Reports

Martian Valleys: Morphology, Distribution, Age, and Origin

Abstract. *Branching valley networks throughout the heavily cratered terrain of Mars exhibit no compelling evidence for formation by rainfall-fed erosion. The networks are diffuse and inefficient, with irregular tributary junction angles and large, undissected intervalley areas. Rather, the deeply entrenched canyons, with blunt amphitheater terminations, cliff-bench wall topography, lack of evidence of interior erosion by flow, and clear structural control, suggest headward extension by basal sapping. The size-frequency distributions of impact craters in these valleys and in the heavily cratered terrain that surrounds them are statistically indistinguishable, suggesting that valley formation has not occurred on Mars for billions of years.*

The Mariner 9 Mars orbital reconnaissance mission discovered ubiquitous valley networks in heavily cratered terrain (Fig. 1). Their branching and coalescent character provoked immediate comparison to terrestrial riverine networks produced by fluvial erosion, a process driven primarily by rainfall (*1*). Liquid water, however, cannot now exist at the surface of Mars for more than a few minutes owing to very low atmospheric pressure and very cold temperatures during most of the year at most latitudes (*2*). It has been suggested that these features, if formed by processes similar to those that operate in the formation of terrestrial river systems, are relics of a more clement epoch (*3*). Thus a major problem in the study of Mars is whether the valley networks could have evolved under current surface conditions or whether a major shift in martian climate occurred. This report summarizes the geological and geomorphological aspects of this problem.

Although martian valleys display a diverse mix of network patterns and morphologies, there are certain unifying characteristics. Martian valleys are distinguished here from channels by the absence in the former of the direct evidence of fluid erosion often found in the latter (*4*). There is no clear evidence (streamlined obstacles, interior channels) of direct fluid erosion in any martian valley. It is possible that such features are too small to be seen in the Mariner 9 and Viking images, although features as small as 100 m can be resolved in some Viking Orbiter images of valleys (Fig. 1). The walls of the valleys are typically rugged and clifflike, with some debris accumulation and talus, and the floors are generally flat. Mantling by materials of eolian and volcanic origin is common. Some valleys display cliff-bench interior topography, similar in character and scale to features in the Grand Canyon of the Colorado River which were formed by differential resistance to erosion (*5*). This type of morphology may be evidence of extensive layering and contrasting materials in the heavily cratered terrain, as suggested by Malin (*6*). The most striking morphological characteristic, however, is the presence of steep-walled, cuspate terminations at the heads of the smallest tributary valleys (such as Nirgal Vallis). These steep-walled amphitheater terminations suggest headward extension (sapping) by basal undermining and wall collapse, as in the predominant mode of headward extension for many terrestrial canyons.

Martian valley networks lack the dendritic pattern so common to terrestrial streams. Characterized by a nearly uniform distribution of tributary directions and filling of the available intra-network space, it is achieved in terrestrial drainage networks through a time-averaged, spatial uniformity of rain in a drainage basin, irrigating all available slopes in the network equally in the absence of strong structural or lithologic control. The martian valley patterns (*7, 8*) show remarkable parallelism and lack of tributary competition for undissected intervalley terrain, and thus appear diffuse compared to most terrestrial systems (Fig. 2). Viewed from satellites, terrestrial drainage systems have a fine filigreed texture, whereas martian systems appear coarse. Further, terrestrial drainage patterns are generally scale-invariant, retaining their dendritic character at increased magnification. Different types of martian valley networks form reoccurring system patterns (*8*) that are scale-variant. Along with system parallelism, these differences of pattern with scale most probably result from the introduction of fluid into the system from a restricted headward source combined with strong structural control (*9*).

It has long been thought that terrestrial river systems modify their longitudinal profiles in an attempt to come to grade, a condition that exists when such variables as slope, width, depth, and load competence reach a steady state (*10*). Horton (*11*) and Howard (*12*) established that angles between intersecting tributaries at their junction are proportional to the slopes of the intersecting tributaries. It is reasonable to expect that tributary junction angles and therefore network patterns should reflect the rate of decline of slopes downstream in drainage networks in a systematic way. Lubowe (*13*) showed that tributary junction angles increase downstream as the size of recipient streams increases. A quantitative model for the systematics of junction angles in surface drainage networks was tested on terrestrial dendritic networks mapped at various scales (*8*). The tributary junction angles increased with increasing recipient stream size in a way closely predicted by the model (Fig. 3). This is not the case in martian valleys, where junction angles are generally shallow ($\lesssim 25°$) and show no significant correlation with position in the network or size of intersecting tributaries (Fig. 3). This suggests that small tributaries on Mars are not consequent on the valley-side slopes of trunk valleys, even though in many cases they appear to be accordant. Hierarchically small tributaries exhibit vertical cross-sectional areas equal to those of main trunk segments and enter at extremely shallow junction angles, neither characteristic being common in terrestrial drainage networks (*14*). Martian network systems do appear to coalesce downhill on regional slopes. Downhill coalescence is suggestive of fluid flow, but uphill-tending headward erosional processes could produce an identical result. Thus, evidence for fluid flow in martian valley systems is of an indirect nature.

