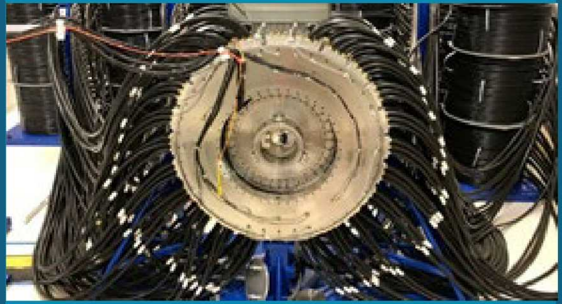
SAND2019-6995C

Shockless compression of hydrated silicate glasses



PRESENTED BY

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21st Conference of the APS Topical Group on Shock Compression of Condensed Matter
17-21 June 2019 in Portland, OR, USA
Session N6 (GPS: Earth and planetary materials)

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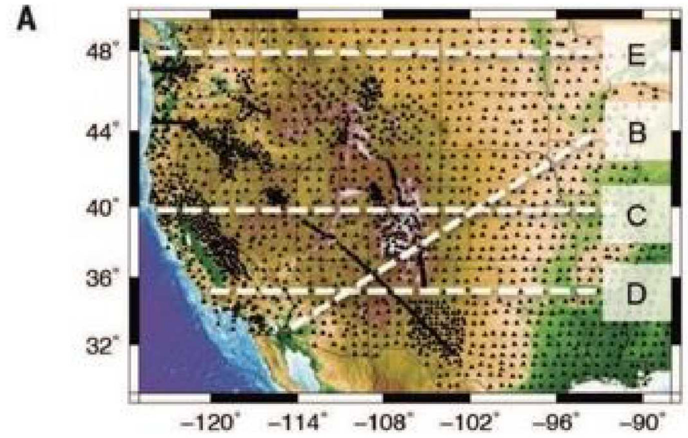
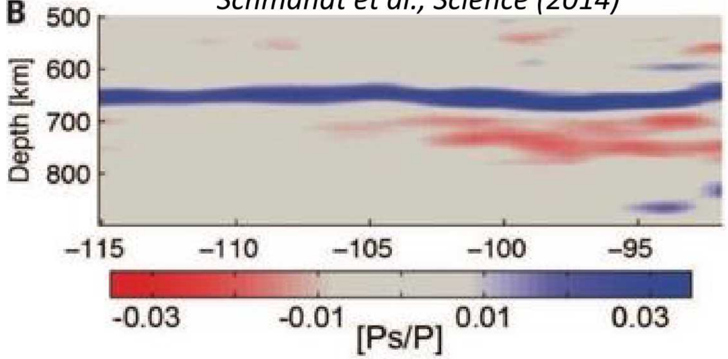
Evidence has been growing that the mantle transition zone (MTZ) contains a significant amount of water …

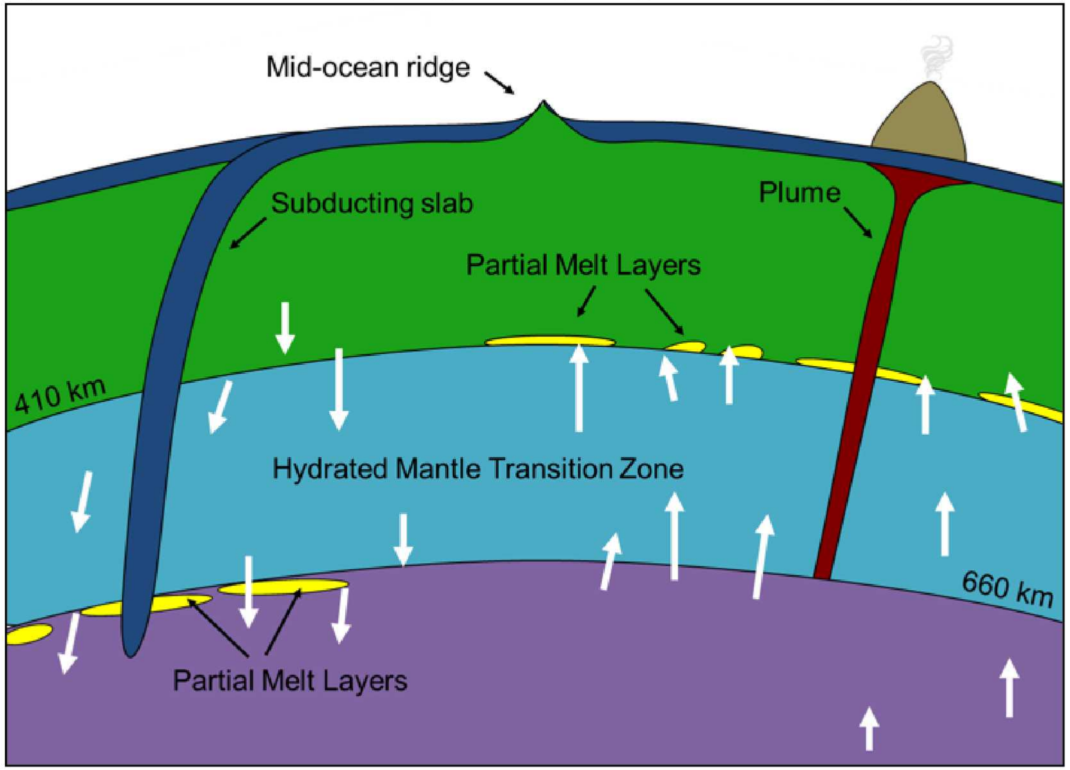
- MTZ = region between seismic discontinuities at 410-km (12 GPa) and 660-km (28 GPa) depths
- Low seismic velocities observed just above and just below the MTZ
  - Partial melting could explain low velocities
  - But present-day geotherm is **below** solidus of mantle minerals
- Polymorphs inside MTZ have high water solubility, those above and below do not
  - If MTZ hydrated, then mantle convection can cause melt by dehydration
- Recent discoveries of water in deep-mantle diamond inclusions



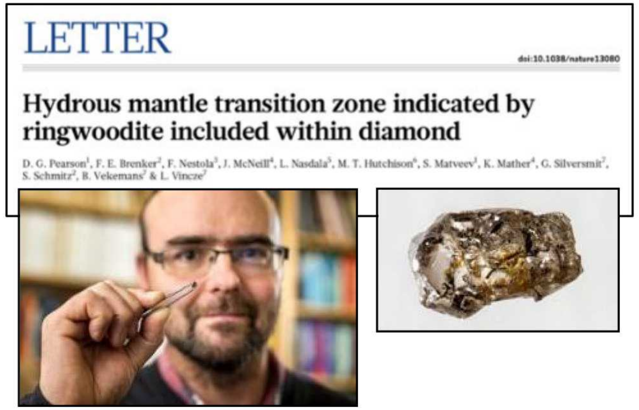
Schmandt et al., Science (2014)



After: Bercovici and Karato (2003), Ohtani (2004), Hirschmann (2006), etc.

