THE LIMITS OF THEORETICAL MODELING AND GEOMORPHIC INTERPRETATION IN ASSESSING THE PRESENT DISTRIBUTION OF SUBSURFACE H_2O ON MARS. S. M. Clifford, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, clifford@lpi.usra.edu.

Introduction: The search for water has been identified as the principal objective and common thread of Mars research [1]. Of the planet's estimated 0.5 –1 km global inventory of H_2O [2], ~0.000001% is found in the atmosphere and ~5-10% is thought to be stored as ice in the perennial polar caps and layered terrain. This leaves ~90-95% of the planetary inventory of H_2O that is unaccounted for, the vast bulk of which is believed to reside, as ground ice and groundwater, within the planet's crust.

The expected distribution and state of subsurface water on Mars, as well as plausible values of the large-scale physical, thermal, and hydraulic properties of its crust, have been discussed by a number of investigators [3-8]. To a first order, subsurface conditions on Mars are expected to resemble those found in cold-climate regions on Earth, particularly the unglaciated, continuous permafrost regions of Antarctica, Siberia, and North America. This similarity is likely to extend to an equivalent level of geologic complexity and spatial variability in such characteristics as lithology, structure, stratigraphy, porosity, volatile content, permeability, and mechanical and thermal properties.

Theoretical Modelling: Given the uncertainty regarding the amount and distribution of subsurface water, a variety of theoretical and geomporphic techniques have been employed to infer where it might reside -- most notably with respect to the stability and distribution of ground ice. The very earliest efforts [9-11] considered the distribution of ice in equilibrium with the zonally-averaged mean annual surface temperature and water vapor content of the atmosphere. Later studies [12-14] examined the stability and evolution of ground ice under disequilibrium conditions, investigating how plausible values of regolith thermophysical and diffusive properties might influence the latitudinal stability of ground ice in an otherwise homogeneous crust. More recent investigations [15-16] have examined how local variations in the radiative and thermophysical properties of the surface could lead to significant geographic differences in ground ice stability, suggesting that – in some regions, under favorable conditions – fossil ground ice might survive at shallow depth even at the equator.

These latter studies have suggested to some that the simple acquisition of high spatial resolution thermal data might allow us to predict the present distribution of ground ice with considerable precision. This belief is based on the assumption that the thermal and diffusive properties of the regolith are well understood and can be extrapolated, with confidence, to depths as great as ~10^2 – 10^3 m. In truth, we are ignorant about many fundamental characteristics of the Martian near-surface and especially of how the thermal and diffusive properties of the crust vary both geographically and at depth – variations that are inherently unpredictable, yet play a determining role in the evolution and vertical distribution of subsurface H_2O.

As evident from the stratigraphic variations visible in a lunar soil profile, terrestrial drill core, or high resolution image of the walls of Valles Marineris, the properties of a planetary crust can vary dramatically on size scales that range from ~10^{-3} - 10^3 m. Given the sheer number of properties that may vary, the potential amplitude of these variations, and the random spatial frequency and thickness of possible layers, the transport properties of the crust can easily change by many orders of magnitude over a depth interval as small as a few millimeters. For this reason, plausible permutations of crustal diffusive and thermal properties can result in intricate combinations of low- and high-permeability strata that yield substantial differences in the local distribution of ground ice.

Theoretical predicitions are further complicated by our ignorance of the local geologic evolution of the crust – especially geographic and temporal variations in crustal heat flow. Indeed, no direct measurements of Martian geothermal heat flow have yet been made, although published estimates (based on a variety of theoretical, compositional, and geophysical arguments, summarized in [5]), suggest a present day mean global value of ~30 mW m^{-2} (±15 mW m^{-2}). Measurements of continental heat flow on Earth [17-18] suggest that regional-scale (i.e., ~10^7 km^2) differences – due to crustal age, thickness, volcanic and tectonic history, elemental content of U, Th and K, as well as temporal variations in mantle convection – yield an additional ±50% variation in heat flow about the crustal mean. Of course, at smaller scales, the range of local thermal conditions may be far greater – varying from nearly isothermal conditions in the ancient highland crust, to gradients of as much as 1-10 K m^{-1} in regions of recent magmatic activity.

These arguments suggest that, although theoretical predictions of subsurface volatile distribution can be of value in understanding potential global and regional-scale behavior, their use at the local scale is likely to provide little insight below the diurnal skin depth – regardless of the precision and resolution to which the present thermal and radiative properties of the surface may be known. This conclusion applies, not only to our understanding of the distribution of ground ice, but to virtually every other aspect of the local volatile structure and physical properties of the crust.

Geomorphic Interpretation: The other principal approach that has been used to infer the distribution of subsurface H_2O, is geomorphic analysis – where the size, density, and geographic distribution of various landforms, attributed to the presence of subsurface liquid water or ice, has been used to infer such properties as the local abundance, state and distribution of H_2O. However, geomorphic analysis has two significant shortcomings: (1) the interpretations are generally not unique and (2) the information it conveys may be millions to billions of years old. These deficiencies seriously limit the utility of geomorphic indicators as reliable and quantitative guides to the present distribution of ground ice and groundwater.

