



Fig 3. Each network is symbolized by its two physiographic parameters, drainage density (K_d) and drainage basin compacity (K_c).

coefficient is similar to that of terrestrial karst terrain drainage basins. This suggests that martian valley networks are developed on a substratum subject to structural constraints that determine the effectiveness of groundwater flow [7] circulation. The physiographic parameter is not representative of a wide runoff surface but more of reduced-area systems such as sapping valleys, the morphology of which is illustrated by the high frequencies of headwater localized in confined units. Given that major concerns are the history of water and the possibility of life, further investigations of ancient valley networks as unequivocal evidence of circulation of subsurface water will promise a significant advance in our knowledge of Mars.

References: [1] Cabrol N. A. (1992) *Z. Geomorphol.*, 37, 57-76. [2] Cabrol N. A. and Grin E. A. (1991) In *LPI Tech. Rpt.* 92-02, 28-29. [3] Cabrol N. A. (1990) *LPS XXI*, 151-152. [4] Pieri D. (1980) *Science*, 210, 895-897. [5] Squyres S. W. (1989) *Icarus*, 79, 229-258. [6] Baker V. R. et al. (1992) In *Mars*, 493-522, Univ. of Arizona. [7] Gulick V. C. and Baker V. R. (1993) *LPS XXIV*, 587-588.

N94-21665

36-91 ABS ONLY 177596

THE EVOLUTION OF THE EARLY MARTIAN CLIMATE AND THE INITIAL EMPLACEMENT OF CRUSTAL H_2O . S. M. Clifford, Lunar and Planetary Institute, Houston TX 77058, USA.

Introduction: Given the geomorphic evidence for the widespread occurrence of water and ice in the early martian crust, and the difficulty involved in accounting for this distribution given the present climate, it has been suggested that the planet's early climate was originally more Earth-like, permitting the global emplacement of crustal H_2O by direct precipitation as snow or rain [1,2]. The resemblance of the martian valley networks to terrestrial runoff channels and their almost exclusive occurrence in the planet's ancient (~4-b.y.-old) heavily cratered terrain are often cited as evidence of just such a period. An alternative school of thought suggests that the early climate did not differ substantially from that of today. Advocates of this view find no compelling reason to invoke a warmer, wetter period to explain the origin of the valley networks. Rather, they cite evidence that the primary mechanism of valley formation was groundwater sapping, a process that does not require that surface water exist in equilibrium with the atmosphere [3-5]. However, while sapping may successfully explain the origin of the small valleys, it fails to address how the crust was initially charged with ice as the climate evolved toward its present state. Therefore, given the uncertainty regarding the environmental conditions that prevailed on early Mars, the initial emplacement of ground ice is considered here from two perspectives: (1) The early climate started warm and wet, but gradually cooled with time, and (2) the early climate never differed substantially from that of today.

Early Climate: Warm and Wet: The density and distribution of the valley networks throughout the heavily cratered terrain suggests that, regardless of whether early Mars started warm or cold, groundwater was abundant in the planet's early crust. However, given an initially warm start, an inevitable consequence of both the decline in Mars' internal heat flow and the transition to colder temperatures would have been the development of a freezing front within the regolith that propagated downward with time, creating a thermodynamic sink for any H_2O within the crust. Initially, water may have entered this developing region of frozen ground from both the atmosphere and underlying groundwater. However, as ice condensed within the near-surface pores, it effectively sealed off the deeper regolith from any further atmospheric supply. From that point on, the only source of water for the thickening cryosphere would have been the geothermally driven flux of vapor arising from the presence of groundwater at depth. Indeed, calculations by Clifford [6] indicate that a geothermal gradient as small as 15 K km^{-1} could supply the equivalent of 1 km of water from higher-temperature (higher vapor pressure) depths to the colder (lower vapor pressure) base of the cryosphere every 10^6 - 10^7 yr. Given the higher geothermal heat flow expected to have characterized the planet 4 b.y. ago, this supply of vapor may have been as much as 3-5 times greater in the past.

Pollack et al. [2] estimate that if the primary mechanism driving climate change was the removal of a massive (1-5-bar) CO_2 atmosphere by carbonate formation, then the transition from a warm to cold early climate must have taken between 1.5×10^7 to 6×10^7 years. For transition times this slow, the downward propagation of the freezing front at the base of the cryosphere is sufficiently small (when compared with the geothermally induced vapor flux arising

from the groundwater table) that the cryosphere should have remained saturated with ice throughout its development.

From a mass balance perspective, the thermal evolution of the early crust effectively divided the subsurface inventory of water into two evolving reservoirs: (1) a slowly thickening zone of near-surface ground ice and (2) a deeper region of subpermafrost groundwater. One possible consequence of this evolution is that, if the planet's initial inventory of outgassed water was small, the cryosphere may have eventually grown to the point where all the available H₂O was taken up as ground ice [7]. Alternatively, if the inventory of H₂O exceeds the current pore volume of the cryosphere, then Mars has always had extensive bodies of subpermafrost groundwater. As argued by Clifford [8], this latter possibility is strongly supported by the apparent occurrence of outflow channels as recently as the Mid to Late Amazonian [e.g., 9,10].

