The iceball

Several spacecraft are or will soon be scrutinizing Mars for reservoirs of water and ice that scientists strongly suspect lie hidden beneath the planet's surface.

WHEN Mariner 4 returned the first close-up images of the Martian surface during its brief flyby in 1965, the impact craters it revealed were a source of great despair for a generation that had been raised on H. G. Wells, Ray Bradbury, and Robert Heinlein. Mars, it seemed, was not the "abode of life" envisioned by Percival Lowell but rather a body that bore a disappointingly familiar resemblance to our Moon — battered, dry, and lifeless.

But after four decades of investigation by robotic spacecraft and laboratory studies of meteorites blasted from its surface, the Mars we know today bears only a superficial resemblance to the one glimpsed by Mariner 4. It is a planet characterized by unexpected diversity and extremes, boasting the largest impact basins, the tallest volcanoes, and the most complex canyon system found anywhere in the solar system. While the scars of ancient impacts are preserved over much of Mars, elsewhere the surface is virtually crater free — a sign that erosion and redistribution of material has occurred within the geologically recent past. Mars, it seems, is far from the dead world it appeared to be 38 years ago.

Arguably the greatest surprise made during our explora-

next door

BY STEPHEN M. CLIFFORD

Can water flow across the modern Martian landscape? Richly detailed images from NASA's Mars Global Surveyor reveal sets of gullies, like these lining a crater wall, that may result from the sporadic escape of water from a near-suface source. Courtesy NASA/JPL/MSSS.

Far left: **The south polar cap of Mars, seen here at its minimum, midsummer size (about 400 kilometers, or 250 miles, across), contains only about a tenth of the ice locked in the frozen slab atop Greenland — though several times that amount may reside within the surrounding and more extensive polar layered deposits. Courtesy US Geological Survey.**

tions was the discovery of water's important role throughout Martian history. Evidence of water, both past and present, is found almost everywhere — from enormous channels that disgorged their floodwaters eons ago to delicate gullies that may occasionally bear trickling streams in modern times.

Because of water's crucial role in the planet's evolution, its necessity for the origin and survival of life, and its potential for sustaining future human explorers, "follow the water" has become the rallying cry for NASA's Mars-exploration program.

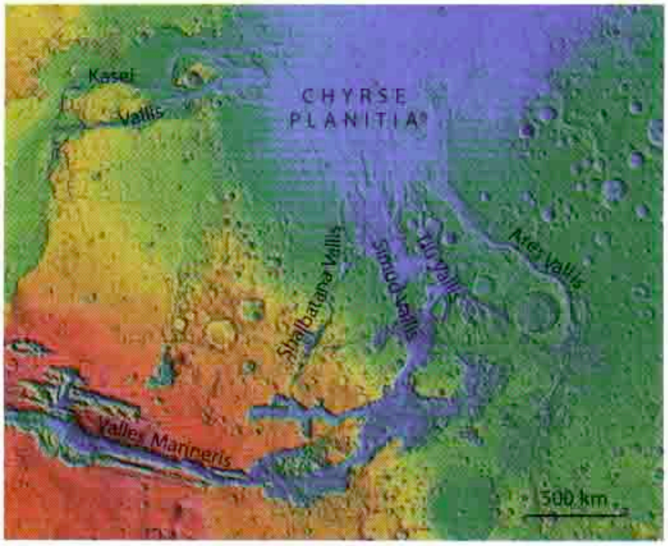
• TAKING A GLOBAL INVENTORY

Estimating the volume of water on Mars has been a difficult task. Initially researchers attempted to compare the relative abundances of various Martian atmospheric gases with their corresponding values on Earth. They thought such comparisons would accurately predict the amount of volatile compounds (including water) that has been driven from the planet's interior over time. However, the inventory of water predicted by these models was invariably small — equivalent to a globally averaged layer of 100 meters or less, compared with Earth's 2.8 kilometers.

The meager inventory implied by atmospheric assays is clearly at odds with the volume of fluid needed to shape the planet's landscape.

