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The Martian drainage system and the origin of valley networks and fretted channels

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Abstract. Outflow channels provide strong evidence for abundant water near the Martian surface and an extensive groundwater system. Collapse of the surface into some channels suggests massive subsurface erosion and/or solution in addition to erosion by flow across the surface. Flat floors, steep walls, longitudinal striae and ridges, downstream deflection of striae from channel walls, and lack of river channels suggest that fretted channels form dominantly by mass wasting. A two-stage process is proposed. In the first stage, extension of valleys at valley heads is favored by seepage of groundwater into debris shed from slopes. The debris moves downstream, aided by interstitial groundwater at the base of the debris, possibly with high pore pressures. In the second stage, because of climate change or a lower heat flow, groundwater can no longer seep into the debris flows in the valleys, their movement almost stops, and more viscous ice-lubricated debris aprons form. Almost all uplands at elevations greater than +1 km are dissected by valley networks, although the drainage densities are orders of magnitude less than is typical for the Earth. The valley networks resemble terrestrial river systems in planimetric shape, but U-shaped and rectangular-shaped cross sections, levéelike peripheral ridges, median ridges, patterns of branching and rejoining, and flat floors without river channels suggest that the networks may not be true analogs to terrestrial river valleys. It is proposed that they, like the fretted channels, formed mainly by mass wasting, aided by groundwater seepage into the mass-wasted debris. Movements of only millimeters to centimeters per year are needed to explain the channel lengths. Most valley formation ceased early at low latitudes because of progressive dehydration of the near surface, the result of sublimation of water and/or drainage of groundwater to regions of lower elevations. Valley formation persisted to later dates where aided by steep slopes, as on crater and canyon walls, and/or by high heat flows and the presence of water, as on some volcanoes.

Introduction

On the Martian surface are a variety of drainage features that have generally been attributed to water erosion. This paper describes the drainage system of Mars and discusses what might be inferred from the characteristics of the system. The main concern is to reassess what processes caused formation of the drainage system, so that the required climatic conditions can be subsequently evaluated. The valley networks receive the most attention because their presence has been viewed as the strongest evidence for warm and wet climatic conditions in the past. The outflow channels and fretted channels are also discussed, mainly to illuminate some issues that might have bearing on the origin of the networks. The paper is partly descriptive. It describes the different elements of the Martian drainage system, emphasizing various properties that must be explained by models for its origin. Other parts of the paper are more speculative, as different possibilities for the origin of the drainage features, particularly the networks, are discussed. One general conclusion is that the valley networks are unlikely to be composed mostly of fluvial valleys, as has been widely assumed. The second conclusion is that mass wasting has played a prominent, if not dominant, role in their formation.

This reevaluation of the distribution and characteristics of the various drainage features of Mars has been triggered by several recent developments. It was recognized early that most of the valley networks are old and that, for their formation, they probably required climatic conditions significantly warmer than present conditions. This led to a simple model for the climatic evolution of Mars in which early Mars was warm and wet and had a thick CO_2 atmosphere, but soon after the end of heavy bombardment, the atmosphere lost most of its CO_2 due to formation of carbonates, and surface conditions changed to those that we observe today [*Pollack*, 1979; *Pollack et al.*, 1987; *Fanale et al.*, 1992]. This simple model is now being challenged on several grounds. While most of the networks do indeed occur in the oldest terrains (Noachian), a significant fraction may be younger than Noachian [*Scott and Dohm*, 1992], and some networks, notably those on Alba Patera, formed relatively late in Martian history [*Mouginis-Mark et al.*, 1988; *Scott and Tanaka*, 1986]. It has also been hypothesized that Mars has experienced recurrent glaciations, some relatively late in its history [*Kargel and Strom*, 1992]. If so, then precipitation and climatic conditions very different from those that presently prevail occurred late. *Baker et al.* [1991], noting the late-forming networks, the late-occurring glaciations, and

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evidence for former, large bodies of water in the northern plains [*Lucchitta et al.*, 1986; *Parker et al.*, 1989; *Chapman*, 1994], suggested that, episodically, throughout Martian history, catastrophic floods left ocean-sized bodies of water in low-lying areas. They hypothesized that these oceans caused major changes in the global climate, that these changes were short lived, but that during the short warm periods, the hypothesized glacial features and young networks formed.

The supposition of a warm, wet Mars changing irreversibly to the present Mars through loss of a thick CO_2 atmosphere has also been challenged on other grounds. First, there is little, if any, definitive spectroscopic evidence of young carbonate deposits at the surface [*Blaney and McCord*, 1989], although *Pollack et al.* [1990] detected 1–3% carbonates in dust in the atmosphere, and *Calvin et al.* [1994] interpret a spectral feature at 4.5 μm that might be indicative of 10–20% hydrous magnesium carbonate. If the networks are to be attributed to a thick CO_2 atmosphere, the carbonate deposits should be at the surface. Second, recent greenhouse calculations suggest that a thick CO_2 atmosphere could not cause surface temperatures to rise to above 273°K because of the formation of clouds, even with the present solar constant [*Kasting*, 1991]. The problem is further exacerbated for early Mars because of the likelihood of a significantly lower solar constant. Third, it has been suggested that networks could form under present climatic conditions by groundwater sapping [*Squyres*, 1989], as a result of hydrothermal activity [*Gulick and Baker*, 1989], or by flow of water under thick ice covers [*Wallace and Sagan*, 1979].

These developments suggest a need to reevaluate the observational data that have led to proposals of climate change. Suggestions for former, distinctively different, climatic conditions on Mars are based largely on the valley networks and the supposition that because, in planimetric form, they resemble terrestrial river valleys, they require terrestriallike climatic conditions for their formation. Yet, although numerous papers have been written about specific features or areas, there exists no comprehensive, up-to-date description of the Martian drainage system as a whole. This paper attempts to provide that. It describes the distribution, characteristics, and interrelations of the valley networks and different types of channels. The main intent is to provide a basis for evaluating how solidly based the hypothesis of a fluvial origin for the networks is, because such an origin is the basis for invoking climate change on Mars. Extensive use is made of recently developed geographic information system (GIS) techniques in describing topological relations and in making correlations between the channel and valleys and other data sets, such as topography and geology.

Background

The valleys and channels of Mars were first recognized during the Mariner 9 mission [*Masursky*, 1973]. Because it was understood at that time that liquid water was unstable at the Martian surface under present climatic conditions, there was some reluctance, initially, to accept these features as fluvial in origin, and alternative modes of formation were examined. The alternatives included erosion by lava [*Carr*, 1974; *Schonfeld*, 1977], erosion by liquid hydrocarbons [*Yung and Pinto*, 1978]; erosion by wind [*Cutts and Blasius*, 1979], erosion by liquid CO_2 [*Sagan et al.*, 1973], liquefaction [*Nummedal*, 1978], and faulting [*Schumm*, 1974]. None of these alternatives have, however, appeared as plausible as water erosion (for summaries, see *Carr* [1981] and *Baker* [1982, 1985], and water is now almost universally taken as the most likely erosive agent in the formation of the valleys and channels. The linear erosional features of Mars have generally been divided into three classes [*Sharp and Malin*, 1975; *Carr*, 1981; *Baker*, 1982]. Most outflow channels start full size, have few if any tributaries, and commonly have bedforms, such as scour marks, on their floors. What have been called valleys start small, increase in size downstream, and form branching networks. Fretted channels are broad, flat-floored valleys that commonly branch upstream, widen downstream, and contain abundant evidence of mass wasting from their walls.

The initial reluctance to accept water as the erosive agent stemmed from the stability relations of water at the Martian surface. Under present climatic conditions, with mean annual temperatures of 215°K at the equator and 150°K at the poles, the ground is permanently frozen to a depth of roughly 2–3 km at the equator and 4–7 km at the poles [*Fanale*, 1976; *Clifford*, 1993]. The exact depth depends on the heat flow and the thermal conductivities of the crustal materials. Thus liquid water is unstable everywhere on the planet within 1 km of the surface. At latitudes less than about 30°, temperatures may be above the frost point at all depths, so that any ice in the permafrost zone will slowly sublime into the atmosphere. The rates will be largely controlled by the rates of diffusion of water vapor through the surface materials into the atmosphere [*Farmer and Doms*, 1979]. Under present climatic conditions therefore water ice is unstable in much of the permafrost zone at low latitudes. The instability of ice at low latitudes has led to the supposition that the near-surface materials have progressively lost any ice that was originally present, as a dehydration front moves to greater depths with time [*Clifford and Hillel*, 1983; *Fanale et al.*, 1986]. Ice stability is, however, affected by variations in the thermal inertia, albedo, and permeability of the surface materials and by mixing of water vapor in the atmosphere [*Paige*, 1992; *Mellon and Jakosky*, 1993], and the *Farmer and Doms* [1979] stability model may be an overgeneralization.

The large outflow channels are widely accepted as having been formed by catastrophic floods [*McCauley et al.*, 1972; *Baker and Milton*, 1974], although a minority view is that some may have been carved by ice masses [*Lucchitta*, 1980]. Because the floods were so large, freezing rates, even under present climatic conditions, would have been trivial compared with discharge rates. Indeed, it has been suggested that very cold conditions and a very thick permafrost zone are necessary for formation of many of the large channels [*Carr*, 1979]. On the other hand, the valley networks are thought to be more analogous to terrestrial river valleys and to have formed not by floods but by the slow erosion of running water [*McCauley et al.*, 1972; *Pieri*, 1976]. Because of the more modest discharges, freezing would likely have been significant under present climatic conditions, and flow of a stream would probably be arrested by freezing before the water flowed the distances required by the sizes of the larger networks [*Carr*, 1983]. The networks have therefore been regarded as strong indicators of former climatic conditions under which liquid water was stable at the surface. A third class of linear erosion feature called fretted channels may have formed by a combination of processes, with ice dissolution and mass wasting probably playing significant roles in addition to fluvial processes [*Sharp*, 1973; *Squyres*, 1978].

At low and midlatitudes, valley networks occur almost everywhere in the heavily cratered Martian uplands, although they are very sparse around Hellas and Argyre, to the east of the Chryse basin, and in Memnonia [*McCauley et al.*, 1973; *Pieri*, 1976, 1980a; *Carr and Clow*, 1981]. The age of the networks in the cratered uplands is controversial. *Carr and Clow* [1981] showed that the vast majority of the networks are in the heavily cratered uplands. The work discussed below confirms that conclusion in the sense that most networks cut Noachian units along most of their length. Generally, the small sizes of the valleys preclude reliable age determination by crater counting, although this has been attempted [*Pieri*, 1976], so superposition relations must be used. The abundance of networks in Noachian units does not necessarily indicate that the networks are Noachian in age. However, the commonly observed superposition of craters, the highly degraded character of most of the networks, and the commonly observed differences in dissection between adjacent Noachian and Hesperian units suggest that most of the networks are indeed old [*Pieri*, 1976, 1980b; *Carr and Clow*, 1981; *Mars Channel Working Group*, 1983; *Baker and Partridge*, 1986]. Despite the likely dominance of Noachian age networks, many networks are younger than Noachian. *Scott and Dohm* [1992] documented superposition relations for several hundred networks and suggested that possibly as many as 30% are Hesperian in age. This conclusion is not necessarily inconsistent with the dominance of networks in the Noachian, for a network may cut Noachian units along almost all its length but debouch onto and cut a Hesperian unit at its mouth, and so be Hesperian in age. Ambiguities in age also result because of the difficulty of distinguishing between Noachian and post-Noachian units at the local scale. Valleys commonly meander between large craters in the uplands. The uplands as a whole and most of the large craters clearly date from the time of heavy bombardment, but younger deposits may have accumulated in some of the sparsely cratered areas between the large craters.

Networks also occur on the flanks of several volcanoes, most notably Alba Patera, Hecates Tholus, and Ceraunius Tholus [*Gulick and Baker*, 1990]. The ages of some of the volcanoes are also uncertain. On the basis of crater counts, *Barlow* [1988] suggests that Hecates Tholus and Ceraunius Tholus are Noachian in age. *Greeley and Guest* [1987], however, map Hecates Tholus as Hesperian. The valleys on the flanks of Alba Patera are unambiguously post-Noachian and appear to be Amazonian in age [*Scott and Tanaka*, 1986; *Barlow*, 1988]. Because of their young age, the valleys on the flanks of Alba Patera are crucial for understanding the erosional history of the planet. Although many uncertainties remain, relations as they are currently understood appear consistent with a general decline in the rate of valley formation from the Noachian through the Hesperian, but with local valley formation occurring on volcanoes at later times. Uncertainties remain because of uncertainties in the precise ages of the units cut by the networks and because superposition relations give only a maximum possible age. Moreover, because all features that have been interpreted as networks have not necessarily formed by the same mechanism, formulating a climatic history from the ages of the networks is hazardous.

Crater degradation rates also appear to have been high in the Noachian and then to have declined. Many of the craters in the cratered uplands, particularly those less than 100 km in diameter, are highly degraded. Some are almost rimless and preserve little evidence of ejecta. Similar sized craters on most younger surfaces are generally almost perfectly preserved. (Exceptions are craters superimposed on relatively young, easily erodible materials such as the Medusae Fossae Formation.) *Carr* [1992] estimated from crater depths that obliteration rates declined by almost 2 orders of magnitude from the Noachian through the Hesperian. On the basis of detailed crater counts, *Craddock and Maxwell* [1993] demonstrated that obliteration rates were higher in the Noachian than in the Hesperian and that the higher obliteration rates persisted longer at lower elevations. They suggested that the decline in obliteration rates could result from the decline in the rate of valley formation. *Grant and Schultz* [1993], on the other hand, suggested that mass wasting and eolian processes dominated over fluvial processes in crater degradation.

The origin of the valley networks remains controversial. Although a consensus has emerged that water or water ice must be the prime agent responsible for their formation, origin of the valleys by fluvial processes has not been proven. Moreover, even if the valleys are fluvial, controversy still remains concerning the relative roles of surface runoff and groundwater sapping. Many valley networks have characteristics, such as widely spaced tributaries with alcovelike terminations, that are strongly suggestive of sapping [*Sharp and Malin*, 1975; *Pieri*, 1980a, b; *Kochel et al.*, 1985; *Howard et al.*, 1988]. Particularly conspicuous examples are the Nanedi and Nirgal Valles. However, other networks are so dense and intricate that some form of surface runoff is inescapable [*Gulick and Baker*, 1990]. The runoff may not, however, be water, but could be the surface materials themselves. Because the mode of origin of the valleys is not understood, the climatic conditions necessary for their formation are not understood. Of particular importance is whether liquid water need be stable at the surface for the valleys to form. Clearly, formation by rainfall requires climatic conditions very different from those that presently prevail. Erosion by meltwater from snow under subzero conditions is theoretically possible but highly improbable [*Clow*, 1987]. Calculations of the stability of streams under an ice cover [*Wallace and Sagan*, 1979; *Carr*, 1983] suggest that, given adequate but modest groundwater discharge from springs, the networks could form by sapping even when surface temperatures are well below 0°C [*Squyres*, 1989]. However, the theoretical calculations do not take into account the vagaries of flow and freezing in small natural streams under subzero conditions. On Earth, flow is generally arrested by the formation of icings [*Carr*, 1983], and there is little reason to believe that the results should be any different on Mars unless the water was significantly above its freezing point as a result of hydrothermal activity [*Newsom*, 1980; *Gulick and Baker*, 1992; *Clifford*, 1993]. Furthermore, formation of valleys by sapping requires that the aquifers be constantly recharged [*Gulick and Baker*, 1993; *Baker*, 1990]. If this is achieved by precipitation, then warmer climatic conditions are required. Other alternatives for recharging aquifers are locally by means of hydrothermal circulation [*Gulick and Baker*, 1992] or, globally, by movement of water from the poles to low latitudes in the deep megaregolith, the circulation being driven by the vertical vapor pressure gradient in the megaregolith at low latitudes and basal melting of ice-rich deposits at the poles [*Clifford*, 1987, 1993].

