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ICE IN CHANNELS AND ICE-ROCK MIXTURES IN VALLEYS ON MARS: DID THEY SLIDE ON DEFORMABLE RUBBLE LIKE ANTARCTIC ICE STREAMS?

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Recent studies of ice streams in Antarctica reveal a mechanism of basal motion that may apply to channels and valleys on Mars. The mechanism is sliding of the ice on deformable water-saturated till under high pore pressures. It has been suggested by Lucchitta [1] that ice was present in outflow channels on Mars and gave them their distinctive morpholoy. This ice may have slid like Antarctic ice streams but on rubbly weathering products rather than till. However, to generate water under high pore pressures, elevated heatflow is needed to melt the base of the ice. Either volcanism or higher heatflow more than 2 b.y. ago [2] could have raised the basal temperature. Regarding valley networks, higher heatflow 3 b.y. ago could have allowed sliding of ice-saturated overburden at a few hundred meters depth. If the original, pristine valleys were somewhat deeper than they are now, they could have formed by the same mechanism.

Recent sounding of the seafloor in front of the Ross Ice Shelf in Antarctica reveals large persistent patterns of longitudinal megaflutes and drumlinoid forms [3], which bear remarkable resemblance to longitudinal grooves and highly elongated streamlined islands found on the floors of martian outflow channels. The flutes are interpreted to have formed at the base of ice streams during the last glacial advance [3]. Additional similarities of Antarctic ice streams with martian outflow channels are apparent. Antarctic ice streams are 30 to 80 km wide and hundreds of kilometers long. Martian outflow channels have similar dimensions. Ice stream beds are below sea level [4]. Carr [5] determined that most common floor elevations of martian outflow channels lie below martian datum, which may have been close to or below past martian sea levels [6,7]. The Antarctic ice stream bed gradient is flat and locally may go uphill, and surface slopes are exceptionally low [8]. Martian channels also have floor gradients that are shallow or go uphill locally and have low surface gradients [9]. The depth to the bed in ice streams is 1 to 1.5 km [10]. At bankful stage, the depth of the fluid in outflow channels was 1 to 2 km, according to the height of bordering scarps [1]. The similarity between Antarctic ice streams and martian outflow channels suggests that ice may have flowed through and shaped the outflow channels [1], and that perhaps the mechanism of motion of Antarctic ice streams also operated in outflow channels. In addition, sliding on deformable rubble may explain the formation of small valley networks.

The large Siple Coast Antarctic ice streams are thought to slide over longitudinally grooved, deforming till, where much of the movement is within the till [10,11]. The till is saturated with water at high pore pressures that nearly supports all of the weight of the ice [10,4]. The small differential between overburden pressure and pore pressure at the bed is more important than the volume of water, but water needs to be supplied to the till interface [4]. For pore pressures to remain high, the ice streams have to act as a seal that blocks the flow of water through them, and the rock underneath has to be of low permeability to prevent the water from draining away. The water is thought to have been derived from melting ice due to geothermal heat and perhaps volcanic heat [10]. Once moving, frictional heat will tend to keep the water from refreezing.

A similar mechanism of sliding on deformable rubble may have operated at the base of outflow channels and small valleys on Mars. Indeed, such a mechanism has recently been proposed by Carr [5] for fretted channels and valleys on Mars. Most of the conditions for the Antarctic sliding mechanism are met for martian outflow channels. In situ rubble from weathering products may have served as the deformable layer. The channel ice may have come from ice dams and jams [1], from frozen or partially frozen lakes [12], from segregated masses akin to ice sills or laccoliths [13], from glacier ice [7,14], or from icings above springs [1]. The channel ice forms the seal above the sliding horizons, the bedrock the seal below so that water could accumulate under high pore pressures. For small valleys in highlands, deformable breccia with mechanical properties similar to till [15,16] likely occurs at 1 to 2 km depth. Layers that may represent impermeable horizons have also been recognized in many places at these depths [17,18]. Such layers may form the seal below the sliding horizons. The ice-saturated ground above [19,5] would provide the seal in the overburden and furnish the water needed to pressurize the pores.

