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Channels and valleys on Mars: cold climate features formed as a result of a thickening cryosphere

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Abstract. Large flood channels, valley networks, and a variety of features attributed to the action of ground ice indicate that Mars emerged from heavy bombardment around 3.8 Gyr ago, with an inventory of water at the surface equivalent to at least a few hundred meters spread over the whole planet, as compared with 3 km for the Earth. The surface water resided primarily in a porous, kilometers thick, megaregolith created by the high impact rates. At the end of heavy bombardment a rapid decline in erosion rates by a factor of 1000 suggests a major change in the global climate. It is proposed that at this time the climate became similar to today's and that this climate has been maintained throughout the rest of Mars' history. The various drainage features represent an adjustment of the distribution of water to the surface relief inherited from the period of heavy bombardment and to a thickening of the cryosphere as the heat flow declined. The valley networks formed mostly at the end of heavy bombardment when erosion rates were high and climatic conditions permitted an active water cycle. They continued to form after heavy bombardment when the cryosphere started to form by a combination of episodic flooding and mass-wasting aided by the presence of liquid water at shallow depths. As the cryosphere thickened with declining heat flow, water could no longer easily access the surface and the rate of valley formation declined. Hydrostatic pressures built below the cryosphere. Eruptions of groundwater became more catastrophic and massive floods resulted, mainly in upper Hesperian time. Flood sources were preferentially located in low-lying, low-latitude areas where the cryosphere was thin, or near volcanoes where a thinner than typical cryosphere is also expected. Floods caused a drawdown in the global water table so that few formed in the second half of Mars' history. The floodwaters pooled in low-lying areas, mostly in the northern plains. Some of the water may still be present as thick ice deposits, some has been lost to space, particularly during periods of high obliquity. Published by Elsevier Science Ltd

Introduction

Mars is the only planet or satellite, other than the Earth, for which we have evidence that liquid water has been abundant at the surface. Temperatures at the surface now are such that the ground is permanently frozen to kilometer depths yet the evidence for liquid water is both abundant and persuasive. Huge flood channels have been eroded into the surface, the oldest terrains are extensively dissected by valley networks that resemble terrestrial river valleys, and water appears to have episodically ponded to form large lakes. In addition, there are numerous features that are best explained as the result of the presence of ground ice. Yet evidence for water today is sparse. Liquid water has not been observed anywhere, water ice has been detected only at the north pole, and the martian atmosphere contains only minute amounts of water vapor. If a significant amount of water is present, it must be hidden below the surface as groundwater or ground ice. Furthermore, climate modeling suggests that it is very difficult to obtain conditions at the surface such that liquid water would be stable, particularly on early Mars when the energy output of the Sun is thought to have been lower than today. The preferential location of seemingly water-worn features in the most ancient terrains is therefore particularly puzzling.

This paper suggests that the water and ice related surface features of Mars that formed after heavy bombardment represent an accommodation of the planet to conditions inherited from the era of heavy bombardment. It is suggested that climatic conditions during heavy bombardment were very different from the conditions that prevailed for much of the rest of the planet's history. When Mars emerged from heavy bombardment water was distributed throughout the impact generated megaregolith. A major change in surface conditions took place at this time such that the climate became similar to today's. A near-surface, permanently frozen cryosphere developed but the cryosphere was thinner than today's because of the high heat flow, being at most only a few hundred meters thick at the equator. The rest of the planet's history is characterized by one-way transport of the water from the high areas, mostly in the south to the low areas, mostly in the north. Shortly after heavy bombardment this transport resulted mainly in the formation and extension of the previously formed valley networks, but as the cryosphere thickened, leakage of liquid water to the surface became more difficult and the main mode of transport was the large floods. The water accumulated in low areas such as the Hellas basin and northern plains where it formed thick ice deposits that were partially or wholly removed during periods of high obliquity. Justification for this model is the main theme of this paper, the arguments being based mainly on geomorphic evidence and on evidence gleaned from the SNC meteorites which are believed to come from Mars.

Evidence for a large near-surface inventory of water

Outflow channels present the least ambiguous evidence for large amounts of water at the surface in the past. These enormous channels start full size, have few if any tributaries, and show numerous indications that they formed by large floods (Carr, 1981, 1996; Baker, 1982). They occur in four large regions: around the Chryse-Acidalia basin, centered at 20°N, 45°W; in Elysium Planitia, centered at 30°N, 230°W; in the eastern part of the Hellas basin, around 40°S, 270°W; and along the western and southern margins of Amazonis Planitia, which is centered at 20°N, 160°W (Fig. 1). Where incised into the cratered highlands the outflow channels are generally a few tens of kilometers wide but where they cross plains may expand to erode swaths hundreds of kilometers across. The streamlined channel shapes, the teardrop-shaped islands and the striated floors are the most distinctive features of the channels, and cause them to closely resemble large terrestrial flood features. Other attributes in common with terrestrial flood channels include cataracts, inner channels, converging and diverging scour patterns, and etched or plucked zones. The bedforms and islands indicate that these sinuous depressions are indeed true channels that were once filled with fluid, and not valleys formed by slow erosion. The resemblance between the martian outflow channels and large terrestrial flood channels is so strong and there is so much other supportive evidence of water and ice that a flood origin for most of the outflow channels can hardly be doubted.

The floods were much larger than the largest known terrestrial floods. Estimates of the discharges made from the channel dimensions and slopes range from $10^7\,m^3\,s^{-1}$ for some of the smaller channels around Chryse Planitia to $3 \times 10^9\,m^3\,s^{-1}$ for Kasei Vallis, the largest outflow channel (Baker, 1982; Robinson and Tanaka, 1990). For comparison, discharges of $10^7\,m^3\,s^{-1}$ have been estimated for the two largest known floods on Earth, the Channeled Scablands in Eastern Washington and the Chuja Basin flood of Siberia (Baker *et al.*, 1993) and the discharge of the Mississippi River peaks at $10^5\,m^3\,s^{-1}$. The total amounts of water involved are much harder to estimate but estimates are that individual flood events released as much as 10^5–$10^6\,km^3$ of water (Carr, 1996).

