

**ORIGIN OF THE VALLEY NETWORKS ON MARS:
A HYDROLOGICAL PERSPECTIVE**

Virginia C. Gulick*

Space Science Division, MS 245-3

NASA-Ames Research Center

Moffett Field, CA 94035

(415) 604-0781

vgulick@mail.arc.nasa.gov

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*also at Dept. of Astronomy, New Mexico State University, Las Cruces, NM

Abstract

The geomorphology of the Martian valley networks is examined from a hydrological perspective for their compatibility with an origin by rainfall, globally higher heat flow, and localized hydrothermal systems. Comparison of morphology and spatial distribution of valleys on geologic surfaces with terrestrial fluvial valleys suggests that most Martian valleys are probably not indicative of a rainfall origin, nor are they indicative of formation by an early global uniformly higher heat flow. In general, valleys are not uniformly distributed within geologic surface units as are terrestrial fluvial valleys. Valleys tend to form either as isolated systems or in clusters on a geologic surface unit leaving large expanses of the unit virtually untouched by erosion. With the exception of fluvial valleys on some volcanoes, most Martian valleys exhibit a sapping morphology and do not appear to have formed along with those that exhibit a runoff morphology. In contrast, terrestrial sapping valleys form from and along with runoff valleys. The isolated or clustered distribution of valleys suggests localized water sources were important in drainage development. Persistent ground-water outflow driven by localized, but vigorous hydrothermal circulation associated with magmatism, volcanism, impacts, or tectonism is, however, consistent with valley morphology and distribution. Snowfall from sublimating ice-covered lakes or seas may have provided an atmospheric water source for the formation of some valleys in regions where the surface is easily eroded and where localized geothermal/hydrothermal activity is sufficient to melt accumulated snowpacks.

1. Introduction

The origin of the Martian valley networks has been debated ever since their discovery, in the 1970's, in Mariner 9 and Viking Orbiter imagery. These valleys have integrated networks of tributaries and are morphologically similar to valleys formed by ground-water sapping processes on Earth. At present, Mars is a cold desert, devoid of liquid water where atmospheric pressures average a mere 0.6% that of the Earth's and temperatures average 220°K. However, the presence of fluvial valleys and large catastrophic flood channels on a variety of different aged terrains indicates that liquid water did flow on the surface or in the near subsurface several times during Mars' geological history. For example, Martian outflow channels, analogous to the large catastrophic flood channels of eastern Washington and Siberia, required enormous

discharges on the order of several 10^6 to 10^9 m^3/s lasting over periods of weeks to months (Baker *et al.*, 1991). Although these channels could still form in today's climate, there is uncertainty as to whether the fluvial valley networks, which required much lower discharges persisting for periods of at least 10^5 years (Gulick 1993), could have formed under similar climatic conditions.

There are two prevailing views as to how the valley networks might have formed. Until recently, the conventional wisdom has been that early in Mars' geological history, greenhouse gases such as CO_2 warmed the surface sufficiently so that liquid water derived from rainfall could erode the surface and produce stream channels and valleys similar to the way such features form on the Earth. However, more recent climate models (Kasting 1991) preclude the existence of such a climate early in the planet's history when many of the fluvial valleys formed in the Southern Highlands region. An alternative view has held that the stream valleys on Mars formed as result of a uniform, globally higher geothermal heat flow, early in the planet's history (Squyres 1989). Both mechanisms have difficulty explaining all of the observed morphologic characteristics of the Martian valleys. Neither explanation can account for the formation of valleys later in Mars' geological history. A third possibility is that geological heat sources, such as igneous intrusions (Wilhelms and Baldwin 1989), and the formation of large impact craters (Schultz *et al* 1982; Brakenridge *et al.* 1985) and volcanos, produced vigorous, localized hydrothermal systems that resulted in ground-water outflow sufficient for valley formation (Gulick *et al.*, 1988; Gulick and Baker, 1989, 1990; Gulick 1993, 1998). An advantage of magmatically produced localized hydrothermal systems is that they could have formed throughout the planet's geological history and could therefore potentially account for the various episodes of fluvial valley formation on Mars.

This paper examines the geomorphology of the Martian valley networks from a hydrological perspective. Morphology, volumes and spatial relationships of several Martian valleys are discussed and compared to terrestrial fluvial valley systems. Valley formation is then re-evaluated in terms of its compatibility with an origin by rainfall, globally higher heat flow, or localized hydrothermal systems.

2. Martian Fluvial Valleys

2.1. Background and Overview

Mars is divided into two major geological provinces, the Southern Highlands and the Northern Plains (**Figure 1**). The Southern Highlands contain the most ancient terrains on the surface of Mars, and are primarily composed of heavily cratered terrains consisting of a blocky, porous impact-produced megaregolith that in many regions is covered by extensive lava flows (Tanaka *et al.* 1992; Squyres *et al.* 1992). These flows together with igneous intrusions and some aeolian or fluviually deposited material form the Highlands' intercrater plains (Carr and Clow 1981; Tanaka 1986; Tanaka *et al.* 1992; Wilhelm and Baldwin 1989; Baker *et al.* 1992; Strom *et al.* 1992). However, the Northern Plains are topographically lower, 3 km on average, than the Southern Highlands. These lowlands consist mostly of younger (less cratered) and smoother plains material composed of lava flows and sediments (Tanaka *et al.* 1992). In addition, the two major volcanic regions Tharsis and Elysium are located in the Northern Plains.

The geological history of the planet is divided into three major time-stratigraphic systems, the Noachian, the Hesperian and the Amazonian (Scott and Carr 1978; Tanaka 1986) (**Figure 2**). The earliest period for which there are preserved surfaces is the Noachian. Noachian terrains formed during the period of heavy bombardment, a time when the planets experienced extremely high impact cratering rates, due either to collisions of accretional debris left over from the formation of the solar system or to comets and asteroids. Depending upon the source of the impacts, this period probably ended on Mars around 3.8 Ga, although Wetherill (1977) suggests that the end of late heavy bombardment might have persisted until 2.8 Ga (Strom *et al.* 1992). Hesperian terrains generally consist of less cratered plains of largely volcanic origin, while Amazonian surfaces generally consist of smooth volcanic plains material, although fluvial, sedimentary and aeolian mantles are common (Tanaka *et al.*, 1992). Most Noachian terrains are located in the Southern Highlands, although Hesperian and Amazonian surfaces are also found in the Highlands. Most terrains in the Northern Plains are Hesperian or Amazonian in age. A variety of Martian volcanoes of different ages are located throughout the Southern Highlands and the Northern Plains.

The earliest fluvial valley networks formed on two Noachian age surfaces, the heavily cratered uplands and the somewhat younger intercrater plains. Superposition relationships and crater density studies indicate that the valley networks are contemporaneous with much of the intercrater plains, although some networks continued to form after the emplacement of these plains units and after the period of heavy

bombardment (Baker and Partridge 1986). The nearly coincident formation of fluvial valley networks and the high degree of impact crater degradation during this time period (Strom *et al.* 1992; Barlow 1988) led to the prevailing theory that early Mars had a thicker atmosphere and a warmer climate (Sagan *et al.* 1973; Pollack *et al.* 1987).

