Sea Ice Ridging and Rafting Structures: Is the microstructural controlled transition from Ductile to Brittle Behavior on Earth also seen on Mars?

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Introduction: Sea ice formation on Mars was postulated by [1], based partially on images showing analogous structures to those reported for the Earth's polar regions. Further examination of additional high-resolution imagery has shown features that resemble sea ice pressure ridges that also have been observed in the Earth's sea ice cover. Fig. 1 is a HiRISE image with ridge-like features. The zoomed area shows that ridges appear on the boundaries of the darker, presumably older material [1] but particularly noted here are the linear, sinuous and rectilinear traces in the lighter material. For comparison, Fig. 2 shows an aerial photographic image of Arctic sea ice with pressure ridge traces that have similar scales to those shown on Mars in Fig. 1.

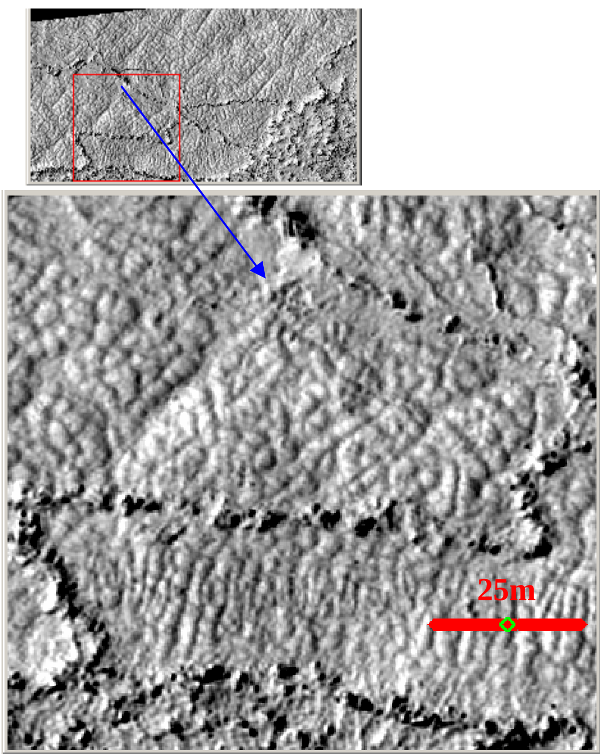

Fig. 1 HiRISC image of Elysium area with ridge-like features (top: 304 m × 167 m, bottom: 100m × 100m).

Pressure Ridges: As seen on the Fig.2, the ridges take on several forms: linear ridges, wave-like or sinuous ridges, and some rectilinear features known as rafts [2,3]. Rafts are usually formed from quite thin sea ice and are over thrusting rectilinear features of relatively low topography as shown in Fig.3. Sometimes several of these features appear side-by-side and are called finger rafts, usually when they occur entirely within thin ice.

Fig. 2 Aerial photo of Arctic sea ice in late winter with pressure ridge features

Fig. 3 Example of a 1 m × 3 m rafted sea ice structure that has been pushed out over the adjacent ice sheet.

Sea Ice Microstructure and Mechanical Properties: The mechanical behavior of sea ice and its ability to transition between rafting and ridging behavior is a function of the elastic mechanical properties. Sea ice is a two-phase material, consisting of solids, principally ice with some solid salts, and liquid brine contained within lamellae of a pure ice matrix in a closely interlocked structure. The relative amount of brine, ice and solid salts is controlled by the thermodynamics of the phase equilibrium, dependent on the amounts and types of dissolved salts and the *in situ* temperature and pressure [4]. At higher brine volumes, sea ice behaves as a ductile material, meaning that it can undergo large strain without fracture and deform plastically at low stress, while sea ice with low or no brine volume will crack at low strain (but higher stress) or undergo brittle failure [5]. On the larger scale, ductile behavior is shown by the thrust structures known as rafts that can form by sheets sliding and moving plastically over each other for meters to tens of meters without fracture (Fig. 3). At the other extreme, with low brine volumes, as the ice sheets try to override, rather than bending and flexing, sheets of ice fracture at low strain and blocks are broken off by their own weight as they are cantilevered out of the water. The characteristic length between fractures is of the order of the ice thickness, i.e. from a few tens of centimeters to 1-3 meters (maximum), leading to linear ridges of a few meters width consisting of piles of ice blocks, as shown on the right side of Fig. 2.