But the planet's surface is telling a very different story. The presence of outflow channels — huge scoured depressions tens of kilometers wide, hundreds of kilometers long, and up to a kilometer deep — argue that an immense reservoir of water was present throughout much of Martian geologic history. Thus, the meager inventory implied by atmospheric assays is clearly at odds with the volume of fluid needed to shape the planet's landscape.

Most outflow channels originate along the transition region between the planet's southern highlands and the lower-lying northern plains, just north of the great equatorial canyon system of Valles Marineris. The abrupt emergences of these channels from regions of disrupted terrain, and the enormity of the braided and streamlined forms found within their beds, testify to origin by catastrophic floods. During these episodes, which spanned the last 3 to 4 billion years, large stores of groundwater apparently escaped from beneath a confining layer of permafrost. Based on a conservative estimate of the discharge rates required to carve these channels, Michael H. Carr (US Geological Survey) calculates that, at the time they formed, Mars may have possessed an inventory of water equivalent to a global ocean 0.5 to 1.0 kilometer deep, stored today as buried ice and groundwater within the planet's crust.



MOLA SCIENCE TEAM (NASA/GODDARD SPACE FLIGHT CENTER)

Throughout the middle of Martian geologic history, evidence suggests that catastrophic outflows repeatedly discharged huge floods onto Chryse Planitia ("Plain of Gold") from storage reservoirs in the planet's southern highlands. Similar events, elsewhere on the planet, may have occurred within the past billion years.

These immense outflows likely formed transient ice-covered lakes or seas, but there is growing evidence that a far larger body of water inundated the northern plains much earlier in Martian history. Timothy J. Parker (NASA/Jet Propulsion Laboratory) first raised this tantalizing possibility in the mid-1980s after he identified possible shorelines in Viking-orbiter images. His interpretation recently received additional support from James W. Head (Brown University) and his colleagues. Using altimetry measurements made by the Mars Global Surveyor spacecraft, they found that at least one of Parker's putative shorelines lies along a boundary of nearly constant elevation — a result most easily explained by erosion associated with a standing body of water (*S&T:* November 1999, page 38).

While the geologic evidence for an ancient ocean appears increasingly persuasive, the sea's genesis and timing are more poorly constrained. Until recently, geologists thought that if a large body of water ever existed it must have resulted from the discharge of the outflow channels and thus would have first appeared about midway through Mars's geologic history. However, Parker and I have taken a different approach, first by considering the hydraulic conditions required to explain the channels themselves and then by extrapolating those conditions backward in time. We conclude that an ocean on Mars (as on Earth) almost certainly condensed shortly after the planet formed.

Why so? When the floods were most active, their source regions in the southern highlands stood some 4 km above the lowest point in the northern plains. In other words, much of the planet's groundwater was stored at high elevations. Such a state is possible as long as the fluid is confined beneath a thick layer of frozen ground, a natural consequence of the extremely cold climatic conditions expected at that time.

But earlier in Mars's history a substantially higher geothermal heat flow (arising from the decay of radioactive elements within the crust) would have made a confined, high-elevation groundwater system impossible. If the current north-south elevation dichotomy dates back to this era, then a primordial ocean — up to several kilometers deep and covering as much as a third of the planet — *must* have occupied the northern plains. Many other low-lying enclosures, such as the Argyre and Hellas impact basins, would have had lakes and seas as well.

• EARLY CLIMATE: WARM VERSUS COLD

While planetary scientists generally agree that early Mars was "wet," we are far less certain about whether the early climate was warm or cold. The existence of small valley networks in the ancient, heavily cratered highlands and their resemblance to terrestrial runoff channels have been interpreted by some as evidence of an early period of rainfall, during which above-

