Pitted rock surfaces on Mars: A mechanism of formation by transient melting of snow and ice

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[1] Pits in rocks on the surface of Mars have been observed at several locations. Similar pits are observed in rocks in the Mars-like hyperarid, hypothermal stable upland zone of the Antarctic Dry Valleys; these form by very localized chemical weathering due to transient melting of small amounts of snow on dark dolerite boulders preferentially heated above the melting point of water by sunlight. We examine the conditions under which a similar process might explain the pitted rocks seen on the surface of Mars (rock surface temperatures above the melting point; atmospheric pressure exceeding the triple point pressure of H_2O; an available source of solid water to melt). We find that on Mars today each of these conditions is met locally and regionally, but that they do not occur together in such a way as to meet the stringent requirements for this process to operate. In the geological past, however, conditions favoring this process are highly likely to have been met. For example, increases in atmospheric water vapor content (due, for example, to the loss of the south perennial polar CO_2 cap) could favor the deposition of snow, which if collected on rocks heated to above the melting temperature during favorable conditions (e.g., perihelion), could cause melting and the type of locally enhanced chemical weathering that can cause pits. Even when these conditions are met, however, the variation in heating of different rock facets under Martian conditions means that different parts of the rock may weather at different times, consistent with the very low weathering rates observed on Mars. Furthermore, as is the case in the stable upland zone of the Antarctic Dry Valleys, pit formation by transient melting of small amounts of snow readily occurs in the absence of subsurface active layer cryoturbation.

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1. Introduction

[2] Abundant coarsely pitted rocks have been observed on the surface of Mars by the Viking 2 Lander [*Mutch et al.*, 1976a, 1977] (Figure 1a) and to a lesser extent at other lander sites and along rover traverses [*Mutch et al.*, 1976b; *Binder et al.*, 1977; *Rover Team*, 1997; *Squyres et al.*, 2004a, 2004b; *Squyres et al.*, 2006; *Smith et al.*, 2009] (Figure 1b). Several hypotheses have been proposed for the origin of these pits, including vesicles (formed by volcanic or impact processes), eolian pitting and fluting, differential weathering of minerals and clasts, salt weathering, water-assisted chemical weathering, and combinations of these.

[3] On Earth, weathering pits are common features on rocks in the Antarctic Dry Valleys (ADV) (Figure 2), where they have been attributed to both chemical and physical weathering processes [*Allen and Conca*, 1991; *Marchant and Head*, 2007; *Staiger et al.*, 2006]; volcanic rocks with vesicles are rare to unknown where pitted rocks are observed in the ADV. The hyperarid, cold-polar desert environment of the Antarctic Dry Valleys is commonly cited as the closest terrestrial analog to Mars [e.g., *Anderson et al.*, 1972; *Marchant and Head*, 2007, and references therein]. Analysis of weathering pits in the ADV therefore helps (1) to provide information on how pits form on the Earth, (2) to identify the environmental conditions necessary for their formation, (3) to assess whether these conditions might be met on Mars currently or in the past, and (4) to apply this information to help distinguish the processes responsible for the origin of pits in rocks observed on the surface of Mars (Figure 1a).

2. Studies of Weathering Morphologies and Pit Formation in Antarctica

[4] The cause of tafonization (formation of hollows with broad, rounded interiors) and alveolation (formation of small pits 0.5 cm to 5 cm deep) in Antarctic rocks (Figure 2) has been the subject of considerable debate since the early 1960s. Abundant evidence has been cited against freeze-thaw or

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wind abrasion as the predominant cause of these weathering morphologies (see *Evans* [1969, and references therein] for a summary of observations). Instead, early studies attributed these morphologies to salt crystallization, whereby damage to the rock and eventual pitting or undercutting occurs when the pressure exerted by the preferential growth of large salt crystals exceeds the tensile strength of the rock [*Wellman and Wilson*, 1965]. Observations that led researchers to favor salt crystallization as the cause of these weathering pits included: 1) their occurrence on slopes of all aspects and at various altitudes, 2) a lack of preferred orientation, 3) the preservation and unaltered appearance of minerals from debris contained within pits, and 4) the accumulation of salts and salt crusts in and around pits [*Evans*, 1969].

[5] More recent studies of weathered dolerite cobbles (Figure 2) in the Dry Valleys indicate, however, that chemical

