“Friction Melts and Coseismic Faulting”
National Earthquake Hazards Reduction Program (USGS-04HQGR0066)
Final Report
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Summary of results from this research

There is increasing awareness that liquid melt generated by friction in the Earth’s crust plays an important role in influencing the seismic and mechanical behavior of fault planes (e.g., Sibson, 1975, Kanamori, et al. 1998). Geological observations of pseudotachylytes along exhumed faults indicate that fault zones melt and cool relatively rapidly during earthquake faulting. The energy source for heating and melting is the product of fault friction shear stress and co-seismic fault displacement. Our understanding of natural frictional melts that occurs during large earthquake slip events has been hampered by the extremely fine grain-size of frictionally fused rock, and the lack of detailed high-resolution microscopy studies that describe features at the crystal lattice-scale. The focus of this project was characterization and systematic dating of a natural suite of samples from the Alpine Fault (New Zealand; Figure 1) as an exhumed analog of processes in today’s San Andreas Fault at depth.

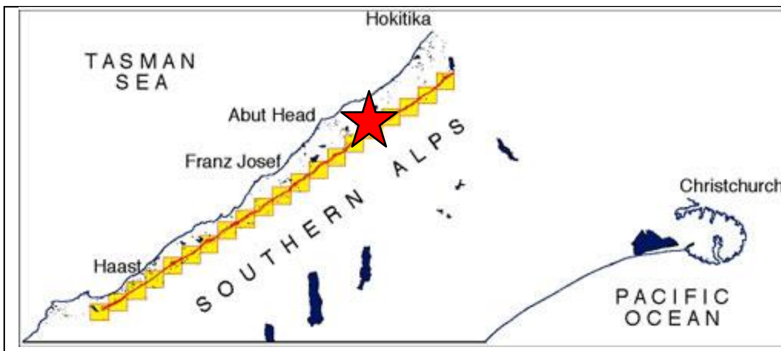

Figure 1. Sampling site along the Alpine Fault, at Harold Creek, near Hari Hari, New Zealand.
From http://www.otago.ac.nz/geology/af/05.html.

Compositional variations were documented in friction melts of the Hari Hari section of the Alpine Fault, New Zealand with multiple stages of melt injection into quartzo-feldspathic schists (Warr and van der Pluijm, 2004). Intermediate to felsic melts were heterogeneous in composition but all fractions show a common trend, with a tendency for the younger melt layers and glasses to be more alkali (Na+K) and Si-enriched, while being depleted in mafic (Fe+Mg+Mn) components. These changes are attributed primarily to crystal fractionation of the melt during transport. Farther traveled molten-layers were on the whole less viscous, mostly due to a higher melt-to-clast ratio, however, compositional change, together with the decrease in volatile content, produced a progressively more viscous liquid melt with time. The glass phase is interpreted as a remnant of this high viscosity felsic residual melt preserved during final quenching. Following initial failure, the formation of largely phyllosilicate-derived, volatile-rich, lower viscosity melt corresponds with the secondary phase of fault weakening. Subsequent rapid crystal fractionation during melt transport, the loss of volatiles and final freezing of residual melt is suggested to be a contributing factor to the strengthening of the displacement surface during seismic slip.

We characterized the complex nature of melting and crystallization in a symmetrically layered, pseudotachylyte vein from the Alpine Fault, New Zealand (Warr et al., 2003). Two melt pulses are recognized, attributed to successive, but rapid injections of frictionally-generated material.

The initial injection, preserved at the vein margins, was proximally derived and contains a high concentration of clasts and a Si-rich glass. This was quickly followed by a second generation of a more distally derived, melt-dominated fraction, which was injected into the weak vein center. Whereas fragments of wall-rock biotite are preserved in the marginal zones, neocrystallized microlitic biotite characterizes both margins and center. The vein biotite is different in composition, microstructure and polytypism from the metamorphic biotite of the wall-rock. In all melt layers, newly formed biotite shows notable signs of syn-flow crystallization, strain features and erosion at crystal-glass contacts, with breakdown of neocrystallized microlites along both crystal edges and faces. These characteristics imply cyclic pulses of heating, melting and crystallization occurred during a single, large earthquake episode, and probably reflects the stick-slip propagation properties of coseismic faulting.

Our modeling of friction melting (Ruff et al., in prep; http://aamc.geo.lsa.umich.edu/Hot_Fault/) constrains the range of friction stress and earthquake displacement combinations that produce sufficient energy to melt a fault zone a few millimeters in width. However, there are additional physical constraints on fault friction stresses and earthquake displacements that help restrict the number of acceptable parameter combinations. In particular, we can use earthquake scaling laws to connect the co-seismic displacement to earthquake size and to earthquake "rise time"; the latter parameter interacts with the fault heating calculations. Earthquake size is the most useful characterization of the co-seismic displacement, and we find from our calculations that there is a minimum size earthquake that will produce observable fault melts. As for fault friction stress, we can use models for the steady-state thermal regime in the crust around a major plate-boundary strike-slip fault, such as the Alpine Fault of New Zealand or the San Andreas Fault in California. The strong upper limit on shear stress is that we cannot allow whole-scale melting at a depth of 15 km (the lower edge of the seismogenic zone and the presumed depth of highest shear stress levels). While there is uncertainty introduced by the choice of the melting solidus, the wet solidus for "granitic" rocks constrains friction stress levels to be less than 140 MPa. However, this highest allowed stress level results in a high surface heat flow anomaly of about 140 mW/m^2. If we adopt the constraint (mostly based on observations from the San Andreas Fault) that the peak surface heat flow anomaly is no greater than 30 mW/m^2, then the maximum allowed shear stress is 30 MPa, and the associated minimum earthquake size that can produce a 1 mm thick fault melt is Mw=5. A weak constraint on the minimum friction stress is approximately 2 MPa. If the stress is smaller than this value, then fault melts can only be produced by unusual "giant" strike-slip earthquakes, such as the late 2004 Sumatra earthquake. We show these modeling results in Figure 2. This analysis shows that melt is readily generated during fault slip, which would explain the growing identification of pseudotachylyte in the field.

