Channels on Mars

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ABSTRACT

By showing that parts of equatorial and mid-latitudinal Mars have a variety of channels and channel-like forms, Mariner 9 photographs provide a basis for speculations concerning surface processes, crustal events, climatological environment, and evolutionary history.

Some large outflow channels display characteristics suggesting scour and plucking by torrential floods similar to the Spokane and Bonneville events of western United States, although such channels are probably not solely the product of flood action. Other channels with dendritic tributaries suggest runoff fed by seepage and headward growth and enlargement by sapping.

Some Martian channels and channel-like forms were probably created or initiated by endogenic processes such as faulting, subsidence, volcanism, fracturing, and crustal extension; others may be due to wind or lava erosion, but the features and relationships of many channels are best accounted for by fluvial action.

Reconciliation of fluvial erosion and the current hostile Martian environment may be possible if the channels are as old as 3 b.y. Such an age is suggested by recent re-evaluations of meteoroidal flux impacting Mars, Moon, and Earth and the chronology of lunar maria. A residual primitive atmosphere possibly congenial to running water on Mars may have permitted fluvial erosion 3 to 3.5 b.y. ago. Haphazard scattering of channels and the likelihood of seepage and sapping suggest that water was supplied to the Martian surface from the lithosphere, not the atmosphere. *Key words: extraterrestrial geology, Mars, planetology, geomorphology, hydrogeology.*

INTRODUCTION

Mariner 9, during 1971–1972, revealed a great variety of channels and channel-like features on the Martian surface. These features demand explanation, and their characteristics provide insight into the history and evolution of Mars. The possibility that some liquid has moved in large volume across parts of the surface of Mars has implications that must be reconciled with other surface features and with concepts of Martian environmental evolution.

Application of the term "channel" to a variety of elongate narrow surface depressions on Mars has been widely practiced, although basically inappropriate. A channel is an open conduit through which some fluid has moved. The bed and banks of a stream constitute its channel, which usually lies at the bottom of a gully, canyon, or valley. With reference to Mars, the term "channel" has come to mean any elongate narrow depression of linear, curvilinear, sinuous, or irregular configuration. Ideally, the term might be limited to erosional features, but confident separation of erosion and non-erosional forms is not possible. However, elongate depressions possibly created by internal processes will be referred to as "channel-like." The large equatorial troughs (Valles Marineris) are not treated, as they are thought to be primarily of endogenic origin with only secondary exogenic modification.

Major focus is upon phenomena most likely to be of exogenic origin, for they provide the most information about processes and environments of the Martian surface. The current mean atmospheric pressure of 6 mb, mean annual planetary temperature of about −80°C, and only a trace of water vapor in the atmosphere forbid liquid water for any significant time on the Martian surface (Ingersoll, 1970). Thus, the possibility of environmental change must be considered.

DESCRIPTION AND CATEGORIZATION OF MARTIAN CHANNELS

Earlier papers treating channels on Mars are concerned more with specific examples than an overall view (McCauley and others, 1972, p. 294; Milton, 1973; Masursky, 1973, p. 4017; Maxwell and others, 1973; Schumm, 1974; Baker and Milton, 1974; Weihaupt, 1974). The present study began with an inspection of all identifiable channels and channel-like forms. Description of all would be such an encyclopedic effort that a simple categorization (Table 1) is provided within which individual channels can be treated.

Channels or channel-like features should be described in terms of the following parameters: dimension, planimetric configuration, cross-section shape, apparent direction of flow if appropriate, head and distal terminations, floor and wall characteristics, relationship to other channels, patterns, relative age, topographic setting, geological setting, and geographic location.

Categories of Channels

Introductory Statement. Channels or channel-like features can be categorized as the products of external (exogenic) or internal

TABLE 1. CATEGORIZATION OF MARTIAN CHANNELS

	Examples*
Exogenic	
Outflow channels	
Primary	Ceraunius channel (Ceraunius, 24° N., 89° W.)
Catastrophically modified	Mangala channel (Amazonis 4°-9° S., 151° W.) Ares channel (Chryse, 0°-13° N., 15°-25° W.)
Runoff channels	
Integrated	Ma'adim channel (Rasena, 16°-29° S., 181°-184° W.) Nirgal channel (Mare Erythraeum, 29° S., 40° W.) Xanthe channel (0°-8° N., 48° W.)
Dendritic tributaries	Ius trough (Tithonius, 8° S., 84° W.)
Slope gullies	Alba region (44.5° N.-117° W.) Sabaeus Sinus (9° S., 328° W.) Intratrough tableland (Ganges, 7.5° S., 49° W.)
Fretted channels	
Primary	Deuteronilus channel (40° N., 338° W.)
Modified	Kasei channel (Lunae Palus, 20°-27° N., 55°-75° W.)
Excavated channels	NW. of Olympus Mons (30° N., 135° W.)
Endogenic	
Fault troughs	Claritas Forsae (17° S., 110° W.)
Subsidence	Elysium (44.5° N., 217° W.) Hephaestus (18° N., 234° W.) Labyrinthus Noctis (6° S., 105° W.)
Exogenetically modified	Ares channel (Chryse, 0°-13° N., 15°-25° W.) Shalbatana channel (1.5°-8° N., 42°-45° W.)

*Names are those tentatively assigned by the International Astronomical Union. In instances where the channel remains unnamed, it is identified by the region in which it occurs. In parentheses are shown the informal names used in earlier publications and the approximate coordinates.

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(endogenic) processes. Most channels of exogenic origin result from erosion, although some channels can be created by marginal accretion or by the accumulation of an alluvial fan or lava flow against an opposing slope. Exogenic channels are open at one end and usually involve longitudinal transport. An exception could be channels created by eolian deflation involving upward rather than longitudinal movement. To accommodate this possibility, an "excavated" category is provided.

Endogenic channel-like forms are the result of internal processes such as fracturing, tectonic movements, collapse of lava tubes, or subsidence resulting from removal of underground support. Composite channels, initiated by endogenic events and subsequently exogenetically modified, may be abundant on Mars.

Outflow Channels. These are mostly large features that start full-born from localized sources. They are broadest and deepest at the head and decrease in size distally. Some appear to be scoured and display features suggestive of massive catastrophic flooding. Many outflow channels emanating from areas of chaotic terrain are probably composite and may be as much endogenic as exogenic.

Runoff Channels. Such channels typically start small and increase in size and depth distally. The headwaters usually have tributary branches. Configurational control by crustal structures can be strong.

Fretted Channels. These are steep-walled features with wide, smooth, concordant floors. Planimetric configuration can be complex, with irregularly indented walls, integrated craters, and control by linear crustal structures, presumably fractures, often evident. Isolated butte- or mesa-like outliers are common, and extensive lateral integration of adjacent channels has occurred locally.

Excavated Channels. Some Martian channels are closed at both ends, suggesting that the missing material moved downward or upward rather than laterally. Many such channels are probably endogenic, but the possibility that some may have been created by upward removal, as by eolian deflation or evaporation, merits consideration.

Endogenic Channel-like Features. A number of Martian channel-like features may not involve erosion. Some are due to faulting, and others may have been produced by the collapse of lava tubes or by subsidence along linear fracture zones owing to ground-ice deterioration or magma withdrawal. Insofar as possible, it is desirable to identify such occurrences and to separate them from exogenic channels.

Modified Endogenic Features. Mars has a number of features which are best accounted for by some endogenic process but which display forms highly suggestive of secondary erosional modification. An example would be a channel-like feature formed by collapse along which some exogenic erosional process has subsequently operated.

GEOGRAPHICAL AND GEOLOGICAL RELATIONSHIPS

Geographical Distribution

Channels readily apparent on Mariner 9 photos are geographically scattered (Fig. 1), but they are most abundant in tropical and middle latitudes (Sagan and others, 1973). It is partly a matter of semantics as to whether regions poleward of above 70° lat harbor features that might be called channels. The configuration and setting of some linear depressions on layered polar deposits suggest that they are probably eolian grooves (Cutts, 1973a). Some of the larger curvilinear forms spiraling outward from the poles may be shallow eroded depressions (Cutts, 1973a, 1973b), or they may be escarpments (M. C. Malin and others, unpub. data) at the edges of accumulated plates (Murray and others, 1972, p. 342; Murray, 1973; Murray and Malin, 1973). The wall slopes of these last features are so gentle (D. Dzurisin and K. R. Blasius, unpub. data) that they are hardly comparable to the channels identified elsewhere on Mars. Maxwell and others (1973) mention a channel in the south polar region, but the feature is so complex geometrically that its character is indeterminable.

Channels or channel-like forms are also sparse, if not wholly lacking, within the broad subpolar plain, between 45° and 70° N. The low-lying area is described as "mantled" by Soderblom and others (1973). A comparable plain does not exist in the southern hemisphere, although evidence of blanketing and exhumation is seen there too, and large fresh channels are not readily apparent poleward of about 40° S. Obscure channels may escape detection in both these regions, and there may be many areas gullied on a scale too fine to be seen.

The erratic and widely separated occurrence of large prominent channels at lower latitudes is noteworthy. Except for channels associated with fretted terrain at about 40° N. and with areas of chaotic terrain near the equator, large channels are randomly dis-

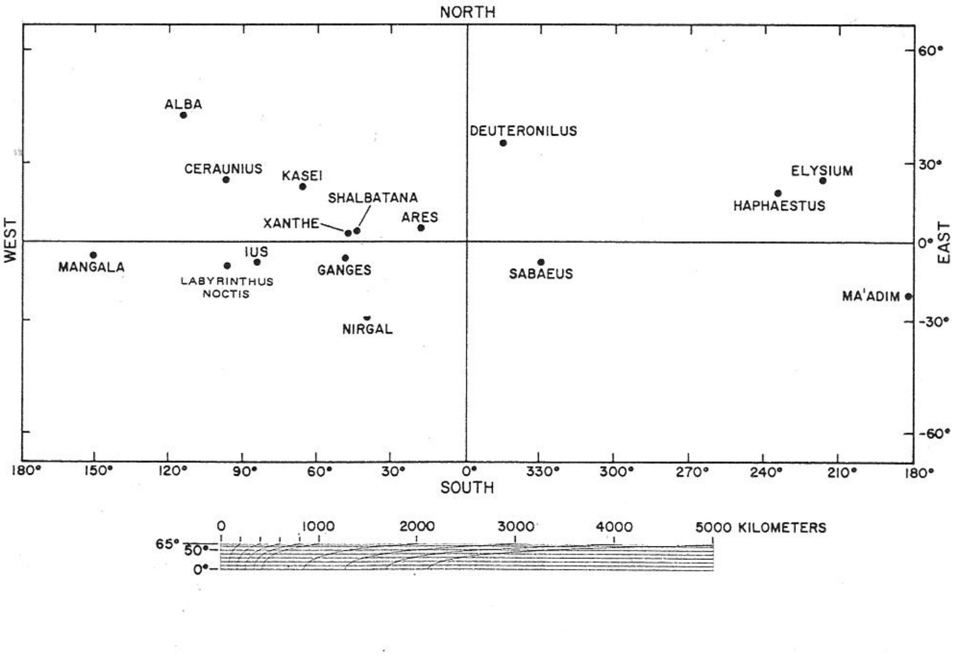

Figure 1. Names and locations of principal channels and areas treated.

tributed, without any obvious interrelationship. Areas of extensive gullying, insofar as visible, are also erratically distributed.

Geological Considerations

Channels are most numerous in areas of heavily cratered older terrain, but channel-like forms, of probable endogenic origin, are most abundant in the younger volcanic regions (West, 1974, p. 7). Areas of recent accumulation, such as the polar regions, the north subpolar annular plain, and the floors of large basins like Hellas and Argyre, are seemingly devoid of channels.

The characteristics and localized abundance of fretted channels presumably reflect in some degree the nature of the crustal rocks or subsurface conditions such as near-horizontal layering, or a horizontal inhomogeneity in physical character (L. A. Soderblom and D. B. Wenner, unpub. data; Sharp, 1973a, p. 4079). Many channels are associated with chaotic terrain which is presumed to form by collapse attending removal of subsurface support (Sharp, 1973a), and the channels themselves may be largely a product of this same process.