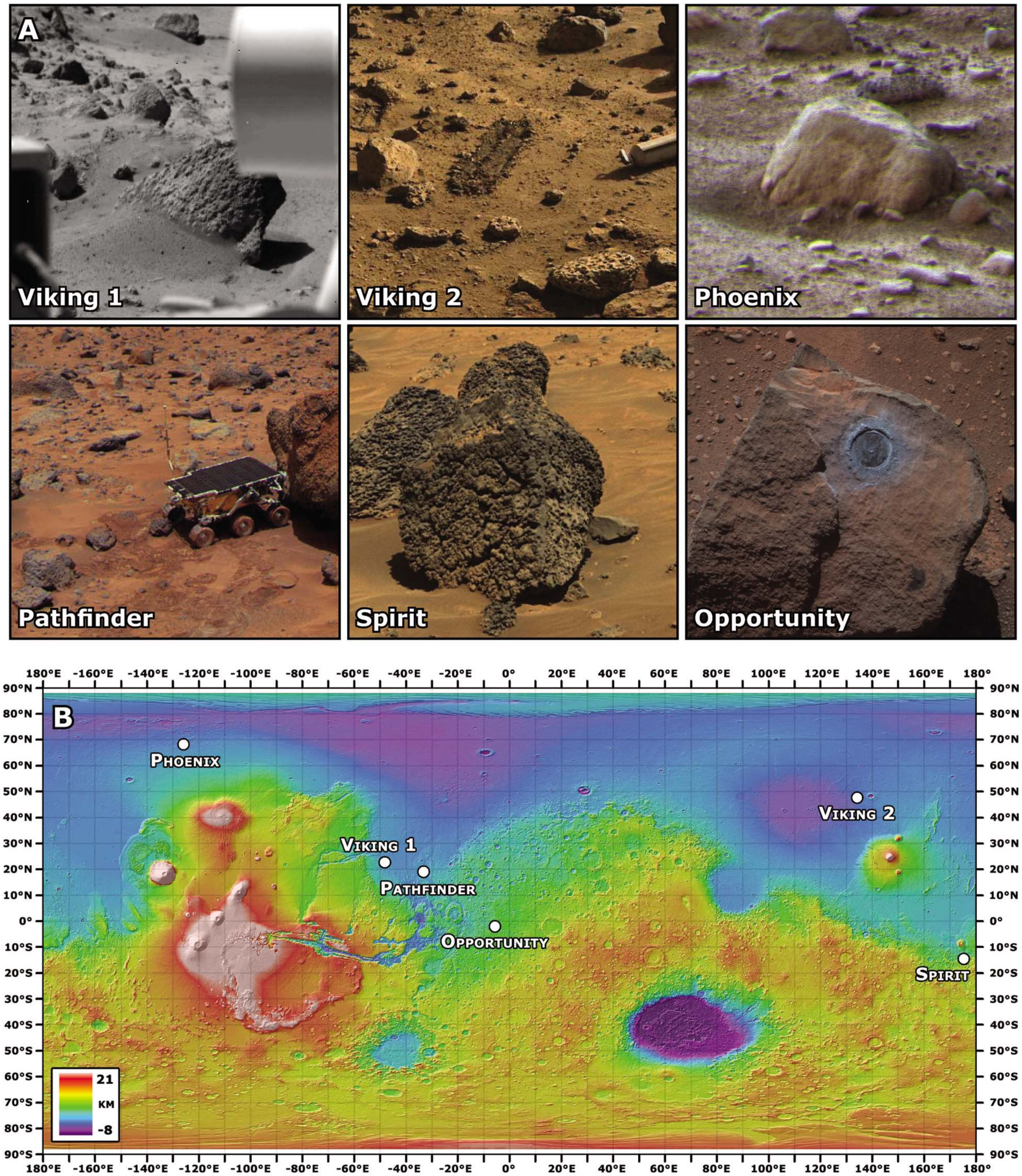

Figure 1

weathering might also play a significant role in dolerite surface evolution and pit formation relative to physical weathering (e.g., salt crystallization, freeze-thaw, wind abrasion) [*Conca and Malin*, 1987; *Conca and Wright*, 1988; *Allen and Conca*, 1991; *Salvatore et al.*, 2010, 2011a, 2011b]. For example, *Allen and Conca* [1991] outlined a scenario (Figure 3) in which a small amount of snow falls on dark boulders preferentially heated to above the melting temperature of water by exposure to peak austral summer insolation. Snowmelt that forms due to these conditions collects in depressions or pits on the rocks and quickly saturates a ~1 mm thick weathering zone underlying the pit bottoms. Chemical weathering takes place during these brief wetting periods in this very thin basal wetted zone, and following evaporation, salts and Fe-rich clay minerals crystallize in the pits. In the pit walls, illite crystallizes and forms in adherent layers segregating K and Al from the salts and clays. Wind erosion then scours the pits and removes the salts and clays from the pit bottom more efficiently than the illite-rich coatings on the pit walls, causing slow downward migration of the pits. Such wetting events occur only during several weeks in austral summer when dark rock surfaces exceed the melting temperature of water and rare snow showers occur, or when windblown snow from the Polar Plateau falls onto such solar-heated rocks [*Marchant and Head*, 2007]. Recent work shows that the products of chemical alteration of the dolerite surfaces themselves may often be much more immature than illite or other hydrated phyllosilicates [e.g., *Salvatore et al.*, 2011a, 2011b].

[6] Recent studies have emphasized the importance of microclimate zones in the ADV and the manner in which geological processes at the macroscale, mesoscale and microscale are influenced by different conditions in these zones. *Marchant and Head* [2007] showed that spatial variations in altitude, along with measured changes in summertime temperature and humidity, yield three zones in the McMurdo Dry Valleys (coastal thaw zone, CTZ; inland mixed zone, IMZ; stable upland zone, SUZ) in which water plays a more or less active role in rock and soil weathering style, rate, and evolution. Pitted rocks occur predominantly in the stable upland zone (SUZ), the zone with the least amount of seasonal meltwater, and the most Mars-like of the three zones. This analysis thus set the stage for detailed study and measurements of pit development in the three zones, rock exposure age dating, and the geological context of the pitted rocks.

[7] Most rocks at the surface in the coastal thaw zone (CTZ) show salt encrustations [*Nichols*, 1968; *Campbell and Claridge*, 1987; *Gibson et al.*, 1983; *Hall*, 1991]. Salts are produced by evaporation of near-surface brines and saline meltwater and the growth and expansion of salts pry loose mineral grains, particularly on coarse-grained rocks, leading to the development of widespread grus (loose collections of mineral grains). In the CTZ, some salt-coated rocks are weathered flat to the soil surface [*Bockheim*, 1997; *Beyer et al.*, 1999]. Salt weathering in the CTZ also leads to the development of tafoni through cavernous weathering of coarse-grained rocks [*Conca and Astor*, 1987]. The long-term effect of salt weathering in the CTZ is to smooth bedrock slopes. Climate conditions of the inland mixed zone (IMZ), with less abundant meltwater, foster the development of widespread desert pavements, with wind-faceted cobbles (ventifacts) and intervening lags of coarse-grained sand and gravel.

[8] In the stable upland zone (SUZ), however, rocks are not subjected to episodes of burial and exposure, as commonly occurs in areas with traditional wet active layers [e.g., *Hallet and Waddington*, 1991]; therefore rock surface textures are almost exclusively related to processes that operate above the ground surface, including wind erosion, salt weathering, and chemical weathering. Given the very dry conditions of the SUZ, salt weathering proceeds at an extremely slow pace, in contrast to the CTZ. Surface erosion rates in the SUZ that are based on analyses of in situ produced cosmogenic nuclides in boulders are as low as ~6 cm/Ma, the lowest measured on Earth [*Summerfield et al.*, 1999a, 1999b; *Brook et al.*, 1995; *Margerison et al.*, 2005; *Staiger et al.*, 2006]. Micro-relief on rock surfaces in the SUZ can be initiated by minor snowmelt that forms on solar-heated rocks [*Allen and Conca*, 1991; *Parsons et al.*, 2005; *Staiger et al.*, 2006]; such meltwater tends to occupy shallow surface depressions (Figures 2 and 3), which originally may have formed by rock surface roughness due to primary fracture geometry, or by secondary processes such as wind scour on exposed rock surfaces [*Selby*, 1977]