Although the floods may have resulted from a variety of causes, the two most likely are massive release of groundwater from below a thick permafrost seal and catastrophic release of water from lakes. The survival of ancient, heavily cratered terrain over two-thirds of the martian surface suggests that a deep, impact-brecciated zone is preserved over most of the martian surface, although it may be in places covered by a thin veneer of younger deposits. The brecciated zone formed during the period of heavy bombardment between 4.5 and 3.8 Gyr ago when impact rates were much higher than during Mars' subsequent history. The zone is likely to be porous and could have a substantial holding capacity for groundwater and ground ice. Binder and Lange (1980) modeled the porosity of the lunar regolith by assuming that it declined exponentially with depth as a result of self compaction such that pore closure is essentially complete at a depth of 20 km. Clifford (1993) scaled this model to Mars and estimated the storage capacity of the martian megaregolith for different values of the porosity at the surface. For surface porosities of 0.5 and 0.3 the holding capacities are respectively 1.4 and 0.8 km of water spread evenly over the whole planet. At present, liquid water is stable only below the zone of permanently frozen ground near the surface.

The base of this permafrost zone is controlled by surface temperatures and the heat flow. Estimates are that at present the zone is roughly 6 km thick at the poles and 2 km thick at the equator (Clifford, 1993). Early in Mars' history, at the end of heavy bombardment, heat flows would have been 4–5 times higher than at present (Schubert and Spohn, 1990) and the permafrost seal would have been 4–5 times thinner for the same climatic conditions. Migration of groundwater would cause hydrostatic pressures to build below the permafrost seal in low-lying areas. If the seal were broken massive groundwater eruptions could occur. Breakout would be favored where the permafrost seal was thin, as at low latitudes or near volcanoes. In order to get the enormous discharges implied by the sizes of the channels the groundwater must have been contained under high pressures below a thick permafrost seal and so the mechanism probably requires mean annual temperatures well below 0°C. The ages of the outflow channels span most of Mars' history, but they formed predominantly in the first half of Mars' history, but well after the end of heavy bombardment (Masursky *et al.*, 1977; Scott and Tanaka, 1986; Greeley and Guest, 1987).

If the Martian megaregolith acted as a groundwater aquifer below the permafrost, then depressions that extended to depths well below the permafrost zone would be susceptible to filling by water. In the Valles Marineris, which extend well below the depth of even today's permafrost, are thick stacks of layered sediments that have been taken as evidence of the former presence of lakes (McCauley, 1978; Nedell *et al.*, 1987). Under present climatic conditions such lakes would form an ice cover. If a lake was deep enough and lasted long enough for thawing of the underlying megaregolith, then groundwater would leak into the lake, thereby compensating for ablation losses at the surface. The lake level would then be controlled by the level of groundwater in the adjacent terrain. Emergence of large flood channels from the lower ends of

