PENN STATE 1855

Penn State Rock and Sediment Mechanics Laboratory

Onset of Strain Localization in Sheared Glacial Till

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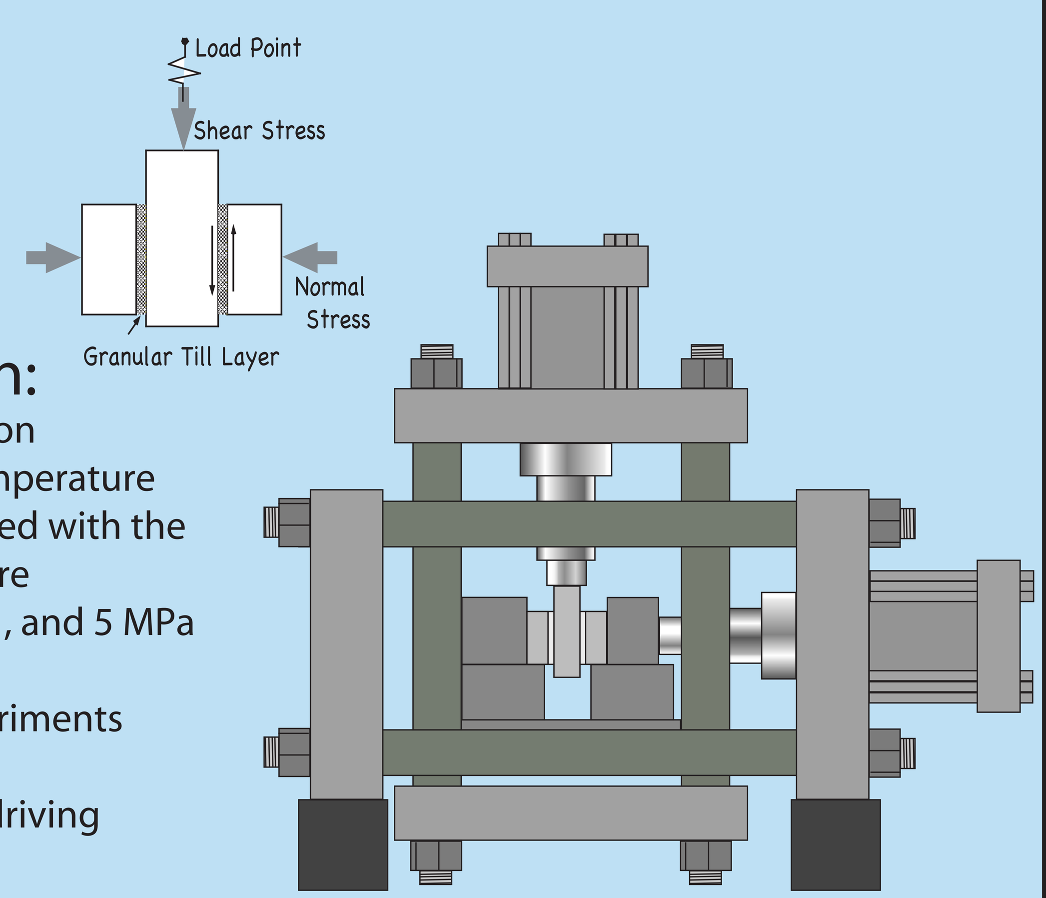
Summary

Strain localization plays a key role in determining the frictional stability of brittle shear zones, which in turn influences the rheology and seismic/aseismic behavior of fault zones and deforming glacial till. Recent studies show that seismic, stick-slip motion occurs in dilatant till layers. It appears that dynamic stresses and fluid migration during localized shear may induce stick-slip instability. However, the laboratory data necessary to test such hypotheses are incomplete. We report on detailed laboratory experiments to measure the onset of shear localization of Caesar till sampled from the Scioto Lobe of the Laurentide Ice Sheet, collected in central Ohio, USA.