Recent modeling of climate change on Mars makes the necessity for resolution of the precise origin of valley networks even more compelling. Modeling in the late 1970s suggested that a 1- to 3-bar CO_2 atmosphere could raise the surface temperature on Mars such that liquid water could flow across the surface [*Pollack*, 1979]. There remained a problem as to how such an atmosphere could be maintained until 3.8–3.5 b.y. ago because, with liquid water present at the surface, the CO_2 would react with the surface materials to form carbonates on a timescale of roughly 10^7 years [*Fanale et al.*, 1982; *Pollack et al.*, 1987]. It was suggested that high rates of volcanism and impact could have sustained the early thick CO_2 atmosphere, and that as the rates of volcanism and impact declined, the atmosphere became permanently fixed as carbonates [*Pollack et al.*, 1987; *Carr*, 1989]. Recently, a more severe problem has emerged. With the reduced solar constant hypothesized for over 3 b.y. ago, an early CO_2-H_2O greenhouse may not be able to create the warm temperatures needed to allow liquid water at the surface, because of cloud formation [*Kasting*, 1991]. Difficulties with the CO_2 greenhouse have led to suggestions that other greenhouse gases may have been involved [*Postawko and Kuhn*, 1986]. Finally, *Baker et al.* [1991] tried to resolve many of the issues raised in this section by suggesting that episodic, short-lived climate changes were triggered by the floods that cut the large outflow channels. They suggested that the floods left behind massive bodies of water and released massive amounts of H_2O and other greenhouse gases such as CO_2 into the atmosphere, thereby causing global, but transient, climate changes. They postulate that the networks formed during these temporary climatic excursions.

GIS Compilation

In order to facilitate characterization of the channels and networks, and make comparisons with other data sets, the network and channel data were compiled in ARC/INFO, a widely used GIS technique [*Environmental Systems Research Institute*, 1992]. The study focused on the region of Mars between 47.5°N and 47.5°S. Channels and valleys were mapped on all 96 of the 1:2,000,000 (2M) Mars Chart (MC) subquadrangles in this region. The quadrangles were then scanned and digitized, and the different types of data tagged. Lines are stored in a vector format. Some information, such as the links of a network are linear and stored simply as a line; other information, such as a geologic unit, is areal and stored as a polygon. Associated with each line and each polygon is an attribute table in which a variety of parameters are listed. Parameters include, for example, line length, location, network identification, stream order, geologic unit, and age. Tic marks indicating the latitude and longitude at the corner of each map were also scanned into the system to provide locations. Once the data were digitized, it could then be transformed into any desired projection.

The network file contains over 827 networks that have more than one branch, and almost 8000 branches, each with an attribute file. The outflow and fretted channels files are somewhat smaller. Because most of the networks are narrow, they are stored mainly as single lines. Extensive editing was required after digitizing to remove artifacts introduced during the scanning and creation of the arcs. In particular, every network was examined to ensure that every link in the network was represented by a single arc, not multiple arcs. Some valleys, such as Ma'adim, are wide enough that they can be represented as areas. To facilitate analysis, two network files were created, one in which the valleys are represented either as lines or polygons according to their width, and another file in which all valleys are represented as lines irrespective of their width. Outflow and fretted channels, being wider than the networks, are stored mostly as polygons. The vector format permits storage at a resolution equivalent to that of the original mapping (i.e., 1:2M), yet allows display at any other resolution. The CD-ROM versions of the US. Geological Survey topography and 1:15M geologic maps were also incorporated in the system for comparative purposes. Although most of the data are stored as vectors, raster data such as images can also be used. The various data sets (networks, outflow channels, topography, geology, images) form different layers within the system and can be merged in any desired combination, and selected subsets of the data (e.g., Hesperian networks with more than 10 branches) can be readily displayed.

In the literature, the drainage features of Mars have been variously described as outflow channels, fretted channels, runoff channels, valley networks, dendritic channels, and furrows. Some of these terms have important genetic implications, and their use can cause confusion. The distinction between a fluvial channel and a fluvial valley is of particular importance. A river channel is a conduit that at times is filled or almost filled with water. Its width is comparable to the river itself. A river valley is a linear depression that almost always contains river channels. Valleys are generally much larger than the river and stream channels that they contain and rarely, if ever, come close to being filled by water. Rivers may change their course, thereby causing channels to branch and rejoin. Valleys are fixed but may widen or be encroached upon as a result of competition between adjacent valleys.

Here a simple fourfold classification of the drainage features was adopted.

1. Outflow channels start several to tens of kilometers wide, at discrete sources. They have few, if any, tributaries, but may divide into multiple branches downstream. Many outflow channels, particularly those around the Chryse-Acidalia basin, expand where they cross the plains, to scour ill-defined areas hundreds of kilometers across. Dark, sinuous markings, downstream from larger channels, particularly in the Utopia and Arcadia Planitiae, are also included in the outflow file.

2. Most fretted channels branch upstream and increase in size downstream. They differ from the networks in that they have floors several to tens of kilometers across on which longitudinal striations can commonly be observed. The floors are mostly flat and the walls steep. Debris flows are common at the bases of walls.

3. Valley networks are composed of narrow (mostly <3 km wide), mostly sinuous depressions that generally increase slightly in size downslope and divide into smaller branches upslope. Many narrow sinuous depressions with no branches are also included.

4. Lava channels are long linear channels that occur only

in volcanic terrain. They commonly have levees and few, if any, branches.

A drainage feature cannot always be unambiguously assigned to one of the four categories. Ma'adim Vallis (20°S, 183°W), for example, has network characteristics in its upper reaches but resembles a fretted channel for part of its length. Mawrth Vallis (20°N, 15°W) has characteristics of both outflow channels and networks. Many fretted channels have linear networklike sections in their upper reaches. These ambiguous features were left undifferentiated but could be included in any group for analysis. While the networks and channels were being mapped, the top of the Noachian was also mapped, as were other features such as canyons and chaotic terrain that might be important for interpretation. Because of ambiguities inherent in geologic mapping from satellite imagery, the extent of the outflow channels and the Noachian terrain differs slightly from that depicted on the published 1:15M geologic maps [*Scott and Tanaka*, 1986; *Greeley and Guest*, 1987].

Outflow Channels

Outflow channels start mostly within four large areas (Figure 1): north and east of the Valles Marineris, northwest of Elysium, the east side of Hellas, and along the south and western edge of the Amazonis-Arcadia basin. Those east and north of the canyons drain into the Chryse-Acidalia basin. Where the channels cut the uplands, they tend to be sharply delineated, but where they cross the Chryse and Acidalia plains their exact extent is difficult to discern. As a result, the areas of Chryse Planitia and Acidalia Planitia depicted as scoured during channel-forming events in Figure 1 differ somewhat from the depictions of *Scott and Tanaka* [1986] and *Scott et al.* [1994]. Several large outflow channels start northwest of the Elysium volcanoes and drain northwestward into Utopia Planitia. While the upstream parts of these channels are clearly delineated depressions, the downstream parts are recognizable simply as dark, sinuous, discontinuous linear features. Similar dark, sinuous markings in northern Arcadia Planitia are also assumed to be outflow channels. The outflow channels are preferentially located in the lowest parts of Mars (Figure 2). Transection relations and crater counts [*Masursky et al.*, 1977] indicate that outflow channels have a wide range of ages, spanning most of Mars' history.

The outflow channels present the most convincing evidence for massive amounts of groundwater on Mars. Most of the outflow channels are believed to have formed by large floods [*McCauley et al.*, 1972; *Baker and Milton*, 1974], and although alternative hypotheses have been suggested, the cumulative evidence for floods appears overwhelming (for summary, see *Baker et al.* [1992]). Many outflow channels start full size at rubble-filled depressions. The relations suggest that most floods formed by massive eruption of groundwater and that during the floods, the aquifers were partly disrupted and carried along in the flood. After, or during the floods, the ground collapsed to fill the void caused by evacuation of the groundwater and aquifer materials [*Carr*, 1979]. The channel dimensions indicate discharges that ranged up to 10^7–10^9 m^3 s^{-1} [*Baker*, 1982; *Komar*, 1979; *Carr*, 1979; *Robinson and Tanaka*, 1990] as compared with 10^5 m^3 s^{-1} for the peak discharge of the Mississippi River. Such massive release of groundwater suggests that,

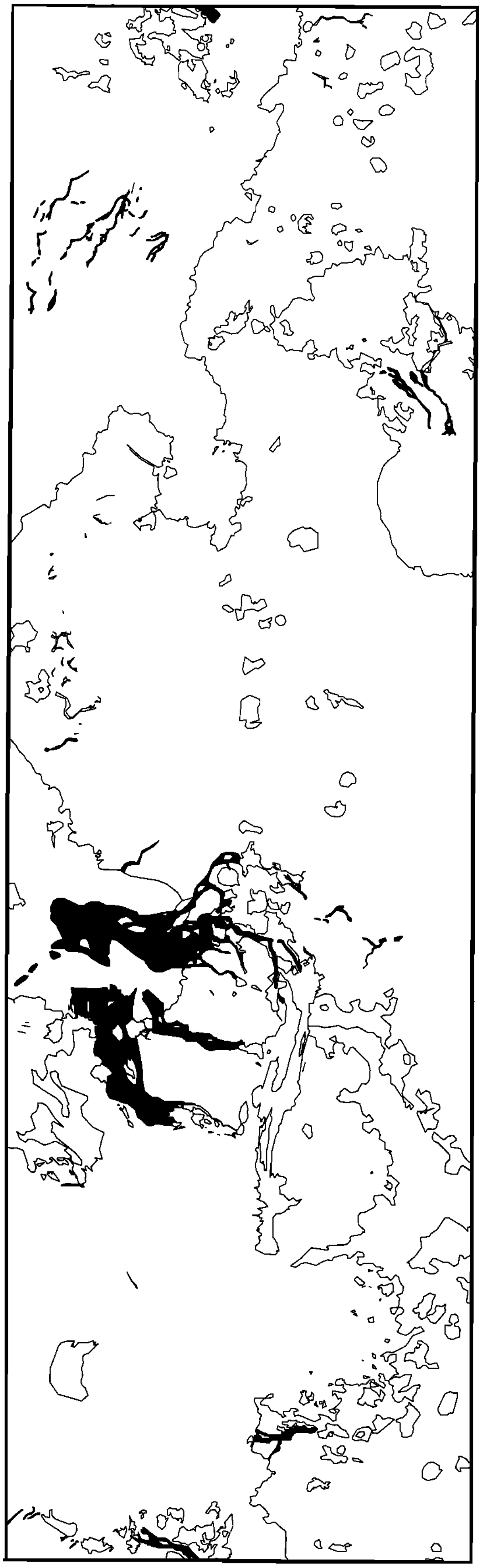

Figure 1. Outflow channels in the ±47.5° latitude band; 0° longitude is in the center. The channels drain mainly into three areas: Amazonis-Arcadia on the left, Chryse-Acidalia in the center, Hellas lower right, and Utopia upper right. The Noachian boundary, the Valles Marineris and areas of chaotic terrain are outlined for reference.

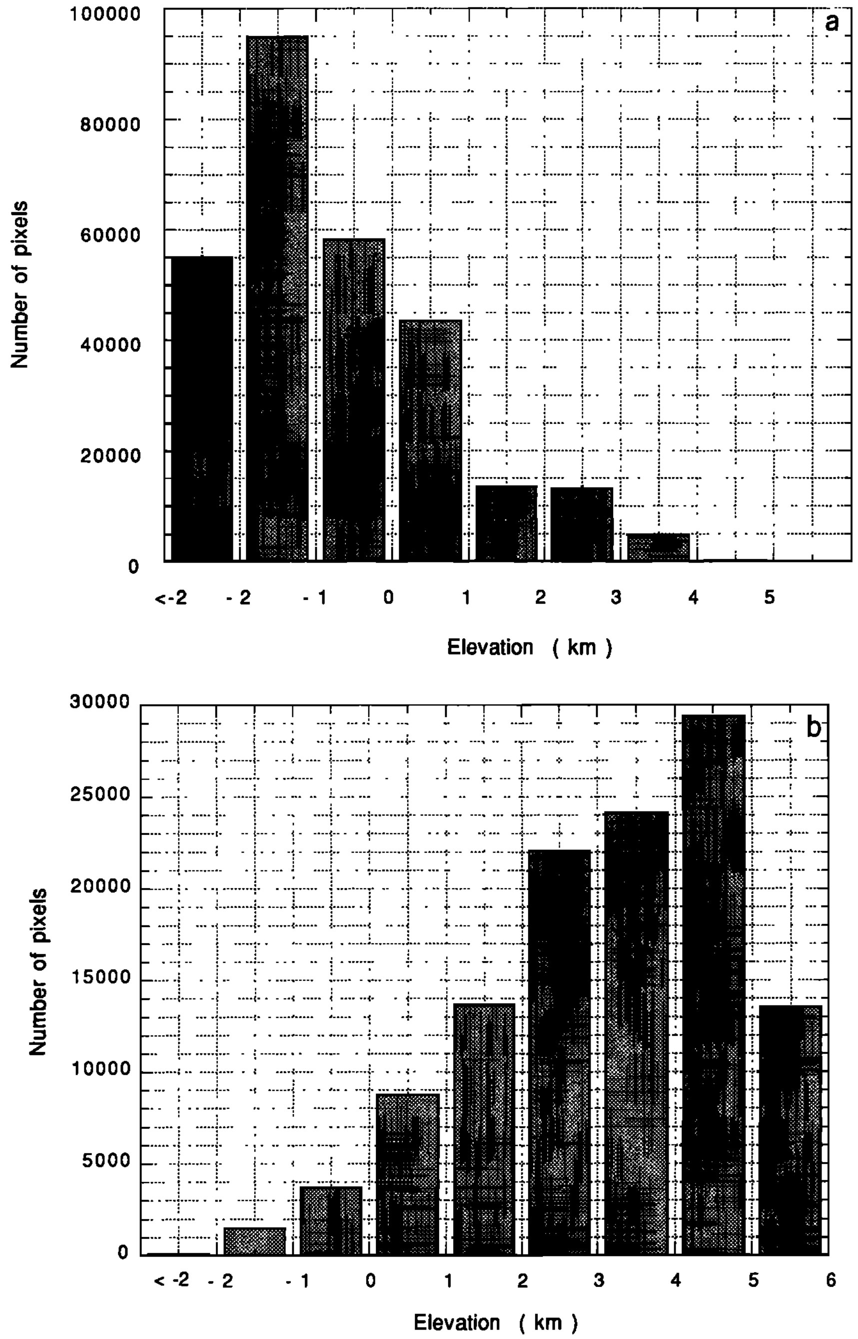

Figure 2. Distribution of channels by elevation. The number of 1/16° pixels in which a channel occurs are plotted against elevation. (a) Outflow channels. (b) Dendritic networks. Shows the preponderance of outflow channels at low elevations and dendritic networks at high elevations.