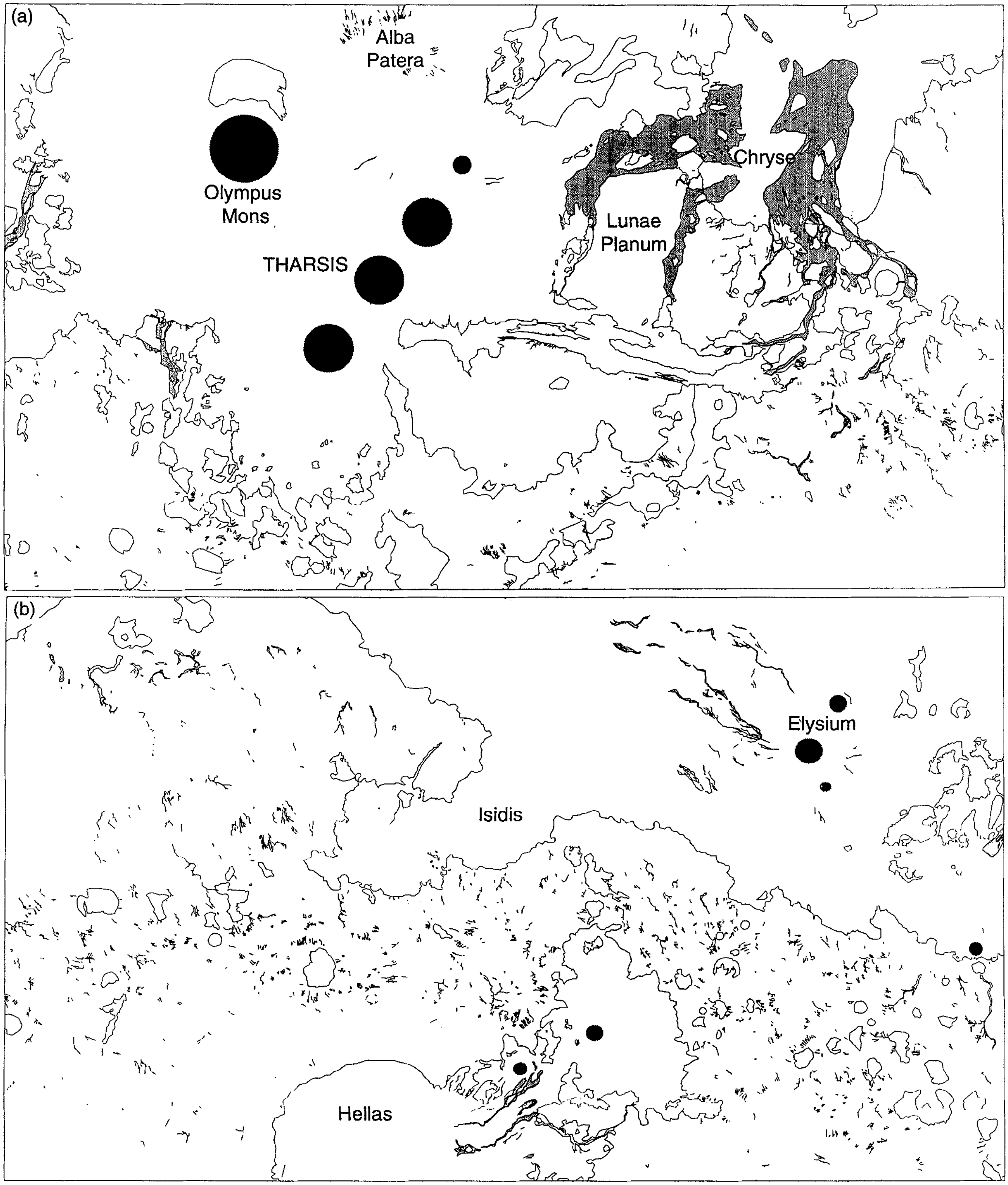

Fig. 1. The distribution of outflow channels (shaded) and valley networks in (a) the western hemisphere and (b) the eastern hemisphere. Outflow channels are in four main areas: around Chryse, northwest Elysium, northeast of Hallas and west and south of Amazonis. Valley networks are mostly within the cratered highlands but also on young volcanoes such as Alba Patera

the canyons suggests that some of the lakes postulated to have been within the canyons drained catastrophically to the east (McCauley, 1978).

The outflow channels provide a means of estimating the amount of water near the surface. The large outflow channels around the Chryse basin have removed approximately $4 \times 10^6\,km^3$ of material to form the outflow channels and chaotic terrain (Carr *et al.*, 1987). If we assume that all the water that flowed through the channels carried the maximum reasonable sedimentary load then at least $6 \times 10^6\,km^3$ of water has passed through these channels or the equivalent of 40 m spread over the whole planet. If we further assume that water was evenly distributed over the whole planet, not just restricted to the Chryse basin, then we get a total inventory of roughly 400 m spread over the whole planet. The equivalent number for the Earth is 3 km. The 400 m estimate is little more than a reasonable guess. The number is too low if much of the water that flowed through the channels did not carry its maximum load, and if much of the groundwater remained in the ground, as was surely the case. The number is too high if groundwater was re-circulated in some way so that the same water passed through the channels more than once. Despite the uncertainties, it is difficult to see how the water inventory at the end of heavy bombardment could have been less than a few hundred meters spread over the whole planet, although only a fraction of this may have reached the surface in the flood events.

Some support for an inventory of this size is provided by the deuterium content of the near-surface water. The D/H ratio in the present atmosphere is 5.2 times that of terrestrial water (Owen *et al.*, 1988; Bjoraker *et al.*, 1989). The enrichment is caused by preferential loss of hydrogen with respect to deuterium from the top of the atmosphere, a consequence largely of diffusive separation of hydrogen and deuterium above the homopause (Yung *et al.*, 1988). Water extracted from SNC meteorites has values of D/H that range from unenriched to 5.2 enriched. The oxygen isotope ratios in water extracted from SNC meteorites is different from the oxygen isotope ratios in the silicates, which led Karlsson *et al.* (1992) to suggest that the surface water has evolved independently from interior water, probably because of the lack of plate tectonics to mix surface water into the interior. The range in D/H extracted from the SNCs is also consistent with water from two sources that have evolved independently, an unenriched mantle source and an enriched crustal source (Watson *et al.*, 1994).

The same D/H enrichment of 5.2 observed in the SNC meteorites and the present atmosphere implies that the surface reservoir undergoing fractionation has not been enriched, within experimental errors, in the last 1.3 Gyr, the age of the meteorites. From the present loss rates and the experimental errors, Donahue (1995) estimated that the reservoir of water undergoing enrichment must be the equivalent of at least 25 m spread over the whole planet otherwise we would see differences between the 1.3 Gyr old water from the meteorites and present day water. Moreover since this whole 25 m is enriched a lower limit of 280 m can be placed on the amount of surface water originally at the end of accretion, which it consistent with the geology.

The presence of large amounts of water at the surface is readily reconciled with the low water contents of the SNC meteorites (Fallick *et al.*, 1983; Kerridge, 1988; Yang and Epstein, 1985; Watson *et al.*, 1994). Much of the water originally present in the interior would have either outgassed or reacted with iron during core formation at the end of accretion (Dreibus and Wänke, 1987). The surface inventory may be simply water that was at the surface at the end of accretion, or the result of additions after core formation (Carr and Wänke, 1991). Lack of plate tectonics prevented mixing of the surface water into the interior.

Additional support for presence of a large near surface inventory of water is provided by indications of the presence of ground ice at high latitudes. At latitudes below about 30°, mean annual temperatures today are above the frost point, so that ground ice is unstable. It will tend to sublime into the atmosphere and be frozen out at the poles. If present climate conditions are typical of much of the planet's history, then the near-surface materials at low latitudes should be devoid of ice unless the ice is replenished in some way. In contrast, at high latitudes, the mean annual temperature is lower than the frost point temperature so that below the depth affected by the annual thermal wave, down to the base of the permafrost, ice is stable. If the surface is water rich, then we should see evidence for ice at high latitudes but not at low latitudes.

Several features observed only at high latitudes have plausibly been attributed to movement of the near surface materials as a result of the presence of ground ice. The two most prominent such features are debris aprons and terrain softening (Squyres, 1979; Squyres and Carr, 1986). At the base of most steep slopes in the 30–50° latitude band are aprons of debris with convex upward surfaces and steep outer margins. They extend roughly 20 km away from the slope. Within valleys longitudinal ridges form where aprons from opposing walls meet. The aprons are not found at low latitudes. The simplest explanation is that at high latitudes, where ground ice is expected from stability relations, talus shed from slopes is mixed with ice. This enables the talus to move slowly away from the slopes to form the aprons. At low latitudes where ice is not expected, the talus is stable and no aprons form. At very high latitudes temperatures are so cold that strain rates in the ice are negligible for the basal stresses expected at the bases of the talus piles so that they do not move.

