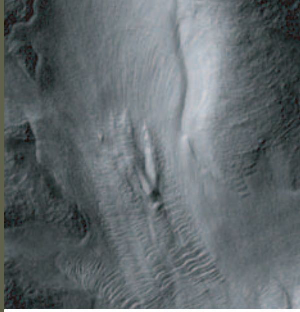

Water at the Poles and in Permafrost Regions of Mars

Philip R. Christensen[1]

The poles and mid-latitudes of Mars contain abundant water in ice caps, thick sequences of ice-rich layers, and mantles of snow. The volume of the known reservoir is ≥5 x 10^6 km^3, corresponding to a layer ~35 m thick over the planet. Hydrogen in subsurface H_2O ice has been detected at latitudes poleward of 50°. Morphological features show downslope flow of ice-rich sediment, and recent gullies have been produced from subsurface aquifers or melting snowpacks. Variations in Mars' orbit on timescales of 50,000 to 2,000,000 years produce significant changes in climate, which result in the transport of water from the poles, where it currently resides, to the lower latitudes, where it may play a critical role in surface geology, mineralogy, and geochemistry.

KEYWORDS: Mars, ice, water, polar caps

INTRODUCTION

Water has long been recognized as a major morphological agent on Mars (Baker this issue), but its present abundance and location remain enigmatic. A possible reservoir for a substantial amount of water is surface and subsurface ice at the poles and mid-latitudes. Recent observations have substantially improved our knowledge of this reservoir, but major questions remain as to its volume, age, and history. Oscillations in the axial tilt, eccentricity, and timing of closest approach to the Sun cause major changes in surface heating, which produce cyclic changes in Martian climate on timescales of 10^5 to 10^6 years (e.g. Pollack and Toon 1982). These changes redistribute polar ice, transferring it to lower latitudes as snow and ice during Martian "ice ages" (e.g. Jakosky et al. 1995). Today the major ice-bearing features are the polar ice caps, the layered units that surround them at both poles, and the mid-latitude permafrost zones that present morphologies strongly suggestive of subsurface ice. Each of these has unique properties, water abundances, and histories, and contributes to the water cycle in varying ways.

POLAR CAPS

The polar caps of Mars (FIG. 1) have been observed since the 17th century and are assumed to be composed of some combination of H_2O and CO_2 ice. The Martian atmosphere is composed of >95% CO_2 with a pressure of only a few millibars. This fact led to the prediction that CO_2 would accumulate at the poles during winter (Leighton and Murray 1966). This prediction was confirmed by orbital temperature measurements (e.g. Kieffer 1979), and global mapping has shown that seasonal CO_2 caps grow well into the mid-latitudes during winter, with perennial ice caps surviving the summer at both poles. The thickness of the seasonal CO_2 ice caps has been estimated from Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) observations to reach approximately 1.5 m near the pole in both hemispheres (Smith et al. 2001), corresponding to ~25% of the total mass of the Martian atmosphere.

As the seasonal caps condense, they incorporate minor amounts of dust and H_2O ice, which significantly affect the sublimation rates the following spring. Assuming a water vapor mass fraction of 1×10^{-5} in the condensing atmosphere, the amount of water stored in the seasonal caps is estimated at ~3×10^{10} kg (~3×10^{-2} km^3) (the Martian atmosphere contains ~10^{-1} km^3 of water). Overall, however, the water within the seasonal caps plays a relatively minor role in the global inventory or annual cycle of water on Mars.

