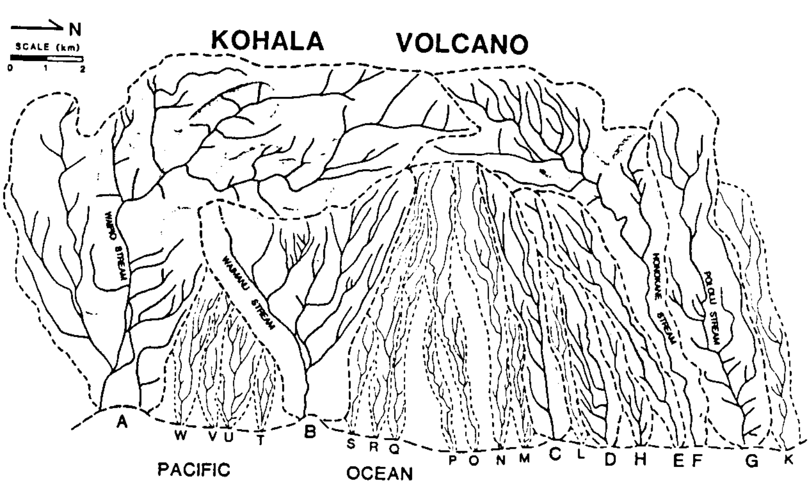

Fig. 1. Drainage networks on northeast Kohala A-G are deep valleys influenced by sapping. A,B,F,G are enlarging today. C,D,E,B may not be enlarging due to upslope piracy by A and F. H-W have negligible sapping.

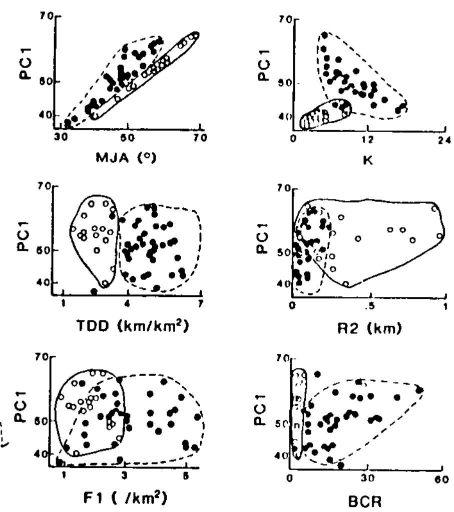

Fig. 2. Principal components analysis for 53 valleys on Molokai and Kohala. Dots are runoff valleys, open circles are sapping valleys

NORTHERN SINKS ON MARS?; B. K. Lucchitta, H. M. Ferguson, and Cathy Summers, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, Ariz. 86001

Most of the large outflow channels on Mars debouch into the northern plains. Despite deliberate searches, however, deltaic or sedimentary deposits have previously eluded detection. Recently, McGill [1,2] has proposed that the polygonally fractured terrain in the northern plains may be composed of sedimentary layers transported there through the outflow channels. The following observations support McGill's hypothesis.

Fractured ground and associated landscapes of disintegration (chaotic and hummocky terrains) are common in low areas on Mars. A low area in the center of Candor Chasma (lat -7°, long 73°) received outwash from several landslide lobes. This area is occupied by flat-lying ceposits that embay the surrounding terrain and have a surface texture of plateaus and hummocks traversed by numerous cracks. Surfaces of two other smaller low spots in eastern Candor Chasma have a similar texture. These cracked surfaces appear to have been developed in sedimentary deposits composed of outwash from landslides that was charged with water [3]; the cracks may have developed when the deposits froze. If the deposits had a large content of ice, its disintegration may explain the later chaotic collapse of some of these deposits [4]. The major area of chaotic terrain in Margaritifer Sinus (lat 0°, long 20°) occupies a regional depression between the Tharsis bulge to the west and cratered highlands to the east. This low area received ancient drainages [5,6,7], which may have left water-rich alluvial deposits that fractured upon freezing. (The outflow channels emerged later from collapsed areas in this terrain.) The occurrence of fractured terrains in low areas that have apparently received influx of liquid materials supports the contention that cracked terrain preferentially developed on sedimentary deposits that contained water or ice.

The polygonally fractured ground in the northern plains occurs in low reentrants of the northern plains projecting into the southern highlands (fig. 1). One reentrant is in Acidalia Planitia (fig. 1, hachured area west of long 355°), another in Utopia and Elysium Planitiae (fig. 1, hachured areas east of long 275°). Polygonally fractured deposits in the reentrants drape over as much as 4 km of relief and only locally occupy the lowest areas of the northern plains. The coincidence of low reentrants and polygonally fractured deposits is consistent with the hypothesis that the deposits are sediments transported into the reentrants from the adjoining highlands. However, it is more difficult to explain why the fractured deposits drape over a surface of considerable relief and are not everywhere deposited in the lowest areas of the northern plains. The deposits may have been laid down as subaerial fans or in standing bodies of water. The uniformity of the deposits, however, argues against their emplacement as fans, which would have filled different areas successively. A standing body of water, depositing sediments from higher levels, would have had to be 4 km deep, an unlikely proposition on Mars. However, if the depositional surface was later warped, a hypothetical body of water could have been much shallower. Postchannel warping may indeed have occurred on Mars: in the Chryse region, channels at lat +15°, long 35° cross a depression 2 to 3 km deep (U.S. Geological Survey, 1:15 million-scale topographic map, unpub. data).

Channels debouch into the reentrants that contain polygonally fractured ground (fig. 1). The reentrant in Acidalia Planitia is surrounded on the south by the mouths of the Chryse channels--Kasei, Maja, Tiu, Simud, Ares, and Mawrth Valles. The Elysium channels--Hebrus, Granicus, Tinjar, and Hrad Valles--debouch into the reentrant in Utopia and Elysium Planitiae. Several grabens that evidence modification by water also trend toward Utopia Planitia. A genetic link between channels and polygonal deposits is further suggested by their similar ages. On the new geologic map of Mars by Scott and Tanaka [8,9], the polygonally fractured deposits and the Chryse and Elysium outflow channels are considered to be late Hesperian and early Amazonian in age.

Sinuous ridges within elongate depressions are abundant near the mouths of the Chryse channels in Acidalia Planitia and in front of the highland scarp in western Utopia Planitia (fig. 1). The ridges (0.5 to 1 km wide) are similar in size and form to ridges at the mouths of ice streams and in ice shelves in Antarctica [10]. Sinuous ridges at the mouth of Ares Vallis [11] resemble ridges on the Rutford Ice Stream and elsewhere in Antarctica, where the floating ice is diverted by shoals [12]. Ridges in depressions are also found where floating ice streams converge. The striking similarity between these Antarctic ridges and those on Mars suggests that material transported through the mouths of Martian outflow channels had characteristics similar to those of floating Antarctic ice streams; the reduced energy regime at the mouth of Martian channels may have permitted their partial freezing. The location of the ridges in front of the Martian highland scarp is similar to the location of the ridges in front of the Antarctic continent, where the bordering ice-shelf ocean is shallow and shoaly. The similarity suggests that the Martian highlands were locally bordered by frozen materials that had mechanical properties similar to Antarctic ice shelves.

