Possible Fossil H₂O Liquid–Ice Interfaces in the Martian Crust

LAURENCE A. SODERBLOM
United States Geological Survey, 2255 North Gemini Drive, Flagstaff, Arizona 86001

AND

DAVID B. WENNER
Department of Geology, University of Georgia, Athens, Georgia 30602

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Throughout the northern equatorial region of Mars, extensive areas have been uniformly stripped, roughly to a constant depth. These terrains vary widely in their relative ages. A model is described here to explain this phenomenon as reflecting the vertical distribution of H₂O liquid and ice in the crust. Under present conditions the Martian equatorial regions are stratified in terms of the stability of water ice and liquid water. This arises because the temperature of the upper 1 or 2 km is below the melting point of ice and liquid is stable only at greater depth. It is suggested here that during planetary outgassing earlier in Martian history H₂O was injected into the upper few kilometers of the crust by subsurface and surface volcanic eruption and lateral migration of the liquid and vapor. As a result, a discontinuity in the physical state of materials developed in the Martian crust coincident with the depth of H₂O liquid–ice phase boundary. Material above the boundary remained pristine; material below underwent diageneric alteration and cementation. Subsequently, sections of the ice-laden zone were erosionally stripped by processes including eolian deflation, gravitational slump and collapse, and fluvial transport due to geothermal heating and melting of the ice. The youngest plains which display this uniform stripping may provide a minimum stratigraphic age for the major period of outgassing of the planet. Viking results suggest that the total amount of H₂O outgassed is less than half that required to fill the ice layer, hence any residual liquid eventually found itself in the upper permafrost zone or stored in the polar regions. Erosion stopped at the old liquid–ice interface due to increased resistance of subjacent material and/or because melting of ice was required to mobilize the debris. Water ice may remain in uneroded regions, the overburden of debris preventing its escape to the atmosphere. Numerous morphological examples shown in Viking and Mariner 9 images suggest interaction of impact, volcanic, and gravitational processes with the ice-laden layer. Finally, volcanic eruptions into ice produces a highly oxidized friable amorphous rock, palagonite. Based on spectral reflectance properties, these materials may provide the best analog to Martian surface materials. They are easily eroded, providing vast amounts of eolian debris, and have been suggested (Toulmin et al., 1977) as possible source rocks for the materials observed at the Viking landing sites.

INTRODUCTION

During the past 15 years numerous theoretical studies have suggested that water ice may be widely distributed throughout the near-surface materials on Mars (Lederberg and Sagan, 1962; Leighton and Murray, 1966; Wade and DeWys, 1968; Anderson et al., 1967; Smoluchowski, 1968; Fanale, 1976). These studies are commonly based on the realization that the mean
annual surface temperature over the Martian globe is well below the H₂O triple point. Fanale (1976) has shown that north and south of approximately the 40° latitudes, the mean annual surface temperature is low enough for subsurface ice to be in equilibrium with the current levels of water vapor in the atmosphere. Additionally Smoluchowski (1968) demonstrated that a fine-grained overburden of debris in the equatorial region could prevent substantial loss of water ice over billions of years, even in the equatorial regions where the temperatures are too high for ice to exist in equilibrium with the atmosphere.

The first morphological evidence that water ice in the Martian crust may have affected terrain development was described by Sharp et al. (1971) on the basis of Mariner 6 images. Those authors described a series of complex erosional terrains in the equatorial region termed chaotic terrain, which developed by the gradual collapse of older terrains. It was suggested that loss of water ice played a dominant role in the formation of these depressed areas. Mariner 9 images showed that the chaotic terrain was only one of several variates of a collection erosionally depressed terrains. These are described by (Sharp, 1973a,b) as chaotic, fretted, and troughed terrains which exist throughout the equatorial region. Studies by Cutts (1973) and Soderblom et al. (1973) showed that the volume of materials incorporated in the polar deposits and thick debris mantles is similar to the volume of material removed from the chaotic terrains. This suggests deflation may have also played a major role in formation of the depressed terrains. Viking orbital imaging data, of much higher quality and resolution, showed a tremendously varied collection of surface landforms which suggest the presence of ground ice (Carr and Schaber, 1977). These geomorphic forms include impact ejecta which appear to have flowed as coherent masses; extensive low-angle debris flows, suggesting creep of ice-ridden materials; and a tremendous variety of collapse terrains suggestive of thermokarst development. Mariner 9 data also showed a variety of channel forms which many observers thought to be evidence for fluvial erosion on Mars (cf. Masursky, 1973; Milton, 1973). Viking data provided substantially more evidence for fluvial erosion and deposition (Masursky et al., 1977).