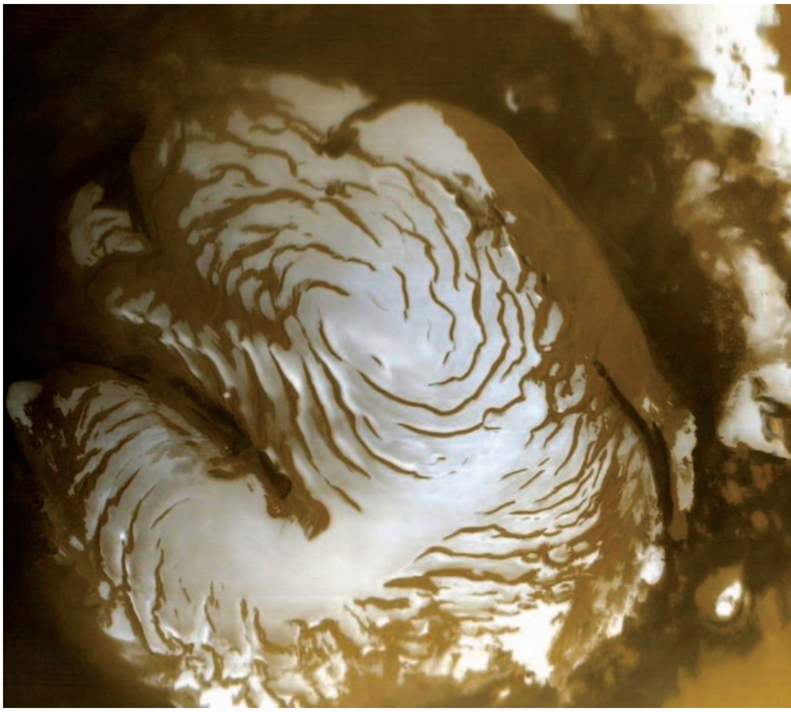

FIGURE 1 The north polar cap of Mars as seen by Viking. This mosaic of images was acquired during northern summer when the ice had retreated to its perennial size. The relatively bright material is H_2O ice. The cap has shrunk to essentially the same location every year that it has been imaged by spacecraft (1971 to present) (James and Cantor 2001). Image width is ~900 km. IMAGE CREDIT NASA/JPL

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In their pioneering work, Leighton and Murray (1966) predicted that CO_2 would condense at the poles to sufficient depth for CO_2 to remain throughout the following summer. Spacecraft temperature observations show that CO_2 ice does survive the summer in the south, but is completely removed from the northern perennial cap, exposing H_2O ice (Kieffer 1979). Sublimation of this ice releases water vapor into the atmosphere, which was initially detected by ground-based observations over 40 years ago (Jakosky and Barker 1984).

The Viking orbiter Mars Atmospheric Water Detector (MAWD) instrument provided the first global map of water vapor and confirmed that large quantities of vapor [~100 precipitable microns (pr µm)] were coming from the northern perennial cap (e.g. Jakosky and Farmer 1982). The MGS Thermal Emission Spectrometer (TES) instrument has provided detailed global maps of water vapor over three Martian years (1997–2004), confirming high water vapor abundances equatorward of the cap in the north, which rise rapidly to ~100 pr µm in late spring once the CO_2 ice has disappeared (Smith 2004).

MAWD data showed no indication of water vapor coming from the perennial south polar cap (e.g. Jakosky and Farmer 1982), consistent with measured temperatures that correspond to CO_2 ice (Kieffer et al. 2000). A notable exception to this pattern was the ground-based water vapor measurements in 1969 that showed a significant increase in water vapor as compared with other seasons or other years. This has been interpreted to indicate that H_2O ice was exposed that year in the south (e.g. Jakosky and Barker 1984). TES observations have confirmed the release of water vapor (~45 pr µm) along the edge of the southern perennial cap, providing conclusive evidence that H_2O ice is now being exposed on the southern cap (Smith 2004). The presence of this exposed ice has been confirmed by direct temperature measurements using the Mars Odyssey Thermal Emission Imaging System (THEMIS) infrared imager (Titus et al. 2003) and by near-IR spectral measurements from the Mars Express OMEGA spectrometer (Bibring et al. 2004).

A remarkable result from the high-resolution MGS Mars Orbiter Camera (MOC) was the discovery of quasi-circular depressions in the perennial south polar cap that are up to 1 km in diameter and uniformly ~8 m deep (Thomas et al. 2000; Malin et al. 2001) (Fig. 2). Some depressions are expanding at rates of 1–3 m per year (Malin et al. 2001). They have been modeled as a layer of CO_2 ice over a substrate of either H_2O ice or high-albedo (dust-free) CO_2 ice (Byrne and Ingersoll 2003). This thin layer of CO_2 ice may be relatively young and, even if completely sublimated, would be a minor contributor to the atmospheric CO_2 inventory. In this case, the atmospheric CO_2 partial pressure, and therefore the atmospheric temperature, would not be much higher than its current value.