Figure 1. (a) Surface textures of rocks on the surface of Mars. Insets show images of rocks at the Viking Lander 1 landing site (12B016); note the rough and pitted surface of the rock in the foreground. Viking Lander 2 landing site (22G144); note the distinctly pitted surface of the rock in the lower right part of the image and several others on the spacecraft side of the trench. Phoenix landing site (RGB composite of Surface Stereo Imager images from Sol 151); note the pitted nature of the upper flat surface of the large block in the midfield, and the highly pitted nature of the rock just beyond. Along the Pathfinder traverse near the landing site (P48985; MRPS81958); pitted rocks occur in the lower left, and the rock just to the right of the rover is very rough and heavily pitted. General rock surface roughness can enhance the mechanism described here (see text). For example, Spirit rover images (Pancam RGB image composite from Sol 810) show a cluster of very rough and heavily pitted rocks; although general pitting such as this can originate from different mechanisms (e.g., original texture, eolian abrasion, etc.) this type of roughness can provide pockets for the accumulation of snow and ice, and shield it from direct solar radiation until rock heating occurs. Opportunity rover images (Pancam RGB composite from Sol 2117; circle is from the Rock Abrasion Tool which has abraded through the weathering patina into fresh rock); fractures and steps in rock surface topography provide locations for collection of snow and ice. Compare to similar rocks in the Antarctic Dry Valleys (Figures 2a–2d and 3a–3c) and additional examples at the Viking Lander 2 site (Figure 4). (b) Topographic map of Mars showing the locations of the Viking Lander 1, Viking Lander 2, Pathfinder, Spirit, Opportunity and Phoenix landing sites.

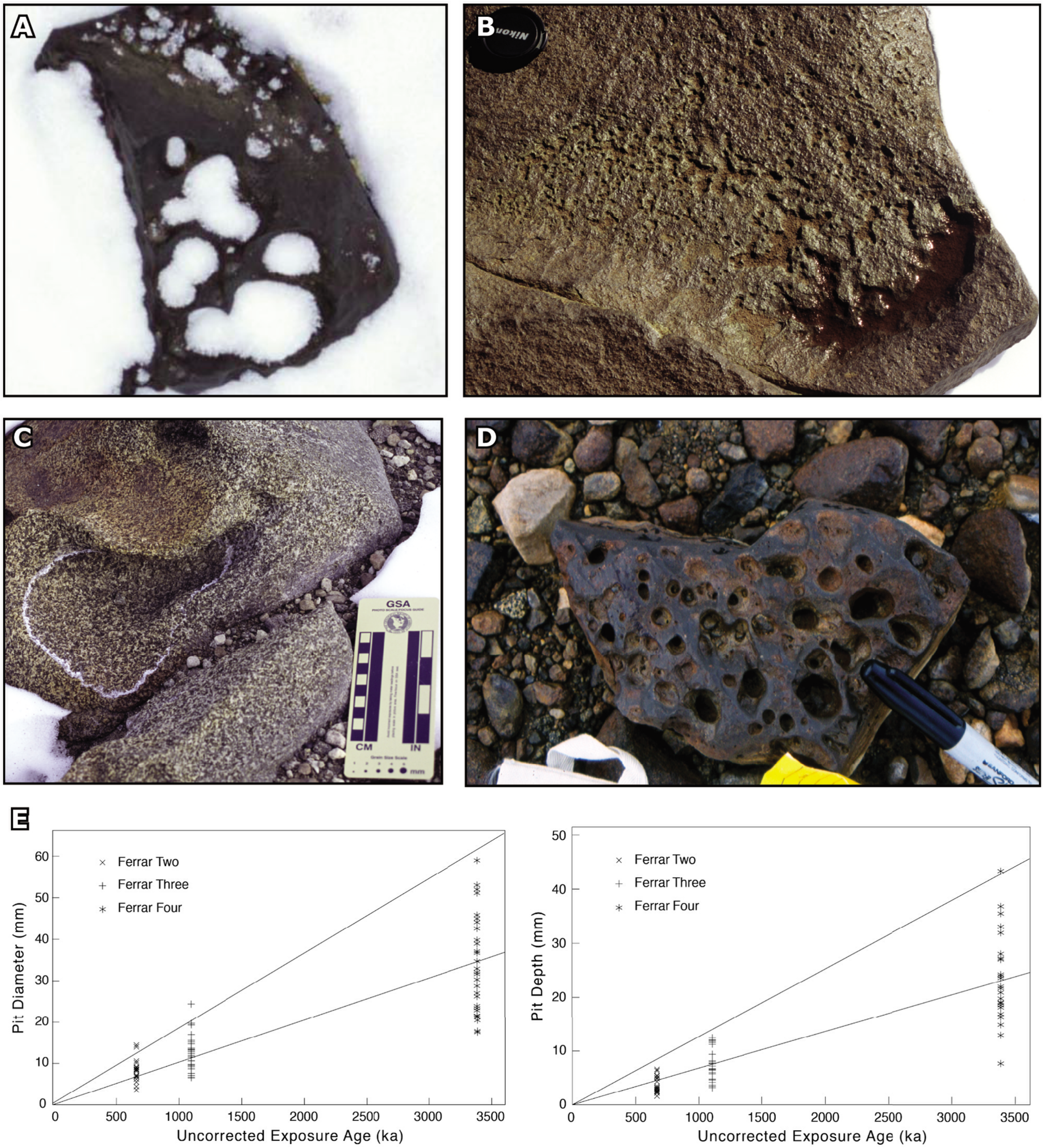

Figure 2. Pits on rocks in the Antarctic Dry Valleys. (a) Snow collects in lows and pits on low-albedo dolerite in the stable upland zone (SUZ); the largest snow-filled pit is ~1.5 cm in diameter. (b) Preferential heating of the surface of low-albedo dolerite rocks in the SUZ causes snow in the depressions and pits to melt. (c) The maximum meltwater in one pit is shown as a white (salt-encrusted) line (e.g., "bathtub ring"); this relatively coarse-grained dolerite shows a greater susceptibility to salt weathering than do the relatively fine-grained dolerite rocks (with crystals < 1 to 2 mm in size) shown in Figures 2a, 2b, and 2d. (d) Ultimately, snowmelt and weathering processes produce deep pits that for fine-grained dolerite rocks tend to increase in width and depth linearly with age. Figures 2a–2d are from *Marchant and Head* [2007]. (e) The maximum diameter and depth of weathering pits on surface cobbles from dated moraines in the SUZ [*Staiger et al.*, 2006]. In each panel, the lower trendline was determined from measuring the mean value for pit size on selected rocks; the upper trendline highlights maximum values. Using mean values, *Staiger et al.* [2006] concluded that the mean width and depth of the largest surface pits on boulders from dated moraines increases by ~10 mm/Ma and ~6.7 mm/Ma, respectively.

