Building Planets One High Velocity Impact at a Time: Silicate Vapor Curve Experiments. M. S. Duncan[1,*], E. J. Davies[1], S. Root[2], D. E. Bliss[2], D. K. Spaulding[1], R. G. Kraus[3], S. T. Stewart[1], S. Jacobsen[4], [1]Dept. Earth Planetary Science, U. California, Davis, CA, USA (*msduncan@ucdavis.edu), [2]Sandia National Laboratories, NM, USA, [3]Lawrence Livermore National Laboratory, Livermore, CA, [4]Dept. Earth Planetary Science, Harvard U., MA, USA.

Introduction: High-velocity impacts between planetesimals (~Vesta-sized bodies, 100–1000 km in diameter) were ubiquitous in the early solar system and a critical step in terrestrial planet formation [1]. Collisions strongly affected the thermal and geochemical evolution of these early-formed bodies [2-5] as they were energetic enough to partially vaporize the impacting bodies [6,7]. Such impacts generated optically thick clouds of silicate melt and vapor that equilibrated while adiabatically expanding and cooling. When the expanding cloud became optically thin, radiative cooling led to condensation of the vapor fraction either onto nearby droplets or as new dust.

In order to describe the thermodynamic processes of these impacts and the post-impact pressure (P)-temperature (T) path, we need comprehensive equations of state of major planet-forming minerals, such as olivines and pyroxenes. Further, experimentally locating the minerals' liquid-vapor phase boundary allows for accurate determination of the P and T during equilibration of the liquid-vapor mixture and upon vapor condensation. The details of the post-impact thermodynamics determine the final distribution of volatile and moderately volatile elements (MVE) between the droplets and dust [8]. Most previous silicate shock experiments were conducted on simplified mineral systems (e.g., SiO_2 or Mg_2SiO_4 versus $(Mg,Fe)_2SiO_4$). Here, we studied forsterite (Fo_{100}), San Carlos olivine (Fo_{90}), enstatite ($MgSiO_3$), and bronzite ($Mg_{0.9}Fe_{0.1}SiO_3$) to determine the effect of iron on the shocked state of the minerals.

Methods: We conducted high-velocity impact experiments with the Sandia Z machine [9] that uses magnetically accelerated aluminum flyers to shock single-crystal silicate minerals to conditions beyond those accessible to light gas gun launch systems. The Z target panel holds multiple experimental configurations (Fig. 1) that yield complementary equation of state information:

1) Steady shock experiments determine the mineral shock state (P, volume, and T) and allow for calculation of entropy (S) on the Hugoniot [e.g., 7,10-12].

2) Shock-and-release experiments determine the T on liquid branch of the vapor curve [10]. Shock and post-shock thermal radiances were measured relative to the quartz standard [11] and T were derived using the measured sample reflectivity.

3) Shock-and-release followed by reverse impact experiments determine the density on the liquid branch of the vapor curve [10,13]. The initial shock generated by the Al flyer transforms the mineral to a supercritical fluid. When the shock reaches the downrange free surface, the fluid expands across a gap of known distance to a downrange window, decompressing to intersect the vapor curve. A thin layer within the decompressing sample is pinned at the liquid density on the phase boundary. This layer forms a dynamically-created liquid flyer that generates a strong shock when it impacts the standard window, in this case quartz [14] or TPX [15]. By measuring the velocity (V_F) of the liquid flyer and the imparted shock velocity in the two different windows, we determined the unknown density of the liquid flyer using the Rankine-Hugoniot equations.
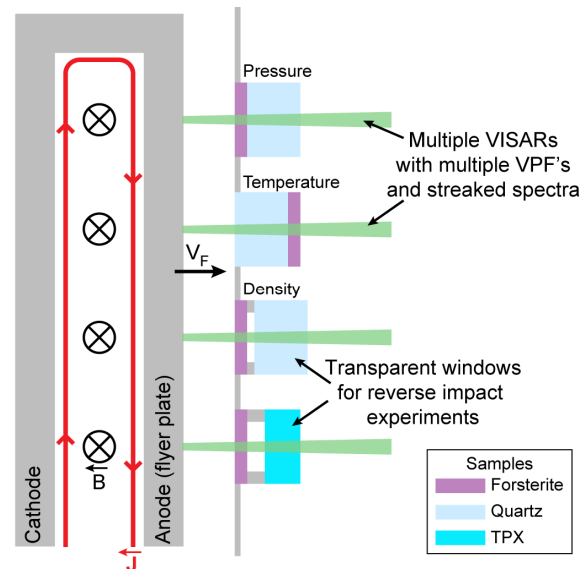

Figure 1. A simplified schematic of experimental configurations for planar shock experiments on the Z machine [8,11]. The top experimental design is used to determine Hugoniot P and T (steady shock); the second design (shock-and-release) is used to determine T at the liquid-vapor phase boundary. The bottom two configurations are shock-and-release followed by reverse impact experiments used to determine the density of the liquid at the liquid-vapor phase boundary.