Volcanism was widespread throughout the Southern Highlands toward the end of the Noachian and into the early Hesperian and dominated the formation of the Northern Plains units throughout the remainder of the Hesperian (Tanaka 1986; Barlow 1988; Strom *et al.* 1992). Although widespread fluvial valley development ceased in the Southern Highlands by the early Hesperian, local areas of fluvial activity continued into the Hesperian in the Tempe, Electris, and Casius regions (Grant and Schultz 1989) and in the Mangala Vallis region (Chapman and Tanaka 1990; Scott and Chapman 1991) as well as on several Martian volcanoes (Gulick and Baker 1990). These include two Highlands volcanoes, Tyrrhena Patera (Noachian-Hesperian) and Hadriaca Patera (Hesperian), and three Lowlands volcanoes Ceraunius Tholus (Noachian), Hecates Tholus (Hesperian), and Apollinaris Patera (Noachian-Hesperian). By the late Hesperian, volcanism became concentrated into two major volcanic regions within the Northern Plains: the Tharsis and Elysium provinces. It is during this period in regions adjacent to these major volcanic provinces that catastrophic releases of ground water formed most of the outflow channels. Although outflow channel formation was concentrated in the Hesperian, flooding continued, albeit at a much lower magnitude, well into the Amazonian.

Fluvial valleys began to form on early Amazonian-aged surfaces on Alba Patera, a Lowlands volcano located along the northern edge of the Tharsis region. These valley systems form the most integrated networks on the surface of Mars, and exhibit some of the highest drainage density values of any Martian valleys (Gulick and Baker 1989, 1990). Unlike other fluvial networks on Mars, fluvial valleys on Alba Patera are most similar morphologically to terrestrial stream valleys, particularly to those formed on the Hawaiian volcanoes (Gulick and Baker 1989, 1990). Note that Alba fluvial valleys formed well after the decline of the putative early Earth-like climate (probably as much as 1 to 2 Gyrs after) which ended soon after the end of the Noachian (**Figure 2**).

Throughout the late Hesperian and early Amazonian, glacial-like landforms resembling arêtes, eskers, and tunnel valleys, modified ancient cratered terrains poleward of approximately 40 or 50°S (Kargel and Strom, 1992). Poleward extensions of the Northern Plains may also have been affected by glaciation

(Kargel and Strom, 1992). The last vestiges of fluvial activity on Mars occurred near Olympus Mons, which is a large volcano in the Tharsis region, and also west of Ceraunius Fossae, where small outflow channels have formed on lava flows that comprise some of the youngest surfaces on the planet (Mouginis-Mark 1990).

2.2. Morphology

Fluvial features on Mars can be broadly divided into two categories: fluvial valleys and outflow channels. The outflow channels are large-scale complexes of fluid-eroded troughs, up to 100 km wide and 2000 km in length, and are characterized by anastomosing channel patterns and large-scale flow features. These channels are similar to those produced by catastrophic flood waters from large glacially-dammed lakes on Earth during the Pleistocene. However, unlike their terrestrial counterparts, fluid flows that carved the Martian outflow channels were cataclysmically released from the subsurface (Baker, 1982; Mars Channel Working Group, 1983). Channels emanate from chaotic terrain, large fractures or elongate depressions. Chaotic terrain consists of slump and collapse blocks in steep-walled arcuate depressions 1-3 km in relief and up to several hundred kilometers in diameter. Loss of overburden support and the subsequent formation of chaotic terrain are attributed to the catastrophic release of enormous amounts of ground water. The detailed morphology and formation of these channels is further discussed in Baker (1982) and Baker *et al.* (1992).

Martian valleys are distinguished from the outflow channels by the absence of bedforms on their floors which are direct indicators of fluid flow (Mars Channel Working Group 1983). Although these valleys may contain channels, only in rare cases can the latter be detected with the resolution of the existing imagery. Martian valleys generally have widths ranging from < 1 km to nearly 10 km and lengths ranging from < 5 km to nearly 1000 km (Mars Channel Working Group 1983). Cross valley profiles range from V-shaped to U-shaped to those with broad flat floors and steep, nearly vertical walls.

Most Martian fluvial valleys are located in the Southern Highlands and can be broadly divided into large and small valley systems. Large or longitudinal valley systems (Baker, 1982) include Nirgal Vallis (**Figure 4**), Ma'adim Vallis (**Figure 5**), Nanedi Vallis, Bahram Vallis, and Al Qahira Vallis (Baker *et al.*,

1992). These valleys are typically several hundreds of kilometers long and range from several kilometers to tens of kilometers wide. In general, these valleys do not display the fluid-flow bedforms that would characterize them as outflow channels. Upper reaches generally form a network of stubby theater-headed tributaries, while lower reaches are sinuous with broad flat floors. The scalloped appearance of these lower reaches is attributed to secondary valley modification processes such as landsliding, undercutting and other mass-wasting processes (Baker 1982; Baker *et al* 1992). Intervalley regions are generally undissected. However, the lower reach of Bahram Vallis does display some streamlined erosional features that fluids flowed around as they debouched from the valley mouth into the Northern Plains (Theilig and Greeley 1979, Baker 1982). Ma'adim Vallis contains an inner channel incising into a series of fluvial terraces in its lower reach. These terraces have been described in detail by Landheim and Greeley (1994) and also by Cabrol *et al.* (1994). Other major differences between Ma'adim and the other longitudinal systems are that Ma'adim is much less sinuous when compared with the other large valleys and does not display the characteristic scalloping along the valley walls nor does it exhibit a network of stubby theater-headed tributaries along its upper reach. The immense size of the untributaried downstream reach does not seem consistent with the relatively small headwater zone and an origin by ground-water seepage (Baker, 1982). The source region is not distinct but it appears to emanate from a series of large fractures. Ma'adim displays a transitional morphology between the other large valley systems and the outflow channels. This morphology implies that Ma'adim may have experienced episodic flooding similar to the outflow channels, separated by long periods of ground water seepage and enlargement by valley wall retreat. Such episodic flooding may have helped to removed scalloped wall morphology that might have formed, straightening and thereby reducing the sinuosity of the valley system. An alternate explanation of the low sinuosity of Ma'adim Valles is that the valley system is primarily a tectonic feature (Brakenridge, personal communication 1995), that was subsequently modified ground-water sapping processes. Such an interpretation would help to explain why Ma'adim lacks an integrated tributary system.

Small valley systems exhibit a wide variety of drainage patterns ranging from well-integrated to mono-filament networks. These valleys are located in the Southern Highlands, on some Martian volcanoes, and on the south wall of Ius Chasma which is part of the equatorial system of large canyons. Valleys in the heavily cratered terrains of the Southern Highlands form laterally extensive networks that are highly degraded. Headwater regions may appear degraded and frequently cannot be traced with the quality of the

existing images. However, in areas where they can be traced, tributaries often originate on crater slopes or issue from fractures. Lower reaches appear buried and later reactivated by the formation of less extensive pristine valleys on the intercrater plains. Many have blunt, theater-headed terminations and numerous stubby first-order tributaries. However unlike most terrestrial river valleys, tributaries often appear to be as deep as the main trunk with steep walls and relatively constant down valley width. Tributaries join main trunk valleys at relatively low mean junction angles when compared to terrestrial drainages (Pieri 1980). Upper reaches have slightly higher drainage densities than the lower reaches (Baker and Partridge 1986). Nearly all Martian valley networks have drainage densities that are much lower than those for terrestrial networks (Pieri 1980a). Drainage densities of most valley systems on Mars range from 0.015 to 0.16 km/km² (Baker and Partridge 1986) compared to the minimum observed terrestrial value of approximately 1 km/km² (Gregory 1976). However, notable exceptions are the valleys developed on Ceraunius Tholus, Hecates Tholus, and Alba Patera. Drainage densities on these Martian volcanoes range from 0.3 to 2.3 km/km² and are comparable to those for drainages developed on the Hawaiian volcanoes (Gulick and Baker 1989, 1990).