Findings from Viking atmospheric investigations also provide important constraints on models which invoke water and ice to explain various Martian morphologies. Measurements of the elemental and isotopic composition of the atmosphere by mass spectrometers aboard the Viking landers and descent modules provide quantitative limits of the outgassed volatiles. Based primarily on the abundance of ³⁶Ar, Owen et al. (1976), McElroy et al. (1977), and Anders and Owen (1977) have argued that the total amount of water degassed from the Martian interior was most likely in the range of 10 to 50 m if uniformly distributed over the planet. This is about a factor of thirty lower than would have been suggested for an Earth analogous Mars which had the same volatile inventory and degree of outgassing (Fanale, 1976).

The purpose of this paper is to present morphological evidence which suggests that below the permafrost zone containing H₂O ice, a second zone exists in which liquid water is stable and at least temporarily resided. It is suggested that this stratification implanted a discontinuity in the Martian crust. This discontinuity is reflected in both the chemical and the physical state of materials above and below the boundary. Material below underwent diagenetic alteration and cementation; material above remained pristine and fragmented, containing variable amounts of ice. Subsequently, this discontinuity controlled the morphologic character of extensive chaotic and fretted terrains which developed in the equatorial regions.
Fig. 1. Distribution of erosional scarps bounding the chaotic, fretted, and troughed terrains on Mars. The troughed terrain (denoted as "Regional of Strong Structural Control") has evidently undergone major tectonic development as well as the erosional stripping discussed in this paper. The shaded relief is from U.S. Geological Survey Map M 25M 2R (I-940).
Fig. 2. Examples of fretted and chaotic terrains which occur throughout the equatorial region. These are mosaics of Mariner 9 mapping frames. Each mosaic covers approximately 600 by 1200 km. Lighting is from the west with solar elevation angles between 15 and 25°. (a) Southwestern section of Mars Chart-11 (center near 35°W, 5°N). (b) Northcentral section of Mars Chart-10 (center near 65°W, 20°N). (c) Southeastern section of Mars Chart-5 (center near 315°W, 40°N).

A UNIFORM DEPTH OF STRIPPING

Chaotic terrain, originally described by Sharp et al. (1971), occurs as broad depressed areas with rough and knobby floors surrounded by breakaway scarps developed by slump and collapse along the boundaries of older higher terrains. Mariner 9 and Viking Orbiter photographs have shown that chaotic terrain is only one style in a variety of erosional forms which form an immense system occupying a significant fraction of the equatorial belt.
Figure 1 shows the distribution of the network of scarps which bound these extensive depressed terrains. Following Sharp we divide these erosional provinces into two general types: (1) troughed terrain described by Sharp (1973a) as “An assemblage of huge parallel troughs, individually up to 200 km wide and hundreds of kilometers long, forms a belt 500 km wide extending for 2700 km . . . . Parallel linear chains of rimless pits and shallow graben on the adjacent cratered upland suggest structural control of trough development by fractures in the Martian crust,” and (2) fretted and chaotic terrain which occur as smooth to hummocky or debris ridden lowlands developed at the expense of the surrounding high plains and uplands and separated from them by irregular scarps of varied planimetric form (Sharp et al., 1971, Sharp, 1973b). Sharp (1973a,b) suggested the evaporation of ground ice and eolian erosion to have been dominant processes in the development of both types of terrain, troughed terrain being additionally developed by tensional faulting. Figure 1 shows the zone of occurrence of the troughed terrain displaying strong structural control. The tectonic influence is further documented by Viking orbital images (Blasius et al., 1977). In this paper we restrict ourselves to the lowlands and surrounding scarps of the chaotic and fretted terrains. Although the mechanism described here may well have been active in generating both types, the troughed terrain is complicated by tectonic influence and thus is excluded from this discussion.

