Earthquake Petrology: Insights into Fault Slip Localization and Fault Heating via Micro X-Ray Fluorescence Mapping and X-Ray Absorption Near Edge Spectroscopy

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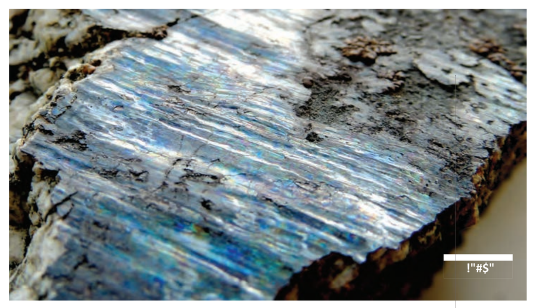
SLAC NATIONAL ACCELERATOR LABORATORY

Motivation



Iridescent slip surface from a small fault in the the footwall of the Wasatch Fault.

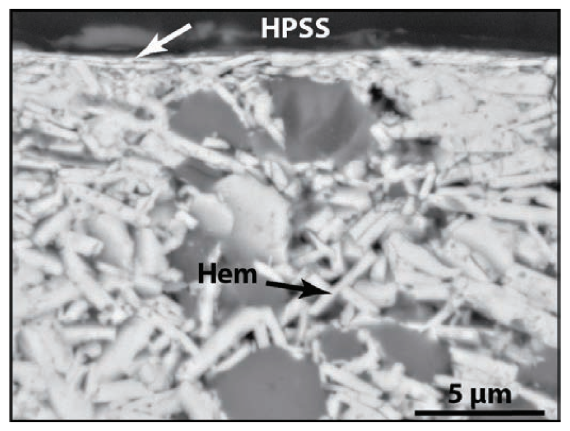
Foliated gouge, San Andreas Fault, SAFOD

Principal slip surface, Chelungpu fault, 2003 rupture.

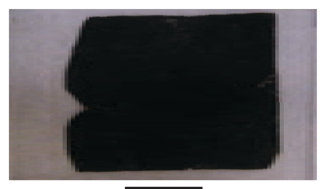
Many naturally occurring faults contain narrow slip surfaces within a damage zone that exhibit a range of fluid-rock interactions and deformation. Deciphering the mechanisms of slip, searching for evidence of seismic heating, and looking for evidence of dynamic weakening typically requires that we examine very thin (1 mm or less) surfaces.

The problem

These fault-related rocks pose observational challenges. We want to examine the composition of just the slip surface, and a range of chemical signals that typical geological methods (optical, SEM microscopy, microprobe) do not easily allow for analyses at the spatial or chemical scales needed.



SEM image of a thin slip surface from the Wasatch Fault sytem. High gloss surfaces are 1-5 um thick, record temperatures of 300˚C (Evans et al. (2014) or as much as 1200˚C (McDermott et al., 2017; see poster 109 at this meeting) consist of oriented ± sintered iron oxide grains.



1 cm

The dreaded black fault rock (DBFR) problem. Many fault-related rocks are nearly opaque to visible light, making optical methods difficutl to use.