Experiments were conducted in a servo-controlled, double-direct shear apparatus with saturated samples at normal stresses of 0.5, 1, and 5 MPa. The layer thickness was either 0.5 or 1 cm prior to shear. Till was sheared in constant velocity or constant shear stress (creep) boundary conditions. Creep experiments were employed to study frictional creep and the localization of strain. Creep was induced after an initial shear strain ranging from 0 to 2.6 to investigate the role of shear fabric on deformation. In creep experiments, shear stress increments began at ~ 2/3rds of the shear strength and continued until tertiary creep occurred. Stress steps were 5% of the shear strength and we determined the resulting strain rate and layer dilation.

Creep experiments show a transition from distributed deformation to localized deformation at low strains. Velocity steps show that Caesar till is a velocity strengthening material, with the critical slip distance decreasing with strain up to 0.7 then remaining constant. Creep experiments show that dilatancy after a stress step decreases exponentially from ~10 µm at shear strain of zero to ~2 µm at a shear strain of 1. Beyond strains of 1 no variation in dilatancy is observed. Decreasing initial layer thickness decreases dilation by the same factor at low strains, but has no effect at strains of 1 or greater. These results imply that shear becomes more localized over a finite displacement in a velocity strengthening material. Beyond the onset of localization variation in strain and driving velocity do not change the characteristics of strain localization. Localized deformation in till implies shallow deformation, which does not stabilize fast glacial slip and may lead to stick-slip motion.

Experimental Setup



Blocks:

- 10 x 10 cm² contact area
- Blocks grooved 0.8 mm with a wavelength of 1 mm

Experimental Design:

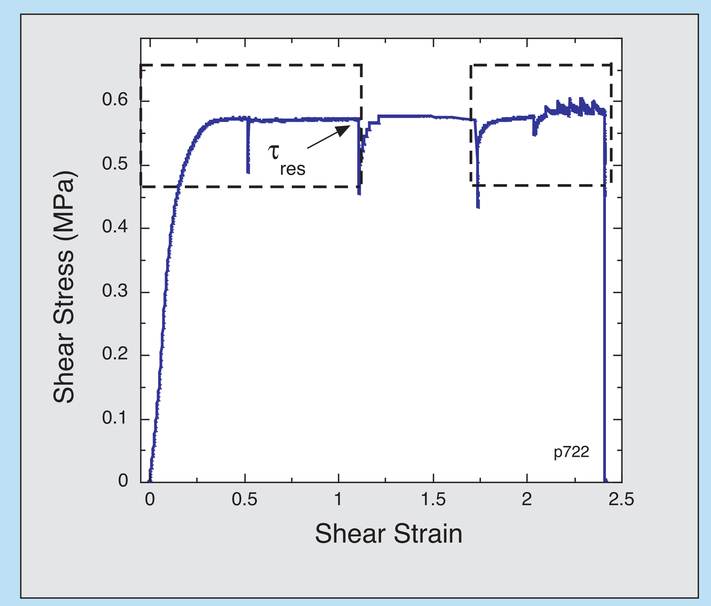
- Double-direct shear configuration
- All experiments run at room temperature
- Saturated experiments conducted with the reservoir open to the atmosphere
- Experiments conducted at 0.5, 1, and 5 MPa normal stress
- Shear stress steps in creep experiments were 5 % of the shear strength
- In rate controlled experiments driving velocity was 1-300µm/s

