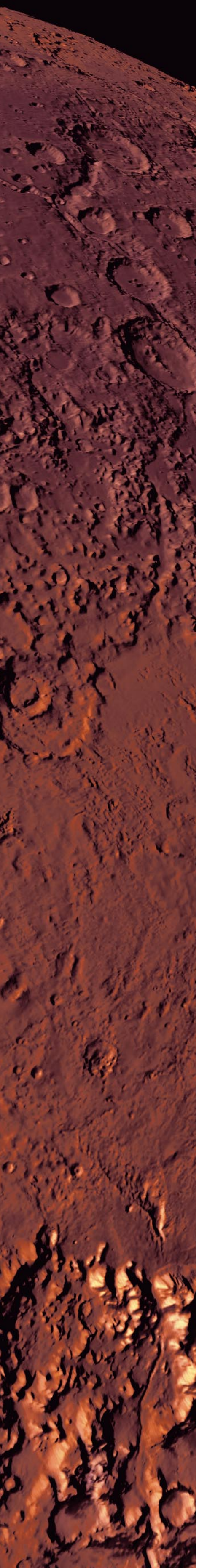

Water and the martian landscape

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Over the past 30 years, the water-generated landforms and landscapes of Mars have been revealed in increasing detail by a succession of spacecraft missions. Recent data from the Mars Global Surveyor mission confirm the view that brief episodes of water-related activity, including glaciation, punctuated the geological history of Mars. The most recent of these episodes seems to have occurred within the past 10 million years. These new results are anomalous in regard to the prevailing view that the martian surface has been continuously extremely cold and dry, much as it is today, for the past 3.9 billion years. Interpretations of the new data are controversial, but explaining the anomalies in a consistent manner leads to potentially fruitful hypotheses for understanding the evolution of Mars in relation to Earth.

When the Mariner 9 spacecraft went into orbit on 14 November 1971, the surface of Mars was shrouded in a global dust storm. Fortunately, by March of 1972, the atmosphere cleared and the true complexity of the Mars landscape was finally revealed to the spacecraft's vidicon cameras. In addition to the immense volcanoes of Tharsis, there was a great equatorial canyon system, Valles Marineris, named for the discovery spacecraft. Most remarkable, however, were sinuous channels and valleys, from whose morphology it was inferred that water had once flowed on the surface of this now dry, unearthly cold planet. The late Harold Masursky, science team leader for the vidicon imaging experiment, wrote in 1973 (ref. 1):

> *The possible fluviatile channels may record episodes when water was much more abundant in the atmosphere than it is at present. Planet-wide warmer interglacial periods would release not only the water locked in the polar caps but also that frozen in the subsurface as permafrost. Similar warmer and colder periods also are characteristic of terrestrial history.*

Although intended primarily as support to landers seeking evidence of martian life, the Viking orbiters of the late 1970s returned 52,603 images of Mars, most of them at much higher resolution than the 7,329 images returned by Mariner 9. The pictures with the highest resolution have a pixel spacing of 7.5 m, although most frames resolve to several tens of metres. Viking orbiter images (Fig. 1) provided the basis for an understanding of water and landscape that prevailed until the past few years[2].

In 1997, the Mars Global Surveyor (MGS) spacecraft was inserted into Mars' orbit, but a variety of problems prevented it from achieving a circular mapping orbit until 19 February 1999. Two instruments are particularly relevant to the scientific study of the Mars landscape. The Mars Orbiter Camera (MOC) achieves a resolution of 1.4 m per pixel, but the required high data volume limits scenes to a kilometre or so in width at the highest resolutions[3]. The Mars Orbiter Laser Altimeter (MOLA) maps the topography of Mars with a precision better than 10 m (ref. 4). Together these instruments provide new data for studying Mars' landforms (Fig. 2), although human reasoning about those landforms remains a matter of long-standing scientific experience.

The study of Earth-like planetary surfaces — geomorphology — is not a disjointed collection of observational facts solely with which to test, or against which to constrain, theoretical models. Rather, such scientific inquiry proceeds from the informed colligation of landform observations to the discovery of consistency and coherence, and, ultimately, to consilience[5] in the theoretical accounting (explanation) of those observations. The key element of this inquiry is the formulation of one or more working hypotheses[6], which are most often suggested (but not proved) by analogies of form and context among landscapes of known origin and those under scrutiny[7]. In the retroductive inferences of geomorphology[8,9], analogy serves merely to suggest fruitful working hypotheses, thereby leading to completely new theories that bind together any newly discovered facts. Mars' landscape provides particularly stimulating opportunities to practise geomorphological reasoning, generating hypotheses that may initially strike some researchers as outrageous[10]. Nevertheless, it is the productive pursuit of such hypotheses that leads ultimately to new understanding, not only of Mars, but also of Earth itself.

The surface of Mars is today extremely cold and dry. The atmosphere at the land surface is over 100 times less dense than that of Earth, and it holds only minuscule amounts of water vapour. For the present obliquity (tilt of the planet's rotational axis with respect to the orbital plane) of 25°, the residual north polar ice cap sublimates water in the northern spring/summer, and the vapour moves to and condenses at south polar areas, a pattern that may reverse in northern autumn/winter[11]. Given its minor role in comparison to that on Earth, it is not surprising that on present-day Mars, water is replaced by wind as the most continuously active surface-modifying process[12].

In stark contrast to the current environment, however, numerous landforms provide signs, or indicators, of extensive past activity of water and ice on the martian surface. From the densities of impact craters on the various terrains it is possible to work out a chronology for this activity, such that Mars is divided stratigraphically into ancient heavily cratered uplands that formed prior to about 3.5 billion years ago (the Noachian epoch), intermediate cratered plains (the Hesperian epoch), and more lightly cratered areas (the Amazonian epoch) (see review in this issue by Zuber, pages 220–227). Water and ice were active on the surface during all these periods. The mode, timing and long-term cycling of water in surficial processes are the phenomena to be considered from the various signs of activity.