POLAR LAYERED DEPOSITS

Thick stacks of sedimentary deposits extend up to 600 km outward from the poles in both hemispheres. These units are ~3 km thick at both poles and are layered down to the resolution of the MOC camera (Malin and Edgett 2001). These layers may have been produced by differences in the amount of airfall dust incorporated into the ice, perhaps as a result of orbit-driven cyclic changes in climate (e.g. Pollack and Toon 1982; Milkovich and Head 2005).

The volume of the north polar layered deposits is estimated to be ~1.2–1.6 × 10^6 km^3 (Zuber et al. 1998). Attempts have been made to determine the density, and thus the ice to sediment ratio, of the layered materials using gravity and topography, but this value has been difficult to constrain.

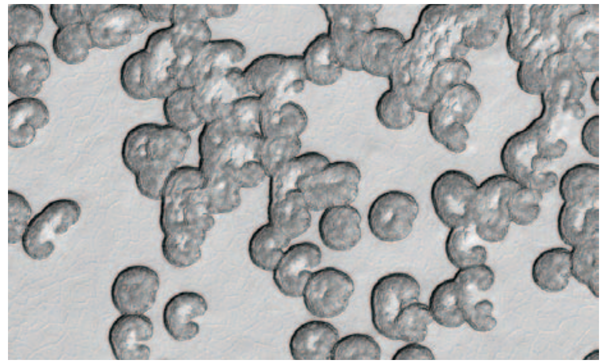

Figure 2 "Swiss cheese" terrain with quasi-circular depressions, located near 86.9°S, 352.4°E. These pits are several hundred meters across and have a remarkably uniform depth of ~8 m wherever they are observed (Thomas et al. 2000; Malin et al. 2001). Some pits have been observed to increase in size over one Martian year (Malin et al. 2001). A possible explanation is that the upper ~8 m thick layer is CO_2 ice, which is gradually disappearing and exposing a stable layer of H_2O ice beneath it (Byrne and Ingersoll 2003). Image width is about 3 km. MOC image R1303615; MGS MOC Release No. MOC2-695

The topographic slopes and gently undulating surface of the northern layered materials are consistent with the slow radial flow velocities for H_2O, but not CO_2, ice rheology. Assuming that the layered deposits are made of essentially pure H_2O ice, the upper limit for the quantity of water in the northern layered terrains is ~1.6 × 10^{18} kg (~1.6 × 10^6 km^3), which corresponds to an equivalent global layer of water ~12 m deep. The areal extent of the southern deposits, which have a similar average thickness, is roughly twice that of the northern deposits, suggesting a water inventory (again assuming pure H_2O ice) that is roughly twice that in the north.

Units within these deposits can be traced for hundreds of kilometers at both poles, suggesting a regional process of formation (Byrne and Murray 2002; Milkovich and Head 2005). A stratigraphic horizon near the base of the northern units is interpreted to have been an extensive sand sea that formed during a period when no icy cap was present (Byrne and Murray 2002). The lack of an ice cap would require a dramatic climate change and would represent a major event in Martian history. Analysis of layers within the upper units of the northern layered terrain shows the existence of ~30 m periodicity, possibly associated with the 50,000 year obliquity cycle (Milkovich and Head 2005); a 100 m unit within this sequence lacks this layering and may represent a recent (0.5–2 Ma) period of ice removal and the formation of a sediment-rich lag. Crater counts also suggest an active process, with ages for the upper surfaces of these deposits of ~30–100 Ma for the southern and <0.1 Ma for the northern deposits (e.g. Herkenhoff and Plaut 2000). These ages likely reflect only the most recent cycle in this process, and cyclic deposition and erosion may have been occurring in the polar regions throughout Martian history.

SUBSURFACE ICE

Ice Stability Models

The stability of subsurface ice depends strongly on the porosity, tortuosity, and thermal conductivity of the surface (Mellon and Jakosky 1995; Mellon et al. 2004). Ice stability models predict that H_2O ice will be stable at all latitudes for obliquities >32° but will diffuse outward from the upper 1–2 m in the equatorial and mid-latitude regions when the obliquity decreases. Mars is currently in an "interglacial" period, with an obliquity of ~25° (Mustard et al. 2001; Christensen 2003), and near-surface ice is predicted to be stable only poleward of ~50° (Mellon and Jakosky 1995; Mellon et al. 2004).

