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Using Shockless Ramp Compression to Investigate Melting in the Earth's Mantle

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Motivation

Seismic low-velocity zones (LVZs) just above and below the mantle transition zone (MTZ), at 440 km and 660 km depths, respectively, are attributed to the presence of molten material.[1-3] Present temperatures at these depths are not hot enough to melt mantle material alone. Convective movement of hydrated material is thought to induce melting via mineral dehydration reactions that occur when relatively wet material moves into a region where water storage capacity is low, as it is in both the upper and lower mantle.[4,5] To interpret the LVZs, we must understand how the density and seismic velocities of dry versus hydrated silicate melts vary with pressure and temperature at mantle conditions.

Equations of state developed for crystalline materials that model compressibility and density with respect to pressure do not accurately predict behavior of melts.[6] Unlike crystalline materials, which have periodic, repeating structures, melts and their frozen counterparts, glasses, are amorphous materials that lack long-range order. In this work, we are using pulsed-power shockless ramp experiments at Sandia National Laboratories DICE facility to determine the equations of state of vitreous-SiO2 as a melt analogue. The results will ultimately be used to interpret the observed seismic structure of mantle LVZs.

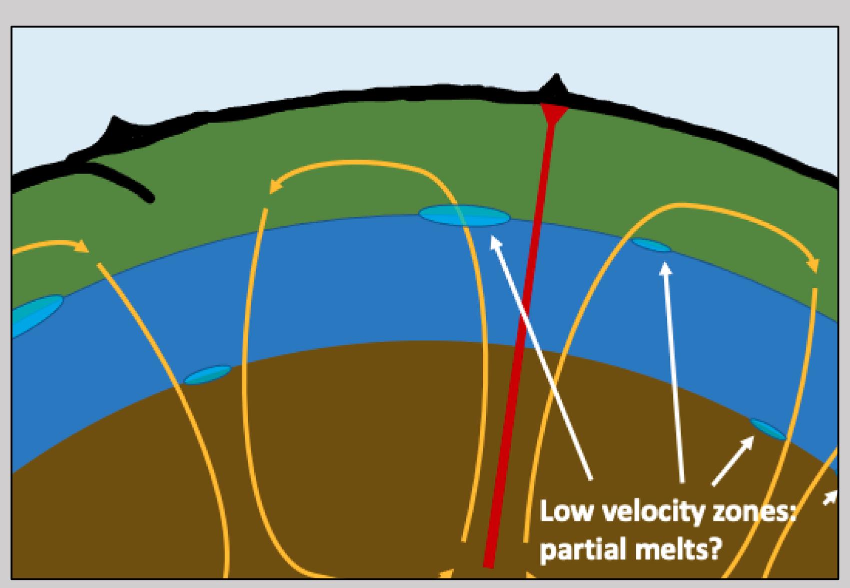

Fig. 1. Seismic low-velocity zones observed just above and just below the mantle transition zone may be attributed to partial melt. Figure modified from Bercovici and Karato (2003), Hirschmann (2006) and Sakamaki (2013).

