Coupled Fluid-Thermal Model of Frictional Melt Generation in a Seismogenic Fault Zone

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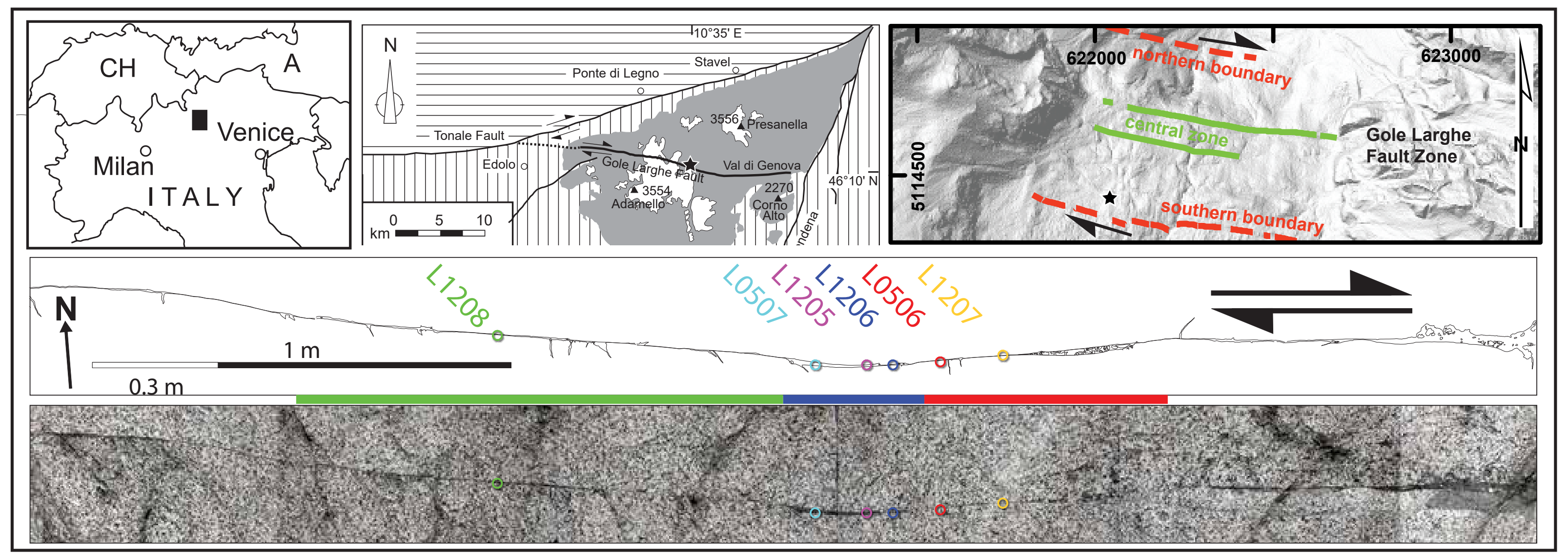
Abstract

Pseudotachylite, a glassy fine-grained rock observed in exhumed fault zones, is considered unequivocal evidence for high slip rate seismic events in the past. Immediately after the nucleation of an earthquake, the wall rocks along the fault plane accelerate to high slip velocity (~1-10 m/s), producing heat flux over 10^7 watt per square meter at seismogenic depth of ~10 kilometers; such heat progressively melts the wall rock until the rupture arrests. Todate, how frictional melt dynamically affects the kinematic properties of faults is not well understood. Our work integrates the Newtonian rheology of melt layer with two-phase Stefan Problem to numerically simulate the viscous stress drop and melt production under slip evolution defined by different Yoffe functions. Results indicate that the incipient melt thickness has negligible effect on the maximum thickness of the melt. Under certain combinations of parameters in the Yoffe function, maximum viscous shear stress and stress drop are comparable to the calculations based on field work. However, the inability to reproduce the melt thickness measured from the sample implies the underestimation of either total slip distance or viscosity, or the complex selective melting process based on individual phases.