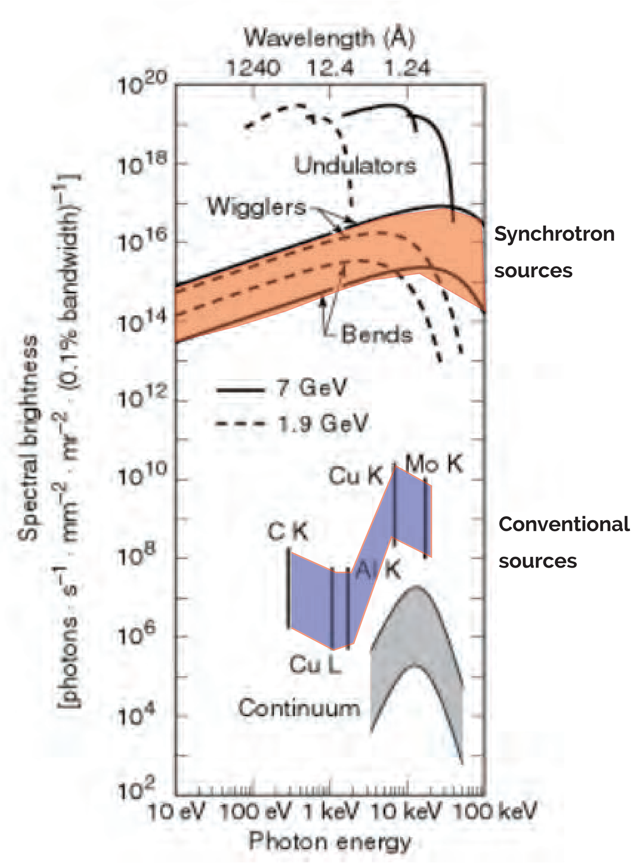
The solution

We use a focused X-ray lightsource at the Stanford Synchrotron Radiation Lightsource to examine slip surfaces. Why?

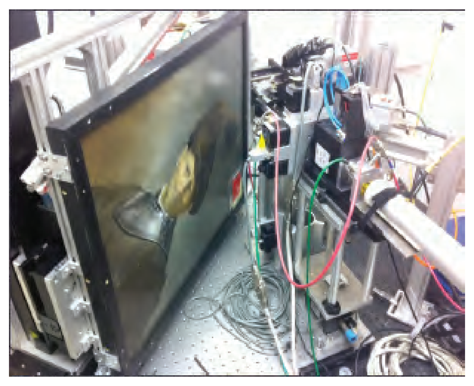
1) BRIGHTNESS - 10^9-10^{11} times brighter than conventional X-ray devices
2) TUNEABLE, FOCUSED 2 µm beam
3) 'SEE' matter not illuminated with visible light or electron beam sources
4) RAPID data acqusition (3000 x faster than electron microprobe methods)
5) MINIMAL SAMPLE PREPARATION - no coatings are required, and samples are examined at ambient temperatures and pressures state
6) ELEMENT SPECIFIC DATA, electronic and geometric structure, oxidation states
7) SIMULTANEOUS X-ray adsorption and X-ray emission analyses
8) LOW COSTS for analytical time and support staff efforts
9) SCALES - Examine samples from the micron to m-long

We examined SAFOD Phase III samples at the SSRL, at beam lines 2-3 and 10-2, which allow us to examine samples up to dimensions 24 by 24 mm, and 300 by 600 mm respectively. Beam line 2-3 examines elements with atomic number Z > Si, and 10-2 works for elements Z > P.

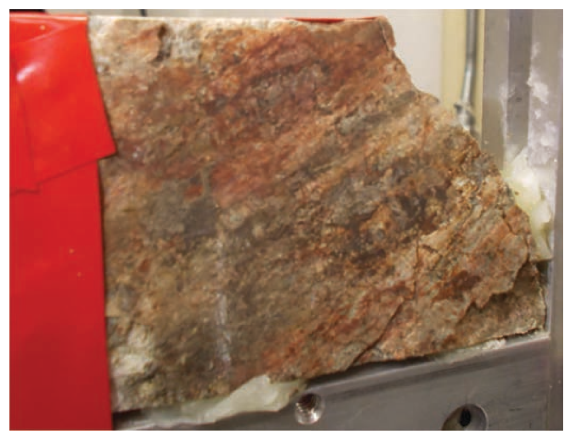
We present results of uXRF mapping of deformed rocks from the San Andreas Fault, and X-ray Absorption Near Edge Spectroscopy (XANES) of samples from the Wasatch Fault, Utah.



Synchrotron radiation is much brighter and operates over a wider range of wavelengths than other methods.



Example of a piece of art in beam line 10-2. We can map elemental distributions, dinstiguish different elements and examine aspects of the electra state with X-ray adsoprption and spetroscopc methods.



Rock sample in line 10-2.