EXAMPLES OF EXOGENIC CHANNELS

Mangala (Amazonis) Channel: Outflow

This channel, within heavily cratered terrain in the southern part of Amazonis region, deserves the careful description and analysis given by Milton (1973, p. 4038). Similarities between large Martian outflow channels and features created by catastrophic terrestrial floods, such as the Spokane (Bretz, 1969) or Bonneville (Malde, 1968) events, are exemplified along Mangala channel (Baker and Milton, 1974, p. 33).

The Mangala system, including a possible source area, extends 350 km along the 151° W. meridian, from approximately 9° S to 4° S., but the principal channel constitutes only 180 km of this distance (Fig. 2). At the channel's southern end, an ovoid area of subdued, hummocky topography displays a plexus of small channels and scars (Fig. 3). Although the northern edge of this 135-km-long by 55-km-wide region may have a crater-like configuration (Milton, 1973, p. 4038), the whole feature looks like an area of seepage. The principal channel extends northward from a constricted outlet at the edge of this area and terminates at the southern margin of a large mare-like plain. In its final 50 km, the channel dwindles to a single dark mark crossing the floor of a 25-km crater.

The upper reach of the principal channel is a gorge 10 km wide with an estimated 500- to 1,000-m depth. In the outlet region of the source area, stripping of a weak surficial blanket accompanied by deeper scour and plucking of underlying bedrock appears to have occurred (Fig. 4). This resembles the Palouse loess–Columbia basalt relationships in the scablands of eastern Washington scoured by the Spokane flood (Bretz, 1959). The northern third of the main channel is anastomotic on a gigantic scale (Fig. 5). Material scoured from the source area and the upper gorge may have come to rest in this broader, shallower, anastomotic reach, although

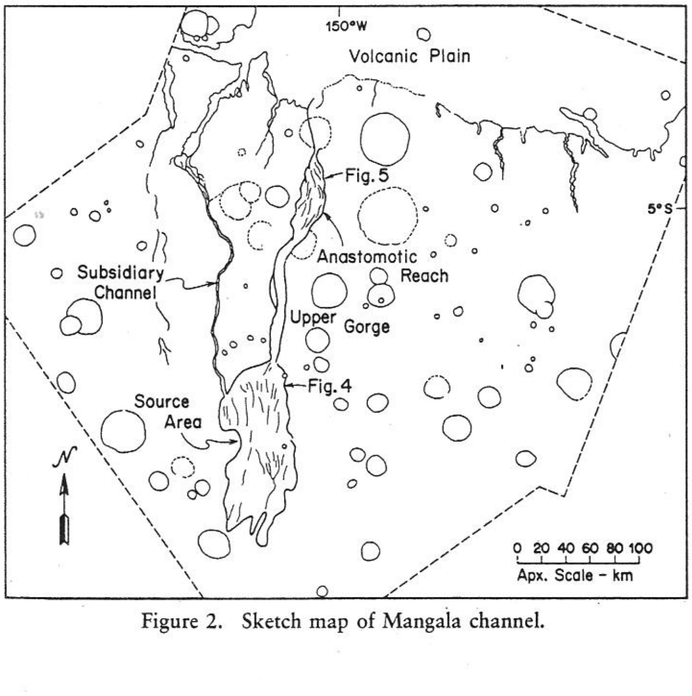

Figure 2. Sketch map of Mangala channel.

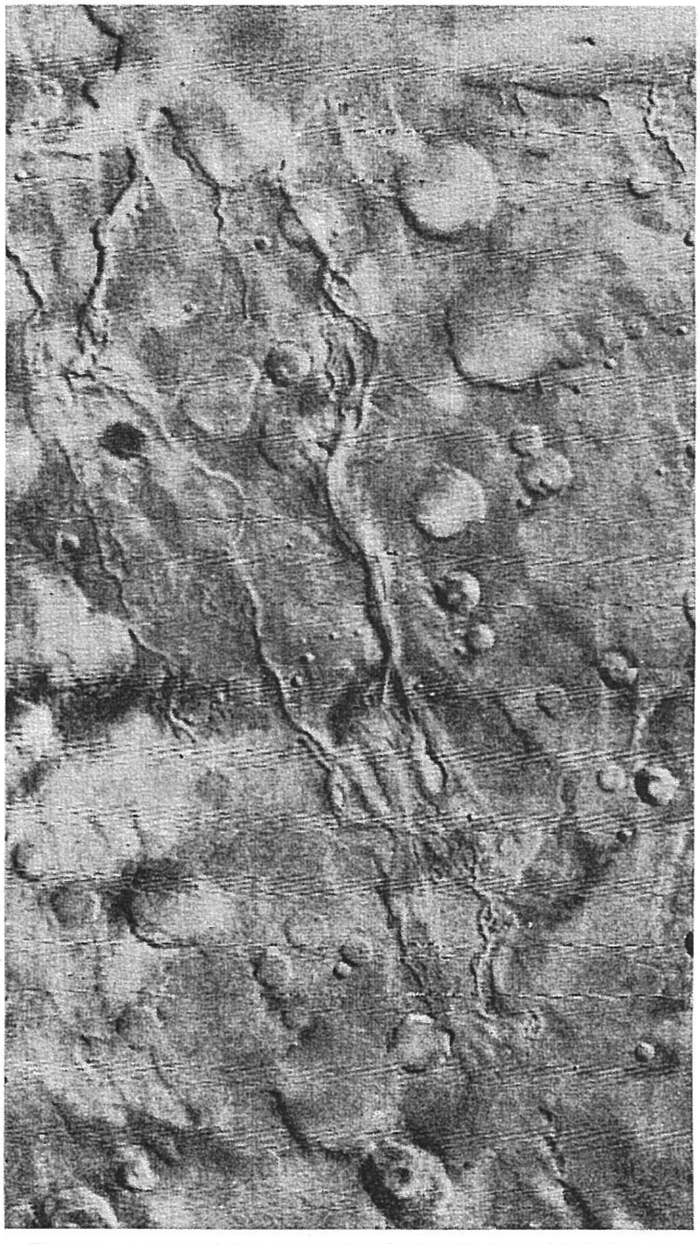

Figure 3. Low-resolution composite of Mangala channel including possible headwater source area and subsidiary channel to west; compare with map, Figure 2. (Width 290 km; DAS 6822723 and 6822798; 146A 13/32 and 146A 15/32; DAS number is a space-craft event clock number unique to each photo; 146A 13/32 is an official JPL catalogue number.)

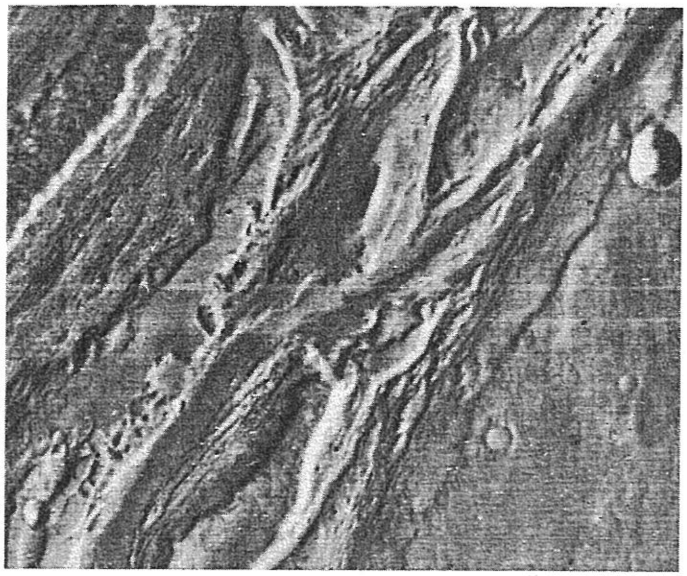

Figure 4. High-resolution photo of "scoured" segment in outlet region of source area, Mangala channel. (Width 40 km; DAS 12499650; 458B 03/15.)

Figure 5. High-resolution photo of anastomotic reach within lower Mangala channel. (Width 26 km; DAS 9628644; 224B 09/10.)

Schumm (1974, p. 378–379) sees instead an analogy with microfracture patterns. A comparison of forms in the scoured and anastomotic reaches of Mangala channel to features produced by the Spokane and Bonneville floods is given in Table 2 (see also Baker and Milton, 1974, p. 31–33).

TABLE 2. COMPARISON OF FORMS ALONG MANGALA CHANNEL WITH SPOKANE AND BONNEVILLE FLOOD FEATURES

Spokane and Bonneville floods	Mangala channel
Anastomosis	Yes
Marginal channels	Yes
Hanging channels	Yes
Transected divides	?
Plucked and scoured bedrock	Yes
Stripped overburden	Yes
Scablands	Yes
Cataracts and cascades	?
Plunge pools	?
Recessional gorges (coulees)	?
Backfill deposits	?
Deltas	?
Bars	Yes
Giant ripples	?

The relationship of gorge to anastomotic reach, the shape and arrangement of intersecting channels in the anastomotic reach, the northward regional slope of the adjoining upland indicated by ultraviolet spectrometer data (Hord and others, 1974), and the location of a possible source area to the south all suggest northward flow within Mangala channel.

The Spokane flood spread widely over a lava plateau in eastern Washington to create the channeled scabland, and floodings occurred repeatedly (Bretz, 1969, p. 510). The Bonneville flood of southern Idaho was a one-time occurrence fed by waters from Pleistocene Lake Bonneville that flowed in a more constricted course along the Snake River (Malde, 1968). A representative Spokane flood involved about 2,000 km^3 of water with a maximum discharge of 750×10^6 ft^3/sec (Baker, 1973, p. 20), or approximately 73 km^3/hr. Water depths may have attained 120 m, and the high discharge may have continued for only a few days (Baker, 1973, p. 20). The somewhat smaller Bonneville flood involved about 1,600 km^3 of water with a maximum discharge of perhaps 1 to 1.5 km^3/hr and a maximum depth of 100 to 120 m. Owing to the smaller outlet and the nature of its dam, the Bonneville flood continued for a longer time period, with an estimated peak discharge for six weeks, and flood conditions for perhaps one year (Malde, 1968, p. 137). The Bonneville flood with its more constricted outlet, more enduring discharge, and more narrowly channeled course may provide a closer analogy to the Mangala channel which may already have been in existence before the episode of flooding. Hartmann (1974, p. 3951–3953) argues for repeated episodes of fluvial activity in Mangala channel separated by intervals as great as 10^7 yr. This is more like the Spokane series of events, except for the much larger temporal spacing. Hartmann's interpretation is based upon features and relationships associated with a single crater which are tenuous and uncertain enough to invite challenge. Furthermore, the timing and sequence of events modeled by Jones (1974, p. 3930–3931) from crater relationships are not consistent with Hartmann's position.

Another, but smaller, channel leads out of the hypothesized Mangala source area and follows a roughly parallel course to the west, first as a relatively narrow gorge which later opens to a wider, possibly alluviated, and locally anastomotic reach that is tapped by a gorge extending headward from the scarp separating the cratered upland from a broad lowland plain. Other headward working gorges indent this escarpment (Fig. 2), but none need to be related to the source area of Mangala channel. This second channel is either older than the principal channel, or it was abandoned relatively early in the history of outflow from the source area. It suggests the possibility of ponding with initial overflow at more than one low point along the rim.

