2015 SCEC Final Report

A New Creep Instability at Intermediate Homologous Temperatures with Application to Slow Earthquakes and Non-Volcanic Tremor

Principal Investigator:

Charles G. Sammis

University of Southern California

Co-investigator

Terence Langdon

University of Southern California

Proposal Category: Integration and Theory

Project Summary

A ductile instability that has the potential to produce slow earthquakes and associated tremor has recently been observed during the High-Pressure Torsion (HPT) processing of metals. In these experiments a thin disc or ring is first subjected to a normal stress in the range of 2 to 6 GPa, and then to a simple shear deformation by the rotation of one of the loading pistons. This instability is especially promising as a mechanism for slow earthquakes because 1) it occurs at intermediate homologous temperatures (i.e. at the brittle-ductile transition), and 2) the strain weakening is not catastrophic but extends over a large strain. TEM micrographs of the deformed specimens indicate that the weakening instability is associated with dynamic recrystallization and the growth of crystals with a relatively low dislocation density. Unlike thermal weakening, grain growth is not a run-away process.

To date, this instability has only been observed in metals having high stacking fault energies and only over a narrow range of homologous temperatures. We have begun a series of HPT tests on metals and alkali halides designed to test our hypothesis that this mechanism is controlled by homologous temperature and stacking fault energy, thus providing a physical basis for the extrapolation from metals and alkali halides to silicates.

Our most significant result to date is the observation of strain weakening in the aluminum alloy (Al 6061) that we were using to test the apparatus. Previous observations of strain weakening in HPT testing have been limited to pure metals and hydrated NaCl. Our observation in an alloy with a significant (>5%) fraction of alloying elements, shows that the weakening is not limited to pure materials, and thus may also occur in rock.

Technical Report

Non-volcanic tremor (NVT) is a recently recognized low-amplitude seismic signal that has been observed in subduction zones [Obara, 2002, Rogers and Dragert, 2003; Schwartz and Rokosky, 2007] and on the deep extension of large strike slip faults [Nadeau and Dolenc, 2005]. The current consensus is that both NVT and low-frequency earthquakes (LFE) are generated by shear slip on the deep extension of major faults [Shelly and Hardebeck, 2010], and may therefore have an influence on the timing of earthquakes in the overlying seismogenic layer.

While there is general agreement that NVT and related phenomena provide a window into the deep roots of subduction zones and strike-slip faults and may play an important role in earthquake mechanics, there is no consensus as to exactly what process generates slow-slip and tremor. Proposed mechanisms generally fall into one of two categories: those that involve a cascade of small earthquakes [Ben-Zion, 2012] and those that are based on a material instability such as creep or rate-state friction in combination with fluid effects. (see summaries in Rubinstein et al. [2010] and Peng and Gomberg [2010]).

The challenge in modeling slow slip events (and associated tremor) as slip instabilities is to find a way to extend the characteristic breakdown distance that characterizes the velocity- or strain-weakening. Segall and Rubin [2007] accomplish this by adding fluid effects to the rate and state models. However, as Ben-Zion [2012] points out, "… existing models typically have many sensitive parameters (e.g. 5 or more) that require careful tuning to explain a few selective observations". Kaproth-Gerecht and Marone [2013] have produced slow slip events in a layer of powdered serpentinite using a double-shear friction apparatus. Their hypothesis is that the material continually switches between velocity weakening at low slip rates and velocity strengthening at high slip rates thus quelling catastrophic slip to produce a large effective characteristic weakening displacement.

A creep instability that has been explored in the context of earthquake mechanics is the adiabatic plastic shear instability [Hobbs and Ord, 1988]. As they point out, structural studies of mylonites and pseudotachylites at the base of the seismogenic zone in exhumed fault zones are consistent with plastic shear during large earthquakes [Hobbs et al., 1986; White, 1996]. However, adiabatic shear instability typically produces a localized catastrophic slip event that is more like a normal earthquake than an LFE [Roberts and Turcotte, 2000].

A plastic slip instability that may be capable of producing slow-slip events was recently discovered during High-Pressure Torsion (HPT) metal processing. In HPT processing, discs or rings of metal are first loaded axially and then sheared by rotation of one of the anvils. The objective is to increase the yield strength by introducing a high dislocation density. The large axial stress is required to suppress fracture since most processing is done at room temperature, which for metals is at or below the brittle-ductile transition (see Zhilyaev and Langdon, 2008 for a review of HPT processing).

Figure 1 shows experimental results for pure aluminum and copper [Edalati et al.; 2013]. In these experiments, the lower piston is rotated at a fixed rate (0.1 rpm) while the applied torque is monitored. Note that the aluminum rings show an initial increase in applied torque associated with dislocation hardening followed by a decrease in torque indicating strain weakening. The aluminum disc does not show a similar strain weakening. This is because strain varies with radius across the disc. Indeed, micro-hardness measurements across the disc reveal a range of radii at which the material has weakened corresponding to the weakening strains observed using the ring sample. TEM micrographs of the deformed discs indicate that the weakening is associated with dynamic recrystallization and the growth of crystals with a relatively low dislocation density.