Valley systems have been found in all parts of the heavily cratered terrain (*8*). The concentration of valleys appears to be greatest in the equatorial zone ($\pm$ 10° latitude), and this apparent correlation has sparked comment (*3*). Also, valleys are seen more often in cratered terrain of low albedo corresponding to the classical dark markings seen from the earth (*15*). This correlation is misleading in the sense that it is not indicative of the original distribution of valleys in the heavily cratered terrain. Valleys (as well as small craters) (*16*) are often inundated by

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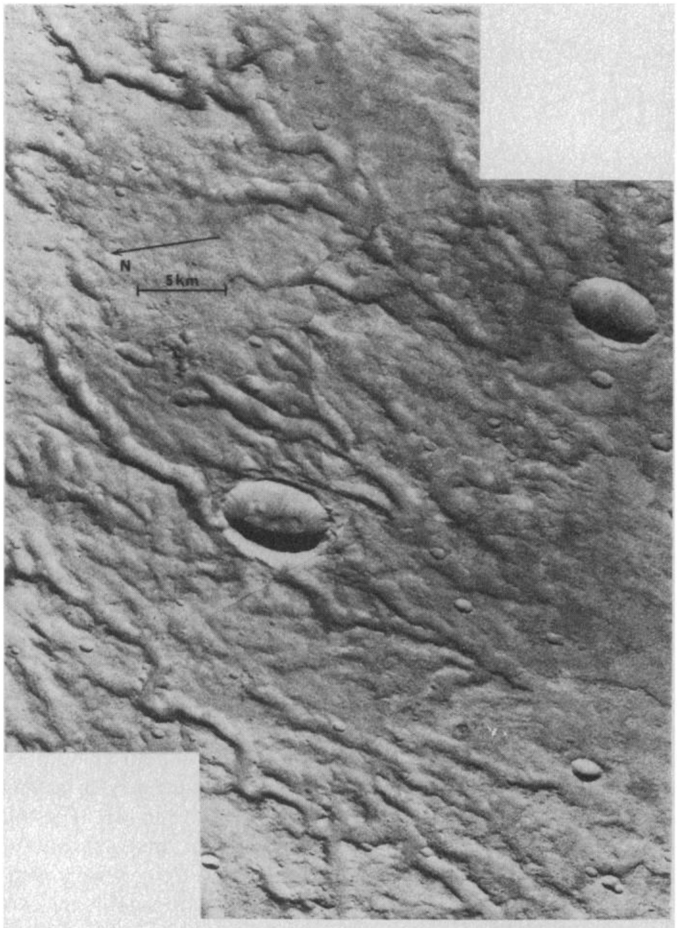


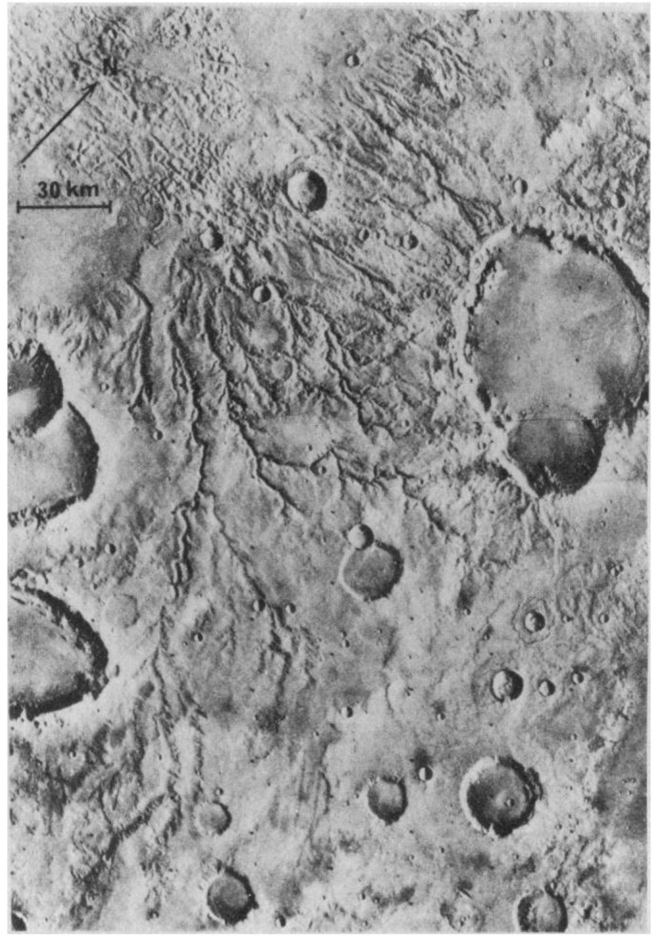
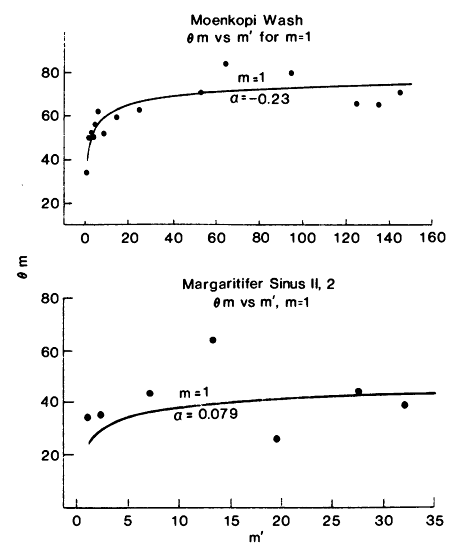