Under present Martian surface conditions, pure water would be frozen solid. Yet, if our interpretations are correct, liquid water beneath ice sheets caused them to flow like ice shelves and to deposit sediments from outflow channels. Two conditions would have permitted the occurrence of liquid water in the northern plains: (1) Mars' climate was warmer until late Hesperian or early Amazonian time, or (2) the water was extraordinarily briny. Brass [13] suggested possible brines for Mars and gave their freezing temperatures. Alkali-chloride brines would freeze at 250 K, $MgCl_2$-alkali-chloride brines would freeze at 218 K, and $CaCl_2$-$MgCl_2$-alkali-chloride brines would freeze at 215 K. At lat ±30° these three brines would produce, respectively, an ice cap 3 km thick, an ice cap 300 m thick, and no ice cap at all [14].

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NORTHERN SINKS
Lucchitta, B. K., Ferguson, H. M., and Summers, Cathy

In summary, several lines of evidence converge to support the hypothesis that the polygonally fractured ground in the northern plains of Mars developed in sinks, on sediments derived from the Martian channels. Some characteristics of the deposits and similarities to Antarctic ice shelves suggest that deposition was in a standing body of water.

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Figure 1. Location of polygonally fractured ground (hachures), channels (arrowed lines), and sinuous ridges (black areas). Highland boundary shown as solid black line; alternative boundary delimiting outliers of cratered highlands shown as dashed lines. Base is shaded-relief map of Mars.

THE ROLE OF FLUIDIZATION IN THE EMPLACEMENT AND ALTERATION OF THE SUEVITE IMPACT MELT DEPOSIT AT THE RIES CRATER, WEST GERMANY: H.E. Newsom, G. Graup*, T. Sewards and K. Keil, Institute of Meteoritics and Department of Geology, University of New Mexico, Albuquerque, NM 87131, USA. *Max-Planck-Institut für Chemie, Saarstr. 23, 6500 Mainz, West Germany.

The emplacement and alteration of impact ejecta has important implications for the formation of regoliths and soils on planets. Examination of suevite (impact melt breccia) at the Ries crater, especially the fresh outcrops at the Otting quarry outside of the crater, reveals an abundance of vertical degassing pipes, which have only been briefly mentioned in the literature. A new search at other outcrops of the suevite revealed that they are widespread, although their abundance varies. The number and width of degassing pipes at the Otting outcrop were measured in 36 2-m-wide sections. Most of the pipes are 2 to 4 cm wide and the pipes occupy 5 to 10% of the upper portions of the outcrop. The size and number of pipes decreases toward the base of the suevite. Within the pipes, the fine grained matrix of the suevite has been removed, leaving coarser fragments that are coated with a layer of light brown clay. The smaller pipes are cylindrical, whereas the larger ones are planar, and all are oriented vertically. At the centimeter scale, the pipes deviate from vertical to go around larger inclusions in the suevite. Similar pipes are observed in ignimbrites [1].

The role of fluidization in the formation of degassing pipes in volcanic ignimbrites is shown by the experimental work of Wilson [2,3]. The effect of gas pressure on the poorly sorted mixture of irregularly shaped particles starts at low gas pressures with no expansion of the material, and the ejection or elutriation of fines cannot occur except at the very surface. At some higher gas pressure, the particles become partially supported by the gas and the deposit partly expands. A maximum pressure can be reached at which an instability occurs and part of the gas flow is concentrated into discrete channels or degassing pipes from which the fines are ejected. A possible internal gas source is the release of steam from the shock heated and melted clasts. Vesicles are common in glass bombs in the suevite. External gas sources are also possible: 1) Gas trapped during the formation of the flow. 2) Air incorporated at the front of a moving flow. 3) Gases released by combustion of vegetation and heating of surface water and groundwater. Heating of groundwater is a possibility, but the suevite at Otting sits on top of 45 m of clay-rich bunte breccia ejecta deposit. Heating of groundwater could have been important in the crater suevite, because groundwater would flow rapidly into the crater. However, our only data on the crater suevite come from drill cores, and degassing pipes have not been described in these samples. The lack of surface soil in the channels can also be explained by fluidization. For poorly sorted samples, Wilson [3] indicates that an upper fines-rich layer is produced by elutriation and is always vigorously fluidized. Bubbles emanating from segregation channels in the underlying material agitate the layer, preventing the channels from penetrating to the surface and sealing the pipes from later surface contamination.

A scenario for the emplacement and alteration of the Ries ejecta is as follows: The lower bunte breccia was emplaced relatively cold and is probably equivalent to the continuous ejecta blankets observed on the Moon.

The suevite deposit contained a significant amount of heat and was emplaced on top of the bunte breccia, but did not incorporate any of the lower deposit. The degassing pipes indicate that the suevite was significantly fluidized after deposition on the bunte breccia. The suevite may represent the fraction of impact melt and ejecta lofted inward and upward by the air flow field produced by the refilling of the hole in the atmosphere from the projectile's passage [5]. The lofted material may form a cloud, analogous to a volcanic eruption column, that can subsequently collapse, creating the suevite deposits. The suevite was deposited on the bunte breccia in a nonturbulent fashion, since the contact of the suevite with the bunte breccia is sharp and usually undisturbed by any movement of the suevite, although occasional bombs pierced the bunte breccia [5]. In addition, there is no evidence for the formation of segregation features before the suevite had come to a complete rest. Wilson [2,3] has shown that segregation features can be produced in flowing material and they are stable against destruction by turbulence in the flowing sheet. However, channels produced during movement of the suevite would not be vertical, in contrast to the observed pipes.

Fission track, ^{40}Ar-^{39}Ar, and paleomagnetic studies suggest that the deposition temperature of the suevite was about 550°C. The high temperature and presence of alteration minerals suggests the degassing pipes were probably conduits for hydrothermal solutions after their formation [6], but based on our petrographic observations, the channeled areas of suevite are probably no more altered to clay minerals than the suevite away from the channels. We conclude that the alteration clays in the suevite and in the degassing pipes, were formed following emplacement. Our clay mineral analyses by X-ray diffraction show that the clays from the Otting outcrop are primarily montmorillonites with some degree of illite interstratification. Significant hydrothermal alteration occurred, even though a limited supply of water was available.

There are important implications of this work for the question of the origin of the martian soil. Suevite deposits, external to craters and subject to erosion, were probably widespread on Mars. In contrast to the Ries, the underlying Martian ejecta blankets probably contained significant amounts of ice, providing water for hydrothermal alteration. Because the heavily cratered terrain on Mars still covers half the planet, hydrothermal alteration of impact melt deposits may have contributed much of the martian soil. The thermal energy in the melt sheets may have also been sufficient to breach the frozen caps on groundwater systems, allowing water to flow out on the surface, possibly forming small valley networks [7].

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VOLATILE INVENTORY OF MARS. R. O. Pepin, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455.

Elemental and isotopic abundances of atmophilic elements and molecules trapped in the glassy lithology of the EETA 79001 shergottite are in good agreement with Viking measurements of martian atmospheric composition(1,2). The data base for the 79001 glass is quite extensive: results from several noble gas studies(3-8), and from nitrogen(6,7) and carbon(9) analyses, are now available. The geochemical case for EETA 79001 in particular, and the SNC meteorites in general, as Mars derivatives is further strengthened by the fact that absolute number densities (particles per unit volume) of gases trapped in the 79001 glass and gases in the contemporary ground-level martian atmosphere *are essentially identical*(10). This remarkable observation, first made by Ott and Begemann(11), certainly sets stringent boundary conditions on details of the trapping mechanism, but these conditions are much more credible than the incredible coincidence that must be invoked in any scenario of non-martian origin.

