SHOCK MELTING OF PERMAFROST ON MARS: WATER ICE MULTIPHASE EQUATION OF STATE FOR NUMERICAL MODELING AND ITS TESTING.

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Introduction: The presence of water/ice/brine in upper layers of Martian crust affects many processes of impact cratering. Modeling of these effects promises better understanding of Martian cratering records. We present here the new ANEOS-based multiphase equation of state for water/ice constructed for usage in hydrocodes and first numerical experiments on permafrost shock melting. Preliminary results show that due to multiple shock compression of ice inclusions in rocks the entropy jump in shocked ice is smaller than in pure ice for the same shock pressure. Hence previous estimates of ice melting during impact cratering on Mars should be re-evaluated.

Background: Numerical modeling of impact cratering on Mars and icy satellites to date exploite simple ice equations of state (Tillotoson's EOS or ANEOS – e.g. [1-3]). Giving relatively true pressure/compression description these EOS'es unable to present properly high pressure ice polymorphs and (especially important) decrease the ice I melting point with pressure and density increase from ice to liquid water. Additional complification for permafrost is that ice inclusion in rocks are compressed in more complicated way in comparison with planar wave experiments used to estimate shock melting pressure for ice (e.g. [4]). Here kinetic effects control the ice compression (c.f. [5]) and multiple shocks enlarged characteristic time of compression works toward equilibrium states. The first published ice VII EOS for hydrocodes [6] illustrates growing interest to hydrocode-friendly ice description.

Multiphase ANEOS: In the presented work ANEOS package [7] is used to construct the individual equations of state for water and up to 9 phases of ice. The additional piece of code is written to find equilibrium lines for all consequent phases and the melting line. Available experimental data are used to fit ANEOS input parameters to density, compressibility and heat capacity of ice/water and energy-entropy jumps across phase boundaries. The output may be presented in several ways. Here we used the simplest one: the table construction with internal energy/density entry and output of pressure, temperature, sound speed, entropy and pure/mixed phase description. Fig. 1 illustrates the variant of EOS without low T-high P phase ice XI. Fig. 2 shows pressure-entropy plot for melting of ices I, III, V, VI and VII and critical entropies for IM and CM of ice (vertical dashed lines). Numerically derived data for pure ice and ice inclusions in rocks are shown by colored symbols. The melting line 2 derived in [4] has a different shape mainly because in the current work new data [8] for ice VII melting has been used.

Testing multiphase H_20 ANEOS: To test the new water/ice EOS Hugoniot curves have been computed by direct numerical modeling with SALEB hydrocode. Pure ice at various initial temperatures has been modeled. At low pressures multi-shock pattern is of cause different in comparison with laboratory experiments, as no kinetic effects have been taken into account yet. Pure ice without kinetic delay of phase transitions reveals different incipient and complete melting (IM and CM) pressures in comparison with [3]: IM pressure is ~2.5 (*vs* 4.5) GPa and CM pressure is ~4.5 (*vs* 5.5) GPa at the initial temperature of 100 K.

The main attention in the presented work is devoted to shock compression of ice/rock mixture as it is one of main questions of impact cratering on Mars. The extensive set of geometries (ice layers, ice inclusions) for various dry porosity of rocks has been tested to estimate IM and CM pressures for ice/rock mixtures (note that usage of pure ice IM and CM pressures in hydrocodes, like in [3], may overestimates melt production). Two effects are expected for ice/rock mixture in shock compression: (i) reverberating shock wave "pump" the final equilibrium pressure by multiple shocks shifting compression toward isoentropic one; (ii) in real pores and fractures local stress concentration may produce "hot spots" (see Fig. 3). The full exploration of these effects is the matter of future. Here we present first instructive results.

Fig. 2 shows pressure-entropy plot for ice inclusions of various shape. The most prominent effect is for a flat ice layer parallel to the shock wave front in hosting dunite. Due to multiple shocks in the ice inclusion one need to reach 3 to 5 times larger shock pressure in the host rock to put the same entropy into ice inclusion. Consequently for T=200K IM and CM pressures for the ice inclusion are ~9 (IM) and ~18 (CM) GPa. In more soft rocks like basalt and granite IM and CM pressures for ice inclusions are lower but well above corresponding values for shock wave propagating in pure ice.