The resulting compound degraded and pristine valley morphology (Baker and Partridge 1986) has important implications for the environment in which they formed. Because the degraded networks are more laterally extensive and have slightly higher drainage densities than the pristine networks, more surface-water flow was probably available during the period when the degraded networks formed. However, junction angles of the degraded networks tend to be high (large), so it is not always apparent from where the flows originate. In contrast, the pristine valleys that formed in the intercrater plains units are structurally controlled (Pieri 1980; Schultz *et al.* 1982 Gulick 1986; Brakenridge 1990). These networks seem to follow either preexisting valleys or underlying fracture patterns (**Figure 6**) suggesting a subsurface water source was important in the formation of these valleys.

Fluvial valleys are also present on some Martian volcanoes in the Southern Highlands and in the Northern Plains (Lowlands). These volcanoes formed throughout Mars geological history. Ceraunius Tholus (Noachian age) (**Figure 7**) and Hecates Tholus (Hesperian age) (**Figure 8**), two Martian volcanoes located in the Northern Plains region have drainage densities that are one to two orders of magnitude higher than those in the Southern Highlands. These values are equivalent to drainage densities

of terrestrial fluvial valleys (Gulick and Baker 1989, 1990). Valleys on Ceraunius and Hecates exhibit a similar compound network morphology as the Noachian valleys in the Southern Highlands. However, the pristine valley segments are not structurally controlled, in that they do not follow preexisting fractures. Instead they have exploited and enlarged preexisting valleys.

Valley development continued episodically in localized areas from early to middle Hesperian on surfaces interpreted as air-fall deposits in the Tempe, Casius, and Electris regions (**Figure 9**) (Grant and Schultz, 1990). However, in the Mangala Valles region (**Figure 10**), there was a considerable hiatus in valley development during the early and middle Hesperian. In this region, the development of theater-headed and ribbon valleys followed soon after the the formation of the Mangala Valles outflow channels in the Late Hesperian, whereas the degraded valleys date back to the Noachian (Chapman and Tanaka, 1990). However, in all these regions, valleys are enlarged, flat-floored and have extremely low drainage densities (Grant and Schultz 1990) which is consistent with a sapping origin. Locally intense volcanic activity appears to be related to the formation of many younger valleys in these regions (Chapman and Tanaka 1990; Grant and Schultz 1990).

Most Martian valleys seem to exhibit a sapping morphology (Pieri, 1980; Carr and Clow 1981; Tanaka 1986; Baker *et al.* 1992; Strom *et al.* 1992; Baker, 1982). The high number of first-order tributaries, particularly when draining directly into the main valley, the blunt theater-headed tributaries, and the similarity in depth between the main valley and its tributaries all are characteristic of valleys formed by ground-water sapping processes. Additionally, many valley patterns are structurally-controlled, regardless of whether fractures are present within the surrounding area. The lack of fractures surrounding a structurally-controlled drainage pattern suggests that ground water preferentially flowed in subsurface fracture systems thereby re-exposing buried structural patterns as valleys formed.

However, not all Martian valleys exhibit a purely sapping morphology. In particular, the morphology of the valleys on the Martian volcanoes does not appear to be controlled by fractures. These valleys form a radial pattern emanating away from the caldera of the volcano. On Ceraunius Tholus, Hecates Tholus, and Alba Patera, valleys form parallel to psuedo-dendritic drainage patterns (Gulick and Baker 1989, 1990). The morphology and morphometry of these and other dissected Martian volcanoes are discussed in Gulick and Baker (1989, 1990).

2.3. Comparison with Terrestrial Sapping Valleys

Although most Martian fluvial valleys have a sapping morphology, most terrestrial stream valley systems exhibit a runoff morphology. Runoff valleys generally have tapered tributary heads that blend in gradually with the surrounding terrain, form integrated networks with drainage densities higher than $1\text{km}/\text{km}^2$ and generally have lower junction angles. If geological features such as fractures, joints, faults, and bedding planes are present at the surface, streams initiated in these regions will flow along these features and form structurally-controlled drainage patterns. A consequence of this mechanism is that while terrestrial valleys exhibiting a sapping morphology are somewhat rare, where they do occur, they almost always form along with runoff-dominated systems, regardless of the geologic nature of the surface or the climate in which they form. On Earth, water is delivered to the surface via an atmospheric hydrological cycle as rain or snow. This precipitation then replenishes both surface water and ground water reserves as water infiltrates or produces surface runoff. With continued supply of water to the region, surface and subsurface flow paths become established, erosion commences, and eventually valleys form. Two completely different locales where terrestrial sapping valleys are particularly well developed illustrate the relationships between sapping and runoff processes.

In Hawaii, sapping and runoff valleys have formed in both humid and semi-arid climatic regimes. Valleys have eroded permeable basalt interbedded with less permeable ash and buried soil horizons. On the older islands, runoff valleys began to form as surface permeability was sufficiently reduced by weathering of basalt surfaces and the subsequent formation of soils. On the island of Hawaii, ash mantles reduced surface permeability enough to form valleys in some areas (Gulick 1987, Gulick and Baker 1989, 1990). As surface erosion progressed, larger runoff valleys started to exhibit a sapping morphology as they tapped into underlying ground-water reservoirs (**Figure 11**; see also Kochel and Piper 1986, Baker *et al.* 1990). The addition of ground water to the fluvial system increased overall stream power and accelerated erosion at the valley head and along its walls. Oversteepening of relief and removal of support for the overlying material caused subsequent collapse in these areas. Headward erosion resulted in the characteristic sapping morphology of theater-headed tributaries and either U-shaped or broad flat-floored valleys with steep walls. Both runoff and sapping dominated valleys in Hawaii formed together as continuum processes in both humid and semi-arid climatic conditions on volcanic landscapes where

permeable basaltic aquifers are interbedded with less permeable ash layers and buried soil horizons

Runoff and sapping valleys also occur together in a completely different geological environment. On the Colorado Plateau, sapping valleys have formed in sedimentary deposits of highly permeable, jointed sandstone that is underlain by relatively impervious rock units composed of mudstone, siltstone and sandstone (**Figure 12**). Runoff-dominated systems are also present and form under the same lithologic, stratigraphic, and climatic conditions as the sapping valleys; morphologic differences are attributed to structural constraints that control the effectiveness of surface and ground-water flow (Laity and Malin 1985). In regions where underlying aquifers dip toward the main canyons, tributaries exhibit a sapping morphology because ground-water outflow can contribute to valley erosion. In adjacent regions where the aquifers are dipping away from the main canyons, although the regional slope of the landsurface is toward the main canyons, tributaries display a runoff-dominated morphology.

