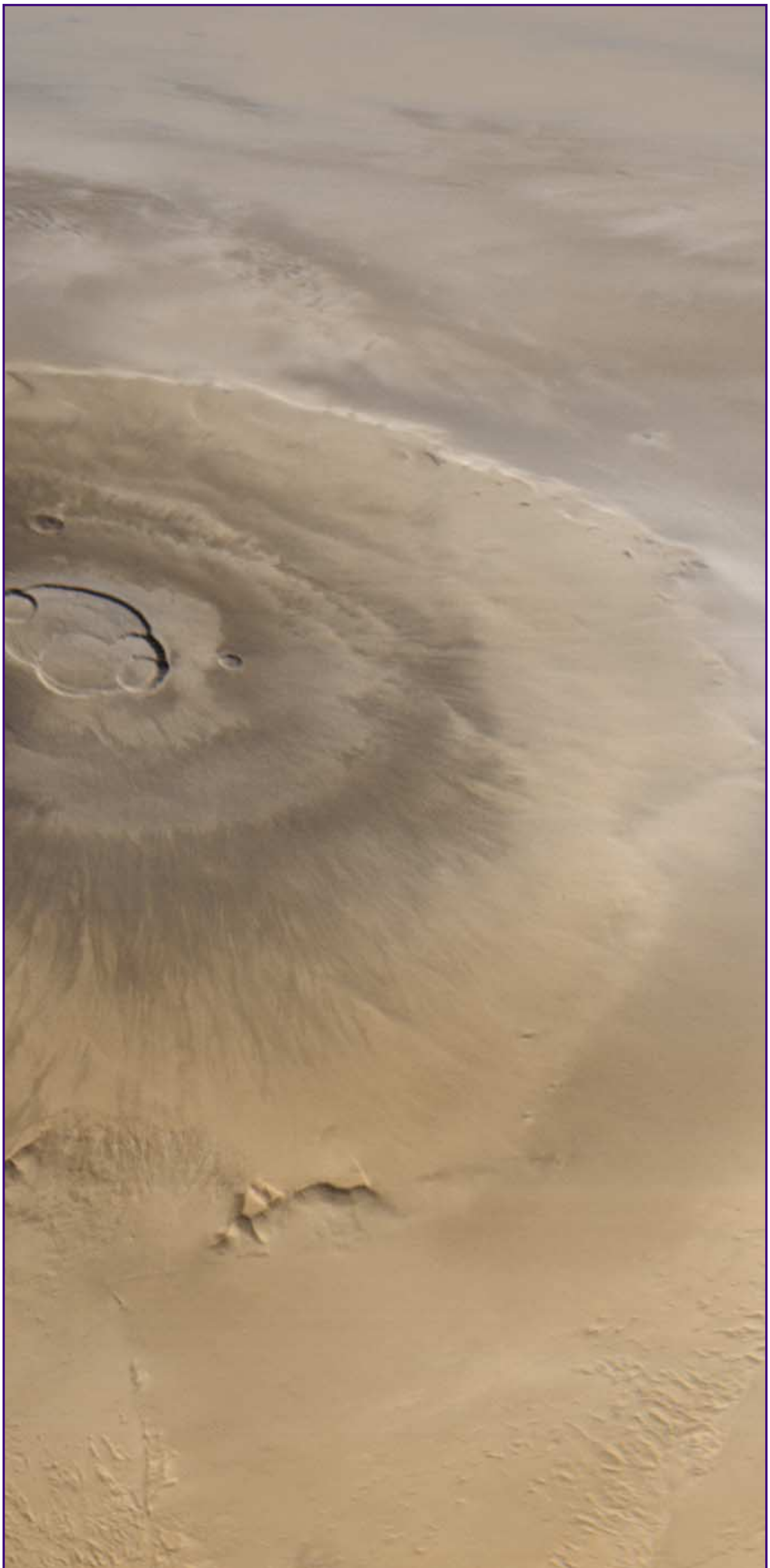


1: Mars Global Surveyor Mars Orbiter Camera wide-angle synthesized colour view of Olympus Mons in April 1998. North is to the left, east is up. Olympus Mons is the largest volcano in the solar system, with a summit height of 24 km above the surrounding plain, a basal diameter of 550 km. It is rimmed by a 6 km high scarp of debatable origin. (Source: Malin Space Science Systems/NASA)

Mars: a

Karl L Mitchell and **Lionel Wilson** summarize the case for martian geological activity in recent times.