Figures 2 and 3 show the variability in the planimetric form of the erosional scarps which bound extensive depressed areas of chaotic and fretted terrains. Examples in Figs. 2 and 3 demonstrate that fretted and chaotic terrain has developed in ancient degraded cratered terrains as well as in younger plains. These photographs portray a peculiar characteristic of the scarps—the remarkable apparent uniformity of the depth to which the erosional processes have operated. The escarpments which occur over a wide range of latitudes and longitudes in terrains of markedly varied relative age, appear to have a very uniform height. Topographic profiles from CO₂ pressure mapping of the Mariner Mars 1971 ultraviolet spectro-
Fig. 3. High-altitude Viking images of chaotic and fretted terrains in the north equatorial region. These images were acquired by cameras aboard the Viking Orbiter I from an altitude of about 30,000 km. In this oblique view north is to the upper left. The scene covers roughly 1500 × 1500 km centered on the equator at 35°W.

Another interesting observation arises from comparison of regional elevations (Wu, 1975) with the locations of the erosional escarpments in Fig. 1. This reveals that the escarpments maintain their apparently uniform height even where the altitude of the original uneroded surface varies by several kilometers over distances of a few hundred kilometers. For instance, the eastern edge of Lunae Planum, bounded by one such scarp (Fig. 2b) varies by more than 5 km in elevation in the area shown. This suggests that the depth to which the erosional process operates is keyed to the actual topographic surface and is not correlated with absolute altitude.

In summary Mariner 9 and Viking photography shows a planetwide erosional system of depressed terrains developed by erosional processes which appear to have operated to a roughly uniform depth of 1 to 2 km below the preexisting surface. This depth does not appear to be affected by either the type or relative age of the terrains being eroded or by the absolute altitude of the original surface.
Fig. 4. Elevation profiles based on Mariner 9 ultraviolet spectrometer data across scarps bounding chaotic and fretted terrains. Data reduction described by Hord et al. (1972)
Under current conditions on Mars, the annually averaged surface temperature near the equator is about 225°C, controlled primarily by radiative equilibrium (Leighton and Murray, 1966; Kieffer et al., 1977). The average temperature decreases with increasing latitude reaching about 200°C at ±45° and about 160°C at the poles based on the Leighton and Murray model. Consequently, below the upper few meters where the diurnal and seasonal fluctuations are damped out, the temperatures are more than 50°C below the triple-point of water; only ice can exist at such temperatures. Fanale (1976) has pointed out that north and south of about the 40° latitudes, the average temperatures are cold enough for ice to exist in equilibrium with an atmospheric water vapor content of 10 precipitable microns. Farmer et al. (1977) have shown that the average annual water vapor content is, in fact, about 10 μm. Further, Smoluchowski (1968) demonstrated that a sufficiently fine-grained and compact overburden of debris would prevent substantial loss of buried ice over cons. Viking lander results have demonstrated that the near-surface materials are extremely fine-grained and compacted; a fine-grained lightly cemented layer termed duricrust exists in the upper few centimeters at both landing sites (Mutch et al., 1977). These factors taken together suggest that H₂O ice may be stable in the near surface (a few meters or tens of meters below the surface) over the entire globe over cons.

The primary region of interest in this paper is the equatorial band, approximately ±30° in latitude. Leighton and Murray (1966) calculate an average model temperature of 215 to 225°C for that region. Variations in surface properties (albedo and emissivity) will cause the actual temperatures to vary by several degrees throughout this region (Kieffer et al., 1977). Hence the average temperature is 50 ± 5°C below the triple-point of water. Fanale (1976) has estimated a near-surface thermal gradient for Mars of about 30°C/km.
assuming K, U, and Th abundance typical of chondrites and a thermal conductivity typical of ice-ridden limonitic soils. The conductivity might be somewhat lower if the surface materials are ice-free or somewhat higher if they are very compact. For example, loose dry sand is a factor of 2 lower and coherent basalt a factor of 3 higher than the value Fanale used. These are clearly extremes; variations are probably much less than a factor of 2. This would imply that the gradient may vary from ~20 to 50°C/km. Hence the depth at which the melting point of ice is reached is probably 1 to 2 km below the surface throughout the equatorial band; liquid water can only exist below this depth. The depth of the interface will vary depending on the local nature of albedo, emissivity, thermal conductivity, and radiogenic concentration.

