ICE-ROCK MIXTURE HUGONIOT: NUMERICAL MODELING. B. A. Ivanov[1], and E. Pierazzo[2], [1]Institute for Dynamics of Geospheres, RAS, 119334, Moscow, Russia (baivanov@idg.chph.ras.ru), [2]Planetary Science Institute, 1700 E. Ft. Lowell Rd., Ste. 106, Tucson, AZ 85719 (betty@psi.edu).

Introduction: Understanding of rock/ice interaction on Mars needs the study of impact cratering in ice-rock mixtures. We present a detailed analysis of shock wave propagation in anice-rock mixture (similar to permafrost) that was recently investigated experimentally. Kraus et al. [1] measured shock and release temperatures along the Hugoniot for a 60/40 vol.% ice-quartz mixture. These important and labor consuming experiments may be used to verify our ability modeling numerically shock wave propagation in permafrost.

Problem Formulation: Ice-rock mixture is a difficult problem for numerical modeling due to the dramatic difference in compressibility and and strength of the components. The shock compresion in such contrast mixtures is accompanied by multiple local shock wave reflections and refractions, giving a finite thickness to the macroscopic shock front (e.g. [2, 3]). In addition, ice within a mixture may be heated to melting temperatures by the shock wave. Hence, the geometry of the melting curve is important for the analysis of experimental and modeling data. Based on recent experimental data [6-8], experiments in [1] provide temperatures for the H_2O in the mixture that are quite close (within the error bar limits) to the melting curve of ice VII. These new melting curves [6-8] have temperatures appreciably higher than those the melting curve from [5], which has been used to build the Harvard EOS for H_2O [4] (Fig. 1). This significant scatter in experimental values of the H_2O melting curve [5-8] implies that experimental data [1] below ~20 GPa may (or may not) reflect partial melting of ice in the quartz-rock mixture during shock compression.

We address these issues in a a set of numerical modeling of Hugoniot states for a rock-ice mixture similar to that of [1] using the ANEOS based equation of state for granite (as a rock proxy) and H_2O [9]. The material's strength model is described in [11, 12].

Numerical Model: The SALEB hydrocode [11] is used in Eulerian mode to model the propagation of a planar shock wave through the rock-ice mixture, modeled as macrovolumes of ice, rectangules of 10 cell high and 16 cells deep, imbedded in a chess-board structure into a rock matrix (Fig. 2, left). The target column is 25 cells wide and >2000 cells deep. The upper part of the grid (800 cells) is a "flyer plate" moving down and generating a downward shock wave in the mixture. The deformed zones and temperature are shown in Fig. 2 for a 10 GPa shock compression.

60/40 vol. % mixture at 100K. A set of numerical "experiments" using a target similar to that used in [1] has been done with a "flyer" velocity increment of 0.5 km/s. Individual tracer records reveal multiple oscillations of parameters, decaying in time. A sliding average over a slab of 50 layers deliver an estimate of the shock parameters. Fig. 3 shows ice and rock temperatures for a set of shock pressure. In general, our modeled values for H_2O are close to esperimental data [1]. Unfortunately, this test does not provide a robust verification of the code and the model EOS – experimental points are located too close to new estimates of the melting curves [6-8], alternative to [4, 5]. Ice temperature in the modeled Hugoniot reaches the melting curve at about 10 GPa and follows it, automatically passing close to the experimental data.

The negligible rock/mineral temperature, assumed in [4], seems to be valid below ~ 8 to 10 GPa; above 8-10 GPa the work of deviatoric stresses (dry friction or plastic work heating) is responsible for 50 to 70 % of the rock fragment's temperature. The strength model parameters used here are derived from macroscopic triaxial tests, thus the fine mineral grains used in [4] have, possibly, much higher strength and smaller plastic heating. However, a macroscopic size of rock fragments, implicitely assumed in the model via strength parameter's choice, may be useful in some geologic situation (eg. Martian ice/water bearing megabrecia).

24/76 vol. % mixture at 200K. The rock/ice mixture modeled in [4] is too "dilute" to be used in models of Martian permafrost over km-size scales. We repeated the numerical modeling of the Hugoniot with the same parameters except for rock content and initial temperature. Results are shown in Fig. 3 (light blue). Despite a much higher initial temperature, ice temperature is below that of the 60/40 mixture for the same pressure and reaches the Ice VII model melting curve at ~25 GPa (higher than for the 60/40 colder mixture). At about 40 GPa, the ice temperatue crosses the modeled melting line (meaning complete melting in the shock front).

In both modeled mixtures we find that at lower shock pressures rock in the rock/ice mixture is heated less than ice. Consequently, over time the equilibrization will proceed via heat transfer from ice to colder rock fragments. Hence, ice will move further away from the melting line. At some critical shock pressure (about 17 GPa for a 60/40, 100K mixture, and about 20 GPa for a 24/76, 200K mixture) the rock temperature at the shock front becomes larger than in ice (despite the higher compressibility, the latent heat of fusion keeps ice at the melting line). Thus, over some range of shock pressures, equilibrization will direct the heat flux from rock to ice (water). The effect of "differential heating" may be masked by kinetic effects in multiphase ice shock compression and shock melting.

Results: We find that in general our model (hydrocode and EOS) produces a Hugoniot curve close to the experimental one. However, model verification is limited by the location of experimental points of [1], close to the new experimental Ice VII melting curves [6-8]. This makes it difficult to evaluate the accuracy of our modelas well as is the interpretation of data in [1] (and, consequently, H_2O EOS parametrization around the Ice VII melting line in [4]).

In our model, decreasing ice fraction results in a decrease of the ice temperature. If this effect is real, it should be possible to plan experiments to change the T(p) locus and test wich of proposed Ice VII melting curves is more suitable for describing permafrost shock compression.