prior to release, the groundwater was contained under very high artesian pressure. High artesian pressures could have developed in low areas, where the outflow channels are preferentially located, by slow migration of groundwater toward these areas under a thick permafrost seal [*Carr*, 1979]. Subsurface melting of ground ice by volcanic heat could also have contributed to local and regional accumulation and migration of groundwater [*Baker et al.*, 1991], as suggested by the location of many outflow channels around the periphery of Tharsis and Elysium. In places, migration of groundwater appears to have concentrated along faults, as indicated by the fault origins of Mangala Vallis and several outflow channels in Elysium. Not all the large floods need have been caused by breakout of groundwater. *Robinson and Tanaka* [1990] suggest that Kasei Vallis formed by drainage of a former lake in Echus Chasma. *McCauley* [1978] suggested that some of the large channels east of Vallis Marineris formed by catastrophic release of water that had ponded within the Valles Marineris. *Scott et al.* [1992] suggested that a large unnamed channel, near the 180° meridian west of Amazonis Planitia, formed as a result of drainage of a lake in southern Elysium Planitia, and *Anderson* [1992] and *Chapman* [1994] suggested that the Granicus Valles, west of Elysium, formed beneath thick ice deposits

Figure 3. In this area, north of Ganges Chasma, the surface appears to have fractured and collapsed into a linear depression leading northward to Shalbatana Vallis, which is off the picture to the north. The relations suggest subsurface drainage of a former lake in Ganges Chasma, the drainage being accompanied by subsurface erosion and/or solution. The large crater that intersects the north rim of Ganges Chasma is 28 km in diameter (897A35-40).

as a result of volcanic activity. *MacKinnon and Tanaka* [1989] propose further than debris flows may have played a prominent role in the formation of outflow channels.

Direct evidence for massive channelized subsurface flow of water is seen in several areas. Figure 3 shows an area where the surface appears to have collapsed to form a 40-km-wide linear depression that extends from Ganges Chasma in the south northward to an area of chaotic terrain that is the source of Shalbatana Vallis. Sediments within Ganges Chasma suggest it formerly contained a lake [*McCauley*, 1978; *Nedell et al.*, 1987]. Collapse of the surface appears to been into a subsurface conduit. The conduit could have formed as a result of subsurface drainage northward from the lake. Similar subsurface drainage is likely for the completely enclosed, partly sediment filled, Hebes Chasma, although in this case there is no evidence of surface collapse.

Not all channels that form full size at a local source and branch downstream are necessarily formed by massive catastrophic floods. The Haephestus Fossae (Figure 4) and Hebrus Valles in Elysium both start at local sources and have streamlined sections upstream, but divide downstream to form a rectilinear network of depressions. Many of the downstream branches of the network are discontinuous, consisting of lines of pits. Similar features on Earth are found mainly in Karst regions [e.g., *Palmer*, 1990], where subsurface flow is channeled through structurally controlled conduits formed by solution of limestone. Subsurface conduits can also form by erosion, although at a much smaller scale, as for example in the loess deposits of China [*Fuller*, 1922]. The lower reaches of the Haephestus Fossae are clearly not formed by flow along the surface but more likely by subsurface flow accompanied by erosion and/or solution.

Formation of the outflow channels must have resulted in the formation of standing bodies of water. As can be seen from Figure 1, most of the outflow channels discharge into the low-lying northern plains of Acidalia Planitia and Utopia Planitia. *Parker et al.* [1989, 1993] pointed out that several features in these plains and the more northerly plains of Vastitas Borealis could plausibly be interpreted as former shorelines and postulated that lakes were formerly present in these areas. *Scott and Chapman* [1991] and *Scott et al.* [1992] have pointed to additional shorelines elsewhere and identified 15 basins larger than 10^5 km^2 in area that could formerly have contained lakes. Under present climatic conditions, such lakes would rapidly form an ice cover. They could stabilize if fed by meltwater or groundwater [*McKay and Davis*, 1991]. However, if not fed, a lake at low latitude will sublime away, whereas a lake at high latitude would freeze and become a permanent ice deposit [*Carr*, 1990].

Baker et al. [1991] suggest that vast areas of the low-lying northern plains were at times inundated as a result of floods. Their sketch map shows oceans filling the northern plains to roughly the 0-km contour, which would imply 6×10^7 km^3 of water. Such a large body of water could not form from single floods, of even the magnitudes seen on Mars, and so *Baker et al.* [1991] proposed that many floods occurred simultaneously. For example, peak discharges for the largest floods are estimated to be roughly 10^9 m^3 s^{-1} (see above). Floods, whether formed by massive release of ponded water, or groundwater under pressure, are likely to be short lived because of drainage of the reservoir or because of fall in artesian pressure in the aquifer. A flood with peak discharge of 10^9 m^3 s^{-1} that declined with a half-life of 1 week would discharge 8×10^5 km^3 of water, or enough to create roughly a 1000 × 1000 km lake, 1 km deep, a far smaller body of water than proposed by *Baker et al.* [1991], although comparable to those proposed by *Scott et al.* [1992].

Thus, outflow channels provide strong evidence for a pervasive groundwater system, but their formation may not require climatic conditions significantly different from the present. Finally, the outflow channels provide the best geologic means for estimating the amount of water near the

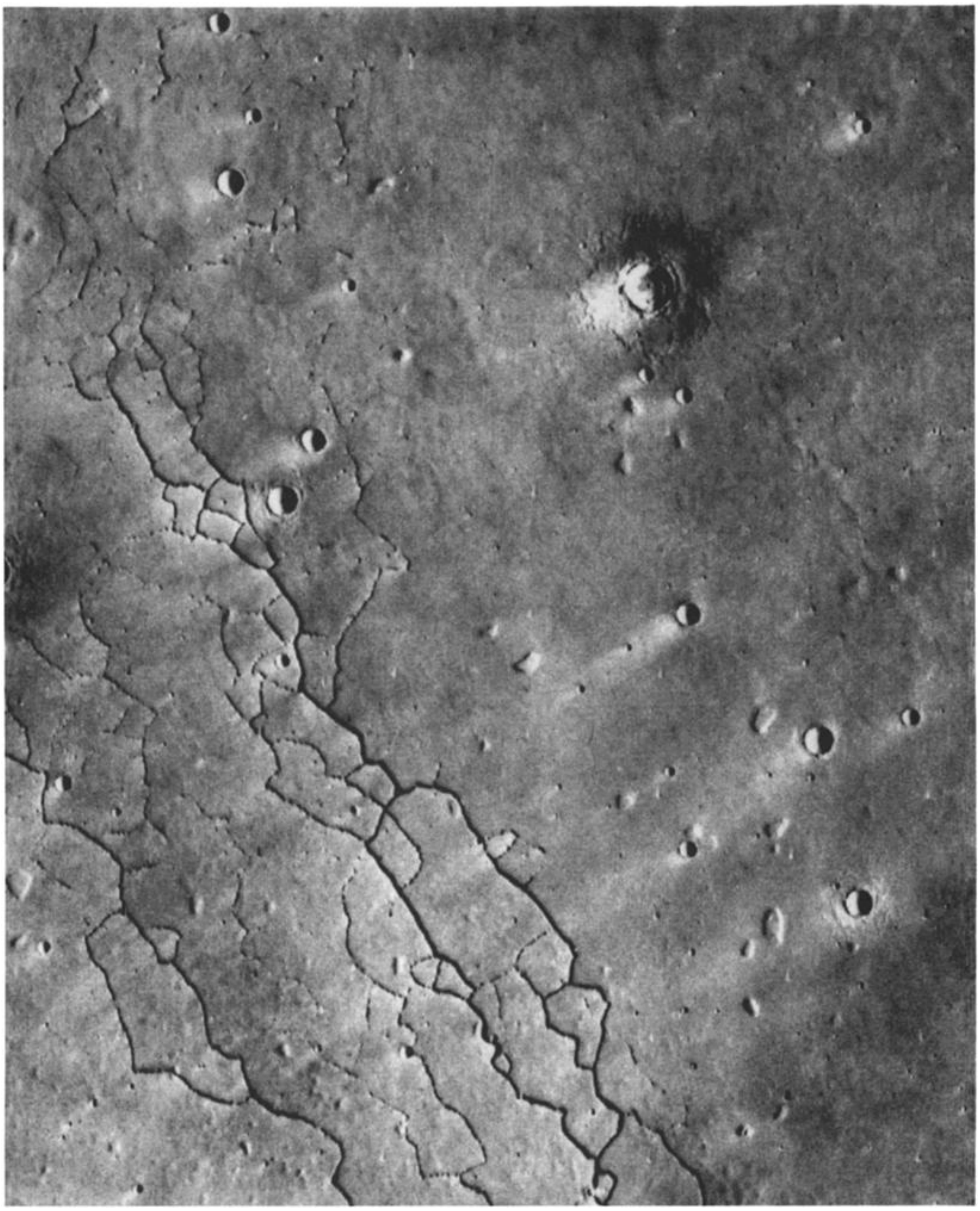

Figure 4. Subsurface erosion and/or solution in the Haephestus Fossae. The Haephestus Fossae have fluvial characteristics upstream and tectonic characteristics downstream, as seen here. The channel starts at a single source and branches downstream. The downstream branches form a rectilinear pattern with many branches consisting of lines of depressions. The pattern resembles that seen in terrestrial karst terrain and suggests subsurface erosion and/or solution (381S13).

Martian surface, and these estimates range up to 1 km spread over the surface [*Baker et al.*, 1991; *Carr*, 1986]. For summaries of how the geologic estimates compare with other estimates, see *Carr* [1986, 1987] and *Fanale et al.* [1992].

Fretted Channels: Origin by Mass Wasting

Fretted terrain is the term applied to a region along the plains-upland boundary between roughly 290–360°W and 30–50°N, in which the low-lying plains to the north complexly interfinger with the uplands to the south, thereby isolating numerous islands of upland surrounded by 1- to 2-km-high escarpments [*Sharp*, 1973]. Almost everywhere within the fretted terrain, debris aprons (Figure 5), with sharply defined flow fronts and convex upward surfaces, extend from the escarpments across the adjacent plains for distances up to 20 km [*Squyres*, 1978]. In contrast to terrestrial debris flows, which form suddenly on water-saturated slopes [*Johnson*, 1970], the debris aprons more likely formed slowly [*Squyres*, 1978; *Lucchitta*, 1984], and may be akin to terrestrial rock glaciers, whose mobility is enabled by the presence of interstitial ice [*Wahrhaftig and Cox*, 1959]. Of primary interest here is the origin of broad (up

Figure 5. Debris aprons surrounding massifs in the fretted terrain at 46°N, 311°W. The aprons are clearly delineated by a convex upward outer margin roughly 20 km from the massifs (338S31).

to 20 km wide), flat-floored, steep-walled valleys (fretted channels) that reach deep into the upland, for they, like the debris aprons, may have formed largely as a consequence of mass wasting. Many of these valleys have longitudinal ridges (84A73) and striae on their floors (231S42) or a broad, complexly eroded central strip (412B65, 461B14).

The debris aprons surrounding mesas and massifs and on the valley walls are the most recent products of erosion in the fretted terrain. Crater counts of *Squyres* [1978] indicate that those in Nilosyrtis date from roughly the base of the Amazonian. The Protonilus flows are younger but cannot be dated because of the scarcity of craters. A major question is whether the processes that formed the debris aprons are also responsible for the gross dissection of the fretted terrain to produce the complicated pattern of mesas and channels. Where unconfined, the debris aprons have clearly delineated outer margins (675B42, 338S31, 97A62) roughly 20 km from the source. The aprons may be presently active and still moving, having reached only 20 km from their source because of the limited time since they started to flow. Alternatively, the aprons may be stable, having reached an equilibrium configuration. Irrespective of which alternative is true, the most recent episode of mass wasting represented by the debris aprons is unlikely to be responsible for formation of the fretted terrain because, to form the terrain, material must be transported for distances far greater than 20 km, and scarps must have retreated for distances far greater than the 5 km implied by the dimensions of the aprons [*Squyres*, 1978].

Where aprons from opposing walls meet, as in valleys, compressional ridges form [*Squyres*, 1978], and it is clear that some of the longitudinal ridges in the valleys formed

Figure 6. Fretted terrain at 35N, 334W. Lines of closed depressions, and fracturing and collapse of the surface suggest subsurface erosion and/or solution. The image is 169 km across (567A08).

simply by the meeting of opposing aprons. But not all the longitudinal features have formed this way. *Lucchitta* [1984] points out cases where striae from the walls curl downstream and become longitudinal striae. She further shows examples where the longitudinal features in the center of the main valley transect striae from side valleys. These longitudinal features almost certainly formed by down-valley flow. The continuity of the striae from the walls with the longitudinal striae suggests that mass wasting has both removed material from the walls and carried it down the valley.

Mass wasting cannot explain all characteristics of the fretted terrain. Removal of subsurface materials followed by undermining and collapse also appears to have played a significant role in the development of fretted channels [*Lucchitta*, 1984]. In Figure 6, several interconnected but partly enclosed depressions merge northward into a continuous fretted channel. In several sections, subsurface drainage has created a conduit into which the roof has collapsed (see also 205S16), leaving fractured sections of the roof in a depression. The collapse features here are similar to that described in the previous section and attributed to collapse into an underground drainage channel from Ganges Chasma to Shalbatana Vallis. Completely enclosed channels also suggest subsurface erosion or solution. A particularly prominent example of a completely enclosed fretted channel, 100 km long and 10–20 km wide, is seen at 38°N, 33°W (567A09). In view of the other evidence for subsurface removal of material, and the lack of supporting evidence of deflation, removal of subsurface material by groundwater erosion (piping), solution, and/or sublimation is favored for the origin of the closed depressions. The closed depressions and collapse features are therefore supporting evidence for former movement of groundwater in the region.

The general geometry of the fretted terrain suggests ex-

Figure 7. Fretted channel with tributaries at 33°N, 341W. The tributaries have alcovelike terminations as expected of a sapping origin, but neither the tributaries nor the main channel shows any indication of the presence of a river valley. The relations are more suggestive of sapping by mass wasting than sapping by fluvial processes.

tensive planation by some form of scarp retreat [*Sharp*, 1973]. The planation is unlikely to have been by the same process that caused the debris aprons, operating under the same conditions, because of the limited distance that the debris flows have transported material from the escarpments. Many of the fretted channels have attributes of sapping, such as alcovelike terminations of tributaries, U-shaped or rectangular-shaped cross sections, and no dissection of interfluves (Figure 7). However, none of the fretted channels in Figure 7 or elsewhere show evidence of fluvial erosion. They do not contain river channels, and the complex texture of their floors indicates clearly that the flat floors are not floodplains. Headward erosion at the head of the channels must have proceeded at a faster rate than recession of the channel walls in order for the channel to form.