This direct evidence for origin of the SNC meteorites on Mars, and for trapping of an unfractionated sample of martian atmospheric gases in the 79001 glass, provides a reasonable basis for comparing the martian and terrestrial atmospheres with more precision than that afforded by the Viking data set.

Isotopes. The $^{20}Ne/^{22}Ne$ ratio, not measured by Viking, appears to be about 10; the average of two estimates(7,8) from the 79001 glass is 10.1 ± 0.7, close to the terrestrial ratio of 9.8. Kr and Xe compositions are non-chondritic; they are generally earth-like except for a small mass fractionation effect favoring the light isotopes,a much higher relative abundance of ^{129}Xe, and evidence that the component structures of martian and terrestrial xenon are significantly different. There is no evidence for measurable amounts of fissiogenic Xe from either uranium or plutonium decay in martian atmospheric Xe. Ar composition is anomalous, although within the range of the recently revised value from Viking(2): the trapped $^{36}Ar/^{38}Ar$ ratio of 4.1 ± 0.2(7) in the 79001 glass is strikingly lower than the values near 5.3 that characterize both the earth and major meteoritic gas carriers. A primordial martian ratio of 5.3 could in principle have been altered by some planet-specific process operating over geologic time, but we have not yet found one that works. A conceptually attractive possibility, cosmic-ray spallation of surface materials, would require irradiation of a planet-wide calcite deposit for much of the age of the solar system with the present galactic cosmic-ray flux in order to fit the data(7).

Elemental Abundances. There is a remarkable empirical relationship between martian and terrestrial abundances ([A]) of N_2, CO_2, ^{20}Ne, ^{36}Ar, ^{84}Kr and ^{132}Xe in *observable* volatile reservoirs (atmosphere at maximum pressure for Mars, and atmosphere, hydrosphere, biosphere, and sedimentary rocks for Earth), which can be expressed as $[A_♂] = 1.27 \times 10^{-4}[A_{earth}]^{0.865}$. The average deviation from this correlation for the six volatile species is $\sim$25%. If the relationship also holds for H_2O, then the known martian water reservoir, the north polar cap, would contain an average of $\sim$150 meters of H_2O ice over its area, equivalent to a planet-wide 75 centimeter water column. The radiogenic gases ^{40}Ar and ^{129}Xe fall well off this correlation, in the direction of higher abundances for Mars.

Relative elemental abundance ratios of noble gases in the martian and terrestrial atmospheres, expressed as $[M/^{130}Xe]_♂/[M/^{130}Xe]_{earth}$ for M = ^{84}Kr, ^{36}Ar and ^{20}Ne, decrease with decreasing mass in a functional relationship of depletion *vs.* mass that points to the operation of some type of mass-fractionating process. This suggests that Mars, or its protoplanetary feedstock, may have suffered mass-dependent noble gas losses from a reservoir that initially was compositionally similar to the Earth's. With this assumption concerning the initial reservoir, an episode of atmospheric escape early in the history of Mars could have generated the observed noble gas depletions; loss of a few hundred meters of water from Mars by hydrodynamic escape of photochemically-produced hydrogen would be required to yield these depletions(12). In the limit of negligible Xe loss during this episode of hydrodynamic escape, the noble gas inventory for Mars, prior to the onset of fractionating losses of the lighter gases, would have been $\sim$ 1/70 of the present terrestrial atmospheric inventory, or > 1/70 if Xe was lost as well. There is no way in this model to further limit this number, or to address quantitatively the question of the "missing" martian volatiles compared to the terrestrial inventory. It may be that these volatiles as well were lost in hydrodynamic escape, during an earlier episode in which the hydrogen escape fluxes were so large that mass fractionation of the noble gases carried away with the hydrogen was negligible(12). Alternatively, they may never have been present, or they remain even now in the interior, sequestered in an extensive undepleted mantle untapped by outgassing processes over the lifetime of the planet.

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GROUND PATTERNS ON EARTH AND MARS; L.A. Rossbacher, Geological Sciences Department, California State Polytechnic University, Pomona, CA 91768-4032.

Polygonally fractured ground can be quantitatively described by nearest-neighbor analysis; the R-statistic indicates the degree to which a pattern deviates from an expected random distribution of vertices and intersections of outlining fractures. For patterns observed on Mars and in cold regions on Earth, most are statistically more regular than random (1).

Because nearest-neighbor analysis is scale independent, patterns with a range of sizes can be compared with each other. The value of this is in being able to compare patterns regardless of size, but the scale of the features cannot be ignored. Preliminary data suggest that, for both Earth and Mars, larger polygons have more random patterns than the smaller, more regular polygons (Figure 1).

Possible explanations for this relationship between size and randomness include evolutionary and process-dependent models. (a) The evolutionary model suggests that the patterns begin as smaller, more regular patterns that are then modified into larger, less regular patterns by enhanced erosion of some fractures and infilling of others (1,2). Processes that modify terrestrial polygons include wind (3,4), flowing water (5,6,7), and vegetation (5,8). The first two of these could also have been effective on Mars. (b) The process-dependent model suggests that both size and regularity of ground patterns are controlled by the processes that form them. In general, thermal contraction processes on Earth create more random patterns - and larger polygon diameters - than ice wedging processes (1). If process is the independent variable, then both pattern randomness and size may follow from that. The role of climate and material are not known yet, but the terrestrial relationships shown in Figure 1 include data from Scandinavia, Alaska, and Canada, and the Martian data come from 4 different places along the boundary between the cratered upland and the northern plains (9).

The similar relationships between size and pattern on Earth and Mars, despite the different absolute sizes of the polygons, suggests an underlying similarity in the factors that control the size, randomness, and origin of the patterns. Further study of the relationship between pattern randomness and size of both terrestrial and Martian polygons should help clarify the relationships among size and randomness, the mechanism of formation, and perhaps the agents of modification.

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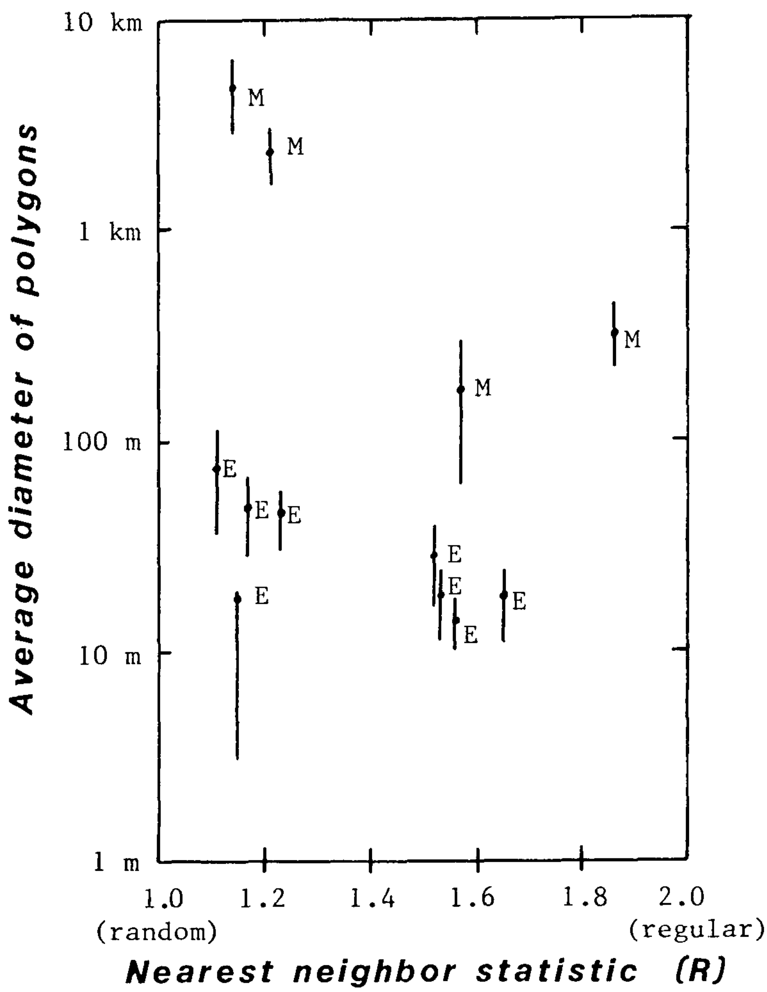

