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Redistribution of water in terrestrial soils at subfreezing temperatures: A review of processes and their potential relevance to Mars

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[1] Any study of water behavior in the Martian regolith should begin with an examination of our current understanding of subsurface water in terrestrial cold regions. The terrestrial analog provides a wealth of readily available information to help formulate and test new ideas about possibilities on Mars. This paper discusses the major mechanisms driving the phenomenal ability of capillary media to redistribute moisture when freezing. It examines both thermally induced and freezing-induced redistribution of moisture, the magnitude of which can vastly exceed the transport expected from Fickian diffusion alone. If the Martian crust is truly water-rich, then these processes (in response to transient thermal disturbances caused by impacts, volcanic and magmatic activity, changes in climate, and potential future human activities) may induce substantial changes in the local distribution of subsurface ice. *INDEX TERMS:* 1823 Hydrology: Frozen ground; 6225 Planetology: Solar System Objects: Mars; 6207 Planetology: Solar System Objects: Comparative planetology; *KEYWORDS:* Frozen ground, Martian ground, thermally induced redistribution, freezing-induced redistribution

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1. Introduction

[2] Investigations of the dynamics of water, ice and/or air in fine-grained terrestrial soils have produced counter-intuitive surprises, known for decades to some geologists, highway engineers and soil physicists, but seldom by the public or by physical scientists in general. Because these processes may also be relevant to understanding the nature and distribution of subsurface water and ice on Mars, we offer this brief re this brief qualitative description of certain terrestrial phenomena of which Martian explorers should be aware.

[3] The evidence for the presence of subsurface water and ice on Mars is expressed in the morphology and distribution of a variety of landforms, many of which resemble cold climate features found on Earth [*Rossbacher and Judson*, 1981; *Carr*, 1986, 1987; *Squyres*, 1989; *Squyres et al.*, 1992]. Taken together, this evidence suggest that Mars is water-rich, storing (in the form of ground ice and groundwater) the equivalent of a global ocean of water 500–1000 m deep beneath its surface [*Carr*, 1986, 1987].

[4] One of the forms in which this inventory of subsurface water may be stored, is as massive bodies of "segregated" ice, similar to those often found beneath arctic landscapes on Earth (Figure 1). If such bodies exist, they are most likely the result of events that occurred under much different environmental conditions than those that characterize Mars today. The most important difference is that on present-day Earth, the hydrologic cycle is sustained by recurrent precipitation from the atmosphere, making it a vital contributor to the occurrence and distribution of ground ice. However, on Mars, it appears to have been a very long time (at least ~4 Ga, if ever) since precipitation could have influenced the distribution of subsurface ice in this way. Nonetheless, it is still possible to identify a number of potential mechanisms by which massive deposits of ground ice may have been formed.

[5] For example, *Clifford and Parker* [2001] have argued that early Mars, like the Earth, may have hosted a primordial ocean that slowly froze as the planet's internal heat flow declined with time. If so, then the existence of this frozen ocean at a time when large impacts, high rates of volcanism, and a variety of sedimentary processes are thought to have been active, suggests that massive lenses of ice from this early period may have been buried and preserved (in part, due to the very low temperatures that are believed to have characterized the planet ever since). Similar deposits may have also originated from the large discharges associated with the formation of the Martian outflow channels, which occurred approximately halfway through Martian geologic history [*Baker*, 1982; *Baker et al.*, 1992; *Carr*, 1996]. As the floodwater from those events entered the planet's northern plains, it likely froze - raising the possibility that substantial amounts of that discharge may still be preserved, buried

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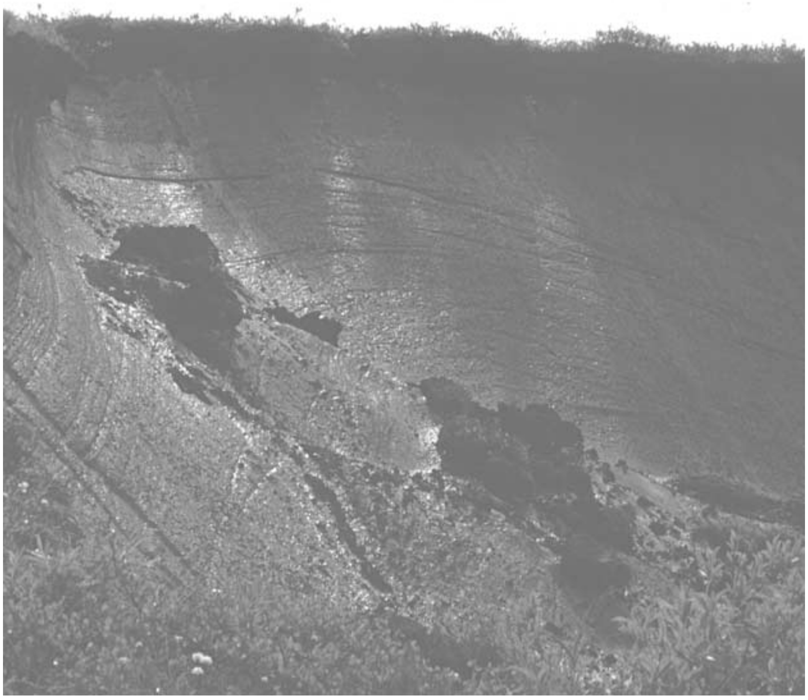

Figure 1. A cliff of massive ground ice fronting on the north shore of Tuktoyaktuk Peninsula, Northwest Territories, Canada. The ice is overlain by a thin mantle of peat, some of which has tumbled down the face of the cliff which is melting owing to exposure caused by beach erosion. Photo by R. D. Miller.

beneath subsequent deposits of eolian and fluvial sediments and volcanics.