One possibility is that the fretted terrain formed early in the planet's history, mostly as a result of mass wasting along scarps, accompanied by water-lubricated creep of the resulting debris (Figure 8), and subsurface erosion and solution. In other words, headward extension of the stubby tributaries in Figure 7 was by mass wasting aided by movement or presence of groundwater, as with most terrestrial valleys that form by sapping, but the resulting debris moved downvalley by mass wasting not by fluvial transport, as is the case with most terrestrial valleys. Headward extension of the valleys was favored by the convergence of groundwater flow, and the consequent enhanced undermining of slopes at valley heads, analogous to the way that terrestrial fluvial valleys extend themselves by groundwater sapping [*Dunne*, 1990]. As conditions changed, because of a declining heat flow [*Schubert et al.*, 1992], but also possibly because of climate change, the 273°K isotherm no longer intersected the base of the debris flows, and the former liquid-lubricated flows stabilized (Figure 8). Talus subsequently shed from escarpments formed the viscous, markedly convex upward, probably ice-lubricated flows that we currently observe, the ice being derived from ground ice in the uplands [*Lucchitta*, 1984]. The transition from water-lubricated to ice-lubricated flows also resulted in major decline (to almost zero) in the rates of scarp retreat, planation, and headward erosion of the valleys. Formation of fretted terrains along the plains upland boundary in the 30–45°N latitude belt may have been favored by large local relief, drainage of groundwater northward

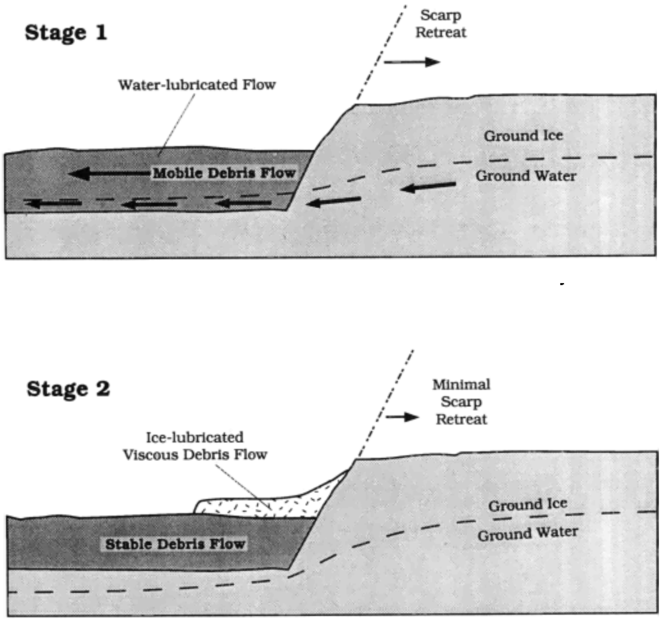

Figure 8. Cartoon of suggested mechanism for formation of the fretted channels. In stage 1, debris shed from slopes is mobilized by seepage of water into the debris, and headward erosion and scarp retreat are relatively efficient. In stage 2, water can no longer seep into the debris because of a change in heat flow or surface conditions, down-channel flow of debris is inhibited, and ice-lubricated debris aprons develop.

toward the plains-upland boundary (Figure 9), and by longer retention of ground ice (and groundwater at greater depths) near the surface at these high latitudes because of the lower loss rates by sublimation [*Fanale et al.*, 1986].

Groundwater is essential to facilitate creep and allow the eroded debris to travel long distances. Movement of fragmental debris is controlled by friction at the grain contacts. In a dry soil the compressive stress (mostly due to the weight of the overlying material) is distributed among the grain contacts, and for most materials, as the compressive stress increases, the shear strength increases proportionately, the proportionality depending on the coefficient of friction of the material [*Brunsden and Prior*, 1984]. With a pore fluid, part of the compressive stress is borne by the fluid and part by the solid skeleton. The compressive stress borne by the skeleton is commonly called the effective compressive stress [*Terzaghi*, 1943]. As pore pressure increases, the fraction of the compressive stress borne by the fluid increases, and the compressive stress at the grain boundaries correspondingly decreases. Since the fluid has no shear strength and the resistance to movement at grain boundaries decreases with decreasing compressive stress, the effect of a pore fluid is to decrease the shear strength of the material. Ultimately, as the pore pressure increases, the material loses its shear strength and liquifies.

As already mentioned, linear closed depressions, collapse of the surface, and presence of an outflow channel (36°N, 350°W) all point to the former existence of groundwater in the fretted terrain, and groundwater is expected as a result of global migration of water toward low areas (Figure 9). Groundwater leaking into the bases of debris flows in the fretted terrain may have so diminished their shear strength that the eroded materials could flow for long distances down the valleys. Presence of a permafrost zone may have enhanced the process by containing the groundwater, thereby enabling pore pressures to build, but the process may also work without a thick permafrost zone. Movement was likely slow, the result of jostling of the debris by temperature fluctuations, by seismic shaking, and by variations in the fluid pore pressures. When the temperature regime changed, and the base of the debris flow froze, then the process of deformation and flow would have been very different. The shear strength of the flow would have been dependent of the combined shear strengths of ice and the rock skeleton, the combination depending on the configuration of the ice and rock materials. In this case, in contrast to the water case, the interstitial material (ice) has a finite shear strength, and so flow is inhibited, particularly on low slopes, although flow could still continue at very low rates [*Lucchitta*, 1984]. The water-lubricated flows and ice-lubricated flows will be examined in detail in a subsequent paper.

Valley Networks

Valley networks are the most common drainage feature on Mars and the one most commonly cited as evidence for former warm and wet climatic conditions. In this section the characteristics of the networks are described in detail. The intent is to assemble the various attributes of the networks and assess what they imply about their origin. It will be argued that the networks have many attributes in common with fretted channels, and may have formed by similar processes, that is, mainly by mass wasting of water-lubricated flows and not by fluvial action. The distinction is of fundamental importance, for with fluvial erosion, the ratio water volume to eroded volume may be as high as 1000:1 [*Gulick and Baker*, 1993], whereas for a slowly moving debris flow with water slowly percolating through its base the ratio is likely to be significantly lower. Moreover, with debris flows, water need not be stable at the surface.

Distribution

Figure 10 shows the distribution of valley networks between 47.5°N and 47.5°S. As has long been recognized, the networks are found mainly in the heavily cratered uplands, the oldest terrains exposed on the Martian surface. These terrains date from the period of heavy bombardment and are designated Noachian in age. To demonstrate the dominance of networks in the Noachian, the map area was divided into 1/16° pixels, and all the pixels that contained a network were identified. Of these pixels, 92% were in the Noachian. However, as will be discussed below, it does not follow that 92% of the networks are Noachian in age. Many of the networks on units younger than Noachian are on volcanoes, particularly Alba Patera. Not all Noachian-aged surfaces are heavily dissected by networks. Arabia Terra, north of the equator, between 340°W and the Chryse and Acidalia Planitiae, is almost devoid of networks. Networks are also sparse in the Noachian of Arabia north of 15°N, between 300° and 340°W, around the Hellas basin, and in Memnonia, between 150° and 180°W. Because most of the uplands are high, the networks are preferentially located at the higher surface elevations (Figure 2b). Within the Noachian itself, networks are preferentially located at elevations of 2–5 km. To demonstrate this relationship, the map area was again divided into 1/16° pixels, and the total number of pixels containing

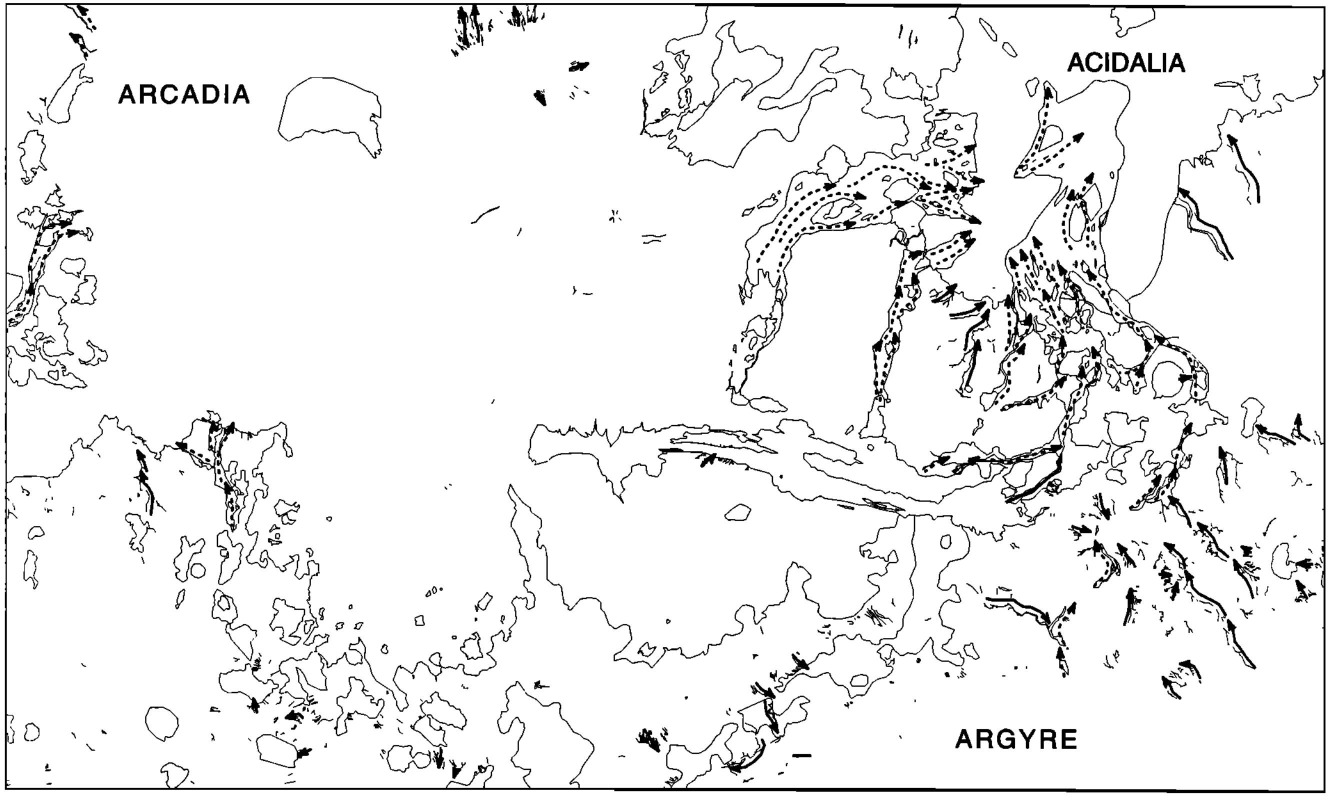

Figure 9a. Directions of flow indicated by the geometry of outflow channels (dashed arrows), fretted channels, and valley networks (solid arrows). Also shown for reference are the Noachian-Hesperian boundary, the Valles Marineris, and regions of chaotic terrain. Western hemisphere. Drainage is mostly toward Arcadia and Acidalia.

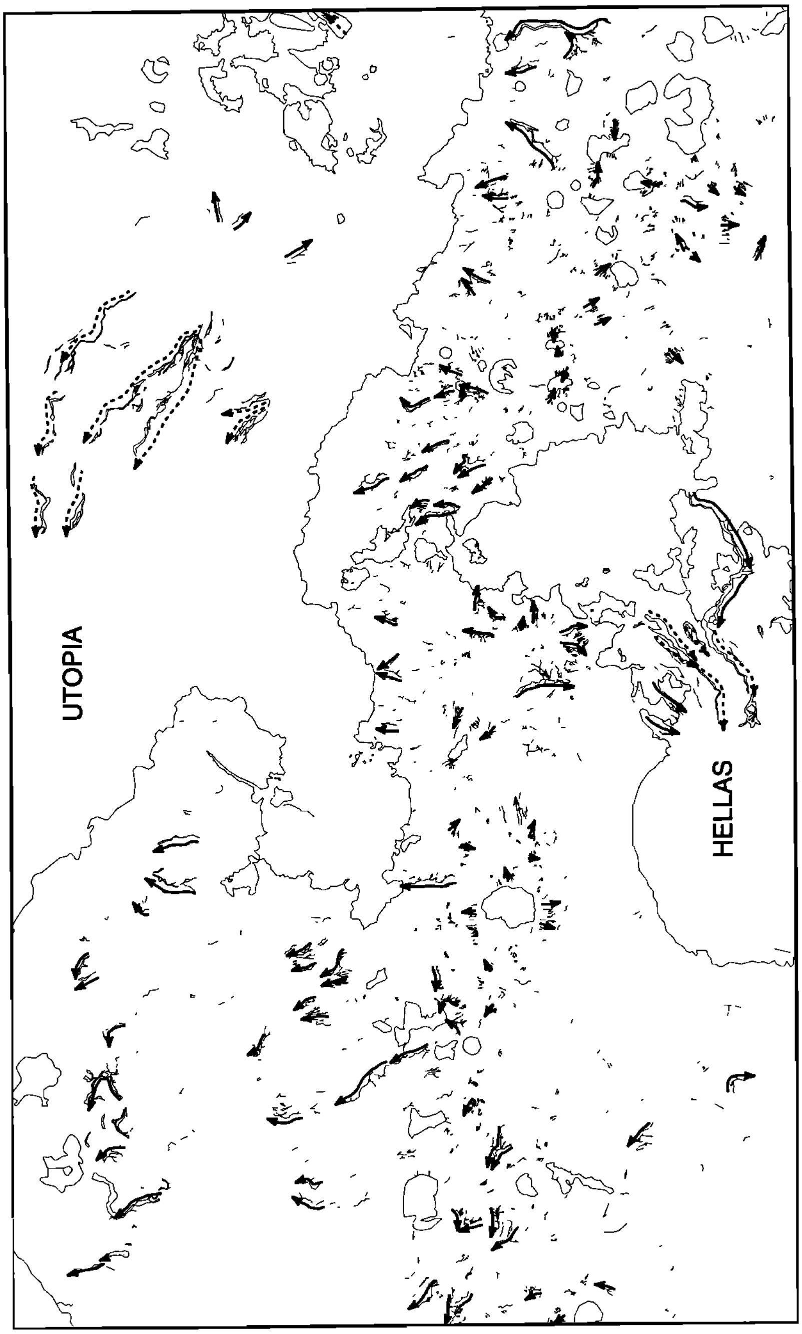

Figure 9b. Same as Figure 9a but for the eastern hemisphere. Drainage in the Noachian is mostly toward Hellas, and northward toward the plains-upland boundary.