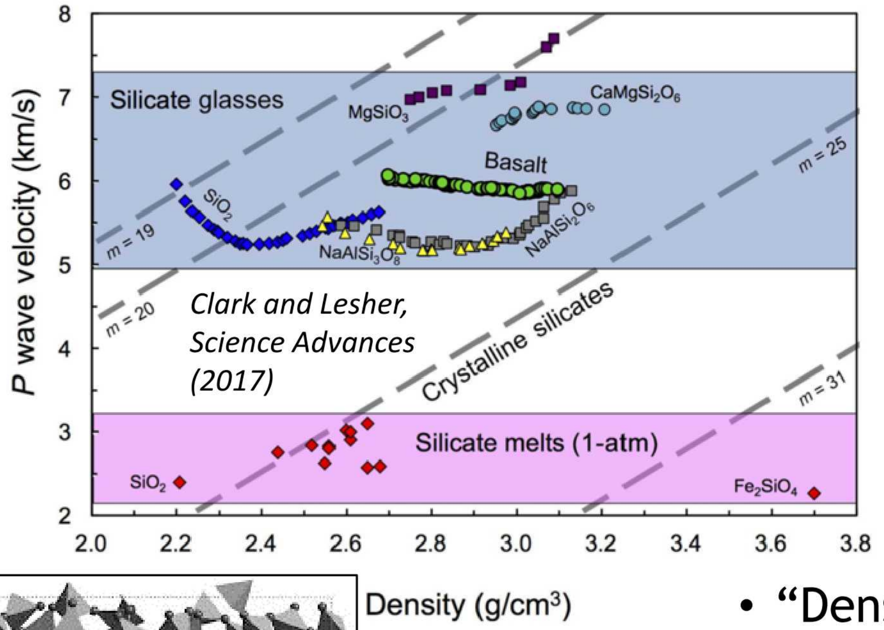


Pearson et al., Nature (2014)

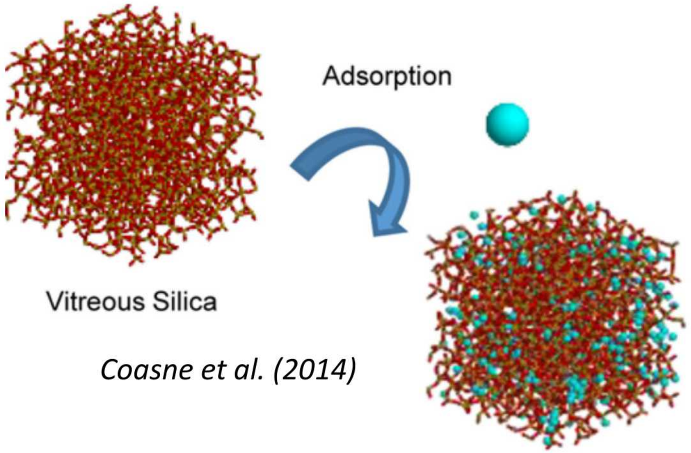


Tschauner et al., Science (2018)

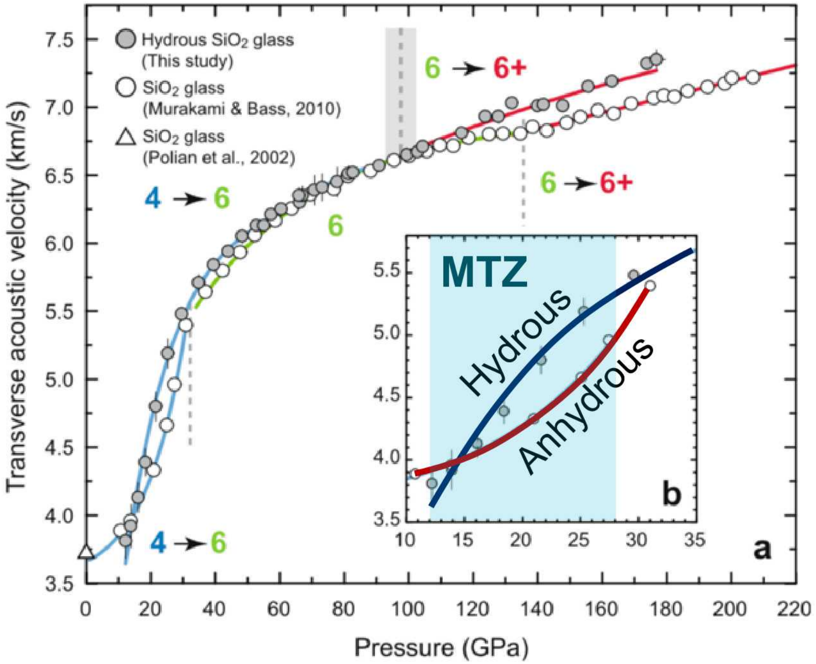
… leading to increased interest in equation-of-state (EOS) measurements of silicate melts & glasses at MTZ pressures



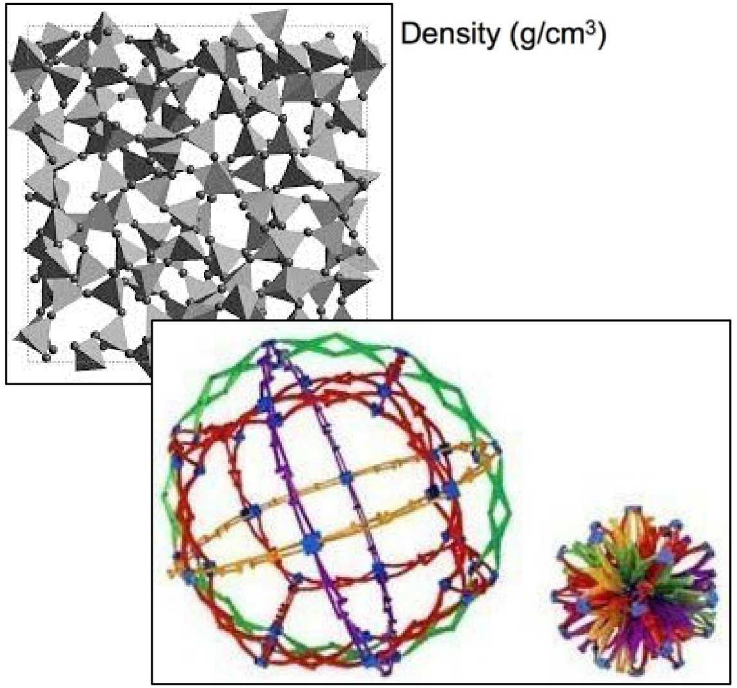
Clark and Lesher, Science Advances (2017)