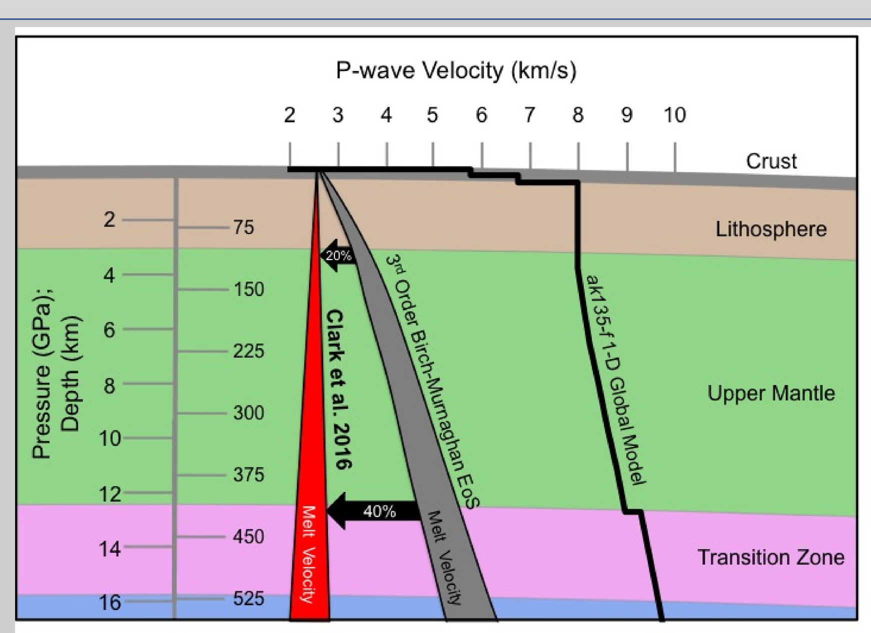

Fig. 2. Schematic of Earth's upper mantle, showing the ak135-f 1-D global reference model for average seismic wave speeds with depth.[7] Equations of state typically used to model behavior of crystalline materials, such as the Birch-Murnaghan EOS, do not accurately predict behavior of amorphous materials like melts and glasses. APS Science Highlight (2016).

Methodology

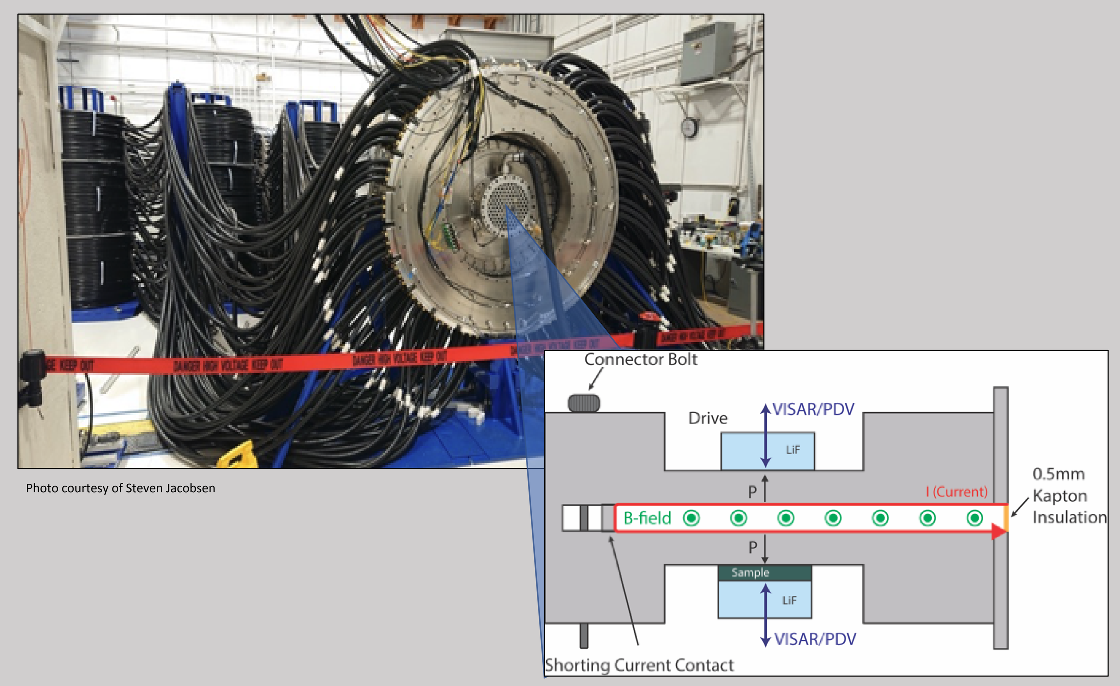

Fig. 4. Left, a photo of the magnetically-driven pulsed power machine Thor, at Sandia National Laboratories. Right, stripline geometry schematic with one side containing just the LiF window, which measures the machine drive. The other side of the stripline contains the stack with both the LiF window and the sample. Pressure is generated by shorting an electric current.