[6] Given this potential, our intent here is to explain two of the most important transport processes that affect the distribution of subsurface H_2O in cold, non-saline terrestrial soils. Neither process is intuitive. One of them is freezing-induced redistribution (of H_2O) in moist soil, not to be confused with thermally induced redistribution that can take place in that same soil when it is ice-free. The other is frost heaving, well known for the mischief it does, but too often attributed to a mechanism (“water expands when it freezes”) that, more than 80 years ago, was shown to be not only inadequate but entirely irrelevant to the “excessive” heaving that causes most serious problems [*Taber*, 1930; *Beskow*, 1935]. “Excessive” (Taber’s word) means that the heaving exceeds (perhaps by huge factors) heaving that represents the volume change of water as it freezes. Such heaving requires a source of liquid water, typically drawn from groundwater. Heaving that represents only the volume change of freezing water is sometimes referred to as “closed system” heaving, responsible for bursting water pipes in an unheated house, or for the growth of a Pingo from beneath the frozen bottom of a recently drained arctic lake, underlain by a large body of wet soil (a talik) being engulfed by permafrost [*Mackay*, 1978].

2. Redistribution Phenomena

[7] The term thermally induced redistribution arises from experiments at room temperature with fine-grained, uniformly moistened soil packed in a sealed column [e.g., *Gurr et al.*, 1952]. When subjected to a temperature gradient, a vapor pressure gradient is established and a process of distillation begins whereby water is redistributed, with condensate accumulating at the cool end at the expense of water in the warm end. As redistribution proceeds, a monotonic gradient of water content develops with an internal pressure gradient that returns liquid water toward the warm end in the manner of a “heat pipe.” If solutes are present in the water they are eluted from the zone of net condensation into the zone of net evaporation.

[8] Investigators found something that they had not anticipated, however: rates of thermally induced transports often exceeded, by very substantial factors, transports that would be predicted by Fickian diffusion of water vapor through the existing air spaces given the nominal (macroscopic) vapor pressure gradient. This anomaly required investigation and the most appealing analysis at the time was advanced by *Philip and de Vries* [1957], who offered equations for “series parallel transport” with which to estimate such thermally induced transport. Those were found satisfactory by some, but not very useful by others [*de Vries*, 1987]. This question has recently been revisited from a somewhat different viewpoint by one of us [*Miller*, 1998]. H_2O transport in cold, fine-grained soils is even more strongly affected by freezing-induced-redistribution. Experiments like those described above were repeated with initially isothermal columns some degrees above the freezing point. *Dirksen and Miller* [1966] discovered, to their surprise, that when one end was chilled to a few degrees below the ice point, the rates of transfer of water within the ice-free zone near the advancing freezing front exceeded the

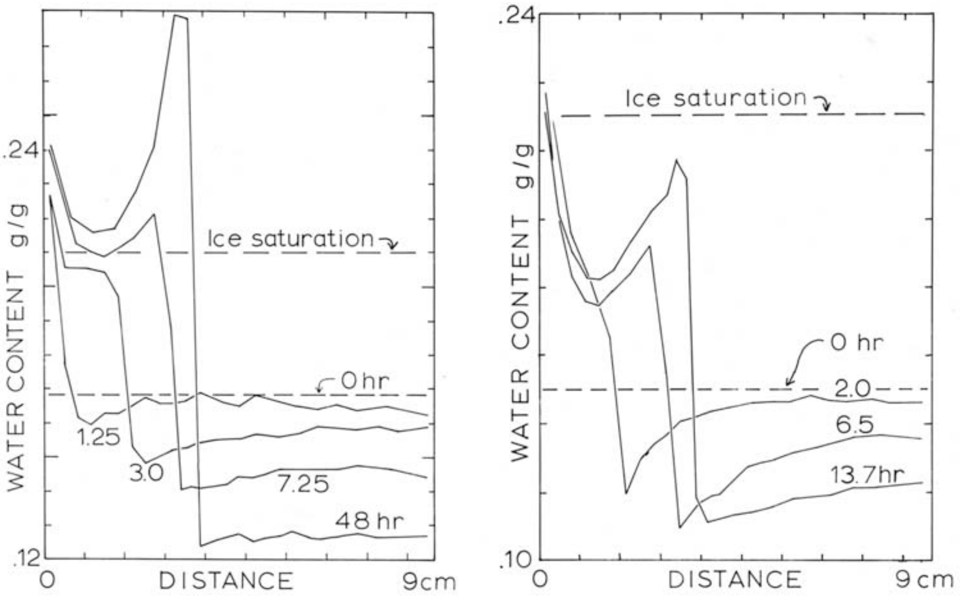

Figure 2. Freezing-induced redistribution in uniformly moistened columns as demonstrated by replicate columns destructively sampled at times indicated. Heaving was observed in the wetter column but not in the other. Reproduced from *Dirksen* [1964].

rates of transfer predicted by the formulations of *Philip and de Vries* [1957] by at least three orders of magnitude! Ice accumulated (sometimes, especially in initially very moist soil, producing frost heave and segregated ice). Inspection showed that the mechanism that produced heave did not operate at the freezing front (as inferred from common concepts of heaving) but rather within a zone somewhat behind the freezing front (Figure 2). As the freezing front advanced, the minimum water content in the retreating unfrozen zone was not at the warm end as expected from thermally induced redistribution, but rather in the unfrozen soil immediately ahead of the freezing front. Clearly, the frozen zone was actively extracting liquid water at a rate that dwarfed any parallel transport by distillation, thereby initiating and sustaining liquid flow toward the freezing front and into the already frozen soil behind that front. In the moister columns, whenever soil behind the freezing front became essentially saturated with accumulating ice, sequential formation of ice lenses near (but behind) the freezing front produced frost heaving (Figure 3). It is significant that those actions took place at temperatures less than a degree below the freezing temperature of water. None of those results had been anticipated and triggered an investigation of the manner in which ice might form in a moist soil [*Miller*, 1973]. They also led to a revised vision of the process of "excessive" frost heaving in air-free, solute-free non-colloidal soils at temperatures within one degree of the normal freezing temperature of water [*Miller*, 1978].