Coasne et al. (2014)



Murakami, Scientific Reports (2018)

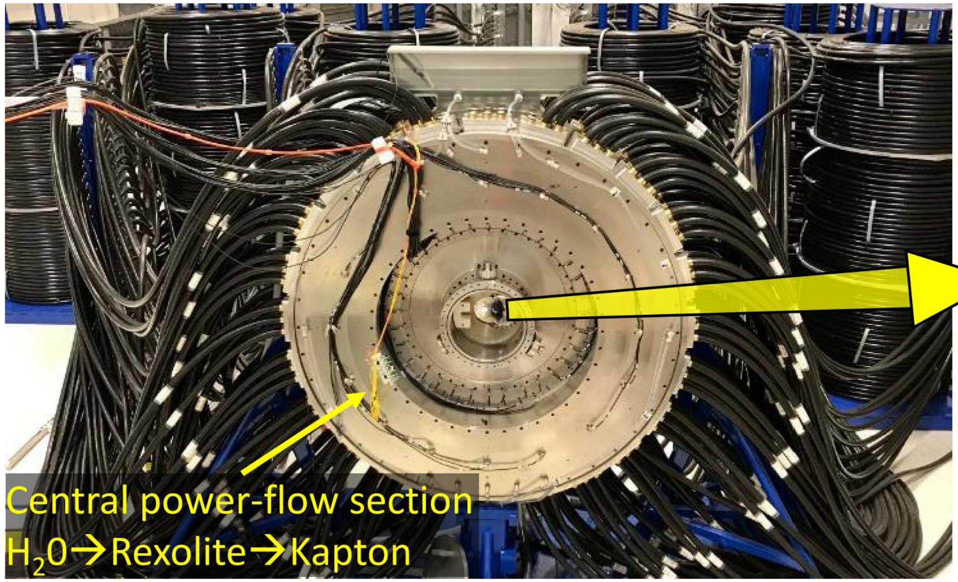


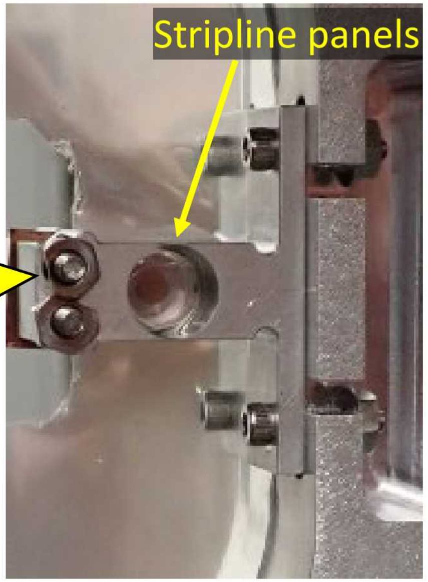
- "Densification" over some pressure range
  - Anomalous compressibility
  - Acoustic velocity depends weakly on pressure/density
  - Structural modification without changing structure (coordination increases)
- H_2O incorporated differently than into crystalline materials
  - Fill interstitial voids and/or bond as silanol (Si-O-H) groups
  - Reduces compressibility (stiffer compression response)
  - Effect's dependence on pressure, temperature, composition unknown
- Hydration-dependence of elastic properties under quasi-isentropic (ramped) compression needed to interpret MTZ-related seismic data

<u>Z-Machine Fundamental Science Project to shock-melt then ramp</u>

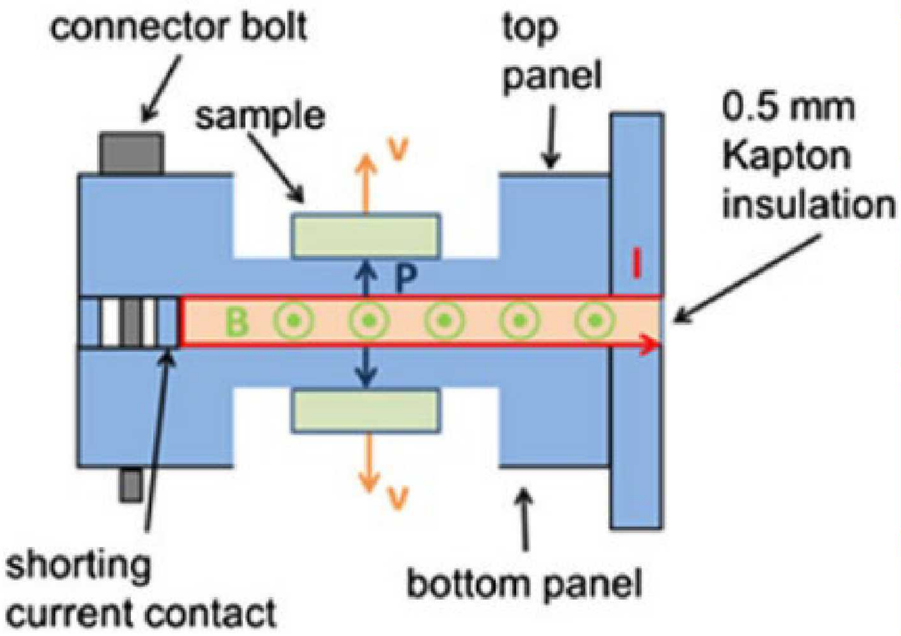
- Complemented by pure-ramp experiments on Thor small pulser

The Thor64 pulsed-power machine is a new facility at Sandia for magnetically-driven dynamic shockless compression of materials





- 64 "bricks" (2 capacitors + 1 switch) arranged in 8 towers
- Machine stores 51 kJ electrical energy when charged to 90 kV
- Switching all bricks synchronously delivers ~2.5 MA to a standard load
- Stripline = parallel flat-plate electrodes shorted at one end
- Ramped ***J***×***B*** force induces ramped stress wave in electrode material
- Wave propagates to sample material, de-coupled from magnetic field
- Both electrodes loaded identically while symmetric
- Fiber-coupled, laser-based velocimetry (PDV, VISAR)