Fig. 1 (left). Close-up of valley systems shown in Viking Orbiter frames 754A16, A17, A18, and A19. This high-resolution view clearly shows the heavily cratered, rugged, eroded appearance of the valleys and surrounding terrain. The disorganized appearance of martian valleys is common at this resolution (48 m per pixel). Amphitheater terminations are present and valley interiors are smooth, as if mantled. There is no evidence of runoff erosion on intervalley surfaces. Inundation and burial of valleys by plains-forming material has occurred at the lower right. Sun elevation angle is 28°, illumination is from the lower left, and viewing angle is 50°. Fig. 2 (right). Digitate network system in Margaritifer Sinus seen in Viking Orbiter frames 084A46, A47, and A48. Long parallel intervalley septa are visible. Amphitheater terminations to tributaries are common. Note the prevalence of stubby tributaries parallel to the main valleys. Evidence of dissection and drainage basin development in intervalley areas is lacking. This pattern, like all martian valley patterns, shows little resemblance to terrestrial dendritic systems. Sun elevation is 35°, illumination is from the right, and viewing angle is 10°.



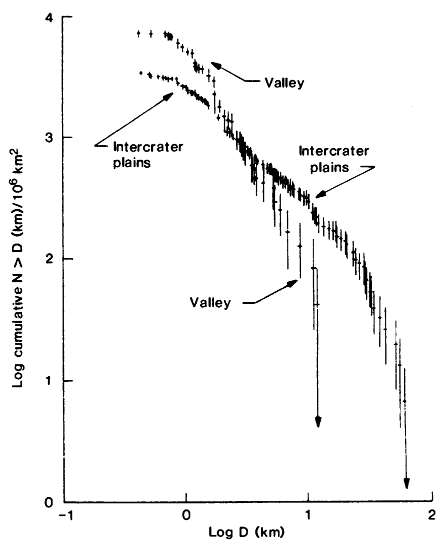


Fig. 3 (left). Plots of mean tributary junction angle (θ_m) for the smallest definable tributaries (magnitude $m = 1$) entering progressively larger recipient stream segments (m'). Junction angle here is defined as the angle of deviation from the outlet of the junction (*12*). Tributary (link) magnitude is defined as in Shreve (*19*). The parameter α is a measure of the concavity of the stream longitudinal profile, adapted from Flint (*20*). The data from Moenkopi Wash, showing a rapid increase in the junction angles of the smallest tributaries, closely follow the curve predicted by the quantitative model (*8*) and are statistically significant, at the .995 level, for a least-squares-fit value of -0.23 for α. This is typical for ephemeral streams with only moderately concave longitudinal profiles. Mature well-developed drainage basins typically show values of α ranging from -0.4 to -0.6. The data, however, show no significant systematic correlation of junction angle with position in the network, suggesting that the martian networks exhibit little or no response to the surrounding topography. Fig. 4 (right). Plot of unbinned cumulative size-frequency distribution of about 700 impact craters in five valley interiors and surrounding terrain. For diameters between 1 and 4 km, the plots are statistically indistinguishable from one another. For larger crater diameters, valleys have slightly fewer craters than the surrounding terrain and are therefore slightly younger. At diameters less than 1 km, the surrounding terrain has fewer impact craters than the valleys, probably due to obliteration of small craters by the formation of younger intercrater plains in areas included in the counts (*21*).

eolian or volcanic materials, forming younger intercrater plains. If mantles are absent in these areas, however, valleys are observed.