3. An Example of "Excessive" Heaving

[9] For demonstration purposes, one of *Taber*'s [1930] classic experiments on frost heaving was repeated with apparatus seen in Figure 4, made with two short lengths of robust Lucite tubing. The upper section in Figure 4 was filled with a silt notorious for its susceptibility to frost heaving. That soil supports a brass weight and is itself supported by a water-saturated disc of filter paper kept wet by water drawn upward through a water-filled tube that dips deep into the lower section, a vented reservoir initially filled with water and provided with a basal electric heater. The assembly was allowed to stand until capillary action thoroughly wetted the soil. The reservoir was then recharged to the level of the air vent, a level plainly visible in the left image of Figure 4 because magnification of a blackened strip on the background grid ceased where water no longer served as a cylindrical lens. The assembly was placed in an insulated box, open at the top so that the brass weight could be exposed to cold air while the basal heater kept the reservoir from freezing. The box was placed in a chest freezer and left overnight. The following morning, the assembly was removed from its insulated box and photographed again, right image in Figure 4. Note that the volume of extruded material that "heaved" the surface weight approximates the volume of water that was drawn from the reservoir, emptied to the tip of the dip tube. Obviously, ice formed at a pressure greater than atmospheric at the expense of water supplied at a pressure less than atmospheric. Observe alternating strata of clear "segregated" ice and frozen ice-saturated soil in the extruded material. Had the load been substantially larger, but thermal conditions the same, heaving would have been slower; alternating strata would have substantially fewer but substantially thicker, ultimately producing the same uplift of the larger weight by the time that available reservoir water had been consumed. Time-lapse photography has shown that successive ice lenses form one at a time, each apparently ceasing to thicken at the moment that a new lens is initiated at a distance below, so that the heaving process itself is continuous rather than intermittent. Each new lens is initiated at a finite distance behind the descending freezing front within what is already rock-hard frozen soil.

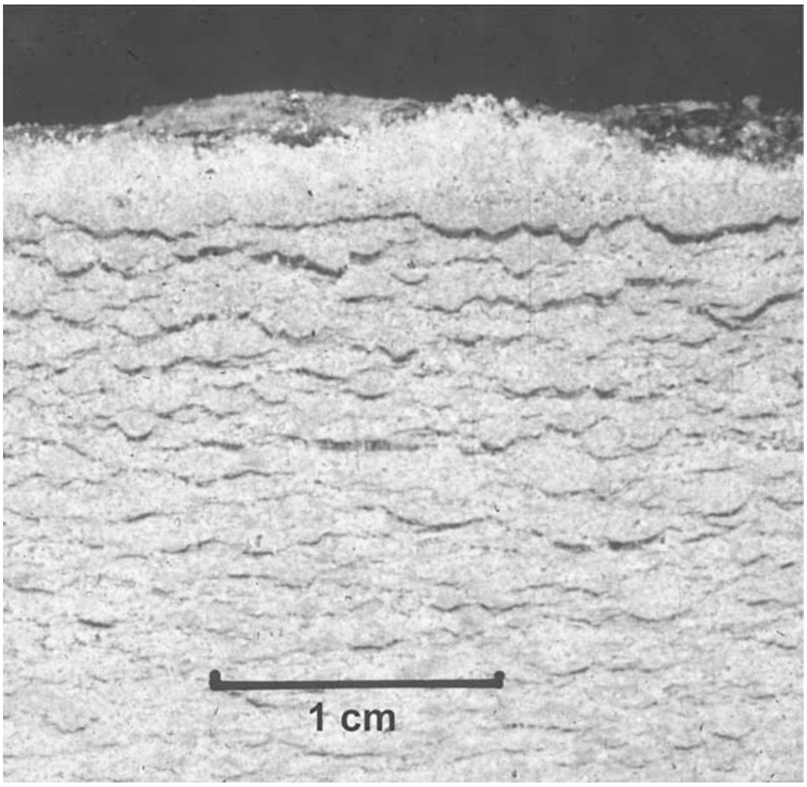

Figure 3. After separating frozen soil from unfrozen in the 48hr column of Figure 2, the frozen portion was split longitudinally, revealing ice lenses. Note the lens-free frozen fringe (lighter in color) on the right margin and the reference bar is 1 cm. Photos by C. Dirksen.

[10] How can such a bizarre process be rationalized? By recognizing a process that has been called thermally induced regelation and its workings.

4. Regelation: Adsorption Space

[11] Experiments [*Hoekstra et al.*, 1965] demonstrated that a droplet of brine embedded in ice will migrate up a thermal gradient by a process of thermally induced regelation. Similar experiments [*Römkens and Miller*, 1973] demonstrated that a glass bead, a grain of quartz, feldspar or mica, embedded in ice, will also migrate up a thermal gradient. In Figure 5, from a doubly exposed negative, the 10-hour movements of a number of glass beads can be seen. Migration velocities are small but increase as grains traverse ever-warmer ice (Figure 6) until finally ejected at an ice-water interface at the zero degree isotherm. This result implies persistence of a mobile film of adsorbed liquid water between the grain and the surrounding ice, a film whose thickness increases with temperature.