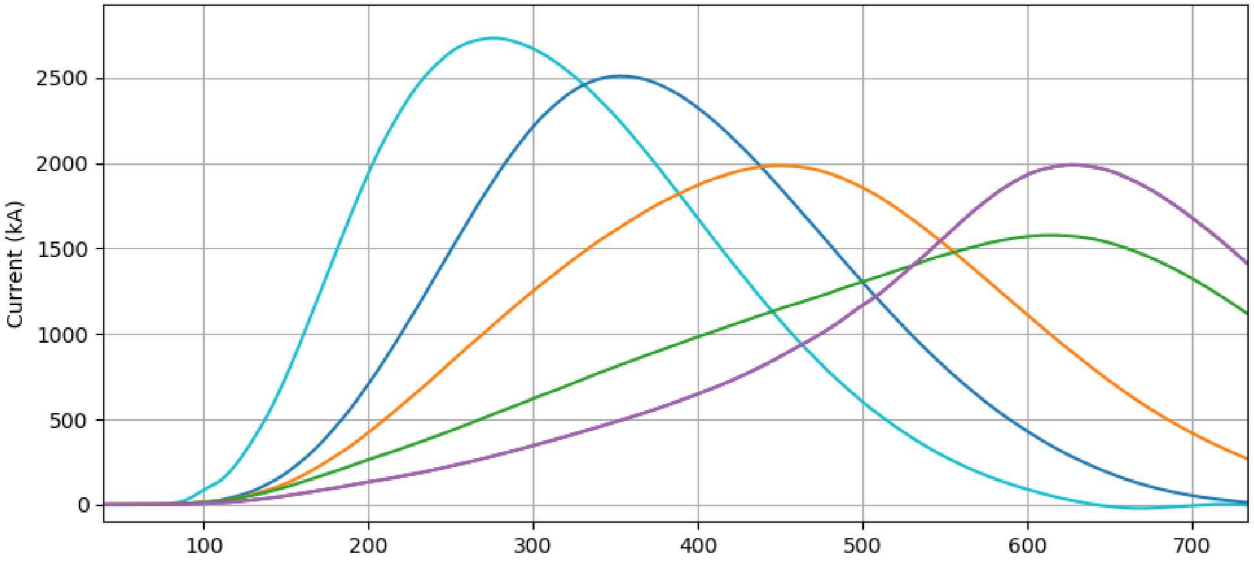


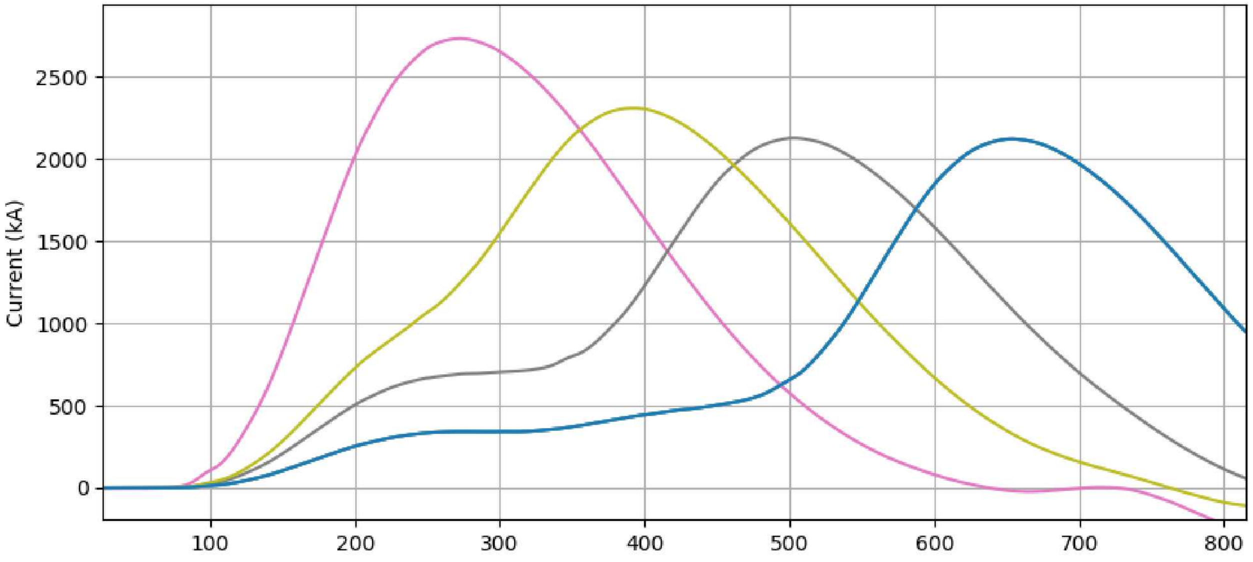
Thor64’s modular energy storage and transit-time isolation allow simple yet fine control of the current pulse shape

Each brick can be independently switched (in practice, trigger them in groups of 4)

Long cables → time isolation of switches

- 500-ns round-trip from brick to load and back = maximum spread in trigger times
- Vary loading rate by a factor of ~10 by changing trigger times and load panel width
  - Increasing rise time decreases peak current → lower magnetic pressure for given load geometry
  - Decreasing stripline panel width increases magnetic pressure → higher *dP*/*dt* for given pulse shape
- For shorter pulses ~2.4 MA peak current…
  - 10-mm wide stripline → ~20 GPa
  - 8-mm wide stripline → ~30 GPa
  - 6-mm wide stripline → ~40 GPa
- Double-ramp pulse shapes, flat-topped pulse shapes, etc.





Experiments have been performed on "dry" (100-ppm H_2O) and "slightly damp" (400-ppm H_2O) Mg-SiO_2 glasses

Collaborating with Corning, Inc. to manufacture samples of hydrated silicate glasses

- Proprietary process based on pioneering work of R. F. Bartholomew et al. from 1980's
- Working on Mg-SiO_2, Na-SiO_2, and pure SiO_2 glasses with up to several weight-% water
- Samples available thus far for Thor experiments have been low-water (100/400 ppm) Mg-SiO_2

Six shots completed to date on Thor:

HSG01 – dry, 440 μm, 10-mm wide panel
- Long shaped pulse (avoid shock)

HSG02 – dry, 693 μm
- Smoother pulse shape

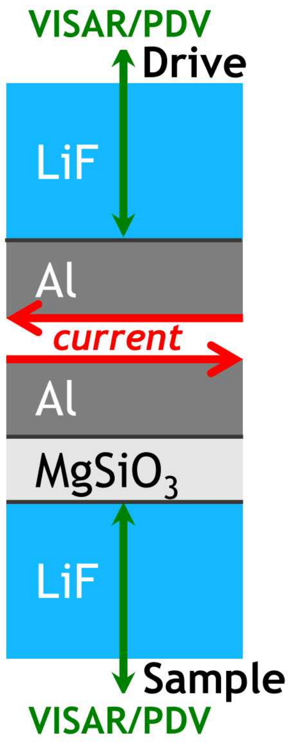
HSG03 – dry, 455 μm
- Shorter pulse, higher P