- Pulsed-power machine Thor can achieve pressures up to 40 GPa via a magnetically-driven pressure wave
- We use Thor to compress samples from pressures ranging from 0 to 30 GPa, which correspond to depths at the base of the MTZ
- Electrical current is stored in groups of capacitors called bricks; bricks are connected to the central power flow section by long cables

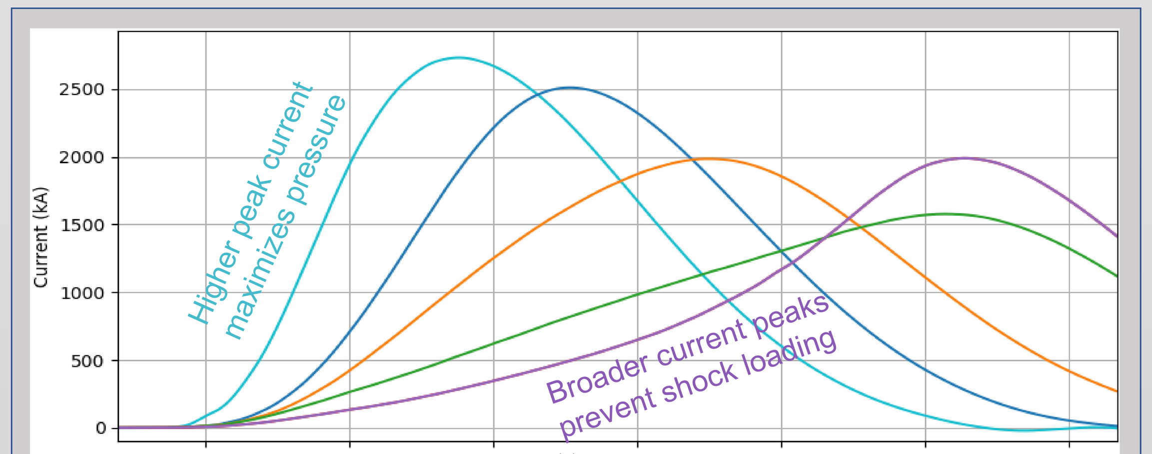

Fig. 5. Examples of pulse shapes: we add time delays to the machine so that bricks are triggered at different times. The application of current over a span of time changes the peak pressure of each shot. Each shot is uniquely tailored to achieve desired experimental pressures without shocking the sample.