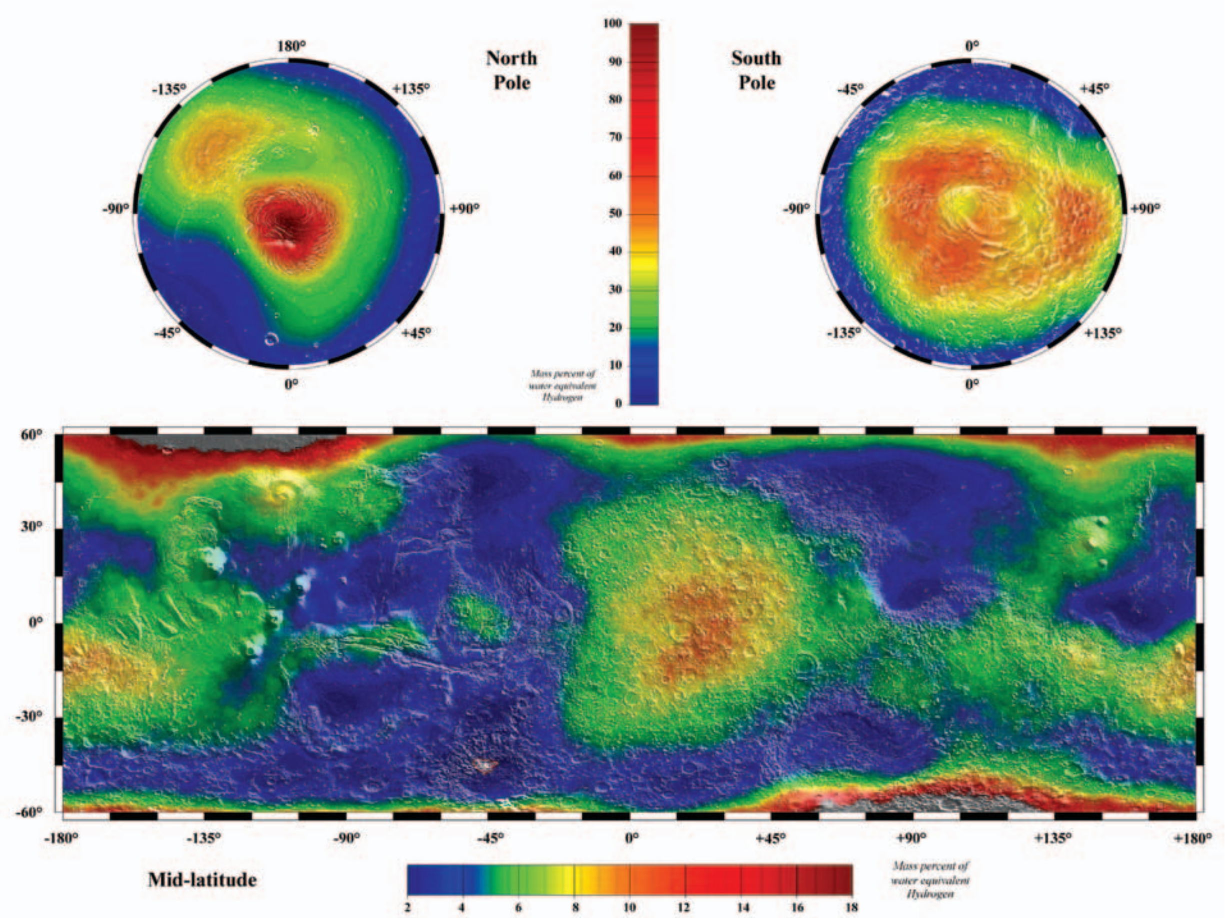

FIGURE 3 Distribution of subsurface H_2O ice. This global map was made using data from the neutron spectrometer that is part of the Odyssey Gamma Ray Spectrometer suite. The abundance of hydrogen in the form of H_2O ice is >30% poleward of ~60° in both hemispheres. Equatorial water-equivalent hydrogen abundances vary from 2% by mass (blue) to 18% (red); polar abundances vary from 0% (blue) to 100% (red). DATA ADAPTED FROM FELDMAN ET AL. (2002)

This prediction is in excellent agreement with the mapping of H_2O ice abundances by the Mars Odyssey Neutron Spectrometer, High Energy Neutron Detector, and Gamma Ray instruments (Boynton et al. 2002; Mitrofanov et al. 2002; Feldman et al. 2002). These instruments discovered high hydrogen abundances in the uppermost meter extending from the pole to 50° in both hemispheres (e.g. Feldman et al. 2002) (FIG. 3). Assuming that the hydrogen is in H_2O ice, the ice content of the upper meter is >70% by volume over large regions in the high latitudes. This great abundance is unlikely to have resulted from gas diffusion into soil pores; instead, it more likely represents accumulation as surface snow or frost.

