Chapter 1

Introduction: Groundwater Sapping on Mars and Earth

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The channel and valley networks of Mars are the most exciting geomorphic features discovered by the Mariner and Viking probes (see the general reviews by Baker, 1982, and the Mars Channel Working Group [MCWG], 1983). Most attention has been accorded to the striking 1000+ km long and 20 to 200 km wide outflow channels generally thought to have been formed by single or episodic catastrophic floods or debris flows caused by any of several possible mechanisms, including interception of a large groundwater reservoir by headward-eroding small channels (Soderblom and Wenner, 1978), volcanic melting of ice producing jokulhaupts (Masursky et al., 1977), ground collapse and groundwater release (Carr, 1979), or debris flows generated by sudden liquifaction of unstable rocks with high water contents (Nummedal and Prior, 1981). Although the valley networks, which are located primarily on old cratered terrain near the Martian equator, were recognized quite early in interpretation of Mariner and Viking images (McCauley et al., 1972), they were not studied extensively until recently (the first systematic study was by Pieri, 1976). Other types of channels, such as the stubby networks dissecting the several-kilometer-high walls of some of the martian canyons, and the intermediate-scale longitudinal valley systems, such as Nirgal Vallis, were also described soon after the Mariner 9 mission but were not studied in detail until recently.

The valley networks are very ancient and are contemporaneous with the late stages of accretionary impacts (Baker and Partridge, 1986), which would place their origin during the putative warmer climate at the height of outgassing. The longitudinal valley networks and scarp-wall networks are sculpted in younger but still very ancient units. These higher-relief channels are harder to date than the shallow valley networks, because mass-wasting processes acting on the valley walls give them a deceptively young age based on crater counting techniques.

The superficial resemblance and similarity of scale of the dendritic valley networks to terrestrial stream systems created primarily by runoff erosion prompted immediate suggestions that the martian valleys were sculpted by runoff occurring early in martian history when the atmosphere was denser and temperatures moderate enough to permit liquid water and rain at the surface (Milton, 1973; Sagan et al., 1973). This comparison proved so compelling that the valley networks were initially called "gullies" (Milton, 1973), "arroyos" (Hartmann, 1974), and "runoff channels" (Sharp and Malin, 1975); only more recently have they been given the less suggestive term "valley networks" (Baker, 1982). The suggestion of a runoff origin was initially resisted by many scientists because of skepticism about the presence of a sufficient reservoir of water on Mars as well as doubts about an early temperate climate. However, support for a large supply of water on Mars has come from studies of the expected volatile content of the impact debris and its outgassing, which suggest the presence of initial water equivalent to a layer 10 m to 150 m deep if spread over the surface of Mars (Squyres, 1984). Some of this water is now present in the perennial polar caps, but, in addition, there is a rich suite of nonfluvial geomorphic features indicative of abundant water, including distinctive crater morphology, flow-like mass movements, patterned ground, chaotic and fretted terrain, possible thermokarst, water-related weathering, possible former glaciers, and volcanic-ice interactions (for a general review, see Carr, 1981; Baker, 1982; and Rossbacher, 1986). Thermal budgets also suggest that an extensive water reservoir could be present in permafrost under the present martian climate (Fanale, 1976). Many climatologists feel that enhanced CO_2/H_2O pressures early in martian history during rapid outgassing may have permitted liquid water at the surface (Pollack, 1979; Cess et al., 1980; Toon et al., 1980; Hoffert et al., 1981). However, there are conflicting models (Postawko and Kuhn, 1986), and

Brackenridge et al., (1985) caution against using the presence of valley networks as independent evidence of an early warm climate.

Despite the general acceptance of the presence of abundant water that, early in martian history, may have been stable as water and involved in precipitation events, several lines of evidence suggest an important, and possibly dominant, role of groundwater sapping processes in sculpting the valley networks, the longitudinal valleys such as Nirgal Vallis (chapter 13), and the valley-wall networks such as those dissecting the southern wall of Ius Chasma (see reviews by Pieri, 1980; Baker, 1982; Higgins, 1982; MCWG, 1983; Higgins, 1984; Kochel et al., 1985). Baker (1982; chapter 8) suggests that sapping processes have been responsible for the formation of the deep, U-shaped valleys dissecting Hawaiian volcanoes and similar features on martian volcanic edifices. Sapping processes are postulated based on two lines of reasoning and evidence. Many of the morphometric features of the valley networks, the longitudinal valleys, and the valley-wall networks are similar to those of terrestrial stream networks in which sapping processes are inferred to be dominant. Such features include (1) theater-shaped valley headwalls (particularly in the longitudinal valleys), (2) strong structural control of valley alignment and planform, (3) hanging tributary valleys, (4) long main valleys with short, stubby tributaries, (5) irregular angles of channel junction, and (6) valley widths that remain nearly constant in a downstream direction (Pieri, 1980; Baker, 1982; Laity and Malin, 1985). However, many of these features might be duplicated on young runoff networks in fractured, layered rocks and possibly in valleys eroded by valley glaciers (Lucchitta et al., 1981; Lucchitta, 1982). A low drainage density compared to terrestrial channels and the seemingly abrupt initiation of the channels have also been cited by these authors, although this argument is weakened by the limits of image resolution (and atmospheric hazes) as well as post-origin modification by impact events, mass-wasting, weathering, and eolian modification.