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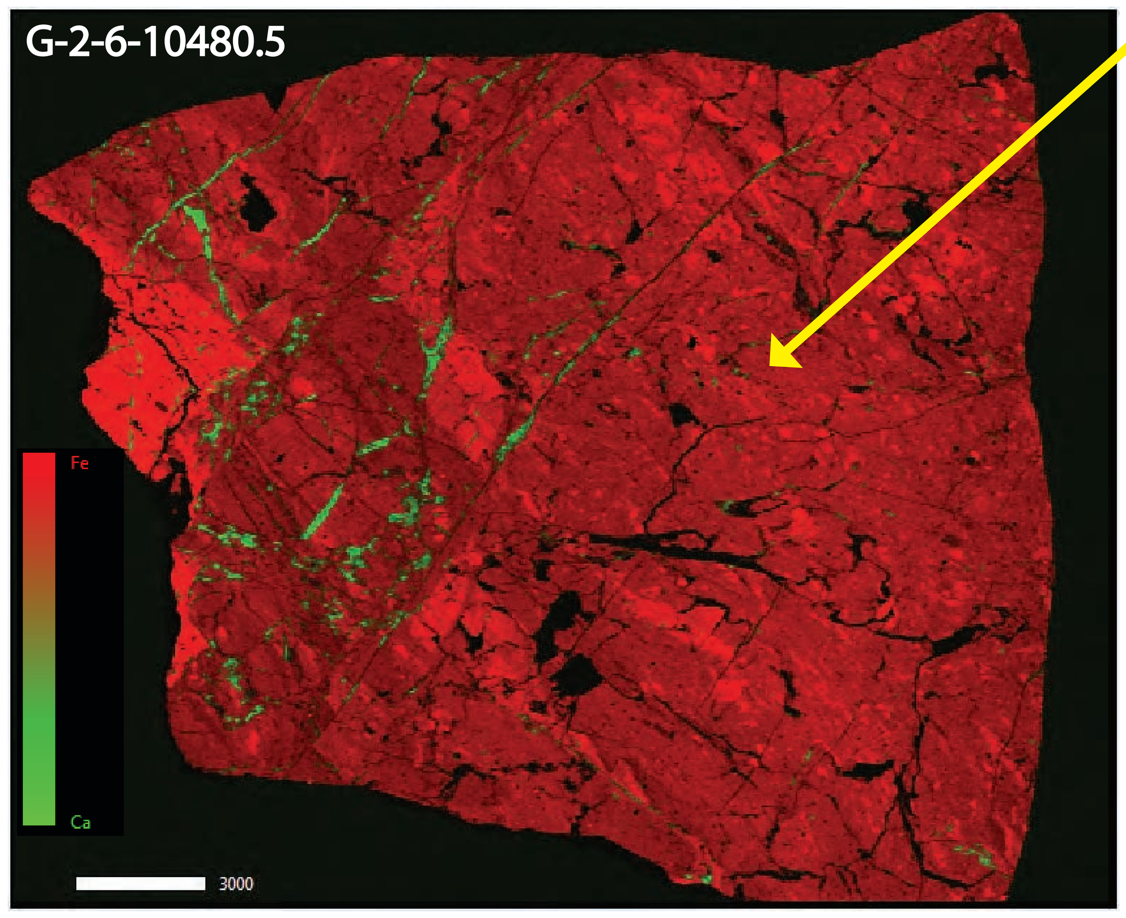
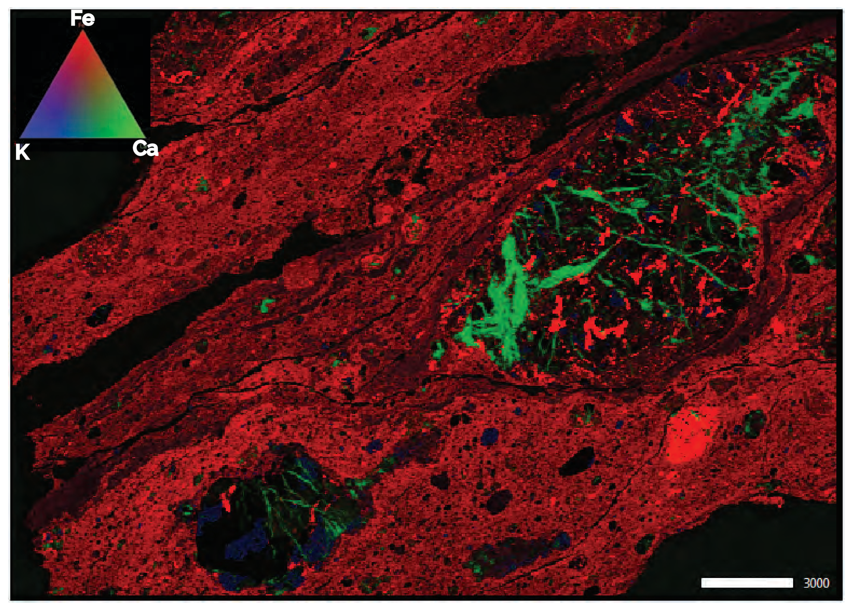
Examples of XRF fault mapping, and X-ray spectroscopy of slip surfaces