NASA/JET PROPULSION LABORATORY

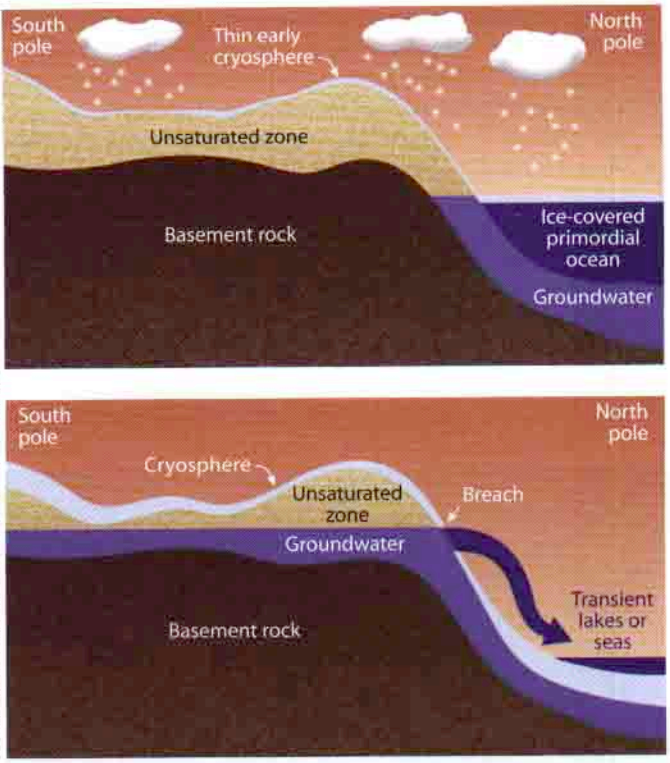
A large outflow channel, 20 km wide, emerges from the depression at left and continues eastward toward an even larger channel called Simud Vallis. Inside the depressed area is what geologists term chaotic terrain — an irregular jumble that may have resulted after groundwater erupted and flowed away, causing the ground above it to collapse.

freezing temperatures were sustained by a massive greenhouse atmosphere containing up to 5 bars (five times the atmospheric pressure at sea level on Earth) of carbon dioxide.

If this is true, then huge amounts of gas were somehow lost to space or sequestered in the crust — because Mars's present surface pressure is just 6.1 millibars. Perhaps large impacts and the solar wind eroded the atmosphere over time, or maybe the CO_2 reacted with liquid water (both on and beneath the surface) to form carbonate rock. Whatever the nature of these removal processes, they must have been very efficient to reduce the atmospheric pressure to the point where liquid water was no longer stable at the surface.

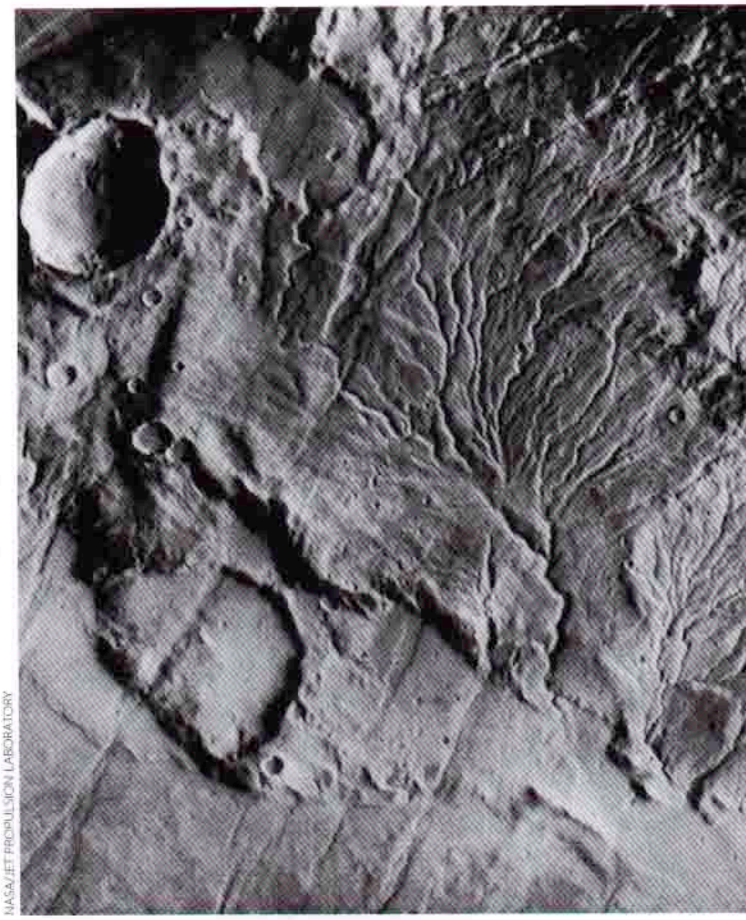
Skeptics of this "warm early Mars" hypothesis counter that creating and sustaining an atmospheric greenhouse of that magnitude would have been extremely difficult — especially considering that the infant Sun was only about 75 percent as bright as it is today. In addition, we have no observational evidence that the required volume of carbonate rock (equivalent to a planetwide layer at least 50 meters thick) is stashed on or beneath the planet's surface. Rather, advocates of a "cold early Mars" argue that the valley networks may simply be the byproduct of the geologic evolution of a water-rich planet — features resulting from various processes, including rainfall, that occurred under climatic conditions no different from those that exist on Mars today.