Abstract

Recent and continuing missions to Mars are showing that the Red Planet may be more geologically active than previously thought. Volcanoes and erosion by running water have shaped the surface. And evidence is growing that fluvial and possibly volcanic processes have been active in the very recent past.

This is an extremely exciting time for everyone interested in the planet Mars. Several spacecraft are either in orbit around Mars, or are on their way to the Red Planet. Much of the interest is driven by the tempting prospect of finding evidence for some kind of living organism on Mars, either now or in the distant past. Yet we are also rapidly realizing that, of all the bodies in the solar system, Mars is the one with geological processes most closely analogous to those on Earth. Even before Mars Global Surveyor (MGS) arrived in 1997, heralding the current spate of missions, we understood from the Viking missions of the 1970s that Mars must have had an interesting history of volcanic activity, and that many of the giant valley systems suggested that copious water flowed on the planet's surface at some time in its history. But the data from MGS and, even more impressively, the recent findings from Mars Odyssey, are showing us that these processes may have been more widespread, and may have occurred much more recently in martian history, than we would have thought possible just a few years ago.

Dating the martian surface

Geologists use stratigraphic mapping to understand the evolution of planetary surfaces. This is based upon the principle of superposition (Shoemaker *et al.* 1962), which states that a surface layer must be younger than any surface unit that lies underneath it. The method has limitations because it can be used to derive only relative ages. In order for this information to be useful for absolute dating, planetary geologists need absolute age markers. On Earth this usually means radiometric dating. Without a sample return mission, our only useful direct data

geologically active planet

from Mars are the limited number of martian meteorites, i.e. the SNC meteorites. Unfortunately, the geographical origin of the SNCs on Mars is unknown, so their use is limited. Nevertheless, analysis of some of the youngest martian meteorites indicate that there may have been volcanic eruptions within the last 100–200 Ma (McSween 1994, Nyquist *et al.* 2001), which provides a starting point for dating the volcanic activity.

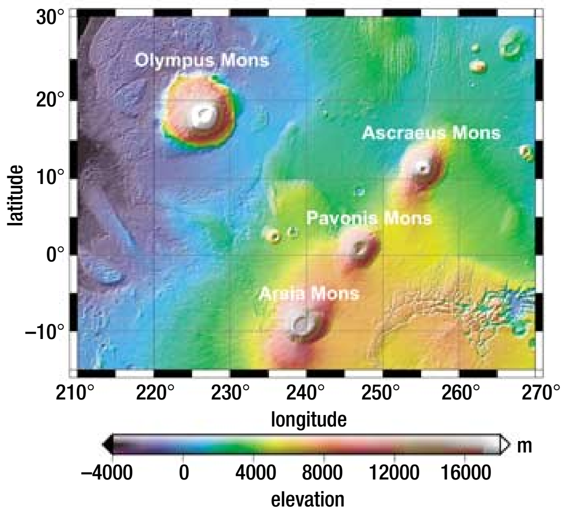
Given these limitations, a method for absolute quantitative ageing of planetary surfaces has been devised, which involves counting the numbers of impact craters that have formed on them (see the article "Crater counting" on page 4.21). Crater counting as a method of absolute dating is problematic at best, because it depends upon a precise model for the impact record of the planet. There has been significant disagreement about this in the literature (e.g. Neukum and Hiller 1981, Hartmann 1999), and despite attempts to reach a consensus (Hartmann and Neukum 2001, Neukum *et al.* 2001), differences between models remain significant (Berman and Hartmann 2002). Derived ages are extremely sensitive to slight statistical variations so crater counts must be performed manually: machine vision methods for detecting craters, although encouraging (e.g. Kim and Muller 2003), are yet to have been established as an operational alternative. In addition, the presence of secondary craters also affects the statistics, but our ability to distinguish them from primary craters is limited, and no definitive statistical method has been devised to deal with this problem.