Sample Characteristics

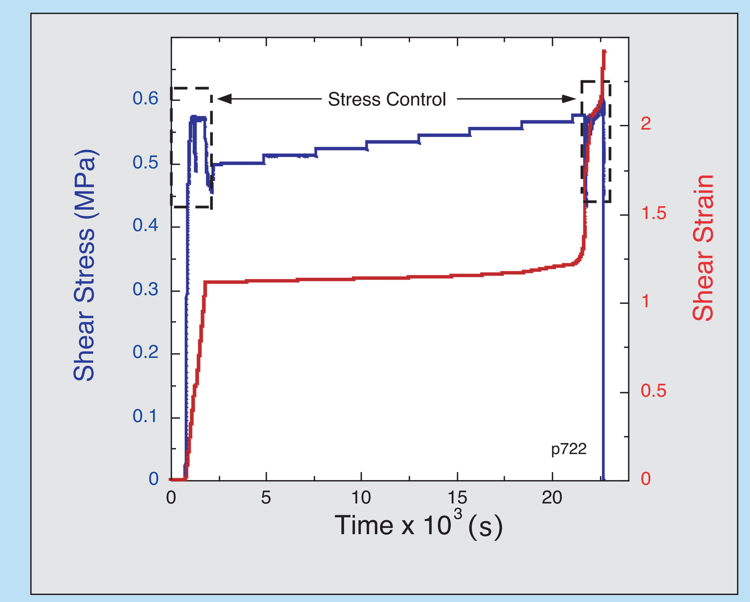
- Caesar till collected in Central Ohio, USA, from the Scioto Lobe of the Laurentide Ice Sheet
- Samples are air-dried and sieved to less than 1 mm
- Bulk sample: 98.9% sand/1.0% silt, 0.1% clay
- Experimental range: 98.7% sand/1.2% silt/0.1% clay

Experiments

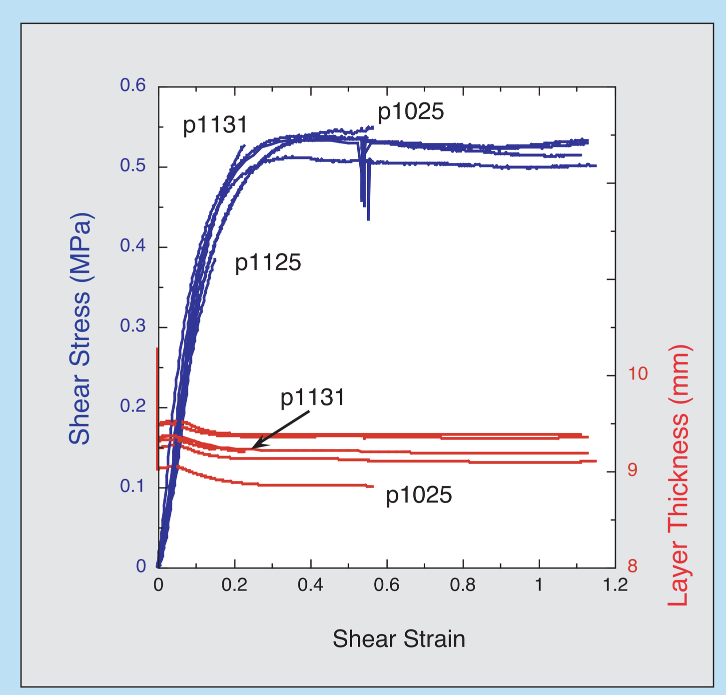
Shear creep experiments are ideally suited to assess the onset of shear localization due small amounts of strain during creep. Shear stress is held constant for 45 minutes then increased by steps of 5% of the steady state shear strength. The amount of shear strain during each step is less than 0.1 during stable creep. The amount of shear strain before creep is varied to investigate the onset of localization. Changes in dilation during creep are used as proxy for fabric development and shear localization. Frictional properties and shear strength are investigated under constant driving velocity .