Signs of subsurface water and ice

Landforms indicative of ground ice in permafrost (perennially frozen ground) on Mars have been known since the early flyby missions of the 1960s. Images from Viking orbiters provided an overwhelming list of permafrost and ground-

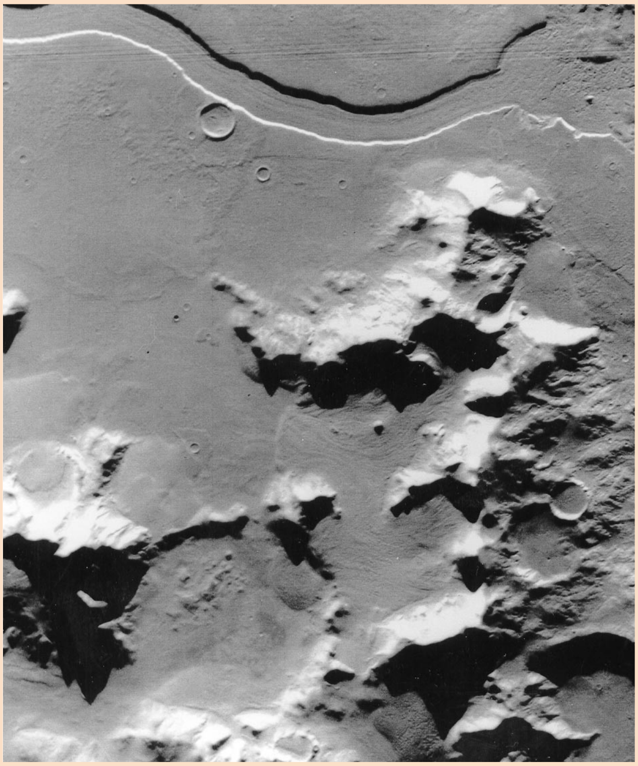


Figure 1 Glaciated terrain east of Hellas Planitia, at latitude 42° S, longitude 252° W. This image from a Viking orbiter mission shows a scene about 180 × 140 km^2. At the top is the lineated valley fill of Reull Vallis, which may be an extant or relict debris-covered glacier about 10 km wide. The uplands at the centre and bottom of the image were eroded to produce forms typical of glacial alpine sculpture[94]. At the base of several uplands are prominent lobate debris aprons. The longest of these, near the centre of the image, extends for 40 or 50 km from the brightly illuminated walls of the sculpted uplands. Prominent flow lineations show that the debris moved by viscous flow, probably facilitated by the plastic deformation of underlying ice. The lack of craters on the flow-lineated surfaces indicates a remarkably recent (possibly continuing) occurrence of the responsible flow processes.

Figure 2 High-resolution Mars Orbiter Camera (MOC) image of a fluvial channel system at latitude 7.9° N, longitude 205.8° W, south of Cerberus Rupes (MOC Image M21-01914). The scene shows an area about 4 km across. A complex of anastomosing channels and streamlined uplands reveals a history of differential fluid erosion of layered bedrock and progressive degradation that produced terrace levels and abandoned spillways. Regularly spaced (about 60-m wavelength) rib-like bedforms are developed transverse to the direction of fluid flow in some of the channels. All these features are best explained by large-scale water flow. The lack of impact craters on the flood-scoured surfaces indicates that this flow occurred very recently in martian geological history. (Image provided courtesy of Malin Space Science Systems.)

ice indicators, including various kinds of patterned ground, thermokarst, hillslope features and mass-movement phenomena[13,14]. Although originally attributed to permafrost processes, the immense polygons, 3–20 km across, of the northern Mars plains are much larger than the contraction-crack polygons typical of terrestrial permafrost terrains. These features are now explained variously as the tectonic uplift of basin floors, perhaps following removal of load from an overlying standing body of water[15], or as the result of Rayleigh convection driven by unstable density or temperature gradients in a catastrophic flood deposit positioned over frozen ground[16]. Recently acquired very high-resolution MOC imagery reveals extensive areas of the northern plains and southern highlands of Mars, notably on crater floors (Fig. 3), where small-scale contraction-crack polygons, tens or hundreds of meters across, cover the landscape[17]. This polygonal terrain, which closely mimics the ice-wedge polygonal terrains of terrestrial permafrost areas, is essentially uncratered, indicating a surprisingly youthful phase of water-related activity on Mars.

Viking pictures revealed that many martian craters have a unique morphology, different from that observed elsewhere in the Solar System. Ejecta surrounding these craters are layered, and each layer has an outer edge terminating in a low ridge or escarpment. Named ‘rampart craters’, the flow-ejecta morphology most likely represents the incorporation of groundwater and ground ice[18], although atmospheric effects on ejecta emplacement may also be important[19]. Thus, layered ejecta morphologies[20] can be used to characterize the past presence of water in various martian terrains[21].

First revealed by Mariner 9, the long and complex volcanic history of Mars contains a wealth of examples of interactions among volcanism, ice and water. Much as in the Pleistocene landscapes of Iceland, martian volcanism has produced features interpreted as table mountains built up on products of sub-ice eruptions, outburst flood channels, and extensive pyroclastic landscapes[22]. Some of the youngest volcanic landscapes occur in the Cerberus Rupes and Marte Vallis region[23], where cataclysmic flood channels[24] and volcanic lava flows[25] occur in close spatial and temporal association. Even Olympus Mons, one of the largest known volcano constructs, has a morphology interpreted by some to be indicative of water/ice volcanic interactions[26]. Its huge aureole deposits, extending 1,000 km, may represent immense submarine landslides[27], similar to those of Earth’s Hawaiian Islands[28].