2.4. *Spatial Relationships of Martian Valleys*

While the morphological characteristics of Martian fluvial valleys are similar to terrestrial fluvial valleys in many respects, the manner in which terrestrial fluvial valleys form and are distributed on geological surfaces and terrains differs markedly from those on Mars. These differences may provide insights into the nature and availability of water sources as well as to the paleoclimatic conditions at the time of valley formation. On Earth, fluvial valleys tend to form on a given geological surface more or less uniformly. While the actual spacing, density, morphology, and degree of network integration of drainages developed on a given surface does vary with geology and climate, drainages tend to be distributed rather evenly across that surface. This characteristic of terrestrial fluvial valley formation appears to reflect the atmospheric nature of the water source. On Earth, rain or snowmelt provides a widespread source of water with which to initiate erosion of a given geologic surface or terrain. On Mars, however, fluvial valleys are not evenly distributed across a surface or terrain unit, but rather tend to form as isolated systems or in clusters (Gulick 1993). Therefore, this nonuniform distribution of valleys across a given surface suggests available water sources were probably more localized on Mars than on Earth.

Another important difference between fluvial valleys on Earth and Mars is that the close spatial association seen between sapping and runoff valleys on Earth is not found on Mars. Since terrestrial sapping valleys typically result from the enlargement of runoff valleys, runoff valleys are typically found

near sapping valleys. In most locales on Mars, sapping valleys are not associated with runoff valleys. Exceptions include valleys found on the flanks of some Martian volcanoes (Gulick and Baker, 1990). A possible explanation for the general lack of associated runoff valleys may be that smaller scale runoff valleys are not resolvable in the available imagery. Associated runoff valleys might also be buried by aeolian, sedimentary, or volcanic debris or mantles. Although this latter explanation is certainly possible, it is hard to imagine all evidence for associated runoff valleys being obscured.

The image resolution explanation can be tested by comparison with terrestrial valleys. The dimensions of terrestrial runoff and sapping valleys on Hawaii (northeast slope of Kohala volcano) and on the Colorado Plateau (lower Escalante River) were measured. The width of the average terrestrial runoff valley in these locales is about 0.3 to 0.5 times the width of the average nearby terrestrial sapping valley. Assuming that a similar ratio holds for Mars, then, in Viking orbiter images where sapping valleys are seen at greater than about 2 to 3 times the image resolution, associated runoff valleys should be visible. However, inspection of most Viking images in which sapping valleys are clearly delineated reveals that existing image resolution should be adequate to detect associated runoff valleys, if they had formed. Because such valleys are not visible, it seems that, unlike their terrestrial counterparts, Martian sapping valleys do not form in association with runoff valleys.

Not only are Martian sapping valleys isolated from runoff valleys, but also some appear to be isolated from each other. Sapping valleys on Mars tend to form either as isolated systems or in clusters on a given surface unit and are separated by large expanses of undissected terrain, particularly within the Southern Highlands (Gulick 1993). These interfluves often remain untouched by erosion for hundreds of kilometers. Fluvial valleys, particularly in the cratered highlands, typically are located in clusters surrounded by vast expanses of uneroded surfaces of the same apparent lithologic, structural, and hydrological setting. Nirgal Vallis (**Figure 4**) is an example of a comparatively large valley system that appears to be completely isolated from any other valleys. First-order tributaries are short and stubby and appear to abruptly terminate into headland regions. In comparison, tributaries of terrestrial sapping valleys terminate rather abruptly with upland regions but then continue into the surrounding uplands as runoff valleys. However, this appears not to be characteristic of Martian fluvial valleys.

Another important difference between terrestrial and Martian fluvial systems is that an asymmetric distribution of valleys around impact craters is common on Mars (**Figure 6**), unlike the more uniform

distribution of drainages around terrestrial impact craters. Therefore, Martian sapping valleys differ from their terrestrial counterparts in their lack of association with runoff valleys and their sporadic distribution. In the heavily cratered terrains, evidence for fluvial erosion is found on the ejecta blankets of impact craters, on some volcanoes, and in intercrater plains regions. Many valleys in the intercrater plains are associated with dark units; these units have been interpreted as igneous sill intrusions (Wilhelms and Baldwin 1989).

To further illustrate the properties of Martian valleys, I discuss an example. Warrego Valles (42.5°S, 92.6°) is a particularly well-formed valley system located in the Southern Highlands of Mars (**Figure 13**). Because the valley system appears at first glance to exhibit a high drainage density, this led many to cite the valley as evidence for an early warm, Earth-like climate on Mars. However, detailed mapping of this system reveals a lack of a hierarchical network of tributaries. As shown in the sketch map, Warrego Valles form a “digitate” system (Pieri 1980) where tributaries drain directly into the main valley. In terrestrial fluvial valleys, small tributaries near the drainage basin divide flow into progressively larger tributaries until the largest tributaries coalesce into the main valley. Therefore, Warrego with its extremely low degree of network integration is not typical of terrestrial runoff valleys.

Other characteristics of this valley system are also distinct from most terrestrial runoff valleys. Warrego Valles parallels the Claritas and Thaumasia fracture systems, and the valley’s tributaries have formed along these fractures. Fluvial erosion is negligible for hundreds of kilometers along the same lithologic unit. At first, the virtual lack of valley development on adjacent regions of the same terrain seems easily explained by a high surface permeability, because drainage density values are typically low on highly permeable surfaces on Earth. However, if the hydrogeologic environment of the terrain in which the valley system formed is examined more closely, it then becomes apparent that regardless of whether the valley formed by sapping or runoff processes, rainfall could not have been the primary water source for erosion. Warrego Valles is formed along an upland/lowland boundary. Because water flows from regions of high to low energy potential, any rain which falls in this highlands region would flow into the lowlands and eventually erode the boundary. The lowlands are the baselevel for this region, regardless of whether the water is flowing on the surface and producing runoff or has infiltrated into the subsurface and is producing erosion by ground-water outflow (sapping). Because rainfall is a relatively uniformly-distributed source of water, fluvial valleys should have formed all along the boundary. Yet the valley system that has been used most often as the best evidence for a warm, wet climate on early Mars is completely isolated from any other

similar erosional features.

It is difficult to envision how rainfall could produce such an anomalous feature. Precipitation would certainly also collect on adjacent areas and therefore eventually produce erosion and subsequent valley formation in the uplands all along the boundary. However, this is not observed. Possible alternatives to rain are snowfall derived from a nearby sublimating lake or volcanic activity and ground-water outflow produced by localized long-lived hydrothermal systems, such as can be produced by magmatic intrusions (Gulick 1993). However, neither mechanism is mutually exclusive of the other. Formation by localized snowmelt would require a persistent water source for a continued supply of snow and a localized heat source to melt the snow. Localized hydrothermal systems can provide sufficient thermal energy to melt accumulating snow (Gulick 1993; Gulick and McKay 1994). Under this scenario, snowfall in surrounding regions would eventually sublimate resulting in little or no erosion. Thus, snowfall melting in areas of localized hydrothermal systems and sublimating elsewhere is a possible explanation for the non-uniform distribution of valleys within a terrain unit.