Despite these problems, it is clear that on some parts of Mars, especially in the southern hemisphere, we are seeing surfaces that were formed at the end of the period of heavy bombardment marking the last stages of planetary accretion. Elsewhere, large areas appear to have been resurfaced no more than a few hundred million years ago. Whether we should expect to see such recent geological activity on Mars is a matter of debate fuelled by uncertainties in the way the internal temperature distribution has changed over time, reinvigorated by the very recent discovery that the core of Mars is almost certainly still partially molten (Yoder *et al.* 2003).

Volcanism on Mars

Mars has several types of volcano, but the largest are the giant shields, such as Olympus Mons (figure 1). Shield volcanoes on the Earth form over locations in the mantle where the heat flow is unusually high and large amounts of magma (molten rock) are produced. The Earth's lithosphere consists of a series of rigid plates, which move relative to the asthenosphere below. As a result, continuing but slightly fluctuating activity in the mantle can produce chains of volcanoes on the surface – the best known of which is the Hawaiian island chain.

On Mars there has been no large-scale movement of the lithosphere in this way, at least during recent geological time, and so large volumes of volcanic rocks have accumulated in a few locations. Recent work on the patterns of thermal convection expected in the mantle of a planet the size of Mars (Schott *et al.* 2001) implies that there are most likely to be two major areas of magma production. This is in good agreement with the observation that two areas of Mars have been very volcanically active through the latter part of the planet's history. One of these, called Tharsis (figure 2), contains five major volcanoes: Ascraeus Mons, Pavonis Mons and Arsia Mons are aligned along a broad dome of crust, with Olympus Mons to the north-west and the much older Syria Planum to the south-east. The other major volcanic area, Elysium, contains the volcanoes Elysium Mons, Hecates Tholus and Albor Tholus.



2: Mars Orbital Laser Altimeter topographic map of Tharsis region, with major shield volcanoes labelled, in planetocentric co-ordinates. (Karl Mitchell, from MOLA IEGDR gridded data product, courtesy of NASA/Goddard Space Flight Center; GMT software)

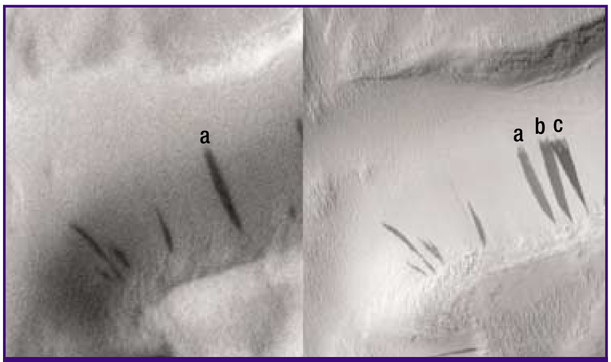
The four largest martian shield volcanoes are all more than four times as wide and twice as high as the biggest such feature on Earth, Mauna Loa in Hawaii. Despite the differences in scale, all of the shield volcanoes on Earth and Mars have similar characteristics – gently sloping flanks, and one or more crater-like depressions at the summit. These depressions, called calderas, are volcanic craters caused by the local subsidence of the crust, and mark the positions of magma reservoirs, bodies of molten rock some way below the surface. Volcanoes of this type grow as a result of the eruption of magma from the magma reservoir, which in turn is fed from the mantle beneath.

The reservoir develops because of the density structure of the volcano. Lava flows containing gas bubbles plus loosely packed fragmental rocks from explosive eruptions give the near-surface layers of a volcano a low density. Magma in the mantle is less dense than the rocks from which it forms and so is positively buoyant at great depth, but it cannot rise into the low-density layers near the surface. At the depth where it becomes neutrally buoyant it accumulates to form a magma reservoir. Fresh magma rising into the reservoir will make it expand slightly, and the extra pressure may be enough to force magma up towards the surface. If it can get to a depth where low pressure allows lots of gas release, it will automatically become light enough to erupt the rest of the way to the surface. Otherwise, it will travel sideways near the level at which it is neutrally buoyant to form an intrusion – called a dyke if it extends mainly vertically, or a sill if it extends mainly horizontally. Some lateral dykes eventually erupt on the volcano flanks, far from the summit and below the level of the top of the reservoir. These eruptions may drain so much magma out of the reservoir that its roof subsides, leading to the formation of a caldera at the surface.