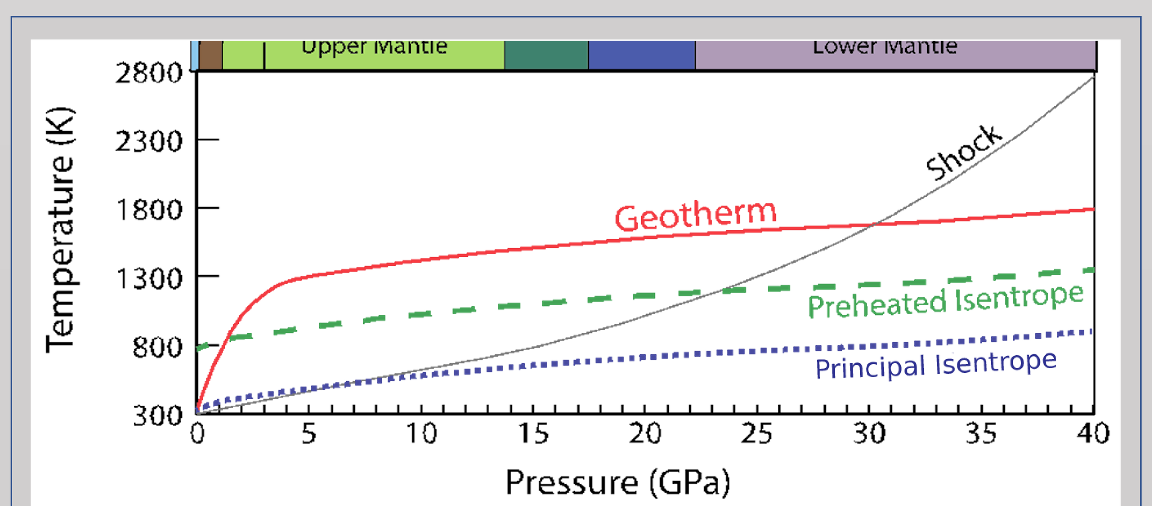

Fig. 6. Thor uniquely mimics the mantle geotherm. Because of its ability to tailor pulses, we can avoid shocking samples and accessing regions of pressure-temperature space that are more similar to the geothermal gradient. The data we obtain from these experiments is directly applicable to seismic observations of the mantle.

Results

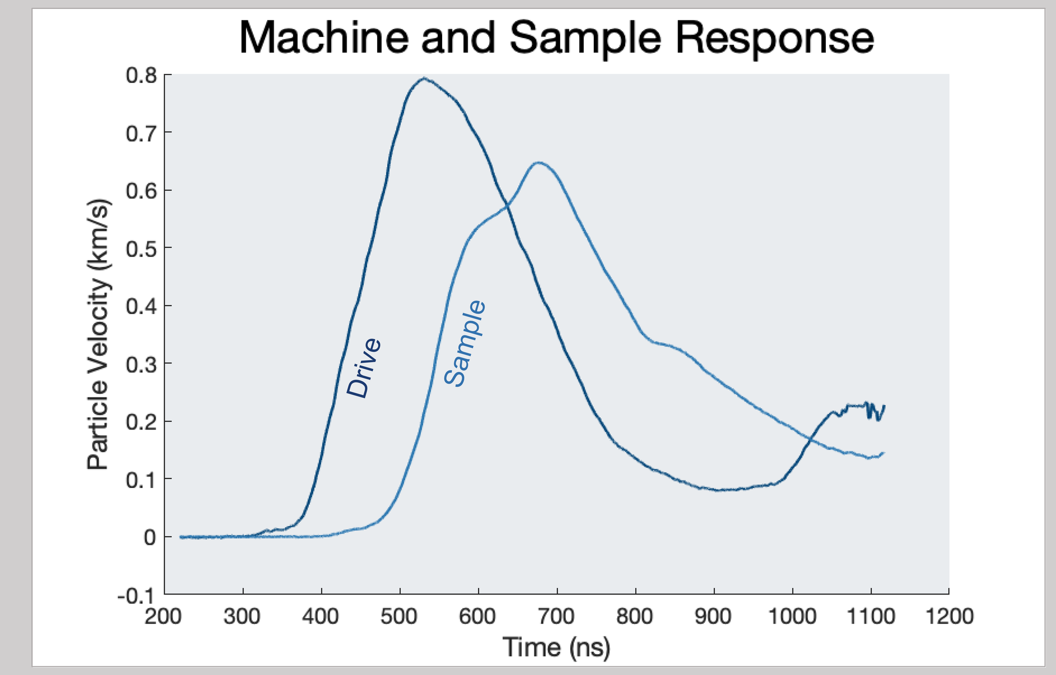

Fig 7. Graph showing the particle velocity vs. time curves of the drive and sample, as measured by VISAR. The sample is vitreous-SiO_2 containing less than 1 ppm H2O

Backwards integration of the drive through space using the equations of motion to produce pressure-velocity history

$$\frac{\partial u_p}{\partial x} = \frac{1}{v_0}\left(\frac{\partial v}{\partial t}\right)$$