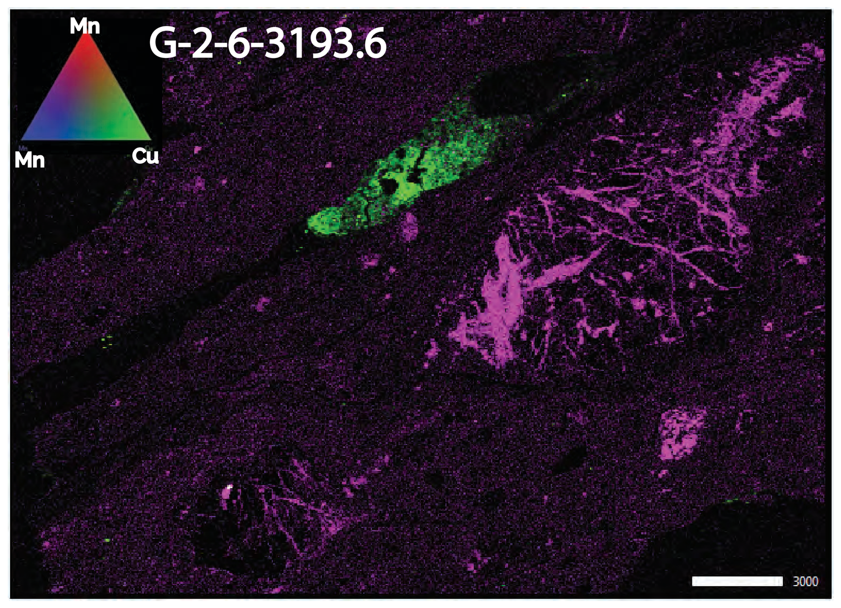
Elemental maps of SAFOD samples with µXRF mapping



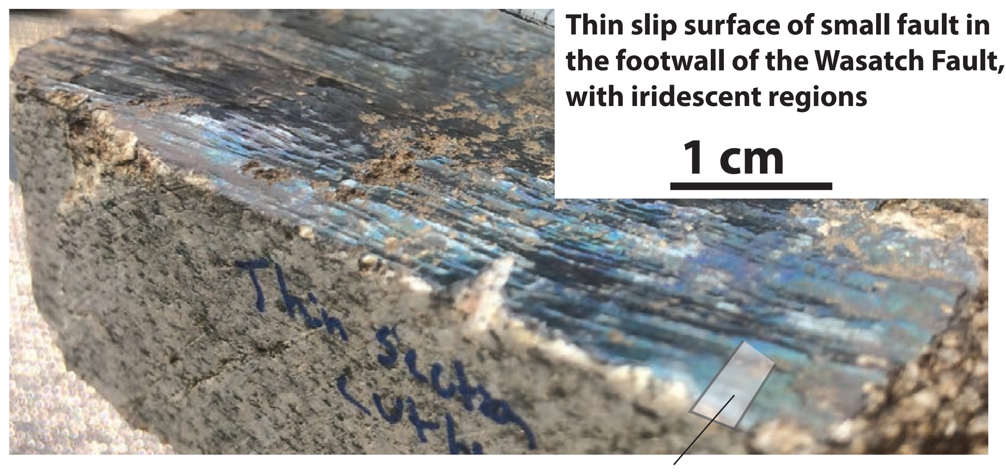
Iron and calcium map of an entire thin section of a foliated cataclasite from SAFOD fault sample. X-ray mapping reveals fine foliation cut by later fractures. Calcite fill some of the fractures, whereas black fractures are open.