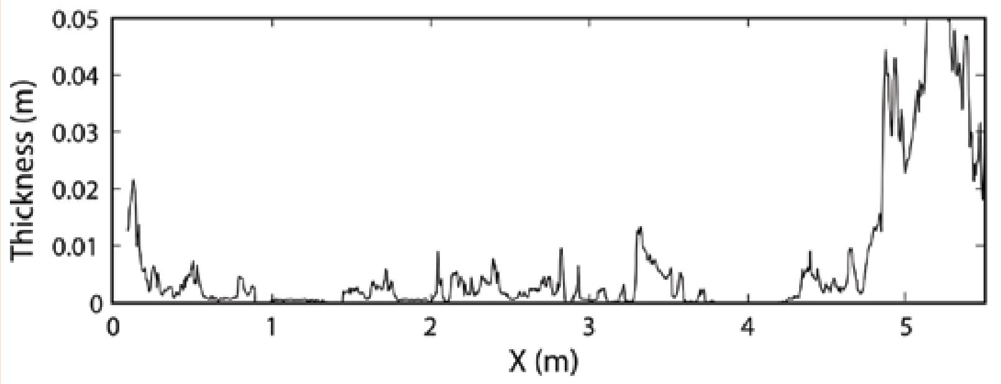
Site Information



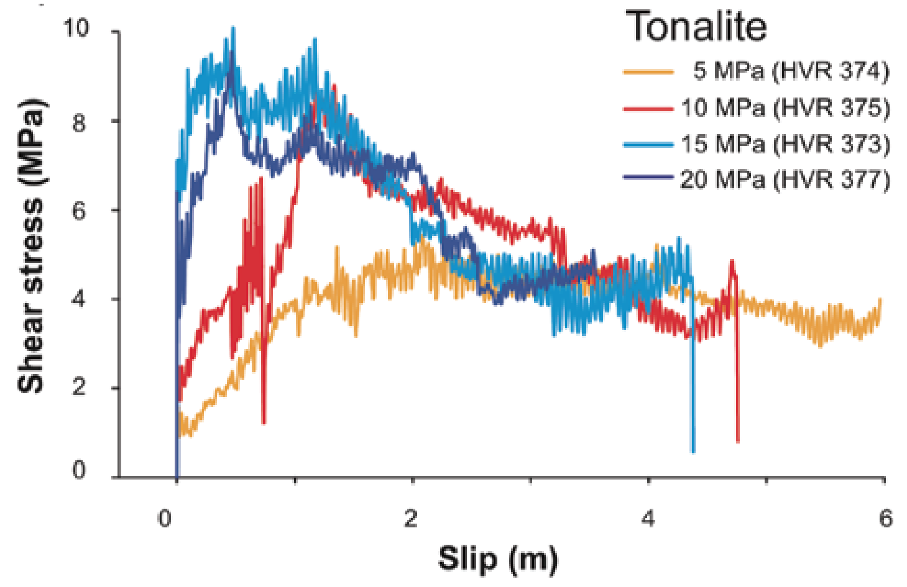
Gole Larghe Fault: Dextral strike-slip fault. Italian Southern Alps. Cross-cutting Adamello Tonalites. Ambient Temperature estimated to be around 250-300 degree Celcius (~9-11km). In the fault zone, pseudotachylite records $^{39}Ar/^{40}Ar$ ages of ~29.8 Ma.

The thickness of frictional melt along the fault zone is highly varied (figure below)(Griffith et al., 2010). In general it is on the order of 0.001m~0.01m. Inferred from the roughly linear relationship between slip displacement and fault vein thickness (Di Toro et al., 2005), the slip displacement has a upper bound of 1m. Dilational jog model places a lower bound of 0.3m.

Field survey and XRF measurement report the following composition of bulk pseudotachylite: 58.26% SiO_2, 18.44% Al2O3, 3.86% CaO, and 2.78% H2O.



Based on the oxide composition (Di Toro and G.,2004), we calculated the non-Arrhenius temperature dependent viscosity based on the model (Giordano et al., 2008). The viscosity is found to vary from 697 Pa s to 41 Pats with temperature ranging from 1273 K to 1473 K.