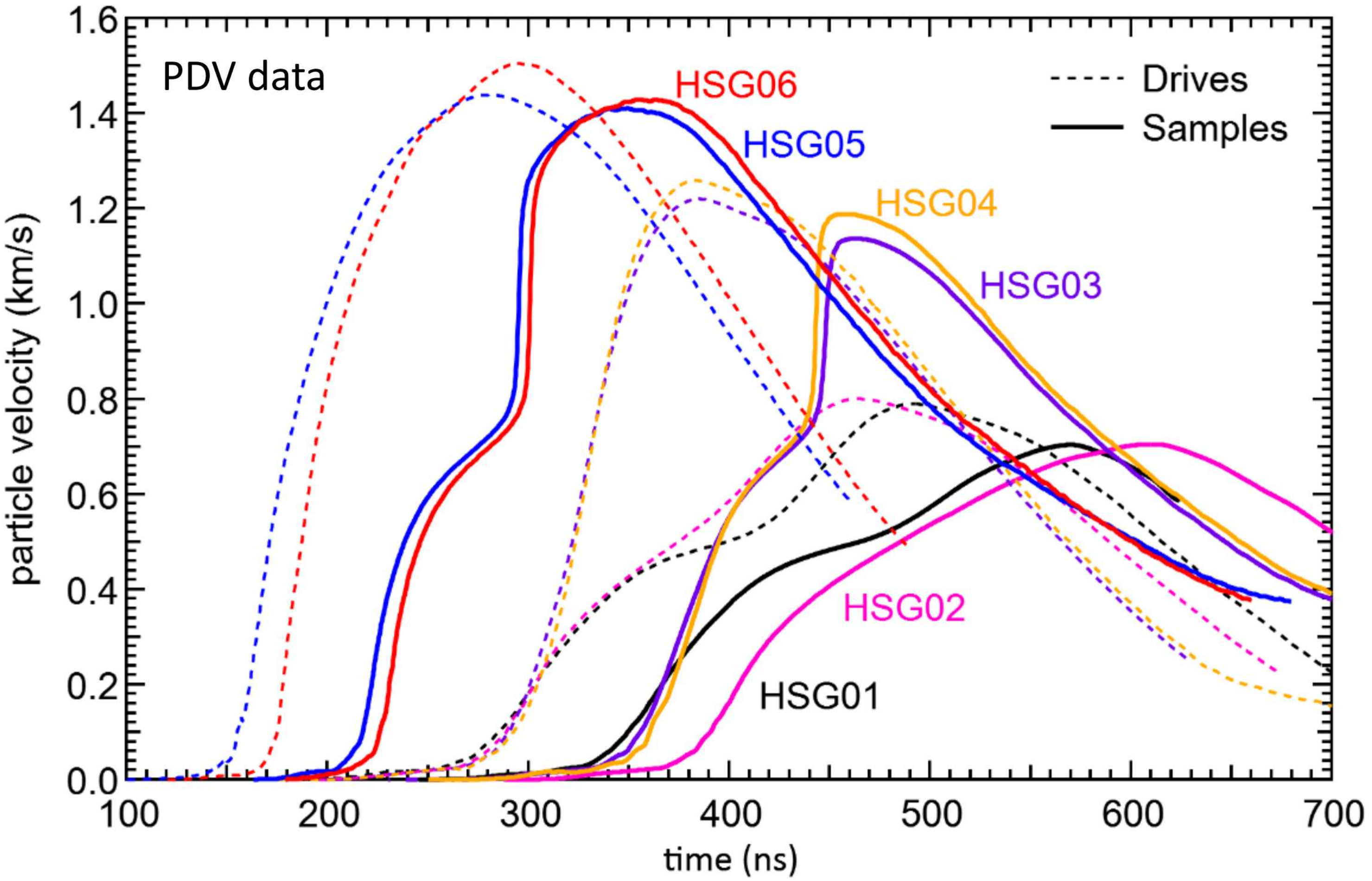
HSG04 – damp, 444 μm
- Repeat last pulse

HSG05 – dry, 465 μm
- 8-mm panel, higher P

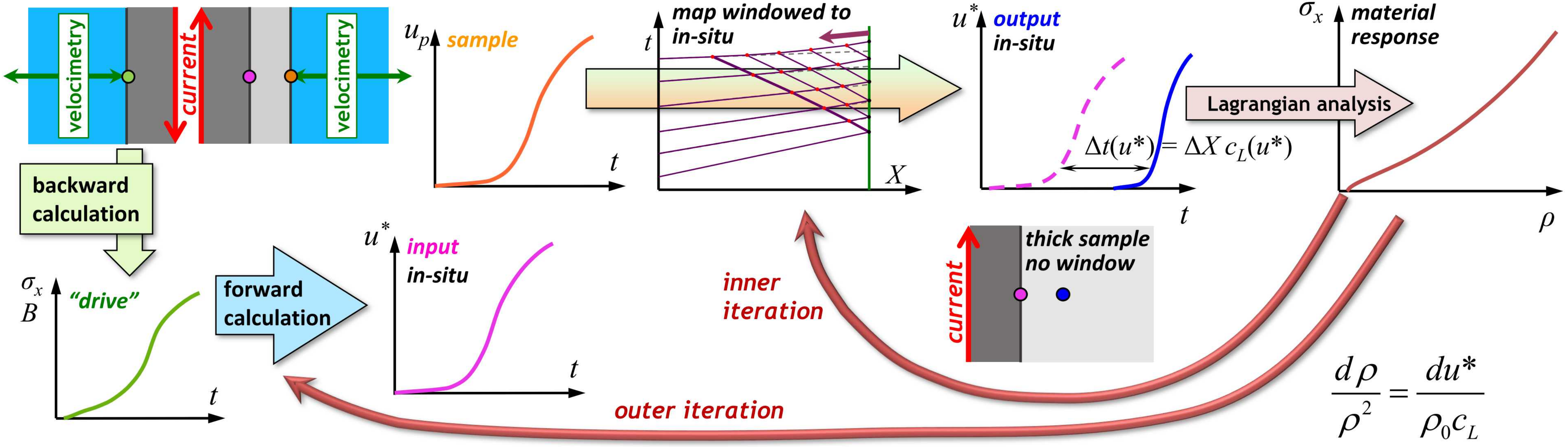
HSG06 – damp, 446 μm
- Repeat last pulse

