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# ROLE OF ARTESIAN GROUNDWATER IN FORMING MARTIAN PERMAFROST FEATURES

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Various landforms possibly related to formation (growth), movement, or decay of ground ice have been identified on Mars, including fretted terrain (*ft*) and associated lobate debris aprons (*lda*) *[1,2,12,13]*, the chaotic terrain *[3]*, concentric crater fills (*ccf*) *[2]*, polygonal ground *[4]*, "softened" terrain *[5]*, small domes that are possibly pingos *[6]*, and curvilinear (fingerprint) features (*cuf*) *[4,7]*. Glaciers may also been formerly present *[8]*. Some of these may involved ice derived from artesian groundwater.

*Mars groundwater and the location of permafrost features:* Several permafrost landforms including *ft*, *lda*, *ccf*, and, possibly, *cuf* are located in narrow latitudinal belts *[2,4,5]* (Fig.1). The lack of such features poleward of ±60° latitude may result from ground temperatures too low for appreciable ice flowage, and the equatorward limit at ±30° is thought to result from climatic disequilibrium of permafrost in equatorial regions. The permafrost features are widely distributed in the northern band, but occur in the southern hemisphere only in the vicinity of Hellas and Argyre (Fig. 1). Squyres *[2]* suggests that the the restricted southern distribution may be due to regolith properties in the vicinity of major impacts. However, these permafrost features reveal a consistent topographic pattern (Fig. 1). *The fretted terrain, concentric crater fills, and lobate debris aprons (and, possibly, curvilinear features) occur along, and particularly near the base of, high-relief regional slopes.* Most are associated with the north-south highland-lowland scarp, but some occur on the lower flanks of Elysium and in the Hellas and Argyre depressions. The southern highlands lacking these features, and in the north these features are absent near the tops of volcanic constructs and rare in the center of the major basins. Their absence poleward of ±60° may be related more to the absence of strong regional slopes than to reduced ice mobility.

The *ft*, *lda*, *ccf*, and *cuf* occur where groundwater may have discharged if it were unconfined *[9]*. Lowland areas are thus more likely to have developed permafrost with a completely saturated regolith than highlands such as the southern hemisphere cratered terrain (which is likely to have been drained of near-surface water during warmer epochs, during the early periods with higher geothermal heat or due to episodes of ground heating by volcanism or impact cratering). Even if early climates were occasionally warm enough for recharge from precipitation, water tables would have been deep in highlands *[9]*.

In addition, the scarp-base locations of permafrost features favor artesian overpressuring. A martian global groundwater model *[10]* was utilized to predict where artesian overpressuring might occur (Fig. 2). In this simulation groundwater is assumed to be recharged (and discharged) in the latitude belt ±20° (groundwater could also be derived from melting of permafrost). Poleward of ±20° a coherent, impermeable permafrost was assumed to extend from the surface to a depth of 1 km at the equatorward limit and to a depth of 4 km at the poles. Figure 2 shows contours of the artesian gradient, defined as $(h - h_c)/(h_s - h_c)$, where $h$ is the hydraulic head, $h_s$ is the surface elevation, and $h_c$ is the elevation of the base of the permafrost. Values greater than zero indicate artesian conditions (values less than zero are not shown). The permafrost features generally occur in areas predicted to have artesian conditions. The exceptions are portions of Deuteronilus, Protonilus, and Nilosyrtus Mensae, which extend high onto the highlands-lowlands scarp. However, the distribution and magnitude of artesian gradients are highly sensitive to the assumed distribution and thickness of ground ice, the assumed locations and magnitude of recharge, uncertainties in the surface topography, and the hydrologic properties of the regolith. Minimally the artesian conditions would assure development of permafrost with ice completely filling voids. In addition, as detailed below and in *[9]*, other effects may have occurred, including springs, supply of water to glacial flows, development of segregated ice, intrusion of ice (or water sills) and pingos, and rapid release of water derived from melting of segregated or intruded ice.

Softened terrain, possibly resulting from creep of ground ice *[5]*, does not follow the above distributional pattern. It is more widely distributed latitudinally and occurs on a variety of topographic setting. If it is a permafrost feature (see dissents *[11]*) it probably does not involve artesian groundwater.