Conservation of mass

$$\frac{\partial \sigma_x}{\partial x} = -\frac{1}{v_0}\left(\frac{\partial u_p}{\partial t}\right)$$

Conservation of momentum

Map velocity in windowed stack to in-situ, then perform Lagrangian analysis to obtain longitudinal stress vs. density tabular equation of state. This updated equation of state informs the next mapping.

$$\frac{d\rho}{\rho} = \frac{du^*}{\rho_0 C_L}$$

$$d\sigma_x = \rho_0 C_L du^*$$

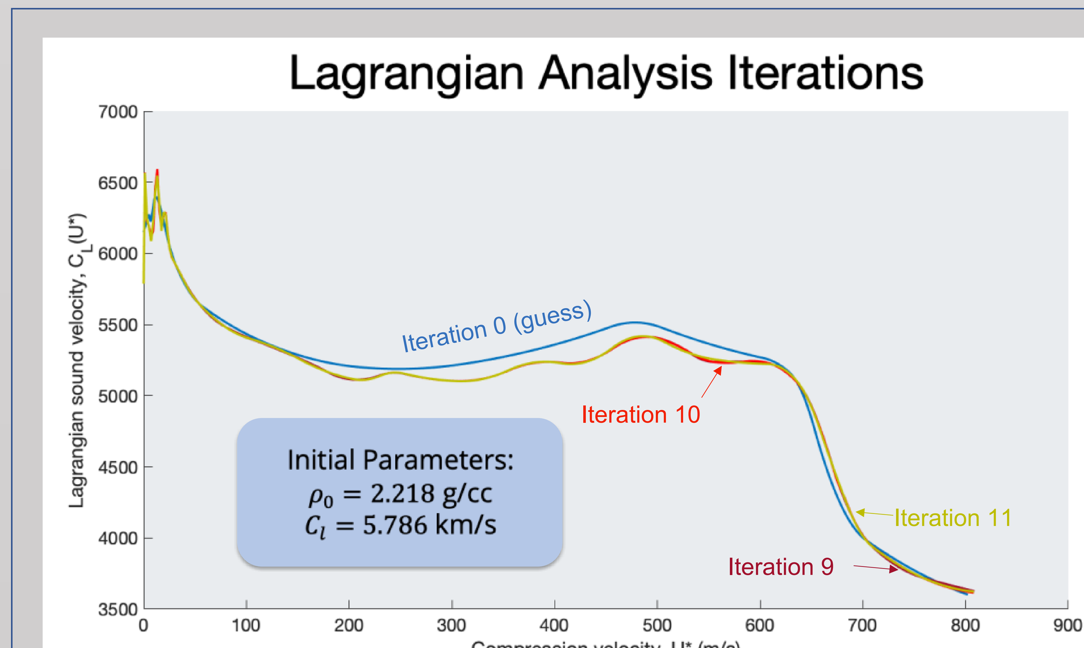

Fig 8. Iterative Lagrangian Analysis (ILA) begins with an initial guess equation of state, and then iterates until the equations of state converge.[8]