PDV 4 channels
VISAR 8 channels





Iterative Lagrangian analysis (ILA) determines stress-density path from velocimetry of LiF-windowed "drive" and sample



$$\frac{d\rho}{\rho^2} = \frac{du^*}{\rho_0 c_L}$$

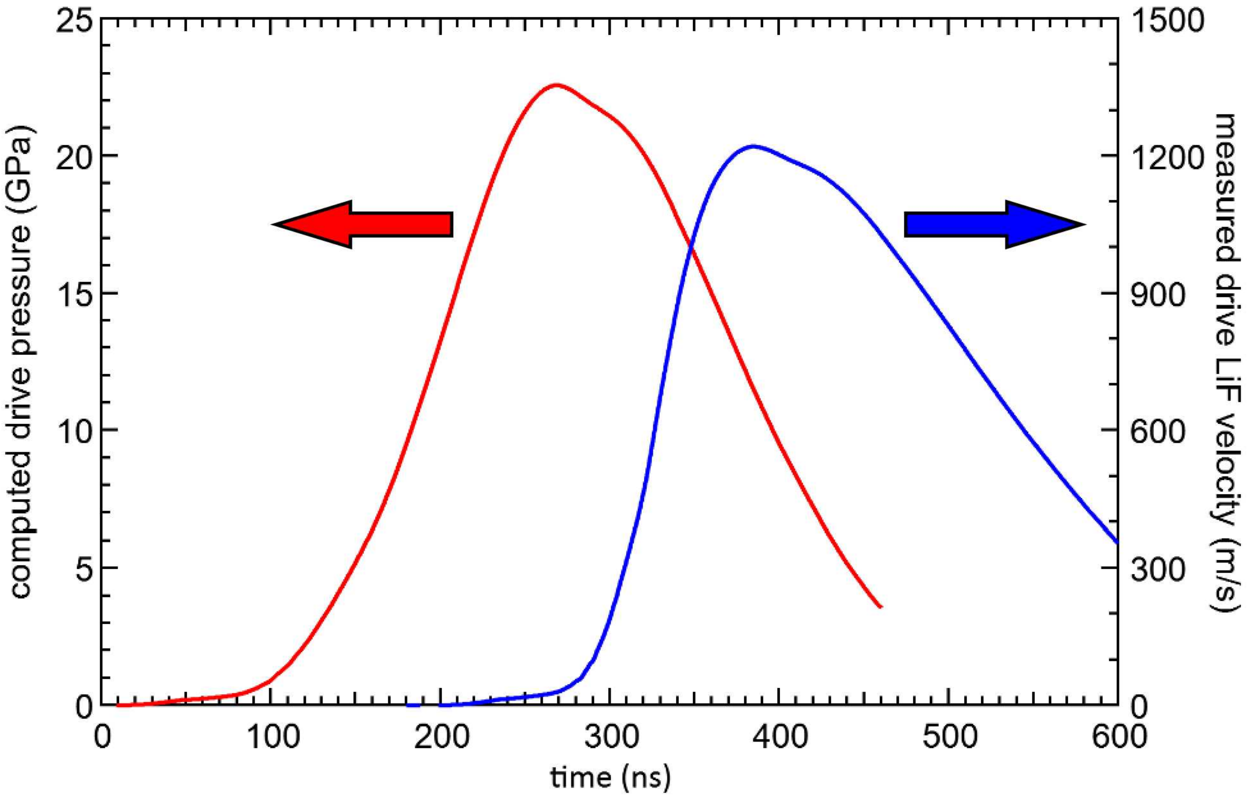
$$d\sigma_x = \rho_0 c_L du^*$$

- in-situ measurements → Direct Lagrangian Analysis (DLA)
- real measurements are free-surface or window-interface
  - map measured $u(t)$ into in-situ $u^*(t)$, then apply DLA
  - map by iterative characteristics technique
    - ➢ referred to as Iterative Lagrangian Analysis (ILA)
    - ➢ *assumes single-valued $\sigma_x(\rho)$ material response*
  - **Single-sample approach:** use drive velocity to deduce sample input

S. D. Rothman & J. Maw (2006)
J.-P. Davis et al. (2014)

Conservation of mass and momentum
Uni-axial strain condition
u_p = particle (mass) velocity
u^* = "compression velocity" (mechanical-EOS variable)
σ_x = longitudinal stress ($P = \sigma_x/3 + 2\sigma_y/3$)
X = Lagrangian (initial) thickness
c_L = Lagrangian sound velocity