The following speculation is offered. The source region has the irregular restless topography characteristic of terrestrial situations where a fluid seeps widely to the surface rather than in a single spot. This seepage might have become ponded to form a body covering about 700 km^2. If the fluid were 1 km deep, some 700 km^3 would have been available to create a small Bonneville-type flood. Overflow at separate low points along the margin of the pond may

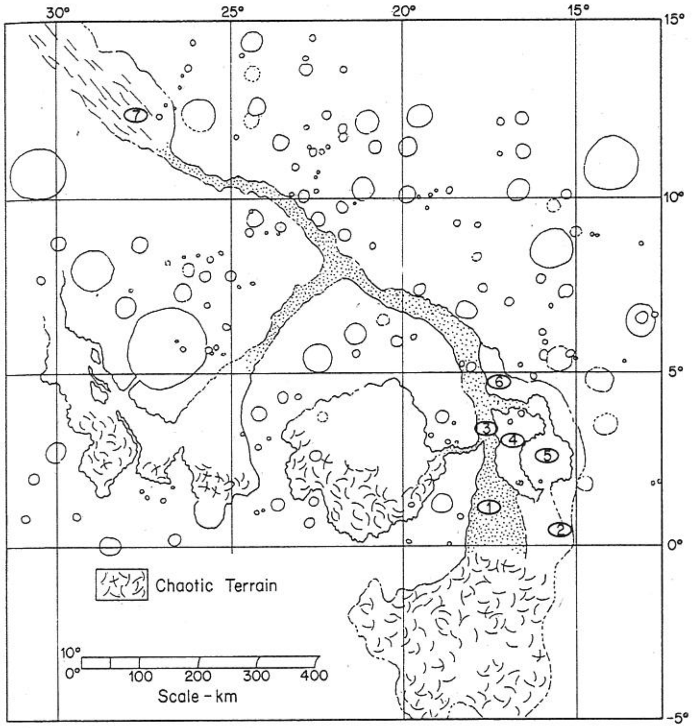

Figure 6. Sketch map of Ares channel. (1) Anastomotic reach, (2) scoured upland, (3) barbed tributary, (4) scoured surface, (5) breached crater, (6) scabland surface, (7) alluviated (?) reach.

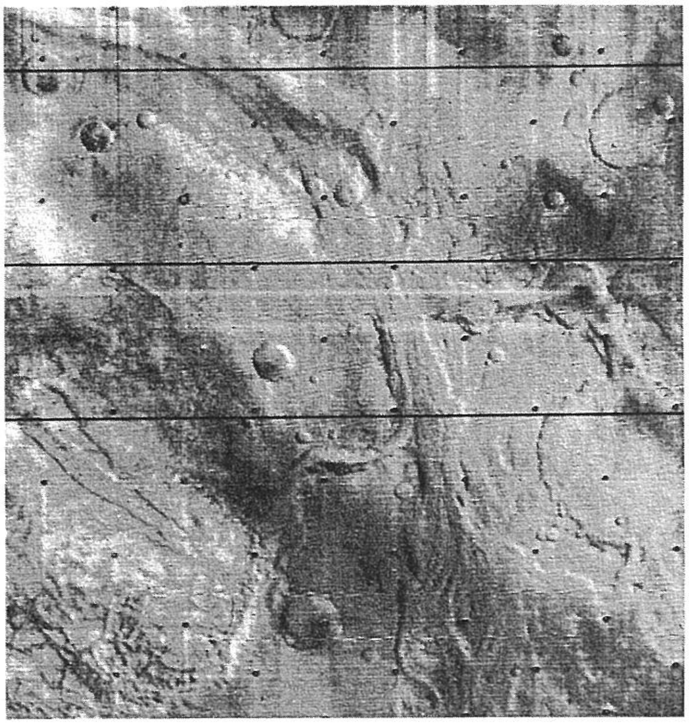

Figure 7. Low-resolution photo of upper part of Ares channel; compare with sketch map, Figure 6. (Width 355 km; DAS 7830583; 174A 20/32.)

have nourished both the principal and subsidiary channels, but more rapid downcutting of the principal channel eventually diverted all the outflow along that path. Other small channels on the upland slope west of Mangala channel and the gorges extending headward from the northern escarpment suggest that at one time this entire area may have been somewhat "juicy," favoring sapping and runoff. Sapping undermines slopes or cliffs causing recession, which, if localized, can produce valley forms. Sapping caused by seepage or ground-ice melting involves liquid which could run down the valley, removing the debris resulting from slope recession. Mangala may have been just such a channel before it succeeded in tapping the principal source area, perhaps by headward erosion, and was flooded.

Ares (Chryse) Channel: Outflow

A number of broad channels emanate from areas of chaotic terrain near the equator between longitudes 15° and 45° W. The longest, extending from the equator to at least 13° N., lies in the Chryse region between longitudes 16° and 25° W. It emerges from a large area of chaotic terrain just south of the equator, receives a major branch from the west at about 2.75° N., and is joined by a broad channel from the east at about 4° N. The west-side branch is a deep, narrow, steep-walled gorge, similar to Shalbatana channel described below. It extends from a circular area of chaotic terrain 80 km to the west. The east-side channel is more of a reintegrated distributary. Another wide, ill-defined branch emanating from areas of chaotic terrain to the south joins from the southwest at about 22° W., 8° N. (Fig. 6).

The trunk channel extends northward 350 km from the equator before turning northwesterly for another 650 km as a brighter, shallower, gently winding, less well defined feature. The total length of Ares channel is at least 1,000 km, and it is succeeded by a broad, irregularly streaked area, with small discontinuous channels, that extends for at least another 300 km and possibly twice as far to about 20° N.

Near the equator, the trunk channel, poorly defined on the east, is at least 100 km wide. It narrows northward to 20 km and then widens to about 30 to 40 km. Depth is perhaps 1.5 km in the southern reach and decreases northward, particularly beyond the big bend. The west-side branch is at least 1 km deep (Hord and others, 1974).

In its southernmost 300 km, Ares channel appears scoured (Fig. 7) and locally anastomotic on a large scale. The land to the east also appears to have been subjected to the same process. Width of the scoured terrain, including the channel, is about 220 km (Fig. 6). The subsidiary east-side channel joining the trunk at 4° N. lies within this scoured area and transects two medium-sized craters (Fig. 6). Cutting a channel out of a crater by means of ponding, overflow, and downcutting of the rim is relatively straightforward, but breaching a crater rim from the outside is more difficult. Headward sapping might do it; in this locality, however, flooding might have been deep enough to overflow low saddles in the crater rims from the outside.

A northward regional slope in Chryse, the sharply barbed junction of the west-side branch (Fig. 6), the configuration of forms in the anastomotic reach, and a possible source of fluid within areas of chaotic terrain to the south all suggest northward flow.

Ares has the characteristics of an outflow channel starting full-born from an area of chaotic terrain and gradually fading into obscurity. The 220-km wide possibly flooded area in the south is similar to the region inundated by the Spokane flood. The lighter albedo north of the big bend and in the debouchment area suggests possible alluviation.

It has been proposed (McCauley and others, 1972, p. 294; Masursky, 1973, p. 4017) that Ares channel and its west-side branch mark the path of a flood discharge out of the areas of chaotic terrain from which they extend. Ares channel certainly displays features suggestive of massive catastrophic flooding (Baker and Milton, 1974, p. 33), but it seems most unlikely that a single flood alone could create a channel of this dimension. It may have been formed by the type of collapse that creates catastrophic terrain and then modified by flooding.

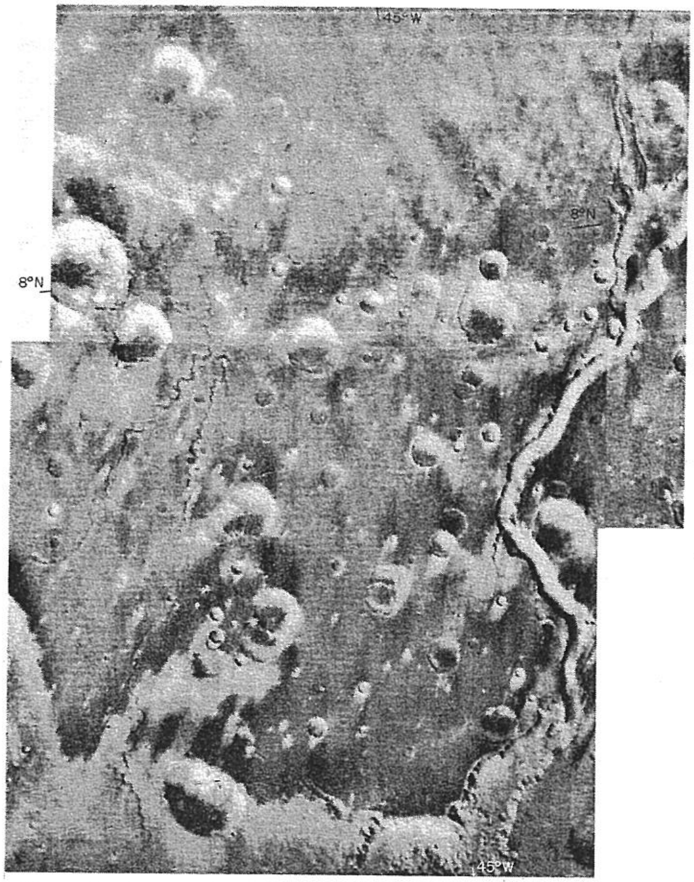

Figure 8. Low-resolution composite of Shalbatana channel (right) and Xanthe channel (left). (Width 485 km; DAS 7614913 and 7614983; 168A 20/33 and 168A 22/33.)

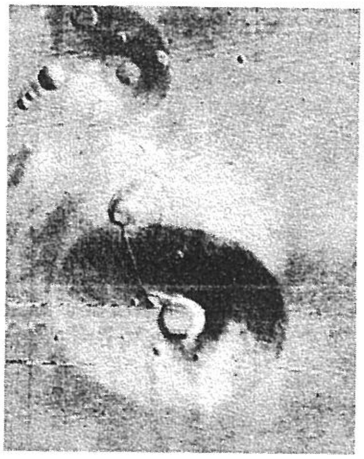

Figure 9. Low-resolution view of Ceraunius Dome, central caldera, channel, and basal closed depression. (Width 205 km; DAS 7183783, 156A 30/33.)

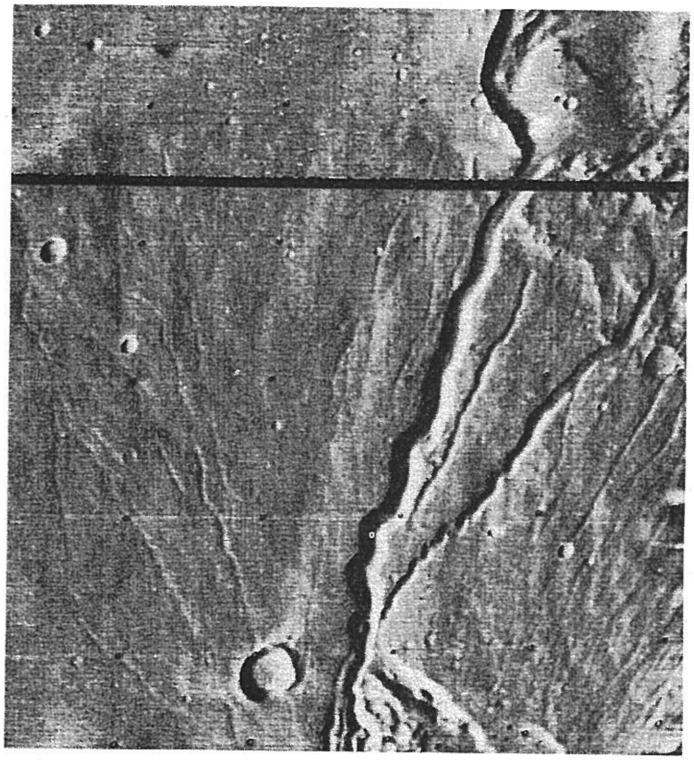

Figure 10. High-resolution view of channels on north slope of Ceraunius Dome. (Width 50 km; DAS 10061454, 236B 12/14.)

Shalbatana Channel: Outflow or Endogenic Modified

This is a single, deep, gently winding channel of strikingly uniform width emanating from chaotic terrain essentially on the equator (Fig. 8). The principal channel extends from 1.5° to 8° N. within the confines of latitudes 42° and 45° W. It traces a 650-km path across heavily cratered terrain before splitting into two narrower and shallower distributaries. The western distributary continues north for another 400 km where it fades out, and the eastern distributary bears northeast about 180 km to debouch into fretted terrain. The prevailing 12- to 15-km width widens to 50 km in the region of distributary separation.