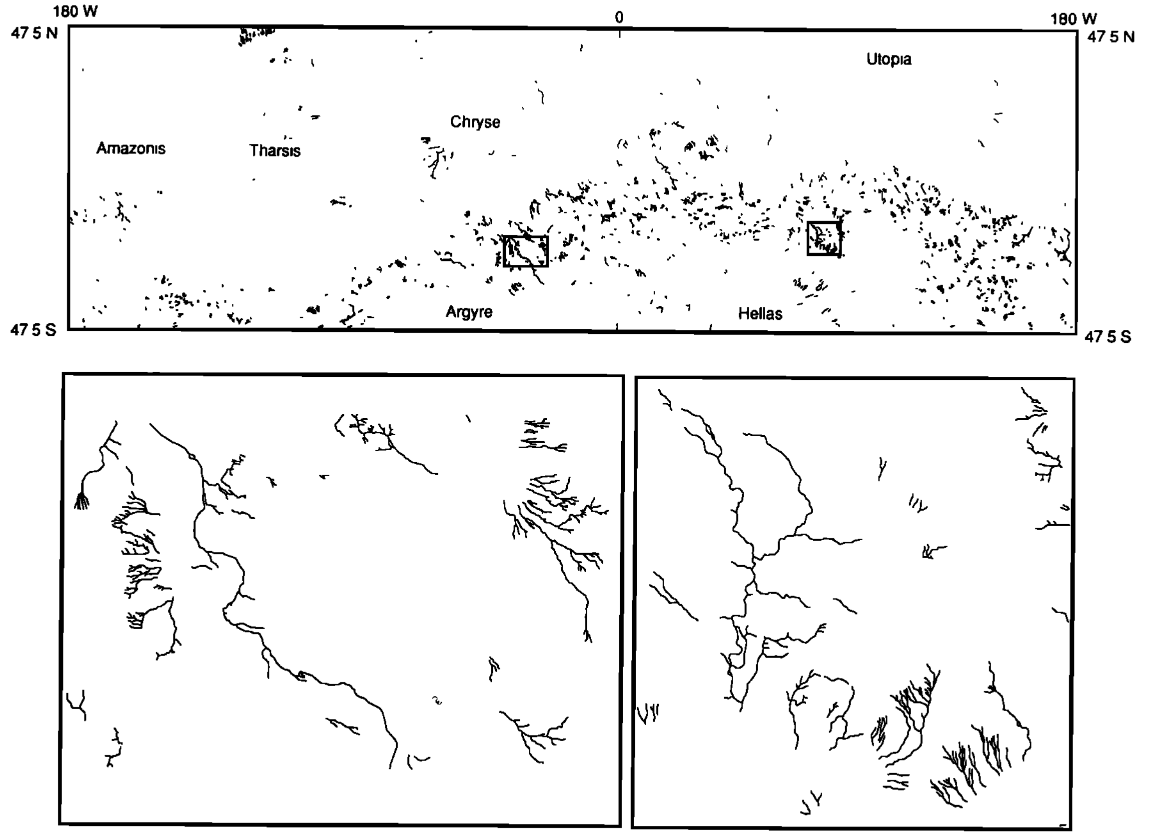

Figure 10. (Top) Distribution of valley networks in the ±47.5° latitude band. The 0° longitude is in the middle. Shows the concentration of networks in the uplands (compare with previous figure) and the disjoint nature of the drainage system. (Bottom) Details from the upper map give an indication of the resolution of the data in the GIS files. (Bottom right) Includes the area shown in Figure 14.

Noachian was determined (4.67×10^6), together with the fraction of these pixels at each elevation interval. The fraction of Noachian-containing pixels that also contained a part of a network was also determined as a function of elevation (Figure 11). For elevations higher than +1 km, 2.4% of the Noachian-containing pixels also contain a valley. For elevations lower than +1 km, only 0.7% of the Noachian-containing pixels also contain a valley. These percentages reflect the scarcity of networks in the low Noachian regions around Hellas and in western Arabia. Thus any hypothesis for the origin of the networks should account for both their preferential location in the Noachian and their preferential location in those parts of the Noachian at elevations greater than +1 km.

Even the regions of relatively high drainage densities are mostly poorly dissected. Local dissected areas are rarely more than 200 km across, and they are commonly 200–500 km from other dissected areas. This localization of the drainage within the dissected regions is the major cause of the speckled distribution pattern within the uplands seen in Figure 10. As previously noted [*Carr and Clow*, 1981], there appears to have been little or no competition between adjacent drainage basins. The pattern of dissection within the locally dissected areas varies greatly from open networks with few branches to dense networks in which adjacent branches can barely be resolved in the available images. Open networks are the most common.

Both local and regional patterns of dissection can be identified. Throughout the uplands are local highs, including rims of large craters, and local lows, such as crater floors and intercrater plains. Most of the local highs have a hilly or hummocky texture; most of the lows appear as smooth

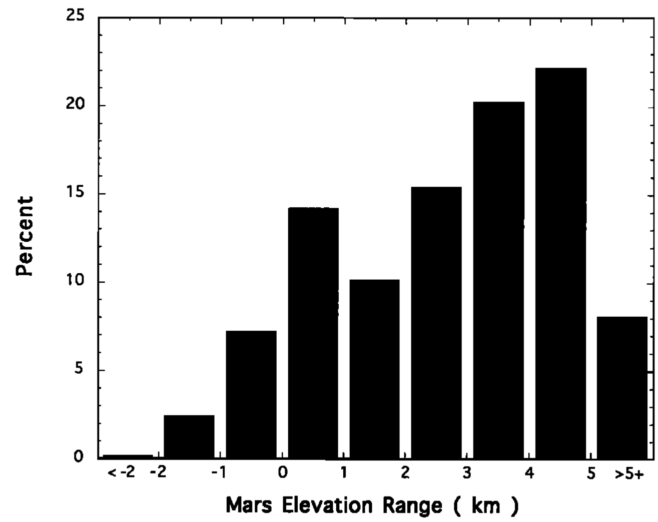

Figure 11. Percentage of 1/16° pixel in the Noachian that contain part of a valley network. Demonstrates the preferential location of networks within the Noachian at elevations of 1–5 km.

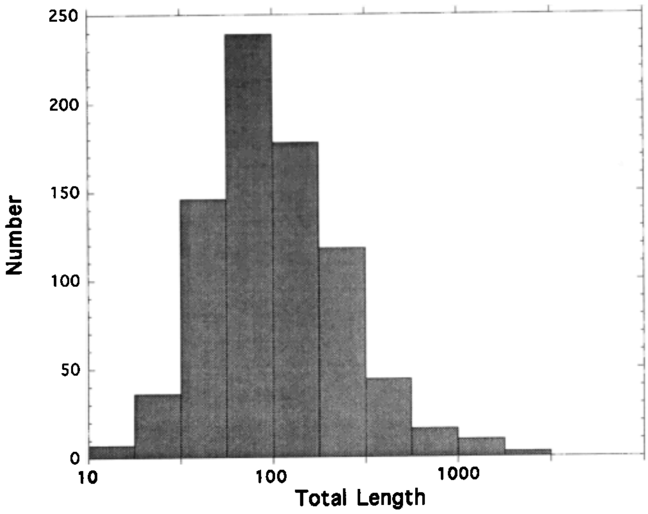

Figure 12a. Number of valley networks versus the total length of channels within the network. Emphasizes the limited size of the networks.

plains or ridged plains, at the scale of observation. Some networks terminate within craters but most start in local highs and drain into low areas between large craters, where they terminate abruptly against the smooth plains. Dissection of the smooth plains occurs, but is rare. Deposits are only rarely observed at the mouths of the trunk valleys.

The local nature of the drainage is demonstrated by Figure 12a. The total length of all the valleys within a given network averages about 100 km, although the total length within a few large ones is over 1000 km. A more significant number is the longest path through the network, from the most distant tributary to the downstream outlet, for this is the distance that eroded material must be transported. For 87% of the valleys, this distance, termed path length, is between 20 and 200 km (Figure 12b). Again, a few large networks have path lengths over 1000 km. The network with the longest path length is an unnamed network at 26°S, 17°W, that is, 1350 km long. These figures have probably been biased toward lower numbers by a variety of processes. Abrupt termination of downstream portions of many networks against smooth plains suggests that the lower reaches are buried and that the networks were formerly larger. In addition, the continuity of some networks is broken by superimposed craters, younger deposits, or simply poor imaging. We can, however, conclude that any mechanism for valley formation must allow for erosion of valleys up to 1000 km long but be such that, in most cases, development of the drainage system is arrested before the longest path length reaches 200 km.

The local drainage patterns are superimposed on a regional drainage pattern (Figure 9). In some areas the regional pattern dominates, in others the local pattern dominates. In Arabia, from 300° to 360°W, and along the plains/upland boundary from 180° to 270°W, the drainage is mostly northward, down the regional slope to the plains/upland boundary. In the Noachis region, from roughly 0°–40°S and 330°–20°W, drainage is mostly northwest, into the low-lying region of chaotic terrain east of the canyons and south of the Chryse basin. Within roughly 2000 km of the center of Hellas, drainage is mostly radial toward Hellas. The regional drainage patterns just described define four large areas in which drainage is toward Hellas, Utopia, Arcadia, and Acidalia (Figure 9). The areas are defined not just by the networks but also by the outflow and fretted channels, and clearly reflect variations in the global topography.

Channels that are unambiguously formed by lava are common on some of the large volcanoes. These are mostly a few hundred meters across. They are generally not observable at the 1:2M map scale, and so were not mapped. A few larger lava channels occur on the Tharsis plains. Several volcanoes, such as Alba Patera, Ceraunius Tholus, and Hecates Tholus, are heavily dissected by channels or networks.

Network Topology

Although considerable efforts have been made to extract information on geomorphic processes from the topology of terrestrial river systems, the efforts have met with little success. Nevertheless, topological techniques may be useful in quantifying differences and similarities between the Martian networks and terrestrial drainage systems. The quantitative approach to fluvial network analysis was pioneered by *Horton* [1945] and *Strahler* [1958]. In the Strahler method, streams are ordered as follows. The smallest fingertip tributaries are designated first-order streams. Merging of two streams of equal order u form a stream of order $u + 1$. Merging of streams of unequal order form a stream with an order the same as the highest order of the merging streams. The order of the network is the order of the highest order stream in the network, i.e., the trunk stream. A network can additionally be thought of in terms of links [*Shreve*, 1966; *Jarvis*, 1977]. Exterior links have a source upstream and a junction downstream; interior links have junctions upstream and downstream. First-order streams are single links; higher-order streams generally consist of multiple links. *Horton* [1945] formulated two laws pertaining to stream networks. The law of stream numbers states that

$$N_u = R_b^{k-u}$$

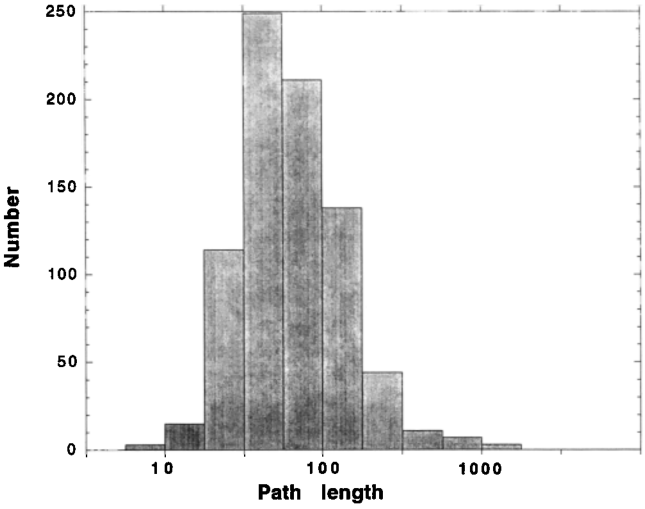

Figure 12b. Number of networks plotted against the longest path through the networks. Indicates the maximum distance that material must be transported to create the network.

where N_u is the number of streams of order u, in a network of order k. R_b, the number ratio, is called the bifurcation ratio. The law of stream lengths states that

$$L_u = L_1 R_L^{u-1}$$

where L_u and L_1 are the average length of streams of order u and 1, respectively. R_L is known as the stream length ratio. For a large number of terrestrial river systems, R_b ranges from 3 to 5 and R_L ranges from 1.5 to 3.5 [*Horton*, 1945; *Strahler*, 1964; *Shreve*, 1966, 1967; *Smart*, 1972].

The Martian networks appear to follow similar laws. Labeling the components of Martian networks according to order presents a problem in that the resolution of the available photography prevents discrimination of the smaller tributaries. The smallest branches with no visible upstream tributaries were labeled first-order valleys with the recognition that they may, in fact, be a higher order, having upstream tributaries not discernible in the available photography. The higher-order branches are probably similarly labeled with a lower order than their real value. However, for terrestrial networks, the bifurcation and stream length ratios are generally constant over a wide range of stream order, so a systematic offset in order should not affect the ratios. Figure 13 shows the number of branches and their lengths as a function of order for 14 large networks. For these 14 networks, the bifurcation ratios range from 2.9 to 7.6, with an average of 4.3, values very similar to terrestrial river systems. The variation of length with stream order is less systematic, the value of the length ratio ranging from 1 to 6.9. The large spread is a reflection of the statistic of small numbers. The fourth-order networks contain only one-fourth order valley, and no network has more than three third-order valleys. The average length ratio of 2.9 for these 14 networks is within the terrestrial range. The global values for the number ratio and the length ratio are 6.8 and 3.2, respectively, for the entire Martian data set. The high number ratio is caused by the large number of networks of order 1 (single valleys) or 2.

It is not clear whether these relationships have any value for determining what processes are responsible for network formation. *Shreve* [1966] pointed out that Horton's laws were properties expected of networks with topologically random configurations. He examined all possible configurations of networks of different order and found that the networks with the highest probability of occurrence are those that follow Horton's law of stream numbers with bifurcation ratios typically found in terrestrial streams. Similarly, by assuming that link lengths vary randomly and are independent of location within the drainage basin, he demonstrated that networks with random topology follow the law of stream lengths. The high probability of networks with stream length ratios of 1.5–3.5 follows because, in topologically random networks, streams of order $u + 1$ typically contain 1.5–3.5 times more links than streams of order u. Thus any process that causes random development of a network should result in an array of networks in which the most common are those that obey Horton's laws. Despite several decades of effort and numerous claims, no clear relationships have emerged that relate topological properties of terrestrial drainage networks to factors of geomorphic interest, such as basin relief, basin maturity, and climate (for summary, see *Abrahams* [1984]). The prospects of extracting information on processes from the topology of Martian networks are therefore bleak.

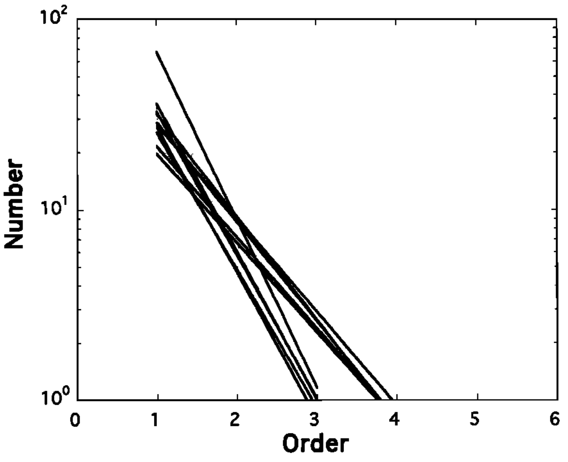

Figure 13a. Number of valleys versus valley order, according to the Strahler numbering scheme, for 14 large networks. The relations are similar to those for terrestrial streams.