Terrain softening is a term applied to a characteristic rounding or muting of terrain at mid to high latitudes. At latitudes less than about 30°, most primary features that formed after heavy bombardment, such as crater rims and fault scarps are sharply defined, having suffered negligible amounts of erosion. At latitudes above about 30°, however, most crater rims and scarps are rounded, and the small crater population is largely missing. Massifs, such as those around impact basins are rounded, and in places are the source of glacier-like tongues of material. Although not proven, the simplest explanation of these differences is that downslope movement of the near surface materials at high latitudes is enhanced as a result of the presence of ground ice. Thus the presence of large amounts of water near the surface, as inferred from the outflow channels, is supported by the seemingly pervasive presence of ground ice at high latitudes, where it is stable, and by the seeming absence of ground ice at low latitudes where it is unstable. If this interpretation is correct, then the lack of rounding of low latitude terrains indicates that significant amounts of ground ice have not been present near the surface for most of Mars' history.

Climate change

Much of the above discussion is non-controversial. However, major issues remain with respect to the effect of the large floods on global climates, the amounts of water participating in each flood episode, and the fate of the water involved. Before discussing these issues, however, we will briefly examine the evidence from erosion rates. The evidence for a dramatic change in crater obliteration rates at the end of heavy bombardment is unequivocal. In the heavily cratered Noachian terrains craters up to at least several tens of kilometers across are present in all states of preservation from rimless, barely discernible depressions to fresh appearing, hardly modified features. Not knowing the cratering rate it is difficult to estimate the erosion rates, but a crude estimate based on extrapolating lunar cratering rates to Mars is $10\,\mu m\,yr^{-1}$ (Carr, 1992), as compared with 10–$1000\,\mu m\,yr^{-1}$ for arid regions of the Earth (Saunders and Young, 1983). At the end of heavy bombardment erosion rates fell dramatically. Basal Hesperian crater populations are perfectly preserved down to diameters at least as small as 200 m (Carr, 1992), as are details of their ejecta blankets (Craddock and Maxwell, 1993). Crater preservation indicates that the average erosion rates since the base of the Hesperian (3.5–3.8 Gyr ago) is not more than $10^{-2}\,\mu m\,yr^{-1}$ (Arvidson *et al.*, 1979; Carr, 1992). Thus, at the end of heavy bombardment the erosion rates declined by about three orders of magnitude, from the low end of terrestrial rates to extremely low average rates for the rest of Mars' history. The cause of the decline at the end of the Noachian is not known but it is difficult to envisage a non-climatic cause. In contrast the very low average rates for the rest of Mars' history implies that if there were major climatic excursions they were short in duration.

In order to explain the presence of (1) highly developed, dense drainage networks on young volcanoes, (2) seemingly glacial features of similar age at high southern latitudes (Kargel and Strom, 1992), and (3) linear features, interpreted as shorelines, at high northern latitudes (Parker *et al.*, 1993), Baker *et al.* (1991) proposed that ocean sized bodies of water ($>10^7\,km^3$) formed episodically in the northern plains as a result of the large floods, and that formation of these oceans caused large but short periods of warm climate during which the valley networks and glacial features formed. They suggested that the oceans formed as a result of several large floods occurring simultaneously, one flood possibly triggering another. According to the model, eruption of the large volumes of water caused massive release of CO_2 as a result of degassing of CO_2 dissolved in the water and release of CO_2 stored in the regolith. The enhanced CO_2/H_2O atmosphere caused global warming, thereby temporarily creating climatic conditions under which fluvial and glacial features could form. The oceans slowly disappeared and the groundwater system was recharged both by processes not clearly explained, a long frozen period ensued, until the next flooding episode. They envisage, therefore, a history characterized mainly by climates similar to today's except for brief but dramatically different oceanic episodes.

There are many uncertainties about this hypothesis, but only those concerning recharge and carbonates are discussed here. The oceans must somehow recharge the groundwater system so that the next flood episode can occur. This could be done either through evaporation and precipitation, or through leakage into the megaregolith underlying the ocean. Yet evidence of precipitation is almost completely lacking. The undissected areas between the networks and between the individual valleys of the larger networks are devoid of any evidence of precipitation, and the post-Noachian craters there have perfectly preserved morphologies. If the water leaked into the megaregolith at the base of the ocean at an elevation of -2 km, how was it raised to cut valleys and channels in the highlands at $+4$ km? Another major problem concerns carbonates. A thick CO_2 atmosphere is invoked to raise surface temperatures, and then temperatures fall as the CO_2 is scavenged out to form carbonates. There clearly should be carbonates younger than the youngest channels yet none have been detected. Moreover the carbonates must be recycled if there are to be multiple oceanic episodes, and in the absence of plate tectonics, it is difficult to see how carbonates can be buried to dissociation depths in order to release the CO_2. The lack of carbonate detection is common to all hypotheses that invoke warm climates for the formation of the valley networks.

This paper is proposing a very different climatic history, one in which the martian climate has remained very similar to today's throughout much of the planet's history, being subject only to the rather modest oscillations caused by obliquity variations. Of the three observations (valleys, glacial features, shorelines) that led to episodic ocean hypothesis only the valleys are discussed here in detail. The proposed glacial features (Kargel and Strom, 1992) are few in number and susceptible to other interpretations. Some of the supposed shoreline features (Parker *et al.*, 1989, 1993) may indeed be shorelines but their continuity cannot be determined with confidence because of the poor photographic coverage of the high northern latitudes, so the size of the implied bodies of water cannot be confidently determined. Valley networks have been widely taken as the strongest indication of major climatic excursions, so the strength of this evidence is examined in more detail.

Origin of valley networks

The ages of valley networks are difficult to determine, but although most are clearly very ancient, they appear to have a wide spread of ages. Most valleys are too small for ages to be determined from superposition of impact craters, so they have been estimated from the youngest unit that a valley cuts. While the vast majority of the valleys are incised in Noachian units, Carr (1995) estimated that 8% of 827 networks mapped were younger than Noachian because some part of the network cut a younger unit. Scott and Dohm (1992) estimated that as many as 30% may cut units younger than Noachian and 10% cut units younger than Hesperian (Scott and Dohm, 1992). The youngest networks are mostly where there are steep slopes, as on crater and canyon walls, and/or where high heat flows are expected as on volcanoes. Thus it appears that the rate of valley formation declined with time, formation being widespread at the end of the Noachian but becoming progressively more restricted with time to areas of steep slopes and/or high heat flows. If the valley networks are close analogs to terrestrial fluvial valleys and require warm climates for their formation then warm climatic episodes must have occurred throughout martian history.