For example, many of the Martian valley networks are located on or near the rims of large craters. This association led Horton E. Newsom (University of New Mexico) to suggest that molten rock created during these collisions may have thawed the surrounding ice-rich crust, triggering massive discharges that then eroded the valleys. Indeed, Teresa L. Segura (University of Colorado) and her colleagues argue that hot ejecta produced by the very largest impacts might have affected the entire planet, creating enough heat to vaporize or melt the polar caps and near-surface ground ice, produce widespread rainfall, and maintain surface temperatures above freezing for as long as 1,000 years. Because only the largest impacts (creating craters hundreds of kilometers across) would have produced



SOURCE: STEPHEN CLIFFORD (LUNAR AND PLANETARY INSTITUTE)

***Top:* Very early in Martian history, the planet's frozen outer crust, or cryosphere, was not yet deep enough to prevent the wholesale discharge of groundwater from the southern highlands onto the northern plains and other low-lying basins. *Above:* Eventually the cryosphere thickened enough to trap the groundwater believed to have been introduced into the subsurface over time by melting at the ice cap's base. But huge reservoirs of fluid sporadically broke through, creating the gigantic outflow channels seen today.**



NASA/JET PROPULSION LABORATORY

Integrated networks of small valleys, like this one in Mars's southern highlands, may hark back to wetter times in the planet's distant past. The largest craters here are roughly 20 km in diameter.

enough melt to modify the global climate, the rapid falloff of the cratering rate early in Martian history might easily explain the subsequent decline in valley-network formation.

• WHERE IS THE MISSING WATER?

Still, the question remains: If Mars once had enough water to create a global ocean up to 1 km deep, where is that water today?

Ultraviolet sunlight breaks water down into hydrogen and oxygen, and the hydrogen can then escape to space from the uppermost level of the atmosphere. But the current rate of this escape implies that through time Mars may have lost at most only a few tens of meters of water by this process. Thus, the bulk of the planet's H_2O should still reside in one of three potential reservoirs: the atmosphere, polar caps, or upper crust. But the amount of water stored in the atmosphere is trivial, only enough to make a global layer *15 microns* (0.0006 inch) thick if it were to condense onto the planet's surface. This leaves the perennial polar caps as the largest visible reservoirs of water on Mars.

Long before the Space Age, telescopic observers had noted that Mars possesses polar caps that grow and shrink by season. Due to the planet's present 25° polar tilt, or *obliquity,* as much as one-quarter of the thin carbon dioxide atmosphere condenses onto the winter pole, producing a deposit of "dry ice" about 1 meter thick poleward of 50°. By late spring this seasonal cap sublimes away, revealing a considerably smaller residual cap that persists throughout summer.

In 1969 Mariner 7 confirmed that the seasonal caps consist of frozen CO_2, but the makeup of the smaller, residual caps remained uncertain until the arrival of the Viking orbiters in 1976. The northern cap proved too warm to be composed of CO_2 ice, and the northern polar atmosphere was saturated with H_2O; these revelations convinced mission scientists that the volatile component of the north perennial cap must be water ice.