Volcanic intrusions, like the magma reservoirs that feed them, are of great significance when thinking about the possibility of life on Mars. The surface temperature is currently below the freezing point of water almost everywhere, almost all of the time, and the thin atmosphere affords almost no shielding from potentially lethal solar ultraviolet light. Any water at shallow depths below the surface (down to perhaps 2–3 km) will also be frozen to form a cryosphere. But in areas where magma reservoirs or intrusions are present there will be a significant increase in available heat, and the range of depths at which organisms might survive will also be increased.

This possibility, that volcanoes are potential havens for biosystems, makes it particularly important that we understand the timing and patterns of volcanic activity. Impact-crater counting, combined with traditional stratigraphy, has shown that the largest Tharsis shield volcanoes may have started to form more than 1 Ga ago, and perhaps even 2 Ga ago, so that their histories span nearly half the age of the planet. This sounds attractive as a way of keeping H_2O as liquid water at shallow depths during the latter part of martian history. But there are problems. First, the presence of multiple calderas, especially those on Ascraeus and Olympus Montes, which have complex overlapping relationships, makes it clear that many generations of magma reservoirs have existed on shield volcanoes. Secondly, if we divide the total volume of any one of the large shields by its total estimated lifetime, we get an average magma supply rate that is simply too small to keep a large magma reservoir hot. This implies that the magma supply from the mantle is episodic, rather than continuous. A cycle runs as follows. A reservoir feeds lava flows and intrusions and has one or more collapse events to produce a caldera. The magma supply from the mantle stops, or becomes very small, and the reservoir cools and becomes almost entirely solid rock. Later, the mantle magma supply resumes and magma ponds at the neutral buoyancy depth to built a new reservoir. The dense mass of the earlier frozen reservoir has changed the stress distribution so that the new one forms in a different position (Scott and Wilson 2000), and a new active cycle begins.

The key issue, of course, is the length of time that a hot reservoir is present and the length of time that the volcano is dormant. Calculations show that the pattern consistent with all of the thermal constraints implies active periods of ~1 Ma interleaved with dormant periods of ~100 Ma (Wilson *et al.* 2001), which is consistent with mantle models (e.g. Schott *et al.* 2001). This has two consequences. First, the long "cold" periods may present insurmountable problems for organisms trying to survive in volcanic havens on the shield volcanoes. But, secondly, these timescales may mean that some martian volcanoes are not dead, but merely sleeping. Crater-counting estimates (Hartmann *et al.* 1999) suggest that some volcanic deposits, e.g. lava flows on Arsia Mons, are no more than 40–100 Ma old and, more controversially (based on the rate of deposition of polar deposits), that some high-latitude volcanic features may be less than 20 Ma old (Garvin *et al.* 2000). It seems entirely possible that volcanism itself is not dead on Mars – it is simply that all of the large shield volcanoes are in the dormant phase at the moment. Given the small number (<10) of them, and the ~100 Ma length of the dormant periods, this is statistically reasonable. So, there may be volcanic activity again on Mars some time in the future – but probably not in our lifetimes.



3: Two Mars Orbiter Camera narrow-angle images of the same area (about 2.8 km across) illustrating the extremely recent formation of dark streaks (b and c) in walls of Mangala Valles at 6.5°S by 208.3°E. Left image: sp237303, aquired on 18 June, 1998. Right image: e0202379, aquired on 26 March 2002. (Karl Mitchell, from raw MOC image data using USGS ISIS software)