There are, however, good reasons to suspect that valley formation depends on local conditions rather than global climate changes. The youngest valleys are very sparsely distributed and restricted mainly to the flanks of volcanoes such an Alba Patera. If the young valleys are the result of recent global climate changes, why is the evidence for climate change restricted to a few volcanoes, and why did this global change not result in higher erosion rates? Three alternative suggestions have been made to explain the valley networks that do not involve climate change: (1) the younger valleys are the result of hydrothermal activity (Brackenridge *et al.*, 1985; Gulick and Baker, 1993), (2) the valleys are the result of groundwater sapping under present climatic conditions (Pieri, 1980; Squyres and Kasting, 1994), and (3) the valleys did not form by slow erosion of surface streams so did not require warm climate conditions (Carr, 1995).

Hydrothermal activity may have been important in the origin of valley networks, not only on volcanoes but also within the cratered uplands where the heat sources would have been large impacts. Water would rise over the heat source and could feed warm springs at the surface thereby giving rise to streams that cut the valleys. Groundwater lost to the surface would be replaced by water that flows in from surrounding regions. Whether streams fed by a hydrothermal spring could, under present climatic conditions, flow far enough to cut the observed valleys before they froze would depend on the initial water temperature and the discharge rates.

Groundwater sapping is a process whereby a valley extends itself by headward erosion at a spring and discharge is again maintained by movement of groundwater from adjacent regions to the spring site. During sapping the water may be warmer than the surface temperatures, even in the absence of volcanic activity because of the local relief and heat flow. Although groundwater sapping under present climatic conditions may have been important in the formation of valleys on volcanoes, where warm springs could have readily developed and the valleys are short and narrow, such an origin appears unlikely for the vast majority of the valleys in the cratered highlands. Many of the valleys originate at rim crests where springs are unlikely. For slow erosion by running water very large volumes of water are needed compared with the volumes of rock eroded. Gulick and Baker (1993) estimated, for example, that in volcanic terrains ratios of 1000:1 are required, and Goldspiel and Squyres (1991) estimated that the equivalent of several kilometers of water spread over the Ma'adim drainage system are required to cut the Ma'adim Vallis. Such large volumes of water imply some groundwater recharge mechanism for which a change in climate would almost certainly be needed. Under present climate conditions, water brought to the surface cannot get back down into the groundwater system because of the thick permafrost. Another reason to be skeptical that slow erosion of streams fed by groundwater springs could form the valley networks under present climate conditions, is that spring-fed streams under sub-zero conditions tend to dam themselves by forming icings. These are common in arctic regions of the Earth (Sloan *et al.*, 1976; Williams and Smith, 1989; Tolstikhin and Tolstikhin, 1974) where conditions are much less harsh than on Mars. It is unlikely that streams could flow across the surface for tens to hundred of kilometers under present climates unless discharges were very high.

There are reasons to doubt that the valley networks formed exclusively by slow erosion by surface streams, irrespective of the source of the water. In this respect it is useful to emphasize the difference between a fluvial valley and a channel. A channel is the conduit in which a fluid flows and may at times be almost completely filled with the fluid. In contrast a fluvial valley may contain many fluvial channels, and is rarely if ever close to being filled with water. Many of the martian valley networks have characteristics more consistent with their being channels of some kind rather than fluvial valleys (Carr, 1995): (1) fluvial channels have not been identified on the valley floors, despite excellent photography (Fig. 2), (2) some valleys have central, longitudinal ridges, so they cannot be flood plains formed by meandering streams as required by the fluvial hypothesis, (3) most valleys do not have V-shaped tributaries upstream but instead maintain a rectangular cross-section, 1–2 km wide from source to mouth, which is more consistent with their being channels than typical fluvial valleys (Fig. 3), and (4) some valleys have levee-like ridges along their sides which indicate that the valley is some form of channel that at one time was almost filled with fluid (Fig. 4).

The discussion above suggests that the martian valleys are not perfect analogs to terrestrial river valleys. There are a number of possibilities to explain the ambivalent relations. One possibility is that the upland valleys formed mostly by fluvial erosion in the Noachian when erosion rates were high, and climatic conditions were likely different, and then were subsequently modified by mass wasting or small floods. Another possibility is that the networks formed mainly by mass wasting aided by the presence of groundwater at shallow depths (Carr, 1995). Some support for the efficacy of mass wasting is provided by fretted channels, in which evidence for downstream movement by mass wasting is abundant and compelling (Lucchitta, 1984). What is envisaged is that failure at a slope creates a scar and a depression filled with loose debris. The loose debris acts as a conduit for groundwater thereby weakening materials at the head of the scar, causing further headward collapse and adding to the debris in the

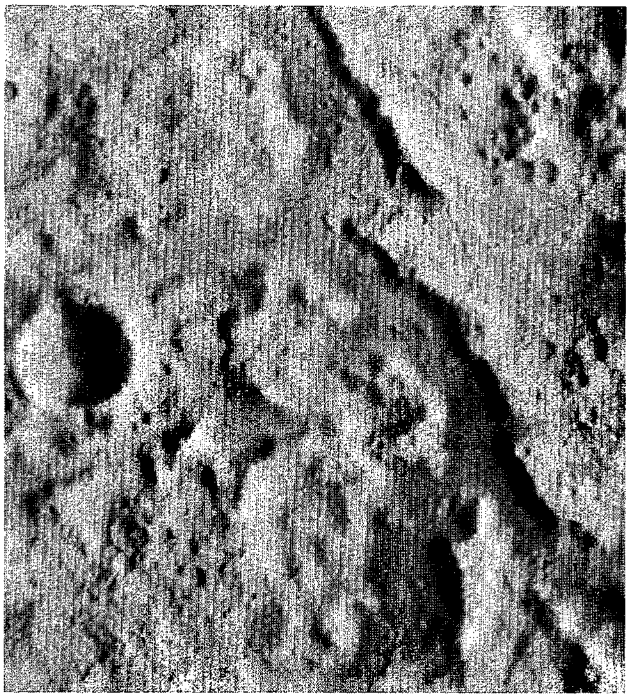

Fig. 2. Typical high resolution view of a branch of part of a valley network. The valley is roughly 2 km across. No trace of a river channel can be seen on the floor. The valleys do not continue to divide into smaller valleys like most terrestrial fluvial valleys. The only tributaries are vague depressions like the one above the crater on the left. At this scale the valley more resembles a channel than a fluvial valley cut by slow erosion of running water (130S19)

