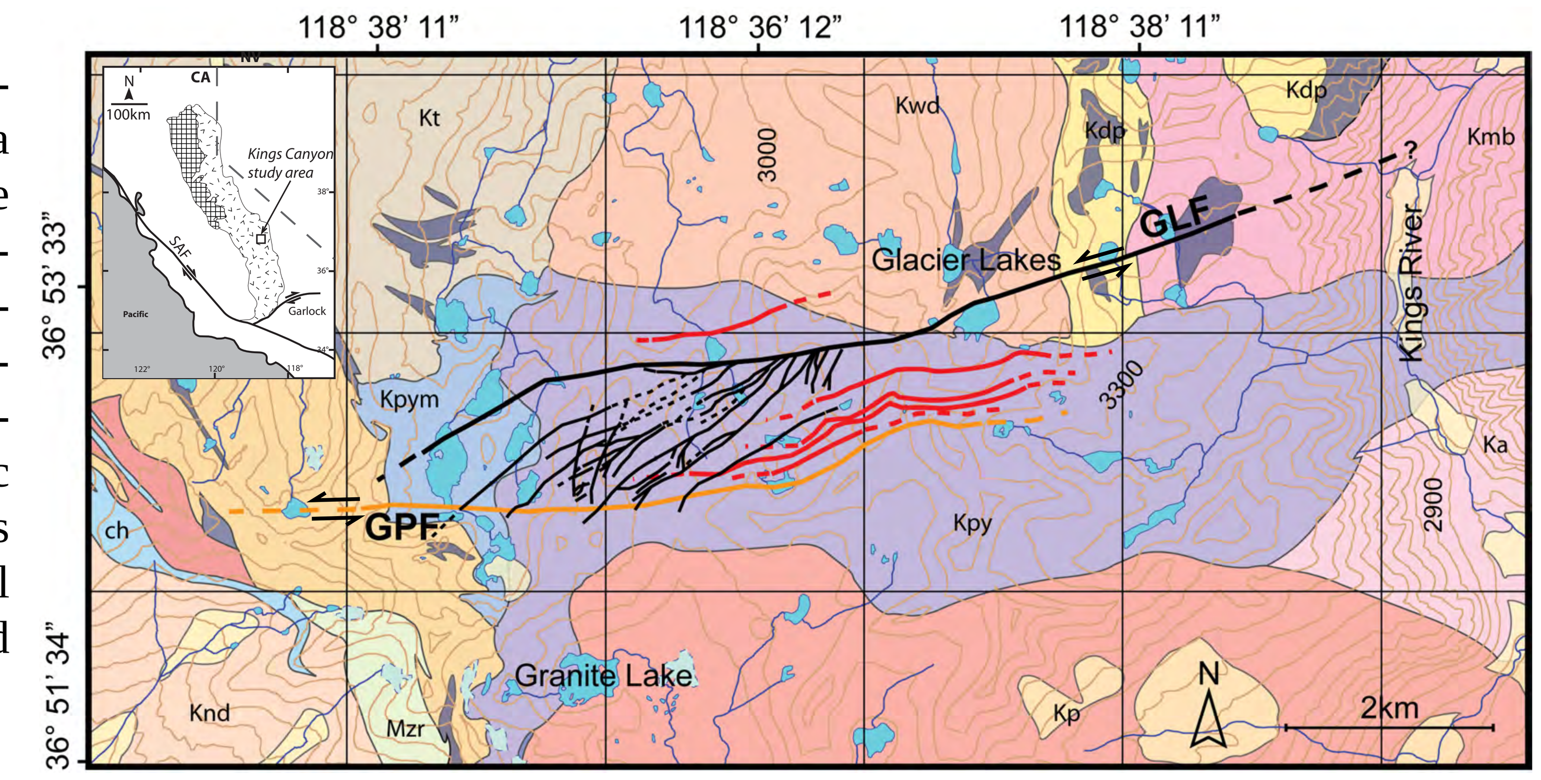
Relating grain-scale observations to coseismic fault friction