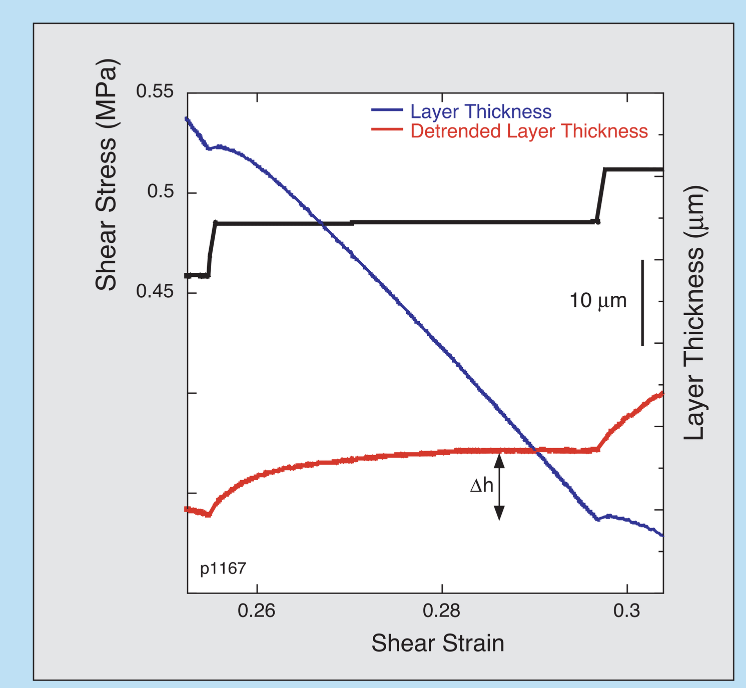
Constant shear stress (creep) experiments. Boxed regions represent displacement controlled sections. Displacement control establishes a consistent shear fabric.



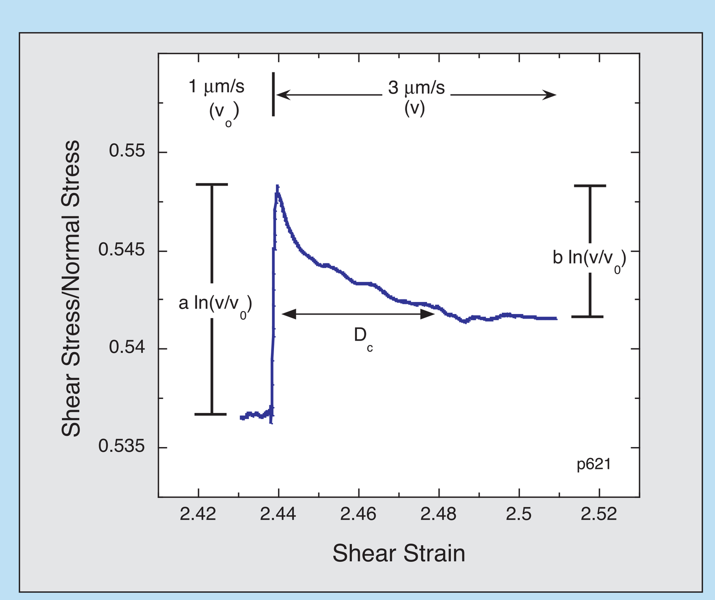
Most strain occurs during displacement control and high shear stress. During stable creep shear strain is less than 0.1.



The amount of shear strain before creep is varied from 0 to 2.6. Layer thickness (corrected for shear thinning) is near constant by a shear strain of 0.2.



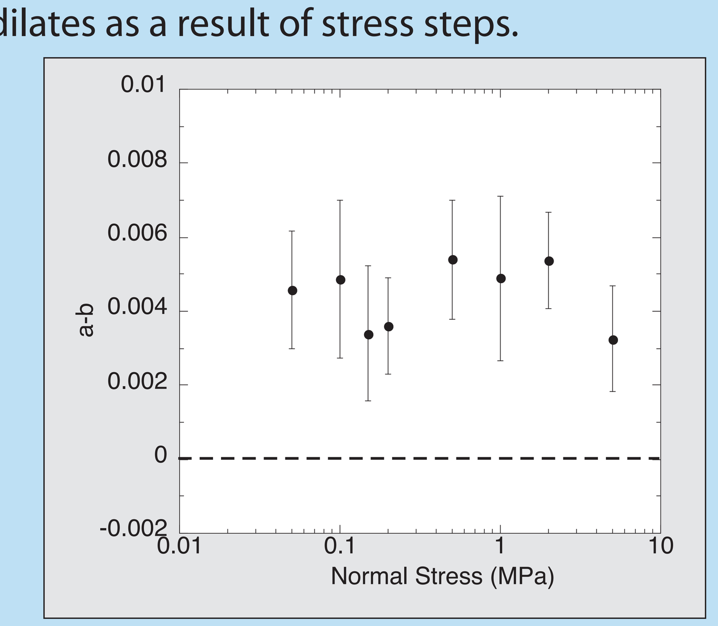
Shear stress is increased in a series of steps. The trend of layer thickness changes as a result of the stress step. When shear thinning is accounted for, the layer dilates as a result of stress steps.



