MESOSCALE NUMERICAL MODELLING OF IMPACT PROCESSING OF PRIMITIVE SOLAR SYSTEM SOLIDS

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Introduction: Previous numerical studies of impact processing (e.g., compaction, heating) of primordial solids [e.g. 1, 2] have estimated 'bulk' pressure-temperature conditions over large (planetesimal) scales. However, primordial solar system solids accumulated as bimodal mixtures of mm-scale zero-porosity inclusions (chondrules) surrounded by highly porous, sub-μm dust particles (matrix). The fine-scale response of such mixtures to shock has not previously been modelled, despite the fact that these mixtures were the precursors to all solar system materials.

To model these bimodal mixtures explicitly, and resolve heterogeneity in shock response at the scale of individual chondrules, requires "mesoscale" modelling [e.g. 3]. Our results [4] provide an important link between meteoritic evidence and the bulk thermal and compaction histories of meteorite parent bodies.

Modelling: A suite of mesoscale numerical planar impact simulations were performed using the iSALE shock physics code [5–7], in which shock waves were propagated through a bimodal mixture of explicitly resolved non-porous disks (the chondrules) surrounded by a highly porous matrix. Chondrules were placed with random sizes (in the range 0.3–1 mm) and spacing within the computational mesh until the desired matrix-to-chondrule volume ratio was reached. An ANEOS-derived equation of state table for forsterite [8] was used to describe the thermodynamic response of the non-porous disks. The solid component of the matrix was described by either forsterite or the serpentine ANEOS table described in [9].

Compaction of porosity and material strength were modeled using the methods described in [6, 7, 10]. The chondrules were given a high cohesive strength (1 GPa), whereas the porous matrix was assumed to be very weak, with a cohesive strength of a few kPa. Simulations spanned a range in impact velocity (v_i = 0.75–3 km/s), initial matrix volume fraction (30–80%) and initial matrix porosity (60–80%), with an initial temperature of 300 K. Lagrangian tracer particles recorded the peak- and post-shock state of the matrix and chondrule material, from which the bulk state was determined. A map of strain was constructed from tracer particle positions using the method described in [11].

Ice: Another suite of simulations were run with explicitly resolved pores filled with water ice (using the SESAME equation of state from [12]), to investigate the effect of impacts on volatile-rich primitive materials.

Validation and benchmarking: The mesoscale techniques implemented in iSALE have been validated against impact experiments and benchmarked against CTH simulations of impacts into granular ceramics [13].

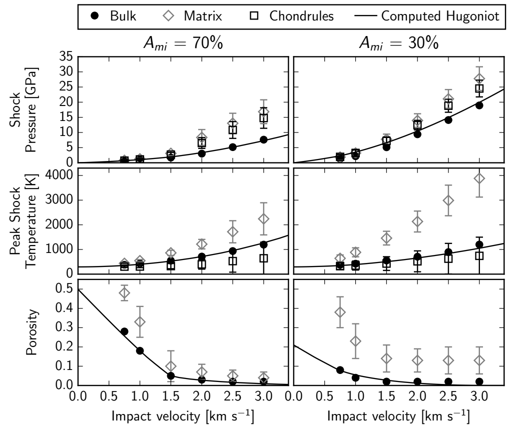

Figure 1: *Comparison of bulk and mesoscale response to shock. Black circles show bulk values of the state quantity, averaged over the sample region; open diamonds and squares (and error bars) show mean (and standard deviation) of the state variable in the matrix and chondrules, respectively. The solid line shows the computed Hugoniot.*

Results: The bulk (volume averaged) shock pressure, temperature and porosity of the mixture simulated using our new mesoscale models are consistent with previous macroscale models (using the bulk values as the initial conditions [e.g. 2]) and Hugoniot curves created with the $\varepsilon - \alpha$ porous compaction model (Figure 1). Resolving at the finer mesoscale, our simulations reveal a complex, heterogeneous response to shock within the mixture. While peak pressures are similar in the chondrules and the matrix, for $v_i > 1.5$ km/s they are ~ 2 times higher than the average bulk pressure recorded (Figure 1); this is a consequence of the mesoscale structure, which creates resonant oscillations about the steady wave amplitude, the peaks of which are recorded in the chondrules and matrix. This has been observed in experiments and numerical models of granular materials and porous rocks [14–16].