Fig. 1. Polygonal ground patterns on both Earth and Mars are generally less regular with increasing diameter. The nearest-neighbor statistic (R) is a measure of the departure from a random pattern (1); only the random (R=1.0) through regular (R=2.0) values are shown here. Error bars represent 1 standard deviation for polygon diameter; complete data listed elsewhere (9). Data for Mars and Earth are labeled M and E, respectively.

THE G-SCALE AND PLANETARY MEGAGEOMORPHOLOGY: HOW BIG IS IT REALLY?

L.A. Rossbacher, Geological Sciences Department, California State Polytechnic University, Pomona, CA 91768-4032.

Megageomorphology considers the large landforms on a planetary surface. These features are defined, in part, by their size relative to the planet itself. The size of landforms has traditionally been compared with analogous forms on Earth, and although this is a valuable approach for comparative study, it fails to illustrate the landform's size relative to the planet itself. This report suggests a way in which the definition of "mega-" can be quantified and adapted to the size of the specific planet.

The size of the area being studied influences the investigation (1), with decreasing detail available with increasing total area. In planetary geomorphology, the scale that can be studied is limited, at both ends, by the size of the planet and the best image resolution available. These restrictions affect both the definition of megageomorphology for that planet and the possibilities for comparing features between planets.

To quantify the area under investigation, physical geographers have used the G-scale as a measure of relative area (2). The G-scale uses a logarithmic relationship to compare the area being studied to the planetary surface area (2, p. 846):

$$G = \log \frac{G_a}{R_a}$$

where both G_a (the planet's total surface area) and R_a (the area being studied) must be measured in the same units. Similar types of logarithmic scales are widely used to describe grain sizes, stellar magnitudes, and pH values (2).

Figure 1 illustrates the relative scales of continent-sized features on the terrestrial planets as a function of the radius of that planet (G_a). The inset shows the planets on a G-scale relative to Earth (G_a = Earth's radius).

Several useful observations can be made from Figure 1. Continent-sized land masses are similar in size, relative to the radius of their planet. Viking images of the Martian surface are better, relative to the size of the planet, than satellite images of the other terrestrial planets. The megageomorphology of any planetary surface must involve features with G-scales less than or equal to the available satellite images of that surface.

Physical geographers have argued that the size of the area being studied influences the framework of the study itself (2). For planetary geomorphology, this influence includes both the area that is being studied and the area that can be studied, limited by the planet's size and image resolution. To date, megageomorphology has lacked a clear definition of the features being studied (3). Use of the G-scale helps to standardize the sizes of landforms relative to Earth or the other planet being studied and facilitates comparisons between landforms on different planets.

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THE G-SCALE AND MEGAGEOMORPHOLOGY

Rossbacher, L.A.

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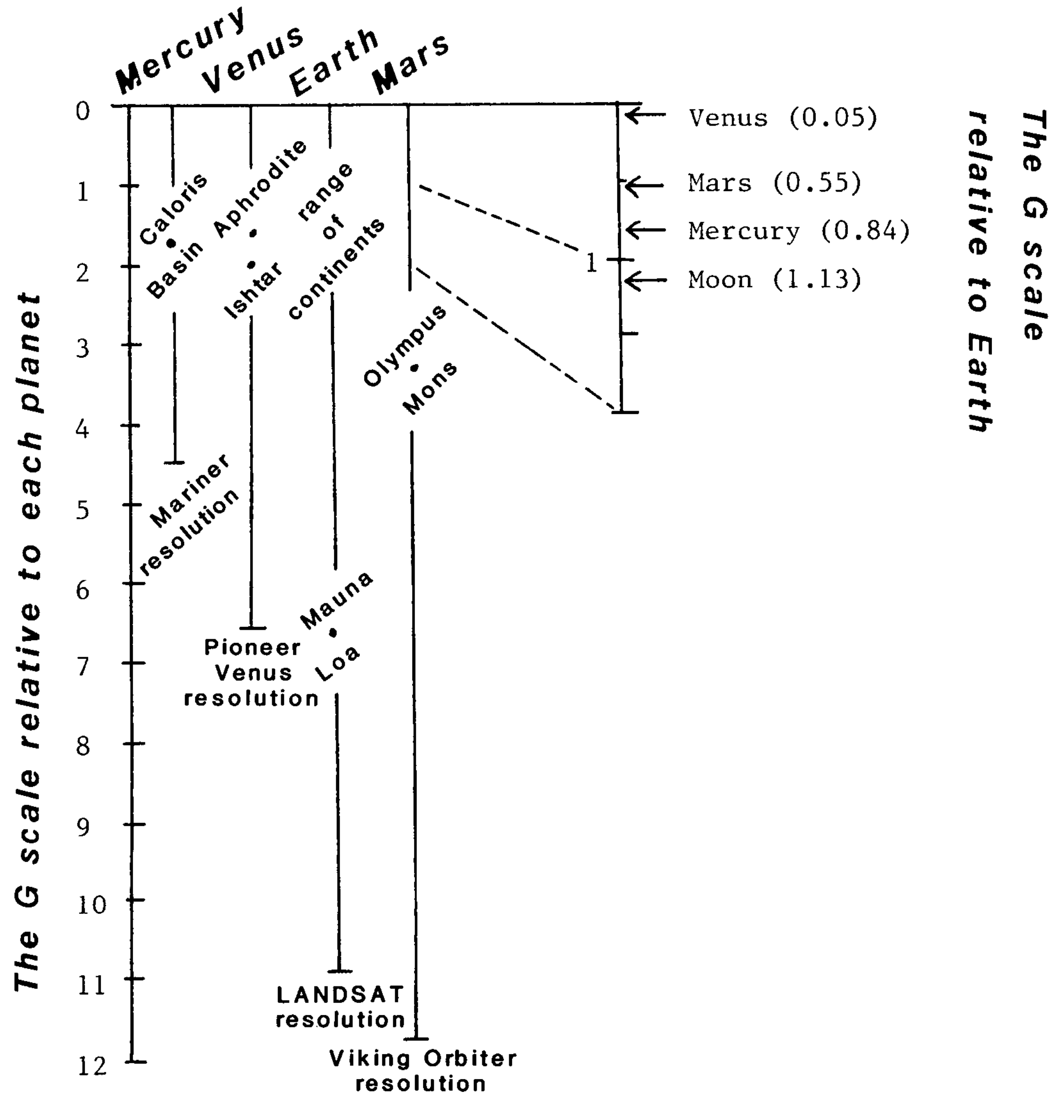

Fig. 1. The G-scales on the left show the range of continent-sized landforms observable on the terrestrial planets relative to the surface area of that body. The observable size ranges from the whole planet's surface area (G=0) to the limits of satellite resolution. Continents on Earth range from 1.06 to 1.83 on the G scale. The inset in the upper right shows the G-scale of the terrestrial planets relative to Earth.