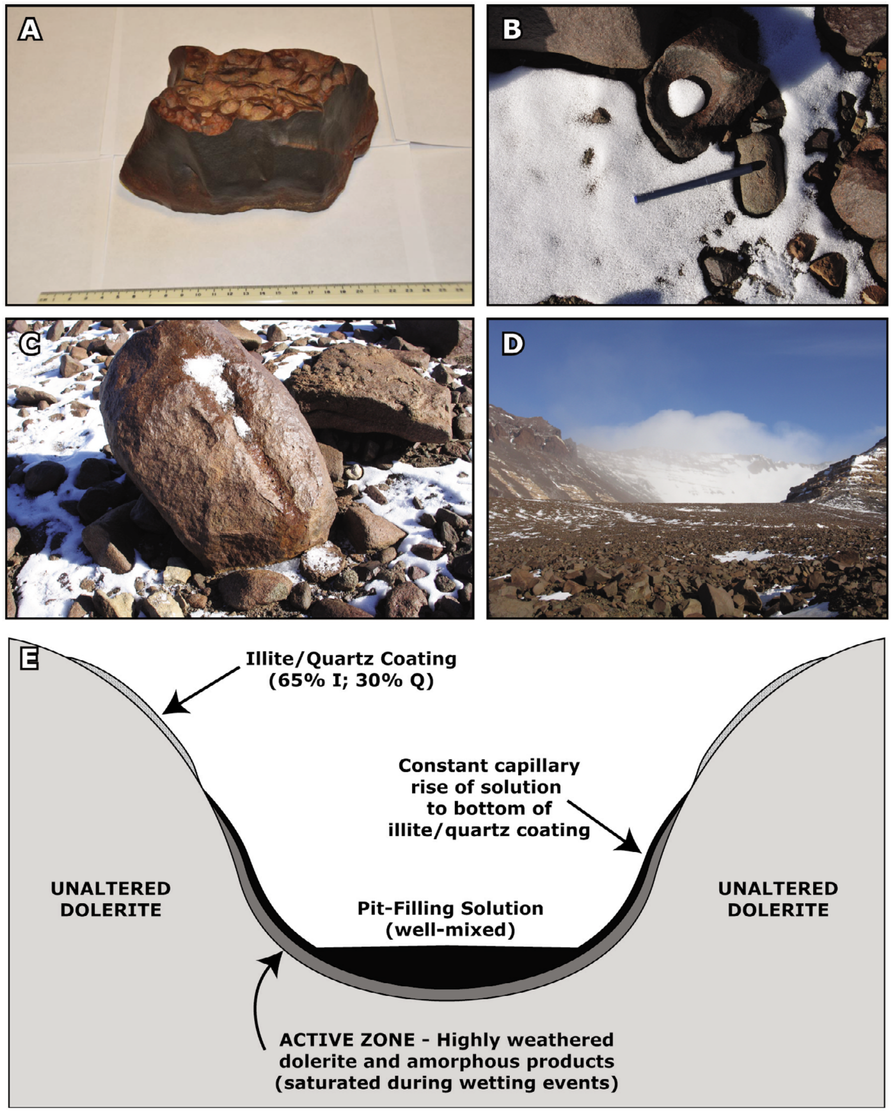

Figure 3. Process of pit formation in the Antarctic Dry Valley: (a) Fine-grained weathered dolerite (16 cm in width) with circular, oval and linear pits on upper surface. As pits enlarge vertically and laterally, pit walls break down to form larger coalesced pits, and elongate pits along fractures (across middle of sample surface). Exposed side of rock has been modified and smoothed by eolian erosion. (b) Coarser dolerite hollowed out into a depression by weathering. Snow has accumulated on the ground and in the circular hollow, and is undergoing sublimation. Solar heating of the dolerite raises the rock temperature above the melting point and causes melting of the base of the snow inside the depression and formation of a puddle of meltwater. (c) Steep-sided dolerite boulder collects snow preferentially in linear depression during snowfall (mean snowfall ranges from 3 to 50 mm yr^{-1} water equivalent in the Antarctic Dry Valleys, with lowest values for interior regions like the stable upland zone [*Fountain et al.*, 2009]). Snow undergoes sublimation, but as the sun rises in the sky, the boulder heats up to the melting temperature of ice, and where the snow is thickest, meltwater forms before sublimation is complete. In this case, due to the depression and the steepness of the rock surface, meltwater runs down the side of the boulder and forms ice at the base of the rock. (d) Perspective view of Mullins Valley from Beacon Valley, showing a typical snow squall on an otherwise clear day. Such squalls deposit snow in sufficient quantities to cause melting in pits and surfaces on dark dolerite boulders. Width of Mullins Valley is about 2 km. All samples and images are from Beacon and Mullins Valley in the stable upland zone [*Marchant and Head*, 2007] of the Antarctic Dry Valleys. (e) Schematic illustration of the mode of formation of a surface pit during a wetting event. Observations in the field and laboratory show that the zone of active weathering is the only area of mineral destruction and this represents the advancing front of the pit. The active zone becomes saturated after only a few minutes and moisture can remain in the zone for hours, depending on total moisture and temperature, even after the pit surface appears dry. Weathering products are removed by eolian activity. After *Allen and Conca* [1991].