The velocity dependence of friction is calculated from:

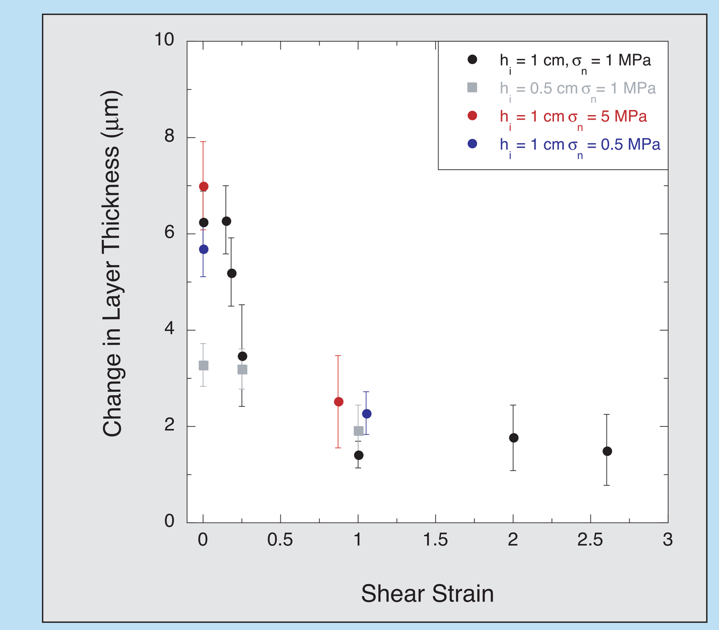
$$a-b=\frac{\Delta\mu_{ss}}{\Delta\ln(V)}$$

All experiments show velocity-strengthening frictional behavior (positive a-b).

