TECHNICAL REPORT – SCEC AWARD 17164

Detecting asperity flash heating on hematite faults with laboratory experiments and hematite (U-Th)/He thermochronometry

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Proposal Category: Data Gathering and Products

Research priorities addressed:
P2d. Understand how inelastic strain associated with fault roughness and discontinuities influences rupture propagation, seismic radiation, and scaling of earthquake source parameters. (*CS, FARM, Seismology*)

P3d. Determine how damage zones, crack healing and cementation, fault zone mineralogy, and off-fault plasticity govern strain localization, the stability of slip (creeping vs. locked), interseismic strength recovery, and rupture propagation. (*FARM, Geology, CS*)

P1d. Quantify stress heterogeneity on faults at different spatial scales, correlate the stress concentrations with asperities and geometric complexities, and model their influence on rupture initiation, propagation, and arrest. (*Seismology, SDOT, FARM, Geology*)

SUMMARY Friction-generated heat is a primary by-product of seismic slip on faults. Heat can activate various mechanisms that lead to low coseismic strength, with important implications for the earthquake energy budgets, the magnitude of strong ground motions, and earthquake self-similarity. Hematite is a common mineral found on small fault surfaces in damage zones and may record the thermomechanical history of fault slip. This project quantifies the temperature, friction, and textural properties of hematite-coated fault surfaces through carefully controlled laboratory hematite deformation experiments coupled with fault rock thermochronometry to (1) compare and thus link experimental and natural hematite slip surface observables and (2) identify potential thermally-activated dynamic weakening mechanisms in hematite.

PROJECT OBJECTIVES & SIGNIFICANCE The **objective** of SCEC-supported foundational hematite low-to-high velocity, rotary-shear experiments is to identify the evolution of friction, temperature, microstructure, and He loss (a proxy for temperature) over a variety of slip displacements and rates. We aim to generate hematite textures that may be diagnostic of frictional heating at sub-seismic and seismic slip rates. Hematite (U-Th)/He thermochronometry can resolve the thermal imprint of friction-generated heat on slip surfaces (Ault et al., 2015). The kinetics of this system respond to short-duration, high-temperature (T > 1000 °C) thermal pulses due to, for example, flash heating of asperities (Ault et al., 2015; McDermott et al., 2017). If dynamic weakening due to flashing heating of a network of asperity contacts (Rice, 2006) occurs in our experiments, then we expect (1) a decrease friction with increasing velocity predicted by Rice (2006) theory and (2) textural and He loss evidence for high, transient temperatures at asperity contacts from the near-seismic slip rates of our experiments. Based on observations from natural hematite fault "mirrors" (e.g., Ault et al., 2015; McDermott et al., 2017), dynamic weakening from flash heating is anticipated on experimental surfaces during fast slip. This project represents the first application of an emerging, novel low-temperature thermochronometry technique – hematite (U-Th)/He dating – to document elevated temperatures in laboratory-generated earthquake rocks.

Our research directly addresses the SCEC5 Science Plan's (2016) research objectives including:

- (Q2) *Off-fault inelastic deformation impact on dynamic rupture and radiated seismic energy:* high-gloss, light reflective or "mirrored" hematite-coated fault surfaces are common in fault damage zones.

Experiments and detailed microscopic and thermochronometric characterization of experimental fault products inform how inelastic strain associated with evolving fault roughness and discontinuities influences earthquake physics (**P2d**).

- (Q3) *Structure, composition, and physical fault zone properties impact on resistance to seismic slip:* experiments and fault rock thermochronometry of experiment run products document whether co-seismic weakening mechanisms – such as flash heating – occur on hematite-coated fault surfaces to evaluate how damage zones and fault zone mineralogy govern strain localization and rupture propagation (**P3d**).
- (Q1) *Fault loading across temporal and spatial scales:* experiments quantify friction evolution over different slip rates. Nano-to-micro-scale experimental fault surface characterization correlate stress concentrations with geometric asperities (**P1d**).