Mars's residual north polar cap, about 1,000 km across, is cut by an enigmatic pattern of troughs that spiral outward from the pole. The origin of these features is still unknown.

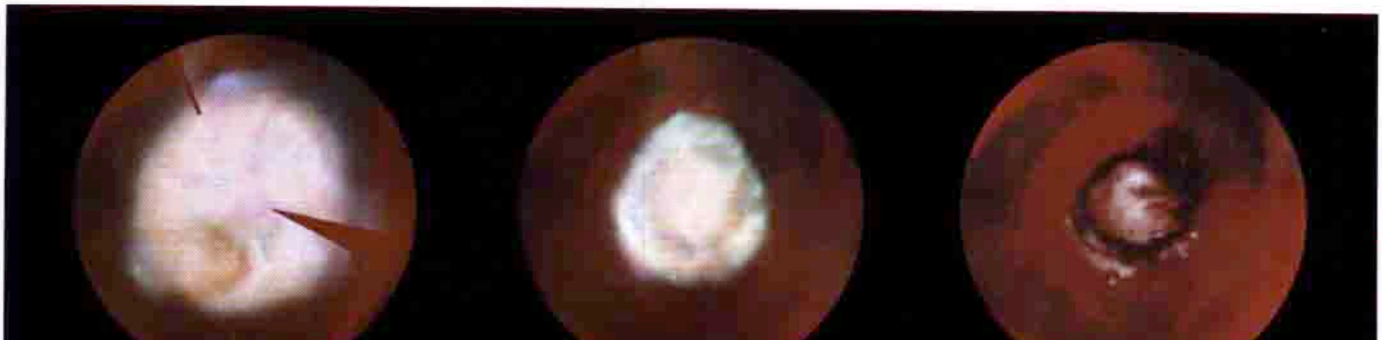
NASA/JPL/MSSS

They expected that the south residual cap would consist of water ice as well. However, Viking found that the southern cap is colder than its northern counterpart and remains covered with CO_2 throughout the year. While the reason for the persistence of CO_2 is still unknown, the low temperature recorded over the southern cap means that it must also act as a condensation "trap" for atmospheric H_2O. Indeed, this process is believed to occur at both poles, resulting in the accumulation of atmospheric water, dust, and other potential contaminants in a sequence of ice-rich layers up to several kilometers deep over the past 10 to 100 million years. Someday, when we are able to explore them in detail, these layers may serve as a Rosetta stone for understanding the geologic and climatic history of the planet.

The total volume of water ice present in the south polar cap is still unknown but likely comparable to that found in the north. So, taken together, the total amount of water locked up in these polar reservoirs might yield a global layer no more than 20 to 30 meters deep. Thus, of the planet's total estimated inventory of 0.5 to 1.0 km of H_2O, between 94 and 98 percent of it remains unaccounted for — the vast bulk of which is thought to reside as ground ice and groundwater beneath the Martian surface.

Because Mars has such a thin atmosphere and orbits at such a great distance from the Sun, it is a very cold place — with a mean annual surface temperature that ranges from about –55°C (–67°F) at the equator to about –119°C (–182°F) at the poles. In addition, the amount of geothermal heat escaping from the Martian interior is thought to be no more than about 40 percent of Earth's. Therefore, we suspect that a significant amount of water is stored as ice in a thick layer of frozen ground, termed the *cryosphere,* that extends from the surface to depths of 2½ to 5 km at the equator and 6½ to 13 km at the poles.

At the Martian surface, the low relative humidity of the at-



During local winter, a broad area surrounding the north pole of Mars is covered with a meter-thick layer of frozen carbon dioxide (left). But as spring arrives (middle and right), the seasonal blanket of dry ice returns to the atmosphere, revealing an underlying "permanent" polar cap consisting of water ice. These pole-on views were assembled from reprojected Hubble Space Telescope images.