A narrow-angle photo shows that the walls are steep and slide scarred. Depth is certainly 1 km, possibly closer to 2 km, and is greatest in the southern and middle reaches where the channel floor appears smooth.

The regional northward slope (Hord and others, 1974), a possible source of fluid within chaotic terrain to the south, and what look more like distributaries than tributaries to the north all suggest northward flow if fluid was involved. The channel just grazes the edge of a large crater, cutting away part of the rim but not producing a breach. Since it starts full-born from a 1.5×10^4 km^2 area of chaotic terrain, it could be classed as an outflow channel. However, collapse owing to ground-ice deterioration within the areas of chaotic terrain obviously tributary to Shalbatana channel could not alone have provided adequate fluid for cutting this channel. The volume ratio of fluid to rock removed would have been roughly 1:1, which is utterly inadequate. If the channel is solely an erosional product, additional fluid has had to come from some other source.

This same argument holds for many of the large channels emanating from areas of chaotic terrain. They may have been formed primarily by the same sort of collapse that created chaotic terrain and then modified by fluid outflows, either sustained or as catastrophic floods. Such channels could be classed as primarily endogenic with exogenic modification (Table 1).

Ceraunius Dome Channel: Outflow

Near the northeast end of the Tharsis Ridge at about 24° N. and 97.6° W., within Uranius region, several channels course down the flank of Ceraunius volcanic dome (Figs. 9 and 10), a well-defined volcanic construct (Carr, 1973, p. 4054) with a base diameter of about 120 km and a summit caldera about 25 km across. If its flanks slope a modest 3°, the height is roughly 3 km. Extending down the northern flank, there is a prominent unbranched channel clearly visible on a wide-angle photo (Fig. 9); a narrow-angle photo (Fig. 10) shows that it is accompanied by two smaller channels to the east. A host of minor channels on other parts of the dome is also revealed.

The principal channel is a little over 40 km long, 2.4 km wide at maximum, and not less than 100 to 300 m deep, possibly twice that. It has a uniform width throughout but is deeper and seemingly V-shaped in its upper reach and shallower, flat floored, and box shaped in its lower part. Planimetrically, it is sinuous in the upper half and more nearly linear below.

The two smaller channels to the east converge to the upper part of the principal channel where they terminate in a hanging position. The easternmost and larger reproduces on a smaller scale the characteristics of the major channel. The intermediate channel is similar to, but not a duplicate of, the others.

These three channels head into an irregular topographic plexus breaching the northwest rim of the summit caldera. The large size of the principal channel and the hanging relationship of the subsidiary channels are hard to reconcile with an origin through collapse of lava tubes, and they do not look like accretional lava channels. An origin by erosion is favored by us and by Carr (1974).

The principal channel debouches into a large circular closed basin at the base of the dome (Fig. 9). Figure 10 reveals that this basin is occupied by a subsidiary cone with a small summit crater, suggesting that the circular depression is a volcanic caldera. The termination of a seemingly erosional channel in a depression rather than in an accumulation is puzzling. The possibility that the depression is a caldera and the hanging relationship of the subsidiary channels provide a basis for the following speculation.

Initially there were three diverging distributary channels coursing down the north slope of Ceraunius Dome, sharing, at a common outlet, discharge from the summit caldera. The westernmost channel, by accident of location, emptied into the basal caldera. This gave it a lower base level, allowing deeper and more rapid downcutting. It shortly captured the discharge of the other channels, leaving them dry and eventually in a hanging position.

Most of the other channels, much smaller and partly discontinuous, that are scattered over the dome's slope (Fig. 10) may be erosional, but they were not fed from the summit caldera. They look more like channels nourished by seepage during a time when the dome was in a "juicy" state.

If the above interpretation has validity, action by some sort of liquid is implied. If the summit caldera were filled to the brim, it would have provided 450 to 500 km^3 of liquid. Downcutting of the caldera rim after overtopping may have been gradual enough to prolong the flow over at least a modest period, allowing the evolution of the three outlet channels as described.

Creation of the Ceraunius channels under the circumstances sketched may not have great environmental implications because of the possible association with volcanism. They do suggest that a liquid has acted locally on Mars to create significant erosional products.

Ma'adim (Rasena) Channel: Runoff

A large isolated channel system extends northward through the Rasena region between west longitudes 181° and 184° and south latitudes 16° and 29° (Fig. 11). The total length exceeds 700 km. A maximum width of 25 km is attained in the northern part, and a width closer to 15 km is representative of the more extensive middle reach. The course is gently winding, not symmetrically sinuous, and the mean path is northward except for the last 140 km, which hook northwestward. The middle reach appears the deepest with an estimated minimal depth approaching 1 km (Hord and others, 1974). The increase in width northward and the pattern of branches in the southern part suggest a northward direction of flow. The surrounding upland is heavily cratered.

The southern (headwaters) area is distinguished by a treelike branching of channels. The trunk is joined by two principal tributaries, 6 to 7 km wide at 25° and 26° S., and these tributaries are in turn branched. The headwater region is further distinguished by its irregular aspect, possibly the product of slump scars and small discontinuous channels. Such features suggest that fluidal seepage may have occurred in this region. Similar characteristics also extend northward along the west side of the trunk channel to about 23° S. Between 23° and 24° S., the trunk channel is irregularly constricted over a 100-km reach. This might reflect a difference in crustal rocks, or it could be the result of unusual seepage and wall collapse.

The channel floor looks mostly smooth at 1-km resolution. Benches lie along the west side in the middle reach, and a few small fresh craters indent the channel floor. At 17.75° S., the channel breaches a 30-km crater as it turns into a northwesterly course. The crater may have caused the course change, the thought being that discharge from the channel somehow gained access to the crater, filling it to the lowest outflow point which happened to be on the northwest side. The channel appears to terminate in another smooth-floored 30-km crater. In this terminal region, much of the terrain is smooth and relatively uncratered, suggesting the possibility of alluviation.

The Ma'adim channel is classed as a runoff feature on the basis of its characteristics. The headwater branches and the uneven terrain of the headwater area suggest seepage as a possible source of fluid. Craters on the channel floor indicate some degree of relative

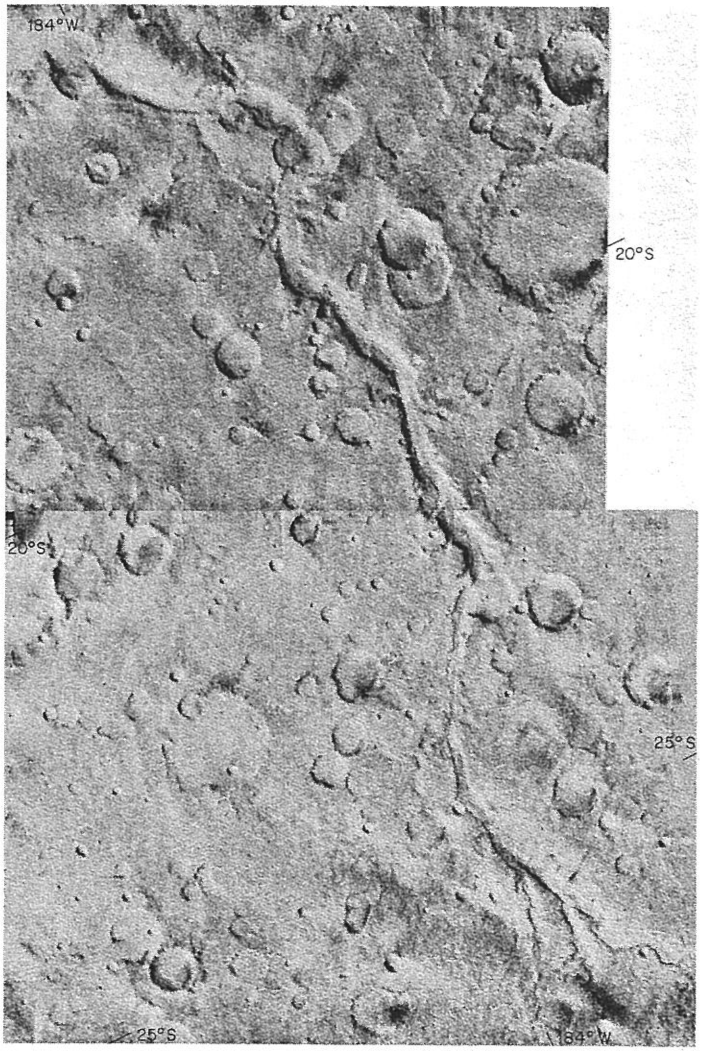

Figure 11. Low-resolution composite of Ma'adim channel. (Width 345 km; DAS 6606703 and 6606773, 140A 07/32 and 140A 09/32.)

antiquity for this otherwise fresh-looking feature. Its overall configuration resembles that of a terrestrial fluvial channel system, although the width is unusually large.

Nirgal (Mare Erythraeum) Channel: Runoff

This is one of the most intriguing channels on Mars. It follows a winding 700-km course south-southeasterly across the moderately cratered Mare Erythraeum region with a midpoint close to 29° S., 40° W. (Fig. 12). Its distinguishing features are short, stubby tributaries of dendritic pattern to the west and a highly sinuous intrenched course to the east. Dendritic tributaries are not limited to the headwaters, there being at least one near mid-course and another just above the mouth, both on the southwest side. These patterns plus a gradual increase in width to about 10 km and in depth to at least 1 km east-southeasterly suggest flow in that direction if a fluid was involved. The floor of the channel is unusually dark in the upper reach. The sinuousity of the lower reach is superimposed on a larger pattern of linear reaches linked by sharp nearly right-angle junctions, presumably reflecting control by crustal structures.

An isolated irregularly sinuous channel-like feature 100 km long lies 80 km northwest of Nirgal channel and enlarges southeastward to an abrupt termination along a zone of structural lineaments in the Martian crust (Fig. 12). It, too, has an unusually dark floor and a configuration somewhat similar to Nirgal channel.

The pattern of tributaries in the upper reach of Nirgal channel is typical of terrestrial sapping and runoff, and the lower reach looks like the valley of an intrenched meandering stream. From analysis of channel width-meander dimension relationships, Weihaupt (1974) favors fluvial activity, although his conclusions are compromised by use of valley width rather than true fluid-channel width, which cannot generally be seen on Mariner 9 photos. Resemblance of the lower reach to some sinuous lunar rilles presumably formed by collapse of lava tubes (Greeley, 1971; Howard and others, 1972) and the abruptly terminating channel-like feature 80 km northwest of Nirgal are reasons for postulating an endogenic influence. Schumm (1974, p. 380) suggests that both the sinuous reach and the dendritic tributaries may be the product of fracturing and extension within the crust.

Thus, the relative roles of exogenic and endogenic influences in creating Nirgal channel are a matter of debate. Milton (1973, p. 4041–4042) favors a single genetic process and obliquely suggests deterioration of ground ice. To us, the facts that this is not a region of young volcanism (Carr and others, 1973) and that the total pattern and configuration of the channels strongly resembles terrestrial sapping and runoff forms suggest that fluidal activity has been the principal, although perhaps not the exclusive, genetic agent.

Figure 12. Low-resolution composite of Nirgal channel, north is to right. (Width 215 km; DAS 9232619, 2160869, 6354843, and 6283023; 213A 07/20, 133A 27/32, 211A 09/20, and 131A 29/32.)

Xanthe Channel: Runoff

This is a relatively narrow angulate channel system with two long branches, lying about 275 km west of Shalbatana channel at 7° N. and 48° W. (Fig. 8). The length of the system approaches 500 km with a maximum channel width of about 4 km in the north, decreasing to 0.5 km southward. Depth is estimated at a few hundred to 500 m and is greatest in the north. Tributaries to the two trunk branches are few and short. The branches join in a manner suggesting northward flow which is consistent with the regional slope of the surrounding heavily cratered upland and with increasing channel width and depth in that direction. A strong angulate pattern in the northern part of both branches and in the combined channel suggests control by crustal structure. The eastern branch is the longer but is obscured in its middle part. The western channel terminates southward at the sharp edge of an ill-defined crater, but the eastern channel extends farther south and gradually fades out.