EARLY CHANGES IN GRADATION STYLES AND RATES ON MARS P. H. Schultz and D. Britt, Brown University, Dept. of Geological Sciences, Box 1846, Providence, RI 02912

INTRODUCTION: The history of an active surface-atmosphere exchange of volatiles on Mars is recorded in the ancient cratered terrains. Large impact basins and craters provide a means to document this process and any changes in style with time. Two large impact basins (Isidis and Argyre) produced large well-defined geologic units and terrains, thereby allowing reliable crater statistics and dentification of time-dependent processes prior to most well-perserved volcanic events. Moreover, the collective impact basin record permits calibration of ancient gradation rates.

APPROACH: The wide annulus of massifs and knobs of Isidis and Argyre provided sufficiently large areas for meaningful crater statistics of large (>30km diameter) craters. Counts were made over adjacent and nested areas in order to test consistency and to derive relative ages of each basin. Within the Isidis annulus, characteristic terrains provided counting areas for dating contrasting surface process: channeled hummocky terrain, etched terrains, and intermassif channeled plains. The channeled hummocky terrain contains a high channel density (length/area) of narrow valley networks cutting both primary Isidis features and old craters. The etched terrains represent a broad region outside the inner high-relief massifs of southwestern Isidis where numerous irregular plateaus, mesas, and relict craters indicate a different style of erosion. The intermassif channeled plains occur along the inner mountainous ring. Shallow meandering channels form a large integrated drainage system that is linked to numerous smaller intermountain basins ("ponds"). These ponds and interconnected tributaries extend beyond the primary inner massif ring through broad canyons.

The Argyre basin presents a dramatic contrast in channel development. Deeply incised, narrow valleys exist but emerge along the scarp or are highly localized. Intermassif plains contain subtle curvilinear channels but the high density networks and furrowed massifs typical for Isidis are missing (1,2). To the south, long curvilinear channels and canyons follow heavily degraded basin structure and topography from beyond the Argyre scarp to the interior where narrow ridges appear to replace the original channel course. Narrow-valleys on ejecta facies superposing Argyre are isolated and unlike the systems within Isidis. Crater statistics have been obtained for the knobby terrain inside the scarp where larger post-terrain craters could not be buried by plains.

Figure 1 and Table I summarizes selected data from this study and permits comparison with other published crater counts of major volcanic events (3). Both the Isidis and Argyre crater distributions contrast with distributions derived for the oldest plains units examined here and elsewhere (4). A rapid fall-off in the number of craters smaller than 20km in diameter may reflect a different production population, enlargement of craters by erosion ($\sim$25%), or a basin secondary crater population (10-50km in diameter). Each possibility is being explored in more detail but we tentatively believe that the distribution curves are indicating active gradational processes since the formation of Isidis and Argyre. The observed crater distribution of Sinai Planum has been used as a "standard" in order to correct for crater loss of ancient terrains and to extend data from small counting areas. These counts have been normalized to $10km/10^6 km^2$ in order to minimize the amount of extrapolations from either ancient or recent terrains.

DISCUSSION: The change in narrow-valley-network (nvn) drainage density within well-defined drainage basins and the change in style with time is shown in Figure 1. As discussed previously (2,5), a rapid change is indicated after the Argyre impact. This can be documented not only by comparison between Isidis and Argyre but also by old impact craters. Four conclusions emerge. First, the interior massif/knobby annulus of Argyre does not appear to be a pristine basin surface but a modified terrain dating from early volcanic plains emplacement. The terrain is similar to but later than the knobby terrains of Elysium, which may be related to an ancient modified basin (6). Second, much later channel development is observed within the Isidis intermassif region. These channels form a long, relatively mature and integrated system. Third, both the etched terrains within Isidis and the nearby volcanic plains of Syrtis Major Planitia date from approximately the same period. Fourth, late-stage (comparable in age to Syrtis Major Planitia) unintegrated run-off channel systems occur within the mantled ejecta facies of old impact craters or are localized in certain deposits/terrains.

These results provide quantitative data for the change in gradation with time on Mars. Prior to the Argyre impact, the formation of narrow valley networks within Isidis resulted in removal of 75% of the crater smaller than 3km in diameter and 30% of craters smaller than 10km and/or 10-25% enlargement of larger craters. The size distribution of large martian impact basins in the ancient cratered terrains suggests broader scale losses during earlier epochs, rather than an absence of basin-forming impactors. The knobby terrain of the Elysium region and the nearby fretted terrain margins developed after the formation of Argyre, at about the time of the earliest volcanic constructs were formed. This process, and presumably the formation of the martian "dichotemy" appears to reflect on erosional event (rather than, or in addition to a tectonic process). The knobby terrains within Argyre may preserve a similar process nearly simultaneous with early volcanic plains emplacement (Sinai Planum). The etched terrains that apparently are associated with the emplacement of Syrtis Major Planitia of southern Isidis may represent an arrested analog for this process. Narrow-valley network formation apparently had ceased except as highly localized occurrences reflecting geothermal activity or emergent springs. The dramatic change in broad-scale gradation rates and style from pre-Argyre to Tharsis times suggest a change from atmosphere-surface exchange to principally surface/subsurface volatile loss including water and perhaps trapped carbonates (7).

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Feature/Unit +	Log N(>10Km)/10^6km^2 *	Channel Density (km/km^2)	Channel Style
Hellas (B)	3.1		valley networks
Isidis (B)	3.0	10^{-1}	valley networks
Uranius Tholus (V)	2.9		channeled
Argyre (B)	2.68	$<2\times10^{-2}$	localized networks
Ulysses Patera (V)	2.62		
Nepenthes Mensae (KT)	2.29		
Elysium Knobby terrain	2.29		
Tharsis Tholus (V)	2.25		
Argyre-massif annulus (KT)	1.98		run-off;emergent
Apollonaris Patera (V)	1.95		channeled
Uranius Patera (V)	1.95		
Tyrrhena Patera	1.93		channeled
Sinae Planum (VP)	1.90		
Syrtis Major Dy (C)	1.85	2×10^{-2}	isolated run-off
Hesperia Planum (VP)	1.83		
Cerulli	1.83		isolated run-off
Isidis-intermassif (ChP)	1.75		integrated run-off
Syrtis Major Planitia	1.75		
Peridier (C)	1.71	$<2\times10^{-2}$	isolated run-off
Lunae Planum (VP)	1.55		
Holden (C)	1.55		

+ B = basin; C = impact crater; V = volcanic construct; KT = knobby terrain; VP = volcanic plain; ChP = channeled plains.