A couple details from application of ILA procedure to these data

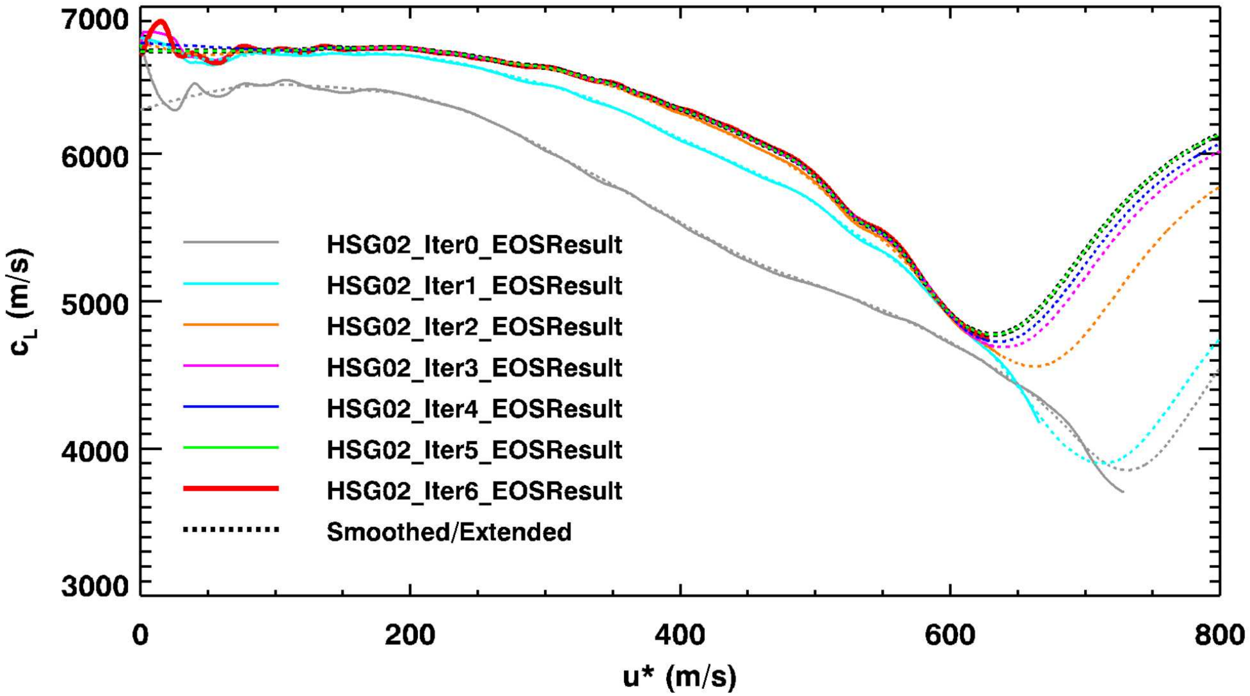


Determine driving pressure by backward integration

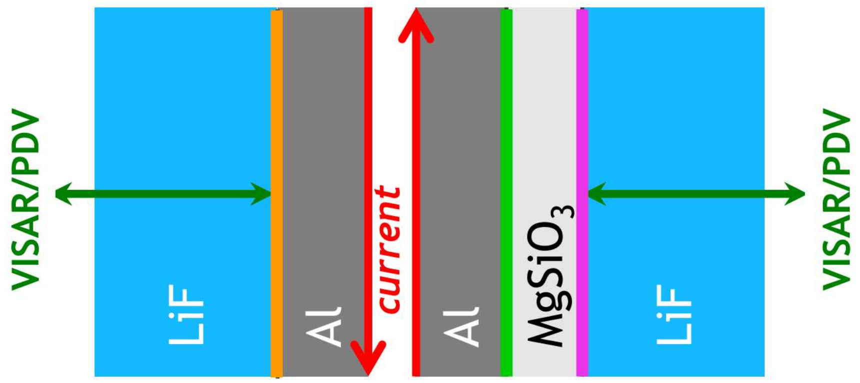
- equations of motion, EOS (neglect strength of Al)
- “equivalent” pressure to reproduce sample input w/o MHD
- valid until acoustic reverberation couples B-field to sample
- simulate sample input using same no-strength Al response

Outer iteration loop to recompute sample input

- Must extend $c_L(u^*)$ beyond previous result to simulate
- Smooth $c_L(u^*)$ below ~100 m/s
- Convergence typically in < 10 iterations



Some experiments had non-negligible bond layer thickness

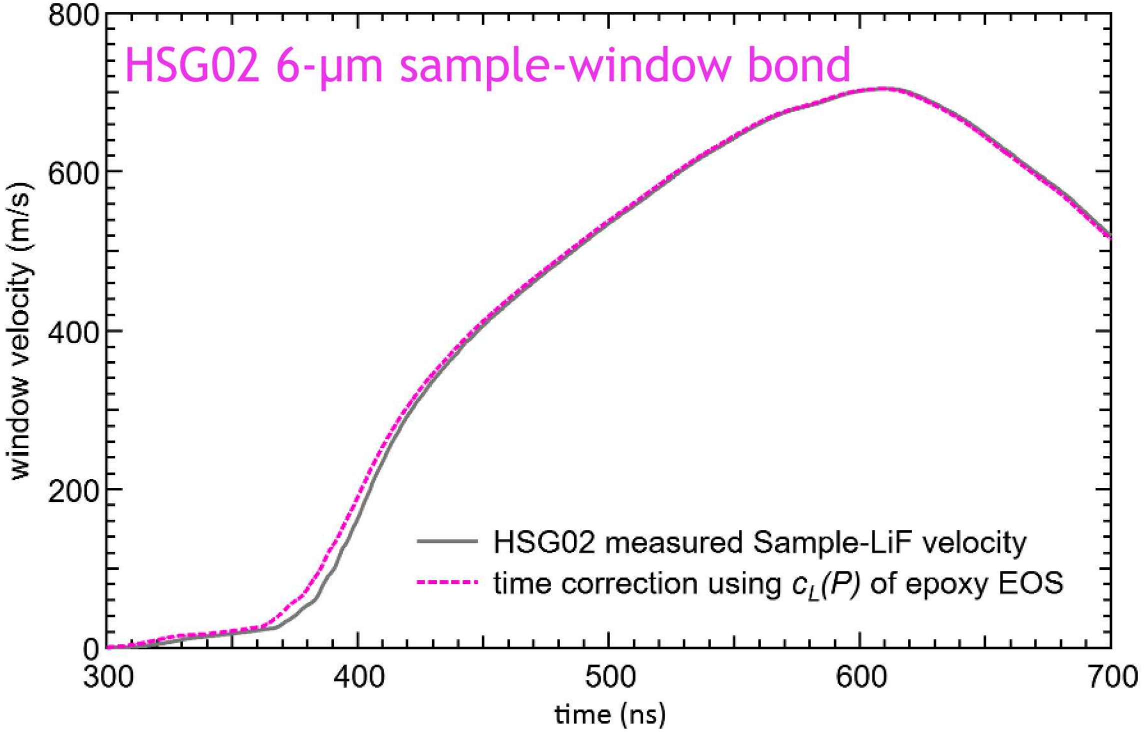


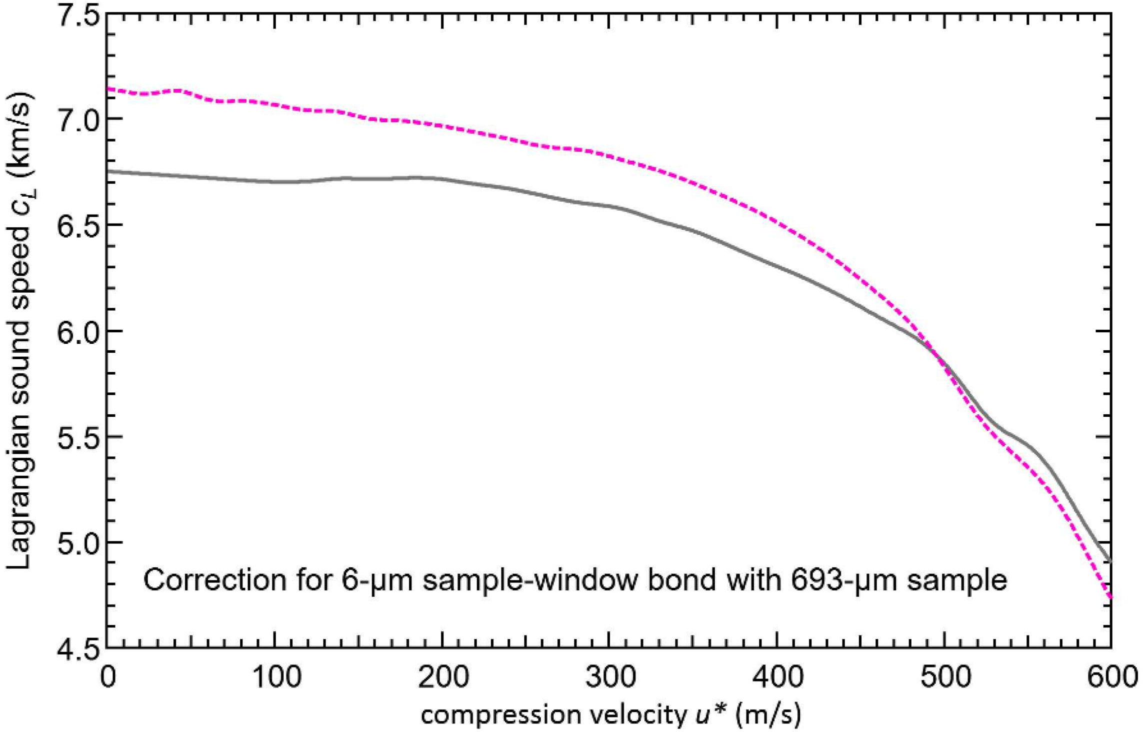
Bond layer < 2 μm thick can generally be neglected