James Kirkpatrick and Zoe Shipton
Contact: james.kirkpatrick@ges.gla.ac.uk

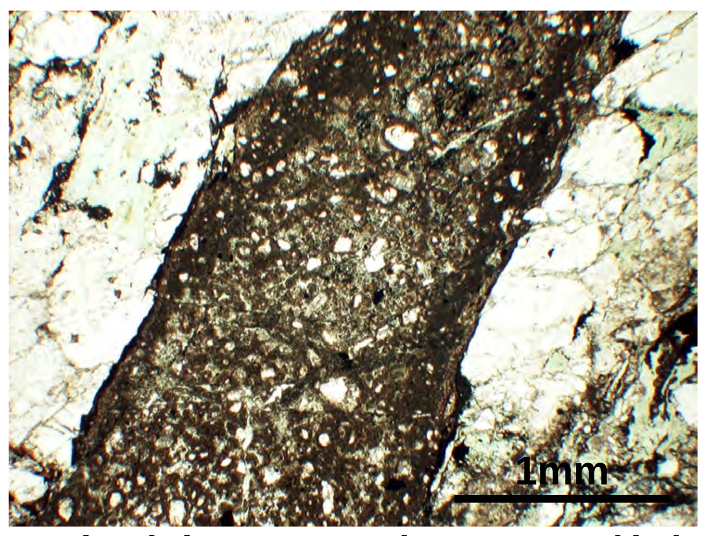
Abstract

We examine exhumed seismogenic faults to investigate the mechanisms that may have achieved dynamic fault weakening during ancient ruptures. Pseudotachylytes that are continuous over the scale of field exposures are indicative of melt lubrication. A fault breccia cross-cutting earlier-formed cataclasites was mobilized during faulting and possibly represents a pressurized fault rock that could have resulted from thermal pressurization or elastohydrodynamic lubrication. Cataclasites in which there is no evidence for melting are present immediately along-strike from pseudotachylyte patches several metres long. The energy required for melting suggests that the pseudotachylytes must have formed during ruptures larger than the patches, implying that the cataclasites also localized seismic slip. The distribution of fault rock types shows that the frictional response to slip during a single event was spatially variable. Re-worked pseudotachylytes also indicate that coseismic processes change over time at a point on a fault. These observations emphasise that macroscopic dynamic fault weakening is a function of multiple coeval processes at micro- to meso-scales. Detailed observations of the discontinuous pseudotachylytes show that the thickness of the slip zone is the critical parameter that controls active coseismic processes. The frictional response of a fault to slip is therefore dependent on the internal structure of faults; given the along-strike heterogeneity of most mapped fault zones, the co-existence of multiple slip weakening mechanisms in a single earthquake will be common.

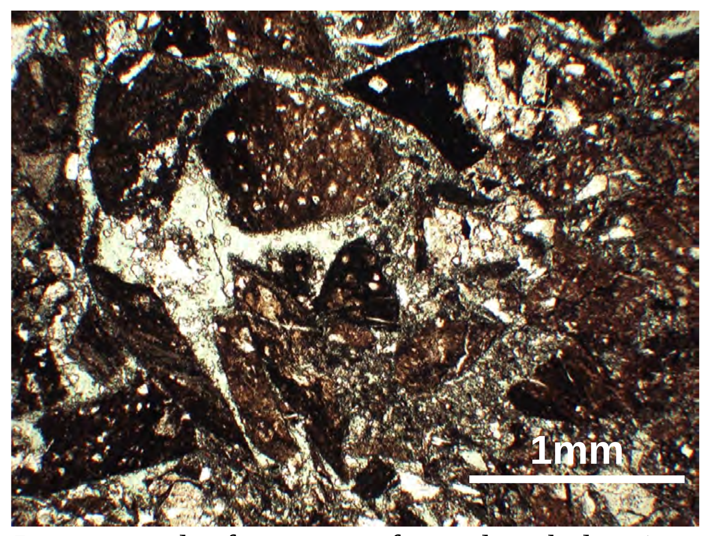


Pseudotachylytes

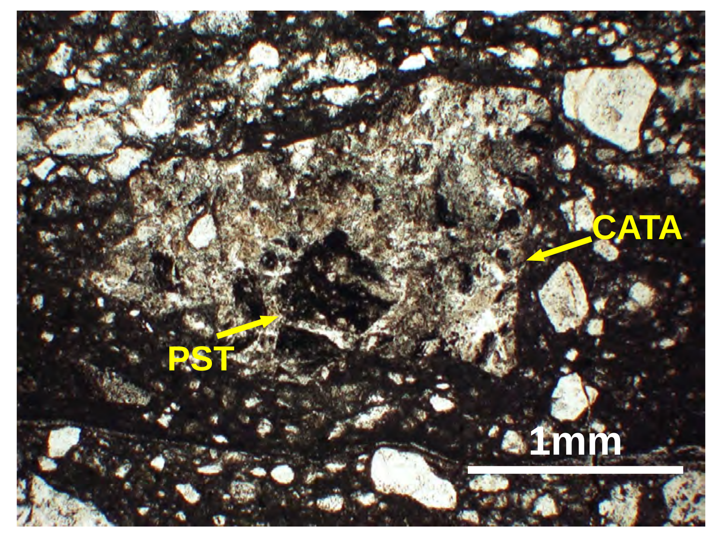
Pseudotachylyte generation surfaces are sub-parallel to fault orientation and cross-cut cataclasites and undeformed host rock. Some are continuous across exposure (lengths of the order of 10m) some are short (<4m).