Dynamic Transition from Ductile to Brittle Behavior: Sinuous ridges represent a dynamic transition from the overthrusting sheets (ductile behavior) to narrow linear ridges (brittle behavior). They are formed first from 10 to 20m sheet overthrusts. During the process of overthrusting, the ice at the leading edge of the sheets undergoes a thermal or hydraulic transformation where the relative brine volume is lowered, leading to a stiffening of the ice and its transition to a brittle structure. The breaking into short blocks observed in brittle behavior is then found, outlining the outer edges of the thrusts, representative of the failure occurring there. The center ridge in Fig. 2, above the scale, is a sinuous ridge formed by this two stage process, ductile overthrusting of adjacent sheets, followed by brittle failure of the edges of the overthrusts, creating a narrow blocky outline of the thrust structures in a sinusoidal form.

Thermal Stiffening of Sea Ice: The thermal process to reduce brine volume and stiffen the ice is probably the most applicable to the Mars case. Stiffening occurs from the freezing of liquid water into ice and precipitation of solid salts within the ice as the ice sheet is exposed on its edges and bottom to lower atmospheric temperatures than the ocean as the ice sheet is pushed out of the fluid and onto the solid surface. An Arctic example of this process is shown in Fig. 4. Here we see the ductile thin sheet bent through a large angle leading to a curved ice sheet at high angle. If the ice remained ductile it would crawl out onto the adjacent sheet as shown in Fig. 3. However, as the sheet is exposed to the low air temperatures as it is moved out of the water, it freezes and stiffens and is able to maintain the curved structure and move almost vertically. Once the cantilever length is too long however, its rigidity transfers the bending moment due to its weight to the hinge point, leading to a stress riser there. The stress eventually causes a tension failure to occur by a crack propagating through the thickness, and the blocks fracture off in brittle failure as shown further along the ridge in the background of Fig. 4.

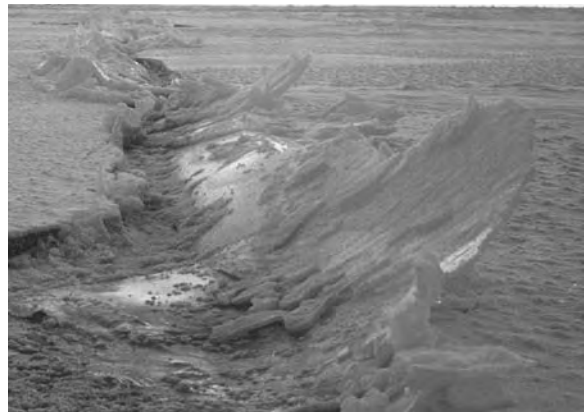

Fig. 4. Example of Arctic's thin, ductile sea ice frozen into its curved shape, while deforming. Brittle failure of the frozen sheet occurs when the stress induced by its weight exceeds the bending strength of the sheet at the hinge.

Conclusions: Side-by-side comparisons of Earth and Mars image pairs have indicated highly similar structures in both sets of imagery. From these, we have also made characteristic measurements on for example, the lengths and widths of rafting thrust structures, the "wavelengths" of sinuous ridges, and floe sizes. From these statistics of characteristic structures, we suggest strong similarities in the apparent material behavior on the two planets. Particularly important and more characteristic of sea ice than other materials is that small temperature changes in the material near the melting point (<5 C) cause large phase changes that result in the highly dynamic transition from ductile to brittle behavior. In the Arctic, these temperature changes take place over time scales of the same order as the deformation rate, i.e. of the order of minutes to hours and result in a continuum of structures, (from rafts to sinuous ridges to linear ridges) that track the mechanical behavior of the material as it transitions from ductile to brittle while deforming (Fig. 4). From the similarity of structures on Mars, we infer that they too first started from a ductile (two-phase) material that underwent a transformation to a single phase while deforming, resulting in brittle behavior near the end of the ridging process. Inferences from the large-scale behavior are also interpretable in terms of characteristic material properties giving potentially fuller information in future on the microstructural composition of the ice cover on Mars and its thermodynamic evolution.

References: [1] Murray, J. et al. (2005) Nature,434 352-356.[2] Hopkins, M. Takhuri, J. and M. Lensu, 1999, JGR, v.104, C6, 13605-13613. [3] Parmerter, R.R. 1975, JGR, v.80, 1948-52. [4] Weeks, W.F. and S.F. Ackley 1986, in *Geophysics of Sea Ice*, ed N. Untersteiner, Plenum Press 1-86. [5] Mellor, M. 1986, in *Geophysics of Sea Ice*, N. Untersteinter ed Plenum Press, p.87-113