Sample-window bond:
- correct measured $u_p(t)$ by adjusting t using epoxy $c_L(P)$

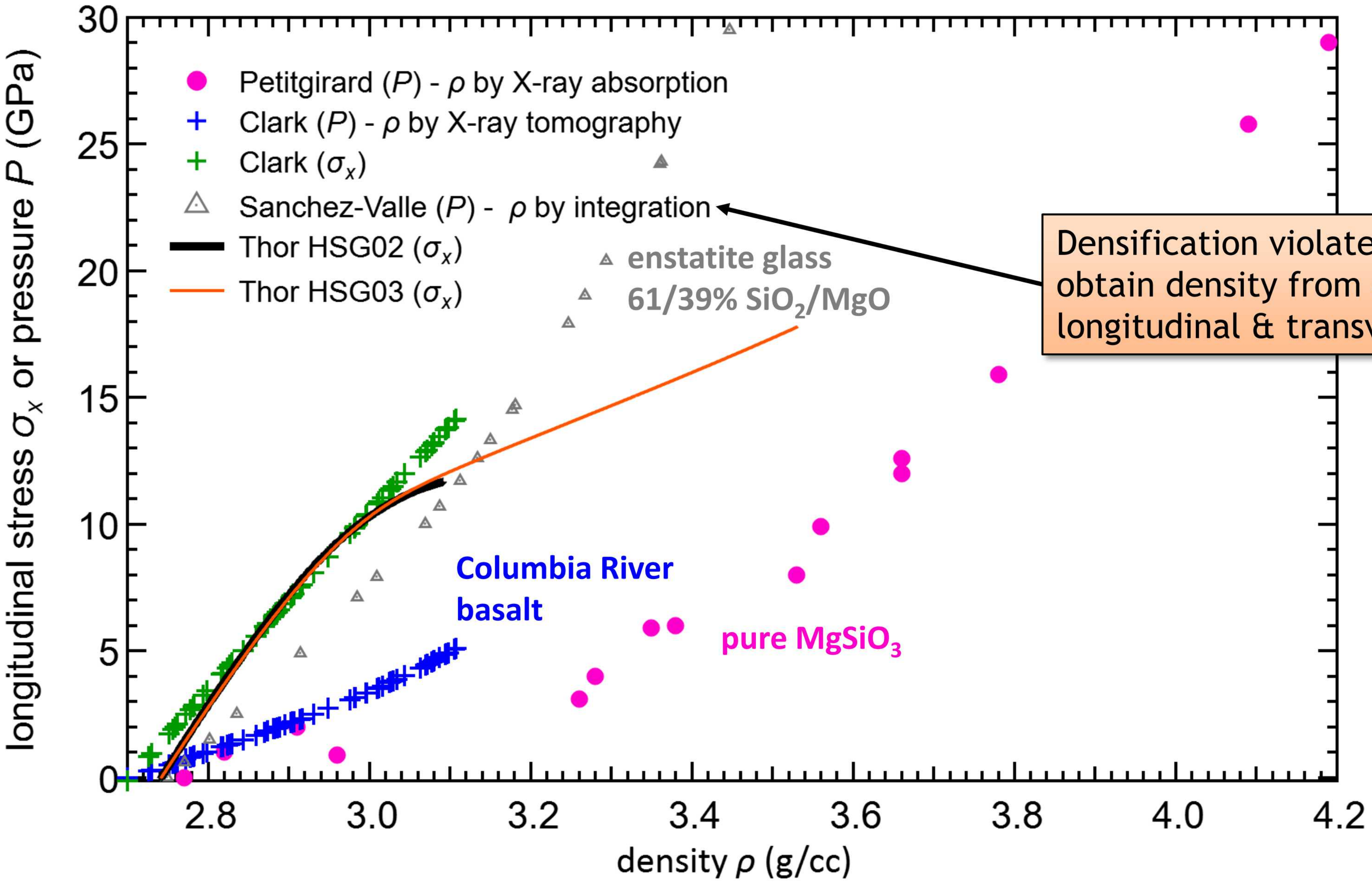
Electrode-sample bond:
- include in simulation of input $u^*(t)$

Drive electrode-window bond: HSG05 19 μm, HSG06 43 μm (!)
- Determine $P_{drive}(t)$ by optimization using simulations





Preliminary results of two Thor shots suggest densification begins above longitudinal stress of 10 GPa, not complete by 18 GPa



Densification violates assumptions needed to obtain density from elastic integration of longitudinal & transverse acoustic velocities

HSG05-06 reach > 25 GPa

- try correcting for bonds
- improve assembly procedure

$$V_B^2 = V_P^2 - \frac{3}{4} V_S^2$$

$$\rho = \int \frac{dP}{V_B^2}$$

$$\sigma_x = \int V_P^2 \, d\rho$$

density measured independently

Plenty more work to do

- Include VISAR data, quantify experimental uncertainties
- Correct for thick glue bonds at drive-measurement window
- Analyze all six Thor shots, including HSG05, HSG06 to higher peak stress
- Further experiments at Thor on pure SiO_2 glass at 0.5 ppm and 1000 ppm H_2O
  - These materials will be used on Z machine in two weeks for shock-melt-then-ramp experiments
- Further experiments at Thor on “wet” (~15,000 ppm H_2O) Mg-SiO_2 and Na-SiO_2 glasses when available

<u>Measurements of compressibility in glasses (hydrous and anhydrous) will complement measurements in melts</u>

elastic properties under quasi-isentropic (ramped) compression needed to interpret MTZ-related seismic data