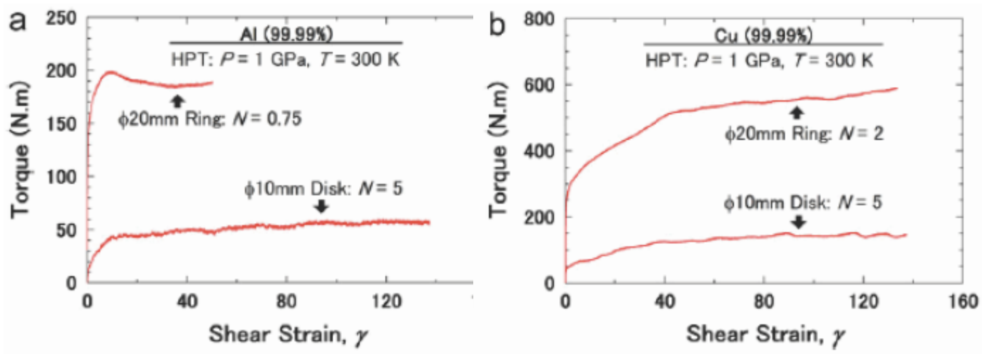

Figure 1. HPT experiemts on a) aluminum and b) copper from Edalati et al.[2013].

Note that while the Al rings show strain weakening beginning at a strain near 10, the corresponding Cu rings do not. Why does Al strain weaken while Cu does not? Two obvious possibilities are: 1) Al is being deformed at a significantly higher homologous temperature and 2) the stacking fault energy in Al is significantly higher than that in Cu (see Table 1).

Table 1. Comparison of Homologous Temperatures and Intrinsic Stacking Fault Energies

	T_m (K)	T/T_m	γ (mJ/m^2)
Cu (at 300K)	1357	0.22	78
Al (at 300K)	933	0.32	166
Mg (at 300K)	923	0.33	120*
Olivine (at 873K)	1423	0.61	164

* The value of γ for Mg was generated by a theoretical model [Muzyk et al., 2012]. The values of g for all other metals were measured.

The high stacking fault energy in Al means that the separation between partial dislocations is very small (on the order of the atomic spacing). A small separation promotes easy cross-slip of the dislocations to other slip planes, which promotes the observed recrystallization. In copper, the separation between partial dislocations is on the order of 12 times the atomic spacing. Edalati et al. [2011] observed similar strain weakening in Mg, which has a melting temperature and stacking fault energy similar to Al (see Table 1). They did not measure torque in this material.

Also included in Table 1 are estimates of T/Tm (at the base of the seismogenic zone) and γ for olivine. There are no robust observations of stacking faults in olivine, because the separation between the partial dislocations is very small (David Kohlstedt, private communication). However, vander Sande and Kohlstedt [1976] measured the separation between the partial dislocations using high resolution TEM. They found d = 40 Å, which is a maximum value. It could be smaller, making the stacking fault energy even higher (Kohlstedt, private communication). Using this value of d, a crude estimate the stacking fault energy is given by

$$\gamma = \frac{\mu a^2}{32\pi d} = 164 \text{ mJ/m}^2 \qquad (1)$$

The key question to be addressed in this proposal is whether the strain weakening mechanism observed in aluminum is expected to operate in olivine (or other relevant minerals) at the base of the seismogenic zone in the crust. Our approach will be to use our high-pressure torsion apparatus to look for strain weakening in a range of metals and alkali halides that bracket the *T/Tm* and γ values estimated for olivine at the base of the seismogenic zone. As described in the next section, the apparatus here at USC is unique in that it also has temperature capabilities up to 200C, thus expanding the range of *T/Tm* values that we can explore. The effects of temperature and strain-rate on this strain weakening mechanism are unknown and form one of the objectives of the proposed research.

Why not work directly with olivine at *T* and *P* conditions found at the brittle-ductile transition in the Earth? At 20 km depth, these are T = 600C and P = 600 MPa, which are difficult experimental conditions for rotary shear experiments, which have mainly been used to study rock and mineral friction. Our approach of scaling deformation mechanisms originally identified in metals to silicates has a long and fruitful history (see, e.g., Stocker and Ashby [1973], and Ashby and Verrall [1978]). Virtually all dislocation mechanisms identified in metals are also seen in oxides and silicates and the rates can be scaled once the controlling variables are identified. The proposed experimental program is designed to test our hypothesis that the stacking fault energy is a controlling parameter in the shear instability by seeing if metals having γ larger then Al also exhibit strain weakening while those having γ less than Cu do not. The implication for olivine and other minerals should then be clear.