These limitations are readily illustrated by consideration of the Martian gullies – which were first interpreted as originating from recent (and possibly contemporary) discharges of liquid water from shallow depth [19]. However, subsequent analyses have raised significant doubts about the uniqueness and plausibility of the shallow aquifer hypothesis.

Some key characteristics of the gullies are: a fluvial-like morphology that incises the local terrain; a shallow depth of origin

(~100-500 m, on topographic exposures as varied as simple scarps, mesas, knobs, crater walls and central peaks); an apparent youthful age (<10^7 years, supported by their fresh appearance and superpositional relationship to other assumed transient landforms); a geographic distribution, in both hemispheres, that is restricted to latitudes between ~30^o and 70^o; a preferential occurrence (by a factor of 2-to-1) on poleward-facing slopes; and a lack of any obvious association with areas of past geothermal activity, such as Tharsis and Elysium [19].

If the gullies were formed by the discharge of liquid water from shallow aquifers, then it implies a combination of geothermal heat flow, crustal thermal conductivity, and groundwater freezing temperature sufficient to reduce the local thickness of frozen ground by a factor of ~10-10^2 over the values generally expected to characterize the cryosphere at mid-latitudes [e.g., 5 & 8]. Of these three variables, the one most likely to exhibit the greatest variability (when considered on a spatial scale of kilometers) is the planet's geothermal heat flow which, in localized areas, might easily exceed the estimated global mean by as much as several orders of magnitude (assuming the presence of local igneous activity). Although an enhanced local heat flow might explain the origin of some gullies [19-20], it fails to explain three of their most notable characteristics: their observed latitudinal distribution, their preferential occurrence on poleward-facing slopes, and – most importantly – their lack of any obvious association with recognized regions of past geothermal activity.

Near-surface liquid water might also occur due to the presence of potent freezing-point depressing salts, such as $CaCl_2$ and $MgCl_2$, which could lower the freezing point by as much as 60 K (to ~210 K) [21-22]. But the involvement of brines in the origin of the gullies is difficult to reconcile with the lack of evaporite deposits and the inability of brines to explain either the latitudinal distribution or poleward-facing orientation of the gullies.

Another possibility is that shallow aquifers arise from the presence of thick mantles of extremely low thermal conductivity regolith, that create a sufficiently large near-surface geothermal gradient that the temperature of the local crust is raised above the melting point at a depth of just a few hundred meters [23]. However, to retain its low conductivity, such a mantle must remain ice-free – a condition that requires that it be diffusively isolated from the underlying aquifer by an essentially impervious barrier. In the abscence of such a barrier, sufficient water vapor will diffuse from the aquifer to saturate the pore volume of the mantle with ice in a geologically short period of time (~10^3 – 10^7 years, [24]), thereby increasing its thermal conductivity enough to cause any near-surface aquifer to freeze. This requirement for diffusive isolation is clearly inconsistent with the widespread occurrence of gullies in such highly disrupted terrains as the interior walls and central peaks of large craters.

Given the difficulty of reconciling the shallow aquifer hypothesis with both plausible environmental conditions and the need to explain the various enigmatic characteristics of the gullies, a variety of alternative explanations – such as liquid CO_2 [25] and dry mass wasting [26] – have been proposed. Yet, these alternatives appear to raise at least as many questions as the shallow aquifer hypothesis.

Currently, the best explanation for the origin of the gullies (or at least the one that appears to satisfy the most serious environmental and observational constraints) is the melting of near-surface ice at times of high obliquity [27-28]. For obliquities >45o, the peak insolation on poleward facing slopes at mid- to high-latitudes can yield summertime surface temperatures that easily exceed the melting. Under these conditions, large amounts of water ice are expected to sublime and melt from the summer polar ice cap – increasing the atmospheric vapor pressure of H_2O sufficiently to allow liquid water to flow readily across the surface. This input of vapor could also amplify the extent of polar warming by creating a transient and localized water vapor greenhouse [29]. Under such conditions, formerly stable near-surface ice deposits could conceivably melt and produce sufficient run-off to form the gullies.

The preceding analysis is by no means exhaustive, nor does it conclusively refute the viability of any of these mechanisms for the origin of some gullies. But it does demonstrate the enormous uncertainties associated with interpreting the volatile significance of many Martian landforms.

Conclusion: Our ignorance about the heterogeneous nature and thermal evolution of the crust effectively precludes theoretical or geomorphic attempts to identify and quantitatively assess the current geographic and subsurface vertical distribution of ground ice and groundwater on Mars. Terrestrial experience has demonstrated that geophysical investigations (involving the application of multiple techniques) are best suited to this task [30]. Although subject to interpretive ambiguity, the acquisition of such data, analyzed in conjunction with other remote sensing information, offers the most technically capable approach yet proposed for conducting a global reconnaissance to assess the distribution and state of subsurface H_2O on Mars.

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