Signs of surface water

The heavily cratered martian highlands are locally dissected by integrated networks of tributaries with widths of about 10 km or less, and lengths from <5 km to nearly 1,000 km. Drainage densities are generally much lower than for terrestrial valley networks[29], although an interesting set of valleys on martian volcanoes is more similar to terrestrial valleys in their general morphology and degree of terrain dissection[30]. Among the other important morphological attributes of martian valley networks are the following: theatre-like valley heads, prominent structural control, low junction angles, quasi-parallel patterns, hanging valleys, irregular widening and narrowing,

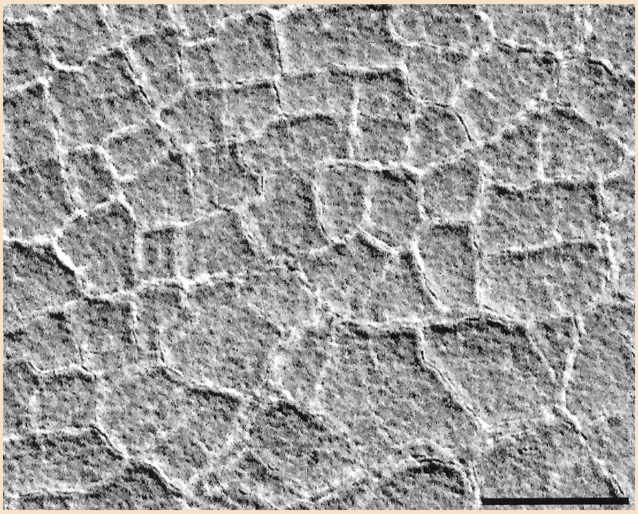


Figure 3 Large contraction-crack polygons developed on the floor of a northern-plains crater at approximately 67.5° N, 312.5° W (MOC Image M01-00294). Note the parallel bright linear ridges or troughs that comprise the boundaries of the polygons. This morphology is typical for terrestrial ice-wedge polygons that develop by the repeated seasonal or episodic melting, freezing and movement of water in the active layer overlying an ice-rich permafrost zone[88]. Scale bar, 200 m.

and indistinct terminal areas[31]. In general, this assemblage of features seems best explained by groundwater sapping processes[32], excellent examples of which occur in the sandstone terrains of the Colorado plateau[33] and in parts of the Hawaiian Islands[34].

Although most of the networks occur in the heavily cratered terrains of Mars[35], as many as 25–35% of the valleys may be Hesperian or Amazonian in age[36]. Moreover, MOC images show that some valleys, which formed early in Mars' history, were later reactivated by smaller flows — a discovery that had been anticipated from Viking data[37]. Another observation, the localized development and incomplete dissection of upland areas by valleys[38], is reinforced by the lack of fine-scale tributaries to valleys observed at MOC resolution[39]. Explanations for such relationships remain contentious, with lack of precipitation as only one of several alternatives, others of which include the probable high infiltration capacities of the martian surfaces[37], the burial of small-scale features beneath mantling deposits, and the local hydrothermal[40] and/or snowmelt processes[32].

Many valley networks have orientations consistent with the effects of surface deformation by extensive volcanic loading at Tharsis, inferred to have occurred by late Noachian time[41]. These networks occur in heavily cratered terrains that show evidence of extensive erosion during the Noachian[42,43]. The average rates for this presumed water erosion are estimated at 10^2–10^4 mm per 10^6 years, which are comparable to the lower range of terrestrial values. But post-Noachian rates are estimated at only 10^{-1}–10^{-2} mm per 10^6 years (ref. 44). This discrepancy led some researchers to postulate an epoch of late Noachian climate conducive to water erosion, followed by post-Noachian conditions that precluded such erosion[2,45]. However, if post-Noachian aqueous erosion episodes are limited to very short episodes[46], then the average post-Noachian erosion will yield the same rate as calculated.

The term 'channel' is properly restricted to one class of martian trough-like landforms that display at least some evidence for large-scale fluid flow on their floors. The principal landform of interest here is the outflow channel, which shows evidence of flows emanating from zones of regional collapse known as 'chaotic terrain'. The martian outflow channels are immense (Fig. 4), as much as 150 km wide and 2,000 km in length. It was recognized shortly after their discovery that they possessed a suite of bedforms and morphological relationships similar to what is exhibited in the 'Channeled Scabland'[47], a terrestrial landscape created by Pleistocene glacial-related cataclysmic flooding in the northwestern coterminous United States[48].

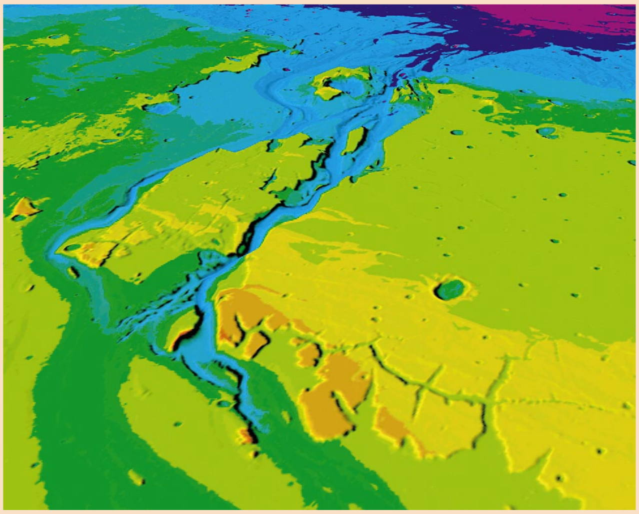


Figure 4 Oblique view of topographic data from the Mars Orbiter Laser Altimeter (MOLA) showing downstream portions of the outflow channel Kasei Vallis. The channelled area extends about 2,000 km from Echus Chasma, which lies to the south (bottom) of the image shown here. Flows in Kasei Vallis extended over a width of about 150 km (bottom of the image) before they turned right (east), as shown at the left centre of the scene. Note the deeply incised sinuous channels and prominent streamlining and scouring of residual uplands (top centre of the image). The northern (left) channel of this incised zone is about 50 km wide, and it is also illustrated by the simplified cross-section at the top of Fig. 5. Elevation is indicated by the colours, progressing from dark blue at –4,000 m, to dark green at about –1,000 m, to dark orange at +2,000 m. (Image produced by T. M. Hare, US Geological Survey, Flagstaff, Arizona.)