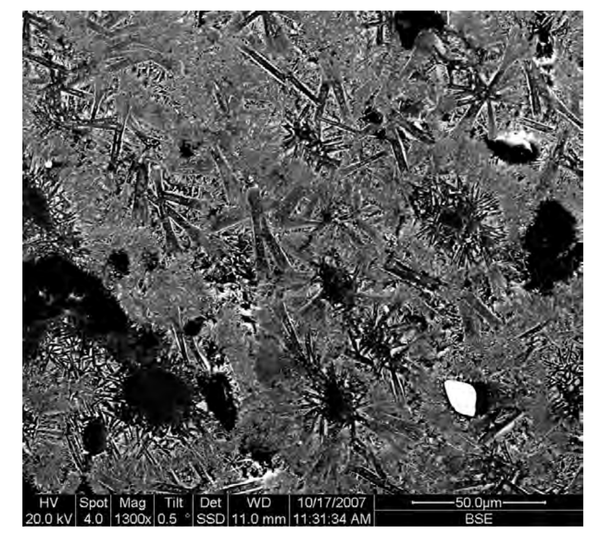
Pseudotachylytes contain cohesive, grey or black material which is often banded parallel to the vein margins. Rounded or embayed clasts within the veins are less than 3mm long and are composed of wall rock quartz and feldspar.



Large, angular fragments of pseudotachylyte in a chlorite matrix. Coseismic processes changed from frictional melting to brittle cataclasis without melting as time progressed.



Re-worked pseudotachylyte (PST) material in a cataclasite fragment (CATA). Pseudotachylytes cross-cut



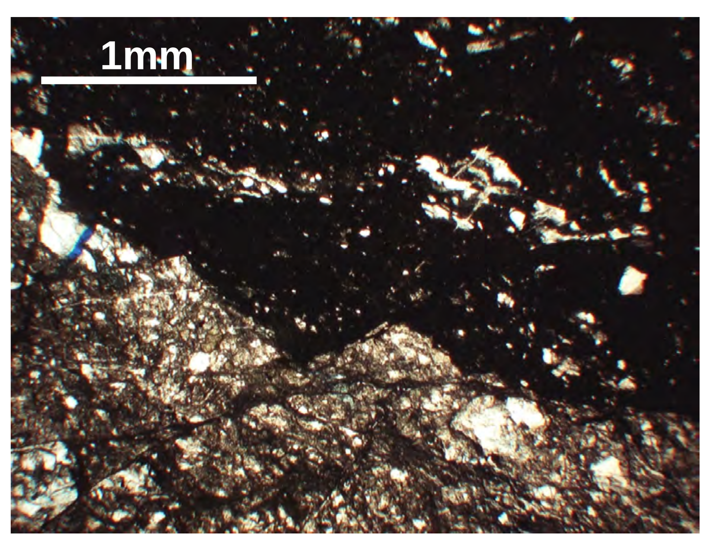
SEM back-scattered electron image showing microcrystallites (≤100 µm long and ~20µm wide). Microcrystallites of different sizes form domains within veins, and aligned long axes define flow fabrics in some cases.

Pseudotachylyte Key Points:
- Observed in 4 out of 7 faults in study area, indicating melting was common.
- Abundance, lengths and thicknesses of continuous pseudotachylytes suggests melt lubrication weakened the faults during seismic slip.
- Chlorite and epidote in the matrix of cataclasites cross-cut by pseudotachylytes shows fluids were present in the faults before, after, and potentially during slip events.
- Fluids did not preclude melting: either no free fluid phase at the onset of slip, or competition between weakening mechanisms is inherent in the frictional response to slip.