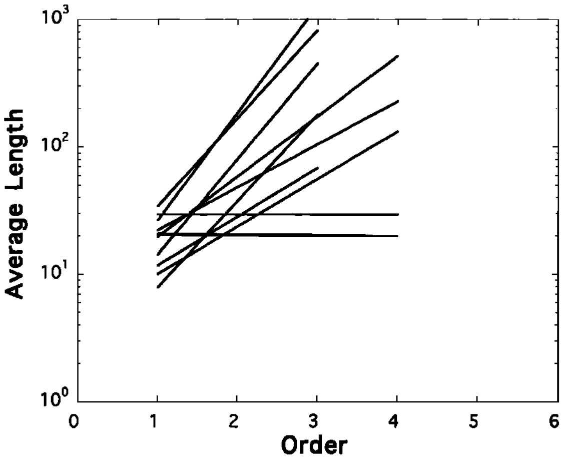

Figure 13b. Stream length versus order for the same networks in Figure 13a. See text for the significance.

The Martian networks have one topological feature not often seen in terrestrial drainage networks, at least at comparable positions within the network. This relationship is shown in Figure 14 and in the lower right panel of Figure 10. At several places within the network, branches split and then rejoin to form islands. The largest island is 20 km across. A splitting and rejoining of terrestrial river channels to isolate islands is, of course, common, and the smaller islands in this image resemble islands within a channel. However, deeply incised valleys on Earth do not normally branch with one branch striking across undissected country to rejoin the main valley tens of kilometers upstream. The simplest explanation of the relations seen here is that the valleys extended themselves by headward erosion and the random headward extension ultimately led to intersection of two valleys or channels that had formerly branched. The relations shown in Figure 14 are not uncommon in Martian networks (see, for example, 535A24, 615A43).

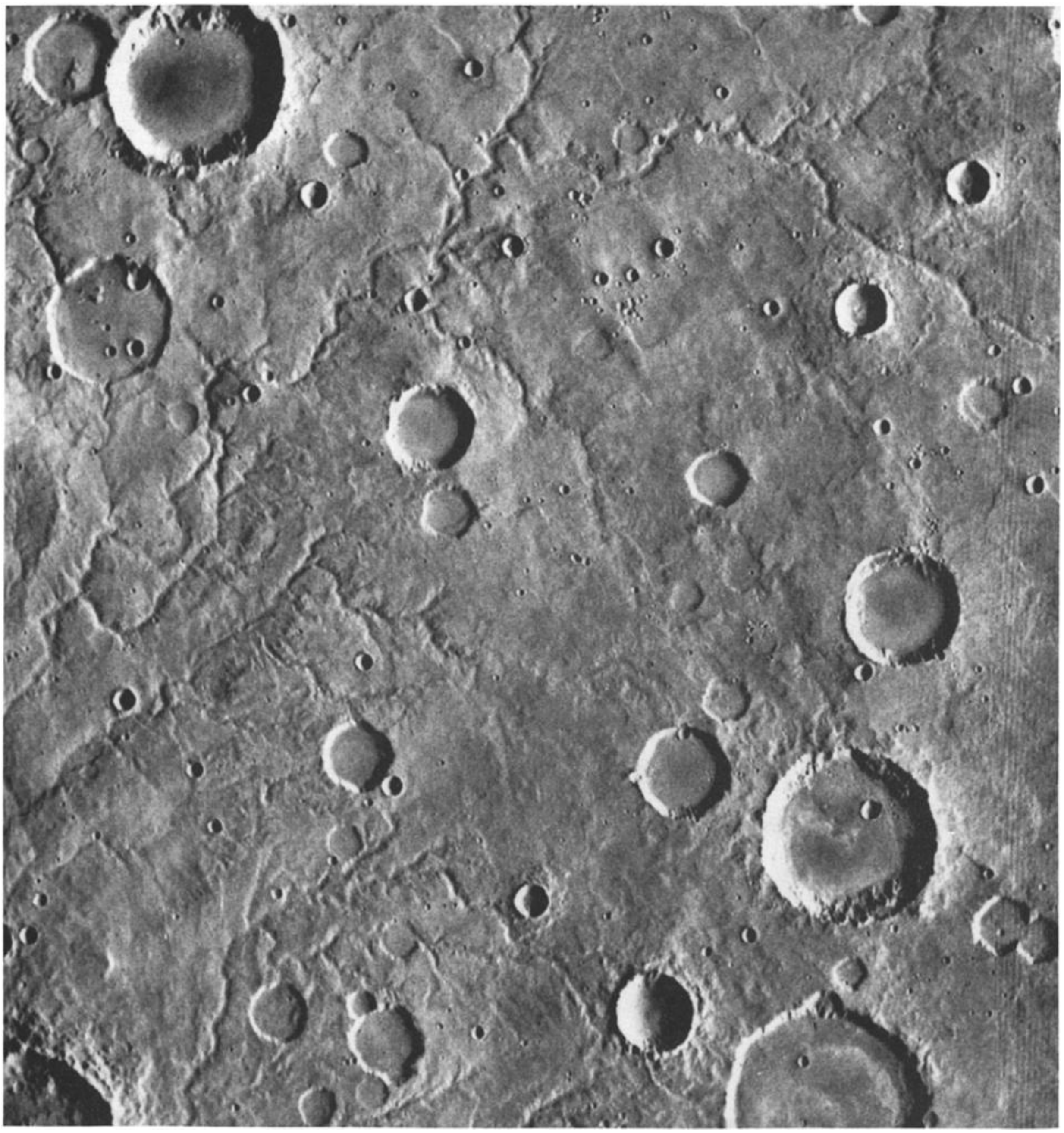

Figure 14. Valley networks at 20°S, 271°W. A large, deeply incised channel on the left branches and rejoins in a manner rarely seen with terrestrial valleys. The image is 271 km across (625A27).

Network Drainage Density

One network property that may be related to climate is drainage density. A number of workers have suggested that terrestrial drainage density (stream length per unit area) is related in some way to precipitation [*Abrahams*, 1984; *Gregory*, 1976; *Gregory and Gardiner*, 1975; *Madduma Bandara*, 1974]. If such a relationship exists, it is complicated, being effected by the presence of vegetation, the maturity of the network, and the precipitation pattern. Terrestrial values for drainage density are mostly in the range 2–30 km^{-1}. For the networks mapped in the more densely dissected parts of the Martian uplands, the equivalent figure is 0.005 km^{-1}. The large difference between these two numbers must be in part a reflection of the mapping scale. The terrestrial valleys are typically mapped at scales of 1:50,000 to 1:100,000; the Martian valleys were mapped at a scale of 1:2M. This is unlikely, however, to be the full explanation. The global network data set shows that the cumulative length of all streams of a given order increases by a factor of 5.2 for a unit increase in stream order. If we make the improbable assumption that all the valleys identified as first order are in fact fourth order, then the drainage density in the most densely dissected parts of the uplands would be 0.7 km^{-1}, still well below terrestrial values. These numbers emphasize the vast difference (2–5 orders of magnitude) in drainage density between the Earth and the Martian uplands, and cast suspicion on the supposition that the terrestrial and Martian networks formed by similar processes.

Network Ages

The problem of network age was referred to in the earlier background section. Tentative maximum ages were assigned to all the networks by examining their intersection relations with the published 1:15M geologic maps [*Greeley and Guest*, 1987; *Scott and Tanaka*, 1986]. The first step was to digitally compare the raster versions of the network and geology files and assign an initial age to a network on the basis of the youngest unit cut by that network. Because of the coarseness of the digital version of the 1:15M geologic map (1/16°), and problems of registration at the pixel scale, all networks close to boundaries were examined on 1:2M mosaics, and the initial age assignment confirmed or denied by inspection. The result was, of the 827 multichannel networks mapped, 34 were assigned a maximum age of Hesperian, the same number, 34, were assigned a maximum age of Amazonian, and the rest were assigned a maximum age of Noachian. In terms of stream length, 146,000 km of network components have a maximum age of Noachian, 8100 km have a maximum age of Hesperian, and 10,300 km have a maximum age of Amazonian. Most of the networks with a maximum age of Hesperian occur in the walls of Valles Marineris, around Argyre, and along the plains-upland boundary, particularly in Memnonia and between 230° and 260°W. Most of the networks with a maximum age of Amazonian are on Alba Patera, and other volcanoes in Tharsis and Elysium, and in the eastern half of the Hellas basin.

As indicated in the background section, determination of true relative age, that is, relating the age of a network to ages as defined by crater statistics [*Tanaka*, 1986], is very difficult, if not impossible, with the data available, although several attempts have been made [e.g., *Pieri*, 1976]. Most of the Viking images of networks have resolutions of 150–200 m. With these resolutions, only craters larger than about 1 km in diameter can be reliably counted, and most network branches are too narrow to have accumulated statistically significant numbers of craters of this size. A few high-resolution images are available on which smaller craters can be counted, but the production function of the smaller craters is not known, and such small craters are subject to removal by such processes as mass wasting and wind erosion or burial. The maximum ages assigned above from intersection relations are also suspect because of uncertainties in the geologic mapping. While extensive geologic deposits can confidently be assigned one of the three age groups on the basis of crater statistics, local deposits cannot. Most of the networks are in the cratered uplands. Many local lows within the uplands appear to be filled with deposits that abut abruptly against local highs, and the boundary between uplands and the younger deposits in the lows can be precisely determined. In many of these cases the deposits in the local lows are sufficiently extensive that they can be dated by crater counts, and most of the deposits in the lows appear to be Hesperian. Most networks terminate abruptly against these Hesperian deposits so the networks are probably Noachian in age. Elsewhere, however, the transition between upland and local lows is gradational, and the dating of networks that terminate in the low areas is very uncertain.

Despite all these uncertainties, some general statements can be made about the ages of the networks. The predominance of networks in the cratered uplands, the commonly observed abrupt terminations against local Hesperian deposits, and the general degraded appearance of networks when viewed at high resolution suggest that most networks are Noachian, although this has not been proven. Estimates of the fraction of younger networks range from 10% (previous section) to 30% [*Scott and Dohm*, 1992]. Most Hesperian networks occur where there is a large amount of local relief, such as in the walls of Valles Marineris and along the plains-upland boundary. The youngest, Amazonian networks are found mostly on volcanoes where slopes are high and high thermal gradients are likely. Small networks that may be post-Noachian in age are also incised into the walls of some large craters such as Cerulli [*Brackenridge*, 1993]. These age relations suggest that network formation was most efficient early in the planet's history, in the Noachian, but continued less efficiently into later epochs, particularly where abetted by high local slopes and/or high local heat flows.

Networks: Channels or Fluvial Valleys?

The distinction between channels and valleys has important genetic implications. Most terrestrial river valleys contain stream channels that normally are much smaller than the valleys themselves. Small streams, given time, can cut large valleys, but only large streams can cut large channels. The supposition that the valley networks are composed of fluvial valleys is based mostly on their planimetric form and on analogy with the Earth. Yet, there is little additional evidence that the valleys are, indeed, fluvial. Most network branches have flat floors and steep walls, and maintain a roughly constant width and depth over long distances. These are characteristics of fluvial channels rather than fluvial valleys. Widths are mostly a few kilometers and depths, mostly 100–200 m [*Goldspiel et al.*, 1993]. Terrestrial fluvial valleys may have flat floors downstream, but the upper reaches in the source regions are mostly V-shaped. This is not true of the Martian networks. If the branches of the networks are fluvial valleys, then they should contain fluvial channels. Channels within valleys are rare, despite some excellent imagery. One example is a small channel in the floor of Al Qahira (419S11), but the inner channel extends only a small way up the main channel, not all the way, as would be the case if it were the channel of the river that cut Al Qahira. The highest resolution images of networks show no traces of river channels on the flat floors of the network branches (e.g., Figure 15 and many others frames listed in the work by *Goldspiel et al.* [1993]). Long midchannel ridges (Figure 16) and leveelike ridges on the sides of the valleys (Figure 17; see also 437S31), occasionally seen in network branches, are never seen in terrestrial fluvial valleys. The leveelike ridges are particularly diagnostic, for they indicate former fluid levels within the channel. (Note that the linear features in Figure 17 are ridges, not breaks in slope or terraces.) In summary, there is no evidence, other than planimetric forme, that the networks are fluvial valleys, and strong evidence that some, at least, are channels of some kind.

Sapping Versus Runoff

Since the networks were discovered, the relative roles of sapping and runoff have been debated [*Sharp and Malin*, 1975; *Laity and Malin*, 1985; *Pieri*, 1976, 1980a, b; *Baker*,

Figure 15. Typical high-resolution view of part of a network. The channels have flat floors that contain no trace of a river channel. Just north of the large crater, a vague tributary, with faint striations on the floor, suggests mass wasting of the surface materials into the main channel. Note the general resemblance, except for scale and preservation, to typical fretted channels shown in Figures 5 and 7. The image is 19 km across (130S19). See also many other similar frames listed in the work by *Goldspiel et al.* [1993].