Ice and water on Mars

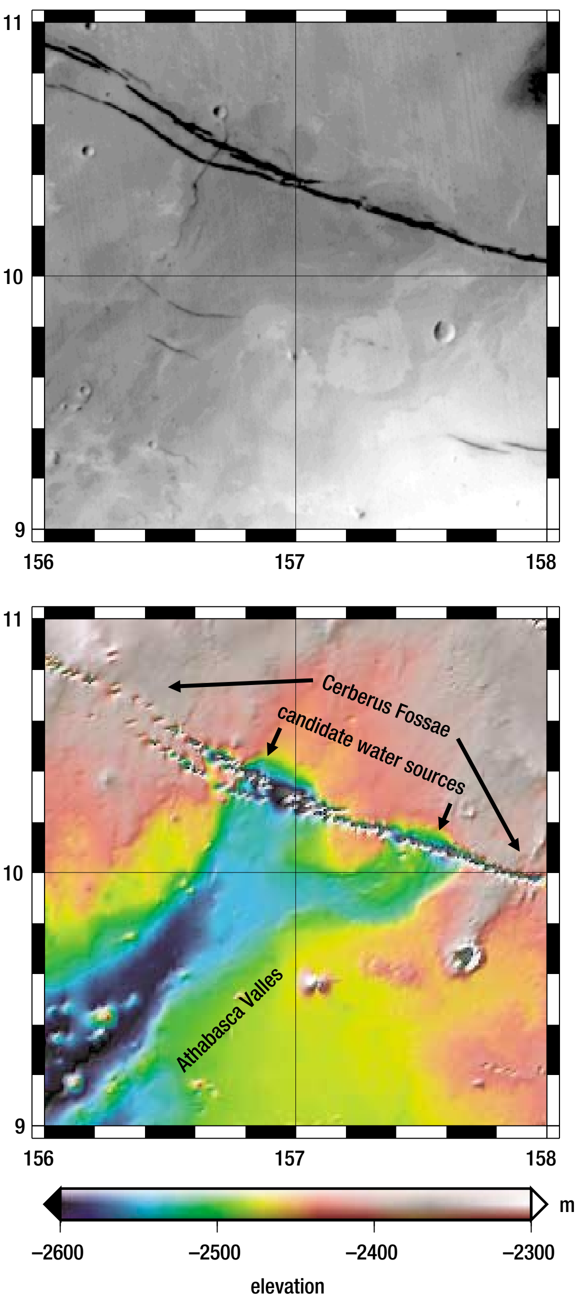
Mars' polar caps are clear evidence that water has existed and continues to exist on Mars. Although perennial CO_2 is evident, the bulk of these caps is semi-permanent water-ice, similar to those of the Earth. Beyond the caps, however, there is only indirect evidence for water on Mars. Even the atmosphere appears to be nearly water-free, which has led some to suggest that Mars is depleted of water. This was clearly not the case in past epochs, though.

Fluvial features, in the form of channels, have been well-documented since the Mariner fly-bys of the early 1970s and are generally attributed to the flow of liquid water on the surface (e.g. Carr 1979, Komatsu and Baker 1996, Carr 2000). Although alternatives such as liquid CO_2 (Hoffmann 2000) have been suggested, none of these has gained much credence. Crater counting has showed a broad range of ages for martian channels, but many are of Upper Amazonian ages, and so therefore could conceivably have been emplaced relatively recently. If so, this presents a conundrum: under present conditions liquid water is unstable on the planetary surface, and so either global or local environmental conditions must have been different (e.g. the atmospheric pressure was greater) at the time of emplacement, or else emplacement was so fast that the water did not get a chance to boil away. Thermodynamic calculations (Wilson and Head 2002a) reveal that, under current conditions, water molecules would boil away from a flat surface fast enough to make the level fall at approximately 6 mm s^{-1}, meaning that these channels would have had to have been emplaced rapidly unless the eroding water was somehow isolated from the atmosphere. Water speeds of ~10 m s^{-1} would be needed, which is consistent with the slopes of the terrains over which they flow if the water flood was up to ~100 m deep. Interestingly, the same calculations for CO_2 reveal a boil-off rate of approximately 6 m s^{-1}, three orders of magnitude greater than for water, which means that in order for the channels, which can be many hundreds of kilometres long, to have been formed by CO_2 flow, velocities of many km s^{-1} would have been necessary. This is inconsistent with the observed sinuosities, to say nothing of presenting formidable problems in understanding the process and dynamics of CO_2 release.