Another observation regarding Warrego Valles that may provide some insight as to its formation is that the valleys exhibit a radial pattern centered approximately on a 35 km diameter impact crater. While the valleys appear to emanate directly from the impact crater, a closer study of the drainage patterns suggest that the valleys have formed on and have delineated a much larger region of circular uplift. Although the impact crater is located near the center of this uplift and the valleys have eroded its ejecta blanket, it is not clear whether the impact crater formed before or after this apparent uplift event. A possible cause of the uplift may have been from a shallow magma intrusion in the subsurface or incipient volcanic activity. Both the subsurface magmatic event and the formation of the impact crater would have resulted in the formation of vigorous hydrothermal systems.

2.5. Erosion Volumes

Determining volumes of Martian valleys is difficult because good topographic data are not available for Mars. Mariner and Viking orbiter spacecraft did not have altimeters or radar, and high-resolution stereo coverage is scarce. Data used to compile the current global topographic maps of Mars are derived from a variety of techniques. Resulting maps from this data have elevation errors ranging from 1km to 2km depending on latitude. Shadow-length measurements have been used to determine the relief of a variety of

landforms including depth estimates of some larger valleys (e.g., Ma'adim Valles) where the valley wall has cast a clear shadow on the floor. Earth-based delay-Doppler radar observations from the Goldstone radar facility during the 1988 and 1990 Mars oppositions have recently been used to determine depths of some geologic features including Ma'adim Valles and the Margaritifer Sinus basin (Goldspiel *et al.*, 1993). Topographic profiles derived from these observations have horizontal resolutions of approximately 3 km and vertical resolutions of approximately 100 m. Photoclinometry has also recently been used to determine cross-sectional profiles of some Martian valleys (Goldspiel *et al.*, 1993), although this technique is subject to error from a variety of sources including device error, surface albedo variations, and atmospheric scattering effects.

Even though good topographic data are not available, it is still possible to constrain the range of estimates of likely valley volumes. Valley lengths and widths can be measured fairly accurately from Viking high resolution images. The difficulty, however, in measuring valley volume is in determining cross-sectional shape and depth. To estimate depth, valley walls are assumed to have either 10° or 30° slopes. Higher slopes would imply a deeper valley depth for a given valley width. To estimate conservative valley volumes, a V-shaped cross-section was assumed even though most Martian valleys are in fact probably not highly V-shaped. As in terrestrial sapping valleys, most are likely either U-shaped or flat-floored. However, the difference between a V-shaped valley and one with a flat floor of the same depth is at most a factor of 2. Alternatively, if valleys were initially V-shaped and became progressively U-shaped, trapezoidal or rectangular in cross-section over time due to masswasting of valley walls and subsequent infilling of valley floors as happens with terrestrial valleys, then the V-shaped cross-section would represent the maximum likely volume. Either way, the uncertainty in valley volume is at most a factor of 2 and such an error is not important in an order of magnitude calculation. To constrain the amounts of water required to form individual Martian valley systems, the eroded volumes of several Martian valley systems were measured. These include valleys on several volcanoes and two of the best developed valleys in the heavily cratered terrain, Warrego and Parana Valles.

Results of valley volume estimates on five Martian volcanoes and for some valleys in the heavily cratered terrain including Warrego and Parana Valles are shown in **Table 1** and **Figure 14(a)**. Valley volumes estimated by other studies are listed as well. Although there is clearly a large range of uncertainty, results compare favorably with those of other studies. Volumes for Warrego and Parana Valles are

remarkably similar to those estimated for the volcanoes Alba Patera, Hecates Tholus, and Ceraunius Tholus. Hadriaca and Tyrrhena Paterae have estimated eroded volumes 1 to 2 orders of magnitude larger, possibly owing to more easily erodible surface materials. It is not clear why valley volumes on the volcanoes are so similar to the two valley systems in the heavily cratered terrains. Younger valleys would have had less time to form than the older valleys and should therefore be smaller and less developed than older systems. In addition, Martian valleys that formed during the period of heavy bombardment when the climate was thought to have been more Earth-like should have larger eroded volumes because erosion rates are assumed to have been much higher during this early period of the planet's geological history. However, because eroded volumes are similar for both younger and older volcano valley systems as well as for the two well developed valley systems located in the heavily cratered terrains, it appears that either climatic controls on valley formation were probably similar throughout Mars' geological history, or that the control on valley volumes was not climatic.

2.6. *Water Volumes*

Although determining the actual volume of individual valley systems is difficult, estimating the volume of water required to erode the valleys is even harder to constrain. The erodibility of a given surface and the amount of water required depends on a variety of factors including the rock types present, slope, degree of weathering, the cohesiveness of surface and subsurface material, in addition to how much, how often and how long liquid water is available for erosion. Because the climatic conditions in which these valleys formed is not known, it is difficult to determine the magnitude, duration and frequency of water flows available for erosion. However, it is possible to estimate to an order of magnitude, the total volume of water required to erode individual valley systems.

Earlier attempts were made by Goldspiel and Squyres (1989) to determine the magnitude of water volumes required to erode Martian valley systems. They used a sediment transport model to estimate the total water volumes required to erode individual Martian valley systems based on the carrying capacity of large terrestrial rivers. These results were then scaled to account for the reduced gravity on Mars. Estimated ratios of water volume to eroded volume for Mars were less than 4 to 1 for grain sizes of

0.03mm and ranged from 19:1 to 26:1 for large mean grain sizes of 0.3mm. They assumed that no work was being done by the flow in eroding source material or in breaking up sediment into smaller grain sizes.

However, Goldspiel and Squyres' assumption that no work was being done by the flow in eroding source material significantly underestimates the total water volume required to erode a valley system. The amount of work done by water in eroding source material is much greater than the amount of work required to transport sediment out of the fluvial system. In order to estimate the total amount of water required to carve a valley system which includes both eroding source material and transporting sediment out of the fluvial system, the following approach was used.

The approach used in this paper was to select a lithologic environment where valleys have formed both on Earth and Mars such as volcanic surfaces and where the ages of the terrestrial surfaces are known. Martian valley volumes are then combined with terrestrial fluvial erosion rates to constrain the total volumes of water required to form each set of Martian valleys. Based on these studies of fluvial erosion on terrestrial volcanic landscapes, sediment volume to eroded volume ratios scaled to Mars' gravity are as large as 1000 to 1. The total water volume using each estimated ratio is shown for each valley group in **Figure 14(b)**. For each locality, each bar represents the range of possible volumes due to the uncertainty in the slopes of valley walls. The lower bar assumes a water to eroded volume ratio of 3:1, the upper bar a ratio of 1000:1. As **Figure 14(b)** shows, the quantity of water passing through the two selected valley systems in the heavily cratered terrain does not drastically differ from that on the Martian volcanoes, barring major differences in lithology.