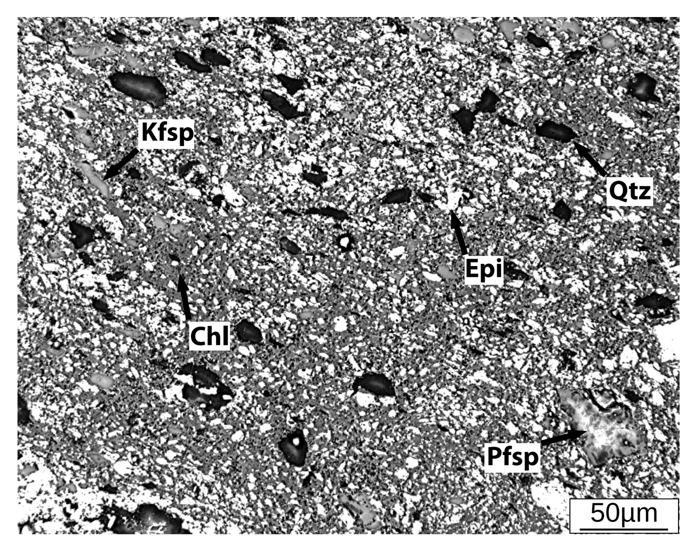
Cataclasites

Cataclasite Key Points:
- Common in all of the Sierra Nevada faults: the majority do not contain obvious evidence for seismic slip.
- Fault breccia filling several injection vein-like structures (right) was mobilized during deformation. Chlorite forms a fine-grained matrix.
- Pseudotachylytes attest to seismic slip rates, the mobilized cataclasite may be the product of a pressurization or granular fluidization process.
- The chlorite matrix in the breccia, suggests hydrothermal fluids were present during coseismic slip: a pressurization mechanism may therefore be the most likely formation process.

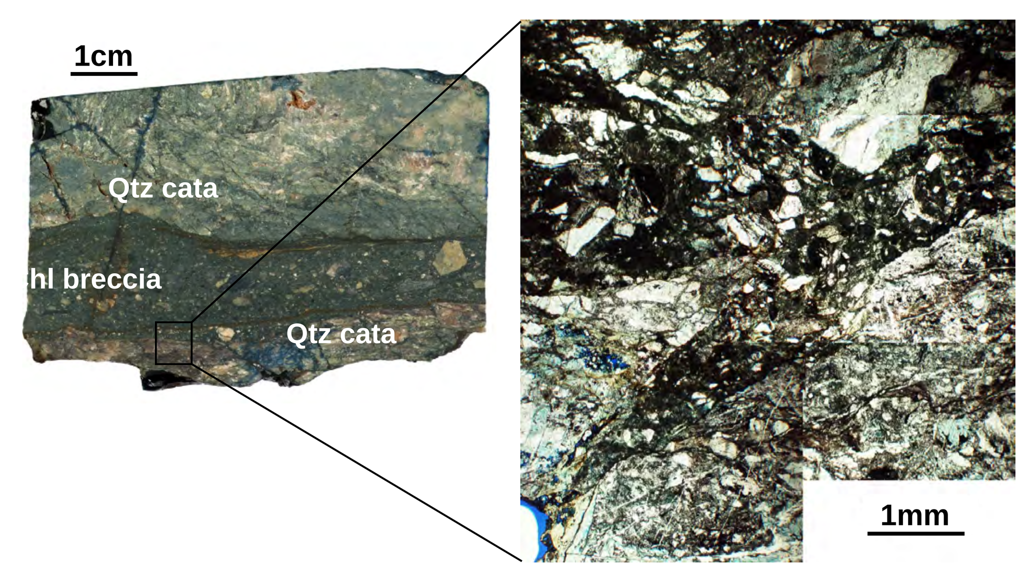
Cataclasites are developed in strands delimiting the most intensely deformed parts of the faults, the fault core. Ultracataclasites are frequently juxtaposed againts cataclasites, with cross-cutting relations consistently showing that the most comminuted unit is the most recent.



Photomicrograph (PPL) of an ultracataclasite (top, dark) juxtaposed against a cataclasite (bottom, pale). The proportion of matrix material in the ultracataclasites is high (typically ≤90%) indicating prolonged bittle comminution of the fault rocks.



SEM-BSE image of ultracataclasite matrix containing rounded and sub-rounded grains (<0.01mm). Fragment compositions (Qtz is quartz, Kfsp alkali feldspar, Epi epidote, Chl chlorite, Pfsp plagioclase) are assessed using energy dispersive X-ray spectroscopy.



Photograph of a polished sample (left) of cataclasite and montage of photomicrographs of the sample (right). Different rock types are identified from microscope observations: quartz-rich cataclasites (Qtz cataclasite) and a chlorite breccia (Chl breccia). An injection vein-like feature containing the Chl breccia intrudes the Qtz cataclasite, extending to the lower left corner of the photomicrographs. Similar structures are present along the boundary between the chlorite breccia and the lower quartz-rich cataclasite (left).