METHODOLOGY

The research team consists of PI Ault (USU), an expert in fault rock thermochronometry and hematite (U-Th)/He systematics, Calzolari (Postdoctoral Fellow (PF), USU) and collaborator Hirth (Brown University), an expert in high-velocity friction experiments, fault mechanics, and earthquake tribology. We hypothesize that dynamic weakening via flash heating occurs on hematite fault surfaces at seismic slip rates. We are testing this hypothesis with a suite of hematite deformation experiments, microscopy, and hematite (U-Th)/He dating of experimental fault material. The experimental workflow is carried out by PF Calzolari and supervised by PI Ault in consultation with collaborator Hirth and includes:

1. Starting material selection and characterization

A well-characterized starting material is key for evaluating textural changes and He loss due to deformation and frictional heating during experiments. Suitable hematite starting material for deformation experiments (1) comprises pure hematite, (2) shows no evidence for grain size reduction by brittle faulting, and (3) contains a sufficient He budget (i.e., old (U-Th)/He dates) to distinguish He loss during experimental fault slip. Undeformed specularite He concentrations and (U-Th)/He dates serve as a baseline to compare results from experimentally deformed aliquots. This comparison will allow us to quantify fractional He loss associated with monitored grain size reduction and recorded surface temperatures over the range of slip velocities.

We acquired a boulder (~30 cm-diameter) of specular hematite from talus in the Wasatch (Wellsville) Mountains between Mantua and Wellsville, UT. We examined this specular hematite/Fe ore petrographically in PI Ault's Mineral Microscopy and Separation Lab at USU and via scanning electron microscopy (SEM) image analysis and electron dispersive X-ray spectroscopy (EDS) with the FEI Quanta 650 Field Emission SEM at USU's Microscopy Core Facility. In particular, we evaluated potential interstitial phases and characterize the plate thickness (grain size) of individual crystallites making up the polycrystalline aggregate.

We extracted individual crystallites from the polycrystalline mass using fine-point tweezers for hematite (U-Th)/He dating to establish a benchmark (U-Th)/He dataset for the undeformed specularite. He is a noble gas and diffuses from individual crystallites by thermally-activated volume diffusion. Individual crystallites are the He diffusion domains and closure temperature increases with domain (grain) size (Farley and Flowers, 2012; Evenson et al., 2014; Farley, 2018). Polycrystalline hematite exhibits poly-domain He diffusion behavior yielding a potential closure temperature range of ~50-250 °C, at a 10 °C/Myr cooling rate within a single aliquot (Bahr et al., 1994; Farley and Flowers, 2012; Evenson et al., 2014; Farley, 2018). Flash heating to >1000 °C during fault slip can induce partial to complete He loss from these hematite crystallites from volume diffusion and recrystallization (McDermott et al., 2017). Hematite (U-Th)/He analysis are conducted at Dr. Peter Reiners' Arizona Radiogenic Helium Dating Laboratory at University of Arizona (UA).