Early Climate: Like the Present: Of course, if early Mars was cold from the start, the initial emplacement of ground ice would have differed significantly from that described by the warm scenario. This possibility was first considered by Soderblom and Wenner [7], who suggest that the initial emplacement of crustal H₂O was the result of the direct injection and migration of juvenile water derived from the planet's interior. There are at least two ways in which this emplacement may have occurred. First, by the process of thermal vapor diffusion [6], water exsolved from cooling magmas will migrate from the warmer to colder regions of the crust. Upon reaching the cryosphere, this H₂O will then be distributed throughout the frozen crust by a variety of thermal processes [11]. As a result, any part of the cryosphere that overlies or surrounds an area of magmatic activity will quickly become saturated with ice. The introduction of any additional water will then result in its accumulation as a liquid beneath the frozen crust, where, under the influence of the growing local hydraulic head, it will spread laterally in an effort to reach hydrostatic equilibrium. As this flow expands beneath areas where the cryosphere is not yet fully charged with ice, thermal vapor diffusion [6] and the other thermal processes discussed by Clifford [11] will redistribute H₂O into the frozen crust until its pore volume is either saturated or the local source of groundwater is finally depleted.

However, the fate of water released to the cold martian atmosphere is significantly different. The direct injection of a large quantity of vapor into the atmosphere (e.g., by volcanism) will lead to its condensation as ice on, or within, the surrounding near-surface regolith. As the available pore space in the upper few meters of the regolith is saturated with ice, it will effectively seal off any deeper region of the crust as an area of potential storage. From that point on, any excess vapor that is introduced into the atmosphere will be restricted to condensation and insolation-driven redistribution on the surface until it is eventually cold-trapped at the poles. Should such polar deposition continue, it will ultimately lead to basal melting [12], recycling water back into the crust beneath the caps. As the meltwater accumulates beneath the polar cryosphere, it will create a gradient in hydraulic head that will drive the flow of groundwater away from the poles. As the flow expands radially outward, it will pass beneath regions where, as a result of vapor condensation from the atmosphere, only the top few meters of the cryosphere have been saturated with ice. As before, the presence of a geothermal gradient will then lead to the vertical redistribution of H₂O from the underlying groundwater until the pore volume of the cryosphere is saturated throughout. In this way, the early martian

crust may have been globally charged with water and ice without the need to invoke an early period of atmospheric precipitation.

This analysis suggests that, whether the early martian climate started warm or cold, thermal processes within the crust played a critical role in the initial emplacement of ground ice. An important consequence of this fact is that, below the depths of equatorial desiccation predicted by Clifford and Hillel [13] and Fanale et al. [14], the cryosphere has probably been at or near saturation throughout its development, or at least until such time as the total pore volume of the cryosphere grew to exceed the total volume of the planet's outgassed inventory of water. The existence of outflow channels with apparent ages of less than 1 b.y. [9,10] raises considerable doubt as to whether this last stage in the evolution of the martian cryosphere has yet been reached.

References: [1] Masursky et al. (1977) *JGR*, 82, 4016-4038. [2] Pollack et al. (1987) *Icarus*, 71, 203-224. [3] Wallace D. and Sagan C. (1979) *Icarus*, 39, 385-400. [4] Carr M. H. (1983) *Icarus*, 56, 476-495. [5] Brakenridge et al. (1985) *Geology*, 13, 859-862. [6] Clifford S. M. (1991) *GRL*, 18, 2055-2058. [7] Soderblom L. A. and Wenner D. B. (1978) *Icarus*, 34, 622-637. [8] Clifford S. M., this volume. [9] Tanaka K. L. and Scott D. H. (1986) *LPS XVII*, 865-866. [10] Mouginiis-Mark P. J. (1990) *Icarus*, 84, 362-373. [11] Clifford S. M., this volume. [12] Clifford S. M. (1987) *JGR*, 92, 9135-9152. [13] Clifford S. M. and D. Hillel (1983) *JGR*, 88, 2456-2474. [14] Fanale et al. (1986) *Icarus*, 67, 1-18.

57-91 N94-21666-97 p. 3
THE HYDROLOGIC RESPONSE OF MARS TO THE ONSET OF A COLDER CLIMATE AND TO THE THERMAL EVOLUTION OF ITS EARLY CRUST. S. M. Clifford, Lunar and Planetary Institute, Houston TX 77058, USA.

Morphologic similarities between the martian valley networks and terrestrial runoff channels have been cited as evidence that the early martian climate was originally more Earth-like, with temperatures and pressures high enough to permit the precipitation of H₂O as snow or rain [1,2]. Although unambiguous evidence that Mars once possessed a warmer, wetter climate is lacking, a study of the transition from such conditions to the present climate can benefit our understanding of both the early development of the cryosphere and the various ways in which the current subsurface hydrology of Mars is likely to differ from that of the Earth. Viewed from this perspective, the early hydrologic evolution of Mars is essentially identical to considering the hydrologic response of the Earth to the onset of a global subfreezing climate.

If the valley networks did result from an early period of atmospheric precipitation, then Mars must have once possessed near-surface groundwater flow systems similar to those currently found on Earth, where, as a consequence of atmospheric recharge, the water table conformed to the shape of the local terrain. However, with both the transition to a colder climate and the decline in Mars' internal heat flow, a freezing front eventually developed in the regolith that propagated downward with time, creating a thermodynamic sink for any H₂O within the crust. Initially, water may have entered this developing region of frozen ground from both the atmosphere and underlying groundwater. However, as ice condensed within the near-surface pores, the deeper regolith was ultimately sealed off from any further atmospheric supply. From that point on, the only source of water for the thickening cryosphere must