One of the P.I.s (Langdon) has a high-pressure torsion apparatus that is capable of normal loads up to a maximum of 8.5 GPa and rotation rates from 0.1 to 3.0 rpm. For our sample dimensions the corresponding strain rates lie between 0.45 and 13.7 s^{-1}. It is equipped with a small furnace that provides a capability of testing from room temperature to 200C. This apparatus is unique in the United States. As detailed below we have fabricated new pistons, calibrate strain gauges, and attached them to the upper piston to monitor torque and produce curves like those in Fig. 1. We have tested the procedure on rings of Al 6061 alloy.

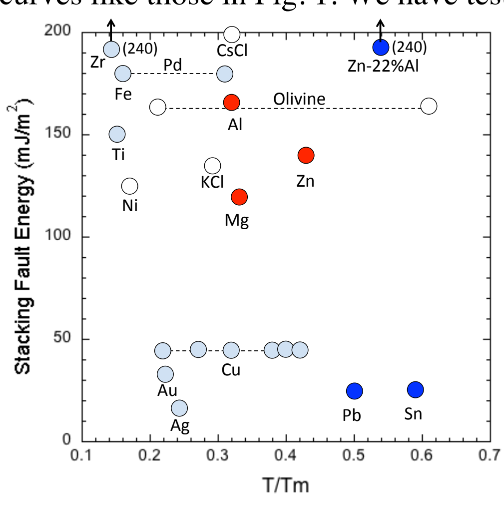

Figure 2. Planned exploration of γ vs T/T_m space to search for ductile instabilities.. The solid red circles indicate the observation of strain weakening. The light blue circles indicate strain hardening with no strain weakening. The dark blue symbols indicate strain weakening with no hardening. The two alkali halides KCl and CsCl have not been measured. The stacking fault energy for Olivine is a lower estimate.

Once we have estimated the strength drop and critical strain that characterize strain weakening associated with dynamic recrystallization in olivine at *T* and *P* appropriate to the brittle-ductile transition, we propose to explore its implications for the mechanics of slow earthquakes. Note that the strain-weakening evident in Al (Fig. 1) can be represented by a slip-weakening friction model where the slip weakening displacement on the fault *d* depends on the strain *e* in the slipping layer of thickness *w* as $d=we$. There are many numerical slip-weakening earthquake models available in the community and we will collaborate with one of our colleagues to introduce our rheology into their model.

We first designed and procured a new set of anvils for the HPT facility, which can accommodate either rings or discs. We next calibrated the strain gauges and data-logger by loading a cylindrical tube with a known applied torque. We then applied strain gauges to the new anvils in order to measure the applied torque during HPT processing, and thus the shear stress applied to the rings or discs being tested.

Our most significant result to date is the observation of strain weakening in the aluminum alloy (Al 6061) that we were using to test the apparatus (Fig 3a). Previous observations of strain weakening in HPT testing have been limited to pure metals and hydrated NaCl. Our observation in an alloy with a significant (>5%) fraction of alloying elements, shows that the weakening is not limited to pure materials, and thus may also occur in rock.

Since the anvils became warm after several rotations, we were concerned that the strain weakening might be due to shear heating. As a first order test, we lowered the strain/rotation rate by an order of magnitude to allow more heat to flow away from the ring. The strain weakening was still observed. As a further precaution, we used a set of thermocouples to monitor temperature in the middle of the anvil (via a hole at the top) near the sample, along the outside edges (<2 mm away from sample) and near the strain gauges. The largest temperature increase we observed was ~80 C at a strain of ~1700. Additionally, a controlled heating test (no applied torque) using a hot plate was conducted to ensure that the observation was not a temperature effect on the strain gauges. The results from that test showed negligible coupling between temperature and strain to temperatures approaching 150 C.

To further corroborate our in-situ experimental results, we conducted Vickers microhardness testing on the Al 6061 discs processed via HPT (Fig 3b). A peak was observed in the microhardness at the same strain as the peak in the flow stress measurements, indicating that the effect was not due to transient thermal weakening but a microstructural change in the fabric of Al 6061.

We are now testing pure Al rings in order to reproduce Edalati's results and have also designed and fabricated a die to press CsCl rings.