There is also geomorphological evidence for palaeolakes, typically within impact craters. Using a validated general circulation model, Haberle *et al.* (2001) determined that pure liquid water could exist on the surface of Mars in the present climate system, in very limited locales, for a short fraction of the year. These correlate extremely well with the location of interpreted Amazonian (young) palaeolakes (Cabrol and Grin 1999), but no convincing mechanism for the link has been presented.

A recent and controversial theory (e.g. Baker *et al.* 1991) is that a massive ocean, referred to as Oceanus Borealis, has existed at times, covering most of the northern plains. It was initially proposed on the basis of the smoothness and apparent flatness of the northern plains, the existence of multiple outflow channels that appear to have carried water into these plains, and features interpreted as shorelines. Although not widely accepted at first, the theory has gained in popularity as a result of topographic data from MOLA (the Mars Orbiter Laser Altimeter) on MGS, which showed that the northern plains were as flat and smooth as originally interpreted, and that the apparent shorelines were at elevations consistent with the ocean hypothesis.

The apparent lack of water on the present martian surface led to suggestions that most of the original water had been lost to space. However, an alternative explanation is that water was trapped in the form of ice within the permafrost regions of the regolith (the porous, fragmental uppermost part of the crust), based on observations that many impact craters exhibit ramparts that appeared to be consistent with impact into an ice-rich substrate. This theory gained credence in the early 1990s, thanks to modelling work by Clifford (1993). He demonstrated that substantial volumes of water,



4: Mars Orbiter Camera wide-angle and MOLA topography of Cerberus Fossae where it intersects the source of Athabasca Valles. 1° equals approximately 60 km. Top: MOC wide-angle image map in planetographic co-ordinates. Bottom: MOLA topographic map in planetocentric co-ordinates. (Karl Mitchell, from 1/128 degree resolution MOC wide-angle mosaics courtesy of Malin Space Science Systems/NASA, and MOLA MEDGR 1/128 degree resolution gridded data product, courtesy of NASA/Goddard Space Flight Center using GMT software)

more than enough to fill a northern ocean, could plausibly be stored within the regolith, and be replenished by sub-basal melting at the poles. His model had additional implications: if the current water budget were sufficient to fill the permafrost, additional water could be stored at greater depths, where temperatures are higher, in liquid aquifers. The consistency of his work with that of previous investigations (e.g. Carr 1979, Baker *et al.* 1991), led to this model being adopted almost immediately, and more recent results, such as the detection of large reserves of near-surface hydrogen atoms in the near-polar crust (Boynton *et al.* 2002) by the Gamma-Ray Spectrometer (GRS) on-board Mars Odyssey, appear to bear out his predictions and impose further constraints.

High-resolution imagery from the Mars Orbiter Camera (MOC) on-board MGS gave planetary scientists their first glance at much of the surface at resolutions comparable to modern terrestrial imaging systems. One of the more intriguing discoveries was observation of apparently geologically recent features resembling terrestrial water-carved gullies, which were used to imply that liquid water has flowed recently on the surface of Mars (Malin and Edgett 2000, Mellon and Phillips 2001). Several explanations for this have been suggested, including periodic melting due to solar melting or geothermal heating, followed by subsurface flow and eruption. The presence of salts, well documented for Mars, can lower the melting temperature of ice sufficiently that melting of near-surface ice during the summer becomes almost inevitable under current atmospheric conditions.

Dark streaks observed on crater and canyon walls have also been attributed to water flow, although an alternative hypothesis is that they are the result of landslides caused by slope instabilities. A recent development, emerging as a result of repeat coverage of certain areas with MOC imagery, is that emplacement of these dark streaks is an ongoing process. A conference abstract given by Motazedian (2003) showed clearly that new dark streaks along a canyon wall appeared between June 1998 and March 2001 (figure 3). If confirmed as being of aqueous origin, this would provide the strongest evidence yet that Mars is hydrologically active.