3. Hydrological Constraints On Valley Origin

3.1. *Aquifer recharge*

Given the above estimates of the water volumes required for fluvial valley formation, it is possible to test whether recharge of aquifers was necessary for the formation of the Martian fluvial valleys. Using estimated drainage areas for the valleys on the heavily cratered terrain (**Table 2**), and assuming subsurface porosities of 10 and 50% and that ground water completely filled all pore space to a depth of 1 km (a typical valley depth), the total volume of ground water contained in the aquifer at any one time can be estimated. These numbers appear in **Table 2**. For Parana and Warrego Valles, the total quantity of water

contained in their aquifers is of order 10^{12} to 10^{13} m³. However, the total quantity of water required to erode these valleys, based on their volumes and water to eroded volume estimates of 3:1 and 1,000:1, ranges from 10^{12} to 10^{15} m³. Therefore, there is enough water in the aquifer to erode the observed valleys only if the aquifer was emptied entirely to a depth of 1 km, the aquifer porosity was large (50%), and the ratio of water to removed sediment is quite small (3 or 4 to 1). As discussed in the previous section, the evidence from terrestrial fluvial valleys strongly suggests much higher ratios of water to sediment volume are required. More realistic assumptions including imperfect emptying of aquifers, lower porosities, and water to sediment volume ratios of 600 to 1000:1 require recycling of ground water. Based on the results of this study, aquifers underlying Martian valleys contain up to 100 (or possibly even 1,000) times less water than is required to form the valleys. Goldspiel and Squyres (1991) similarly concluded that recycling was likely required for the valley systems that they studied. Clearly if the Martian valleys required water volumes comparable to similar terrestrial valleys, then a mechanism must have acted to recharge the underlying aquifers as they discharged.

3.2. *Recycling Mechanisms*

Whether the formation of Martian valley networks provides unequivocal evidence for drastically different climatic conditions remains debatable. Although Martian valley networks have been used as evidence for the existence of an Earthlike climate and hydrological cycle early in the planet's history, such a theory cannot explain the formation of better integrated, terrestrial-like valley networks later in Mars' geological history. In addition to the geological evidence and arguments, climate modeling seems to preclude the existence of a temperate climate early in Mars' geological history (Kasting 1991) but such a climate may have been possible later when the sun's luminosity was closer to today's value. However, hydraulic gradients must be maintained to form fluvial valleys. If an atmospheric hydrologic cycle was absent or was not sufficient to maintain such gradients, then subsurface energy sources must have maintained hydraulic gradients. Two possibilities are a global, uniformly higher heat flow and localized energy sources, such as magmatic intrusions.

3.2.1. *Uniform, globally higher heat flow.*

Squyres (1989) suggested that Mars had a globally higher heat flow early in its geological history bringing liquid water to within 415 meters of the surface. Recently, however, Squyres and Kasting (1994) concluded early global heat flows were likely even higher ranging from 180 to 360 mW m⁻². Using these higher values, they estimated that liquid water may have existed within 150 to 300 m of the surface, a depth comparable to most of the Martian valley systems. Higher heat flows, on the order of six times the present estimated values, are expected early in the planet's history because of the dissipation of accretional heat and a higher production of radiogenic heat (Fanale *et al.* 1992). The contribution to planetary heat flow around 3.8 Ga from accretional heating is estimated to be 70 mW m⁻² (Schubert *et al.* 1979), while the contribution from the radiogenic component during this time is estimated to have been between 100 and 300mW m⁻² (Fanale *et al.* 1992). The current heat flow is estimated at 30 to 60 mW m⁻² (Squyres and Kasting 1994).

A major problem with the early globally higher heat flow hypothesis to explain the presence of valley networks is that it lacks a mechanism with which to initiate fluvial valley formation. While such a heatflow would initiate ground-water circulation at depth, formation of the Martian valley networks probably required water tables much closer to the surface. Both Squyres (1989) and Squyres and Kasting (1994) imply that Martian sapping valleys may be formed merely by the existence of liquid water at the present depth of the valley floor. However, terrestrial fluvial valleys require ground water to intersect the surface to initiate fluvial valley formation by sapping processes only. Water tables deeper than several meters would require incision and subsequent erosion of valleys by surface runoff processes down to the level of the ground water table. Once the valley floor has intersected the ground water table, then erosion by sapping becomes an important valley forming process.

A second problem with a uniform, globally higher heatflow hypothesis is that it would produce vertical temperature gradients needed for upward ground-water flow, but it would not by itself produce anomalously large, localized horizontal temperature gradients. Such lateral gradients are required to draw colder, denser ground water in from more distal regions of the aquifer to replace the warmer, more bouyant ground water discharging to the surface. In this way, ground-water outflow becomes concentrated resulting in higher regional discharges. Localization of outflow increases the likelihood of erosion at the surface and the eventual formation of fluvial valleys.

A third problem with invoking the early globally higher heat flow hypothesis to explain the presence of valley networks on Mars is that valley networks continued to form throughout the planet's geological history. Interestingly enough, the best developed fluvial valley networks formed on Hesperian and Amazonian aged Martian volcanoes, well after the decline of the globally higher heat flow.

Still another problem with the globally higher heatflow hypothesis is that it doesn't appear to be compatible with the observed spatial distribution of valleys on geological surfaces, as discussed earlier in this paper. If the Warrego Valles region is again used as an example, then ground water should have been flowing out of the aquifers all along the plateau boundary. Warrego Valles doesn't appear to be located along a particularly low or high region along the boundary, so that prolonged ground-water outflow should have produced erosion all along the boundary not just where Warrego Valles is located.

3.2.2. *Hydrothermal systems.*

A third possibility, however, is ground-water outflow driven by vigorous, localized hydrothermal circulation resulting from igneous intrusions, volcanos, and large impact craters forming in a permeable, water-rich subsurface. Such geologic features are all locales for valley formation on Mars, particularly in the heavily cratered terrains. Localized hydrothermal systems could have formed throughout Mars' geological history and can produce both large horizontal and vertical temperature gradients in the ground-water system. Depending on the volume of the associated magmatic intrusion, Martian hydrothermal systems can circulate ground water into the surface environment for several million years; therefore, such systems can maintain hydraulic gradients over the timescales required for valley formation (Gulick 1993). Rather than replenishing ground water through rainfall and infiltration, numerical modeling demonstrates that a Martian hydrothermal system replenishes itself by continually drawing in colder, denser ground water radially from more distant parts of an aquifer (Gulick 1993). Ground-water outflow produced by hydrothermal systems associated with magmatic intrusions exceeding several 10^2 km^3 is sufficient to form fluvial valleys on Mars (Gulick, 1993)(Figure 15). Over its lifetime, the total quantity of ground water that passes through the modeled hydrothermal system is comparable to that needed to form a single outflow channel. Only the duration and rates of ground-water outflow are different. Since, the outflow channels did form, subsurface aquifers of the required magnitude to form fluvial valleys must also have existed on

Mars.

Futhermore, the clustered distribution or localization of sapping valleys on Mars and the absence of associated runoff valleys, as discussed earlier, strongly suggests localized, subsurface sources of water. In short, a rainfall genesis should produce associated runoff valleys, and a more uniform or widespread distribution of fluvial valleys within a given terrain type or surface geologic unit. A uniform, globally higher heatflow should not produce such localized sapping valleys. It is for these reasons that localized hydrothermal systems are invoked for Martian valley genesis. Such hydrothermal systems would be localized in surface extent, yet (as the simulations suggest) draw ground water from great distances while focusing outflow into relatively small regions. The hydrothermal discharge would also preferentially produce landforms associated with persistent ground-water outflow--the sapping valleys.