Discussion

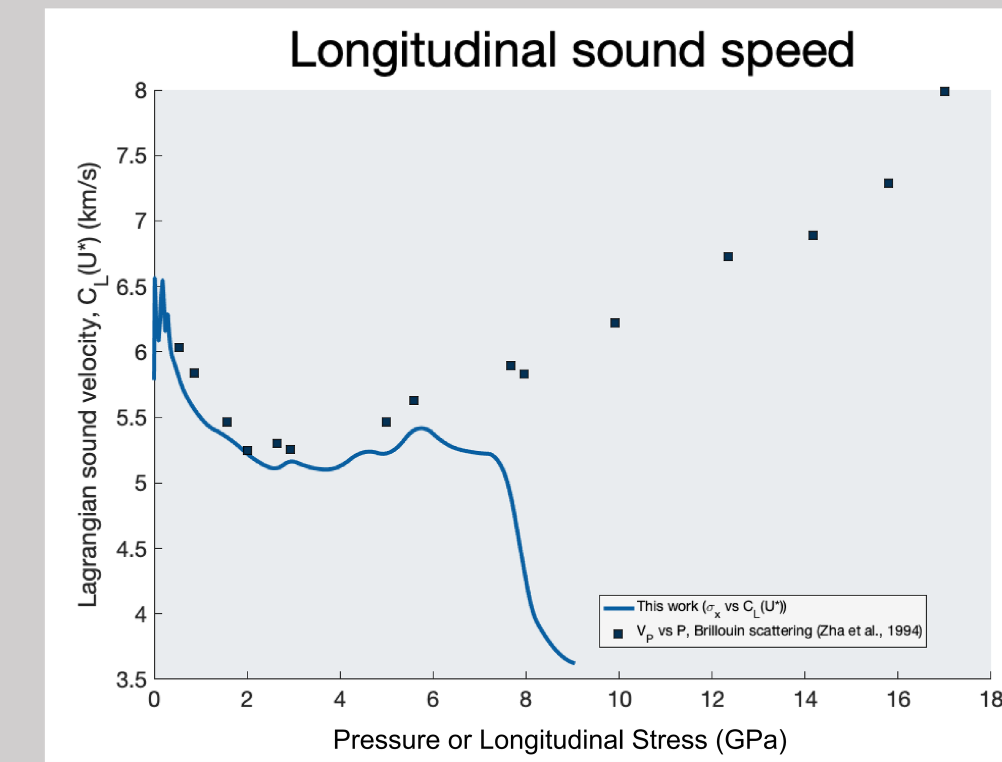

Fig 9. A comparison of longitudinal sound speed between this work and Zha et al.'s results from static compression experiments. Our data shows a dramatic decrease in sound velocity at significantly higher pressures.

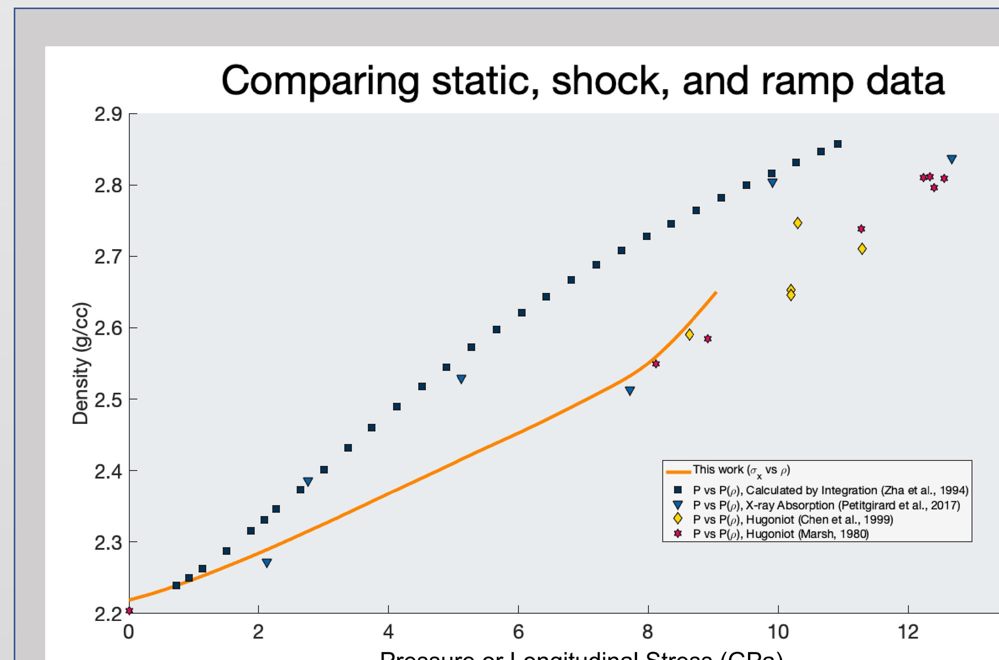

Fig 10 A side-by-side comparison of static and shock datasets from previous works (refs. 9, 10, 11, and 12). Our data shows a change in slope, which might indicate a phase transition in SiO_2 glass.