PHILIP JAMES (UNIVERSITY OF TOLEDO) AND NASA

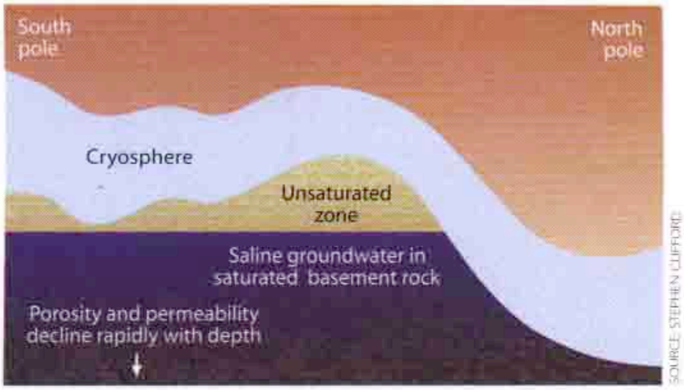
mosphere means that ground ice is thermodynamically unstable at the "warm" latitudes equatorward of 40° — it is lost by sublimation into the atmosphere. Depending on local conditions and variations in subsurface properties, the average depth of this desiccation can range from centimeters at the planet's middle latitudes to as much as 1 km near the equator.

Ground ice could also be present as massive deposits in the northern plains, an expectation based on the evidence for an early ocean and for repeated flooding by outflow channels later on. As a result, the sequence of volatile-rich layers underlying the plains is likely to be quite complex, having been built up through multiple episodes of flooding, freezing, sublimation, and burial. This complexity has undoubtedly been compounded locally by impacts, volcanism, and other geologic processes, as well as by extreme climatic fluctuations associated with variations in the planet's obliquity.

William V. Boynton (University of Arizona) and his colleagues have recently bolstered the case for an ice-rich subsurface with measurements from their neutron spectrometer on NASA's 2001 Mars Odyssey spacecraft. They found that at mid- to high latitudes the topmost meter of the Martian soil (the maximum depth to which this instrument can probe) is rich in hydrogen. By implication, this suggests the presence of great quantities of water ice, because no other hydrogen-bearing compound is believed to exist on Mars so abundantly (*S&T:* September 2002, page 22).

If Mars has more water than what can be stored as ice within the cryosphere, any excess will be stored beneath it as groundwater — saturating the lowermost porous regions of the crust below the cryosphere. Over time the planet's gravity will distribute this subterranean fluid globally to equalize its pressure and minimize the need for wholesale flow, effectively creating what is termed *hydrostatic equilibrium*.

Of course, it is also possible that all this deep-seated groundwater may no longer exist, beyond whatever might be produced sporadically when ice is melted by localized geothermal activity. More and more of the groundwater may have been frozen into the thickening cryosphere as the planet's internal heat flow declined with time. This possibility could also explain the corresponding geologic evidence for a sharp decline in outflow-channel activity over the last 1 to 2 billion years.