[12] We will not review controversies about mechanism(s) that might account for a film with the postulated attributes [e.g., *Dash et al.*, 1995] but invite the reader to assume any mechanism that would cause a grain surface to exhibit a strong affinity for liquid water but no discernible affinity for ice or air. The operative force field must decay rapidly with distance and abruptly vanish at an interface with surrounding ice or air. Thus, in this simple-minded view, a perfectly ordinary phase boundary provides a sharp discontinuity between an adsorbed film in “adsorption space” and ice or air in “capillary space”.

[13] The Gouy-Chapman model of a diffuse electrical double layer at grain surfaces provides a plausible mechanism that would have the desired attributes. If ions of one sign (say, cations) preferentially dissociate from the surface of a solid, or if ions of one sign (say anions) are preferentially adsorbed by that surface, the surface will acquire a (negative) surface charge balanced by an equal and opposite (positive) charge that resides in what will be a diffuse atmosphere of counter-ions (and a local paucity of co-ions) in the adjoining solution. The net concentration of ions decays rapidly with distance. There is abundant evidence that such double layers exist on surfaces of silicate clays of colloidal size (extremely high specific surfaces) with few reasons to doubt that they also exist at surfaces of coarser grains. Among information supportive of this view is stabilization of soft soils by geotechnical engineers who use electro-osmosis to extract water.

[14] Displacement of the outer fringes of a diffuse ionic atmosphere by encroaching ice (from which ions are inherently excluded) implies a liquid necessarily enriched with solutes throughout the constricted adsorption space; colligative effects would include depression of the freezing point at the interface with ice. Hence the equilibrium thickness of adsorption space for a grain embedded in ice would decrease if temperature decreased.

[15] Given a phase-specific adsorption force that diminishes rapidly with distance, minimization of potential energy within adsorption space requires a spherical grain

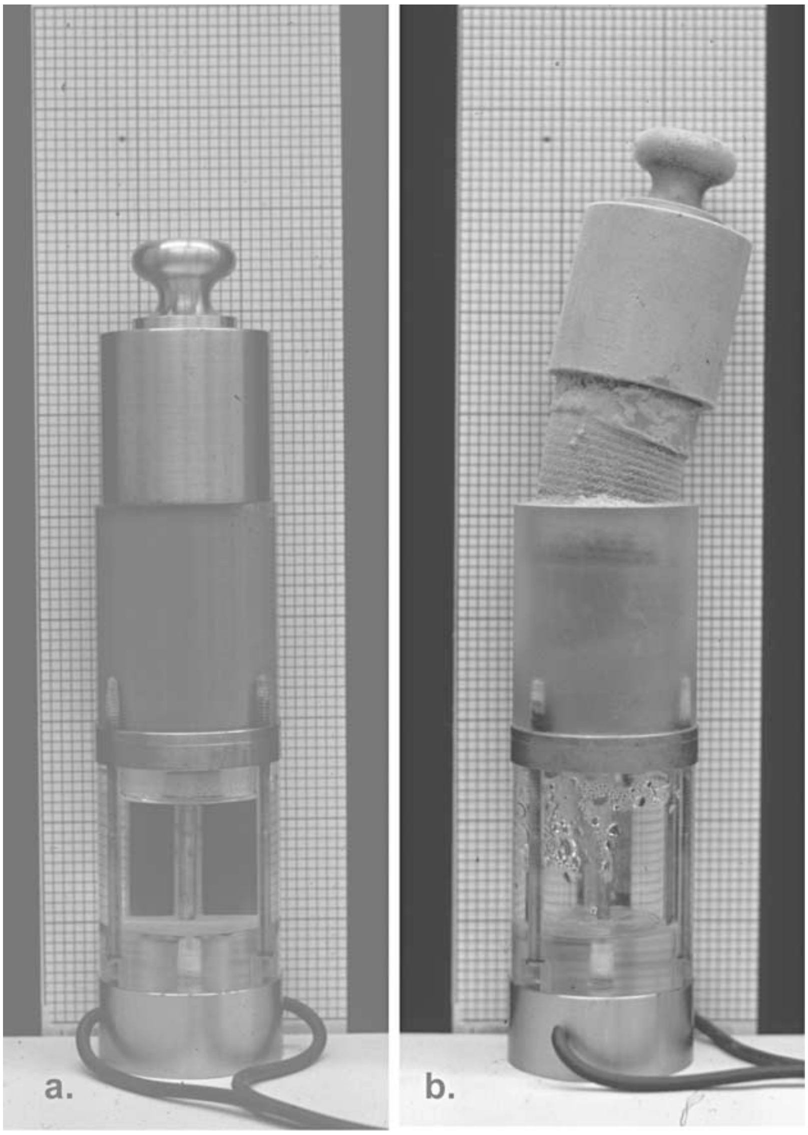

Figure 4. A re-creation of one of Taber's experiments photographed before and after spending overnight in a chest freezer. Details in text. Photos by R. D. Miller.

to spontaneously center itself within that space. But if one imposes a temperature gradient, the film should adjust its thickness (by phase change) in such a way that the freezing point depression of the film at the interface would match the local temperature; the cold side of the film would be thinner than the warm side. A gradient-induced tendency toward asymmetry would be incompatible with a self-centering tendency whereupon the grain would migrate up the temperature gradient by thermally induced regelation, moving ever faster as it crosses isotherms until expelled through the ice-water interface at the freezing isotherm [*Black*, 1992].

5. Freezing in Capillary Space

[16] We now consider the dynamics of H_2O in a capillary space where water, ice and/or air can coexist unaffected by the postulated adsorption force of surrounding grains except as it assures the presence of an adsorbed film, whether adsorption space is bounded by ice or by air. Various experiments and microscopic observations support the proposition that at temperatures below, but near, the ice-point, specific surface free energies ("surface tensions") of air-water, ice-water and ice-air interfaces interact to control the shapes of those interfaces within capillary spaces between grains with surface films of adsorbed liquid water.