Morphological Evidence for Subsurface Ice

The presence of ice-rich materials in the mid-latitudes has long been postulated on the basis of (1) lobate, grooved, and ridged textures suggestive of flow on channel, crater, and mesa walls (FIG. 4); (2) unusual lobate crater ejecta possibly formed by fluidization of ground ice; (3) evidence for volcano–ice interactions; and (4) possible evidence for glacial landforms and processes (see review by Clifford et al. 2000).

Additional evidence for ground ice comes from a pervasive "basketball" surface texture found between 30° and 50° in both hemispheres (Mustard et al. 2001). This unit is 1–10 m thick and is interpreted to result from the desiccation and erosion of once ice-rich soils that formed through diffusion of water vapor into soil pore spaces (Mustard et al. 2001). This material does not have a hydrogen signature, in agreement with the predicted desiccation of the upper 1–2 m at these latitudes (e.g. Mellon and Jakosky 1995; Mellon et al. 2004). However, the mantle changes poleward to a smooth, unpitted surface with a high hydrogen abundance, suggesting that it may also have formed by direct condensation of snow or frost. In this case, this unit may contain substantially more water than the $1.5–6.0 \times 10^4$ km^3 initially suggested (Mustard et al. 2001). The number of small, fresh craters on these mantling units is low, suggesting that these mantles are possibly as young as 0.15 Ma but most certainly less than 10 Ma (Mustard et al. 2001).

Further evidence for ice-rich mantles is found in 1–10 m thick deposits that preferentially occur on pole-facing slopes, have features suggestive of flow, and have a distinct, rounded edge marking the upslope boundary (FIG. 5) (Carr 2001; Christensen 2003). These characteristics suggest ice-rich mantles that were once more extensive but have been removed from all but the cold, pole-facing slopes where near-surface ice is stable under solar illumination. Ice-rich materials have also been suggested in glaciers in numerous areas including Hellas and the western flanks of the Tharsis volcanoes (e.g. Head et al. 2005).

MODERN GULLIES

Recent gullies are found in the 30–50° latitude range in both hemispheres (e.g. Malin and Edgett 2001), and their origin is the topic of vigorous, ongoing discussion. It has been proposed that they form from a range of processes, but the most plausible hypotheses are the discharge of liquid water from subsurface aquifers, the melting of pore ice that diffused inward from the atmosphere during periods of colder temperatures, and the melting of a snow layer