Assume now that earlier, during the outgassing of Mars, these temperature conditions existed. Based on the atmospheric abundance of 36Ar, Owen et al. (1976), McElroy et al. (1977), and Anders and Owen (1977) have estimated that a total of only 10 to 50 m of H2O could have devolved from the Martian interior. This is an equivalent depth averaged over the planet. Presumably this water was released in conjunction with volcanic eruptions. Gradually H2O liquid migrated laterally, upward, and downward from subsurface intrusions and surface eruptions. Ice formed in the region above the melting point isotherm. Because an overburden of 1 to 2 km of ice and debris would easily allow the buildup of H2O partial pressure to a few millibars, particularly in volcanic regions where outgassing was concentrated, liquid water condensed at depths below the melting point interface. As ice continued to fill the upper zone, the thermal conductivity increased (probably by much less than a factor of 2) and the liquid–ice interface gradually moved deeper in the crust. Materials in the lower wet zone underwent solution weathering, diagenesis, and cementation, depending on the local availability of water; material above remained pristine containing variable amounts of ice.

Assuming a porosity of about 10%, the total volume of water which could be stored in the upper zone is much greater than that available. Thus any residual liquid soon migrated to the upper zone or to the poles. If the H2O was freed in conjunction with volcanic eruption it was probably locally concentrated. Notice in Fig. 1 that the major occurrence of the chaotic and fretted terrains is just east and downslope from the Tharsis volcanic region. If the outgassing were concentrated in regions such as this it is possible that the ice layer may be locally saturated and diagenesis more advanced in the subjacent zone.

Later in Martian history, following the major period of outgassing, the extensive erosional complex of the equatorial region developed. The chaotic, fretted, and troughed terrains which make up this system are thought to have developed by a combination of processes involving sublimation of the ice, geothermally induced melting of the ice, gravitationally induced collapse, torrential floods of ponded water, tectonic adjustment, and eolian deflation (Sharp et al., 1971; Sharp, 1973a,b; Carr et al., 1976; Masursky et al., 1977). It is proposed here that the stratified nature of the crust, resulting from zones of stability of H2O liquid and ice, strongly influenced the morphology of these stripped terrains. The erosional processes operated to a roughly fixed depth for two reasons. First the lower zone would be more resistant to erosion having undergone cementation and alteration during outgassing where liquid water was locally present. In contrast the upper zone remained a pristine collection of fragmental impact breccias and volcanic ash deposits and flows containing variable amounts of ground.
ice. Second, many of these processes may require ice to mobilize the debris. As only the zone above the interface has contained ice, only that zone would be mobilized. In areas where outgassing was concentrated and the ice layer saturated, such processes would be dramatically enhanced.

MORPHOLOGICAL EVIDENCE FROM VIKING

The Viking Orbiter Imaging Systems provided images of higher resolution and of substantially lower noise content than Mariners 4, 6, 7, and 9. Additionally, the Martian atmosphere was extremely clear at the time of Viking arrival (Carr et al., 1976). As a result, a variety of unusual morphologies have been photographed by Viking with detail far exceeding that available from Mariner 9. Contained in the Viking data are numerous examples which strongly support the hypothesis that water ice and running water have played a dominant role in shaping the Martian

![Mosaic of Viking Orbiter frames of a typical impact crater displaying peculiar ejecta flow. This morphology may have resulted from impact in ice (Carr et al., 1977). The crater, located near 22°N, 34°W, is about 20 km in diameter. The images were acquired on the third revolution of Viking Orbiter I.](image-url)
Fig. 6. Mosaic of Viking Orbiter I images of large outflow channel. These images, acquired on the 14th orbit, cover about 100 by 200 km, centered near 28°N and 42°W.
surface. Illustrative examples are provided here; such evidence is described in detail by Carr et al. (1977), Carr and Schaber (1977), and Masursky et al. (1977).