[17] It has been shown that gradual freezing of water in a small glass capillary involves an advancing ice-water interface that could be mistaken for the retreating meniscus of an air-water interface when air displaces water from that same capillary [*Skapski et al.*, 1957]. In a water-saturated ice-free fraction (4–8 μ) of silt (mostly quartz) in which capillary space far exceeded adsorption space, stepwise reductions in temperature caused stepwise replacements of pore water by ice. After the soil was thawed, those replacements were mimicked by replacements of pore water by air from those same pores with the match based on the inference that the surface tension of the air-water interface was 2.2 times greater than that of the ice-water interface (Figure 7) [*Koop-*

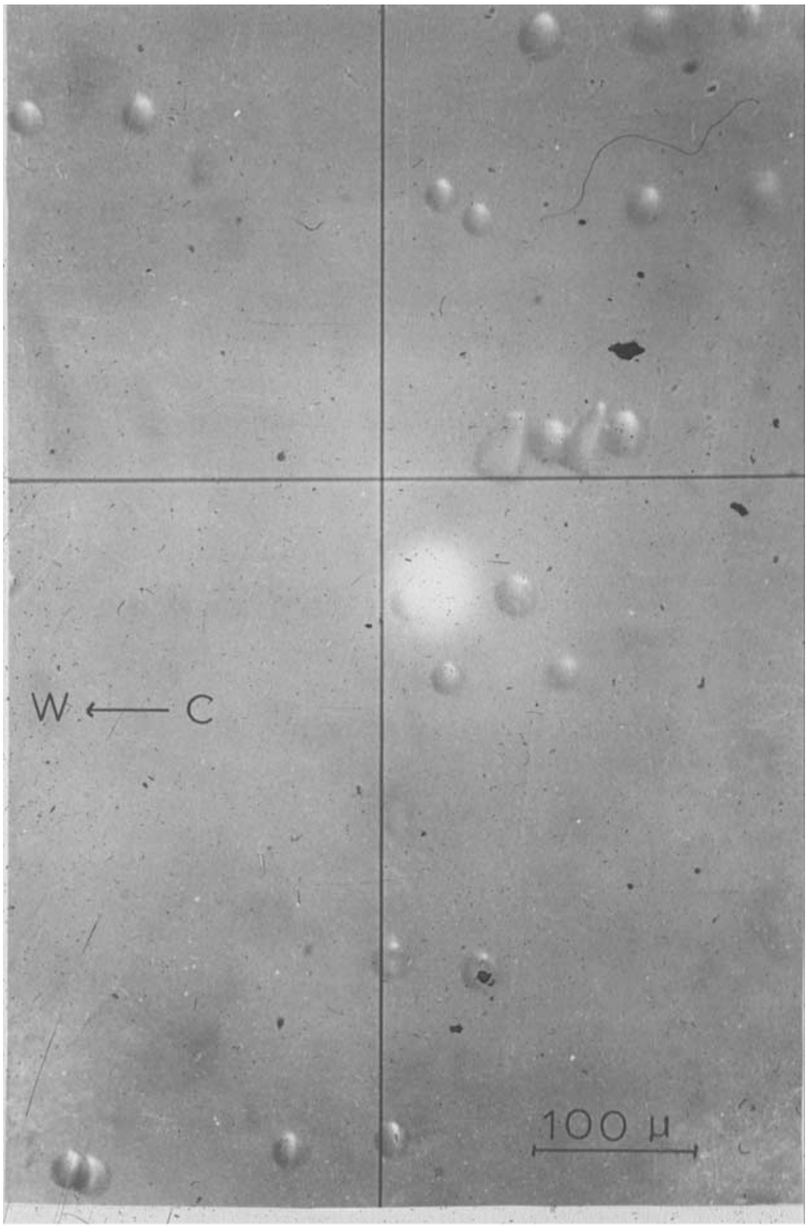

Figure 5. Two exposures made 10 hr apart showing right to left migrations of glass beads embedded in ice with a temperature gradient of 1.55°C/cm. Photos by M. Römkens.

mans and Miller, 1966]. Recognizing that the soil would be a source of minor impurities, that relationship agreed as well as could be expected with theoretical values for very pure water and ice calculated in the context of homogeneous nucleation of freezing of supercooled water [*Hesstvedt*, 1964].

[18] As ice or air displaces water from capillary spaces it increases the resistance to liquid flow but, on the other hand, the curves of Figure 7 imply that nominally frozen soil retains mobile water in microscopic capillary spaces at temperatures significantly below the ice point and this presumption has been verified [*Black and Miller*, 1990].

[19] If we accept propositions that at temperatures near the ice point, all three interfaces tend to obey the well-known LaPlace surface tension equation, while pressures in water and ice obey the appropriate form of the Clapeyron equation (phases at unequal pressures), we have a basis for computing equilibrium configurations of three coexisting phases (water, ice and air) within capillary space in a fine-grained soil. For this purpose, one needs to recognize evidence of the apparent existence of thin films of liquid at ice-air interfaces that allow them to adjust their shapes [*Nakaya and Matsumoto*, 1953]. If such a film has the surface energy of an air-water interface on one side, and that of an ice-water interface on the other, the apparent interfacial energy of the resultant “sandwich” interface would be the sum of those two. Hence what looks like and ice-air interface would function as a single interface with a surface energy equal to that sum.