An 80-km-long channel resembling Xanthe lies midway between

Xanthe and Shalbatana channels, at about 8° N. and 45° W. It seems to head on the cratered upland in no specifically recognized source area. This and the Xanthe channel look like runoff features that increase in size downstream, possibly being fed by seepage along their courses, and both resemble Nirgal channel.

Dendritic Tributary Channels: Runoff

These features are best displayed along the south side of equatorial trough, Ius, at about 8° S., 84° W. (Fig. 13). Here deep narrow channels with a pinnate to dendritic pattern of tributaries extend south from the steep wall of the trough into a modestly cratered upland. A shorter development of similar channels lies on the north side of Ius trough.

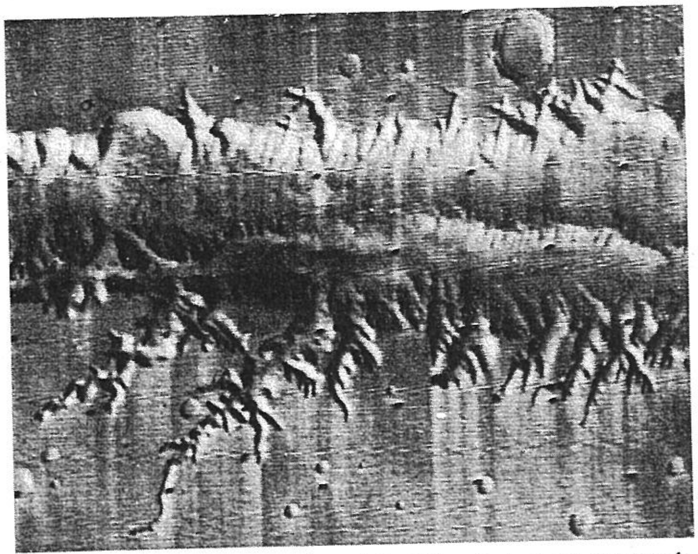

Figure 13. Low-resolution view of dendritic tributaries to Ius trough. (Width 345 km; DAS 5851963, 119A 29/32.)

The largest channel is 10 km wide at most, 150 km long, and has a conservatively estimated depth of 1 to 1.5 km, thus approaching the Grand Canyon in size (Milton, 1973). Strong structural control of channel development, presumably by fractures, is expressed by the linearity and parallelism of channel reaches and by sharp angular junctions between tributaries and trunk. Trunk channels are aligned principally northeast-southwest. The equatorial troughs, also clearly controlled by crustal structures, have an east-west trend which is not expressed within the tributary channel pattern.

The decrease in channel width, depth, and abundance of secondary tributaries outward from the trough wall suggest that channel development was progressively outward, possibly by a sapping mechanism. This interpretation is supported by the pattern and alignment of channel reaches. Disposal of debris delivered to the channel floor could have been most easily accomplished by some sort of runoff, possibly fed by seepage related to the sapping.

The weaker development of channels on the north side of Ius trough could be due to the facts that the regional surface slope is northward and layering in near-surface crustal materials is also probably inclined in that direction. This arrangement would be like the oppositely oriented situation at the Grand Canyon of Arizona where long tributaries on the north and short tributaries on the south are due to a regional southward slope of the plateau surface and of the underlying sedimentary beds. These conditions lead ground water toward the Grand Canyon on the north and away from it on the south.

Slope Gullies: Runoff

These features are mostly 0.5 to 3 km wide, up to tens of kilometers long, and with estimated depths possibly as great as 500 m. On a terrestrial scale, they would be called canyons, but use of the term "gully" seems reasonable here to emphasize their clustering in groups, setting on slopes, and smaller size relative to other Martian channels.

Three examples of heavily gullied slopes seen with particular clarity on Mariner 9 photos are described. Gullies seem to favor slopes within areas of heavily cratered older terrain, Sinus Sabaeus, for example, but they also occur in areas of young volcanic rocks.

Alba Volcanic Area. A cluster of short, wide, gully-like forms accompanied by three longer channels (Fig. 14) lies in Alba at about 44.6° N., 117.2° W., on what may be a volcano (Milton, 1973, p. 4045) or a collapsed shield volcano (Carr, 1973, p. 4054–4055). Some gullies are dendritically integrated, but single channels orthogonal to slopes are more the style.

Figure 14. High-resolution view of gullies in Alba. (Width 50 km; DAS 7039898, 152B 32/32.)

Many of these features are relatively short, wide, broad-floored, steep-walled, and box-headed, a morphology hardly typical of terrestrial gullies. Adjacent slopes are largely ungullied, although seemingly similar in other respects. The entire region looks mantled, but the gullies appear to be developed in the mantle rather than obscured by it. Milton (1973, p. 4045) may regard the gullied areas as patchy remnants of a more extensive development, and a few small fresh craters cutting the gullies could be cited as indicating some degree of antiquity. However, neighboring ungullied areas have even more and larger craters. The width, flat floors, steep walls, and box heads suggest that sapping may have played a major genetic role. These gullies are classed as runoff features, possibly fed by ground-fluid seepage. This could explain why adjacent slopes are ungullied; they simply were not supplied with lithospheric seepage fluid. The three larger, longer channels with weakly developed dendritic patterns that are associated with this gullied terrain look like typical runoff channels, except that they appear to be interrupted by unchanneled reaches. Perhaps those reaches represent areas of alluviation.

Gullies in Sinus Sabaeus. The outer slopes of a large impact-crater rim (Milton, 1973, p. 4045) in Sinus Sabaeus at about 9° S., 328° W. display a crudely radial pattern of large gullies. These features up to 3 km wide, 50 km long, and possibly 500 m or more deep are mostly integrated into dendritic networks and look more like terrestrial gullies than the features in Alba. They fade out on the surrounding lowland. Sinus Sabaeus with its heavy population of large craters appears to be an old part of the Martian surface. In many places, it displays irregular linear patterns which at high resolution seem to be albedo markings of unknown origin.

Anyone wishing to argue for rainfall on Mars should consider the Sabaeus Sinus gullies, for they occur on old terrain and have runoff characteristics. However, these gullies could just as well be the product of seepage-fed runoff.

Intra-trough Tableland Gullies. On the floor of equatorial troughs, Ganges, at about 7.5° S. and 49° W., is an eroded tableland composed of stratified materials. The lower parts of the tableland slopes are dissected by closely spaced, parallel, linear, unbranched, and largely unintegrated gullies as much as 7 or 8 km long and 300 to 400 m wide (Fig. 15). Their depth may be on the order of 100 m.

These gullies head at a relatively uniform elevation on the slope along the outcrop trace of a prominent dark layer. The impression is that of a "weeping" layer as though ground fluid has been brought to the surface. Some gullies die out downward on the slope, but many extend to its base. A number have abrupt box heads. The inclination of the slope is about 12° (D. Dzurisin, unpub. data).

These gullies are geometrically similar to terrestrial rilles but of much larger scale. The box heads suggest local sapping with runoff downslope to create the channels.

Deuteronilus Channel: Fretted

Channels are abundant within the extensive area of fretted terrain in the Deuteronilus-Protonilus region between 300° and 350° W. and 30° to 45° N. Like fretted terrain itself, these channels have wide smooth floors, abrupt steep walls, and planimetric complexity. A large irregular channel debouching into Ismenius Lacus at about 338° W. and 40° N. is representative (Fig. 16).

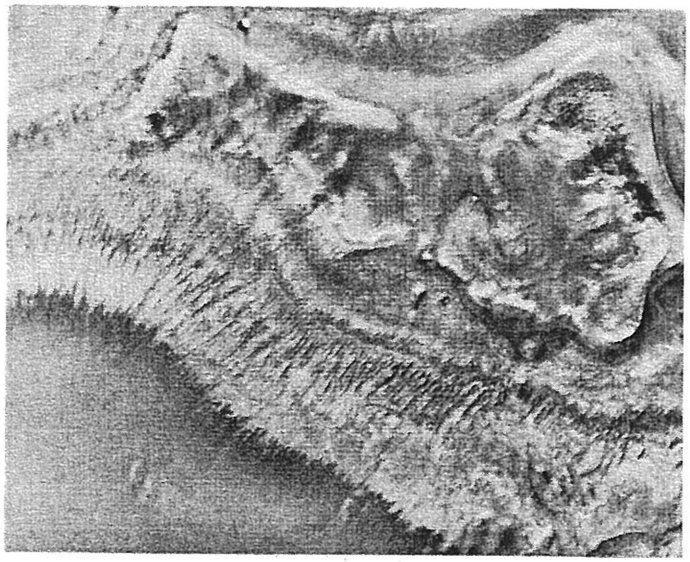

Figure 15. High-resolution view of gullies on flank of tableland within Ganges trough. (Width 45 km; DAS 9017614, 207B 15/21.)

This channel starts with two short narrow branches near 31° N. and follows a winding 750-km course northward to terminate in a large circular lowland. The upper reach has a width of 1 to 5 km which widens to 35 to 40 km in the lower half. The channel is box-shaped in cross section with a smooth, seemingly unscoured floor and abrupt walls. Its depth is estimated between 1 and 2 km, consistent with the local relief of etched terrain (Hord and others, 1974).

The walls are irregularly indented and scalloped with numerous deep alcoves and an occasional integrated crater with a concordant floor level. Although its head is branched, Deuteronilus channel is

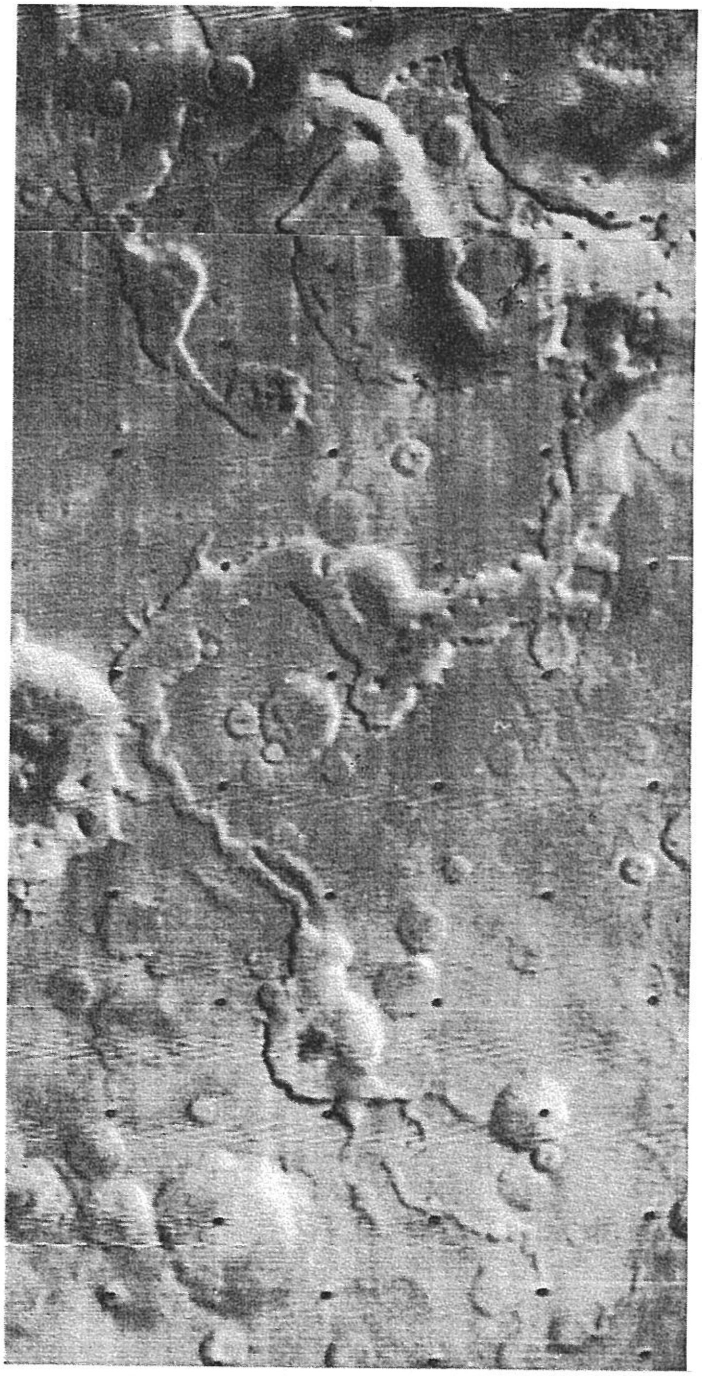

Figure 16. Low-resolution composite of fretted channel in Deuteronilus region. (Width 350 km; DAS 9378149 and 9378289, 217A 12/17 and 217A 14/17.)

essentially without tributaries save for three short gullies extending headward from the channel wall at a bend. Associated features are islands and residual knobs that rise abruptly from the channel floor. Other fretted channels display this characteristic more strongly, and in places, an irregular plexus of channels separated by islands has been formed by lateral integration. Some fretted channels have linear reaches intersecting at sharp angles or equally linear tributaries with angular junctions, suggesting control by crustal structure, presumably fractures (Fig. 23).