Hight velocity rock friction experiment (Di Toro et al., 2006, left Fig) clearly shows a two-stage weakening and strengthing until a significant stress drop. Despite on tonalite, the experiment, however, is unable to achieve the normal stress that is comparable to seismogenic depth at ~ 10km. The extrapolation of lab result, therefore, needs numerical simulations.

Physical Model

Solid Space

$$\frac{\partial T}{\partial t} = \alpha_s \frac{\partial^2 T}{\partial x^2}$$ *(Heat diffusion)*

$$q = \tau V$$ *(Heat flux boundary condition)*

Melt Space

$$\frac{\partial T}{\partial t} = \alpha_l \frac{\partial^2 T}{\partial x^2} + \mu_{(T)}(\frac{dv}{dx})^2$$

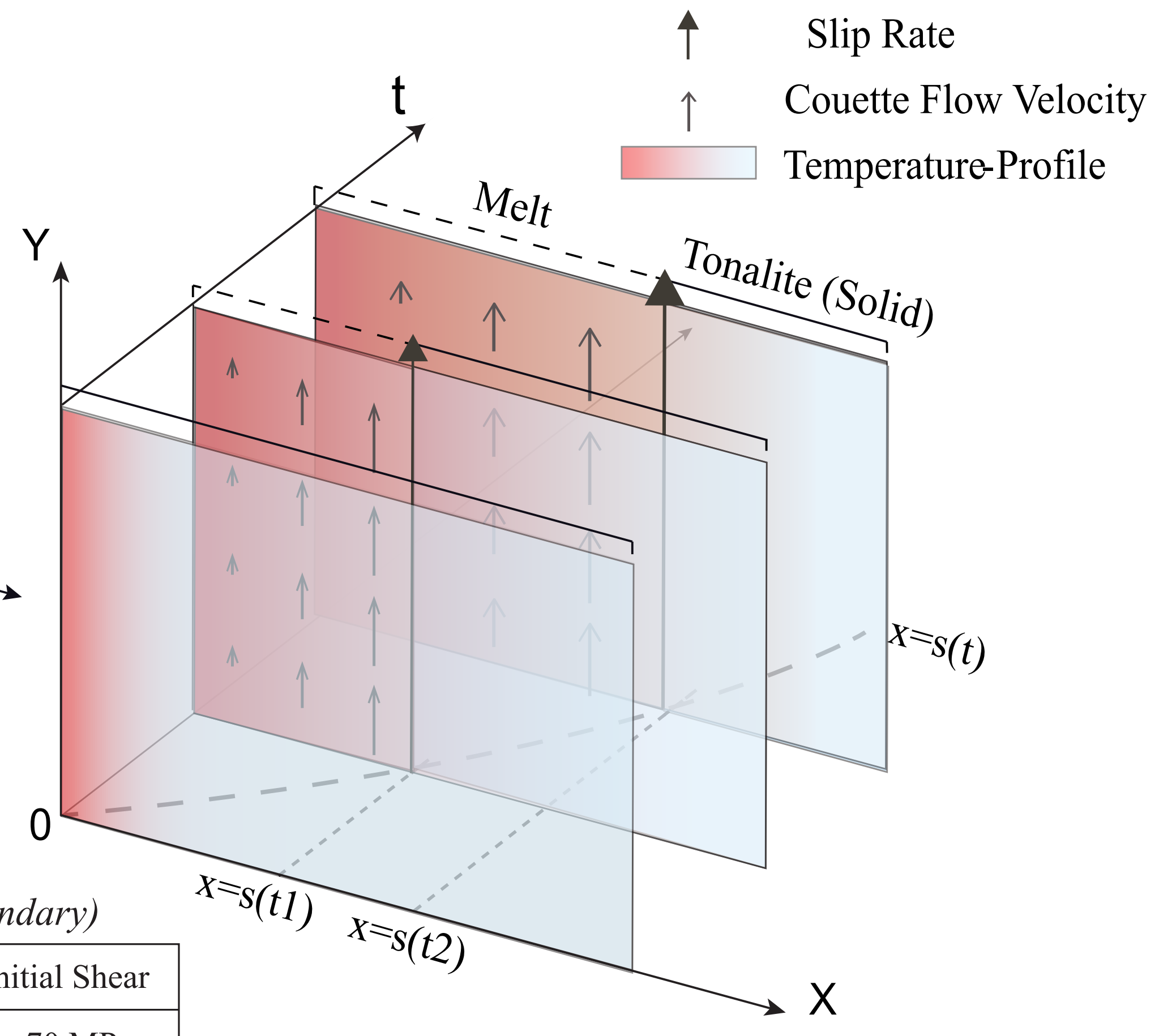
(Heat diffusion with internal heat source)