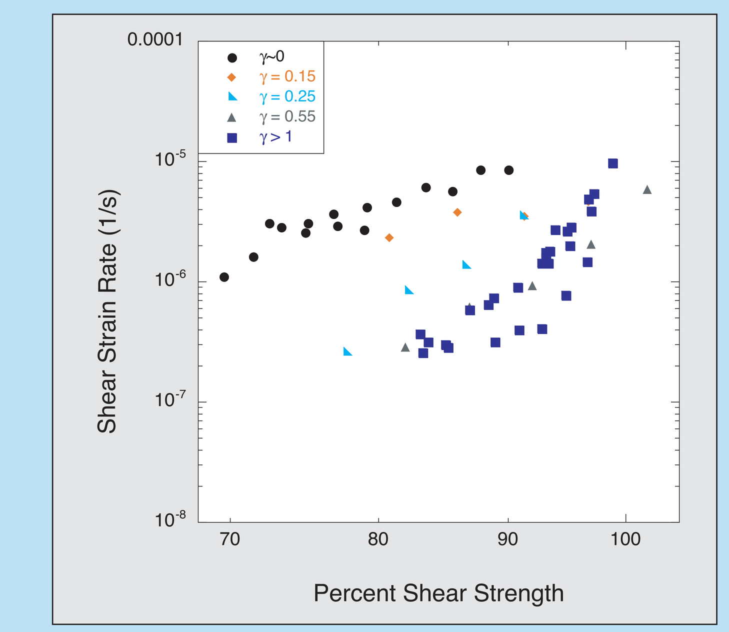


Fabric Development

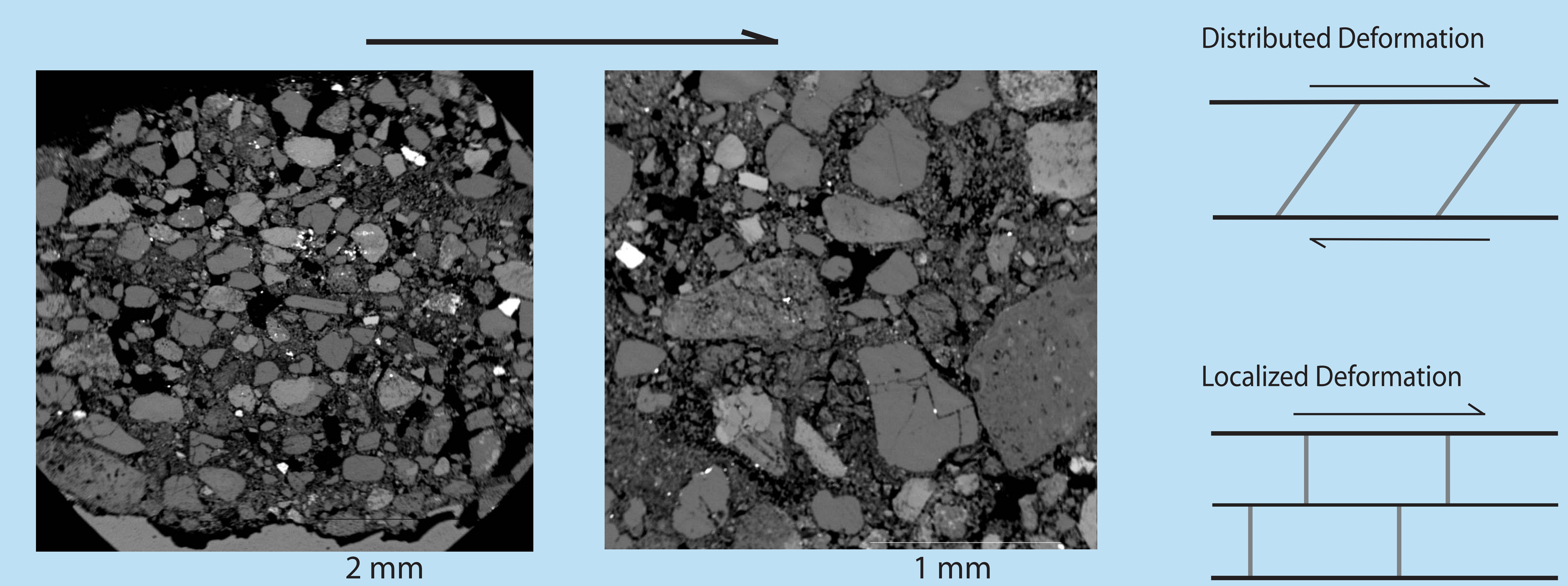
Layer dilation implies that fabric develops rapidly at low shear strains then remains constant. Changing layer thickness and normal stress only effect dilation and fabric development at low shear strains. Increased shear strain reduces the resulting shear strain rate from stress increases.



Layer dilation progressively decreases until shear strain of 1, then remains constant. Layer thickness influences dilation at low shear strain. At low strain greater normal stress leads to greater dilation.



Shear strain rate shown as a function of initial strain before creep. Data are shown for a range of normalized shear stress. Strain rate decreases with increased strain and the degree of shear localization of strain.



SEM imagery of experiment p1344 shows heterogeneous distribution of high and low porosity zones

Conclusions

1. Velocity Dependence of Friction
   Caesar Till is a velocity-strengthening material at all shear strain and normal stresses tested.

2. Fabric Development
   Changes in layer dilation shows that fabric develops gradually until a shear strain of 1, then remains constant until a shear strain of 2.6.

3. Shear Localization
   During distributed deformation, dilation scales with layer thickness. By a shear strain of 1, layer thickness does not effect dilation implying a transition from distributed to localized deformation. Localized shear decreases shear strain rate.