The upland surface into which fretted channels are developed is relatively old cratered terrain. A broad plain occupying a depression, identified by radio-occultation observations (Kliore and others, 1973) lies to the north. This upland-lowland relationship and the increase of channel width and pattern complexity northward suggest that the Deuteronilus channel drains in that direction and that it started in the north and grew progressively southward.

Deuteronilus and other fretted channels look like the product of erosion, although Schumm (1974, p. 380) urges an origin by fracturing and crustal spreading in at least one instance. The wide flat floors, the steep irregularly indented walls, the integrated craters, and local channel plexuses strongly suggest both headward and lateral growth by wall recession under the attack of some undermining process, in the same manner that fretted terrain develops. Whether the sapping involves ground ice (Sharp, 1973a) or ground water (Milton, 1973) remains a matter for consideration. The more pressing problem is the disposal of debris shed by the retreating walls. This could involve pickup and transport either by wind, some liquid, or a subtle type of mass movement. A firm choice is not possible from anything seen on the photos, but regardless of the agent or mechanism, these are erosive processes and the fretted channels are regarded as largely erosional products.

Kasei (Lunae Palus) Channel: Modified Fretted

As defined by Milton (1973, p. 4040), this channel complex consists of quasi-parallel north and south branches uniting around the east end of a large peninsula and continuing east-northeastward as a single broad feature (Fig. 17). The location is between latitudes 20° and 27° N. and longitudes 55° and 75° W. in a region of lightly cratered upland indented by steep-walled fretted features. A relatively featureless, probably volcanic, plain lies to the west, and more heavily cratered terrain lies eastward. Channel sizes and the configuration of junctions suggest eastward flow if fluid is involved.

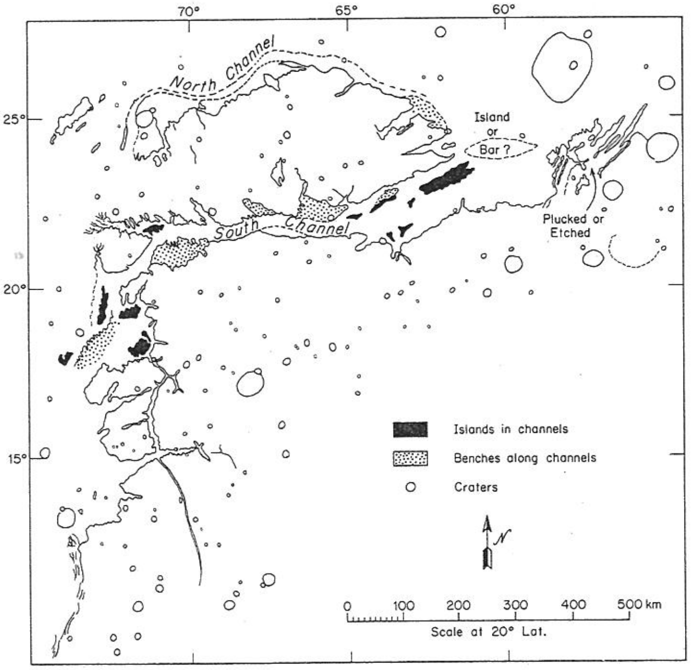

Figure 17. Sketch map of Kasei channel.

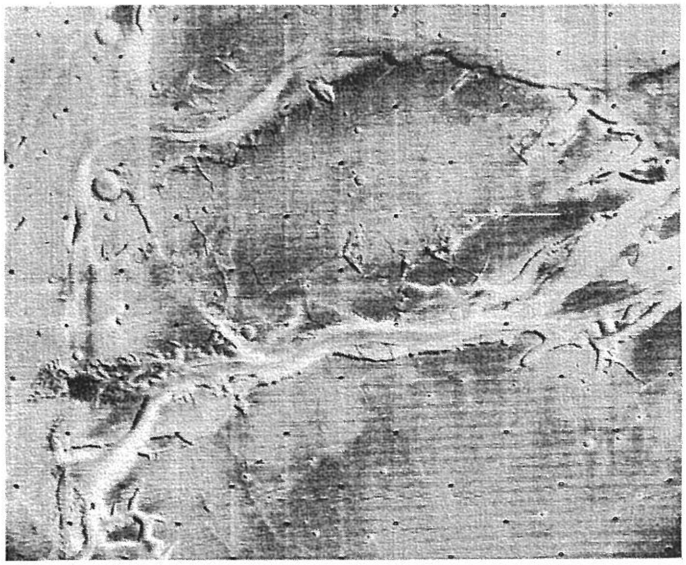

Figure 18. Low-resolution view of central part of Kasei channel; compare with sketch map, Figure 17. (Width 610 km; DAS 7399733, 162A 30/33.)

The northern channel appears as a gently sinuous bright streak up to 18 km wide and 300 km long (Fig. 18) which seems topographically confined only by the abrupt north edge of the peninsula. The south channel is well defined by steep walls 2 to 3 km high (K. R. Blasius, unpub. data) and 15 to 55 km apart, increasing in separation eastward. The unified channel extending to the east is shallower and at least 150 km wide. Greatest length of the channel system is 1,200 km.

The upland peninsula between channel branches is indented by many small fretted features, some markedly linear, and the south wall of the south channel displays a number of fretted alcoves and indentations. Both channels bend south in their headwaters, and west of the curve in the south channel, there is a patch of intricately fretted terrain with a tree-like pattern. The south channel heads in a complex of fretted features (Fig. 17). The southern channel also has remnants of a bench or benches along both sides, one as much as 50 km wide (Fig. 17). These look more like stripped features controlled by horizontal layering in crustal materials than like fluvial terraces.

The southern channel has a large bedrock island in its eastern part and several smaller islands farther west. A streamlined feature, identified in Figure 17 as an island or bar, lying near the junction of north and south Kasei channels, is regarded by Baker and Milton (1974, p. 35) as a bedrock mass scoured, grooved, and plucked by a huge catastrophic flood (Fig. 19). An area of highly irregular terrain, at a level intermediate between the channel floor and the upland (Fig. 17), lies south of the unified channel and east of the peninsula. Although this terrain might be the result of overbank flooding, the requirement of a water depth possibly approaching 1 km suggests that an alternative origin by fretting merits consideration.

Baker and Milton (1974, p. 33–37) describe features in the Kasei channel, suggesting to them the work of a huge catastrophic flood. The implied dimensions of this flood, 400 m deep and at least 150 km wide, plus the lack of any identifiable source of flood fluid impels a search for an alternative explanation. The abandoned horseshoe cataracts cited could have been produced by fretting, the exhumed craters could have been uncovered by deflation as proposed

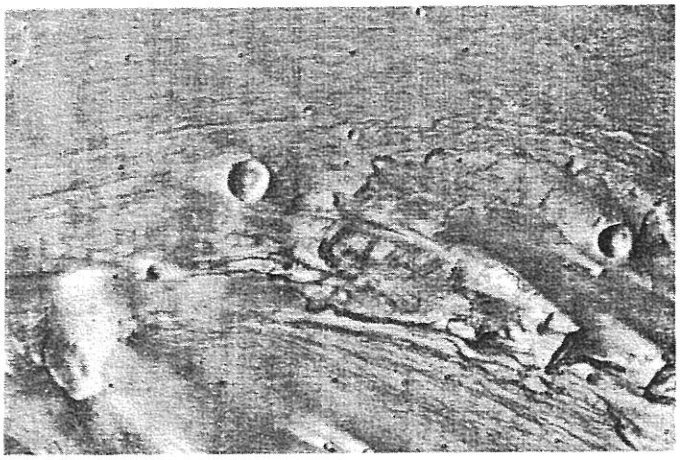

Figure 19. High-resolution view in eastern Kasei channel showing northern half of streamlined island or bar at bottom, linear grooves, and feature interpreted as horseshoe cataract complex Baker and Milton near center. (Width 60 km; DAS 10277479, 242B 9/10.)

elsewhere on Mars (Soderblom and others, 1973), the long linear grooves and markings might be of eolian origin, and the 2-km relief on the channel floor (K. R. Blasius, unpub. data) appears extreme for hydraulic plucking and might actually be the result of fretting.

The abundance of fretted forms along the margins of the south channel and at its head suggest that the entire Kasei channel complex may be principally the product of fretting with only secondary modification by fluidal or eolian activity. Small fresh craters on the channel floor suggest a modest degree of antiquity for the Kasei feature.

ENDOGENIC FEATURES

Fault Determined

Faulting, mostly in younger volcanic rocks, has created linear troughs or graben. Such features can be so modified by subsequent erosion that their tectonic origin becomes obscure, but little evidence supports the thought that many Martian channels are of this nature. However, fractures have surely guided the development of Martian channels formed by erosional processes, especially fretting and sapping.

Martian troughs formed by faulting are commonly open at both ends. They are also relatively straight, flat floored, steep walled, and of reasonably uniform width. They tend to occur in groups of parallel, en echelon, or sharply intersecting sets, characteristics which are indicative of tectonic origin.

Subsidence Forms

Mars has many long linear depressions with relatively large width/length ratios, some of which are topographically closed at both ends. Most of these are flat floored and steep walled, although some are U shaped. They often occur in groups and usually terminate abruptly at both ends; most do not have branches or tributaries. Lengths up to 25 km, widths to 5 km, and depths of perhaps 1 km or more are representative. Many are relatively straight (Fig. 20) or gently curvilinear, but some are highly irregular and locally combine to produce reticulated networks (Fig. 21). The creation of these features through exogenic erosion, other than possibly by eolian deflation, seems so difficult that an origin by subsidence is suggested. Sinuous Martian features resembling lunar rilles may have formed by collapse of lava tubes (Greeley, 1971; Howard and others, 1972). Subsidence features occur most abundantly in volcanic terrains.

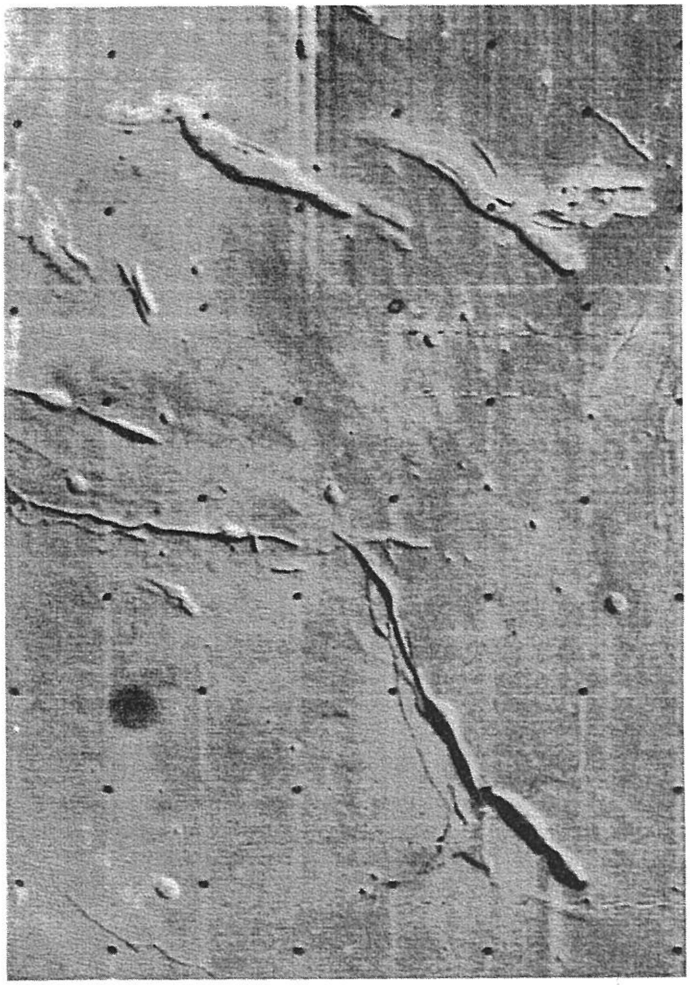

Figure 20. Low-resolution view of channel-like endogenic subsidence features in Elysium region. (Width 365 km; DAS 7651453, 169A 30/32.)