At their largest scale, the outflow channels are broadly anastomosing and split by residual uplands, or 'islands', of pre-flood-modified terrain (Fig. 2). The channels have low sinuosity and high width–depth ratios. Pronounced flow expansions and constrictions occur, as do prominent divide crossings, hanging valleys and structural control of erosion. At a finer scale, streamlining of the residual uplands is very well developed, as are longitudinal grooves, inner channels, cataract complexes, scabland and bar complexes. Although a variety of other fluid-flow systems have been invoked to explain these features, the whole assemblage of these landforms is best explained by cataclysmic flood processes, with particular analogy to the origin of the Channeled Scabland[31,49]. Nevertheless, it is also recognized that some important differences derive from the peculiar martian environment, notably its lower gravitational acceleration, its much lower atmospheric pressure and its prevailing subfreezing temperature in comparison to Earth. These special conditions on Mars would influence such factors as sediment transport mechanics[50], cavitation and ice formation[51], debris flow[52] and possible large-scale ice processes in the channels[53].

The sizes of martian outflow channels imply immense discharges of water, exceeding any known flood flows on Earth (Fig. 5). The calculated peak-flow magnitudes are comparable to those of the high-discharge western boundary currents of Earth's world ocean, such as the Gulf Stream, the Kuroshio and the Agulhas[54]. These currents are integral to Earth's climate system, distributing heat poleward from equatorial latitudes. Major disruption of Earth's circulation pattern provides an endogenetic model for large-scale terrestrial climate change[55]. By analogy, Mars' climate could have been impacted by the megaflood discharges transferring water and heat from the equatorial Tharsis volcanic province to the northern plains of the planet[46].

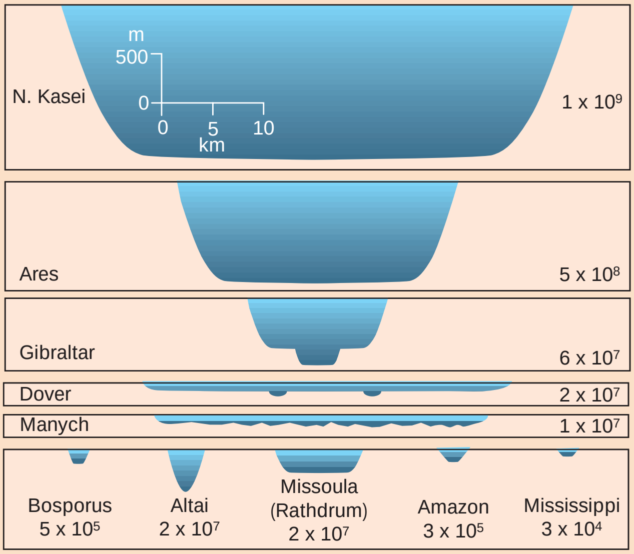


Figure 5 Comparison of simplified channel cross-sections for cataclysmic flood channels on Mars (upper two channels) and Earth (lower channels). Peak discharges are indicated in cubic metres per second. Gibraltar, Dover and Bosporus are straits that were inundated by flows that spilled between marine basins. Manych, Altai and Missoula (Rathdrum) are associated with glacial meltwater floods that developed at the end of the last ice age. The two modern rivers, Amazon and Mississippi, are dwarfed by the ancient flood channels. More detail on the floods associated with these channels is provided by Baker[54].

Outflow activity was probably initiated in the Noachian[56], and outflow events occurred during the early Hesperian[57], the late Hesperian/early Amazonian[58,59] and, surprisingly, during the past 10 million years[23]. The latter floods occurred in the Marte Vallis/Cerberus Rupes region[60] and the Tharsis area[61]. Thus, principal fluvial events (and possibly associated climate change) occurred right up to most recent martian history. Alternatively, however, outflow channel events are considered to be random outbursts from a progressively thickening cryosphere[62].

Integral to the controversy over post-Noachian water-related climate change on Mars is the lack of understanding of how such immense discharges can be released from the martian subsurface. The role of the cryosphere seems important, perhaps for generating pressurized aquifer confinement[63]. Dike emplacement and penetration of the ice-rich cryosphere[64], pressurized volcanic influences on fracture systems[65] and decompression of gas hydrates deep in the crust[66,67] are other possible factors in the cataclysmic release of outburst floods.

The largest outflow channels delivered their immense discharges to the northern plains of Mars. Evidence of temporary inundation of the northern plains was recognized on the basis of Viking data[40,68–70], and some aspects of the inundation hypothesis are consistent with new results from the MOLA instrument[71]. These include the extreme topographic smoothness of the northern plains, the apparent burial of wrinkle ridges, correlation of basin topography with landforms of likely aqueous origin, gradation of outflow-channel floors to ancient inundation levels, consistency of inundation volumes with possible Mars water balances, and some correspondence of one of the possible shoreline levels to a deformed ancient equipotential surface[71]. However, landforms interpreted as diagnostic of shoreline processes[72] are not confirmed by detailed study of MOC imagery[73]. Named 'Oceanus Borealis'[46], the northern-plains inundation remains controversial as to its size, age (or ages), persistence and episodic formation. Other interpretations of the northern-plains inundation include the emplacement of massive debris flows[74], effects of glaciation[75] and a complex layering of both ice- and water-laid deposits[76].

Figure 6 MOC image (M09-04718) of small gullies and other hillslope features in the central peak area of Hale Crater (latitude 36° S, longitude 37° W). Scale bar, 200 m.