References: [1] Kraus R.G. *et al.* (2010) *EPSL, 289*, 162-170. [2] Riedel W. *et al.* (2008) *Int. J. Impact Eng., 35*,155-171. [3] Crawford D.A. *et al.* (2003) *Large Met. Imp. Abs.*, #4119. [4] Senft L.E. & S.T. Stewart (2008) *MAPS, 43*, 1993-2013. [5] Frank et al. (2004) *GCA, 68*, 2781-2790. [6] Goncharov (2009). [7] Dubrovinsky & Dubrovinskaia (2007) in, *GSA Special Papers 421* (ed. E. Ohtani), pp. 105-113. [8] Schwager B. & R. Boehler (2008) *High Press. Res.: An Int. J., 28(3)*, 431-433. [9] Ivanov B.A. (2005) *LPSC, 36*, #1232. [10] Redmer R. et al. (2010) *Icarus*, In Press. [11] Ivanov B.A. et al. (2010) *GSA Spec. Pap. 465*, 29-49. [12] Collins G.S. *et al.* (2004) *MAPS, 39*, 217-231.

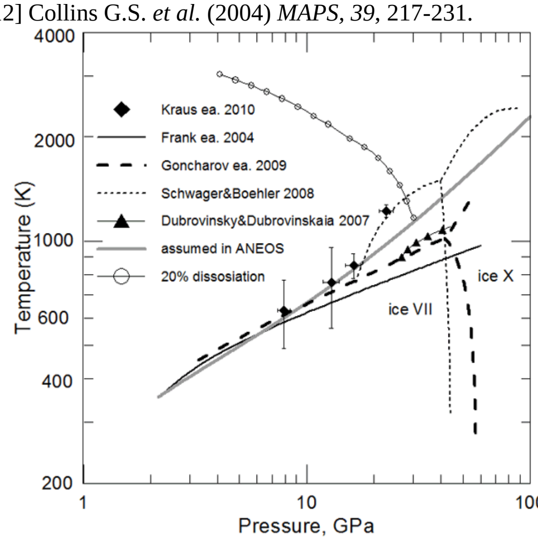

Fig. 1. Experimental data [1] vs. melting curves for ice VII: [5], used in [4], and recent experimental data [6–8]. *Gray curve*: melting curve assumed in the ANEOS H_2O [9]. Solid line with open dots is an estimated 20% dissociation boundary [10].

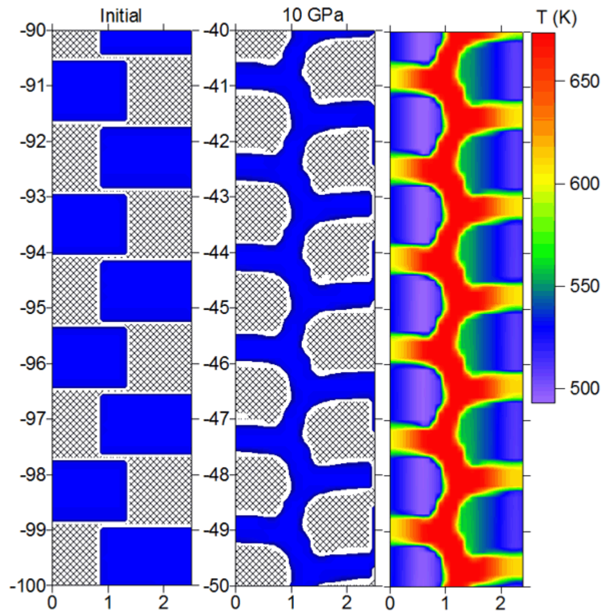

Fig. 2. Section of the computational grid. Cell size is 0.1×0.1 length units. Total width (25 cells) is shown, total depth of the target is 100 length units. The ice (*blue*) and rock (*cross hatched*) zones are shown in the initial position (left panel) and behind the 10 GPa shock wave (center panel). The right panel shows theice temperature, varying from ~600K to 670K depending on the surrounding geometry.

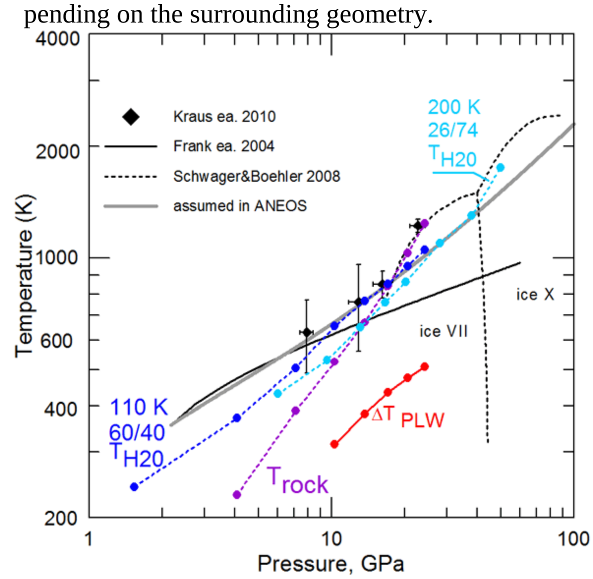

Fig. 3. Same as in Fig. 1 with the addition of the 2D Hugoniot modeling for a 60/40 vol.% ice/quartz mixture initially at T~110K (to match the experiments in [1]. *Blue* and *purple dots with dashed lines* designate temperatures in H_2O and rock, respectively. *Red dots and solid line*: estimated plastic work (PLW) rock heating due to deviatoric stress action (dry friction). *Light blue dots and dahsed curve:* ice temperature for a 26/74 vol.% mixture initially at T=200K.