The plexus of linear, U-shaped depressions in Labyrinthus Noctis (6° S., 105° W.) occurs in an area of extensive faulting, but these depressions do not seem to be a direct result of faulting, for they truncate and cut across fault troughs (Fig. 22). They are initiated as linear strings of small funnel-shaped, rimless depressions which enlarge and eventually coalesce to create a continuous integrated depression. Collapse, guided by fractures, attending removal of subsurface material seems a likely genetic cause, especially in view of depths possibly as great as 5 km (Hord and others, 1974).

MISCELLANEOUS FEATURES

Mars displays a host of additional channel-like forms. Some are so obscured or fragmented that description is almost meaningless, and others are similar in character and implications to features already treated. A few special examples are accorded specific comment here.

An unusual set of gently curvilinear parallel depressions about 1 km deep is seen at the north base of the large shield volcano, Pavonis Mons (Middle Spot) at 3° N., 112° W. Since these channels appear to open at the west end, they might possibly have been produced by sapping guided by a concentric fracture system encircling this volcanic shield, or they might be concentric graben passing under younger lavas to the west. These features are shown on low-resolution photo DAS 7111193.

At 31.1° N., 228.7° W., there is a 15-km-wide, smooth-floored channel with a local anastomotic pattern, smoothly curving abrupt walls, and several teardrop islands. The anastomotic arrangement

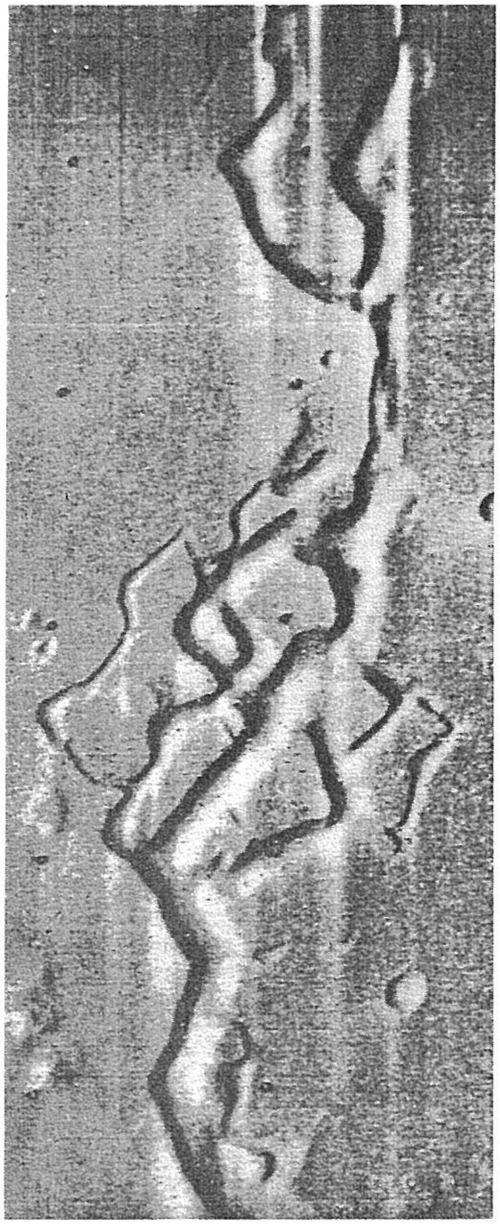

Figure 21. High-resolution view of reticulate pattern of endogenic channel-like subsidence forms, Hephaestus. (Width 20 km; DAS 10241214, 241B 06/08.)

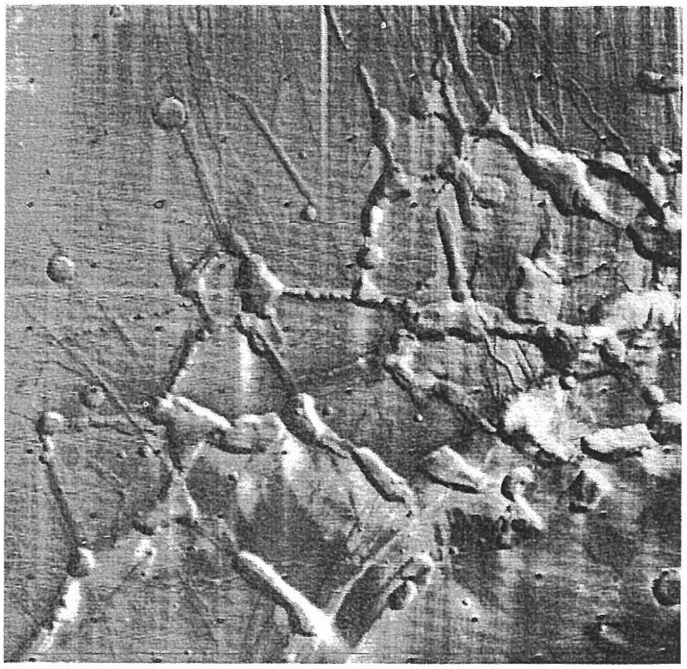

Figure 22. Low-resolution view of plexus of channel-like endogenic subsidence forms in Labyrinthus Noctis. (Width 330 km; DAS 7182803, 156A 15/33.)

involves intrenched channels, but the pattern suggests fluidal activity. This area has a blanketed aspect, and a number of small, fresh, bowl-shaped craters pock the channel floor, suggesting relative antiquity. The site is shown on high-resolution photo DAS 8910729.

A radiating pattern of channel-like forms is found within a circular area 200 km across, centered at 20.8° S., 255° W. The channels are unbranched, relatively straight, 2 to 3 km wide, smooth floored, and steep walled; many start and terminate abruptly. Two or three are longer, a bit wider, somewhat more sinuous, and distinctly deeper than the average, and one of these crosscuts other channels. A 20-km crater or caldera into which no channel extends lies at the center.

The setting looks like a volcanic dome with summit caldera and flanks riven by off-flowing channels (Carr, 1973, p. 4056). However, an ultraviolet spectrometer profile shows it to be a basin. The channels thus converge radially inward rather than diverging outward, and this is consistent with an observed headward decrease in size. If a fluid has been involved, it should have been ponded, and indeed, the channels do not traverse the featureless basin floor. Channel breadth and cross-section configuration suggest the possibility of considerable wall and headwater sapping which could in turn imply seepage. This feature is shown on low-resolution photo DAS 8909224.

A fretted complex lies between 18° and 20° N. and 73° and 75° W. which is best described by a photograph (Fig. 23). The elongate depressions are clearly initiated along and controlled by fractures. Vertical relief is estimated to be on the order of 0.5 to 1 km. Because so much material is missing, this complex might be regarded as a product of crustal spreading, which nicely disposes of the material. However, from comparison with other areas of fretted terrain, where a spreading mechanism seems inappropriate, this complex is regarded as more likely the product of a sapping and debris-removal process.

The number and variety of channels and channel-like forms visible on the Martian surface at resolutions of 1 to 3 km, and in local spots at resolutions of 100 to 300 m, cause one to wonder what exists in finer detail. The Martian surface may be riven by countless small gullies. Conversely, fracturing, mass movements, impact emissions, volcanism, and albedo contrasts of diverse origins can create an impression, at low resolution, of more extensive gullying than is seen to actually exist on high-resolution photos of the same area.

AGES OF CHANNELS

All writings on Mars involve considerable speculation; let the reader be warned that this is particularly true of the following pages. The readily apparent channels are clearly younger than many other Martian topographic features. They have also been generally regarded as youthful in absolute age owing to sharpness of outline, absence of extensive blanketing, lack of secondary modification, and especially the paucity of superimposed small, fresh craters. Crater relationships provided the basis for earlier estimated ages of possibly a few hundred million years (Hartmann, 1974, p. 3953; Jones, 1974, p. 3930).

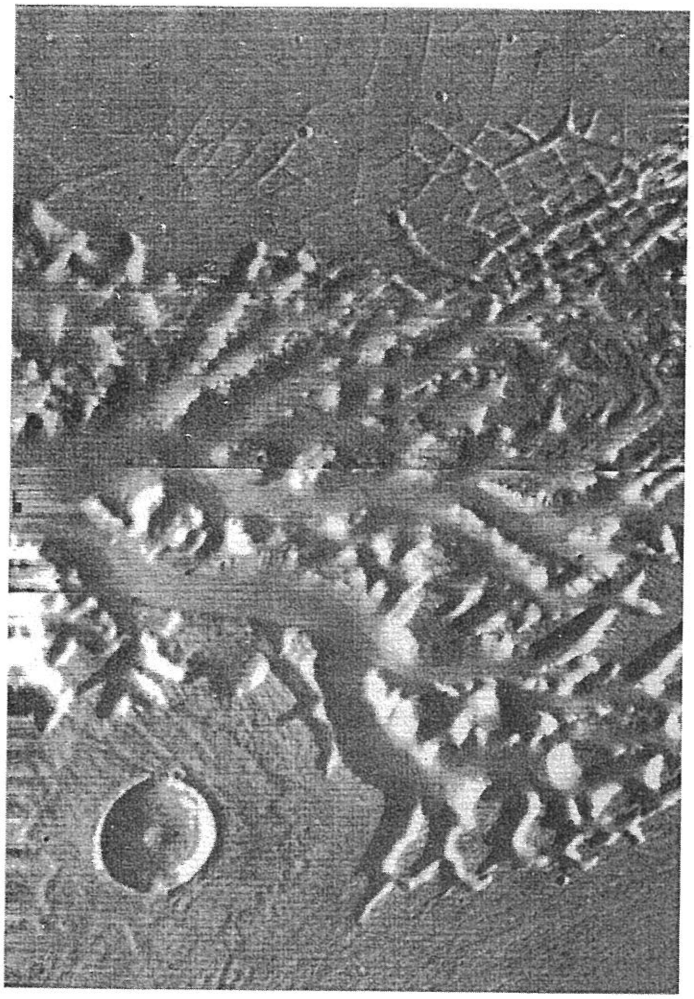

Figure 23. High-resolution composite of fretted terrain complex with strong fracture control. (Width 60 km; DAS 13313730 and 13313800, 667B 03/13 and 667B 04/13.)

Recent re-evaluation of the source of meteoroidal bodies impacting the Martian surface (Wetherill, 1974; E. M. Shoemaker, unpub. data; Metz, 1974) suggests that the flux of meteoroidal impacts on Earth, Moon, and Mars may have been closely similar after the early accretionary stage. These planetary bodies were subject to an early, heavy, but rapidly decreasing flux of impacting bodies until about 3.8×10^9 yr ago, when a rapid transition occurred over about 600 m.y. to a much lower and nearly steady flux at about 3.2×10^9 yr ago (Soderblom and others, 1974). Under this concept, the abundancy of craters suggests that many Martian surface features, including channels, may be of about the same absolute age as the comparably cratered lunar mare, that is, 3 to 3.5×10^9 yr.

This speculative age has significant implications with respect to features displaying possible evidence of fluidal activity. Mars might, at that time, have had a relatively dense residual volatile-rich atmosphere, generated by accretionary and impacting processes, which was congenial to liquids upon the Martian surface. The duration of such an atmosphere is unknown, but it might have extended well this side of the 3 b.y. mark. The concept of an early residual atmosphere has been stated many times before (see Öpik, 1966, p. 263), but the new lunar chronological record and the newly proposed interpretations of cratering histories (Soderblom and others, 1974) bring more concrete support to this earlier speculation.