[20] Using those premises, the LaPlace equation and the Clapeyron equation, one of us undertook an exercise to

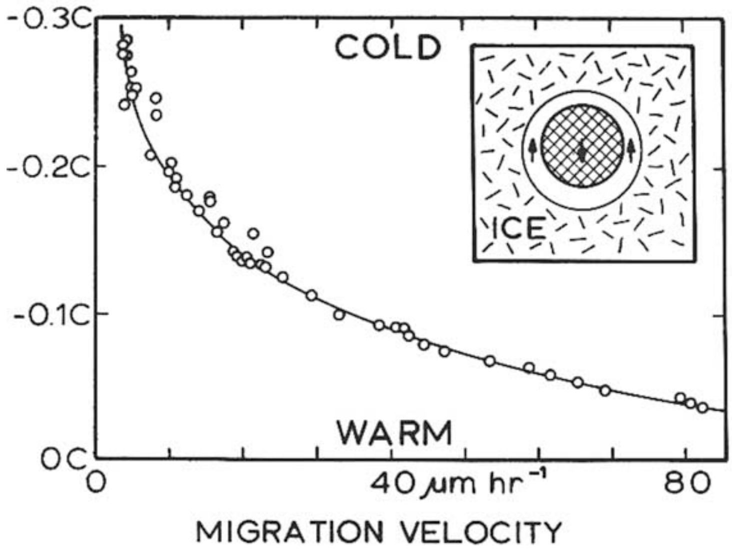

Figure 6. Migration rate in ice of a single glass bead (radius 13 μm) asA it approached the 0°C isotherm. Temperature gradient: 1.14°C/cm. After *Römkens and Miller* [1973].

calculate equilibrium configurations for water, ice and air in extremely simple pores, specifically, pores formed by sets of infinitely long, identical cylindrical rods in regularly stacked arrays [*Miller*, 1973]. A sample result is diagrammed in Figure 8 for arbitrary states in which water and air pressures are always the same; water pressure is less than atmospheric pressure. For a pore with any given geometry, above a critical subzero temperature, t*, ice could not coexist at equilibrium with water and air in that pore. Below a second critical temperature, t**, air could not coexist at equilibrium with water and ice in that same pore. Only between those critical temperatures could all three phases coexist at equilibrium. With air pressure constant, critical temperatures change as pore configurations change and as water pressure changes. *Colbeck*'s [1982] remarkable photographs of ice-air and ice-water interfaces coexisting in glass beads illustrate these phenomena (Figure 9). In a pore of different geometry, a jump to saturation can be triggered in another way; in Figure 10, a pore is also on the verge of filling with ice at some temperature t**.

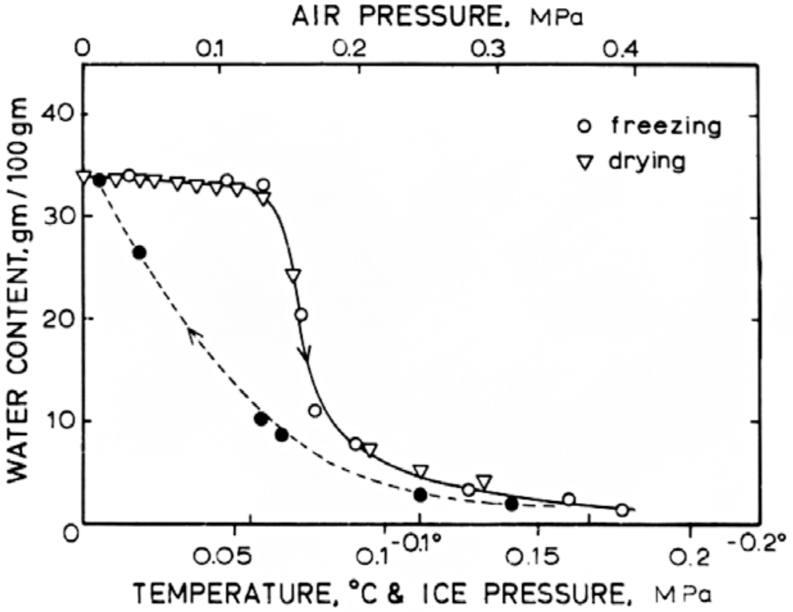

Figure 7. Water content of a single undisturbed sample of 4–8 μ silt as a function of (1) ice pressure (lowest scale) calculated from the Clapeyron equation with water pressure constant (triangles) and (2) air pressure (top scale) with water pressure still constant (open circles) and an assumption that the surface tension of the ice-water interface exceeded that of an air-water interface by a factor 2.2.

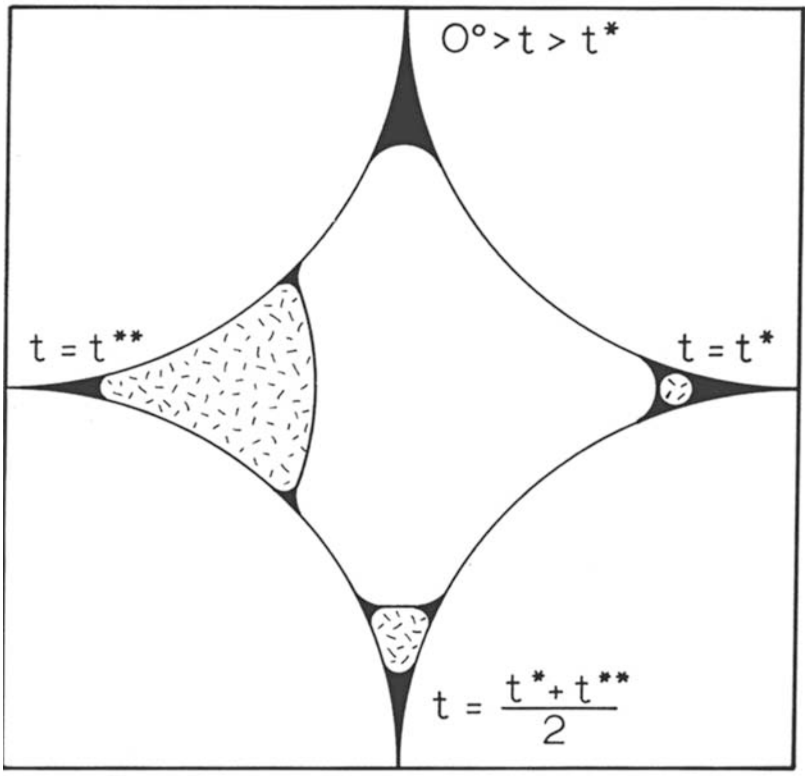

Figure 8. Calculated configurations of air-water, ice-water and ice-air interfaces for two critical temperatures and an intermediate temperature in a pore of the indicated shape. Above t*, ice could not coexist with water and air (the ice would all melt). Below t** air could not coexist with water and ice (the pore would fill with ice).