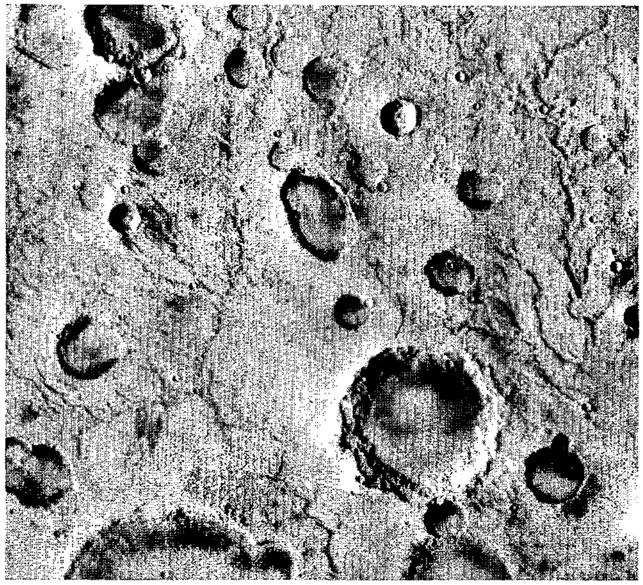

Fig. 3. Typical highland scene with valleys winding between the craters. Unlike terrestrial river valleys, these valleys maintain a roughly rectangular cross-section and constant width from source to mouth. Large areas between networks and between branches are undissected. The scene is 280 km across (618A28)

Fig. 4. Levee-like ridge bounding a channel. The ridges probably indicate former levels of fluid in the channel and show that the valley did not form by slow erosion of running water, but was at one time nearly filled with fluid (443S13)

depression. The debris, being loose and water saturated at its base tends to move slowly downstream enabling further erosion at the valley head. In this way networks could grow slowly over many millions of years. According to this proposal, river channels are not observed within the valleys of the networks because they never existed. The valleys themselves are channels down which was transported mass-wasted debris. The process just described would stop or slow considerably when the water table dropped or the heat flow declined such that no water could enter the base of the debris flows. We should therefore expect that valley networks would have formed most readily early in Mars' history, when heat flows were high and before the near-surface equatorial regions lost their water, and that their formation would have persisted longest where mass wasting was facilitated either by high heat flow or steep slopes, which is consistent with the observations.

The mechanism just described would be a very slow and inefficient process, but whatever caused the valley networks was very inefficient. Despite a cumulative record that covers billions of years, drainage densities in the highlands are only 0.001–0.01 km^{-1} compared with 2–30 km^{-1} for most of the Earth (Carr, 1995). Except in rare instances, individual branches of networks are separated from each other by undissected areas and large undissected areas separate the networks from each other. If we assume that the terrestrial drainage patterns have developed over approximately 10^8 years, the average rate of valley formation has been about 10^4–10^6 times smaller on Mars than on Earth.

Another possibility is that the upland valleys were formed by episodic but frequent floods, much smaller than those that subsequently formed the outflow channels. In this case the valleys are true channels through which have passed floods comparable in width to the valleys themselves. The large outflow channels have been ascribed to massive release of groundwater trapped under high hydrostatic pressure below a thick permafrost, as discussed above. Early Mars could have had only a thin cryosphere because of the high heat flow. During this early period massive floods may not have been possible because the thin cryosphere could not have contained the large hydrostatic pressures required to generate the large discharges. Breakout would have occurred before large hydrostatic pressures could develop. Because of the lower hydrostatic pressures, the breakouts would have been much more modest in size than those that later formed the typical outflow channels. Discharges could still have been large enough to permit flow for tens to hundreds of kilometers before freezing. Indeed, if Mars did have abundant near surface water and a thin cryosphere, it is difficult to see why such floods would not occur given the surface relief. Small episodic floods could, therefore, have contributed to the formation of the valley networks. This is a possible explanation of the levee-like ridges on the sides of some valleys, as seen in Fig. 4.

The discussion above refers to typical upland valleys. The valleys on volcanoes differ from those in the uplands. They are narrower, being generally less than 300 m across, V-shaped, have higher drainage densities, and have plausibly been attributed to hydrothermal activity (Gulick and Baker, 1989). They may have been able to form under present climatic conditions if fed by warm springs, particularly if they are incised into easily erodible ash deposits, as has been suggested (Mouginis-Mark *et al.*, 1988).

Proposed drainage history

Mars emerged from heavy bombardment with very large surface relief. Much of the southern hemisphere was at an elevation of +3 km or higher and much of the northern plains was at an elevation of −2 km or lower. The planet had a deep impact generated megaregolith which appears to have been nearly saturated with groundwater judging from the sources of subsequent floods at elevations of +1 km and the presence of valley networks at even higher elevations (Fig. 5). A dramatic change in global climates is strongly suggested by the dramatic drop in erosion rates at the end of heavy bombardment. Conditions during heavy bombardment had enabled water to be distributed throughout the megaregolith, irrespective of the surface elevation. It is postulated that during heavy bombardment climatic conditions were warmer than at present and that the conditions enabled global circulation of water. At the end of heavy bombardment the climate changed to one that resembles today's, and this climate persisted for the rest of the planet's history. The drainage features that developed subsequently represent an accommodation of the distribution of the water to these new conditions.