The distribution of the valleys has an obvious bearing on the question of their age. Valley systems have not been detected on plains material younger than Lunae Planum (*7, 15*). This has been corroborated in recent mapping by Carr (*17*). By implication, the martian valley systems must be older than both Lunae Planum and the intercrater plains.

Another way of determining relative age is by counting the number of impact craters in the valleys and comparing the size-frequency distribution to that of both the immediately surrounding terrain and other types of terrain (Fig. 4). There are two main observations. First, the valleys have high densities of superimposed craters, implying very long exposure. Second, there is no significant difference between the density of craters in the valleys and in the surrounding terrain, implying that the valleys are roughly as old as the ancient surrounding terrain. Thus, several lines of evidence suggest that the valley networks were formed early in the history of Mars.

Martian valley systems are diverse and can be classified by network pattern and morphology. The diversity is most likely the result of several processes acting in variable structural and lithologic regimes. Dendritic patterns, prevalent on the earth, are absent on Mars; diffuse patterns, inefficient at filling space, predominate. Valley interiors display steep, clifflike walls, flat floors (without direct evidence for erosive fluid flow), and amphitheater terminations, suggesting basal sapping. Networks of these valleys are widely distributed in heavily cratered terrain, including south polar areas, although the visibility of valleys may vary due to widespread superposition of eolian debris mantles and ubiquitous younger intercrater lava flows. Size-frequency distributions of craters in the valleys indicate that there is no significant difference between the age of the valleys and that of the surrounding ancient terrain. This, combined with the lack of valleys in terrain younger than Lunae Planum and their partially obliterated appearance, suggests that valley formation processes have not been active on Mars for billions of years. It is concluded that valleys were formed on Mars during an ancient epoch by erosional processes involving not rainfall but the movement of groundwater and its participation as a liquid or a solid in the undermining of less competent strata, causing progressive headward collapse (*18*). These processes, combined with modification by impact and eolian processes, have produced the degraded valleys seen on Mars today.

DAVID C. PIERI
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103

References and Notes

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22. I thank L. Soderblom, E. Morris, and H. Masursky for their help in the early phases of this study, and C. Sagan, J. Veverka, A. Bloom, and W. Travers for their help during the thesis work. I am also grateful for the tireless encouragement, criticism, and friendship of M. Malin. Supported by Planetary Geology Program (NASA) contract NAS 7-100, the National Research Council at Jet Propulsion Laboratory, and NASA grant NGL 33-010-082 at the Laboratory for Planetary Studies, Cornell University, Ithaca, N.Y.

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Solar Neutrino Production of Long-Lived Isotopes and Secular Variations in the Sun

Abstract. *Long-lived isotopes produced in the earth's crust by solar neutrinos may provide a method of probing secular variations in the rate of energy production in the sun's core. Only one isotope, calcium-41, appears to be suitable from the dual standpoints of reliable nuclear physics and manageable backgrounds. The proposed measurement also may be interesting in view of recent evidence for neutrino oscillations.*

Solar neutrinos provide a unique opportunity for probing the fusion reactions that occur deep in the solar core (*1*) and for testing properties of the neutrino over distance scales not attainable in terrestrial laboratories. To date, we have only a single measurement of a portion of that neutrino flux, from the ^{37}Cl experiment of Davis and co-workers (*2*). The result, 2.2 ± 0.4 SNU (*3*) [1 solar neutrino unit (SNU) = 10^{-36} capture per target atom per second], is quite surprising in view of the most recent prediction for the standard solar and weak interaction models, 7.0 SNU (*4*). It is not clear whether this discrepancy is due to a misunderstanding of solar physics, of the neutrino, or, less likely, of the chemistry of the ^{37}Cl detector.

The standard solar model predicts that approximately 70 percent of the expected ^{37}Cl rate is due to capture of the high-energy neutrinos produced in the β decay of ^{8}B (see Table 1). The production of these neutrinos depends critically on the central temperature of the sun. Davis's results have thus stimulated the development of a number of nonstandard models in which this temperature, and consequently the ^{8}B neutrino flux, are reduced (*5*). Probably the most popular such models have been those with a low heavy-element abundance, and correspondingly diminished opacity, in the solar core. However, the fine structure recently observed in the 5-minute solar oscillation (*6*) has been attributed to a higher velocity of sound than would occur in such models.

Another class of nonstandard solar

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