1982, 1990; *Carr*, 1981]. Valleys formed by groundwater sapping tend to have abrupt, alcovelike terminations, U-shaped cross sections, undissected interfluves, and low drainage densities. The configurations of sapping networks show strong structural control, and the valleys tend to maintain their size for long distances downstream because of the small number of tributaries. These are attributes of a large number, if not the majority of the Martian networks. Sapping characteristics are particularly well developed in some of the larger networks, such as Nirgal Vallis and Nanedi Vallis. The evidence for sapping is so strong that some workers have suggested that the valleys formed exclusively by groundwater sapping [*Pieri*, 1976; *Squyres*, 1989] and that their formation did not require climatic conditions warmer than the present, but only higher heat flows to permit liquid water at shallow depths [*Squyres*, 1989]. However, some networks have attributes more consistent with surface runoff. They are so dense and intricate and so fill the drainage area (Figure 18; 373S44, 606A56, 754A11-17) that origin by groundwater sapping alone is unlikely. Some form of surface runoff is required. Another very common relationship, seemingly inconsistent with groundwater sapping, is origin of channels at crater rim crests (Figure 19). Such an origin would require, improbably, that springs were located

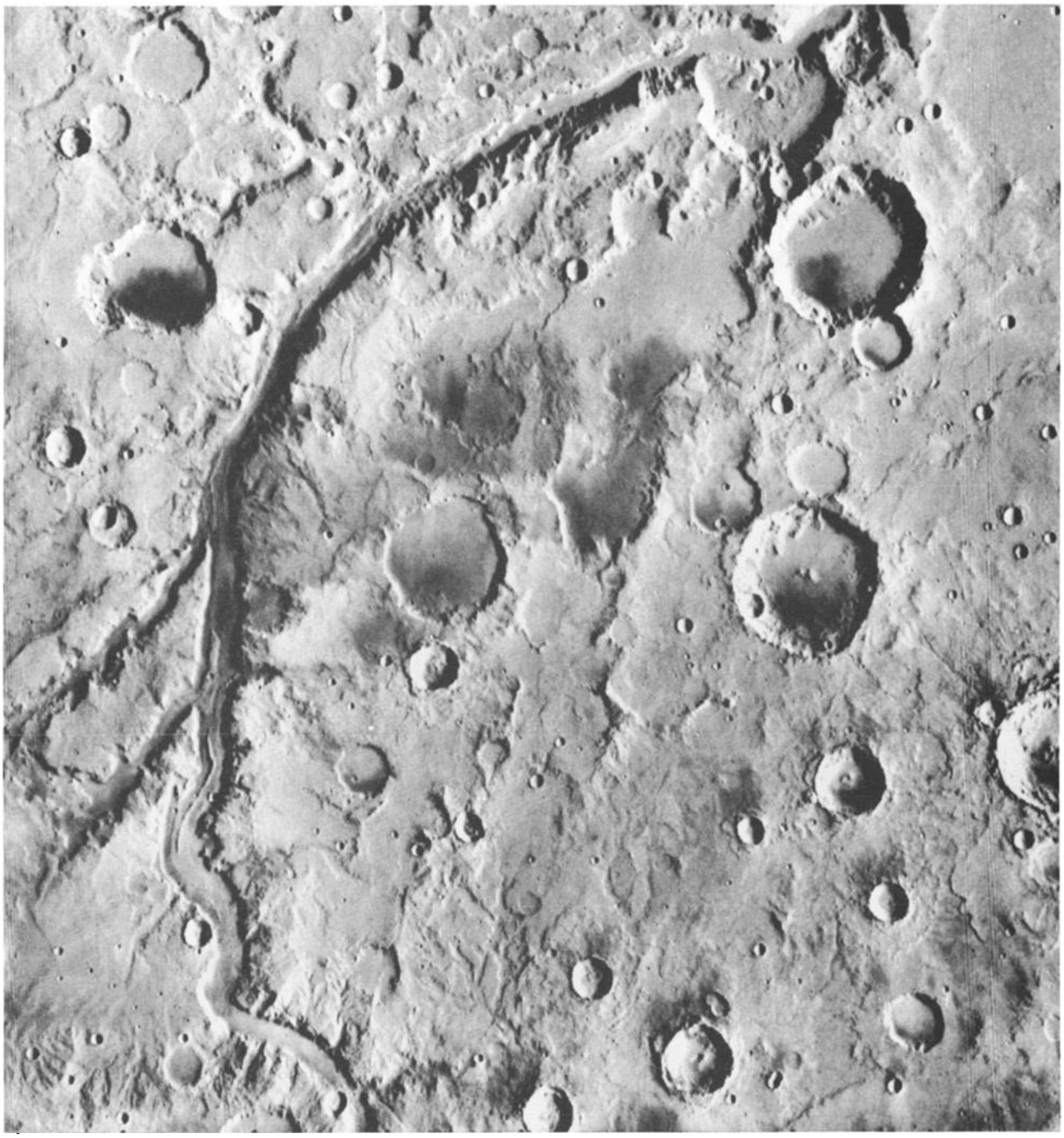

Figure 16. Ma'adim Vallis at 25°S, 182°W. The main trunk channel in this network has a median ridge along much of its length. Such a ridge is inconsistent with the floor of the channel being a floodplain. It resembles a median moraine such as might form by the merging of glacial streams or debris flows. The image is 244 km across (597A70).

at rim crests, where no local hydraulic head could develop. Alternatively, erosion on the steep, inward facing crater walls has beheaded the valleys, but this still leaves the valleys starting at the highest points in the local terrain, which is not a problem if there is surface runoff, but is a problem for a purely sapping hypothesis. Thus the Martian networks have characteristics suggestive of both sapping and surface runoff.

Mass Wasting and the Origin of Valley Networks

If the networks are composed of some kind of channel and not fluvial networks, as was just argued, then what was the material that filled the channel floors? Water is unlikely. Streams of the dimensions of the channels (3 km wide, possibly many meters deep) would have left bedforms in the valleys, as in the case of the outflow channels, and no

Figure 17. Leveelike ridges bounding a channel at 12°S, 161°W. The ridges may indicate former levels of fluid within the channel and are strongly suggestive that the linear depression is a channel of some kind, not a fluvial valley formed by slow erosion. The image is 63 km across (443S13).

bedforms are observed. Moreover, flood sources would be required at the head of each tributary, for which there is no evidence. It was argued above that fretted channels were true channels and formed largely by mass wasting aided by the presence of groundwater, which abetted headward erosion and lubricated the resulting debris flows. While the evidence is less compelling, valley networks may have formed in a similar way. They have many of the attributes of fretted channels, except that they appear to be older, lack debris aprons, and are mostly narrower. The resemblance between networks and fretted channels suggests that similar processes might have been involved in their formation, except that in the case of the networks, the processes generally affected the surface materials to shallower depths and terminated earlier, and the last stage, formation of debris aprons, did not occur.

The resemblance between fretted channels and networks is particularly striking along the plains-upland boundary

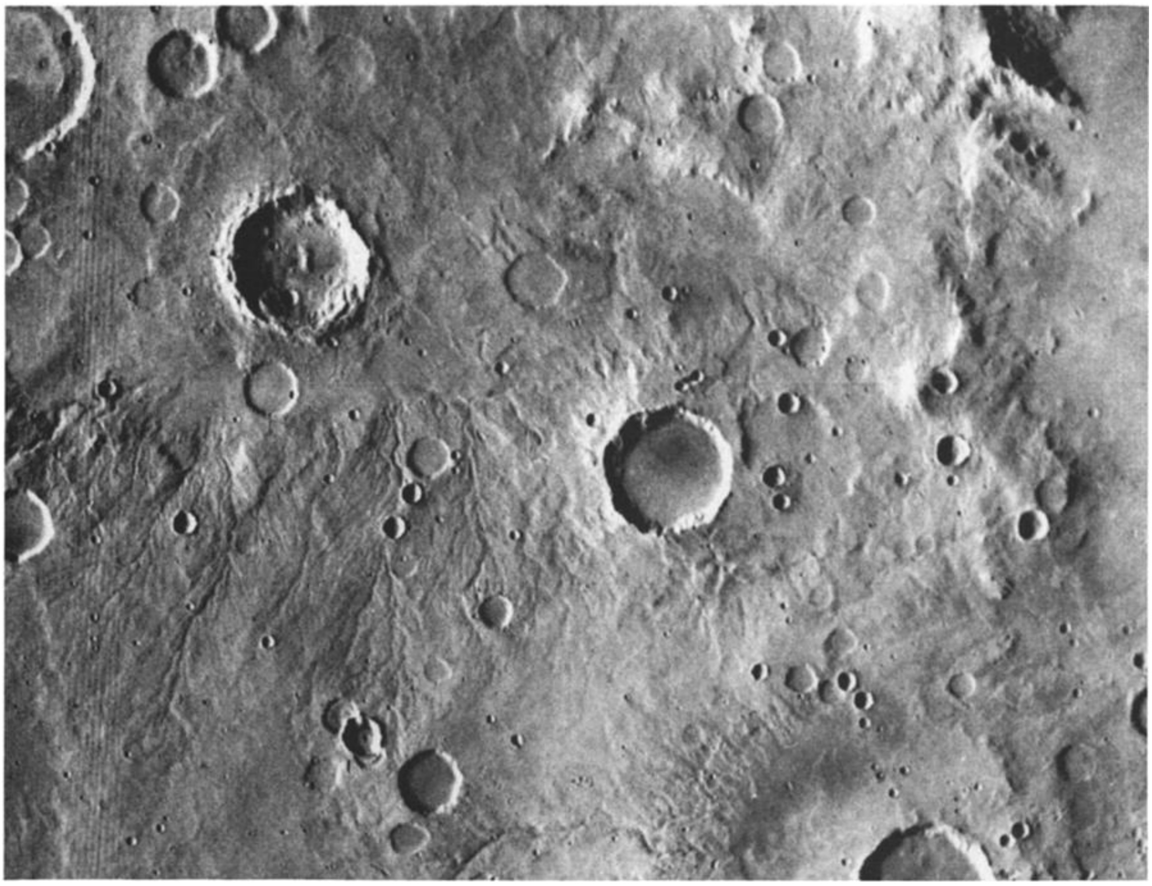

Figure 18. Dense drainage network at 25°S, 267°W. The drainage density is so great that a fluvial origin by groundwater sapping alone is unlikely. Precipitation is also considered unlikely because of the extreme localization of such dissection. Flow of the surface materials, abetted by groundwater, is proposed for the origin of such networks. The image is 290 km across (625A31).

between 180°W and 220°W, where several broad flat-floored valleys extend from the boundary deep into the uplands, the largest being the Ma'adim and Al Qahira Valles. Ma'adim Vallis is 15–20 km wide and 1.5–1.8 km deep along most of its length. Its floor is mostly flat, with no trace of a central valley, although in places there is a central ridge as in many fretted channels. A particularly long median ridge at 26°S, 183°W is 50 km long (Figure 16). The ridge is difficult to reconcile with a fluvial origin. If Ma'adim formed by the slow erosion of running water, then its floor must be a floodplain cut by a meandering stream, which is inconsistent with the central ridge. Ma'adim Vallis has all the characteristics of a fretted channel except that the flat floor is more heavily cratered and hence older than a typical fretted channel, and there are no debris aprons at the base of the walls. Ma'adim Vallis is also striking, in that the large size of the trunk branch seems incommensurate with the modest size of the upstream drainage network. If formed by mass wasting, then the size of the upstream drainage basin is of secondary importance in determining the size of the channel, in that most of the debris that flowed down the valley was derived from the erosion that formed the valley itself and so was equivalent in volume to the valley itself. This contrasts markedly with fluvial erosion, in which the volumes of water required to erode valleys are orders of magnitude larger than the volumes of material removed [*Gulick and Baker*, 1993], and large catchment areas are generally needed to cut large valleys.

The resemblance between fretted channels and valley networks is also seen at high resolution. Numerous views of networks at resolutions of tens of meters per pixel show that most network branches, like fretted channels, have U-shaped or rectangular-shaped cross sections rather than V shapes, as expected of small fluvial valleys [*Goldspiel et al.*, 1993]. This is the shape expected of channels that form as a result of plastic behavior (debris, ice, lava) rather than of those that form by water erosion [*Johnson*, 1970, chap. 14]. Moreover, like fretted channels, the widths vary little along the path of the channel. Most exceptions to the U shape are where there are steep slopes, as in the walls of the canyons and along some sections of the plains/upland boundary. In addition, some valley networks, like fretted channels, show evidence of subsurface erosion and/or solution, although this is rare. An example is shown in Figure 20, where a channels terminates in a string of closed depressions.

On the basis of the characteristics of networks listed in this section and analogy with the fretted channels, I am suggesting that the networks could have formed by headward erosion, mainly as a result of mass wasting, and that the eroded debris was carried downstream mainly by slow creep, possibly lubricated by ground ice and/or groundwater. Although mass wasting may have occurred on steep

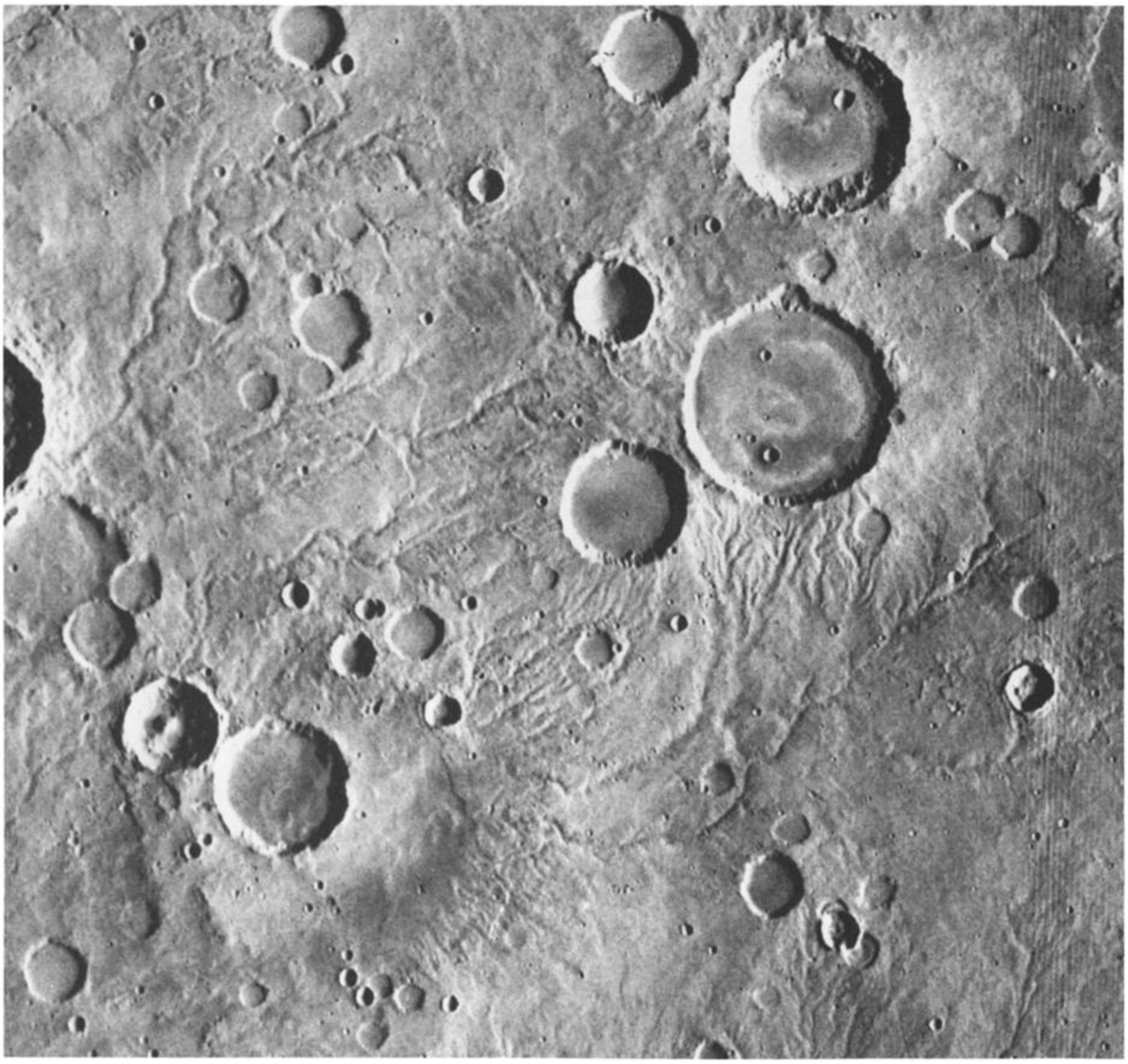

Figure 19. Origin of valley networks at crater rim crests near 22°S, 269°W. This commonly observed relationship is unlikely to result from fluvial erosion involving groundwater sapping because of the unlikely placement of springs at rim crests. Mass wasting of the surface materials is the suggested origin. (Another possibility here is that the crater filled with groundwater and overflowed, but elsewhere, valleys extend to the crest of ridges that are not crater rims.) The image is 286 km across (625A29).

slopes, such as crater walls (204S19, 407B74), without the aid of groundwater, ground failure at the valley heads and creep of debris down the channels would have been greatly facilitated by the presence of groundwater. Channel formation could have been initiated at any steep slope. Once failure occurred, then further erosion and slope failure would have been favored at the scar because of the convergence of groundwater flow, as in the case of groundwater sapping on Earth [*Dunne*, 1990]. The scar would develop into a channel that would continue to extend itself headward as long as seepage and the consequent slope failure were favored at the channel head. The process would have stopped on low slopes when climate change and/or lowering of the water table prevented further groundwater seepage into the eroded debris. As suggested for fretted channels, creep of the eroded debris may have been facilitated by the presence of a thick permafrost zone that permitted high fluid pressures at the base of the debris flows. In this model the channel forms as a result of slope failure, mainly at the head of the channel but also on the channel walls. The debris that fills the valley has little or no erosive capability. The main difference between the proposed mechanism and a fluvial origin is that the debris shed from slopes moves slowly down the valley en masse, rather than being transported by surface streams.