Water needs to be liberated at the base of the sliding masses to generate high pore pressures. The depth to melting can be calculated from the heatflow equation $z= k/Q\ (tp-ts)$; where z=thickness of the measured layer, here the depth to melting; k=thermal conductivity; Q= heatflow; tp= temperature at the lower boundary of the layer, here the melting temperature; and ts=annual mean surface temperature. Depth to melting can be measured to the 273 K isotherm for water ice, or to the 252 K isotherm for NaCl brines, which are likely to occur on Mars [21]. The depth at which water ice overburden would melt on Mars under current equatorial surface temperatures (218 K [20]) is nearly 5 km, using a heatflow of 30 mWm^{-2} [20] and a thermal conductivity of ice of $k=2.6\ J\ m^{-1}\ s^{-1}\ K^{-1}$ (after Glen [21]). Clearly, this depth is in excess of the common depth of outflow channels. Evidently, warmer climates would be needed to make the ice-stream mechanism work. However, outflow channels date from the martian mid-history or even late history [22], when the existence of warmer climates is conjectural. Therefore, elevated heatflow is needed to liberate water from ice at the base of the outflow channels.

The possible association of channels and valleys with regions of elevated heatflow is suggested by proximity to grabens [23]; dark, most likely mafic, materials [24]; and volcanoes [25]. Assuming a heatflow of 90 mWm^{-2}, representative of some volcanic regions on earth [26], and using the other parameters given for ice above, melting of ice overburden would have occurred at a depth of 1.6 km using the 273 K isotherm (water ice) and at 1.0 km using 252 K (NaCl brines). Thus, on the floor of ice-filled, 1- to 2-km-deep outflow channels, water could have been liberated in the equatorial areas of Mars if the region had elevated heatflow due to volcanism.

Past heatflows have been addressed by Schubert and Spohn [2]. Their model estimates mantle heatflows of about 40 mWm^{-2}, 1 b.y. ago; of about 70 mWm^{-2}; 2 b.y. ago; and of about 100 mWm^{-2}, 3 b.y. ago. Accordingly, 2 b.y. ago and earlier, melting would occur at depths of 2.0 km or less (273 K isotherm, water) or 1.3 km or less (252 K isotherm, NaCl brine), and ice could have flowed in outflow channels.

Most valleys on Mars are ancient (upper Noachian, [22]) and formed during a time when heatflow was elevated and melting occurred at much shallower levels than today. The depth to melting critically depends on the thermal conductivity used for the martian highlands. Clifford [20] proposed a thermal conductivity of $2.O\ J\ m^{-1}\ s^{-1}\ K^{-1}$ (an average between frozen soils and vesicular basalt). Rossbacher and Judson [19] used a thermal conductivity of $0.8\ J\ m^{-1}\ s^{-1}\ K^{-1}$ (frozen limonitic soil). Applying current surface temperatures, Schubert and Spohn's [2] heatflow values of 3 b.y. ago, and Clifford's [20] thermal conductivity, the depth to melting of ice-rich rock overburden would have been 1.1 km (273 K isotherm, water) or 0.7 km (252 K isotherm, NaCl brine). Using Rossbacher and Judson's [19] thermal conductivity, the depth to melting of ice-rich overburden would have been 0.4 km or 0.3 km, respectively. The latter depths fall within the range of depths of small valleys on Mars [27], especially if one assumes that the valleys have been infilled with erosional debris. Thus, about 3 b.y. ago, during times of elevated heatflow, water may have been liberated at the floor level of small valleys, allowing pore pressures to build. Given lack of restraint at the bottom of slopes and local concentration of fluids, the ice-rich ground could have become mobilized and slid in the manner of Antarctic ice streams.

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