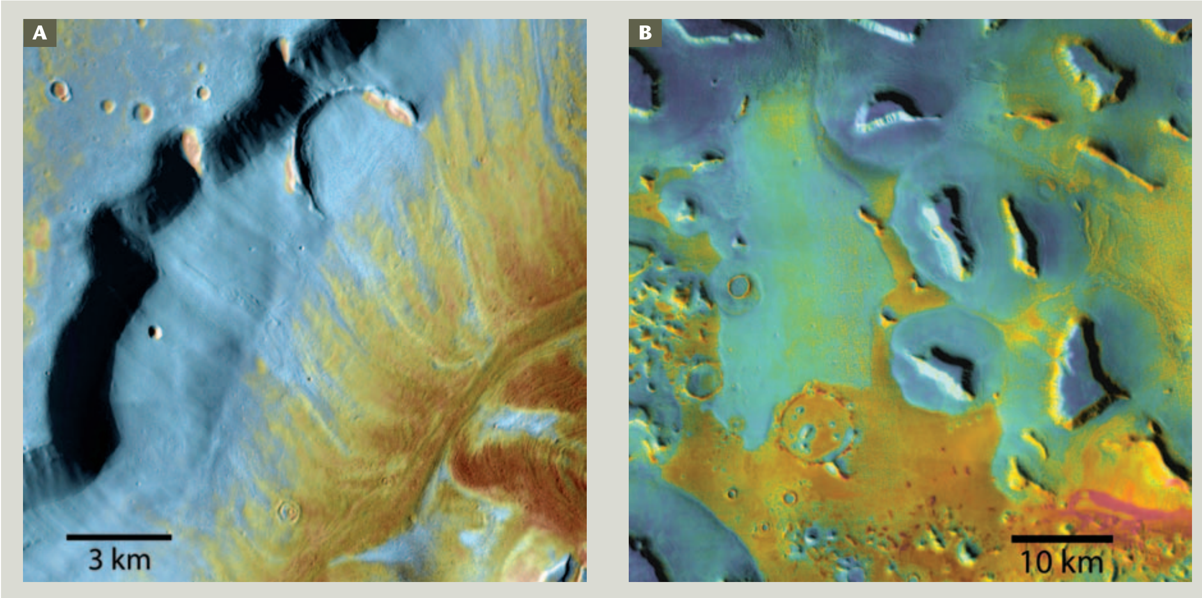

FIGURE 4A Ice-rich terrains in the northern mid-latitude region. Ice-rich soils have flowed down the wall of this valley centered near 37.6°N, 15.8°E. This image is a mosaic of THEMIS VIS images that has been colorized using the daytime temperatures determined by the THEMIS IR camera. Bands of bright material can be traced more than 10 km downslope. They show the flow reaching the bottom of the local slope and turning northeast to continue to flow down the valley. Temperatures range from –40°C to –34°C, with colder temperatures (blue tones) associated with darker or rockier surfaces and warmer temperatures (reddish tones) related to brighter or dustier surfaces. IMAGE CREDIT NASA/JPL/ARIZONA STATE UNIVERSITY

FIGURE 4B Lobes of ice-rich material flowing off mesas in the northern hemisphere. THEMIS VIS images colorized using nighttime temperatures from the THEMIS IR camera. Lobes of material are colder at night, and therefore they are finer-grained and less rocky than the substrate over which they are flowing. These distinct differences in surface properties between the lobes and the substrate provide strong evidence that this process is youthful and possibly active, because there has not been sufficient time for the homogenization of the properties of these different surfaces. Mosaic of THEMIS images centered near 43°N, 27.5°E. IMAGE CREDIT NASA/JPL/ARIZONA STATE UNIVERSITY

deposited during periods of higher obliquity when surface ice was stable at these latitudes (see review by Heldmann and Mellon 2004).

Of these models, the melting of pore ice does not account for the fact that as the surface and subsurface temperatures warm, the upper soil layer will become desiccated before significant liquid water can be produced (Mellon and Phillips 2001; Christensen 2003); if ice forms by vapor diffusion, it will dissipate by the same mechanism. Water released from subsurface aquifers (Malin and Edgett 2001) explains gully morphology, latitudinal distribution, and slope position (Heldmann and Mellon 2004). However, this model does not account for the presence of gullies on isolated knobs and dunes where there is no obvious aquifer source—the survival and recharge mechanism that would allow these aquifers to persist to the present—nor their formation only at latitudes poleward of 30°.

Lee et al. (2001) and Hartmann (2002) suggested that melting snow might carve Martian gullies, based on analogies with similar gully morphologies in cold regions on Earth. This model was developed (Christensen 2003) by noting the association of gullies with ice-rich, pole-facing slope mantles (FIG. 5), and by incorporating models for snow formation at high obliquity (e.g. Jakosky et al. 1995) and a model of melting within dusty Martian snow (Clow 1987). In this snowmelt model, water is transported from the poles to mid-latitudes during periods of high obliquity. Melting of this snow layer occurs at low obliquity as mid-latitude temperatures increase, producing liquid water that is stable beneath the insulating layer of snow. Gullies form within and beneath the snow as meltwater seeps into the loose slope materials and destabilizes them. Patches of snow remain today on pole-facing slopes, where they are protected against sublimation by a layer of desiccated dust/sediment. The primary argument against snowmelt is the presence of gullies on slopes of all azimuths (Heldmann and Mellon 2004).