*Role of artesian groundwater in formation of fretted terrain, lobate debris blankets, and concentric crater fills:* The *ft*, *lda*, and *ccf* are thought to result from slow flow of debris and ice outward from steep scarps, with differences primarily resulting from variations in the topographic setting (narrow troughs, scarp margins, and crater interiors). Mechanisms that have been proposed are gelifluction *[12]*, rock-glacier flow with ice derived from seasonal frosts incorporated in mass-wasted debris *[2]*, and flow of ice-rich layers beneath the uplands, which thereby erodes the scarp margin *[13]*. As pointed out by Squyres *[2]*, the shape of the debris blankets suggests bulk movement rather than surficial movement of the debris, casting doubt on gelifluction. Lucchitta *[13]* has criticized seasonal frost trapping as being insufficient to generate a high enough ice/rock ratio to permit bulk flow. In addition, the debris blankets show very little variation with aspect, which would probably occur if deposition and ablation of seasonal frosts were involved. In turn, the mechanism of flow of ice-rich layers beneath the plateau units is also deficient. Emplacement of a high ice content beneath the plateau units must be accomplished (filling voids and development of segregated or intruded ice from artesian groundwater is one possibility). However, if ice-rich layers in the plateau material were involved in bulk flow, lowering (as the ice flowed out) and tilting (due to areal variations in ice content) of the plateau surface should occur, as well as break-up and separation into small blocks due to tensional stresses on coherent upper layers. This breakup would be accentuated by upward displacement of geothermal isotherms below plateaus (see below). Although Lucchitta *[13]* points out an instance of such effects along a fretted channel margin there is little evidence for downdrop, tilting, or relative movement of residual upland blocks and mesas.

A somewhat different mechanism for generation and flow of ice relies on artesian water pressures. The height of fretted terrain scarps is on the order of 1-2 km, about the same order of magnitude as the permafrost thickness. Therefore the bottom of the permafrost is displaced upwards below the scarp (Fig. 3A), and the thinnest permafrost is found near the scarp base. If the sub-permafrost aquifer were saturated and under artesian pressure, the gradient through the permafrost would be greatest near the scarp base, and this, coupled with the tendency for the saturated regolith to flow downwards and outwards could lead to a steady-state situation in which outward flow of ice and debris from the base of the scarp (aided, perhaps, by development of segregated ice and ice intrusions) would be balanced by replacement of ice by flow and freezing of groundwater (Fig. 3B). Depending upon the locus of the lower ice-water contact, greater or lesser amounts of regolith would be incorporated in the outward glacial flow (with corresponding variation in backwasting rates). This speculative scenario requires modeling of the heat budget, groundwater flow, ice movement, and regolith response to demonstrates its feasibility.

*Source of glacial ice:* The former presence of glaciers has been suggested based upon identification of possible moraines or ice-carved features *[8]*. Although groundwater as a water source for such glaciers has been suggested *[8]*, objections have been raised. Carr *[14]* notes that springs in Arctic areas do not form large masses of ice, but flow for long distances before freezing. Lucchitta *[8]* feels that the confined form of the putative glaciers occupying portions of Mars' outflow channels is not the domical shape that might form from freezing of water reaching the surface. However, glaciers may have been fed by a mechanism similar to that suggested for the lobate debris blankets (Fig. 3B) in which groundwater does not have to reach the surface. A variety of phenomena might accompany such glaciation, including rapid headcutting of the scarps (Fig. 3B), creation of ice-dammed lakes with the potentiality of catastrophic draining, and jokulhlaups created by episodic draining of sub-ice lakes created by intrusion of groundwater.

*Pingos and other pseudo-volcanic structures:* Numerous small domes, some with central depressions, occur on the southern portion of the northern lowlands. The predominant explanation is that they are small volcanic domes *[15]*, although an origin as pingos has also been suggested *[6]*, based upon the very strong resemblance in size and form of open-system pingos to small volcanic cones *[17]*. An origin as either closed- or open-system is possible, with the position near the highland-lowlands boundary possibly providing the requisite artesian pressures for the latter type.

References: *[1]* Sharp, 1973a,b, *J. Geophys. Res., 78,* 4063-72, 4073-83; *[2]* Squyres, 1978, *Icarus, 34,* 600-13; Squyres, 1979, *J. Geophys. Res., 84,* 8087-96; *[3]* Carr, 1979, *J. Geophys. Res., 84,* 2995-3007; Nummendal and Prior, 1981, *Icarus, 45,* 77-86; *[4]* Rossbacher and Judson, 1981, *Icarus, 45,* 39-59; *[5]* Squyres and Carr, 1986, *Science, 231,* 248-52; Squyres, 1989, *Icarus, 79,* 229-88; *[6]* Lucchitta, 1981, *Icarus, 45,* 264-303, Costard and Dollfus, 1986, *LPI Tech. Rpt. 87-02,* 211-2; *[7]* Parker et al., 1989, *Icarus, 82,* 111-45; *[8]* Luchitta, 1982, *J. Geophys. Res., 87,* 9951-73; *[9]* Howard, 1991, Role of Groundwater in Formation of Martian Channels *[This volume]*;.*[10]* Howard, 1991, A Martian Global Groundwater Model *[This volume]*; *[11]* Zimbleman et al., 1988, *LPSC XIX,* 1321-2; Moore, 1990, *J. Geophys. Res., 95,* 14279-89; *[12]* Carr and Schaber, 1977, *J. Geophys. Res., 82,* 4039-54; *[13]* Lucchitta, 1984, *J. Geophys. Res., 89,* B409-18; *[14]* Presentation at 1989 Fall AGU; *[15]* Frey and Jarosewich, 1982, *J. Geophys. Res., 87,* 9867-70; *[16]* Muller, 1959, *Medd. om Gronland 153(3),* 127p.