The second line of reasoning for a sapping origin is based on the presumed greater ease of formation of valley networks by sapping than by runoff. The valley networks are formed on heavily cratered terrains, which are likely to be very permeable due to heavy fracturing resulting from impacts and the brecciated and relatively coarse-grained nature of impact debris (little silt or clay-sized debris is formed by impact processes), as noted by Baker and Partridge (1986). Although some weathering would have occurred during early martian history, it was probably rudimentary and limited by the reducing atmosphere. Furthermore, the impact-cratered surface includes numerous craters and other enclosed depressions, encouraging infiltration. Finally, infiltration producing sapping could have occurred by gentle rains or snowfall, whereas runoff requires rains of thunderstorm intensity on relatively permeable materials.

Even though sapping processes can occur as a result of weathering and erosional processes at points of emergence of regional groundwater flow, large volumes of water are required to produce a well-developed sapping network. The most efficient process of sapping erosion occurs in unconsolidated sediments, where the limiting factor is simply the transporting capacity of the spring-fed flows. Experiments by Howard and McLane (in press) (see chapter 5) typically exhibited sediment concentrations in the outflows of about 1%, with a high of 10%. This suggests that a minimum of 10 times more water than volume of eroded sediment must be discharged in order to create a sapping valley network. Even in unconsolidated sediments, a ratio of 100- to 1000-fold is more reasonable. In consolidated rocks, valley erosion is limited by the rate of weathering of rocks at the sapping face by solution of cement (or melting, if the cement is ice), salt-fretting, freeze-thaw, or other process (Laity and Malin, 1985). These processes are generally much slower and may require water to eroded rock ratios of 10^5 or greater. The rocks of the heavily cratered terrain (probably largely impact breccias), the ridged-plains units in which many of the longitudinal valleys are formed (probably lava flows with interbedded tuffs or sediments), and the chasma walls in which the valley-wall networks are eroded (probably lava flows and sediments) are presumably moderately cohesive to well indurated. The implication of these considerations is that valley networks and other putative sapping channels are unlikely to have resulted from one-time dewatering of upland groundwater reservoirs, unless the contributing upland area was much larger than the channel network. Certain of the longitudinal valleys and chasma-wall networks may be of sufficiently small size compared to their potential groundwater source areas to have formed by a one-time dewatering, although it is difficult to envision a scenario for an initial charging of these uplands at a rate much faster than rates of regional groundwater flow unless the water was immobile (frozen). Brackenridge et al., (1985) suggest that heating of groundwater from impact melts produces hydrothermal groundwater that could produce valley networks by sapping. Although they produce estimates of possible water release rates, they do not compare total release volumes to volumes of eroded rock, so that it is difficult to assess the efficacy of the proposed hydrothermal sapping.

Experiments conducted in the University of Virginia sapping tank (see chapter 5) indicated that sapping channels do not generally form in unconsolidated homogeneous sediments with even small percentages of clay or silt. Groundwater flow rates through such sediments are so slow that very high hydraulic gra-

dients (on the order of 0.3 to 0.4) are required to initiate erosion. Under such high gradient conditions, erosion occurs not by grain-by-grain entrainment and channel development, rather by viscous mud flow. This phenonmenon was not further investigated, but it may form a partial analog to debris flows in the chaotic and fretted terrains, such as the types discussed by Squyres (1978, 1979) which have generally been interpreted as periglacial features. Consolidated fine-grained sediments generally do not exhibit such features, eroding by overland flow or by piping erosion.