Fault rock distribution

RIGHT: Pseudotachylyte generation surfaces are developed in patches up to 4m long along well-exposed portions of some faults. The thickness of one fault core strand in the Skeeter fault changes from ~35cm to ~2cm within 10m along strike. Pseudotachylyte is present in the narrow part of the strand.

The pseudotachylyte defines a slip zone with a thickness up to 0.25mm, and is not itself deformed so must have been generated in the most recent increment of slip on the strand.

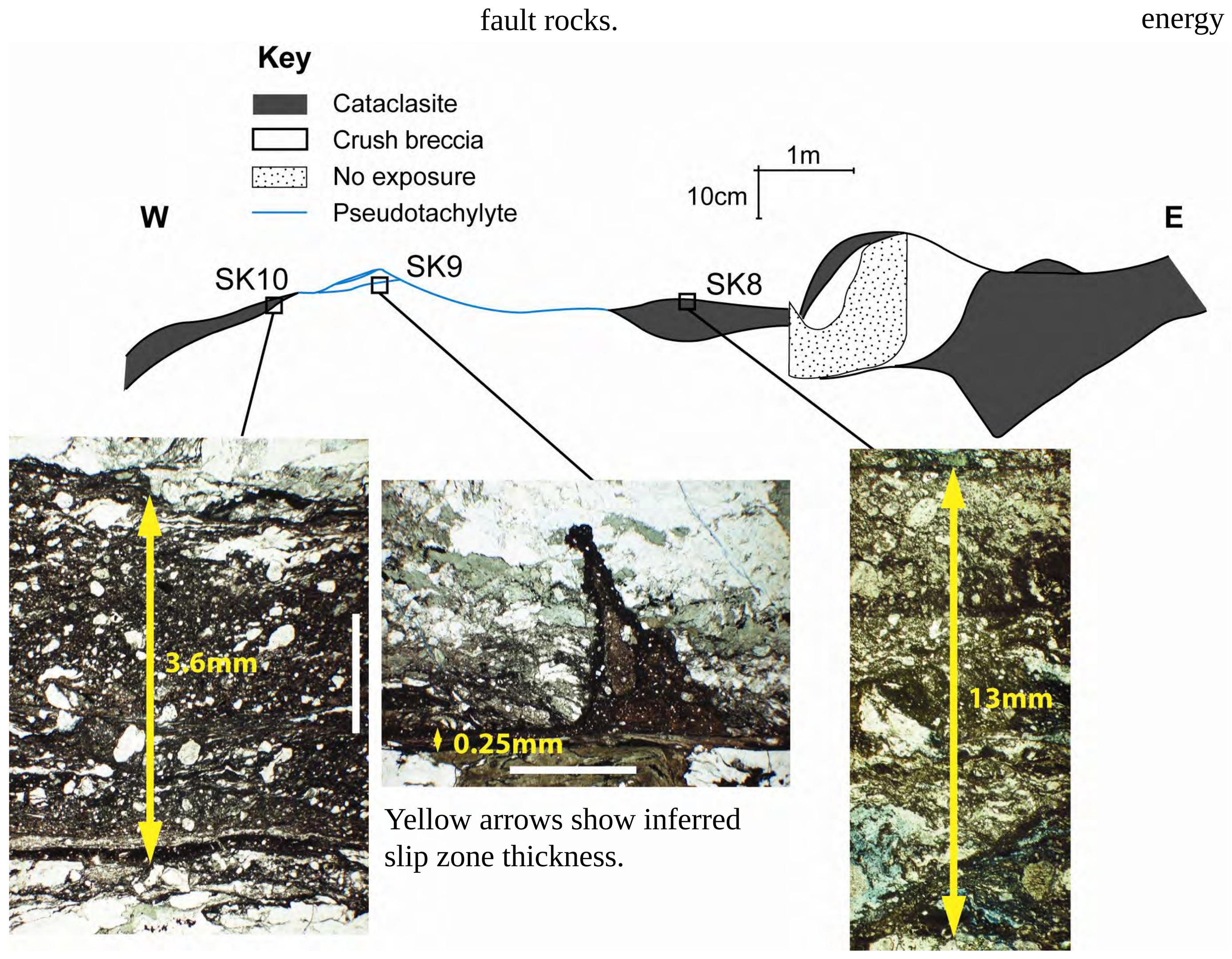
The adjacent, wider parts of the fault core contain foliated and non-foliated cataclasites. Cross-cutting relations suggest the most recent increment of slip in the cataclastic fault cores was localised onto zones 13mm and 4mm thick.