An age possibly exceeding 2 to 3 b.y. for Martian exogenic channels has implications concerning subsequent weathering and erosion. If the channels in equatorial and mid-latitudes are billions of years old, eolian blanketing and erosion have been remarkably ineffective there, as recognized by Soderblom and others (1974). The contrast between sharp fresh channels and barely discernible channels would ordinarily be taken as indicative of great age differences. However, intense weathering and erosion during the ancient transition period may have significantly modified channels created early within that epoch compared to those formed near its close. The difference in apparent age of individual channels created during the transition interval may thus be great compared to the modification suffered by all channels during the last 2 to 3 b.y. This is not to say that all parts of the Martian surface have been geologically inactive during the last 2 to 3 b.y. In the polar regions, eolian deposition and eolian erosion may have been effective right up to the present (Cutts, 1973a), and the related blanketing and exhumation in subpolar areas (Soderblom and others, 1973) may also represent more recent activity.

The scattered distribution of exogenic channels is subject to at least two interpretations. If the channels are as old as 3 b.y., they should be missing in areas where later accumulation has occurred. The lack of large fluidal channels in the polar regions, in the subpolar annular depositional belts, and in areas of younger volcanism, which may be older than previously thought (Young and Schubert, 1974, p. 159), supports such an interpretation. Yet the channels within heavily cratered old terrain are also widely scattered without evidence that this is due to obscuration in the intervening areas. The haphazard geographic distribution, particularly of outflow and runoff channels, may reflect primarily a scattered distribution of sources of fluid.

WHAT LIQUID?

Frequent reference has been made to fluid and to fluidal activity, with an implication that the fluid was liquid, not gaseous (Milton, 1973, p. 4040). Liquids most worthy of consideration are lava, water, or aqueous solutions.

Carr (1974) analyzes channel erosion by lava on lunar and Martian surfaces. On Earth, magma erodes by picking up fragmental material (Asquith, 1973), but Carr favors fusion and removal of bedrock by the through-flow of hot, highly fluid lava. Any channel formed or significantly modified by this process should be tributary to a considerable accumulation of lava. Although lava fields may not be easily recognizable, Mariner 9 photos strongly suggest that they are not present in the debouchment areas of many Martian channels. Those channels, at least, are presumably not the product of lava erosion, and Carr (1974, p. 20–22) makes no claim that the major Martian channels are formed by this process. Other volcanic channels probably result from lava accretion and lava-tube collapse (Greeley, 1973).

The most effective erosive liquid on Earth is water, which is also a feasible liquid for Mars. Significant contemporary erosion by water is prohibited by the present Martian environment, except under unusual and probably local circumstances. Heated volcanic water, possibly rich in freezing-point depressants, might have created the Ceranius Dome channels (Fig. 9). Since the largest of these channels terminates in a caldera, it is not a likely product of lava erosion, for the volume of lava required would probably have obliterated the caldera. The filling required by fluvial debris would be much less. Reasons for considering the caldera antecedent to the channel have previously been given.

It seems less likely that outbursts of liquid water from the areas of chaotic terrain at the heads of large outflow features, like the Ares channel (Fig. 7), could be effective under present conditions. Slowly outflowing water would surely freeze or evaporate, and even a catastrophic flood would probably not be able to carry with power and vigor hundreds of kilometers across the Martian surface before suffering a similar fate, although Lingenfelter and others (1968) propose such an event on the Moon. Milton (1974) suggests a mechanism for getting large discharges of water from subsurface carbon dioxide clathrate (Miller and Smythe, 1970) that might be effective under a somewhat less rigorous environment.

The storage of water on or beneath the surface to supply large floods is a problem under present conditions. Surface water would freeze and evaporate, and a pond could form only if ground-water seepage occurring under an ice cover was great enough to prevent total freezing and to exceed the loss by evaporation from the frozen surface. A local change in geothermal gradient would probably be required to support such seepage. Underground storage of water for floods (McCauley and others, 1972, p. 321) would not seem satisfactory because the water would be too greatly dispersed through pores and interstices of the crustal rocks to be rapidly discharged. Maxwell and others (1973) escape this problem by invoking meteorite impact with nearly instantaneous melting of ground ice. Even if this mechanism is sound, it can apply to only the minor number of Martian channels that originate in craters. The carbon dioxide clathrate hypothesis of Milton (1974) seems more generally applicable.

Outflow of runoff channels fed by continual seepage, in which the liquid medium is water, currently suffers even more severely from the freezing and evaporation handicap. However, since lava flows, wind, or density currents may not account for many, perhaps most, erosional Martian channels, consideration must be given to water or aqueous solutions as possible genetic agents, in spite of the environmental problems.

SUMMARY DISCUSSION ON THE ORIGIN AND IMPLICATIONS OF MARTIAN CHANNELS

Martian channels and channel-like features come in many sizes, shapes, and patterns. They are surely not of a single origin. Some may be created by influences acting from within the crust, others may result from external erosive processes, and some channels are probably composite, the result of exogenic modification of an endogenic feature.

Most Martian channels or channel-like features imply removal of material. An exception would be a channel of accretion made by greater accumulation along the margins than in the channel itself. Some lava channels on Mars are attributed to accretion (Greeley, 1973), and certain terrestrial sedimentary channels are of accretional origin. The material missing from a channel may have moved down, up, or parallel with the surface, either laterally away from the channel or longitudinally along it. Relative downward motion can occur by tectonic faulting or warping, or by subsidence and collapse resulting from removal of underlying support through solution, deterioration of ground ice, or magma withdrawal. Upward movement occurs in the instance of explosions, impacts, or eolian deflation, with only the last seemingly worth serious consideration with respect to elongate depressions. Lateral movement can result from extension within the crust (Schumm, 1974), and longitudinal removal usually occurs through transportation by some exogenic process.

Since some Martian channel-like features are closed at both ends, their creation through erosion would have to be by solution or deflation. Solution is suspect because of the need for abundant solvent and soluble rocks. Arguments are advanced for eolian erosion on Mars (Arvidson, 1972; McCauley, 1973; Sagan, 1973; Cutts, 1973a), but deflation as the sole cause of closed-end channels is contested by the highly localized erosional requirement, the need to reduce all material to extremely fine size, the likely inhibition of deflation by development of coarse surface armors, and the lack of evidence of associated eolian deposits (Hobbs, 1918, p. 56; Ball, 1927; Smith, 1969, 1972, p. 72–74). The most feasible means of creating closed-end channel-like features on Mars seems to be by downward movements of endogenic origin. As to the exogenic erosive processes which may have helped form other Martian channels, mass movements, wind, ground-ice sapping, ground-water sapping, and flowing liquids deserve consideration.

Erosional forms on steep faces may have been created by mass movements — for example, the parallel U-shaped features interpreted as avalanche chutes (Sharp, 1973b) after Blackwelder (1942) and Matthes (1938). However, as shown by Milton (1973, p. 4040), there is little reason to attribute the large scoured channels of Mars to any mass-movement process, including density currents or volcanic glowing clouds.

The capacity of wind to create channels, other than the polar grooves (Cutts, 1973a; Soderblom and others, 1973) and possibly the aureole of grooved terrain around Olympus Mons (Carr and others, 1973; McCauley, 1973, p. 4129), remains an open question, but wind may have modified channels created by other processes. A possible example is Kasei channel (Fig. 18) in which the lineation and streamlining, attributed by Baker and Milton (1974, p. 35–37) to fluvial flood action, may be the product of eolian activity.

Longitudinal erosion and transportation in any channel requires disposal of both the transported material and the transporting medium. In the instance of avalanche chutes, the material resides in detrital slopes below, and disposal of gravity is no problem. Material carried in eolian suspension can be widely dispersed, and air is also easily disposed of. However, eolian suspension is likely to be accompanied by saltation and traction, and this bed-load material should form accumulations not far removed from the erosional source (Hobbs, 1918; Smith, 1972). They are not yet distinguished on Mars in association with channels, although their recognition is admittedly difficult.

For channels supposedly cut by lava (Carr, 1974), disposal of the eroding medium is an acute problem. In addition to the eroded material, a much larger volume of lava must be accommodated in the debouchment area. Although unequivocable identification of lava fields on Mariner 9 photos is admittedly difficult, a great many eroded Martian channels have nothing suggestive of lava accumulations at their mouths.

The problems regarding water are not only its disposal but also its source and the environmental conditions that would permit it to act on the Martian surface. Disposal is not too difficult, as the water could have percolated into the ground or evaporated into the atmosphere. Under current conditions, the percolated water would freeze to ground ice, and any vaporized water, after perhaps having first been precipitated temporarily as local snow, would eventually be captured in the cold traps of polar ice. The problem then becomes the amount of ice that resides in the polar blankets, including layered deposits, a subject of considerable debate. Over a long time, however, significant amounts of water may have dissassociated and escaped to outer space (McElroy, 1972; Sagan and Mullen, 1972, p. 55; Fanale, 1971).

The suggestion (McCauley and others, 1972; Maxwell and others, 1973) that Martian water sources may have been largely lithospheric, rather than atmospheric, finds support in the following relationships. The large erosional channels (Mangala, Ma'adim, Ares, Nirgal, and Ceraunius) are isolated features largely unaccompanied by other channels and unrelated to each other beyond the fact that they occur principally in heavily cratered older terrain and in equatorial or subequatorial regions. Even the smaller dendritic tributaries and slope gullies are localized. This suggests that water has been made available only locally. If the water were atmospheric (Hartmann, 1974, p. 3954), this would require significant precipitation only in spots. By contrast, the above channels all have possible local sources of lithospheric water. For Mangala and Ma'adim, the sources are large headwater seepage areas, and for Ares, it is chaotic terrain. For Nirgal channel, seepage into the headwater tributaries and into the trunk channel could have occurred. The larger channels on Ceraunius Dome have an obvious source in the central caldera.

The concept of water being supplied at localized spots of the Martian surface from underground sources thus has appeal. Parts of the Martian crust and surface became temporarily "juicy" (Fanale, 1971, p. 285), at which time water was supplied to the surface in the form of seeps. In places, seepage could have nourished a system of gullies which dispersed the water widely over the terrain; in other situations, the seepage was integrated by branches and tributaries to feed a major channel; and in some places, the water may have been ponded and eventually released as a flood. Evidence for huge catastrophic floods is good in Mangala and Ares channels, and according to Baker and Milton (1974) also in Kasei channel, although the means of accumulating and storing water is a problem. Storage could have occurred in the headwaters seepage area of Mangala and within the extensive areas of depressed chaotic terrain at the head of Ares.

Martian lithospheric water might represent juvenile waters coming from a crystallizing magmatic body, or it might be melted primordial ground ice. Why the "juicy" spots should be randomly distributed is, perhaps, just a vagrancy of nature. Channels on Mars are concentrated into areas equator-ward of 40° N. and 60° S., with greatest abundance in equatorial areas (Sagan and others, 1973), but this may reflect blanketing by younger deposits in subpolar regions (Soderblom and others, 1973) more than some environmental influence. Even in equatorial regions, catastrophic floods might experience difficulties under the currently rigorous environment, and a slower, continuing discharge would probably be ineffective. The fretting process that possibly plays a role in channel development would also suffer if it involved ground-water sapping and runoff.

Derivation of water from the lithosphere rather than the atmosphere only partly solves this environmental problem, but it may significantly reduce the degree of environmental amelioration required. Producing widespread precipitation from the atmosphere is one thing, and keeping water fluid on the surface is another, especially if the water is initially warm and contains some freezing point depressant. Rather than an atmospheric pressure of 1,000 mb (Sagan and others, 1973), perhaps a fraction of that would suffice.

Irrespective of the degree of amelioration, the erosional channels do seem to require that at some time, possibly in the far distant past, the surface environment of Mars has been less rigorous than it is at present. This is what the channels appear to say in spite of various models, theories, and arguments to the contrary.

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