Evidence for past lakes abounds in numerous impact craters on Mars[77]. Most of the lakes formed in the Upper Hesperian and Lower Amazonian[78]. Lacustrine terraces and Gilbert-type deltas indicate that the lakes must have persisted for 10^3 to 10^4 years (ref. 79). Standing water in lakes for such timescales requires a major change in climate from present-day conditions, although ice-covered lakes could persist for considerable time at current conditions or for those associated with the range of variation in Mars' orbital parameters[80]. The relationships at the Gale Crater palaeolake are particularly interesting because of extensive work[81,82] indicating a relatively young age. However, the first interpretation of MOC images claimed that the Gale Crater deposits and all martian lake deposits were Noachian in age[83]. This ancient age designation was even applied to extensive sedimentary deposits in the Valles Marineris, an interpretation that has been strongly challenged following public release of the images[84,85]. Ironically, the claim of a Noachian age for the deposits requires their extensive exhumation late in martian history in order to account for the lack of impact craters on the exposed surfaces. Such a presumed erosion event would require even more extreme martian climate change than would the aqueous emplacement of the deposits that many investigators originally associated with post-Noachian lacustrine activity[77,79–81]. This important scientific controversy continues.

Perhaps the most striking discoveries made from MOC images are the very young, relatively small-scale debris-flow gullies (Fig. 6), initially explained as the result of groundwater seepage and subsequent surface runoff[86]. The gullies have morphologies essentially identical to those that are common on terrestrial hillslopes in periglacial environments[87], such as coastal Greenland, Iceland, Svalbad and arctic

Canada. On Earth, initiation of debris flow occurs when soil water saturation follows surface melting of snow cover or ground ice[88]. Remarkably, the Mars gullies generated debris-flow deposits that are superimposed on aeolian bedforms and on small-scale contraction-crack polygons[86], all of which are uncratered. Thus, the various age indicators show the gullies and debris flows to be extremely young, probably active within the past several million years of Mars' history.

The profound implications of a recent Earth-like origin for the young gullies led some researchers to seek alternative mechanisms that might generate debris flows on Mars. Ideally, the modelled processes should be able to occur in the current cold, dry environment. For example, the existence of CO_2 vapour-supported debris flows might, in theory, permit build-up of a liquid-CO_2 aquifer behind a near-surface dry-ice barrier that is subsequently breached by heating[89]. In one extreme scenario, Mars is hypothesized as both currently being and always having been an extreme cryogenic world in which water behaves largely as a solid mineral, and nearly all manifestations of fluid-flow phenomena involve CO_2 gas or liquid[90]. This 'white Mars' model postulates a history of mean temperatures continuously lower than those prevailing today.

Signs of glacial ice

Given that periglacial landscapes on Earth involve warmer climatic conditions than do glacial landscapes[91] (Fig. 7), it is interesting that glacial interpretations of martian landforms have generally been more controversial than have periglacial interpretations. A strong case was made for the contribution of glacial processes to the origin of landforms associated with certain outflow channels[92], and both glacial and flood outflow processes can operate together or sequentially in large-scale channel morphogenesis[93]. Nevertheless, the scale of the presumed climate changes occurring late in Mars' history that would have been necessary to account for glaciation led many researchers to express extreme scepticism in regard to any glacial interpretation[2].

The most intricate assemblages of glacial landforms are hypothesized to explain landscapes in the mountainous uplands adjacent to the Argyre and Hellas impact basins[94]. Local alpine glacial sculpture in the Charítum Montes, south of Argyre at latitude 57° S, includes cirques, horns, aretes, grooves and V-shaped valley troughs. Many of the cirques and troughs seem to be occupied by extant or relict rock glaciers or debris-covered glaciers (see discussion below). The adjacent floor of Argyre Planitia has landforms that can be interpreted as moraines, drumlins, esker-like ridges, kettles, outwash plains and glaciolacustrine plains[94].

The esker-like ridges (Fig. 8), which are 10–200 km long, have proven to be a source of lively controversy at professional meetings. Taken as individual landforms, these sinuous ridges have been variously explained as sand dunes, inverted stream valley fills, igneous or clastic dikes, lake beach ridges, mudflow levees and the wrinkle ridges generated by deep-seated faults. MOC images of the Argyre Planitia sinuous ridges (Fig. 9) reveal apparent sedimentary strata, boulders and discontinuous ridges, with heights of 10–100 m, and widths of 200–2,000 m. Together with the associated glacial landforms, the esker interpretation seems to provide a consistent hypothesis explaining all relevant observations.

Even more prominent esker-like ridges are associated with the Hesperian-aged Dorsa Argentea Formation at latitudes 75–80° S. Numerous morphological similarities show these ridges to be similar to terrestrial eskers[95]. The eskers seem to have been produced by the meltback of ice-rich deposits, perhaps deriving from an extensive south polar ice cap in the middle (Hesperian) portion of Mars' history[96]. The drainage from this ice cap was carried through prominent valleys to the Argyre impact basin, where it constituted a temporary lake.

MOC images of lineated valley fills in the northern fretted terrain and valleys draining to Hellas, plus images of the lobate debris aprons in uplands near Hellas (Fig. 1) and Argyre, show features interpreted to represent very recent glacial flow. These include crevasse-like fracture concentrations and medial moraines displaying glacier-like patterns of tributary convergence and downvalley flow. The surfaces of the lineated valley fills and lobate debris aprons are uncratered, indicating likely emplacement within the past several million years. MOLA profiles of lobate debris aprons in Deuteronilus Mensae (latitude 40° N) and Protonilus Mensae (latitude 46° N) reveal shapes best explained by solid-state deformation of ice hundreds of metres thick[97]. However, at current Mars surface temperatures and very low accumulation rates (<1 cm yr^{-1}), flow rates for these large ice masses would be so slow[98] that they could not be produced on the timescale of 10^6–10^7 years implied by their uncratered surfaces. Because the hypothesized glaciers are associated with outwash and other water-drainage landforms[94], higher past temperatures are implied, and these could achieve Earth-like strain rates in the deforming ice.