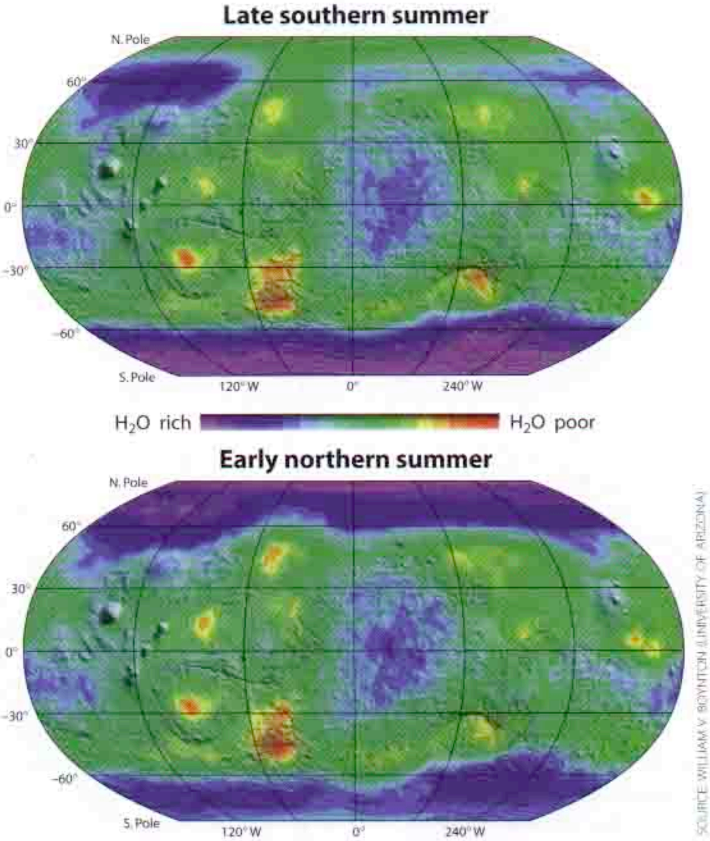
SOURCE: STEPHEN CLIFFORD

Today the outer crust of Mars is frozen so solidly, and to such great depth, that any remaining liquid water should lie kilometers beneath the surface. Thus, researchers are puzzled by spacecraft views showing evidence of recent flows across the Martian landscape.

• THE GULLIES

Not everyone is convinced that Mars's liquid water must be cached several kilometers or more beneath the surface. In 1999 Michael C. Malin and Kenneth S. Edgett (Malin Space Science Systems) identified features in high-resolution images from Mars Global Surveyor that they interpreted as water-cut gullies inside crater rims and on other steep slopes. These gullies, seen on pages 30 and 36, typically lie between 100 and 500 meters below the surrounding terrain and occur in both hemispheres within the latitude band of 30° to 70°. Their fresh-looking character suggests that they formed recently — and perhaps are forming today — by discharges of liquid water emanating from near-surface aquifers (*S&T:* September 2000, page 56).

However, significant doubts have been raised about the uniqueness and plausibility of this interpretation. It's enormously difficult, given plausible environmental conditions, to imagine how such an aquifer could be so shallow without freezing. Also, the gullies' locations don't correlate with areas of known past geothermal activity, and they preferentially occur on poleward-facing slopes. These characteristics have led researchers to advance a variety of other hypotheses, ranging from mini-landslides to the release of more exotic fluids, like liquid CO_2.

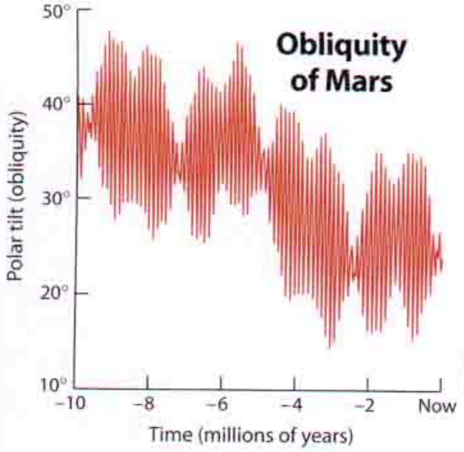


SOURCE: WILLIAM V. BOYNTON (UNIVERSITY OF ARIZONA)

By mapping the rate at which neutrons escape from the Martian surface, the 2001 Mars Odyssey spacecraft can estimate how much hydrogen (and, by implication, water ice) lies buried in the topmost layer of the Martian surface. *Top:* During late summer in the southern hemisphere, virtually all areas at high southern latitudes contain abundant water ice (magenta and blue) — up to 60 percent by volume. The hydrogen signature is not as evident in the far north because that polar region is mantled by its wintertime cap of carbon dioxide frost. *Bottom:* As summer approaches in the north, the seasonal CO_2 frost disappears (only to re-form on the south cap) and reveals water ice surrounding the north pole. Because Mars Odyssey's neutron spectrometer can probe down only to a fraction of a meter, a far larger reservoir of ground ice (and groundwater) may exist deeper down.