Elemental maps of melange-dominated sheared fault rocks. Fe-Ca-K map (left) and Cu-Mn map (right) reveals shear fabrics, since there other there are several dilated fractures a subseqguntly sheared matrix. Cu-rich zone is present, and higher K and Mn content.

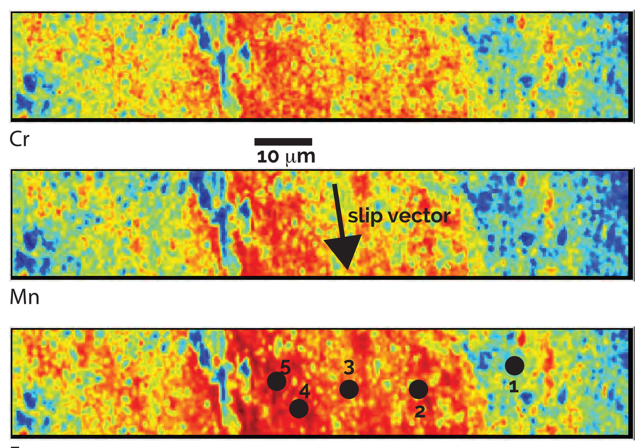




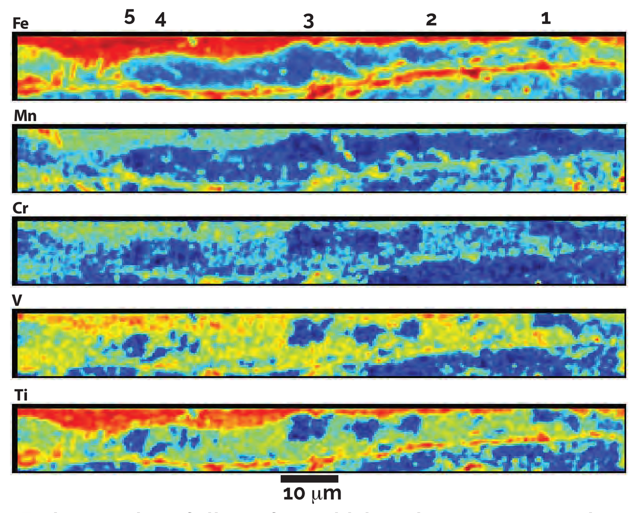
Evidence for asperity flash heating? We previously hypothesized that iridescent zones on small hematite coated slip surfaces were the result of thermally activated reduction of iron - the production of microscale magnetite formation at asperities. We use the X-ray beam at SSRL to map distribution of elements on slip surfaces, and in sections perpendicular to the slip surface, and use X-ray Adsorption Near Edge Spectroscopy (XANES) to show that there are "hotspots" of reduced iron associated with asperity highs on the fault.