[21] Such findings rationalize the inference that the ice phase provides an active sink for liquid water behind the freezing front. Given a stationary freezing front, the cold side will tend to become ice-saturated while the warm side tends to be desiccated. However, the presence of salts in the Martian regolith or groundwater could affect the validity of this conclusion. For this reason, if this possibility is deemed likely, redistribution experiments, similar

Figure 9. In a pore with a different configuration than Figure 8, ice-saturation would occur at a higher temperature. This one is at the brink of becoming ice-filled.

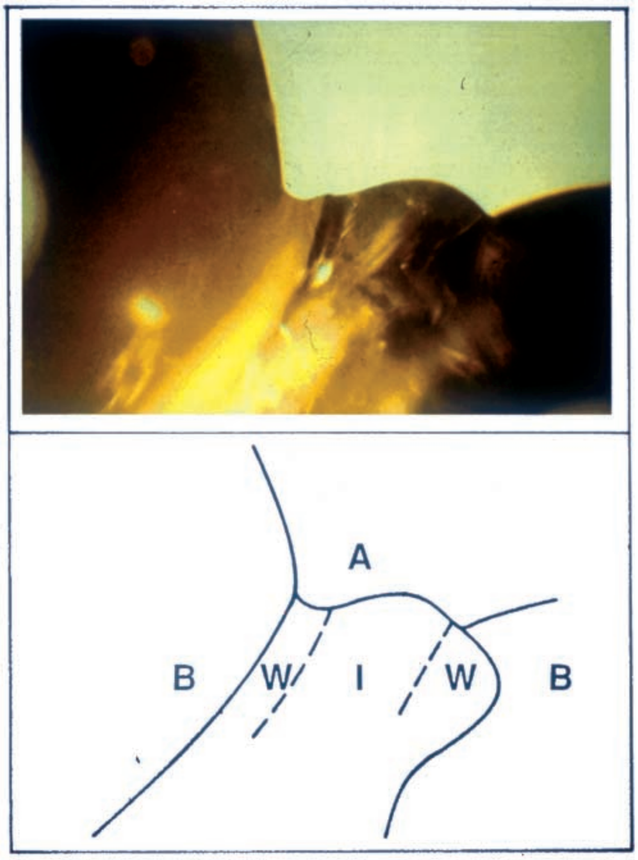

Figure 10. Photograph of ice-water and air-water interfaces in a crevice between glass beads with radii of 1.5 mm After *Colbeck* [1982].

to those described above, should be repeated under anticipated Martian conditions with a range of solute compositions and concentrations.

6. Heaving

[22] A fine-grained terrestrial soil thoroughly wetted from above by irrigation, or from below by capillary action as in Figure 4, typically contains tiny bubbles of entrained air that occupy perhaps ten percent of the total pore space, an incidental detail that will be ignored in a discussion of frost heaving in the demonstration of Figure 4. In that instance, freezing began at the surface and proceeded downward. Pore water changed to ice, progressively engulfing soil grains in the same manner as those same grains would be engulfed by air if the water table were being lowered. That is, a "capillary fringe" envisioned by hydroligists as a water table subsides below a soil surface would have a icy counterpart, a "frozen fringe," developed if a freezing front had descended through that same soil instead of a drying front. In that case, the temperature gradient in the progressing ice fringe would engender a tendency for grains being engulfed by ice to move downward by thermally induced regelation. That tendency would be frustrated if the grains, resting on stationary underlying grains, cannot move. If grains embedded in pore ice can't move downward, the pore ice will moves upward, by regelation, if it is free to do so.

[23] As we have seen, inclinations for relative movements of grains and ice would be most pronounced in the warmest ice closest to the freezing front (where adsorbed films are thickest) but would diminish rapidly as the freezing front continued downward, leaving grains behind to get progressively colder. Each engulfed immobile grain acts as a thermomechanical engine, potentially providing exerting thrust on a stationary ice lattice. If ice movement is opposed by a small load, only the warmest grains are needed to provide thrust to lift that load. Thus, colder grains left behind a descending freezing front may soon find themselves being carried along ("eluted") with the moving ice even though they will soon find themselves free to move (ever more slowly as temperature continues to fall) in the opposite direction with respect to the moving ice lattice itself. If loads are large, more grains are required to provide the needed thrust, but rates of heave will be small.

[24] Elsewhere [*O'Neill and Miller*, 1985], one can find explanations and computed demonstrations of a specific mechanism whereby a continuous ice lattice in continuous motion will produces alternating bands of frozen soil and lenses of more or less clear ice as seen in Figure 4b. Load to be heaved and availability of water at the freezing front are major factors in determination of how rapidly the ice will move as well as where and when a new ice lens will appear and for how long it will grow before the next lens is initiated nearer the freezing front.