Initial Results: Our high-velocity shock experiments on a variety of silicate minerals measure their Hugoniot states (Fig. 2). Our main focus thus far has been on forsterite (Fig. 3), as previous work has constrained the P, T, and S of the Hugoniot [12,7]. Notably, our experimental data is yielding lower critical point temperatures compared to the M-ANEOS forsterite model [16]. These temperatures are more similar to molecular dynamic simulations of $MgSiO_3$ [17], though our liquid densities are higher.
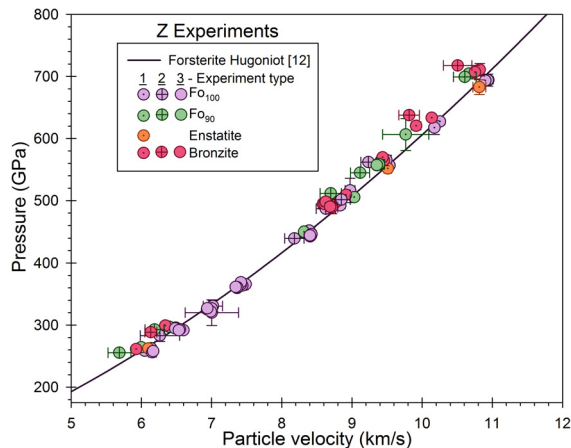
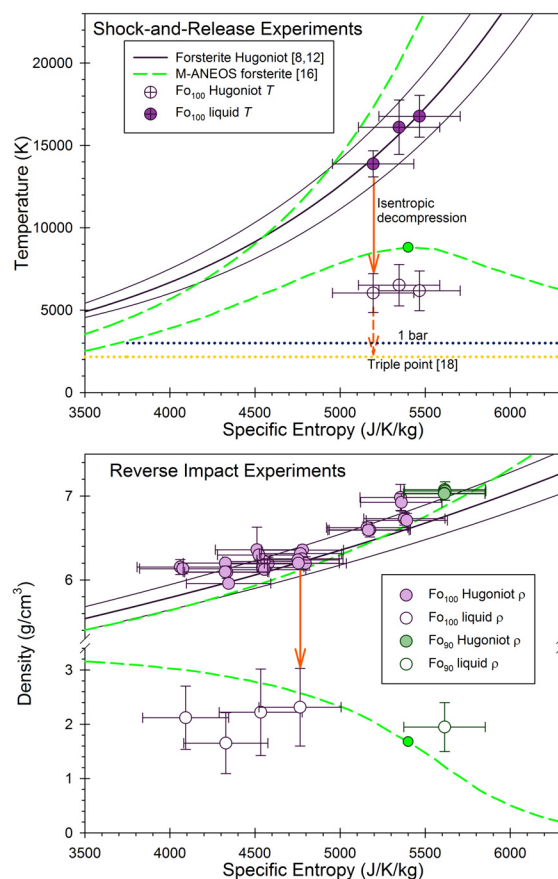**Figure 2.** Silicate Hugoniot states obtained at the Z machine.

Figure 3. *Preliminary* results for the Hugoniots and vapor curves for forsterite and olivine. M-ANEOS [16] forsterite Hugoniot and vapor curve (green dashed lines and critical point) shown for comparison. **(top)** Calculated *S* on the Hugoniot (filled circles) with example release path to the liquid-vapor dome shown by the arrow. Temperatures on the liquid-vapor dome determined from shock-and-release experiments (open circles). The onset of vaporization and the vapor fraction depends on the ambient *P* (e.g., forsterite triple point at 5.2 Pa [18] or 1 bar = 10^{-4} GPa). **(bottom)** Silicate density on the Hugoniot (filled circles) and phase boundary (open circles) determined from reverse impact experiments.

Implications: Impacts that lead to partial vaporization are easily achieved during planet formation [1]. In a vaporizing impact, the shocked minerals decompress along an isentrope to the liquid-vapor phase boundary (orange arrow, Fig. 3). The decompressing fluid transforms to a mixture of liquid and vapor, whose proportions can be calculated using the lever rule and the specific entropies of the sample and phase boundary. As the system continues to cool and decompress, the phases intersect the triple point and the melt droplets freeze, closing the system geochemically. When the system becomes optically thin, depending on the details of the vapor plume, radiative cooling will reduce the *S* of the system. Then, the melt will freeze and vapor will condense as new dust or onto nearby melt droplets. As a result, the MVE concentrations will vary with particle size after a vaporizing impact. Size sorting processes in the protoplanetary disk can lead to bulk separation and cumulative changes in MVE abundance from collisions [8].

Conclusions: Impact vaporization was a major process during planet formation, but the role of impacts in fractionating volatiles has been debated. We conducted shock experiments on major planet-forming silicate minerals to locate the liquid-vapor phase boundaries and critical points. Our experimental data on forsterite show significant deviations from the widely-used M-ANEOS model [16], and the model equations of state should be improved using these new data. These experiments provide essential information to understand mobilization and fractionation of volatiles during impact processes.

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