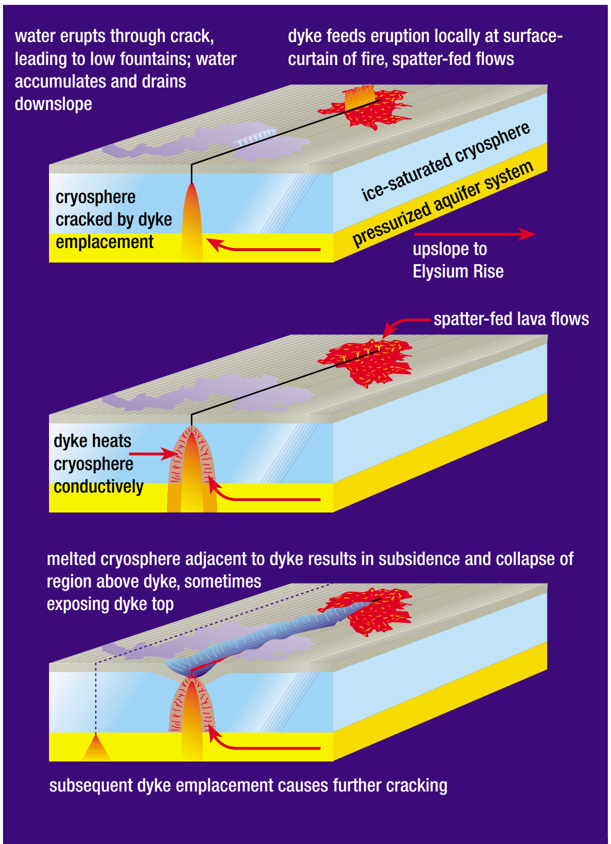
Volcano–ice interactions

We mentioned earlier the presence of the large shield volcanoes concentrated in two regions of Mars where mantle thermal activity has been concentrated. These regions are characterized by another set of distinctive features – systems of depressions called grabens radiate away from them. Grabens are valleys formed when the crust subsides between a pair of steeply dipping faults, and this inevitably implies that some tensional force has acted in the crust at right angles to the strike of the grabens. In general this tension could be caused by any suitable source of stress – doming of the surface in some places or subsidence elsewhere. Indeed, the very presence of the large volcanoes and the underlying swell due to the hot mantle provide a simple explanation for the grabens near the volcanoes themselves.

However, some of these grabens extend for more than 2000 km – in some cases nearly 3000 km – from any plausible source of stress, and it is tempting to interpret them as being produced by the lateral intrusion of giant dykes fed directly from magma formation zones in the mantle (Wilson and Head 2002b). This is a particularly attractive explanation for the sets of grabens that spread northward from Tharsis, because there is no obvious volcanic feature located exactly at the point that seems to be the focus of the radiating pattern. Evidence for similar swarms of giant dykes exists on other planets (Ernst *et al.* 1995). On Earth we see sets of dykes that radiate for at least 2000 km from common sources inferred to be deep in the mantle, though these are all ancient features, and erosion has stripped away all evidence of whether grabens were present at the surface above these dykes. However, on Venus we do see patterns of grabens and fracture systems radiating away from volcanically active areas, and here the problem is that, as on Mars, we have no direct evidence of what is beneath the surface.

In the case of the martian graben systems, we do have some indirect evidence of what is beneath the surface, because a variety of water-related features have their sources located at points along these giant graben systems. The best studied so far is the system of valleys called Athabasca Valles, located between the Tharsis and Elysium volcanic provinces in an area dominated by large areas of sheet-like lava flows, the youngest of which Berman and Hartmann (2002) date at less than ~200 Ma, using Hartmann's (1999) crater-counting methods. The floors of the valleys show all the hallmarks of modification due to fast-flowing water – scoured and braided channels, and streamlined "islands" of land that resisted being eroded by the flood (Burr *et al.* 2002). The source of the water is indicated unambiguously by the topography of the area (figure 4) and coincides with two adjacent segments (a total horizontal length of about 35 km) of an extensive system of grabens called Cerberus Fossae. There is uncertainty, in this case, as to the source of the grabens: their orientation is such that they could possibly be radiating from either the Tharsis or the Elysium region. However, the morphology of the Fossae in the region of water release makes it clear that they are underlain by dykes. Furthermore, estimates of the age of the water channels are less than 20 Ma (Berman and Hartmann 2002), which implies that the Cerberus Fossae volcanic intrusions are also this young.