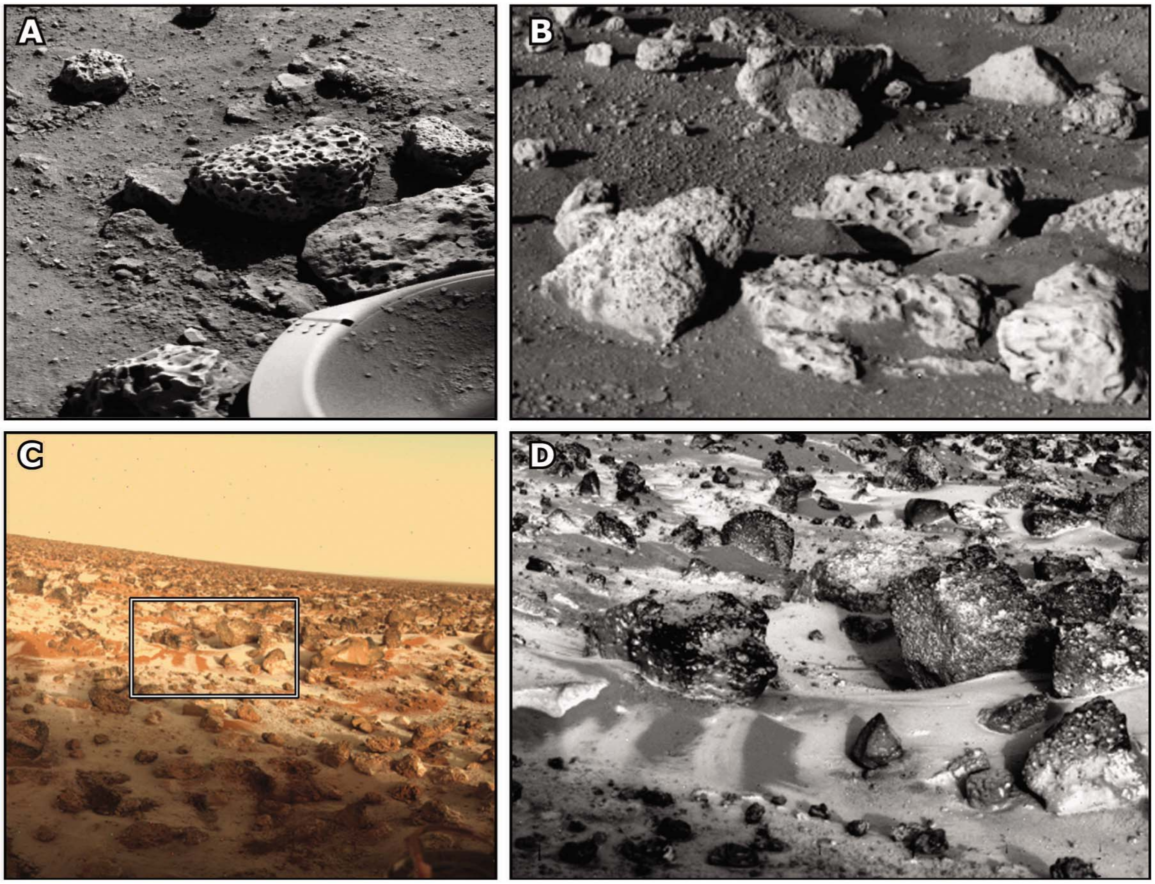

Figure 4. Images of the Viking Lander 2 landing site (47.97°N, 229.59°W) showing evidence for heavily pitted rock surfaces. (a) Pitted rocks in the vicinity of the lander footpad; the rock at the top of the footpad is ~35 cm across (portion of 22A001). (b) Pitted rocks near the edge of a trough (top of image) (portion of 21A024). Pits are ~1–2 cm in diameter. (c) Frost and snow deposition at the VL 2 site in northern winter (image P21873). (d) Enlargement of area in the central part of Figure 4c showing the location of snow and frost deposition in lows and small drifts between rocks and ripples, and in pits and troughs in the rocks [*Jones et al.*, 1979; *Wall*, 1981]. Snow and frost deposition under appropriate seasonal conditions may lead to the formation of local meltwater on heated rock surfaces on Mars and focused chemical alteration to produce pits, similar to the situation on Earth [see *Allen and Conca*, 1991; *Marchant and Head*, 2007; *Parsons et al.*, 2005; *Staiger et al.*, 2006].

(see also Figure 1a). Through positive feedback these pits attract more snow, producing additional and ever deeper and wider pits (Figures 2 and 3). In the SUZ this process can produce a network of pits and micro-rills on the surface of rocks (Figure 2). Inclined rock surfaces form micro-rills such that meltwater spills out from pits and flows down the rock surface (Figure 2). The average depth and width of weathering pits at the Ferrar Glacier in the SUZ shows a near-linear increase with exposure age [*Staiger et al.*, 2006] (Figure 2e).

[9] In summary, the relatively wet seasonal climate conditions of the CTZ foster the development of widespread near-surface brines and relatively rapid rates of salt weathering. The rate of degradation due to salt weathering decreases inland, with measured rates for bedrock erosion in the SUZ being an order of magnitude lower than that measured near the coast [*Summerfield et al.*, 1999b]. Surface weathering effects are, however, visible in the Mars-like SUZ as pitted-rock surfaces; well-formed pits appear only on rocks in the SUZ that have been exposed at the ground surface for >1 to 2 Ma [*Parsons et al.*, 2005; *Staiger et al.*, 2006].

3. Application to Mars

[10] Rocks and surface features differ as a function of latitude on Mars (Figure 1) [*Marchant and Head*, 2007]. At the midlatitude Viking 2 landing site (47.7°N [*Mutch et al.*, 1976a, 1977]), sediment-filled contraction-crack polygons similar to those seen in the ADV inland mixed zone are observed [*Mutch et al.*, 1976a, 1977] and are also seen elsewhere in this latitude band in orbital Mars Orbital Camera (MOC) high-resolution images [e.g., *Malin and Edgett*, 2001; *Mangold et al.*, 2004; *Levy et al.*, 2009] (Figure 4). Also observed at the Viking 2 site are heavily pitted rocks previously interpreted to be formed by vesiculation or differential weathering of clasts or phenocrysts [e.g., *Mutch et al.*, 1976a] (Figures 1a and 4). Although rock pitting occurs in lower abundance, polygons similar to those at VL-2 are not