Models of the thermal history of Mars indicate that the heat flow at the end of heavy bombardment was around 150 $mW\,m^{-2}$ as compared with a value for today of 30 $mW\,m^{-2}$ (Schubert *et al.*, 1992). Taking plausible values for the thermal conductivity, Clifford (1993) estimated that the nominal thickness of the cryosphere at the equator today is 2.3 km, so that the thickness at the end of heavy bombardment should have been about 400–500 m for the same climate conditions. But large local variations in thermal conductivity are to be expected so that thickness could have varied substantially about this nominal value.

Most of the surviving valley networks in the uplands likely formed toward the end of heavy bombardment during the period of high erosion rates and when climatic conditions were different from today's. But at the end of heavy bombardment conditions changed dramatically as indicated by the change in erosion rates. The valleys may have continued to form very slowly despite the change in conditions. Immediately after the end of heavy bombardment the presence of liquid water at shallow depths would have facilitated mass wasting. The valleys could have acted an conduits down which mass wasted debris flowed and may have further enlarged themselves slowly by mass wasting. Small-scale floods may also have been common in this early era, thereby contributing to valley formation, but floods of the scale that later occurred did not form because of the thin cryosphere. With time, two processes caused the rate of formation of valley networks to decline. The first was the declining heat flow and the consequent increase in the thickness of the cryosphere which prevented further water-abetted mass wasting. The second was loss of near surface water and ice at low latitudes as a consequence of their instability and sublimation into the atmosphere. At higher latitudes ice remained near the surface, mass wasting continued, although at a low rate, the result being the formation of the fretted channels. At low latitudes valley formation continued only on steep slopes such as crater and canyon walls, and was mainly by mass wasting. Valley formation also continued on volcanoes possibly as a result of surface streams fed by warm springs.

Further thickening of the cryosphere prevented small-scale leakage of water from below the cryosphere to the surface and as a consequence large hydrostatic pressures could build at the base of the cryosphere where the relief and interconnectivity of the aquifer were appropriate. Occasional disruption of the cryosphere in these areas resulted in massive floods. Breakouts were favored in low

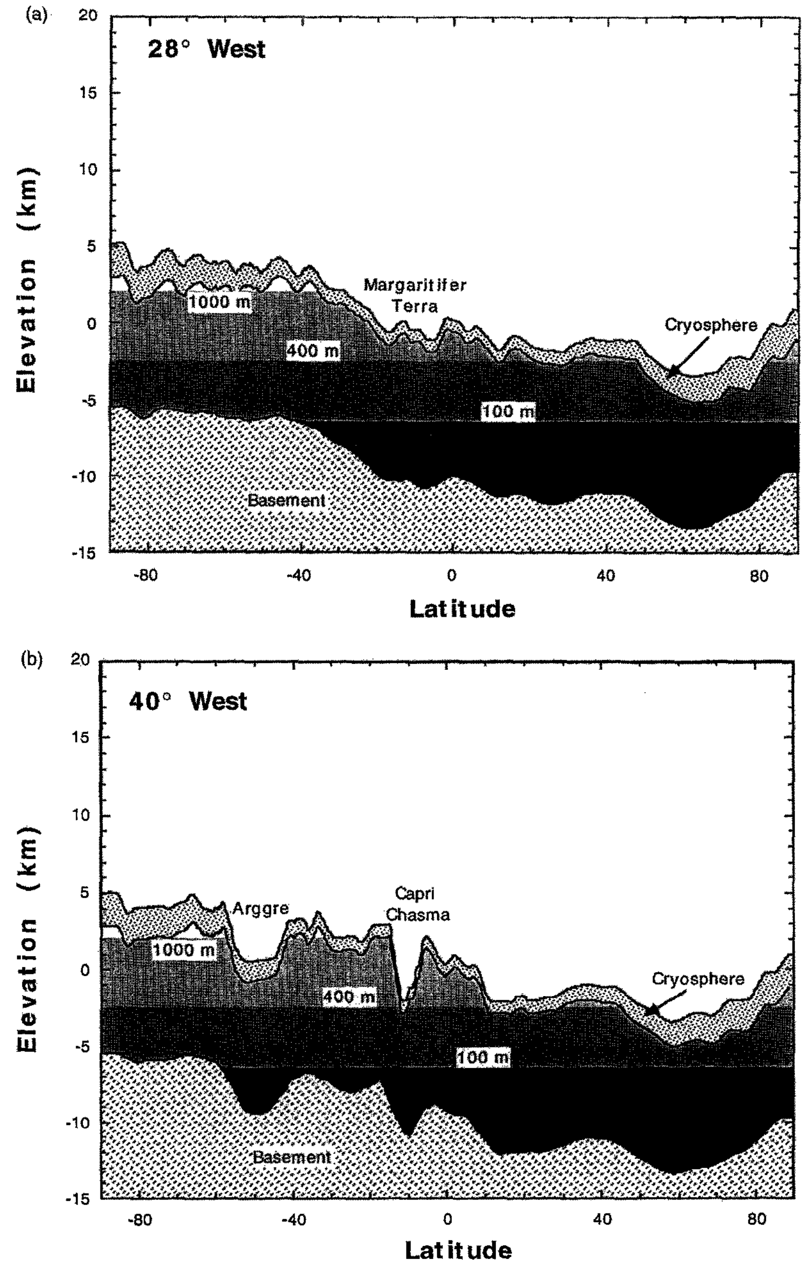

Fig. 5. (a)–(d) North–south profiles through the megaregolith at different longitudes as shown. The basement is where the porosity falls to below 1% according to the model of Clifford (1993). The numbers at different levels show the holding capacity of the megaregolith, expressed in terms of the equivalent depth of water spread over the whole planet. Capacities were calculated assuming a 50% surface porosity and exponential decay with depth. The cryosphere indicates the depth to which the ground is permanently frozen for a heat flow of $90\,mW\,m^{-2}$, roughly that of middle Mars history. Eruption of groundwater from below the cryosphere in places where the cryosphere was thin (low latitudes, volcanoes) caused drawdown of the global aquifer system and transfer of water to low-lying regions