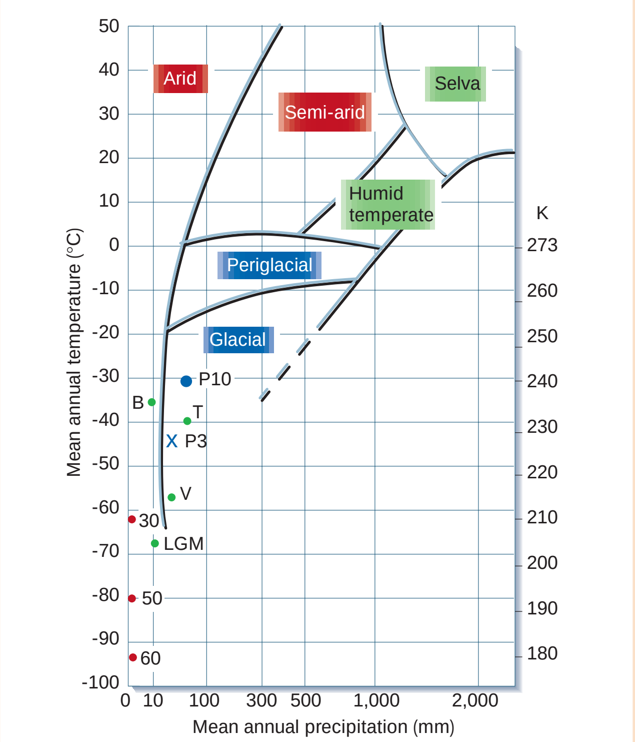


Figure 7 Morphogenetic regions for climate-related landforms on Earth[91]. Note the expanded precipitation scale at lower values. Modern terrestrial glacial environments include Taylor Dome (T) and Vostok (V) in Antarctica. Beacon Valley (B) occurs in the cold-arid, nonglaciated Dry Valley region of Antarctica. Conditions inferred from the last glacial maximum (LGM) in Antarctica were most similar to those of modern middle latitudes on Mars (30, 50 and 60 are the Mars conditions at the indicated latitudes). Modelled conditions[118] for ancient Mars at 300 mbar (300 hPa) atmospheric pressure (P3) and 1,000 mbar (P10) could have been comparable to the cold glacial conditions on modern Earth.

One school of glacial geomorphological thought holds that a continuum exists on Earth from true glaciers to debris-covered glaciers, and then to remobilized talus or till[99]. The last phenomena would certainly be classed as rock glaciers, which another geomorphological school holds strictly to be permafrost phenomena[100]. The prevailing hypothesis for the Mars lineated valley fills and lobate debris aprons follows the permafrost theory in its claim that deformation is achieved in ground ice that cements slope-derived debris[101]. In contrast, following the continuum theory, one can hypothesize that recently active, true martian glaciers carved the V-shaped troughs, cirques, aretes and other landforms of local highland terrains. These ancient glaciers would have had large accumulation areas, requiring atmospheric transport of water to the site and a net surplus of input from snow to offset losses by sublimation and meltwater runoff.

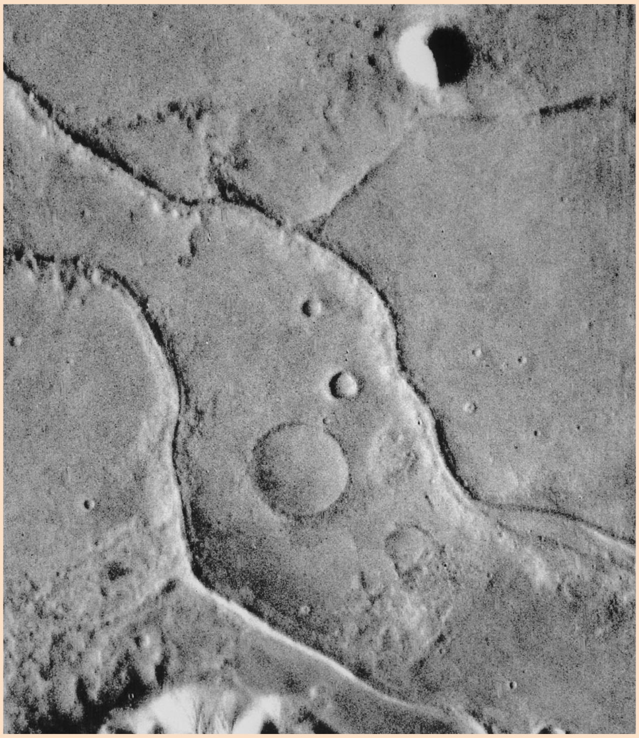


Figure 8 Esker-like ridges in southern Argyre Planitia (latitude 56° S, longitude 40° W). This Viking orbiter image (567B33) shows a scene about 50 km across. The ridges are sharp-crested and about 1,000 m in width.

Figure 9 Portion of MOC Image MOO-01511 showing detail of esker-like ridge in southern Argyre Planitia (Fig. 8). This image shows a scene about 3 km in width.

When climate shifted to more adverse conditions, such that input of snow no longer exceeded losses, the glaciers wasted back. But debris accumulating on the now extensive ablation zone would have greatly reduced sublimation loss. Moreover, if temperatures also fell, meltwater loss would cease. The resulting debris-covered glacier might still have had a very small accumulation zone at its head, and this could sustain continued flow of ice at very slow rates, as observed in rock glaciers on Earth[102].