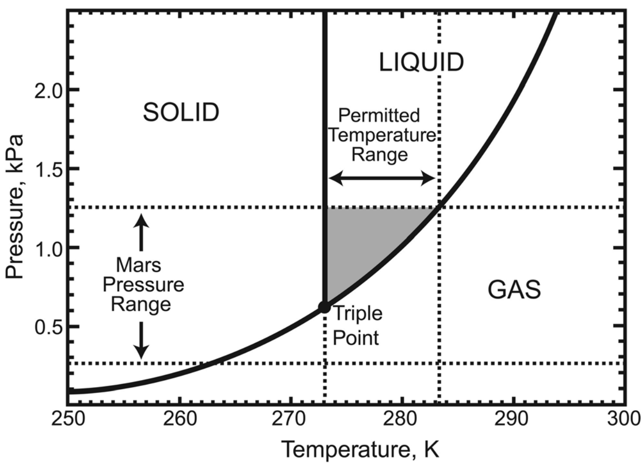

Figure 5. Phase diagram for water in pressure-temperature space. Shaded area represents the range of atmospheric pressures and surface temperatures on Mars where metastable liquid water could form. After *Haberle et al.* [2001].

seen at lower latitude sites (Viking 1, Pathfinder, and Mars Exploration Rovers, all below 23° latitude, Figure 1 [*Mutch et al.*, 1976b; *Binder et al.*, 1977; *Golombek et al.*, 1999; *Squyres et al.*, 2004a, 2004b, 2004c; *Levy et al.*, 2009]).

[11] *Allen and Conca* [1991] suggested that the Viking pitted rock features (Figure 4) may have formed by processes more similar to those that formed the pits in the Antarctic Dry Valley rocks in the stable upland zone (SUZ) [see also *Marchant and Head*, 2007; *Parsons et al.*, 2005; *Staiger et al.*, 2006], than by vesiculation or differential weathering. During winter at the Viking 2 site, deposition of frost and snow on rocks and on intervening ground was observed (Figure 4) [*Jones et al.*, 1979; *Wall*, 1981], but was not seen at lower latitudes. These observations suggest that the deposition of snow on rocks with a thermal inertia and albedo sufficient to retain heat and cause localized melting of snowfall, could have been a factor in the formation of the observed pitting, as appears to be the case in the stable upland zone and parts of the inland mixed zone of the Antarctic Dry Valleys [e.g., *Allen and Conca*, 1991].

[12] The question is: Can transient melting of snow or frost occur today on Martian rocks in the same way as it occurs in ADV? *Haberle et al.* [2001] used an atmospheric general circulation model to determine where, and for how long, the surface pressure and surface temperature on Mars would meet the minimum requirements for the existence of metastable liquid water in the present climate system (Figure 5). *Hecht* [2002] analyzed the possibility of producing transient liquid water under present-day Martian conditions. He concluded that liquid water can be produced by melting and exist for short periods of time (tens of minutes), if a number of circumstances are met simultaneously. These conditions include the following:

[13] 1. It is necessary to have atmospheric pressure above the triple point of water (Figure 5). This condition is met at lower elevations, including all the northern plains of Mars, which also contain the Viking and Pathfinder landing sites (Figure 1b).

[14] 2. It is necessary to have frost or ice on the surface. Deposits of ice and dust (water ice nucleated on dust particles) up to a few millimeters thick were seen at the midlatitude Viking Lander 2 site for 249 Mars days during winter following a dust storm [*Jones et al.*, 1979; *Wall*, 1981] (Figure 4). Seasonal water-ice frost regularly occurs in the spring and early summer season at high latitudes on Mars [*Langevin et al.*, 2007] and can occur in favorable places at midlatitudes. Water frost and ice have been detected in OMEGA data between 15°S and 30°S near aphelion seasons [*Carrozzo et al.*, 2009] and CO_2 and H_2O ice patches were observed as low as 24°S in MOC images [*Schorghofer and Edgett*, 2006].

[15] 3. It is necessary to heat up this frost to the melting point quickly, so that it melts before it sublimates. As has been long understood [*Ingersoll*, 1970], in most cases intensive sublimation of ice under Martian conditions would effectively cool the surface and preclude melting by solar heating; some special conditions are needed [*Hecht*, 2002].

[16] 4. For rapid heating to occur, it is necessary to have the proper geometry at the specific location of the frost or ice, so that the sun first hits the surface late enough, at such time that it is already far above the horizon. Such places can easily be found on rocks of complex shape (Figure 4).

[17] 5. Another requirement is a perihelion season, when Mars is close to the sun, and the radiative energy flux from the sun (insolation) is higher.

[18] 6. A high relative humidity of air is desirable in order to retard the rate of sublimation.

[19] 7. Surface albedo should be low (to effectively absorb solar energy).

[20] 8. The surface thermal inertia should be low to facilitate rapid and strong heating.

[21] All these conditions can be met for rocks on Mars today except the last one, because rocks have inherently high thermal inertia and cannot be heated as strongly and as quickly as low-thermal-inertia soils. Thus, the *Hecht* [2002] mechanism of transient melting does not appear to provide a mechanism for melting of water ice on rock surfaces under present conditions. Below we analyze whether or not the process of transient melting of water ice on rocks is possible in the geologically recent past.

4. Conditions Under Which Transient Melting of Water Ice on Rocks Could Occur on Mars in the Past

[22] Transient metastable liquid water on rock surfaces can be formed by melting of snow and ice or by condensation from vapor (dew). The latter requires saturation of the atmosphere with water vapor at air temperatures above the melting point of water (273 K), which probably does not occur on Mars unless the climate system is quite different from the present (e.g., in the Noachian). Thus, a liquid phase can be formed only by melting of a solid phase. This requires that the three following conditions be met (Figure 5): (1) atmospheric pressure should be above the triple point pressure of H_2O (612 Pa); (2) rock surface temperature should be above the melting point (~273 K); and (3) there should be some solid H_2O phase available for melting.