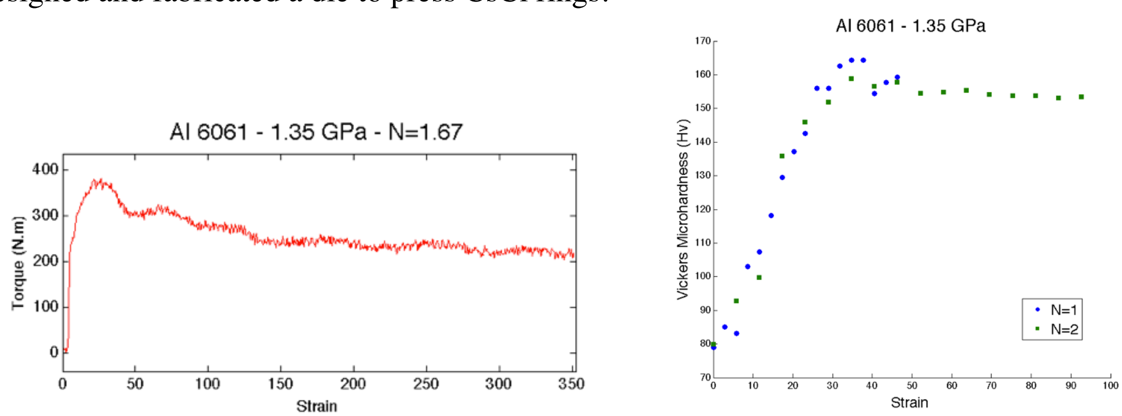

Figure 3. Strain weakening in Al 6061. Panel (a) on the left shows shear stress. Panel (b) on the right shows microhardness. Note that a peak occurs in both at about the same strain.

Intellectual Merit

This proposal thus directly addresses the SCEC4 research priority 5: "Causes and effects of transient deformations: slow slip events and tectonic tremor" and specifically (5c) "Collaboration with rock mechanics laboratories on laboratory experiments to understand the mechanisms of slow slip and tremor" and (5d) "Development of physics-based models of slow

slip and tectonic tremor …". Our work may also be relevant to research priority 3: "Formulation of theoretical and numerical models of specific fault resistance mechanisms for seismic radiation and rupture propagation, including interaction with fault roughness and damage-zone properties". From a disciplinary perspective, we are addressing the seismology group's focus on Tremor: "Tremor has been observed on several faults in California, yet it does not appear to be ubiquitous. We seek proposals that explore the distribution and source characteristics of tremor in California and *those that explore the conditions necessary for the generation of seismically observable tremor*. Our proposed work also addresses the FARM group priority for 2014: "Investigate the relative importance of different dynamic weakening and fault healing mechanisms, and the slip and time scales over which these mechanisms operate."
This work has supported USC graduate student Marshall Rogers-Martines and has fostered collaboration between the Earth Sciences and Materials Sciences departments at USC.

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SCEC Budget: February 1, 2014 to January 31, 2015

I. SALARIES AND WAGES	
Principal Investigators	
Charles G. Sammis, 0.25 mo	3,975
Terence Langdon	0
Graduate Student Research Assistant, 6 mos	14,250
TOTAL SALARIES AND WAGES	18,225
II. FRINGE BENEFITS	
31.1% of I (not charged to student salary)	1,236
TOTAL FRINGE BENEFITS	1,236
III. MATERIALS AND SUPPLIES	
Strain gauges and associated electronics	1,000
Publication Charges	1,500
Computer Usage	500
TOTAL MATERIALS AND SUPPLIES	3,000
IV. TRAVEL	
Two Trips to SCEC Meeting	800
TOTAL TRAVEL	800
TOTAL DIRECT COSTS	23,261
MODIFIED TOTAL DIRECT COSTS	23,261
V. OVERHEAD	
62% of MTDC	14,422
TOTAL OVERHEAD	14,422
TOTAL SCEC REQUEST	37,683

Current Support for Charles Sammis

Title: FA9453-12-C-0210   Generation of High-Frequency P and S Wave Energy by Rock Fracture During a Buried Explosion
Agency: AFRL/NNSA
Amount: $589,562
Period: 5/25/12 - 5/25/15
2.0 summer mos/yr

Title: A New Creep Instability at Intermediate Homologous Temperatures with Application to Slow Earthquakes and Non-Volcanic Tremor
Agency: SCEC
Amount: $25,000
Period: 02/01/2014 – 01/31/15
0.25 AY

Title: A High-Resolution Study of Microearthquakes on the San Andreas Fault at SAFOD
Agency: SCEC
Amount: $25,000
Period: 02/01/2014 – 01/31/15
0.25 AY

Title: The Potential for Decoupling Explosions in Fractured Hard Rock: Examples from Kazakhstan Historical Data and a New Field Study
Agency: Weston Geophysical Corporation
Amount: $180,000
Period: 08/01/14 – 07/31/16
1.0 summer mo/yr

Pending Support for Charles Sammis

Title: A New Creep Instability at Intermediate Homologous Temperatures with Application to Slow Earthquakes and Non-Volcanic Tremor
Agency: SCEC
Amount: $37,683
Period: 02/01/2015 – 01/31/16
0.25 AY

Title: Linking off-fault seismicity to transient creep on the deep extension of fault planes.
Agency: SCEC
Amount: $35,415
Period: 02/01/2015 – 01/31/16
0.25 AY