3.3. *Possible Atmospheric Source Contributions*

Although ground-water outflow associated with localized hydrothermal systems is sufficient to form valleys and would be consistent with the morphology and spatial distribution of the Martian valleys, this does not rule out the possibility of atmospheric water contributions. Atmospheric snowfall melting in hydrothermal areas (particularly along the perimeter of such regions) and sublimating elsewhere might also play a role in producing a non-uniform valley distribution (Gulick and Baker, 1993). As an example of such a possibility, Gulick and McKay (1994) explored the possibility of an atmospheric source of water for the fluvial valleys on the northern flank of Alba Patera. Because outflow channel formation is coincident with the age of the valleyed surface on Alba, ponding of outflow channel discharges in the Northern Plains near Alba may have provided a source of water (Gulick and Baker 1989,1990). Water vapor could sublimate from the resulting frozen body of water and accumulate on the northern flank of Alba Patera.

The rate of sublimation from snowpacks located at colder, higher elevations on the northern flank is approximately an order of magnitude less than the sublimation rates from the ice-covered water body. The net result is accumulation of snow on the volcano's northern flank. For atmospheric temperatures equal to 250°K, snow accumulates at a rate of approximately 100 cm per year at an elevation 2km above the ice-covered body of water. Under present atmospheric temperatures of 220°K, atmospheric transport of water vapor is insufficient to cause significant snow accumulation. Gulick and McKay also concluded that

geothermal/hydrothermal systems operating throughout the volcano's formation would be sufficient to melt accumulating snow packs and produce liquid water runoff and infiltration thereby recharging high level aquifers.

Gulick *et al.* (1997) considered the possibility that CO₂ released from the ground water, regolith, magmatic activity, and polar caps during formation of the outflow channels might have produced sufficient greenhouse warming (Baker *et al.* 1991) to raise atmospheric temperatures to 250°K. They concluded that if CO₂ condensation (Kasting, 1992) is taken into effect, >1 bar released at 1 Ga or > 2 bar at 2Ga, would result in temperatures remaining at or above 250°K for periods of approximately 10⁷ years. Therefore, if the appropriate quantities of CO₂ could be released, then a significant snowpack might form on the northern flanks of Alba Patera and other high elevation regions. If the surface is easily erodible and is geothermally active as was Alba Patera, then valleys might have developed over time. Regions not volcanically or geothermally active would not have experienced snowmelt or erosion, but instead would be zones of accumulation. These accumulations of snow would eventually sublime or become buried. Other volcanically active areas during this time such as Olympus Mons, might also have experienced snowmelt, but snowmelt would have rapidly infiltrated into the permeable lava flows that comprise the volcano's surface. In comparison to the ash deposits on Alba, the lava flow surface of Olympus Mons would have been highly resistant to erosion.

Another possible episodic source of CO₂ is from obliquity variations. Jakosky *et al.* (1995) suggest that the polar caps could contain the equivalent of 0.85 bar of CO₂ as ice, or 0.2 bar of CO₂ as clathrate. During periods of high obliquity, CO₂ could be released from the caps and perhaps cause occasional periods of more clement climate. However, this source of atmospheric CO₂ would not necessarily be coincident with outflow discharges. Therefore, obliquity variations by themselves would not provide a surface water source for atmospheric precipitation sufficient for forming fluvial and glacial features. However, an interesting result of this work is the possibility that up to 0.85 bar of CO₂ may plausibly be stored in the north polar cap. If such a reservoir indeed exists, it would have been released to the atmosphere by the flood waters that ponded in the Northern Plains during outflow channel formation (Baker *et al.* 1991) and would have resulted in global temperatures close to 250K (Gulick *et al.* 1995, 1997) at 1Ga. However, Mellon (1996) disagreed with Jakosky *et al's* conclusion that the polar caps could

contain such large quantities of CO₂. He concludes, instead, that if the lower thermal conductivity of CO₂ clathrate is considered, then the polar caps presently can not hold more than several hundred millibars of CO₂.

4.0 Concluding Remarks

The formation of fluvial valleys on Mars required the presence of persistent liquid water flow in the surface environment. As such the presence of these valleys provides clues to unravelling the planet's paleoclimatic history. Because most of the valley networks appear to have formed in the most ancient terrains of Mars, the valleys have been used as apriori evidence for a globally warm, wet earthlike climate early in the planet's history. More recently, it has been proposed that the valleys formed directly as a result of a globally higher heat flow early in the planet's history (Squyres 1989). However, in this paper, I have argued that many of the detailed characteristics of the valleys and their distribution in time and space, are not consistent with either of these interpretations. Some of the most integrated and best developed Martian valley systems that most resemble terrestrial fluvial valleys formed well after the period of globally, uniformly higher heat flows or more clement climate. Many of the older, larger (longitudinal) sapping valleys that supposedly formed during the warm, wet epoch are isolated from one another and from runoff valleys. Many of the older, smaller valleys are located in clusters leaving large expanses of the same geologic surface essentially untouched by erosion. Similarly, most small Martian valleys exhibit a sapping dominated morphology and do not appear to form in association with runoff valleys as do terrestrial sapping valleys. These characteristics and others are not consistent with a rainfall origin, or with a globally, uniformly higher heat flow early in the planet's history.

An early globally, uniformly higher heat flow would allow liquid water to exist within hundreds of meters of the surface, however this condition alone does not provide a mechanism for initiating valley formation since ground water needs to intersect the surface. This early high heat flow also does not explain the formation of fluvial valleys throughout the Hesperian and Amazonian periods. Furthermore, the lack of associated runoff valleys as well as their clustered distribution within a given geologic surface seems to indicate the importance of localized, endogenic sources of ground-water outflow as opposed to a more uniformly distributed subsurface source. Hydrothermal systems associated with magmatic intrusions

exceeding several 10^2 km^3 can produce sufficient ground-water outflow to form valleys and would result in localized regions of valley formation (Gulick, 1993; 1998). In addition, localized geologic heat sources capable of producing vigorous hydrothermal systems such as magmatic intrusions, volcano formation, large impact crater formation and tectonism were clearly present at least periodically throughout Mars' geologic history and should have produced sustained ground-water outflow relatively late in Mars geological history. Snowfall resulting from sublimating ice-covered lakes, if present, could have accumulated at higher elevations during periods when surface temperatures exceeded approximately 250K. Snow accumulation in areas of vigorous geothermal or hydrothermal activity (particularly along the perimeter of such regions) would provide melt water to produce erosion and subsequent valley formation if located at higher elevation on easily erodable surfaces.

Finally, it is interesting to note that recent interpretations of the SNC meteorites, which almost certainly come from Mars, indicate the circulation of CO_2 -rich ground water in the near surface environment (Romanek C.S. *et al.*, 1994). Furthermore, Swindle *et al.* (1995) and McSween (1994) proposed that near surface water was responsible for the alteration of the SNC meteorites and that this water was liberated by nearby magmatic activity possibly as recently as 180 million years ago. These results support the presence of hydrothermal activity as well as the exchange of CO_2 from the subsurface to the atmosphere via ground-water outflow late in Mars' geological history. Future Mars orbiters and landers may provide further geological and geochemical evidence for Martian hydrothermal systems throughout the planet's history as well as provide additional clues to the origin(s) of fluvial valleys on Mars.

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FIGURE CAPTIONS

Figure 1: Location map of major terrain boundaries and volcanoes on Mars (after Gulick and Baker, 1990).