$$\rho\frac{\partial v}{\partial t} = \frac{\partial}{\partial x}(\mu_{(T)}\frac{\partial v}{\partial x})$$

(1D Navier-Stokes Equation ignoring pressure gradent and body force)

$$L\rho\frac{ds}{dt} = -k\frac{dT}{dx}|_{s(t)-} + k\frac{dT}{dx}|_{s(t)+}$$

(Stefan Condition: Latent heat of fusion equals to net heat fluxes at the moving boundary)

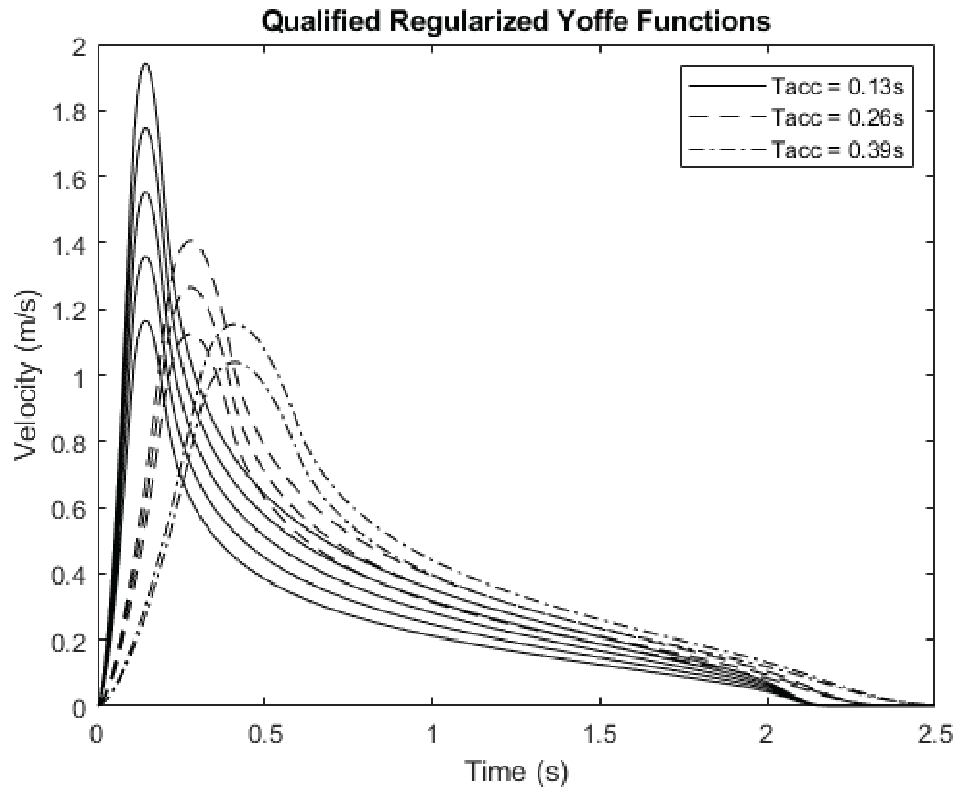


Fusion Temp	Amb. Temp	Time Ave V	Initial Shear
1473 K	400 K	0.05 - 0.5m/s	70 MPa

The initial condition is found solving the thermal evolution of boundary heat flux on an infinite half-space. We assume an incipient melt layer as thick as 4.75 micron, interpreated as the area average of melt patches around asperities (Hirose and Shimamoto, 2004). The analytical solution

$$T = T_0 + \frac{2\tau V}{k}\left(\sqrt{\frac{\alpha t}{\pi}}e^{\frac{-x^2}{4\alpha t}} - \frac{x}{2}\int_{\frac{x}{2\sqrt{\alpha t}}}^{\infty} e^{-x^2}dx\right)$$

indicates the interdependence between V (initial time average velocity), x_1 (melt thickness), and the time t_1 for temperature at x_1 to reach the threshold of fusion. We present the sensitivity test of these parameters in the result section.