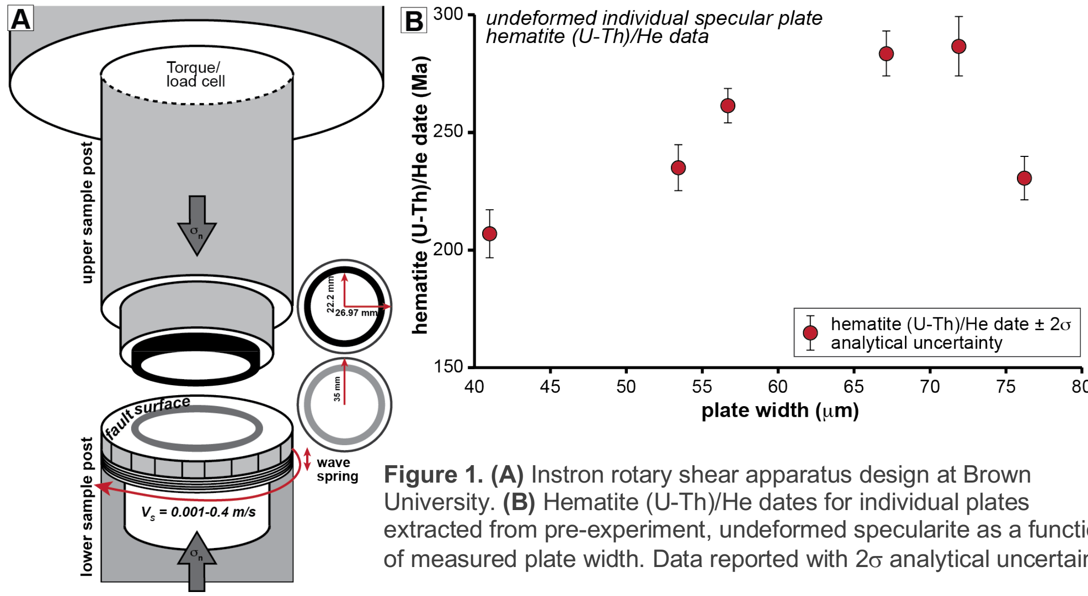

Figure 1. (A) Instron rotary shear apparatus design at Brown University. **(B)** Hematite (U-Th)/He dates for individual plates extracted from pre-experiment, undeformed specularite as a function of measured plate width. Data reported with 2σ analytical uncertainty.

II. Hematite deformation experiments Hematite deformation experiments evaluate (1) material suitability for deformation in a rotary shear apparatus, (2) mechanical properties of hematite (friction, velocity-strengthening, velocity-weakening, healing effects), (3) length scales of grain size reduction during cataclasis, and (4) thermal activation of dynamic weakening mechanism during fast slip. Ongoing experiments use the *Instron* rotary shear apparatus at Brown University (Fig. 1A). Our approach of conducting experiments to progressively larger displacements allows us to explore the evolution of friction, temperature, and hematite He loss with increasing slip. Experimental measurements include displacement, slip velocity, normal stress, and friction coefficient. An initial set of experiments determined the appropriate experiential set up, boundary conditions, and workflow for using the Instron apparatus.

III. Experiment product microscopy and He characterization In our preliminary experiments and on-going work, we recover fault surface material from key locations to document the range of nano- to micro-textures and progressive wear of surface asperities over a range of slip displacements and velocities. We target sample material containing potential evidence for high temperatures after small displacements but fast slip rates, even at relatively low nominal normal stress. We document hematite crystal morphology, grain size, and texture generated with SEM, electron backscatter diffraction (EBSD), and transmission electron microscopy (TEM). USU's SEM is equipped with EBSD to analyze hematite crystallographic preferred orientation. Focused ion beam (FIB)-generated TEM wafers of experimental samples will be analyzed at the Nanofab lab at University of Utah with a FEI Helios Nanolab 650i FIB interfaced with a FEI Quanta 600 FE-SEM and JOEL JEM-2800 S/TEM. Fault surfaces are dissected to analyze crystal morphology and texture at and immediately below the slip surface, document lattice defects and density, and composition of potential polygonal and lobate crystals that are the imprint of paleoasperities (McDermott et al., 2017).

We analyze experimental hematite fault surfaces, created over a variety of displacements/velocities, with the hematite (U-Th)/He method. In particular, regions of the fault surface exhibiting textural evidence for friction-generated heat are targeted for (U-Th)/He analysis and compared with samples lacking such textures and to the undeformed starting material data. If frictional heating at asperity contacts occurs during fault slip, then we expect that hematite He dates from hematite slip surfaces will be younger than the starting material reflecting He loss by thermally-activated volume diffusion and/or recrystallization. With increasing displacement in experimental samples, hematite He dates should decrease, due to grain size reduction, increased fault surface temperature, and resulting He loss.

PRELIMINARY RESULTS SEM back-scattered electron and secondary electron imaging and EDS mapping show the target undeformed hematite is a polycrystalline aggregate – similar to undeformed specularite veins observed in some fault damage zones – of densely-packed specularite plates (~2-80 μm-thick) with trace interstitial calcite. Hematite (U-Th)/He dates from individual crystals (41-77 μm-thick, n = 6) extracted from the polycrystalline aggregate range from 207 ± 10 Ma to 287 ± 12 Ma (2σ analytical uncertainty; Fig. 1B). Although not all dates overlap with in 2σ, it is not a problem because they are positively correlated with plate thickness (Fig. 1B), reflective of the grain size control on post-formation He loss over the specimen's pre-experiment thermal history. More importantly, (U-Th)/He results confirm this material has an appreciable pre-experiment He budget to document He loss during deformation experiments.