The temperature rise, ΔT, for uniform adiabatic shearing in a slip zone of width ts is given by:

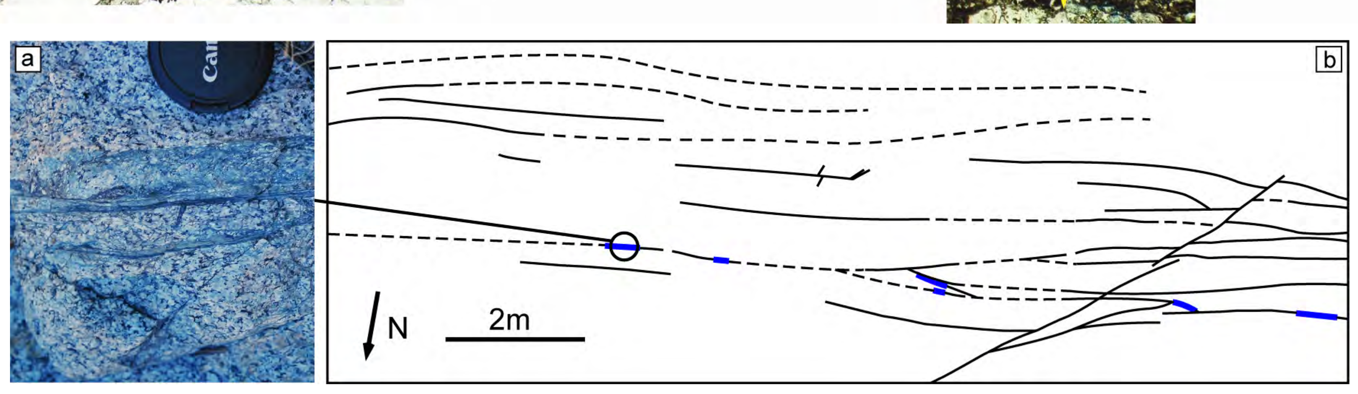
$$\Delta T = \frac{\tau_f . u}{c_p . \rho . t_s}$$

Assuming a coefficient of friction of 0.6 and that the normal stress acting on the fault is lithostatic, then at the maximum likely depth of fault slip, 11km, τf is ~170 MPa. Using cp = 1000 J/kg °C and ρ = 2500 kg/m3, the temperature rise, ΔT is ~109°C for ts = 0.25 mm, which is insufficient to melt any of the minerals in the host rock even at the elevated temperatures likely at the depths these faults were slipping at (~240°C at 8 km for a geothermal gradient of 30°C/km).

This simple analysis shows that pseudotachylytes must have formed during small earthquakes that ruptured areas greater than the length of the pseudotachylytes.



Yellow arrows show inferred slip zone thickness.



a. Photograph of a pseudotachylyte generation surface and injection vein in the Seven Gables Trail fault, camera lens for scale is ~60mm diameter. b. Map of the fault core strands in the fault (dashed where uncertain) and the patches of pseudotachylytes developed in the fault (blue lines).

Conclusions

- Our observations show multiple slip weakening mechanisms must have been active during single slip events.
- Two weakening mechanisms are identified from deformation products: continuous pseudotachylytes represent melt lubrication, a mobilized fault breccia is indicative of pressurized coseismic fluids that could have resulted from thermal pressurization and/or elastohydrodynamic lubrication.
- Pseudotachylytes in some faults are discontinuous at exposure scale, adjacent cataclasites contain no evidence for melting.
- The energy required for melting shows pseudotachylyte patches several metres long must have formed during ruptures larger than the patches, implying the adjacent cataclasites also localized seismic slip.
- The distribution of deformation products shows the coseismic processes during a single rupture event are spatially variable, and also that the active slip weakening mechanism at a point on the fault can change over time.
- Geologic evidence emphasises that macroscopic dynamic weakening is a function of multiple coeval processes at micro- and meso-scales.
- The width of the slip zone controls which processes are activated during slip.
- Along-strike changes in slip zone thickness indicate the frictional response to slip was characterized by spatially variable slip weakening distance, dynamic frictional strength, stress drop and slip magnitude.
- Given the along-strike heterogeneity of most mapped fault zones, the co-existence of multiple slip weakening mechanisms in a single earthquake will be common.