We adopt regularized Yoffe function as the slip rate function. The original Yoffe function is an anlytical solution to the fracture mode in the form of self-similar, self-healing pulse (Nielsen and Madariaga, 2003). Convolution with a triangular function eliminates the singularity at rupture tip with inputs of slip distance, half-duration, and total rise time (Tinti et al., 2005). Selected functions are shown below which are regulated by total rise time <3s and peak velocity >1m/s typical for high slip rate seismic event of seismic moment of 7.

Results

Fig 1. Shear stress and melt layer thickness evolution att V = 0.5m/s, w = 5/50/100 micron; at V = 0.05m/s, w = 5/50/100 micron.

[Upper left] If the incipient melt layer was too thick, shear stress would not strengthen to reach seismogenic level. Shaded area indicates most shear stress levels drop to a few megapascals with little difference between each Yoffe function.

[Upper Right] The thin shaded area implies that despite a factor of 10 difference in thickness. The values of max thickness are numerically close, yet much smaller than melt thickness measured in the field ~ a few hundreds micron.

[Lower Right and Lower Right] Runs using 0.5m/s as initial time-average velocity indicate qualitatively similar response from min shear stress and max thickness.

Fig 2. The Maximum thickness achieved at V=0.05m/s and V=0.5m/s, with a fixed thickness w=4.75micron. In general, a shorter rise time (equivalent to higher peak velocity) produces larger thickness as datapoints with rise time = 3s is consistently larger than rise time = 1s.

Results (Cont.)

Fig 3. The problem with melt layer growth. To address the mismatch between the field measurement and our simulation, Tf = 1473K/1373K/1273K/1173K, V=0.05m/s, w = 4.75 micron.