A peculiar crater morphology found to be widespread from the Viking data, is shown in Fig. 5. These craters display ejecta blankets which appear to have flowed out. Such craters are typically 5 to 20 km in diameter. It has been suggested by Carr et al. (1977) that this morphology was produced by impact in ice and/or water-saturated ground. If true, craters displaying such ejecta blankets can be used to establish the stratigraphic or relative age and lifetime of the ice. The oldest flow-ejecta craters would then provide a minimum age for the major outgassing. The youngest of such craters in a particular region would mark the time at which the ice shell was lost.

Figure 6 shows the head of a broad channel near Capri Chasma. Carr et al. (1976) and Masursky et al. (1977) have suggested that such morphologies may reflect endogenic melting of ground ice, ponding, and release as a flood much like subglacial eruptions and floods found in Greenland. We concur with this interpretation and suggest further that the tremendous variation in morphology of the Martian fluvial systems (dendritic patterns, catastrophic floods plains) may result from the highly variable nature local slopes of the terrains. As mentioned earlier, the Martian ice shell would form in lowlands and highlands alike. Hence, heating of flat plains areas could produce ponding and flooding; heating of rough highland terrain would produce a myriad of springs, as ponding would be impossible in areas of substantially local relief. Such multiple sources would have generated the observed dendritic drainage patterns (e.g. Fig. 7); rain, persay, may not therefore be required to produce such patterns.

**Fig. 7.** Viking Orbiter I frames displaying a myriad of dendritic channels in the south equatorial highland region. The frames in this mosaic were acquired on the 84th orbit and cover approximately 250 × 500 km centered near 27°S, 2°W.
GEOCHEMICAL IMPLICATIONS

Although it is difficult to predict what specific geochemical reactions might occur as a consequence of the above-mentioned model, one might expect that basalt would interact with H$_2$O ice and liquid at the time of intrusion or extrusion. In a terrestrial environment, lavas react with water to form palagonite, a highly oxidized, soft brown-to-yellow isotropic mineraloid. If this palagonite were in communication with liquid water below the freezing-point interface, one might expect further diagenesis. In a terrestrial aqueous environ-

![Graph](image)

Fig. 8. Comparison of spectral reflectivities for Antarctic palagonites and for Martian bright and dark regions (from McCord and Westphal, 1971). The palagonite spectra were supplied by T. V. Johnson and F. P. Fanale of the Jet Propulsion Laboratory. The Antarctic samples show deep absorptions near 1.4 and 1.9 μm due to absorbed water. The samples are trachy-basalts which vary from strongly (A, B) to weakly (C) palagonitic. The comparison is not intended as an identification but as a demonstration that deep ferric absorptions and high infrared reflectivities as observed for Mars are produced by simple interaction of basaltic lavas and ice.
ment, palagonite is unstable and probably alters to carbonates, zeolites, and montmorillonites (Nayudu, 1964, Bonatti, 1970). In fact compositional measurements by the X-ray fluorescence experiments aboard the Viking landers are most compatible with a mineralogy consisting of iron oxides, iron rich clays, carbonates, and sulphates which may have been derived from palagonitic material (Toulmin et al., 1976, 1977).

Terrestrial analogs that are possibly similar to those occurring in the Martian environment exist in cases where subglacial eruption of basaltic lava forms palagonite. This process is thought to be of major importance in Iceland (Sigvaldason, 1968) and the Hallet (Hamilton, 1972) and Marie Byrd Land (Le Masurier, 1972) Provinces of Antarctica, where composite palagonite breccia–basalt units and palagonite tufts are abundant. These units are exposed in near vertical cliffs ~2000 m in the Hallett area and may reach thicknesses of 5 km below the present ice cap level in some of the Marie Byrd Land localities (Le Masurier, 1972).