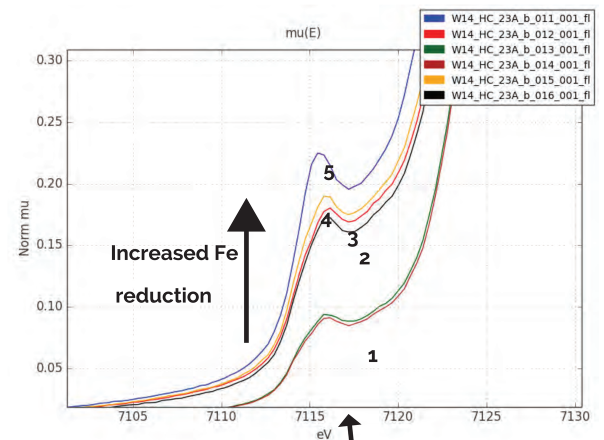
Approximately location of field area

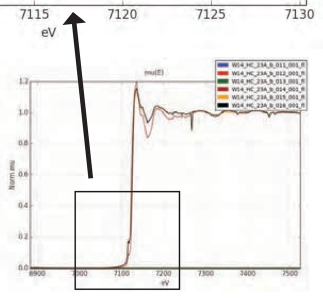


Map view of part of an Fe-coated slip surface



End on section pf slip surface with key element concetrations

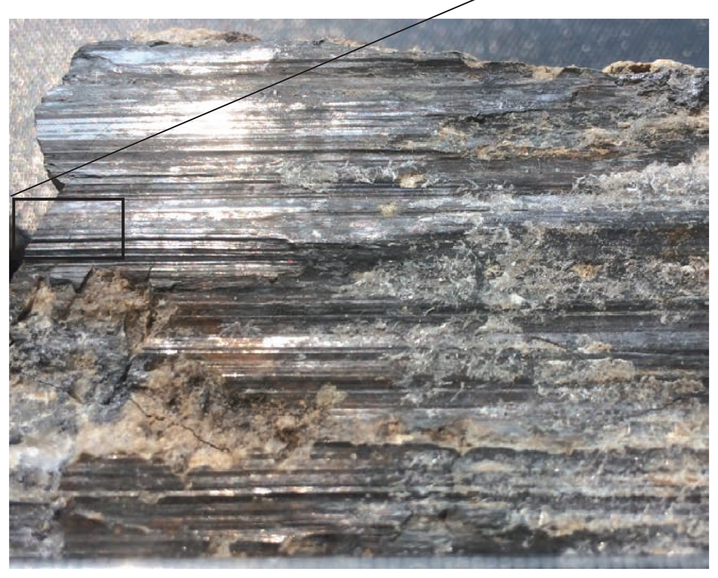




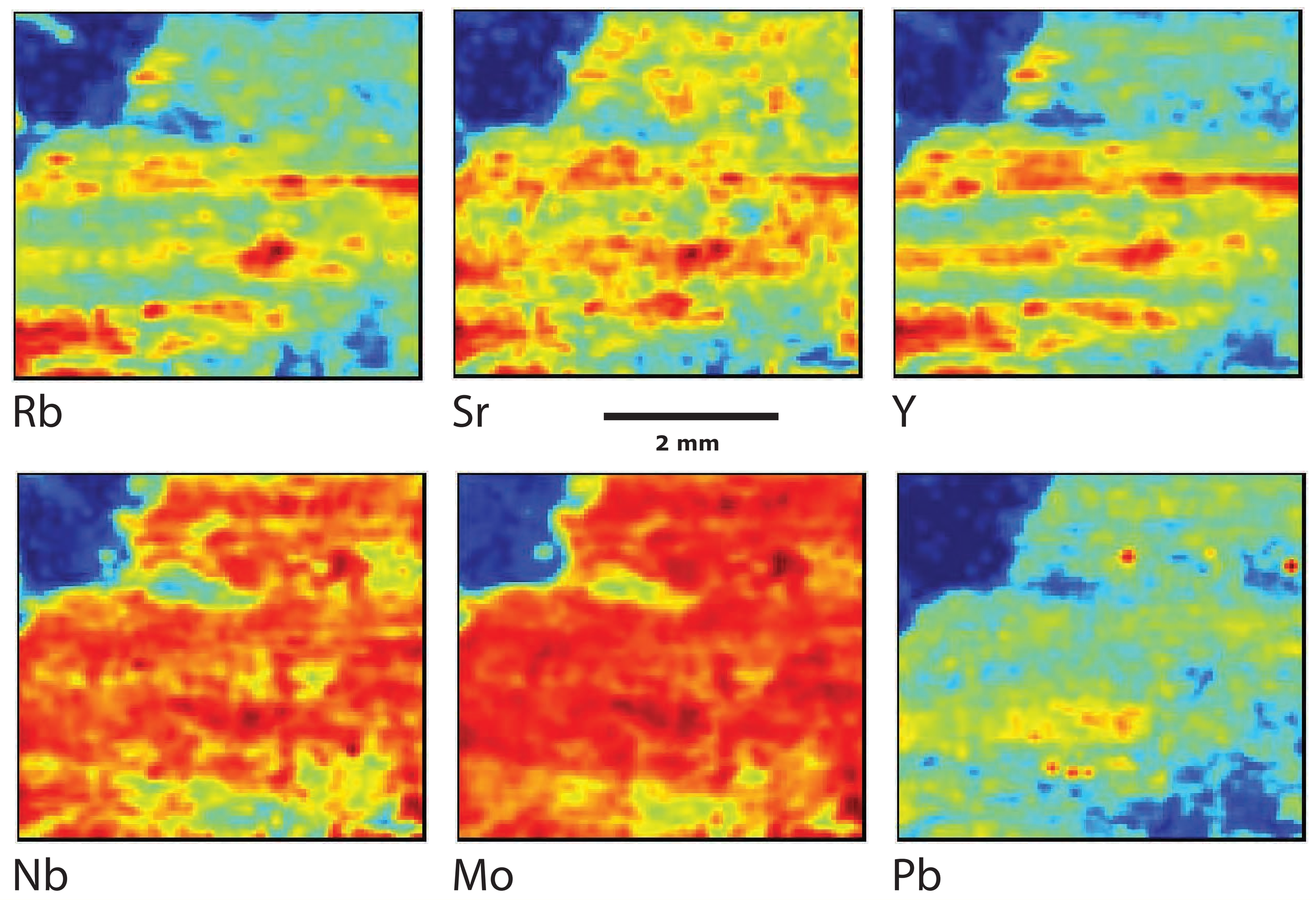
XANES spectra for 5 sites across an asperity.

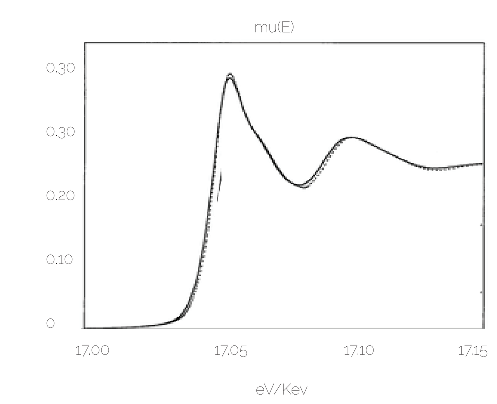
The chemistry of iron reduction suggests that these zones represent at least 400˚C of heating: McDermott et al (2017; and this meeting, poster 109) suggest T > 1000˚C.

These data indicate that the small-displacement faults slipped seismically, and serve as natural analogs for seismogenic faults.