A mass-wasting mechanism is consistent both with both open "groundwater sapping" patterns and with dense "surface runoff" patterns, since a network would develop by headward erosion, perhaps aided by groundwater sapping, but the runoff is mostly the surface materials, not precipitation. Channels could also extend to crater rim crests by dry mass wasting. Leveelike peripheral ridges are simply explained as marking former levels of debris within the channels. Median ridges are analogous to longitudinal moraines formed where streams of debris from different branches

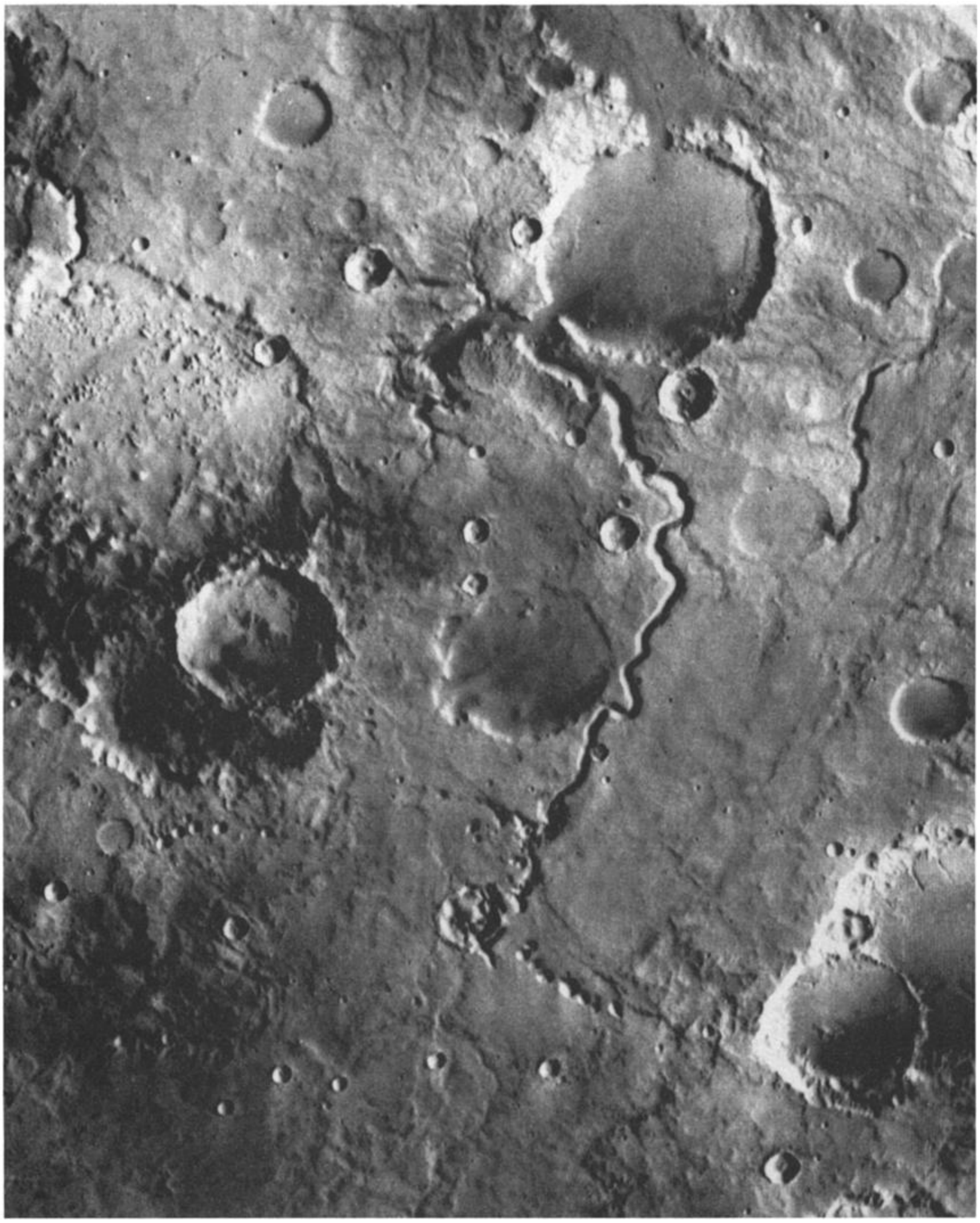

Figure 20. Drainage channel at 5°S, 249°W whose source is a line of closed depressions. The depressions suggest subsurface erosion and/or solution. The channel is about 200 km long (379S45).

merge. Branching and rejoining of channels are explained by extension of channels headward by mass wasting.

While mass wasting is envisaged as the dominant process, other processes may have contributed to formation of the valley networks. If groundwater was present, then piping may have occurred as shown in Figure 20. Floods may have occasionally occurred if artesian pressures were high enough, although there is little, if any evidence of floods outside the source regions of the outflow channels shown in Figure 1. What appears unlikely, in view of the evidence presented in this section, is that the networks are composed of river valleys that were cut by slow erosion of running water.

The main difficulty with the mass-wasting hypothesis is the mobility of the mass-wasted debris. Is fragmental debris sufficiently mobile that, given time, material could be transported over 1000 km? This question cannot be answered with assurance and it is doubtful that modeling of the process will answer the question. However, as has been previously noted [*Carr and Clow*, 1981], whatever the process that created the channel networks, it was very inefficient. Dissected areas have drainage densities orders of magnitude less than the Earth's, and large areas are left undissected, despite a geologic record that spans billions of years. If we conservatively assume that the main active channel-forming period was very short, lasting only 100 m.y., from 3.8 to 3.7 b.y. ago, then material must move 1 cm/yr to travel 1000 km. But we saw above that very few valleys are over 1000 km long; the path lengths for 87% are under 200 km. Furthermore, the period of active channel formation is likely to have been much longer than 100 m.y. It appears likely therefore that movements of only millimeters per year or less are required to form most of the networks. As indicated under fretted channels, movement of mass-wasted debris would have been aided by jostling as a result of temperature fluctuations, seismic shaking, impacts, and variations in fluid pore pressure. The biggest uncertainty is the yield strength of the material.

The ages of valley networks suggest that their rate of formation declined rapidly after the end of the Noachian. Several factors such as climate change, a declining heat flow, and loss of near-surface water could have contributed to the decline. The valley networks occur mostly at low latitudes. Down-channel movement of debris appears to have continued to a later date in the fretted channels in the 30°–50° latitude band (compare Figures 5 and 15). Persistence of movement to a later date at high latitudes suggests that progressive dehydration of the surface materials at low latitudes [*Clifford and Hillel*, 1983; *Fanale et al.*, 1986] was a significant factor in the decline in channel development at low latitudes. Loss of water from the low-latitude uplands was probably largely due to its instability and consequent sublimation, but slow migration of groundwater from high to low areas, following the pattern of surface flow shown in Figure 9, could also have been a contributing factor. The absence of debris flows and the crispness of the low-latitude terrains [*Squyres and Carr*, 1986] emphasize the efficacy of this loss of near-surface water at low latitudes.

Channels on Volcanoes

Most young channel networks are on volcanoes. They represent one strong piece of evidence against the simple climate change model in which early Mars was warm and wet but changed early to conditions that resemble the present, and persisted for most of Mars' history. The channels on the volcanoes are part of the reason that *Baker et al.* [1991] suggested episodic climate changes throughout Mars' history. If warm, wet conditions are invoked for early Mars to explain the valley networks, they must also be invoked to explain the relatively young channels on volcanoes, unless some channel-forming process, unique to volcanoes, has been operating. One such process is hydrothermal activity [*Gulick and Baker*, 1992]. One problem with invoking global changes to explain the much younger channels on volcanoes is that channel development on volcanoes is very localized. Ceraunius Tholus and Hecates Tholus, for example, are well dissected, but adjacent plains and nearby volcanoes are undissected. Moreover, only a small number of volcanoes and other young surfaces are dissected, and their total area represents a minuscule fraction of the planet's surface. The extremely local nature of this young dissection suggests local causes rather than global change.

Mouginis-Mark et al. [1988] suggested that the channels on the flanks of Alba Patera formed by groundwater sapping in poorly consolidated ash deposits and presented a variety of arguments for the presence of ash. *Reimers and Komar* [1979] also suggested that the channels formed in ash but proposed nuees ardentes as the erosive agents. If indeed ash is present on the flanks of volcanoes, then it should be susceptible to mass wasting. Any water in the volcanic gases diffusing outward through the volcanic edifice would freeze near the surface under present climatic conditions. High heat flows on the volcano flanks would result in the presence of liquid water at shallow depths, promoting sapping and downslope movement of the surface materials.

Some support for a mass-wasting rather than fluvial origin for the channels on the flanks of volcanoes is provided by a large channel on the northern flank of Ceraunius Tholus (516A24). The channel starts near the summit and ends in an impact crater adjacent to the volcano. It is roughly 50 km long and 2 km wide. The depth is not known, but an upper limit of 100 m is reasonable (the channels on Alba Patera are a few tens of meters deep [*Goldspiel et al.*, 1993]), giving a channel volume of 10 km^3. A deposit at the mouth of the channel, within the impact crater, has a surface area of 57 km^2, so if 200 m thick, is adequate to contain all the material eroded from the volcano to form the channel. *Gulick and Baker* [1993] suggest that the channels on the Martian volcanoes are fluvial and point out that in terrestrial volcanic landscapes, the ratio of rock removed to water that caused the removal may be as low as 1:1000. If the channel on Ceraunius Tholus was eroded by running water, where did the hundreds of cubic kilometers of water come from that eroded the channel just described, and where did it go? If the same water repeatedly flowed down the channel as a result of hydrothermal circulation, how did the water reenter the system? A simpler explanation of this, and other channels on volcanoes, is that they formed by mass wasting of poorly consolidated ash with only minor involvement of liquid water. Mass wasting of poorly consolidated ash deposits may be possible under present climatic conditions, possibly aided by the presence of liquid water at shallow depths as a consequence of the high heat flow, and by temperature fluctuations and seismic activity associated with the volcanism.

Summary

Outflow channels provide the best evidence for abundant water near the Martian surface and an extensive groundwater system. Collapse of the surface into some channels suggests massive subsurface erosion and/or solution, in addition to erosion by flow across the surface. The large sizes of the outflow channels imply large discharges. The discharges are so large that the outflow channels could form under present climatic conditions.

The fretted channels contain abundant evidence of mass wasting. Throughout the fretted regions in the 30°–50° latitude bands, debris aprons occur at the bases of most steep slopes. Formation of the debris aprons involved mass movement of material shed from the slopes to distances generally no more than 20 km. Formation of fretted valleys requires downstream transportation of material for distances of several tens to hundreds of kilometers. Flat floors and steep walls, longitudinal striae and ridges, downstream curling of striae from the channel walls, and lack of river channels or any other evidence of fluvial activity, within the main channels, all suggest that the fretted channels form by mass wasting, not fluvial activity. A two-stage process is proposed for formation of the fretted terrain. In the first phase, fretted channels developed by headward erosion. Mass wasting at valley heads was favored by seepage of groundwater into the debris shed from slopes. The eroded debris moved downstream, again lubricated by groundwater. Movement was by creep, the strength of the debris flow at its base being lowered by interstitial water, possibly with high pore pressures as a result of a permafrost seal, although this may not be necessary. Completely enclosed valleys, and sections with collapsed roofs suggest subsurface erosion and/or solution was also involved, as with outflow channels. In the second stage, as a result of climate change or a lower heat flow, liquid water could no longer enter the bases of the debris flows, and further movement was largely inhibited. The presently observed debris aprons developed as a result of ice-lubricated flow.

Valley networks are found almost everywhere in the cratered uplands, but drainage densities are orders of magnitude less than on Earth. The low drainage density, and the short length of most networks, combined with the probable long time over which they formed, suggest that whatever processes caused the networks, it was extremely inefficient compared with terrestrial fluvial processes. Approximately 70–90% of the networks cut only Noachian units. Most networks that cut younger units are in places of unusually steep slopes or high heat flow (canyon walls, plains/upland boundary, volcanoes). The networks topologically resemble terrestrial river systems, but the genetic implications of this resemblance are unclear. U-shaped or rectangular-shaped cross sections, leveelike peripheral ridges, median ridges, and lack of river channels on their floors, all suggest that the networks are composed of some kind of channel, not fluvial valleys. Most networks have characteristics that suggest some sapping process was involved in their formation, but the occasional very dense network and origin of channels at crater rim crests suggest the process was not simply groundwater sapping.

Because of the resemblance of many of the networks to fretted channels, and the lack of evidence for fluvial activity, other than planimetric shape, it is suggested that the networks formed, like the fretted channels, mainly by mass wasting aided by groundwater seepage into the mass-wasted debris. Groundwater seepage was favored at channel heads, as with terrestrial streams that form by groundwater sapping, thereby enabling headward extension of the valleys. The process was slow. Downslope movement of the debris in the channels need have been no more than millimeters per year to explain the low drainage densities observed despite a geologic record representing hundreds of millions of years.

The rate of formation of channel networks declined with time. The rates may have been high very early in the planet's history because of a different climate and/or high heat flow, then declined as the climate and/or heat flow changed. Formation persisted longest in places such as crater and canyon walls, where mass wasting was facilitated by high slopes or on volcanoes where high heat flows permitted liquid water at shallow depths. The process may have ceased early at low latitudes because of lowering of the water table as a result of progressive dehydration of the surface materials to greater depths as a consequence of the general instability of water at these latitudes [*Fanale et al.*, 1986]. While the process of formation of valley networks and fretted channels may have been similar, debris aprons did not develop at low latitudes because of the lack of ground ice.

The climatic implications of the scenario just described are not clear and will be examined in detail subsequently. But the valley networks are not the only evidence for climate change on Mars. Erosion rates declined dramatically at the end of the Noachian [*Carr*, 1992; *Craddock and Maxwell*, 1993], and climate change at this time is one plausible explanation.

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