Since palagonitization may be a common geologic process on Mars, dehydration experiments were made upon several Antarctic samples of palagonitic trachy–basalts in order to examine how this material might respond to a simulated low-pressure environment. These samples, when placed under vacuum, were observed to undergo rapid dehydration immediately upon evacuation at room temperatures. Within 12 hr approximately 75% of the total water was removed; heating to 200°C for 2½ hr removed about 95% of the water. The dehydrated palagonite, when removed from the vacuum system, became noticeably weaker and could easily be disintegrated to dust-sized particles. In the Martian environment, one might easily envision large masses of palagonite breccia undergoing both rapid physical disintegration and generation of dust upon being exposed at the surface.

Additionally, spectral reflectance measurements were kindly provided to us by the Viking palagonites by Torrence V. Johnson and Fraser P. Fanale of the Jet Propulsion Laboratory. These data are compared in Fig. 8 with spectra obtained by McCord and Westphal (1971) for Martian bright and dark areas. Deep absorption features in the palagonite spectra near 1.4 and 1.9 μm are due to the relatively abundant water in the samples. Samples A and B are strongly and sample C weakly palagonitic. The spectral comparison is not intended as an identification of Martian surface materials in any sense. It does demonstrate that a simple process, interaction of basaltic lava and water, which very likely has occurred on Mars, can produce materials with deep ferric absorptions and high infrared reflectances quite similar to those observed for Martian surface materials.

**SUMMARY**

Mariner 9 and Viking Orbiter images reveal an immense erosional system which has affected a large part of the Martian equatorial region. These terrains termed chaotic and fretted by Sharp (1971, 1973a,b), develop as broad depressed regions bounded by breakaway scarps. A variety of erosional processes appear to have operated to a roughly uniform depth in terrains of widely differing relative age. These observations suggest to us that a major lithologic discontinuity occurs at this depth below the original surface.

A model consistent with these observations is advanced which suggests that during planetary outgassing the Martian crust was thermally stratified with respect to the stability of liquid and solid H₂O. One can predict from reasonable geothermal gradients that the H₂O freezing point would lie 1 to 2 km below the surface. As outgassing
commenced, ice formed above the interface; liquid H₂O condensed below. In regions where outgassing was concentrated, for instance near volcanic centers, these zones may have become saturated. In the liquid H₂O environment below the interface diagenesis occurred including cementation which increased the resistance to erosion. In the ice regime above any natural weakness of near surface material (eolian, impact debris, and volcanic deposits) was preserved in the absence of chemical alteration. Subsequently, a variety of erosional processes stripped the ice-laden zone away. Erosion stopped at the liquid-ice interface for two reasons: (1) the lower zone is more resistant to erosion, and (2) ice may be required to mobilize the debris.

The model proposed here provides possible explanations for a number of other observations including:

1. Both the Martian plains and adjacent older Martain highlands show erosive stripping to apparently same depth. The model proposed here suggests the discontinuity developed after both were emplaced.

2. Viking Orbiter frames display craters 5 to 30 km in diameter with ejecta blankets which appear to have moved as a coherent flows. If such craters were formed in ice-laden zone following devolatization; the oldest of them may give a minimum age for major period of outgassing.

3. Viking orbital images suggest that in some areas intermittent torrential floods issued from the crust. In other areas ubiquitous dendritic channel networks developed. The model suggests ice masses would have been emplaced in highland and lowland areas alike. Endogenic heating of such masses in mountainous terrains would result in gradual release of water from multiple source areas, producing integrated systems. By contrast heating in low areas could result in subsurface ponding and subsequent rapid release of floods.

4. The chemistry of the soil at the landing sites (Toulin et al., 1976; Baird et al., 1976) suggest weathering products requiring substantial amounts of water. Injection of volcanic lavas into such ice-laden provinces would produce palagonites which have been suggested as possible source materials. Spectral reflectance data for analogous terrestrial materials (Antarctic basaltic palagonites) contain deep ferric absorption bands and high infrared reflectivities similar to those observed for materials exposed on the Martian surface.

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