The role of groundwater sapping in the development of terrestrial drainage networks was long overlooked but is now receiving greater attention. Most of the early literature on sapping processes is reviewed by Dunne (1980) and by Higgins (1982, 1984). With the exception of piping processes in badlands, most of this literature is qualitative and speculative. Piping is the hydraulic erosion of sediments and soils by throughflow along joints and dessication cracks, producing subsurface rills and gullies that in badlands and terraces commonly result in a karst-like landscape. Piping networks are generally of small size and have been qualitatively described in many papers.

Groundwater sapping, as distinct from piping, is a generic term for weathering and erosion of soils and rocks by emerging groundwater, at least partially involving intergranular flow (as opposed to the channelized throughflow involved in piping). Higgins (1984) distinguishes between concentrated erosion at springs ("spring sapping") and "seepage erosion," where groundwater discharge is laterally uniform. These are endpoints of a continuum, and it is debatable whether the distinction is useful. Further discussion of the definition of groundwater sapping is provided by Howard and Kochel (chapter 2). Higgins (1984) provides an extensive discussion of possible examples of groundwater sapping processes and landforms from the pre-1980 literature.

Dunne (1980) suggested that groundwater sapping may be an important process in the development of the headward ends of terrestrial drainage networks in certain physiographic soil settings. However, in these drainage headwaters, runoff erosion and mass-wasting of the soil are also important, so that the strongly incised, gullied, or theater-headed valleys do not occur.

Recently, Pillans (1985) has demonstrated that erosion by emergent groundwater at terrace scarps on New Zealand has created theater-headed sapping valley systems. Schumm and Phillips (1986) note that similar channels at a different location in New Zealand have formed partially by groundwater sapping and partly by runoff erosion, terming these "composite channels." They suggest that certain martian channels may likewise have a composite origin.

Karst landforms in soluble rock are clearly products of groundwater erosion, but with the exception of solutional processes in limestones with high intergranular permeability (Back et al., 1984), solution occurs primarily along joints, bedding planes, and other fractures, producing a landscape of blind valleys, enclosed depressions, subterranean channels, and resurgences that is similar to landforms produced by piping. The literature on karst is extensive; see, for example, Jennings (1985) and papers in LaFleur (1984).

Almost all the literature on landforms produced by groundwater sapping is descriptive. As a result, it has been difficult to quantitatively compare terrestrial networks of sapping origin with potential martian analogs, and comparisons to date have been primarily qualitative (e.g., Higgins, 1982; Laity and Malin, 1985; Schumm and Phillips, 1986). At the resolution of Viking images, the only method of quantitative comparison of martian and terrestrial drainage networks is by use of planimetric morphometric parameters. Pieri (1979, 1980) measured the junction angles within stream networks on Mars and on Earth as a basis for comparison. Kochel et al. (1985) and Baker and Partridge (1986) measured several traditional measures of drainage basin morphometry on martian valley systems for comparison with terrestrial valleys, but both studies had to face the difficult question of defining drainage areas where divides are not evident. It is interesting that all the morphometric comparisons were between the martian channels and typical terrestrial channel networks formed by runoff, with the result that significant differences were found that are primarily related to the distinctive morphometric features described above. To date, such comparisons have not included measurements made on terrestrial stream networks of suspected sapping or composite origin, nor have they included glaciated valley networks, thermokarst valleys, or very immature runoff networks in fractured, layered rocks. The first systematic attempt to distinguish morphometrically between runoff valleys and possible sapping valleys has been the study of Hawaiian valley morphology (Thompson, 1984; chapters 2 and 10).

The processes acting in groundwater sapping have in general not been quantified in terms of mechanisms, rates, or resulting landform morphology. The only exception is the quantitative characterization of groundwater sapping in noncohesive sediments. Howard and McLane (in press) performed experiments on sapping processes in a two-dimensional flow tank and were able to theoretically model the processes and produce a numerical simulation model for the landform evolution (see chapter 5). Experiments on channel network development in sediments in a three-dimensional chamber have been conducted, and progress has been made toward a theoretical simulation model (see chapters 5 and 6).

Because of the complexity of the weathering processes that produce sapping in consolidated rocks (including cement solution, interstitial deposition of minerals, and frost wedging), modeling of these processes can probably only be done in a general way. For example, a reasonable process assumption might be that sapping rates are proportional to a power of seepage rates, with, perhaps, a critical, threshold seepage rate below which no sapping occurs.

Studies of canyon development in the Navajo Sandstone on the Colorado Plateau have provided the strongest documentation for an important role of groundwater sapping processes in a large terrestrial valley system (Laity and Malin, 1985). This book addresses the role of groundwater sapping in forming landforms on the Colorado Plateau. The impressive evidence as well as unresolved questions are summarized in chapters 2-4.

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