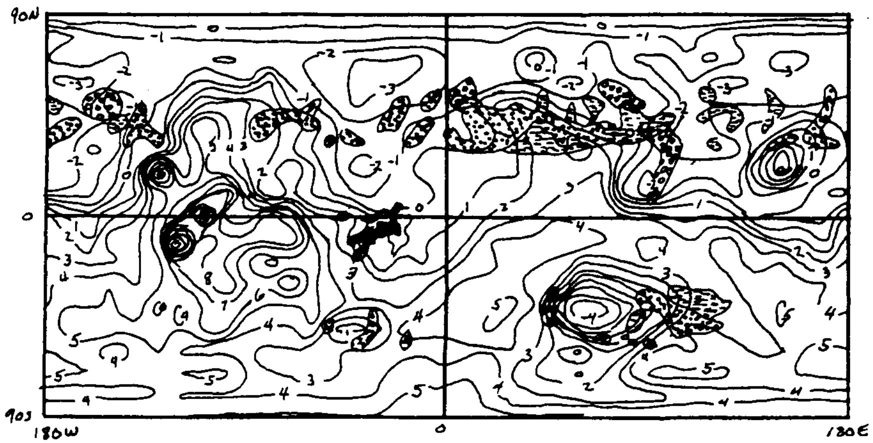


Fig. 1. Generalized Mars topography, showing location of fretted terrain (heavy dots), concentric crater fills (dashes), curvilinear features (open circles), and chaotic terrain (cross-hatching). Based upon published maps *[2,4,5]*.

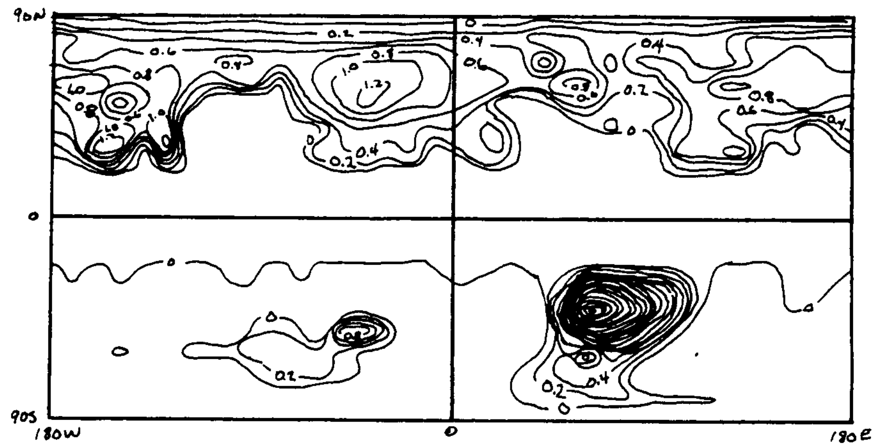


Fig. 2. Contours of steady-state artesian gradients through near-surface permafrost under conditions of complete permafrost poleward of ±20° latitude and recharge in equatorial regions.

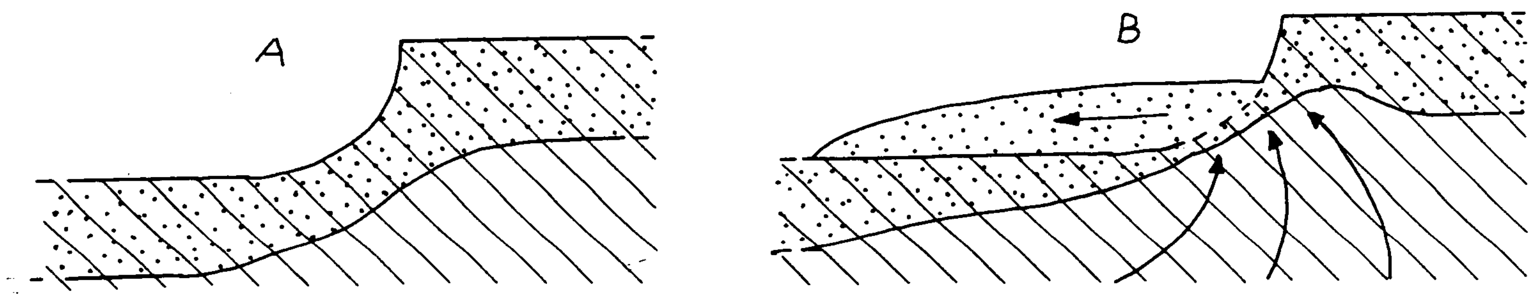


Fig. 3. (A) Distribution of permafrost beneath a scarp under conditions of no groundwater or ice flow, and (B) Distribution of ground ice, debris apron, and ice and water flow patterns under hypothesized model for origin of lobate debris apron. Dotted areas are permafrost or ice-cored debris apron, ruled areas are regolith.