For the extremely cold conditions that currently prevail on Mars, debris-covered ice would have sublimation rates as low as 10^{-5} cm yr^{-1} (ref. 103). Thus, even very small accumulation rates over small areas might sustain a positive net mass balance, although flow rates would be extremely slow in a glacier at a mean annual temperature of –75 °C (the current condition on Mars at about 45° latitude). Of course, present water precipitation at this latitude is effectively zero, and water condensation occurs today primarily at near-polar latitudes.

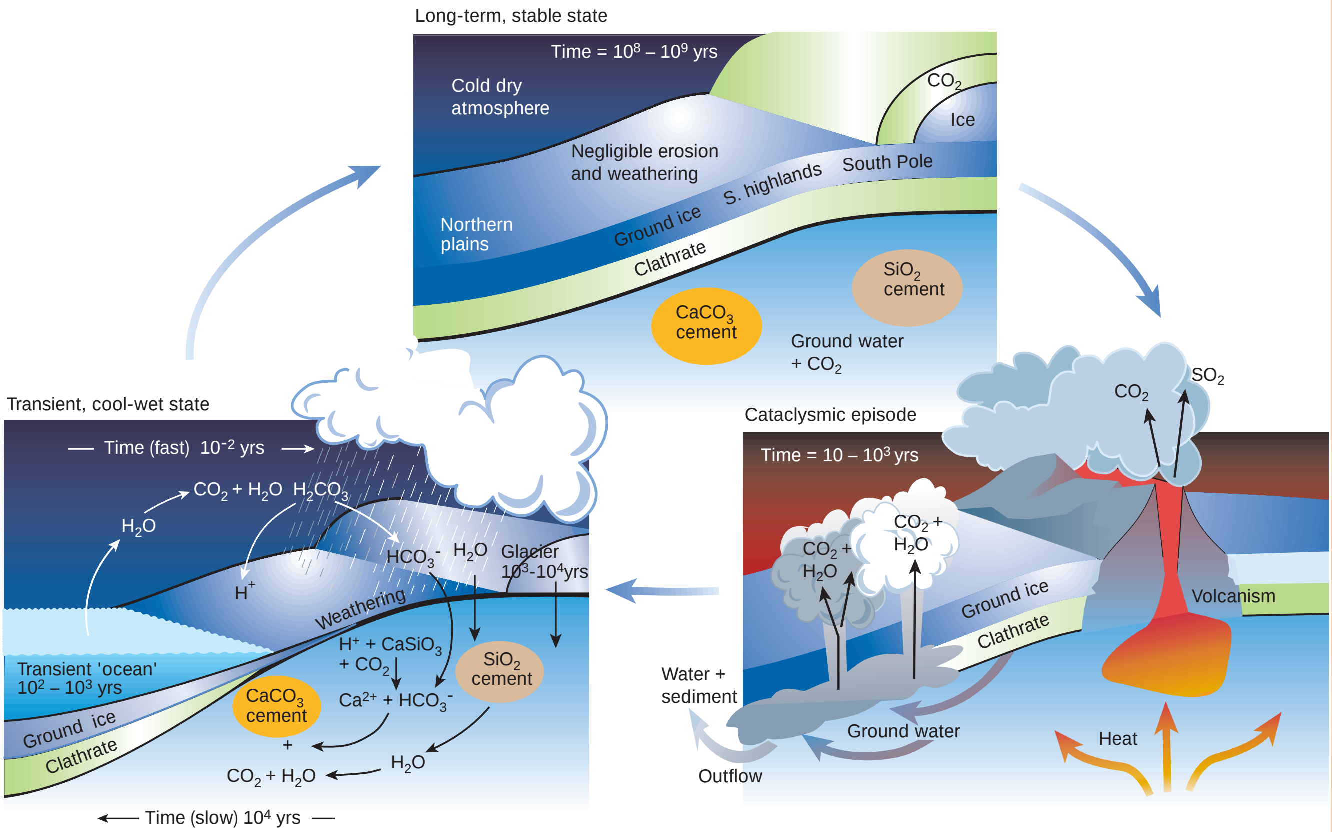
The current mean annual temperature at Vostock on the East Antarctic Ice Sheet is –57 °C, and the accumulation rate is only 2 cm yr^{-1}. During the Last Glacial Maximum, ice-core data indicate that mean annual temperatures may have been as much as 20 °C colder, and accumulation rates may have been less than 1 cm yr^{-1} (ref. 104). These conditions are very close to those on Mars today (Fig. 7), although Earth atmospheric pressures are, of course, much higher. In Beacon Valley, part of the Dry Valley region of Antarctica, precipitation is currently less than 1 cm yr^{-1} water equivalent, and the mean annual temperature is –35 °C. The area is ice-free, but relict glacial ice occurs beneath a 0.5-m debris cover that is dated at 8.1 million years (Myr) old[105]. The indicated sublimation rate is 10^{-5} cm yr^{-1}, the same rate noted above for debris-covered ice on Mars. With present-day conditions on Mars so close to those in parts of Antarctica (Fig. 7), it is reasonable to invoke a climate-change scenario to explain the observed glacial phenomena.

Temperatures achieved during the Last Glacial Maximum are representative only of Earth's most recent glacial epoch, the Late Cenozoic. Earlier periods of prolonged, extensive glaciations (megaglaciations) of Earth occurred in the Late Palaeozoic (~260–340 Myr ago), Late Devonian/Early Carboniferous (~350–360 Myr ago), Ordovician/Silurian (~430–450 Myr ago), Late Proterozoic (~500–900 Myr ago), Early Proterozoic (about 2,200–2,400 Myr ago) and Archaean (~2,910–2,990 Myr ago)[106]. The Late Proterozoic glaciation is particularly enigmatic, as there is evidence that Earth may have switched into Mars-like icehouse conditions by freezing the surface of the global ocean[107]. The extreme glaciation is explained alternatively as a result of a huge change in planetary obliquity[108] or as a runaway cooling that terminates cataclysmically with a super-greenhouse build-up caused by volcanism[109]. The rapid melting of ice and weathering of the land surface lead to carbonate precipitation in the ocean, thereby terminating the super-greenhouse.