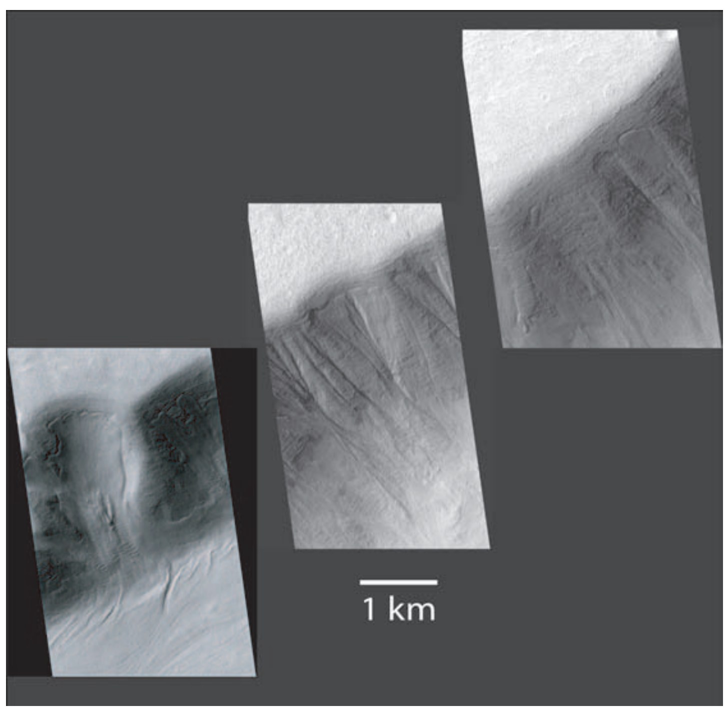

FIGURE 5 Ice-rich mantles and associated gullies on poleward-facing slopes in the southern hemisphere. This collage shows MOC images from the northwest wall of Dao Valles, between 33° and 35°S. These images show (1) well-developed flow features with compressive ridges, which are strongly suggestive of ice (left panel); (2) mantles of ice-rich material and gullies that are present only where the mantles are lacking (center panel), and (3) depressions with associated gullies, some of which still have mantles, whereas others are free of mantling material (right panel). These landforms could be explained by the melting of a snow mantle, forming gullies that are visible only in those locations where the snow has completely disappeared. MOC IMAGES LEFT TO RIGHT: M03-04950, M09-02885, AND M0-3-6266

SUMMARY AND OUTSTANDING QUESTIONS

The poles and mid-latitudes of Mars contain a large reservoir of H_2O ice, including ~5×10^6 km^3 in polar layered materials, >6×10^4 km^3 in mid-latitude mantles and ice-rich sediments, and ~3×10^{-2} km^3 in the seasonal ice caps and atmosphere. This known reservoir, if melted, would form a layer of water ~35 m deep over the entire planet. Portions of this reservoir appear to move to lower latitudes on 10^5–10^6 year timescales. Aquifers or melting snow or both have produced liquid water at the surface in the very recent past, and these areas hold exciting promise for future exploration for past or present life. Many questions remain, and among the most intriguing are the following:

1. What is the age and history of the polar layered deposits?
2. Have the polar ice caps ever been completely removed, and what produced the significant climate change that this would imply?
3. What is the total inventory of subsurface ice?
4. What are the source(s) of the water responsible for forming the modern gullies?

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REFERENCES

Bibring J-P and 13 co-authors (2004) Perennial water ice identified in the south polar cap of Mars. Nature 428: 627-630

Boynton WV and 24 coauthors (2002) Distribution of hydrogen in the near surface of Mars: Evidence for subsurface ice deposits. Science 297: 81-85

Byrne S, Ingersoll AP (2003) A sublimation model for martian south polar ice features. Science 299: 1051-1053

Byrne S, Murray BC (2002) North polar stratigraphy and the paleo-erg of Mars. Journal of Geophysical Research 107(E6): 5044, DOI 10.1029/2001JE001615

Carr MH (2001) Mars Global Surveyor observations of fretted terrain. Journal of Geophysical Research 106(E10): 23571-23594

Christensen PR (2003) Formation of recent martian gullies through melting of extensive water-rich snow deposits. Nature 422: 45-48

Clifford SM and 52 co-authors (2000) The state and future of Mars polar science and exploration. Icarus 144: 210-242

Clow GD (1987) Generation of liquid water on Mars through the melting of a dusty snowpack. Icarus 72: 95-127

Feldman WC and 12 co-authors (2002) Global Distribution of neutrons from Mars: Results from Mars Odyssey. Science 297: 75-78

Hartmann WK (2002) Comparison of icelandic and martian hillside gullies. Proceedings of Lunar and Planetary Sciences 33: Abstract 1904