Temperature dichotomy: Moreover, there is a large dichotomy between the temperatures recorded in the matrix and the chondrules: The massive difference in compressibility between the porous matrix and the nonporous chondrules results in much greater energy deposition in the matrix. Consequently, while the chondrules record only a modest temperature change, well below the bulk temperature increase, the post-shock temperature increase in the matrix is much larger (hundreds of K) than in the bulk and highly variable. The juxtaposition of hot matrix and cold chondrules imply that the temperature difference is shortlived: the chondrules act as a heat sink, equilibrating the mixture to the bulk post-shock temperature in seconds.

Initial matrix fraction: As shown in Figure 2, a decrease in the initial matrix fraction leads to an increase in peak pressures (due to the decrease in bulk porosity). The bulk temperature decreases by $\sim$ 20 K over the range of matrix fractions (30–80%, for v_i = 2 km s^{-1}), despite both the matrix and chondrules experiencing higher peak and final temperatures: This is due to the greater volume fraction of cold chondrules reducing the average temperature. At low velocities ($\sim$ 1 km s^{-1}), the matrix is compacted more in simulations with a lower matrix fraction, due to the higher peak pressures. At higher velocities ($>$ 2 km s^{-1}), the matrix is less compacted in the low-matrix-fraction simulations, as it is sheltered in the interstitial spaces between chondrules (bottom right of Figure 2).

Material: For simulations with a serpentine matrix, there was little difference from the forsterite-matrix simulations at low velocity (1 km s^{-1}). At 2 km s^{-1}, the matrix temperatures were lower in the serpentine matrix than an equivalent forsterite simulation, due to the phase change of the water content buffering the temperature increases.

Conclusions: For a range of impact velocities and initial matrix fractions, our mesoscale simulations of low-velocity impacts on primordial solid materials can produce final materials with properties (porosity, matrix abundance) similar to meteoritic material. Using this method to model specific scenarios allows, for the first time, a full quantitative analysis of the shock evolution of primitive materials, and thus enables a firm link between numerical modelling and measurements of meteoritic samples.

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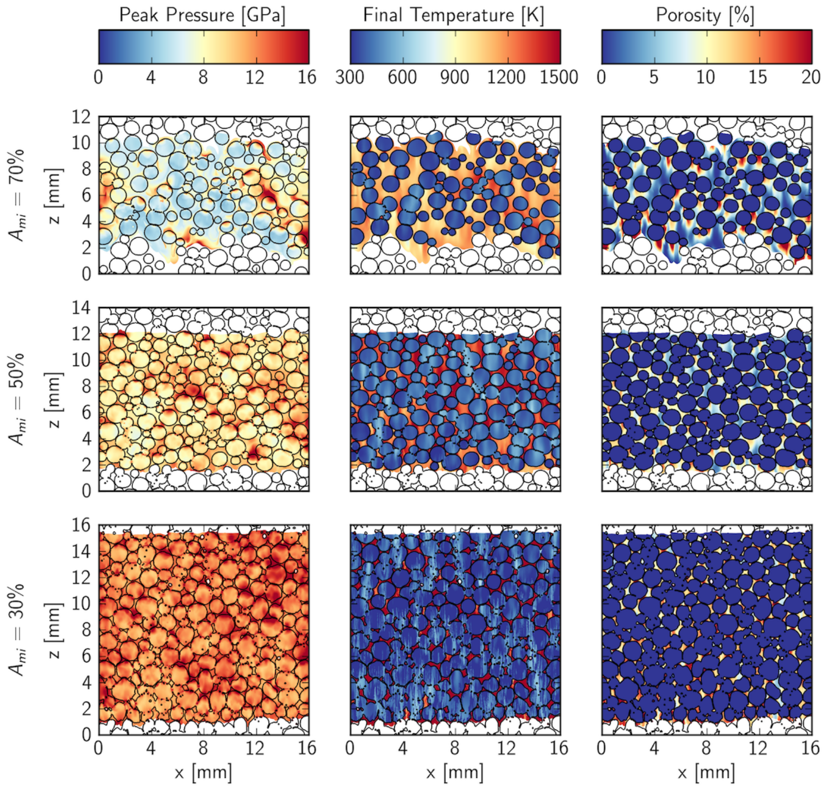

Figure 2: *Comparison of 3 simulations with different initial matrix fractions (with v_i = 2km s^{-1}).*