Preliminary experiments led by PF Calzolari evaluated the Instron functionality and suitability of our specular hematite to withstand rotary shear. The specularite boulder was slabbed using a water-cooled tile saw at Brown University. These experiments were conducted on a 1-cm-thick slabs of specularite mounted as the lower plate and a quartzite upper plate. Experimental conditions include 2-5 MPa normal pressure, sliding velocities of 0.085-340 mm/s, slip distances of 50-600 mm, and ambient temperature and humidity. Figure 2 summarizes experiment textural observables from pilot experiments. These include a 20-100 μm-

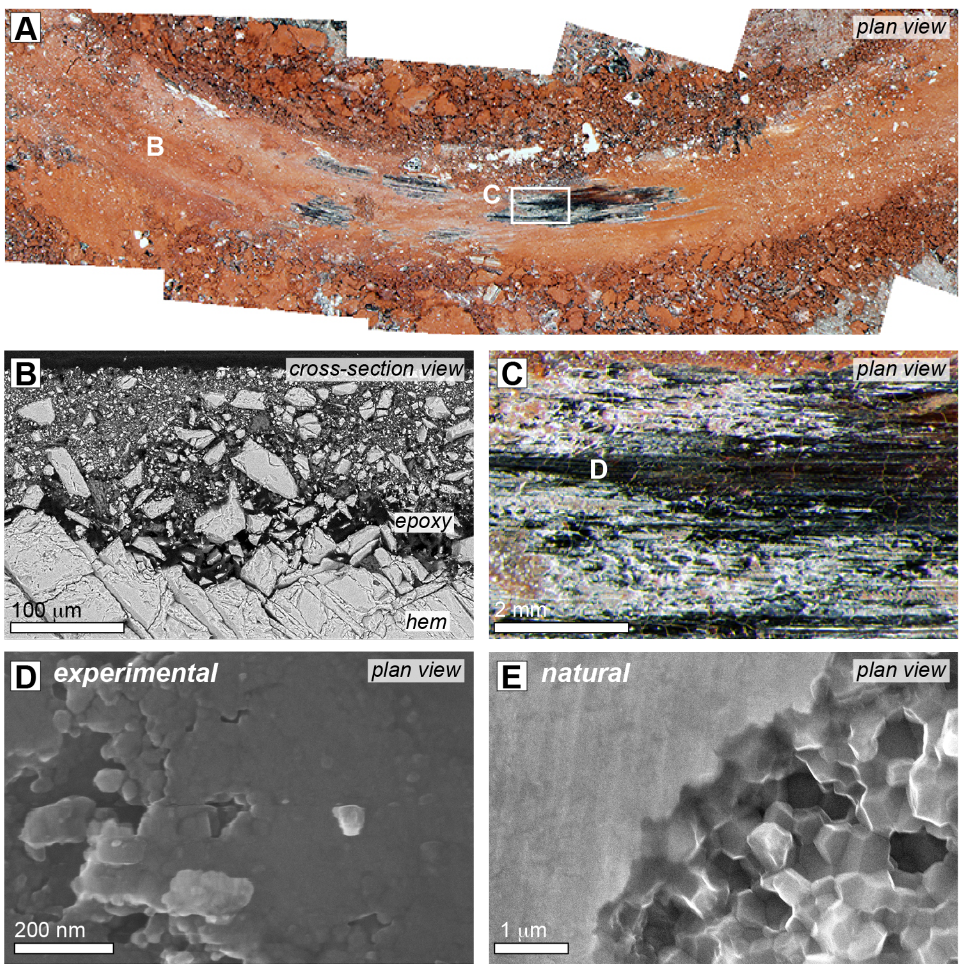

Figure 2. (A) Merged photo montage showing hematite run product from Run 11 (5 MPa, slip velocity 340 mm/s, displacement 4 cm) denoting the location of **(B)** cross-sectional SEM back-scattered electron image of cataclasite and (**C)** close-up of incipient fault mirror. **(D)** SEM secondary electron image of experimental mirrored surface in plan view with sintered polygonal and lobate grain boundaries. **(E)** Comparative SEM image from Sandia Mountains hematite fault mirror, also in plan view.