Conclusions: There is no unique CM and IM pressure for shock melting of ice in permafrost. These values depend on dry rock porosity and ice inclusion shape. Numerical modeling with new EOS for water/ice looks useful to study permafrost shock melting.

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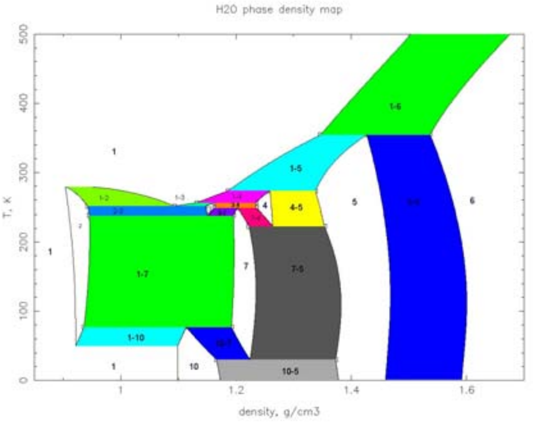

Fig. 1. Multiphase ANEOS for water ice in the density-temperature plot. White areas correspond to pure phases. Material numbers are as in the input file: 1 – water, 2 – ice I, 3 – ice III, 4 – ice V, 5 – ice VI, 6 – ice VII, 7 – ice II, 10 – low temperature ice (simulated ice XI). Colored areas show mixed phase states with corresponding numbers of mixed phases. Left boundary of ice areas corresponds to the assumed maximum affordable negative pressure of 0.1 GPa.

Fig. 3. (Right column) The simulated fragment of rock/ice mixture planar compression (granite boulders ~0.5 m in diameter with ice (blue) at –13°C in voids. The granite projectile compresses the target moving downward with the velocity of 0.8 km/s (average vertical stress of 4.3 GPa). Color graph (color scale in kJ/kg/K) shows ice/water entropy, designated with the color scale. Average entropy of ice is about 2.9 MJ/kg/K, corresponding to partial melting of ice after release. Average entropy vs average pressure for this geometry is plotted in Fig. 2 (labeled as "granite boulders"). Typical computation is done for initial rock cylinder's diameter of ~ 1 m. Static strength properties with dry fiction behavior after failure are assumed both for rocks and ice. During ice phase transition plastic limit is assumed to be 1% of the effective (very low) bulk compressive modulus computed for the equilibrium phase mixture.

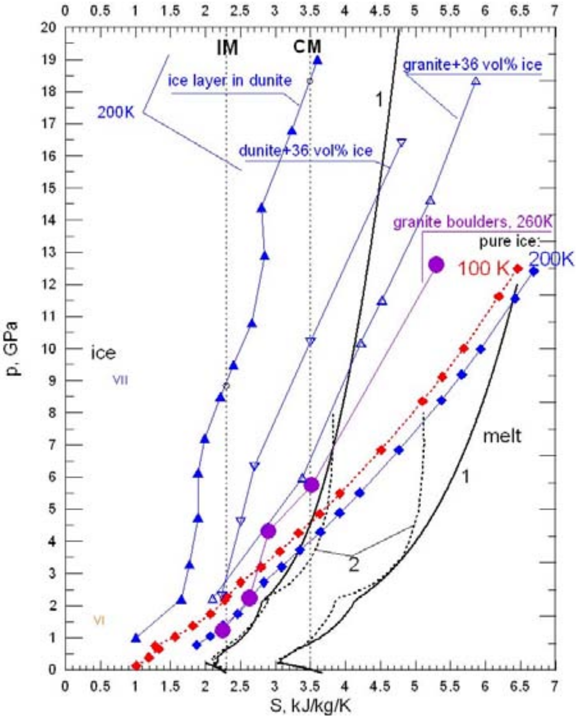

Fig. 2. Entropy-pressure and ice melt boundaries (1 – the presented model, 2 – according to [4]). Red and blue diamonds are for ice Hugoniot at 100K and 200K. Triangles: the ice filled fracture in dunite at 200K. Other cases are labeled in the figure.