Acknowledgements

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References

1. Schmandt, B., S. D. Jacobsen, T. W. Becker, Z. Liu, and K. G. Dueker. "Dehydration Melting at the Top of the Lower Mantle." Science 344, no. 6189 (June 13, 2014): 1265–68.
2. Song, T. R. A., D. V. Helmberger, and S. P. Grand. "Low-Velocity Zone atop the 410-Km Seismic Discontinuity in the Northwestern United States." Nature 427, no. 6974 (February 2004): 530–33.
3. Sakamaki, T., A. Suzuki, E. Ohtani, H. Terasaki, S. Urakawa, Y. Katayama, K.-I. Funakoshi, Y. Wang, J. W. Hernlund, and M D. Ballmer. "Ponded Melt at the Boundary between the Lithosphere and Asthenosphere." Nature Geoscience 6, no. 12 (December 2013): 1041–44.
4. Bercovici, D., and S.-I. Karato. "Whole-Mantle Convection and the Transition-Zone Water Filter." Nature 425, no. 6953 (September 2003): 39–44.
5. Hirschmann, M. M. "WATER, MELTING, AND THE DEEP EARTH H_2O CYCLE." Annu. Rev. of Earth and Planetary Sciences 34, no. 1 (May 1, 2006): 629–53.
6. Clark, A. N., C. E. Lesher, S. D. Jacobsen, and Y. Wang. "Anomalous Density and Elastic Properties of Basalt at High Pressure: Reevaluating of the Effect of Melt Fraction on Seismic Velocity in the Earth's Crust and Upper Mantle." JGR: Solid Earth 121, no. 6 (June 2016): 4232–48.
7. Kennett B.L.N., E.R. Engdahl and R. Buland. 1995. "Constraints on seismic velocities in the earth from travel times" Geophys. J. Int. 122, 108–124.
8. Davis, J.-P., J. L. Brown, M. D. Knudson, and R. W. Lemke. "Analysis of Shockless Dynamic Compression Data on Solids to Multi-Megabar Pressures: Application to Tantalum." *Journal of Applied Physics* 116, no. 20 (November 28, 2014): 204903.
9. Zha, C.-S., R. J. Hemley, H.-K. Mao, T. S. Duffy, and C. Meade. "Acoustic Velocities and Refractive Index of SiO 2 Glass to 57.5 GPa by Brillouin Scattering." Physical Review B 50, no. 18 (November 1, 1994): 13105–12.
10. Petitgirard, Sylvain, W. J. Malfait, B. Journaux, I. E. Collings, Eleanor S. Jennings, I. Blanchard, I. Kantor, et al. "SiO_2 Glass Density to Lower-Mantle Pressures." Physical Review Letters 119, no. 21 (November 21, 2017): 215701.
11. Chen, G. Q., T. J. Ahrens, W. Yang, and J. K. Knowles. "Effect of irreversible phase change on shock-wave propagation." Journal of the Mechanics and Physics of Solids 47 (1999): 763-783.
12. Marsh, S. P. LASL Shock Hugoniot Data (University of California Press, Berkeley, 1980).
13. Wang, Y., T. Sakamaki, L. B. Skinner, Z. Jing, T. Yu, Y. Kono, C. Park, G. Shen, M. L. Rivers, and S. R. Sutton. "Atomistic Insight into Viscosity and Density of Silicate Melts under Pressure." Nat. Comm. 5, no. 1 (May 2014): 3241.

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