Figure 2: Chronology of Mars' geological and fluvial history. Numbers indicate the number of craters with diameters greater than 8 km per million square kilometers (Barlow 1988) on a given surface. The top row below the numbers are the ages of some Martian volcanoes; below that are the ages of some key terrain types, according to Barlow (1988). The dashed lines show the approximate age of the various fluvial valleys based on the age of the surfaces on which they have formed (After Gulick and Baker 1990). The approximate age of ancient glaciations is from Kargel and Strom (1992).

Figure 3: Fluvial valleys developed on the northern flank of Alba Patera, an Amazonian aged Martian volcano. These valleys are the youngest, best developed, and most earthlike on the planet. Figure from Gulick and Baker (1989, 1990).

Figure 4: Nirgal Valles (28°S, 48°W). Example of a large (longitudinal) valley system in the intercrater plains region. Note the stubby theater-headed tributaries and lack of associated runoff valleys. Valley pattern appears to be structurally controlled by underlying fractures. Valley is 800 km long.

Figure 5: Ma'adim Valles (23°S, 183°), a large (longitudinal) valley system with an indistinct source region that terminates in Gusev Crater to the north. Note the lack of tributary development as is characteristic of other large (longitudinal) valley systems. Valley is approximately 900 km long.

Figure 6: Fluvial valleys in the Margaritifer Sinus region of the Southern Highlands. This region is the most densely valleyed region in the ancient Southern Highlands. The valley network in the upper left is Parana Valles; note the degraded headwater tributaries and the pristine lower segments. This system has formed on dark units of the intercrater plains that are thought to be igneous sill intrusions (Wilhelms and Baldwin 1989). Valleys are also present around impact craters; note the asymmetric distribution.

Figure 7: Fluvial valleys developed on Ceraunius Tholus, a Noachian aged volcano. The presence of pristine (solid lines) and degraded (dashed lines) morphology suggests some valleys have been reactivated. (Viking Frames 516A24, 622A56, 622A58, 622A59, 622A60).

Figure 8: Fluvial valleys developed on Hecates Tholus, a Hesperian aged volcano. Black shaded areas on sketch map indicate areas of valley enlargement. Figure from Gulick and Baker (1990).

Figure 9: Valley development in the Electris deposit. Valleys have broad, flat floors, exhibit little tributary development and do not incise underlying plains units. The Electris deposits are interpreted as a volatile-rich airfall deposit by Grant and Schultz (1990). Image is oriented north-northwest. Large crater in center is approximately 50 km in diameter. Viking Image 372S31.

Figure 10: Valleys developed in the East Mangala Vallis region in late Hesperian and early Amazonian surface units. Image width is approximately 300km. Image is oriented with North on top. MDIM MI05S147.

Figure 11: Fluvial valleys on Kohala volcano, Hawaii. Dashed lines delineate the ridge axis of Kohala volcano; elevations given along the ridge are in meters. Shaded areas show regions of significant valley enlargement resulting from ground-water sapping processes. Note that runoff and sapping valleys have formed in close spatial association in the humid climate of the volcano's northeastern flank. Drainage development is highest on this flank, because the steep, high elevation windward-facing slopes intercept warm, moisture-laden trade winds and produce anomalously high rates of precipitation (250 cm/year averaged over the northeastern flank; 500 cm/year near the summit (Stearns and MacDonald 1946)). Yearly rainfall and therefore drainage development is much lower along the southwest flank, because it lies in the rain shadow of the volcano's summit. Rainfall and drainage development on both windward and leeward slopes decrease sharply toward the northwest with decreasing ridge elevation. Rainfall averages less than 25cm/year on the northwestern flank.

Figure 12: Fluvial runoff and sapping valleys developed in the Navajo sandstone. Dark shaded areas represent valley floors. West-flowing canyons are formed by sapping. East-flowing canyons are formed by surface runoff (From Laity and Malin, 1985). Note the close spatial association of runoff and sapping valleys in this sedimentary, semi-arid environment.

Figure 13: (a) Warrego Valles. This valley system is often invoked as evidence for a past warmer, wetter atmosphere on Mars. (b) Sketch map of Warrego Valles. Note first order tributaries drain directly into the main valley system. (c) Regional view of Warrego Valles. Note the lack of comparable fluvial erosion elsewhere along the boundary. See text for description and location.

Figure 14: (a) Total eroded volumes of valleys on six Martian volcanoes and for Warrego and Parana Valles two well developed heavily cratered terrain (HCT) valleys. Volumes for both HCT valleys were comparable. The thickness of each bar indicates the range of uncertainty in eroded volumes assuming valley walls have between 10° and 30° slopes. (b) Estimated total water volumes required to form these valleys. For each locality, bar thickness is the range of uncertainty in valley volumes based on slopes of valley walls. The lower bar for each locality are the total calculated water volumes assuming the 4:1 water to sediment volume from Goldspiel and Squyres (1991). Note that these volumes represent an extreme lower limit to total water volumes because the volume of water required to erode source material was not considered. The upper bar for each locality is the total water volume based on a 1000:1 water to sediment volume, a ratio derived by Gulick (1993) from estimates of terrestrial fluvial erosion scaled to Mars' gravity (Figures from Gulick 1993).

Figure 15: Figure is similar to Figure 14b, except horizontal lines show the total quantity of ground-water outflow by numerical models of Martian hydrothermal systems associated with magmatic intrusions of 50, 500, and 5000 km^3 . Note that 500 km^3 intrusions can provide sufficient ground-water outflow to form most Martian valleys (Figure from Gulick, 1993).

Table 1: Estimated volumes eroded by valleys on selected Martian volcanoes and selected valleys in the Martian heavily cratered terrain (m²)

Volcano	This Work 10° slopes	This Work 30° slopes	Crown and Greeley (1991)	Mouginis-Mark <i>et al.</i> (1989)
Alba Patera	2×10^{10}	7×10^{10}	-	$5.3 \times 10^{10} - 1.7 \times 10^{11}$
Hecates Tholus	1×10^{10}	4×10^{10}	-	-
Hadriaca Patera	1×10^{12}	4×10^{12}	10^{12}	-
Ceraunius Tholus	2×10^{10}	4×10^{11}	-	-
Tyrhena Patera	1×10^{10}	3×10^{12}	10^{12}	-

Valley System	This Work 10° slopes	This Work 30° slopes	Goldspiel and Squyres (1991)
Warrego Valles	4.1×10^{11}	1.3×10^{12}	-
Parana Valles	4.3×10^{11}	1.4×10^{12}	$1.5 \times 10^{12} - 2.9 \times 10^{12}$
Mare Tyrhenum			
Large	6.6×10^{11}	2.2×10^{12}	$3.7 \times 10^{11} - 7.1 \times 10^{11}$
Small	1.0×10^{12}	3.2×10^{12}	$5.0 \times 10^{11} - 9.5 \times 10^{11}$
Ma'adim Vallis	7.9×10^{12}	2.6×10^{13}	1.3×10^{13}

Table 2: Estimated aquifer water volumes (to 1 km depth) for two integrated tributary valley systems in the heavily cratered terrain of Mars

Valley System	Drainage Area (km ²)	Aquifer Water Volume (km ³)	
		10% porosity	50% porosity
Warrego Valles	29,800	2,980	14,900
Parana Valles	55,300	5,530	27,700