* adjusted using crater statistics for Sinae Planum

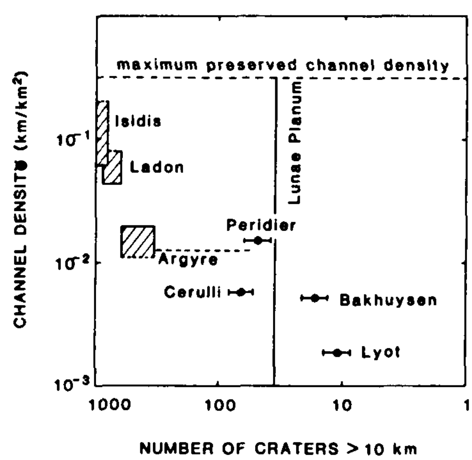

Figure 1. Production rate of narrow valley formation on selected basins and craters indicated by channel density (length/area) and superposed crater density (number > 10km/10^6km^2).

THE YOUNGEST CHANNEL SYSTEM ON MARS; K. L. Tanaka and D. H. Scott, U.S. Geological Survey, Flagstaff, Arizona 86001

On Mars, the youngest channel system--which is also one of the largest--extends for about 3,000 km from southeastern Elysium Planitia into western Amazonis Planitia (Fig. 1). This system appears to originate within the knobby cratered material (unit kc) around Cerberus Rupēs, a set of narrow, en echelon fractures that extends for more than 1,000 km. The channels grade into smooth, channeled plains material (unit cp) in a large depositional trough, centered near lat 5° N., long 203° between the Elysium rise and the southern highlands. The channel deposits are distinguished from surrounding plains material (unit pu) by a generally low albedo; they are also marked by light-colored teardrop-shaped areas and wispy patterns that differ both in form and orientation from local wind-streak markings. Most of the channels' albedo patterns, as well as teardrop-shaped bars, appear to be primary markings that indicate flow directions.

South of Cerberus Rupēs, at about long 204°, the channel flow direction is southward, dividing to the east and west. To the east, the channeled plains material is as wide as 750 km, but it narrows south and east of Orcus Patera. In its widest part, the channeled plains unit embays remnants of knobby cratered material (unit kc). In the narrow stretch are channel bars and terraces and streamlined albedo patterns. The density of craters larger than 1 km in diameter is less than 50 per million km^2 [1] for the channeled material near Orcus Patera; craters are sparse on the channeled plains to the west as well. Detailed inspection shows that most craters larger than about 1 km in diameter appear embayed by the unit, suggesting that it is only tens of meters thick. Except for eolian and polar deposits, on which resurfacing is probably still active, this channeled plains material has the lowest crater density and, therefore, the youngest relative age of any material of regional extent on Mars.

On the basis of our study of this channel system in the Cerberus Rupēs region, we offer the following proposals: (1) Faults within the region may have provided conduits for escaping subsurface melt-water fed by aquifers in the knobby cratered material, (2) channeling and flooding contributed materially to resurfacing of the northern lowland region of Mars, and (3) the climate on Mars was conducive to fluvial activity during very recent geologic time.

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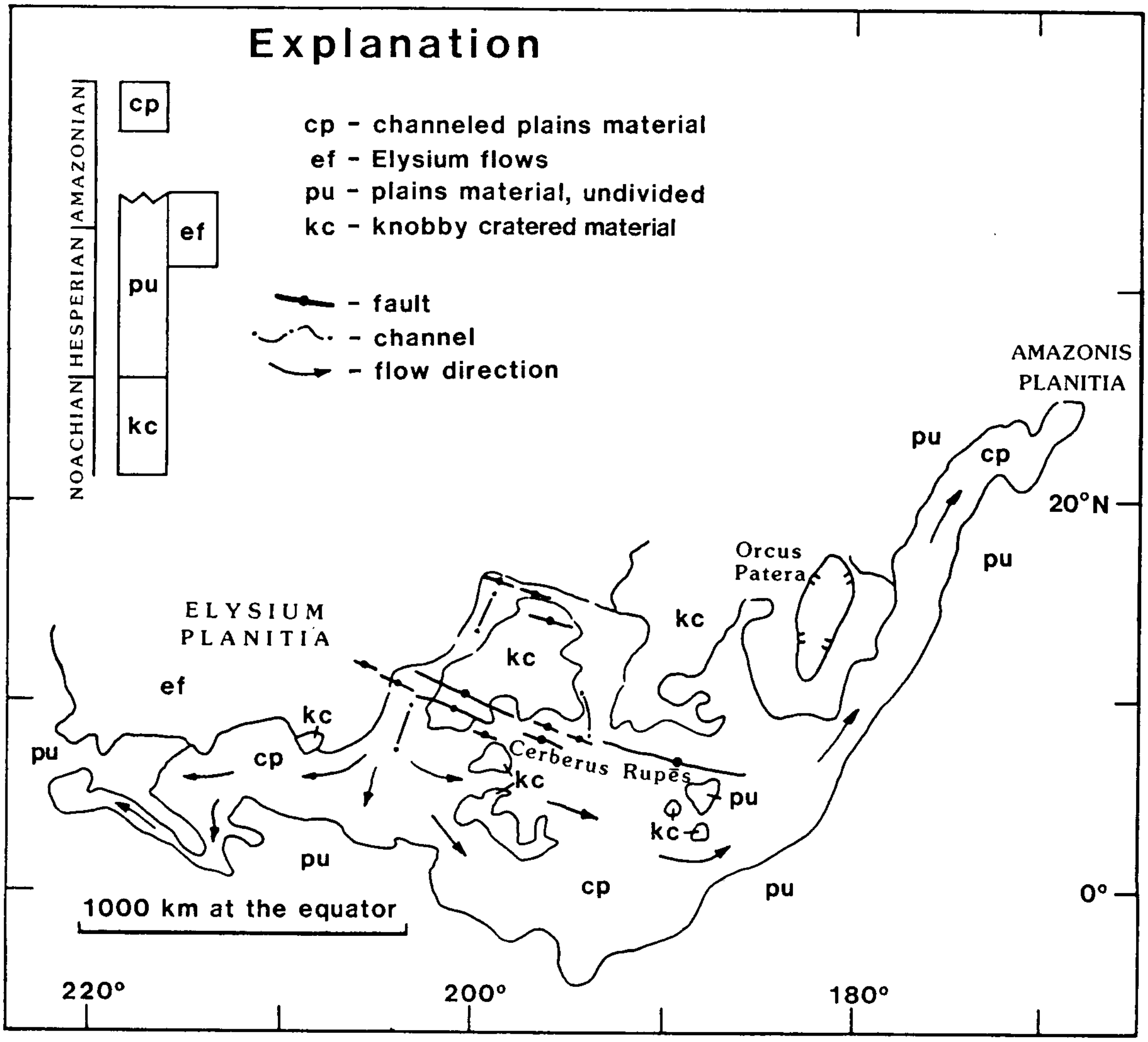

Fig. 1 Geologic map showing channel system in the Cerberus Rupēs region, Mars

LAVA-ICE INTERACTIONS ON MARS; D. E. Wilhelms, U.S. Geological Survey (MS-946), Menlo Park, CA 94025

Diverse phenomena that are consistent with origins by the interaction of basaltic lava with ice-rich sediment characterize ten geologic provinces in a large area of Mars between lat 30° N.-30° S. and long 115°-225° W.