[25] The action of frost heaving, like freezing-induced redistribution takes place within a very narrow range of temperatures slightly below the normal freezing point. When ground temperatures are well below this range, neither process is likely to contribute to the formation of significant quantities segregated ice. On the other hand the tendency for droplets of brine to migrate through ice (up a temperature gradient) could conceivably result in pockets of saline water within or beneath the frozen Martian regolith. The likelihood of developing brine pockets by this mechanism is poor, however, if the local geothermal gradient is small.

7. Massive Ice in Permafrost

[26] This discussion is limited to dynamic processes that can lead to bodies of clear ice formed within terrestrial soil that is already frozen. Ice lenses formed during seasonal freezing (Figure 1) of normally unfrozen soil are one thing. Permanently frozen massive ice that is so often found beneath arctic landscapes on Earth are another. What follows is our version of a mechanism described in a paper by *Guoding* [1983]. It represents a process of "inverted" heaving which can produce thick layers of more or less pure ice below the bottom of a seasonally thawed "active layer" at the top of deep, cold terrestrial permafrost. In Figure 1, the "active layer," is peat, a slowly accumulating residue of tundra vegetation at the ground surface, perhaps admixed with aeolian silt. When dry, peat is a good thermal insulator and can serve as a summer check-valve for the exchanges of heat with the environment. Snowmelt in early summer or summer rain, or both, percolate into the thawing zone and tend to accumulate at the bottom by (1) gravitation and (2) thermally induced redistribution. In late summer or early fall, as inputs of heat dwindle, moist or wet soil above the

permafrost table begins to freeze from the bottom up. A frozen fringe advances upward, providing (if not already saturated with water and ice) an active sink for water extracted from the as-yet-unfrozen zone (freezing-induced redistribution). If the active layer is fine-grained (or peaty), heaving can take place. This time, small grains (or porous residues of peat) in the inverted frozen fringe can move (upward), lifting overlying components of the active layer and leaving behind a layer of fresh, more or less pure ice. Until the rising freezing front encounters a second freezing front descending from the soil surface, overlying grains constituting the active layer and the soil surface will be displaced upward. If, during the following summer, thawing penetrates to the same depth (relative to the now-elevated ground surface), ice formed the previous fall, just above the old permafrost table, will not thaw and the permafrost table will have been elevated by an accretion of more or less pure ice. Given repetitious annual cycles of thawing, a massive accumulation of more or less pure ground ice can be generated and will appear to be below the permafrost table, a level which has, in fact, been stepping upwards year by year. If there are annual additions of plant residues or aeolian silt, or both, at the soil surface, corresponding relicts of previous additions left behind in each year's increment of new ice. Perhaps, however, many peaty strata combine residues from a period of years, united by a summer when thawing was deeper than the average.

[27] Neither of the authors has enjoyed an opportunity to collect appropriate samples for carbon dating of peaty residues that could support this postulate. One of us (R.D.M) has a long history of urging colleagues engaged in field studies of permafrost to collect and date such samples from exposures like that in Figure 1.

[28] The above scenario for accumulation of massive ground ice beneath extensive areas of terrestrial permafrost depends upon (1) fine-grained or peaty soils (2) deep cold permafrost with (3) an active layer that annually thaws and re-freezes and (4) recurrent precipitation derived from sources of oceanic scale. Where soils are coarse-grained, the scenario depends upon development of a mat of arctic tundra to generate a peaty active layer.

8. Summary Implications

[29] Were the potential for the thermal and freezing-induced redistribution of H_2O on Mars based solely on the mechanism most responsible for its occurrence on Earth (i.e., seasonal thaw) then its expected influence on the distribution of subsurface ice on Mars would be minimal. However, there appear to be a variety of other plausible mechanisms that may promote the redistribution of ice in the Martian regolith.

[30] As noted previously, there is considerable evidence that the crust of Mars is water-rich [e.g., see *Squyres et al.*, 1992; *Clifford*, 1993; *Carr*, 1996]. Given this assumption, the principal requirement for the thermal and freezing-induced redistribution of H_2O is the occurrence of thermal disturbances sufficient to cause significant melting and a steep thermal gradient. There are at least four mechanisms that may do so. The first is the natural volcanic and magmatic evolution of the crust, for which there is considerable evidence of past activity [e.g., *Greeley and Spudis*, 1978; *Mouginnis-Mark et al.*, 1992]. Second, impacts can produce large local transient thermal disturbances (through the production of impact melt) that may persist for periods as great as 10^3 to 10^6 years [*Newsom*, 1980; *Clifford*, 1993]. Third, it is known that the Martian obliquity (axial inclination) has a period of $\sim 10^5$ years, with an amplitude that varies chaotically on a timescale of $\sim 10^7$ years, reaching values as high as 60° [*Laskar and Robutel*, 1993; *Touma and Wisdom*, 1993; *Clifford and Parker*, 2001]. During such times, temperatures in the summer hemisphere can reach values in excess of 273 K for continuous periods of many months at high latitude (alternating with winters where the temperature plummets to <140 K). Finally, such temperature conditions may also arise as a result of future human activity; for example, a heated human habitation module, nuclear power source, or lander/ascent vehicle might be accidentally placed on a surface consisting of ice-rich, fine-grained soil. Unless active measures are taken to avoid such environments, or to mitigate the thermal disturbance associated with these activities, the resulting thermal and freezing-induced redistribution of ice could have disastrous consequences for the stability and integrity of exploration equipment and facilities.

[31] While we can deduce much about the potential behavior of freezing-induced redistribution of H_2O in the Martian regolith by examining our terrestrial groundfreezing experience, we still must perform further experiments and modeling specifically designed for the Martian environment. The thermal and hydrologic environments of the two planets are just too different to rely on simple extensions of our terrestrial experience alone.

[32] **Acknowledgments.** We thank Stephen Clifford of LPI and Jason Soderblom of Cornell University for their helpful conversations and recommendations about the Martian environment.

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