The glacial epochs of Earth are explained by two classes of theoretical models: external and internal. External causes include the orbital parameters, axial tilt (obliquity), precession and eccentricity, all of which acted as the 'pacemaker' of Pleistocene glaciations[110]. Internal causes include the role of conveyor-belt oceanic circulation[55] and the arrangement of continental relief on the planet[111]. For Mars, it is possible to imagine an internal scenario capable of explaining the diverse observations summarized in this paper (see Box 1), although there have been many objections raised to an earlier version of this model[2]. Alternatively, the complex variability of Mars' obliquity over long timescales[112,113] may be able to mobilize water[114] in ways that will explain relatively recent manifestations of glacial action, lakes, fluvial gullies and the melting of near-surface ground ice.

Is it possible, as a theoretical matter of pure physics, that the numerous martian landscapes, temporal associations of landforms, and proximal-to-distal relationships — all analogous to water-generated process-form relationships on Earth — could have been produced by a fluid that mimics the behaviour of water? For appropriate relationships with temperature and pressure, CO_2 is a possible candidate for achieving the necessary physical behaviour[90]. Moreover, the CO_2 hypothesis is parsimonious in the sense of being

Box 1
Cyclic and episodic change on Mars



A genetic model, presented in an early form in 1991 (ref. 46), predicts both long-term (10^8–10^9 years) and short-term (10^3–10^4 years) aspects of a global martian hydrological cycle (see figure above). The episodic inundation of the northern plains of Mars is one component of the short-term portion of the cycle. The hypothesis explains the phenomenally long epochs of post-heavy-bombardment time during which the Mars surface clearly had extremely cold and dry conditions similar to those prevailing today. The alteration of this prevailing condition with quasi-stable, short-duration warmer (cool) and wetter conditions explains many young landforms that require such conditions, including glaciated terrain, crater lakes, melting of permafrost, and other water-related landforms that occur throughout Mars' history.

Internal planetary heat could have provided the trigger for the massive outflows that transformed martian climate during the geologically short epochs of climatic change. Superimposed on the long-term monotonic decline in mantle heat flux for Mars, one can predict short episodes of higher heat flux to the surface. These episodes of higher heat flow seem consistent with the magmatic and tectonic history of Mars[119].

The huge floods would have acted to initiate climate change through release of CO_2, leading to greenhouse warming[120]. During the short-duration thermal episodes of cataclysmic outflow, a temporary cool-wet climate would prevail. Water that evaporated off a transient 'ocean' would be transferred to uplands, including the Tharsis volcanoes and portions of the southern highlands, where precipitation as snow would promote the growth of glaciers. However, such a cool-wet climate is inherently unstable for Mars. Water from the evaporating ocean would be lost to storage in highland glaciers, and through infiltration into the porous lithologies of the martian surface. This would lead to the demise of warm conditions owing to the progressive loss of CO_2 through dissolved gas in infiltrating acidic water, and through silicate weathering carrying bicarbonate into the subsurface by infiltration. Subsequent underground carbonate deposition would then release CO_2 to the groundwater, which would become trapped beneath an ice-cemented permafrost zone. The latter develops as the greenhouse effect declines, because of atmospheric loss of water and CO_2 over a timescale of 10^3–10^5 years. Concurrent decline in planetary heat flow, following the triggering peak episode, would lead to a downward extending permafrost zone that would progressively incorporate the recharging water and groundwater. As the permafrost extended downward into the stability field for CO_2 clathrate, this gas hydrate would accumulate above the gas-charged groundwater. Thus, the underground sequestering of clathrate, gas-charged groundwater and carbonate cements comprise the long-term reservoir for carbon on Mars. Only occasionally, and for relatively short duration, does carbon get transferred to the atmosphere, as greenhouse-promoting CO_2, during cataclysmic ocean-forming episodes triggered by pulses of high heat flow. The whole process would be cyclic as illustrated in the diagrams.

capable of generating flow phenomena for the current near-surface environment of Mars. If Mars, unlike Earth, were not perturbed over geological time by major epochs of climate change, then a perpetual 'white Mars' might well occur. Nevertheless, it would be remarkable that this white Mars landscape evolved locally to generate surprisingly detailed copies of what on Earth is readily produced by the long-term action of water and ice. It is also a measure of simplicity in a hypothesis that the most natural explanation, in this case an aqueous origin, tends to accord with greater consistency to the observed phenomena.

In choosing to explore the consequences of a water-based explanation for Mars' geomorphology, and the associated implications for both ancient and very recent climate change, one is not assured of easily testable hypotheses. The extensive hydrosphere implied by past aqueous activity on Mars may only be extant as ground ice in the thick permafrost zone and as underlying groundwater. Yet, this is the type of environment in which the extremophile progenitors of Earth's biosphere probably evolved[115]. Indeed, early Mars provided an arguably better habitat for the inception and incubation of early life than did early Earth[116]. Episodic, brief episodes of aqueous activity on the martian surface may have exposed this biosphere to produce possible fossil indicators of its existence. More speculatively, a deep subsurface biosphere containing methanogenic archaea could have produced methane that accumulated beneath a growing martian cryosphere. The result could destabilize the martian cryosphere (see Box 1) and perhaps change the climate on short timescales[117].

Ultimately in geomorphological investigation, one chooses the working hypothesis that is most fruitful with regard to connection to other lines of scientific inquiry, while still providing consistency and coherence in explaining the whole complex of available observations. The water-generated landforms and landscapes of Mars have proven especially difficult to unite under a single working hypothesis. Nevertheless, whatever explanation one chooses as a working hypothesis, its roots in the complex detail of Mars' landscape features ensure that it will provide a highly probable basis for further productive inquiry.

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