Head JW and 13 coauthors (2005) Tropical to mid-latitude snow and ice accumulation, flow and glaciation on Mars. Nature 434: 346-351

Heldmann JL, Mellon MT (2004) Observations of martian gullies and constraints on potential formation mechanisms. Icarus 168: 285-304

Herkenhoff KE, Plaut JJ (2000) Surface ages and resurfacing rates of the polar layered deposits on Mars. Icarus 144: 243-253

Jakosky BM, Barker ES (1984) Comparison of ground-based and Viking Orbiter measurements of Martian water vapor: Variability of the seasonal cycle. Icarus 57: 322-334

Jakosky BM, Farmer CB (1982) The seasonal and global behavior of water vapor in the Mars atmosphere: Complete global results of the Viking atmospheric water detector experiment. Journal of Geophysical Research 87: 2999-3019

Jakosky BM, Henderson BG, Mellon MT (1995) Chaotic obliquity and the nature of the Martian climate. Journal of Geophysical Research 100(E1): 1579-1584

James PB, Cantor BA (2001) Martian north polar cap recession: 2000 Mars Orbiter Camera observations. Icarus 154: 131-144

Kieffer HH (1979) Mars south polar spring and summer temperatures: A residual CO2 frost. Journal of Geophysical Research 84: 8263-8289

Kieffer HH, Titus TN, Mullins KF, Christensen PR (2000) Mars south polar cap spring and summer behavior observed by TES: Seasonal cap evolution controlled by frost grain size. Journal of Geophysical Research 105(E4): 9653-9700

Lee P, Cockell CS, Marinova MM, McKay CP, Rice JW (2001) Snow and ice melt flow features in Devon Island, Nunavut, Arctic Canada as possible analogs for recent slope flow features on Mars. Proceedings of Lunar and Planetary Sciences 1809 (abstract) [CD-ROM]

Leighton RB, Murray BC (1966) Behavior of carbon dioxide and other volatiles on Mars. Science 153: 136-144

Malin MC, Caplinger MA, Davis SD (2001) Observational evidence for an active surface reservoir of solid carbon dioxide on Mars. Science 294: 2146-2148

Malin MC, Edgett KS (2001) Mars Global Surveyor Mars Orbiter Camera: Interplanetary cruise through primary mission. Journal of Geophysical Research 106(E10): 23429-23570

Mellon MT, Jakosky BM (1995) The distribution and behavior of Martian ground ice during past and present epochs. Journal of Geophysical Research 100 (E6): 11781-11799

Mellon MT, Phillips RJ (2001) Recent gullies on Mars and the source of liquid water. Journal of Geophysical Research 106(E10): 23165-23180

Mellon MT, Feldman WC, Prettyman TH (2004) The presence and stability of ground ice in the southern hemisphere of Mars. Icarus 169: 324-340

Milkovich SM, Head JW III (2005) North polar cap of Mars: Polar layered deposit characterization and identification of a fundamental climate signal. Journal of Geophysical Research 110: E01005, doi:10.1029/2004JE002349

Mitrofanov I and 11 coauthors (2002) Maps of subsurface hydrogen from the High Energy Neutron Detector, Mars Odyssey. Science 297: 78-81

Mustard JF, Cooper CD, Rifkin MK (2001) Evidence for recent climate change on Mars from the identification of youthful near-surface ground ice. Nature 412: 411-414

Pollack JB, Toon OB (1982) Quasi-periodic climate changes on Mars: A review. Icarus 50: 259-287

Smith DE, Zuber MT, Neumann GA (2001) Seasonal variations of snow depth on Mars. Science 294: 2141-2146

Smith MD (2004) Interannual variability in TES atmospheric observations of Mars during 1999–2003. Icarus 167: 148-165

Thomas PC, Malin MC, Edgett KS, Carr MH, Hartmann WK, Ingersoll AP, James PB, Soderblom LA, Veverka J, Sullivan R (2000) North-south geological differences between the residual polar caps on Mars. Nature 404: 161-164

Titus TN, Kieffer HH, Christensen PR (2003) Exposed water ice discovered near the south pole of Mars. Science 299: 1048-1051

Zuber MT and 20 co-authors (1998) Observations of the north polar region of Mars from the Mars Orbiter Laser Altimeter. Science 282: 2053-2060