There are, then, three possibilities for the origin of the water. Perhaps heat from the dyke melted part of the cryosphere, and this water caused the flood that eroded the valleys? This option has to be discounted, because dykes are essentially vertical features, meaning that the contact area between the dyke and the cryosphere would be at most 35 km long and 2–3 km deep (the likely thickness of the cryosphere). Even giant dykes on Mars are at most a few hundred metres wide (Wilson and Head 2002b) and so enough heat to melt ice would penetrate laterally only a few times the dyke thickness, at most around 5 km. Thus even if the cryosphere were 80% ice by volume, the volume of water produced would be no more than about 500 km^3. From the morphology of the valley system, *Burr et al.* (2002) estimated that a water flux of 1–2 million $m^3 s^{-1}$ flowed from the source. The duration implied by this flux and the water volume just calculated is about four days. This might be long enough to explain the amount of erosion seen, but it would require a 5 km wide, 2 km deep, 35 km long depression in the source area. In fact there is a depression with about this length and width around the source, but it is less than 100 m deep, far too small to provide the required water volume (and possibly suggesting that in this region the average ice content of the cryosphere is more like 5% than 80%).



5: Sequence of events in Head *et al.*'s (2003) model for the formation of Cerberus Fossae and Athabasca Valles.

The second option for the source of the water is that magma from the dyke spread out horizontally to form a sill at a depth that was shallow enough to melt much of the cryosphere from below. Clearly, a horizontal sheet of hot rock can heat the cryosphere far more efficiently than a vertical dyke. However, we again have the problem of explaining how a sufficiently large volume of water can be removed from the cryosphere without causing subsidence of the surface. A 100 m subsidence of an area 70 km by 70 km would suffice, but we see no evidence for subsidence on this scale around the source of Athabasca Valles – and in other areas that are clearly the sources of water floods (e.g. Aromatum Chaos, Juventae Chasma, Hydraotes Chaos) we *do* see massive surface collapse, on the right scale to be source areas.

This leads us to the third option: that the main effect of the intrusion of the Cerberus Fossae dykes was simply to fracture the cryosphere and provide a pathway to the surface for liquid water that was already present in an aquifer system beneath the impervious cryosphere (Head *et al.* 2003) (figure 5). It is easy to show that a 35 km long fracture need only be ~2 m wide to accommodate a flux of 2 million $m^3 s^{-1}$. The limiting factor is not the fracture geometry but is instead the permeability of the aquifer itself. An aquifer consisting of closely packed, fine-grained material would not allow the required flow rate, but a system of interconnected fractures would do so readily.

This picture of a highly fractured crust at a depth of only a few kilometres in the Athabasca Valles area is quite in keeping with the fact that the volcanic plains here overlie much more ancient crustal rocks which may still "remember" the fracturing caused by impact bombardment during the final stages of accretion of Mars.

Summary

The interpretation of improved data from current Mars missions, and improvements in our theoretical understanding of the processes at work on the planet, are causing a strong trend towards consideration of Mars as a geologically dynamic planet. Evidence of geologically recent and even what is essentially present-day fluvial activity seems particularly convincing. Although Mars is clearly near the end of its volcanic life, there is a case for Mars not being volcanically extinct, though the chances of seeing an eruption during our lifetimes are not good. The episodic nature of activity on martian volcanoes suggests that they may not be the best places to look for evidence of the long-term survival of biosystems. However, the accumulating evidence that large-scale, long-lived subcryosphere aquifers may be common even today improves the odds that at depths of a few kilometres we might find surviving organisms from earlier, more benign periods of martian history. ●

Karl L Mitchell and Lionel Wilson, Planetary Science Research Group, Environmental Science Department, Lancaster University, Lancaster LA1 4YQ, UK. k.l.mitchell@lancaster.ac.uk

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