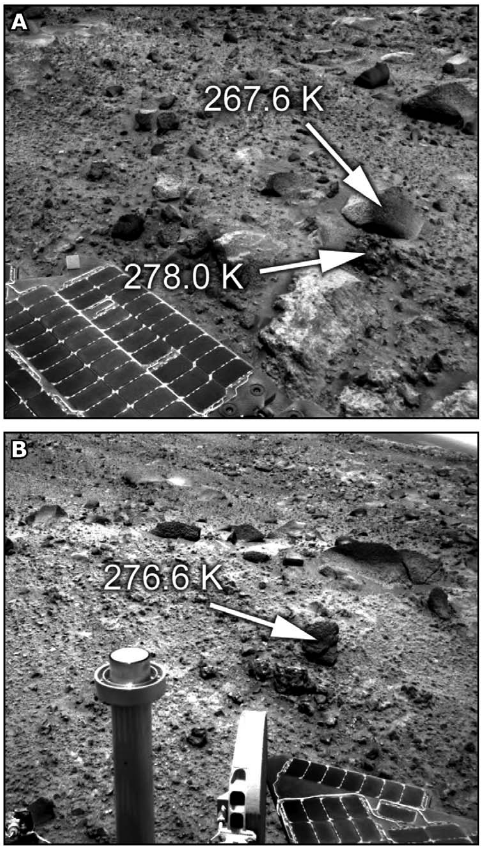

Figure 6. Spirit rover MiniTES [*Christensen et al.*, 2003] observations showing the heating of rocks above the melting point of water. (a) MiniTES derived soil temperature of 278.0 K on SOL 553 (L_s = 255.1°) for the darker rock and MiniTES derived rock temperature of 267.6 K on SOL 557 (L_s = 257.6°) for the brighter rock; in the latter case the rock facet orientation did not favor high temperature for the local time of observations. (b) MiniTES derived rock temperature of 276.6 K, in excess of the melting temperature of water, on SOL 552 (L_s = 253.8°). (L_s, areocentric longitude of the Sun, is a quantitative measure of season; the perihelion is at L_s = 250.9°.

4.1. Atmospheric Pressure Above the Triple Point Pressure of H_2O

[23] Currently, pressure exceeds 612 Pa during some part of the year for a significant part of Mars (Figure 5), except for high mountains, the highest plateaus, and the highest parts of highlands. For all landing sites (Figure 1b) it exceeds 612 Pa at least during a part of the year. In the past the available inventory of atmospheric CO_2 might have been higher. The amount of CO_2 stored in the present-day perennial southern polar cap is small [*Thomas et al.*, 2009]. However, a solid CO_2 deposit equivalent to 400–500 Pa of atmospheric pressure was recently found inside the south polar layered deposits (PLD) [*Phillips et al.*, 2010]. In addition, over 1000 Pa of undetectable CO_2 can potentially be hidden in a form of clathrate hydrates intimately mixed with H_2O ice or in thin layers or small pockets. All this CO_2 could have been in the atmosphere at some time in the geologically recent past, producing atmospheric pressure above the triple point everywhere except in the high mountains. Thus, in the past, this melting condition could be met in even wider areas than at the present [*Haberle et al.*, 2001]. During periods of low obliquity the atmospheric pressure was significantly lower, because the major component of the atmosphere (CO_2) condensed in cold traps in the polar areas [*Kieffer and Zent*, 1992], and melting was impossible [*Kreslavsky and Head*, 2005, 2010].

4.2. Rock Surface Temperatures Above the Melting Point of H_2O:

[24] Currently, soil temperature routinely exceeds 273 K for soil surfaces in the low and midlatitudes. Rocks have a much higher thermal inertia and hence experience much lower peak temperatures than soils. We analyzed temperature retrievals obtained by the MiniTES thermal infrared spectrometer onboard the Mars Exploration Rover Spirit [*Christensen et al.*, 2003] in Gusev crater (Figure 1), where there are abundant rocks of basaltic composition [*McSween et al.*, 2004]. As expected, temperature retrievals for rocks were systematically lower than for the surrounding soils (Figure 6). During afternoons in the perihelion season, however, the illuminated rock faces often showed temperatures of 275–290 K, well above the freezing point of water (Figure 6b). In the aphelion season, however, rock temperatures were significantly lower than 273 K. Thus, although rocks cannot be heated up quickly, they can be heated up to sufficiently high temperatures to produce melting. On Mars the surface temperature is to a great extent controlled by direct energy input from solar radiation, heat exchange with the atmosphere being significantly less important than on the Earth. To obtain high surface temperatures on a rock facet requires a favorable orientation of the specific facet with respect to the Sun; different facets experience their highest temperatures during different parts of the day and during different seasons, depending on the facet orientation. As is the case in Antarctica, rock albedo plays a significant role [*Marchant and Head*, 2007]: it is much easier to melt ice if the rock is dark (Figure 6). For the eccentric Martian orbit (relative to the Earth), distance from the Sun also plays a significant role: the peak insolation changes significantly between perihelion and aphelion. At the Spirit landing site, temperatures of rock facets above 273 K were detected only close to perihelion, when Mars was closest to the Sun. Temperatures were significantly lower during the aphelion season. Thus, in the past, high temperatures on rock surfaces should be expected only during periods of high eccentricity (such as at the present). It is much more difficult to melt ice if eccentricity is low. Obliquity plays little role on temperatures on rock facets in low and midlatitudes: for a wide range of facet orientations, a facet would directly face the Sun during some season and some time of the day, regardless of obliquity. Thus, transient snow melting on rocks is favored during periods of relatively high eccentricity (Figure 7).

4.3. Solid H_2O Phase Available for Melting:

[25] Availability of solid H_2O is the most difficult requirement to meet. Currently, small amounts of ice are observed seasonally at high latitudes just after sublimation of the seasonal CO_2 ice [e.g., *Langevin et al.*, 2007]. Calculations by *Hecht* [2002] showed that low thermal inertia is