Aeolis province (MC-15 SW, MC-23 NW): An intricately textured deposit near Aeolis Mensae has provided some of the most definitive clues to lava-ice interaction [1]. Narrow ridges are probably moberg dikes formed by intrusion of basalt sills into ice-rich ground and subsequently exhumed by erosion. Volcanic debris created during the interaction apparently has been mobilized by meltwater and flowed as lahars.

Elysium-Hecates province (MC-7 SW, SC; MC-15 NW): Channeled, thick, irregularly textured deposits originating near Elysium Mons and Hecates Tholus have been interpreted as megalahars created by the intrusion of lava into an ice-rich substrate [2]. Several of the moberg tablemountains and ridges in the province [3] were formed by intrusions into the lahars, showing that the lahars retained interstitial ice for some time after their deposition. The exhumation of the resistant tablemountains and a distinctive etched texture of the lahars shows that the lahars, unlike martian lavas, were subject to erosion. Fluid lahars (jökulhlaups) are thought to have been generated by lava flowing over ice-rich ground [4]. These flows have eroded exposed parts of the thicker lahars.

Phlegra-Orcus province (MC-15 NE): The thick, distinctively etched, viscous lahars and the smoother, fluid, erosive flows are also evident near Phlegra Montes, Orcus Patera, and other dense concentrations of knobby terrain. Lavas apparently dominate other parts of northern Elysium Planitia. These spatial associations indicate that the knobby terrain was the source of the meltwater in the lahars and jökulhlaups.

Apollinaris (MC-8 SW, MC-15 SE, MC-16 NW, MC-23 NE): Much of the upland-lowland front (ULF) is characterized by soft-textured, easily erodable deposits called the Medusae Fossae Formation (MFF) [5], which has been variously interpreted as silicic ignimbrite [5,6], stranded former polar deposits [7], aeolian deposits [8], or palagonitic mudflows (lahars) [9]. Thickening of the MFF toward the volcano Apollinaris Patera suggests that at least this part of the MFF is volcanic in origin, although partly eroded and redistributed by the wind. Partly degraded and partly resistant materials like those of the Elysium-Hecates lahars form the contact between the soft material and the Elysium plains, and also form islands in the plains. Thus, basaltic lavas from Apollinaris could have interacted with ice-rich material along the ULF, thereby forming the lahars and creating abundant palagonitic tuff that constitutes the soft material of the MFF. Jökulhlaups created by meltwater from these interactions apparently swept over southern Elysium Planitia, eroding the lahars and crater rims, and depositing extensive (though thin) sediments relatively recently in martian history.

Amazonis Planitia (MC-8 NW, NE, SW): Some of the probable jökulhlaups that originated near Apollinaris and elsewhere flowed NW along a broad braided channel into Amazonis Planitia [10], where they deposited sediment over a large area. This sediment is eroded into distinctive, irregular, cell-like textures whose hollows probably represent concentrations of less-resistant debris than that which forms the "cell walls" and plateaus.

Nicholson province (MC-8 SW, MC-16 NW): The soft MFF terrain is replaced along the ULF between the crater Nicholson (0°, 164° W.) and long. 172° W. by dark-and-light stratified mesas surrounding knobby terrain. The overall map pattern of degraded terrain and resistant mesas, many of which are sinuous, is like that of the Elysium-Hecates lahars, except that more material has been removed here. Small pedestal craters with extensive but partly eroded ejecta blankets show that the wind has removed some of the MFF. More severely eroded pedestal craters occupy broad valleys whose geometry suggests fluid-flow origin. Erosive jökulhlaups originating from the lahars or the original zones of lava-ice interaction probably formed these valleys and removed most of the MFF. The redeposited MFF sediment merges with the cell-textured sediments of northern Amazonis.

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Wilhelms, D. E.

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Medusae Fossae-Gordii Dorsum province (MC-8 SW, SE; MC-16 NW, NE): This most complex and also best-photographed province has provided good insights into the process of lava-ice interaction. It contains thick, extensive, stratified deposits of the soft facies of the MFF, whose stratigraphic relations with resistant ledges of probable lava suggest an origin as palagonitic tuff. The MFF has been eroded into yardangs [9], whose orientations differ in the various layers, and has been redistributed locally as eolian dune fields. Windows eroded in these soft deposits reveal lahars, probable lava sills, fluid-flow lineations emanating from beneath the sills, channels eroded by fluid flow, sediments deposited from the flows, tablemountains, and possible moberg ridges.

Mangala Valles (MC-16 NE): Based on the relations reported above, I interpret the complex, braided outflow-channel system Mangala Valles [11] as another product of lava-ice interaction. Dark, coherent plains that are probably composed of lava occupy many crater floors, a large trough between massifs of the >2,000-km-diameter "Daedalia" basin, and belts of upland parallel to Mangala and the Daedalia rings. The same material also forms a sinuous intrachannel ridge (7.5° S., 151.5° W.), which apparently formed by the flow of lava in an earlier, smaller channel and was exhumed by erosion of weaker material of its former banks. Episodic lava intrusions may have melted ice contained in the upland deposits, and the resulting meltwater may have cut the channel system.

Fluid flows emanating from the mouth of Mangala (4° S., 150.5° W.) and from parallel channels have eroded a broad path through the MFF and crater ejecta as far as 9° N., 153.5° W. This erosion is like that of the Nicholson province, and its sediment adds to the Amazonis deposit.

Olympus-Biblis province (MC-8 NE, SE; MC-9 NW, SW): Etched, channeled flows resembling the lahars of the Elysium-Hecates province occur NE of Olympus Mons. The much-studied, controversial Olympus Mons aureole has been interpreted as another manifestation of lava-ice interaction [12]. This interpretation is supported by the similarity of short, irregular ridges of the northern Medusae Fossae-Gordii province to the ridges that characterize the aureole. The ridges of the NW-most aureole lobe have a gridlike pattern lacking evident pull-apart gaps, suggesting that this lobe formed nearly in place. Most of the aureole, however, is partly allochthonous, having slid outward along decollement surfaces from an origin closer to the mountain [13,14]. This relation is particularly evident where the SE aureole lobe has overthrust older terrain NW of Biblis Patera. Meltwater from the lava-ice interaction could have lubricated the flow. Furthermore, flow patterns of some of the weblike sediments of Amazonis suggest sources in the aureole.

Uplands (MC-16; MC-23): The history of the lava-ice interactions in the above "lowland" provinces is consistent with one or more episodes of recycling of ice originally contained in deposits of the uplands. Loss of some of this ice converted the upland deposit into knobby terrain along much of the ULF and in northern-plains outcrops, such as those of the Phlegra-Orcus and Nicholson provinces. However, sufficient ice remained to interact with the lava to form lahars and the MFF, and the uplands retained still more of the ice in relatively cohesive deposits.

Much of the evolution of the landscape of Mars can be ascribed to this process, highly diverse in detail but basically originating from the inevitable interaction of two of the most common martian geologic materials, ice and basalt.

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SPATIAL RESOLUTION AND THE GEOLOGIC INTERPRETATION OF MARTIAN MORPHOLOGY. James R. Zimbelman, Lunar and Planetary Institute, 3303 NASA Road 1, Houston, Texas, 77058.

Morphologic features distinguishable in images comprise the principle data source for interpreting the geologic history of planetary bodies. In order to assess the processes that are responsible for the surface features visible in spacecraft images, it is necessary to have a spatial resolution sufficient to reveal landforms diagnostic of the processes. From published papers describing Martian geology, there would appear to be a wide range of spatial resolutions sufficient to allow the identification of the origin of various landforms. The large quantity of high resolution images obtained after the Viking Primary Mission provide a valuable data source for reexamining some of the geomorphic processes that are firmly entrenched in the literature about Mars.