NASA/JPL/MSSS

A swarm of narrow gullies cascades down the rim of an unnamed Martian impact crater at latitude 42° south. Patches of winter frost still cling to the crater walls. The origin of these gullies (trickling water? rockslides?) has been hotly debated among researchers.



SOURCE: JIHAD TOUMA AND JACK WISDOM (MIT)

Today the tilt (obliquity) of Mars's polar axis is very similar to Earth's. But this tilt varies between 15° and 35° over 100,000 years, with even wilder swings (0° to 60°) on 10-million-year time scales. These swings may trigger huge changes in the Martian climate, as the vast caches of water ice stored in the polar caps and subsurface are vaporized and driven into the atmosphere.

The explanation most consistent with the environmental and observational constraints is that surface or near-surface ice deposits periodically melt when Mars's obliquity is greatest. During the early 1990s two independent teams of researchers — Jihad R. Touma (American University of Beirut) and Jack Wisdom (Massachusetts Institute of Technology), and Jacques Laskar and Philippe Robutel (both of Paris Observatory) — discovered that the planet's polar tilt varies chaotically between 0° and 60° on a time scale of about 10 million years.

The resulting changes in solar insolation can produce enormous swings in climate. For example, for obliquities greater than 45°, summertime surface temperatures at mid- to high latitudes will exceed the melting point of ice for hours to months at a time and will force large amounts of water ice to sublime and melt from the summer polar ice cap. The corresponding increase in surface temperature and atmospheric pressure would permit liquid water to flow readily across the surface. At midlatitudes, this may result in the melting of previously stable near-surface ice deposits, producing enough runoff to form the gullies.

The origin and age of the gullies remain topics of intense debate. And because of the enormous implications of a possible fluvial origin — whether recent or not — no hypothesis will be dismissed lightly as the search for near-surface reservoirs of water continues.

• FOLLOW THE WATER

On Earth, wherever there is liquid water, there is life. In the past few decades we have discovered organisms in a host of seemingly inhospitable environments, including deep underground (*S&T:* September 1999, page 32). Thus, the potential for groundwater on Mars (whether shallow or deep) raises the tantalizing possibility that Martian life, if it ever got started, may have adapted to a subterranean existence. We also recognize that water has played a key role in the planet's geologic and climatic evolution, likely having shaped the landscape through rainfall, catastrophic floods, various cold-climate processes, and standing bodies of water ranging from lakes to a hemispheric ocean.

Although the evidence for a large reservoir of subsurface water on Mars appears strong, the case for it has necessarily been built on inference and interpretation. Over the next decade, however, geophysical investigations conducted from both high above the planet and on its surface will provide several opportunities to verify whether Mars is water-rich.

The first such opportunity occurs late this year, with the arrival of the European Space Agency's ambitious mission consisting of a polar orbiter called Mars Express and a sophisticated lander called Beagle 2. Among the instruments carried by the orbiter is the Mars Advanced Radar for Subsurface and Ionosphere Sounding, which will map the distribution of water and ice within the top several kilometers of the crust. In 2005 a second ground-penetrating device will be flown on NASA's Mars Reconnaissance Orbiter. Called Sharad (for "shallow radar"), it will employ a shorter wavelength that will limit the depth probed to only a few hundred meters but will significantly improve its ability to detect any shallow reservoirs of liquid water.

Over the next decade, the results from these experiments will be supplemented by the seismic and electromagnetic investigations of other ambitious missions that will yield a wealth of information about the evolution of Mars's climate and crust, the structure and history of its polar layering, the planet's geothermal state, and its seismic activity.

But for many researchers the most awaited results will be the improved insights provided regarding the three-dimensional distribution and state of water in the subsurface. We will be especially eager to find the most accessible occurrences of liquid water and massive ice deposits — unique environments that someday may be visited by human explorers. Within the next 15 to 20 years, the analysis of samples acquired from such sites could well provide a definitive test of whether life ever evolved on Mars and, if so, whether it survives to the present day.

An expert on hydrologic systems at the Lunar and Planetary Institute in Houston, Texas, Stephen Clifford *specializes in the past and present roles played by water on the red planet.*