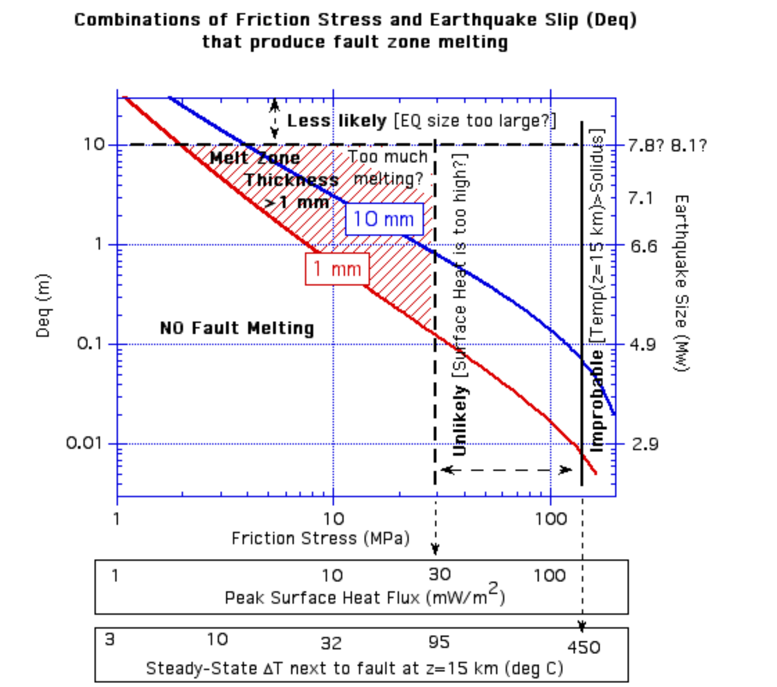

Figure 2. There is minimum value of the product of earthquake co-seismic slip (Deq) and fault friction stress required to produce a melt zone thickness of 1 mm, shown by the bold line labeled "1 mm". The line for "10 mm" thick melt zone is also shown. The Deq axis can be translated into earthquake size (axis at right). The friction stress can be translated into peak surface heat flux, and the associated steady-state maximum temperature rise (these two axes are shown below the friction stress axis). The hatched region shows the most likely combinations of friction stress and earthquake size that produce the observed exhumed pseudotachylytes.

The age and depth of exhumed friction melts along the Alpine Fault were studied using Ar dating (Warr et al. 2007). Laser ablation $^{40}Ar/^{39}Ar$ step heating analysis of 20 pseudotachylyte veins from a single location along the exhumed central portion of the active Alpine Fault of New Zealand yield total gas age values between 1 and 19 Ma. Evidence is presented that these veins are genetically related and formed during coeval episodes of seismogenic melting at shallow crustal depth, contrasting with a spread in formation ages. The total gas ages show an exponential decrease with increasing proportion of melt matrix and K content, indicating that incomplete degassing and mixtures of radiogenic Ar sources characterize these samples. Calculation of intercepts for all-clast and all-melted matrix end-member components show apparent age variations of ~570 000 year (Quaternary) for friction melting of ~332 Ma (Lower Carboniferous) source rock. Assuming an average exhumation rate of 6–9 mm/year for this period of uplift and erosion, these results imply that friction melts were generated during major slip episodes at ~3.5–5 km crustal depth. These relatively shallow depths were recently drilled and sampled in the SAFOD project, offering the distinct possibility that friction melts may be recognized in seismogenic strands of the San Andreas Fault (van der Pluijm et al., 2007). We also conclude that reliable dating of young pseudotachylyte can be made by combining chronologic study with clast-matrix quantification of genetically related vein assemblages.

In summary, our work showed the intricacies of friction melt formation in natural fault rocks. Pulses of friction melt generation may occur during a single seismic cycle, with evolving chemistry and melt properties. We were also able to show a relatively shallow formation depth for friction melts, which suggests that they may be quite common in natural fault zones. Their role in the mechanical properties of seismogenic faults may, therefore, also be more significant than previously recognized.

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Sibson, R.H., 1975. Generation of pseudotachylyte by ancient seismic faulting. *Geophys. J. Roy. Astrono. Soc*. 43, 775-794.

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Publications resulting from this research

Journal Publications:

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