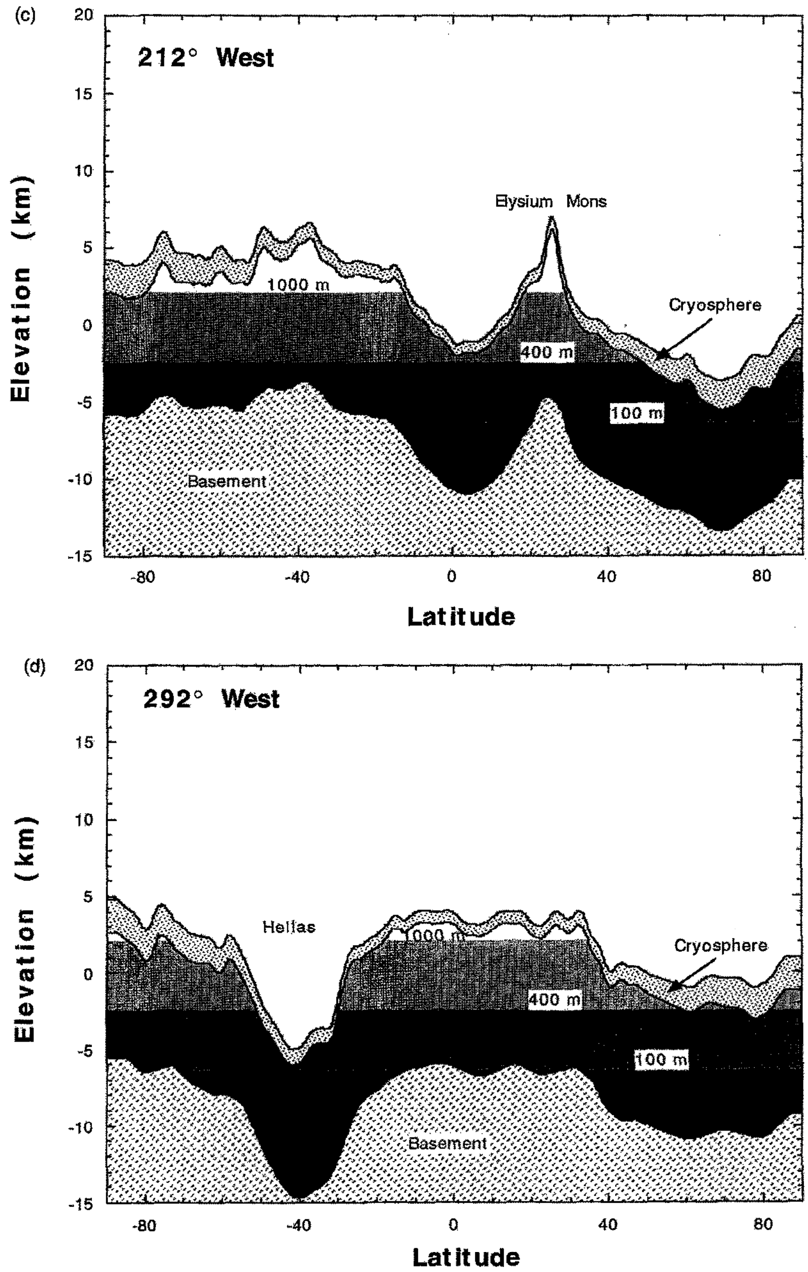

Fig. 5. (*Continued*)

areas where the cryosphere was thinnest, hence the origin of many floods in the low lying, low latitude areas south of Chryse Planitia. Breakouts were also favored near volcanoes such as Hadriaca Patera and Elysium Mons because of the thinner cryosphere in these regions of high heat flow. Meanwhile the canyons were forming by processes that are not understood. The depressions that formed extended well below the cryosphere so were susceptible to being filled with groundwater from the surrounding terrain. Lakes formed in the canyons and thick stacks of sediments accumulated. Some of the lakes may have drained catastrophically to the north and east to form additional flood features.

The fate of the water that passed through the channels is uncertain. Lakes must have formed at the ends of the channels. If the climate was similar to today's then the lakes would have frozen. Most of the outflow channels terminate at high latitudes where ice is permanently stable at depths larger than a few meters, except for extremes of obliquity. If buried below a thin layer of dust, therefore, the lakes would form stable ice deposits. Many of the peculiarities of the low-lying northern plains could be attributed to such deposits (Chapman, 1994; Costard and Kargel, 1995). Lakes that form at low latitudes would sublime over geologic time and the water would ultimately be frozen out at the poles. Part of the water sublimed from low-latitude lakes and that fraction which sublimed from the high latitude lakes may now be locked in the polar layered terrains at the poles. Part may have been lost to space, particularly during periods of high obliquity when sublimation of water from the poles, and hence the water content of the atmosphere, was greatly enhanced (Jakosky, 1990).

Flood events appear to have peaked in late Hesperian.

This could have resulted from two causes. The first is that further thickening of the cryosphere to 2–3 km would have inhibited breakouts. The second and probably more important reason was that the large floods caused a draw-down in the global aquifer system so that hydrostatic pressures could no longer drive water to the surface.

Over the last 3.8 Gyr, therefore the drainage system caused a net transfer of water from the megaregolith in the high standing areas, mostly in the southern hemisphere to low-lying, near surface reservoirs, mostly in the northern hemisphere. Some of the water transferred may still be present as thick ice deposits in the low-lying areas, but much may have been lost to space, particularly during periods of high obliquity.

There are many uncertainties with respect to the scenario just described. To resolve the uncertainties we need to more closely examine the valley networks to see if they are indeed fluvial. We need a better look at the northern plains to assess whether ocean sized bodies of water accumulated there. We need to probe the lowest lying areas at high latitudes to see if ice deposits are present. We should look for weathering horizons that might be indicative of warm post-Noachian climatic conditions. We are now at the start of a period of renewed Mars exploration and prospects are good that some of these observations will be made in the next decade.

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