Figure 1

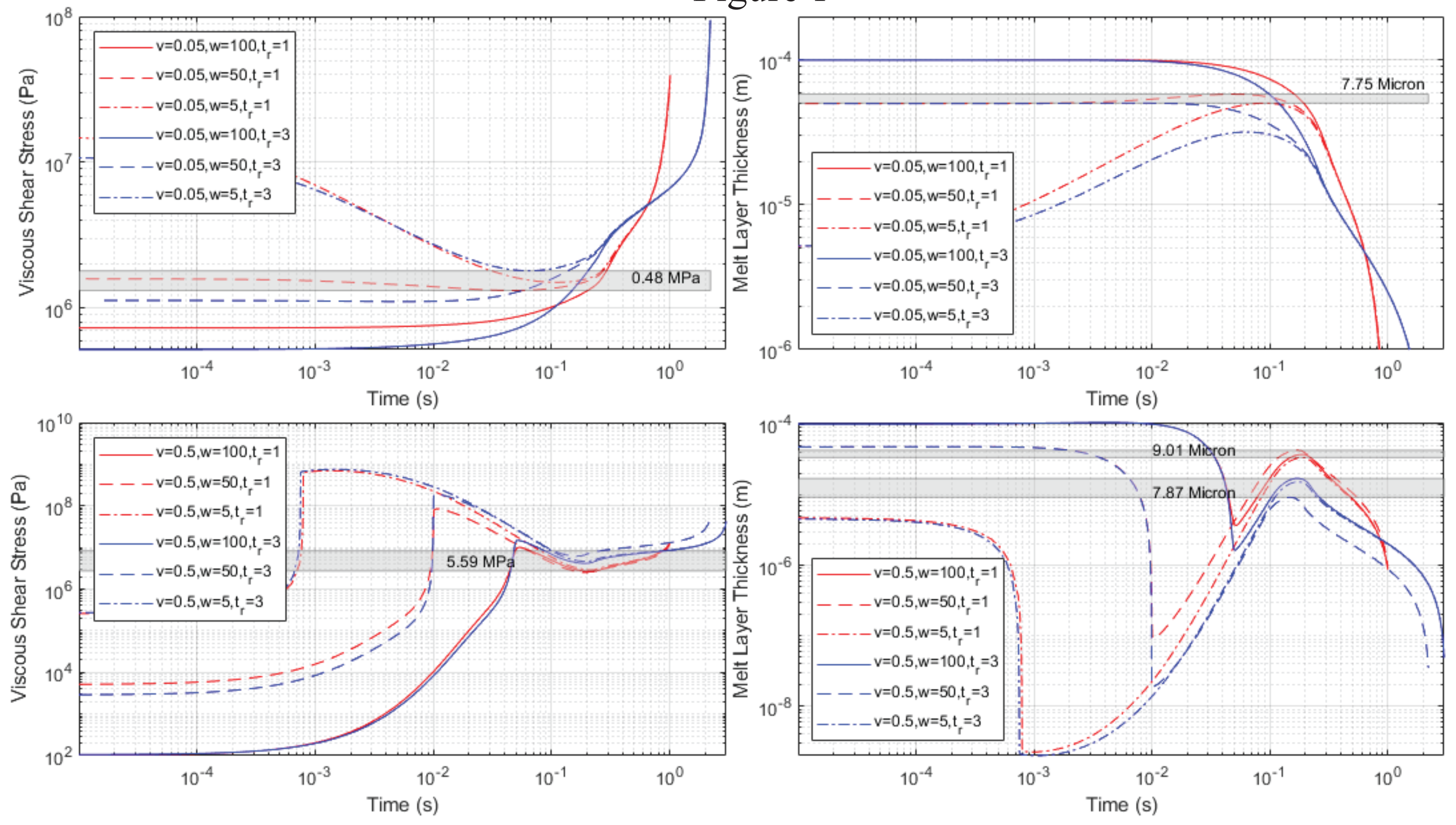


Figure 2

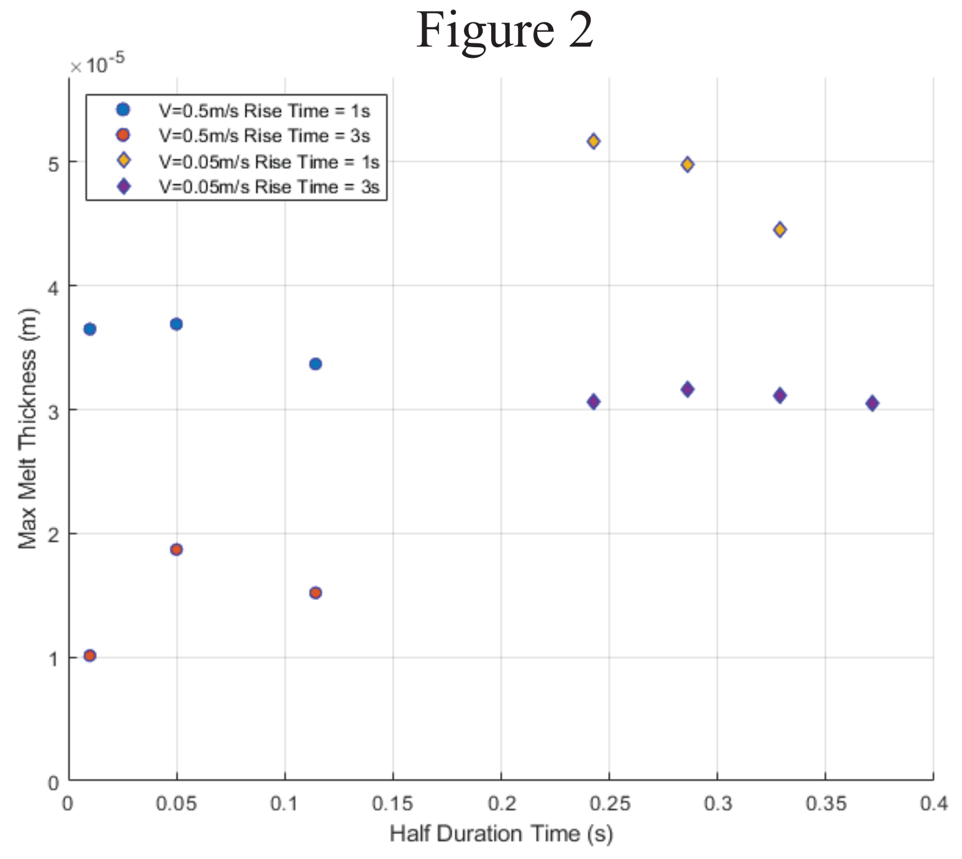
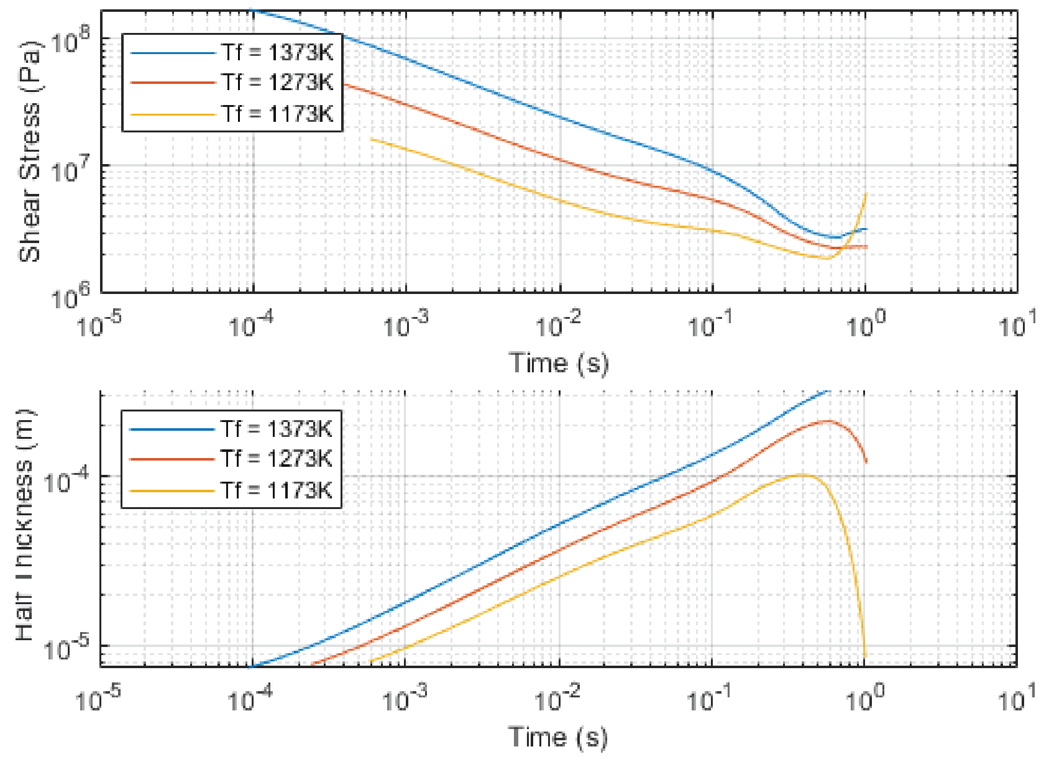


Figure 3



The original choice of 1473 K as fusion temperature considers the melting temp of plagioclase. However due to the selective melting nature of biotite during frictional melt formation, eutectic temperature is too low while plag temp might be too high. Interestingly the power law distribution in Fig 3 implies a self-similarity solution before the melt solidifies.

The underestimation of thickness can also be attributed to the poor constraint on max slip displacement.

Next Step:

1. Upper bound of 1m might be a conservative estimate. A parametric sweep using progressively larger total rise time should be investigated in order to understand the melt thickness evolution.
2. The argument of dynamic shear stress. How do we reconcile/position our simulation results with estimates of energy partitioning based on several competing theories.
3. Surface roughness. Preferential melting of biotites during the formation of melt has been valided by a few works. We are curious if the surface roughness or topographical difference - which we have quantified - is controlled by the respective melting temperature of quartz and biotites before the melt solidifies into pseudotachylite.