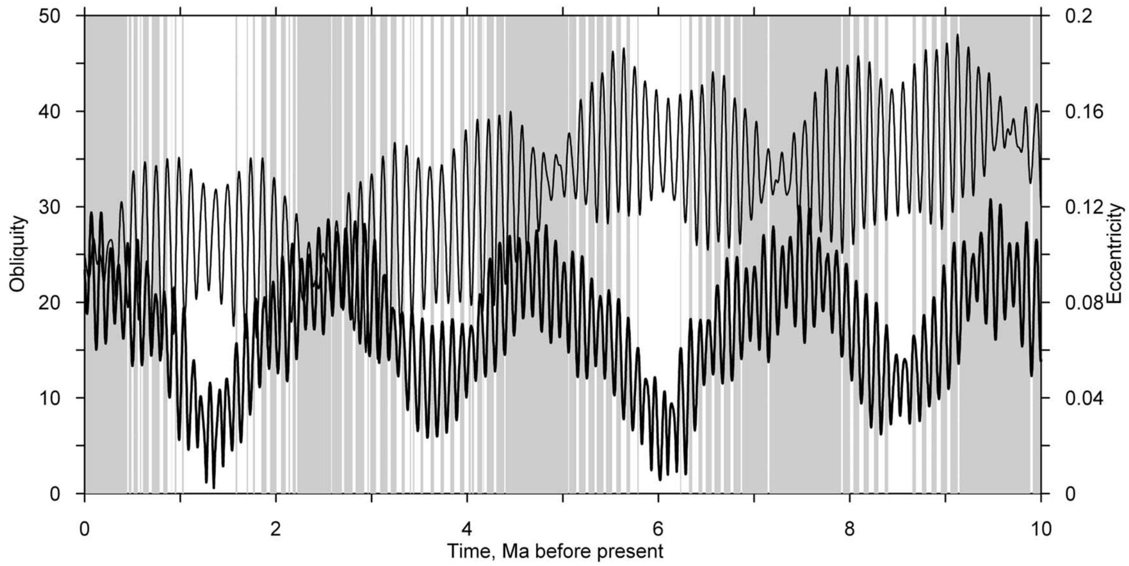

Figure 7. Evolution of eccentricity (bold line) and obliquity (thin line) for the last 10 Ma calculated by *Laskar et al.* [2004]. Shaded areas illustrate periods of time when transient snow melting on rocks is allowed by relatively high obliquity and eccentricity. During these periods, two of the three criteria for pit formation are met. For example, although obliquity and eccentricity conditions for melting are met at the present time, actual snowfall is not likely to occur on Mars under present climate conditions and thus no melting is likely to occur. For illustration purposes the thresholds are arbitrarily chosen at an eccentricity of 0.06 and an obliquity of 20°.

needed to melt this ice: for high thermal inertia the temperature rises too slowly, and the ice sublimates before it melts, even if the other conditions are favorable for quick heating. No seasonal ice deposits are currently observed in the tropics. Diurnal (nighttime or in local shadows) condensation of frost is possible; the total amount of H_2O able to condense diurnally, however, cannot exceed the column abundance of H_2O, which presently does not exceed ~100 microns. Thus, diurnal condensation cannot provide a reasonable amount of ice for melting, and the high thermal inertia of rocks would not allow melting, even if diurnal condensation is significant.

[26] The most effective way to get a solid H_2O phase suitable for melting is the precipitation and/or wind transport of snow on warm rocks, as is seen in Antarctica [*Marchant and Head*, 2007]. In this situation the high thermal inertia of rocks favors melting. Snow falling from clouds has been observed by Phoenix [*Whiteway et al.*, 2009], but no snow reached the ground at the time of observation. Currently, day-time snowfalls do not occur in the tropics and midlatitudes. Thus, the absence of a suitable solid H_2O phase apparently precludes melting on rock surfaces under present-day conditions. The situation, however, could be significantly different in the very recent past if the atmosphere was much wetter than it is now. *Jakosky et al.* [2005] speculated that if the perennial CO_2 cap was absent a few hundreds of years ago (as suggested by morphological observations [*Thomas et al.*, 2009]), the water ice exposed by the removal of the CO_2 ice in the southern polar area would release significant water vapor during warm (perihelion) southern summers. It is commonly thought that high obliquity causes evaporation of H_2O from the polar layered deposits (PLD) and a consequent increase of atmospheric humidity [e.g., *Forget et al.*, 2006]; development of sublimation lags, however, can retard or stop this process. Tropical mountain glaciers [*Head and Marchant*, 2003] and numerous ice features in the midlatitudes, such as debris-covered glaciers [e.g., *Head et al.*, 2010] and the frozen effluent of outflow channels [*Kreslavsky and Head*, 2002] are additional sources of water vapor. All of these mechanisms, processes, and events could lead to local snowfalls and transient melting in the past history of Mars.

[27] In the presence of surface salts both pressure and temperature requirements are less stringent. Perchlorates recently discovered in the Martian soil [*Kounaves et al.*, 2010] are very effective in reducing the pressure and temperature required for melting (sulfates, abundant on Mars, are much less effective). However, as we described above, the "bottleneck" in the melting process is the necessity for the presence of a solid phase of water suitable for melting. Abundant salts would not allow melting unless increased atmospheric water vapor produces local minor snowfalls (as is the case in the stable upland microenvironment of Antarctica Dry Valleys [*Marchant and Head*, 2007]). In the presence of chlorides and/or perchlorates, transient liquid phases can be formed by deliquescence, but this process also appears to require higher atmospheric humidity.

5. Summary and Conclusions

[28] We find that on Mars today each of the conditions required for melting snow and ice on rock surfaces are met locally and regionally, but the conditions are very unlikely to occur together to produce the type of melting that forms pits in the Antarctic Dry Valley environment. The combination of conditions favoring this process, however, are

highly likely to have been met repeatedly in the geological past (Figure 7). Slight increases in atmospheric water vapor content (due, for example, to the loss of the south polar CO_2 “swiss cheese” terrain) could favor the deposition of snow on dark rock facets that had been heated to above the melting temperature during favorable conditions (e.g., perihelion), causing melting and the type of locally enhanced chemical weathering that can cause pits. As in the case of the Antarctic Dry Valleys, this combination of conditions is not likely to occur continuously, but rather is very seasonal in nature and only occurs during parts of some days during these seasons. Furthermore on Mars, even when these conditions are occasionally met, the variation in heating of different rock facets under different Martian conditions means that different parts of the rock may weather at different times. When pit formation by transient melting of small amounts of snow does occur, only small amounts of melting are necessary and the process can proceed in the absence of seasonally wet active layer cryoturbation, as is the case in the upland stable zone of the Antarctic Dry Valleys.

[29] Together, these conditions are consistent with the very low weathering rates observed on Mars (and in the SUZ of Antarctica). This mechanism of weathering on Mars will also be limited by the albedo of rock surfaces, with preferential occurrences on exposed darker rocks, and those not covered by dust. A deeper understanding of the nature of this type of weathering in the Mars-like Antarctic Dry Valleys [*Marchant and Head*, 2007] will provide further insights into the chemistry, mineralogy and rates of weathering on the surface of Mars.

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