As an example of the importance of spatial resolution, let us examine some images of the Acheron Fossae region of Mars (39^{o}N, 135^{o}W). Acheron Fossae is a semicircular deposit about 700 km across with abundant grabens and en echelon fractures and with numerous small channels on crater walls and the flanks of ridges (1, Fig. 1). Images from the Viking Primary Mission revealed several smooth-floored valleys and linear to acruate ridges within the distal ends of some valleys (Fig. 2). These ridges often parallel the sides of the valleys, mimicing the outline of the surrounding uplands. This terrain was identified as lineated valley fill and interpreted to be the result of mass movement induced by creep of interstitial ice within erosional debris from the surrounding highlands (2). Subsequent images of considerably higher spatial resolution reveal features that cast considerable doubt on the ground ice interpretation for these valley fill features. Linearly oriented mounds and ridges, separated by tens to hundreds of meters and tens of meters in height, are abundant within low-lying areas both on the gently rolling plains and between the rounded knobs of upland material (Fig. 3). Both the size and planimetric form of the small mounds are suggestive of an aeolian dune field (although slip faces are not resolved on individual mounds). The smooth-floored valley is also revealed to be completely covered by similar linearly oriented ridges (Fig. 4). Again the size and planimetric form of the ridges strongly support an aeolian dune field interpretation for the valley floor material. It is particularly instructive that the ridges near the bottom of Fig. 4 tend to be concentrated along the medial portion of the tributary channels leading into the main valley. This further supports an aeolian origin for the ridges as echo dunes concentrated near but slightly away from a significant break in slope (3). These images indicate that an aeolian origin is much more likely for the valley fill material at Acheron Fossae than is an ice-laden debris flow origin.

At least 1/10th of the Viking Imaging data set has a spatial resolution of 20 m/pixel or better (data obtained from a BIRP search; see 4). Although about half of these images are of no use for morphologic analyses, due to obscuration of the surface by atmospheric dust, the remaining images should be considered to be the prime data set for assessing the validity of various geologic processes on Mars.

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SPATIAL RESOLUTION AND THE INTERPRETATION OF MARTIAN MORPHOLOGY
J.R. Zimbelman

Fig. 1. Portion of Acheron Fossae and Arcadia Planitia. Frame 852A04, range 10216 km, resolution 255 m / pixel, center at 40°N, 133°W. Outline shows location of Fig. 2.

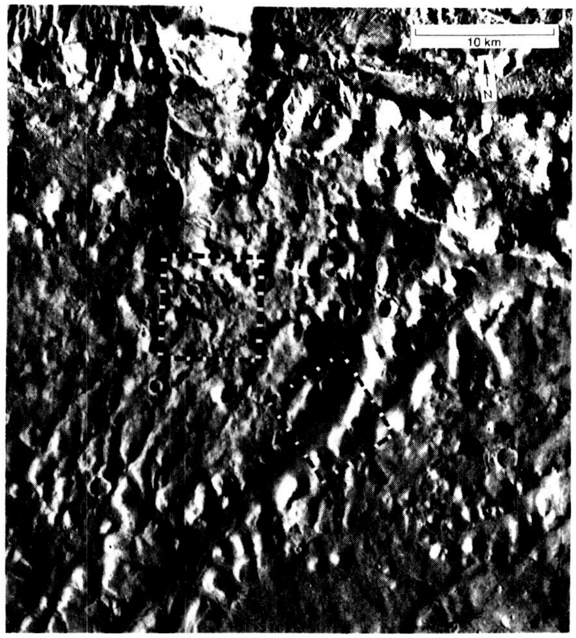

Fig. 2. Frame 129A40, range 2264 km, resolution 57 m/pixel, center at 38°N, 135°W. Outlines show locations of Figs. 3 & 4 (left and right, respectively).

Fig. 3. Frame 442B03, range 367 km, resolution 9 m/pixel, center at 38.4°N, 135.2°W. Note dunes in topographic lows.

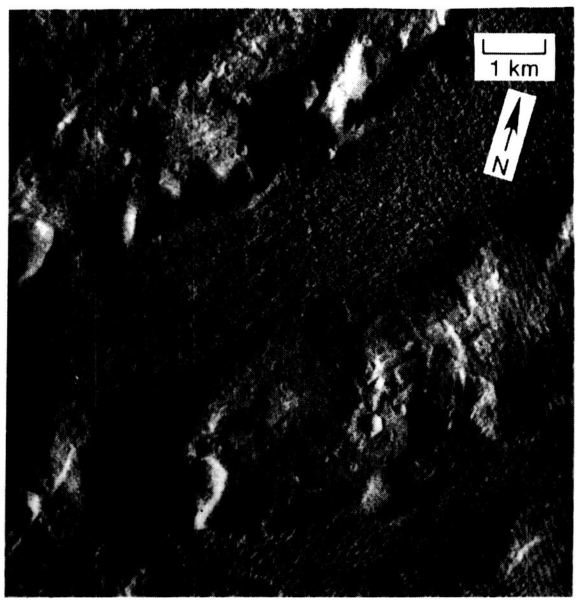

Fig. 4. Frame 442B10, range 325 km, resolution 8 m/pixel, center at 38.2°N, 135.0°W. Note dunes on valley floor and within tributary channels.

List of Speakers

G. R. Brakenridge
Department of Geological Sciences
Wright State University
Dayton, OH 45435

Eric H. Christiansen
Department of Geology
University of Iowa
Iowa City, IA 52242

Stephen M. Clifford
Lunar and Planetary Institute
3303 NASA Road One
Houston, TX 77058

Herbert Frey
Goddard Space Flight Center
Greenbelt, MD 20771

James L. Gooding
Code SN2
Planetary Material Branch
NASA Johnson Space Center
Houston, TX 77058

Wendy S. Hale-Erlich
Amoco Production Company
New Orleans, LA 70150

Vicki M. Horner
Department of Geology
Arizona State University
Tempe, AZ 85287

H.-P. Jöns
Geol. Institut
Tubingen University
3392 Clausthal
F. R. Germany

Jeff S. Kargel
Department of Planetary Sciences
University of Arizona
Tucson, AZ 85721

R. Craig Kochel
Department of Geology
Southern Illinois University
Carbondale, IL 62901

B. K. Lucchitta
U.S. Geological Survey
2255 N. Gemini Drive
Flagstaff, AZ 86001

Horton E. Newsom
Institute of Meteoritics
Department of Geology
University of New Mexico
Albuquerque, NM 87131

Robert O. Pepin
School of Physics and Astronomy
University of Minnesota
Minneapolis, MN 55455

Lisa A. Rossbacher
Geological Sciences Department
California State Polytechnic Institute
Pomona, CA 91768

Peter H. Schultz
Department of Geological Sciences
Brown University
Providence, RI 02912

Kenneth L. Tanaka
U.S. Geological Survey
2255 N. Gemini Drive
Flagstaff, AZ 86001

Don E. Wilhelms
MS 946
U.S. Geological Survey
Menlo Park, CA 94025

James R. Zimbelman
Lunar and Planetary Institute
3303 NASA Road One
Houston, TX 77058

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