thick cataclastic band of angular, micron-scale clasts and subrounded nanoparticles (Fig. 2B) and mm-wide-patches of light gloss, light-reflective surfaces in high slip velocity runs (Fig. 2C). SEM imaging shows these zones comprise sintered nanoparticles with polygonal or lobate grain boundaries (Fig. 2D). Macro- to nano-scale textures and crystal morphologies are analogous to what has been observed on natural hematite fault mirrors (e.g., Fig. 2E; Ault et al., 2015; McDermott et al., 2017). Velocity-step tests at sub-seismic slip velocities document that hematite exhibits a low coefficient of friction ranging from 0.25 to 0.44 (Fig. 3) and exhibits velocity-strengthening behavior.

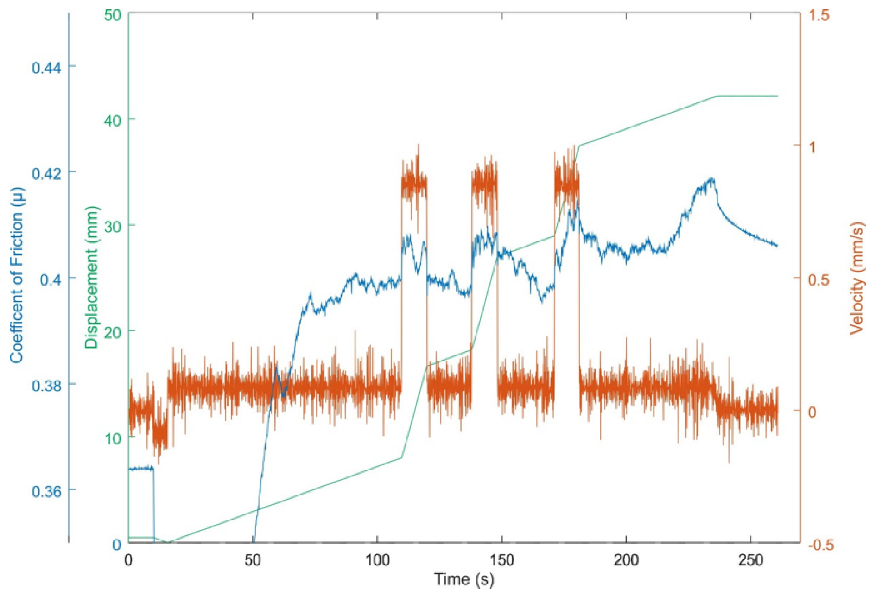

Figure 3. Coefficient of friction (blue line), displacement (green line), and slip velocity (orange line) as function of time for experiment Run 10.

CHALLENGES AND NEXT STEPS

During this first stage of this project, we encountered and overcame several technical and operational challenges. The Instron rotary shear apparatus – housed at Brown University – was relocated to a new laboratory, requiring reassembly and testing prior to use. During this process, we inspected and replaced faulty or inoperative components, installed a new water cooling system, and upgraded the data acquisition system. Moreover, we developed a new lower sample holder that allows us to replace and retrieve the experimentally-produced material in a nondestructive and rapid manner, thus improving sample quality and experiment turnaround time.

The next research phase, to be completed in July 2018, will be dedicated to high-velocity friction experiments on the previously characterized specular hematite at different normal loads and slip distances. The objective of these experiments is to deform the hematite at conditions sufficient to produce textures diagnostic of fast slip and attendant elevated temperature and to evaluate friction, temperature, and textural changes over a range of conditions. The experimentally-produced thermal signature will be assessed (1) via evidence of a dramatic reduction in fault friction likely due to the onset of a thermal dynamic weakening mechanism, (2) evaluating nano- to micro-scale texture and crystal morphologies of the run products indicative of elevated temperatures (Chen et al., 2013; Fondriest et al., 2013; Smith et al., 2013; Ault et al., 2015; McDermott et al., 2017; Pozzi et al., 2018) and (3) documenting hematite He loss through comparative (U-Th)/He analyses. In future experiments, average experimental surface temperature will be measured using thermocouples inserted in drill holes terminating just below the surface on the lower plate and with an infrared detector to spot measure temperature at multiple surface locations.

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