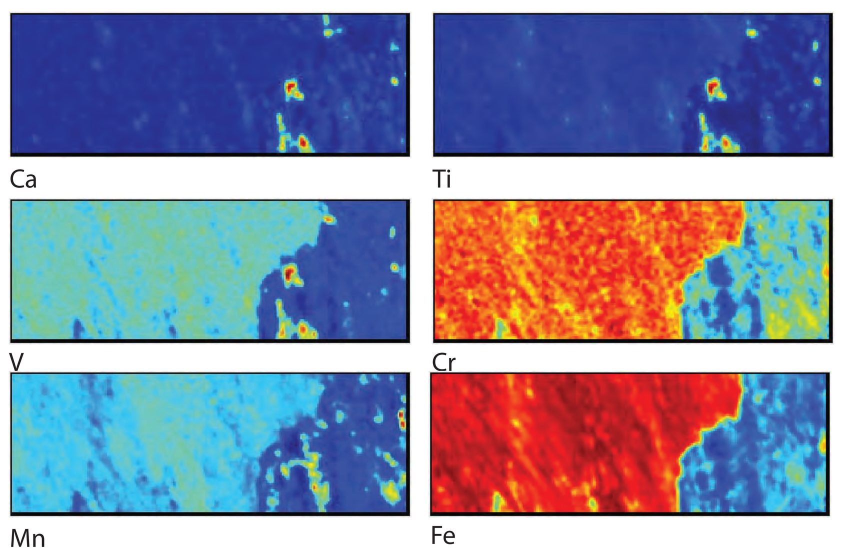
1 cm





If reduction is associated with aspertiy flash heating, then the counter example - lack of thermal-induced reduction on weak faults, should be observed. We examine an MoS_2 coated fault surface (μ =0.2 or less) from New Mexico, and map the presence of Mo and Y. No reduction of Mo or Y is observed, consistent with a weak fault that slipped at low temperatures (<200°C). Note that this shows that high gloss, high luster fautls do not always indicate hot, fast slip.

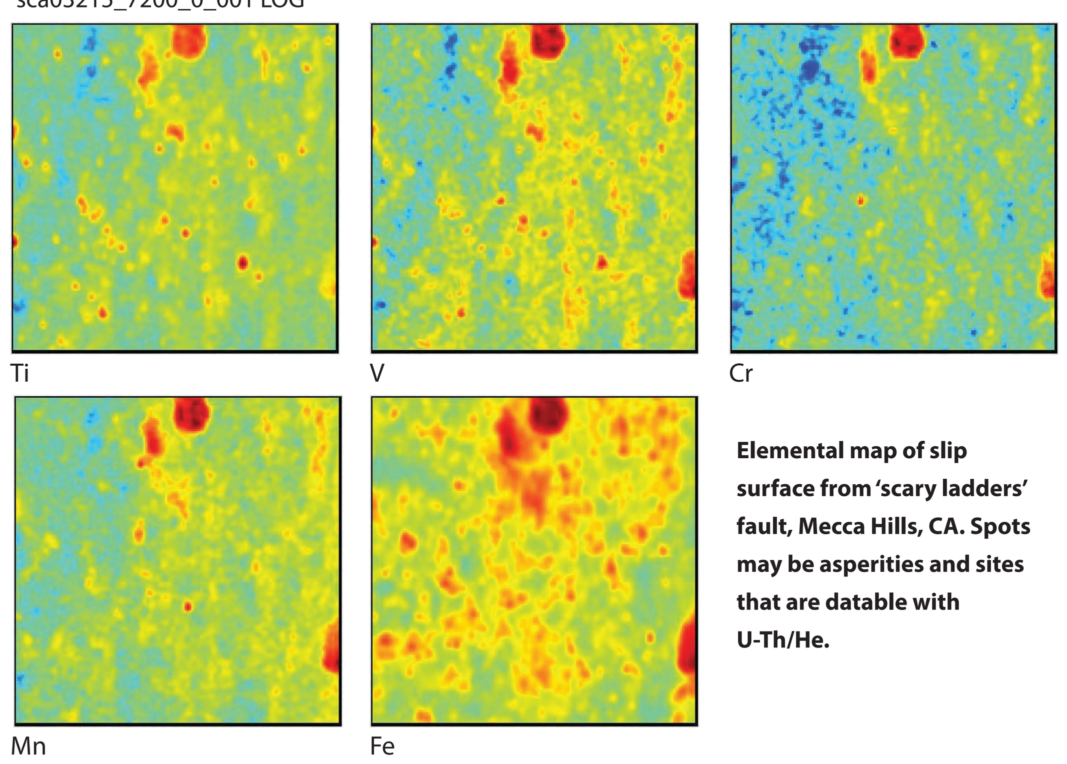
AM_PCFS6_36315_ME_7132_001 LINEAR



Painted Canyon Fault, Mecca Hills, CA.

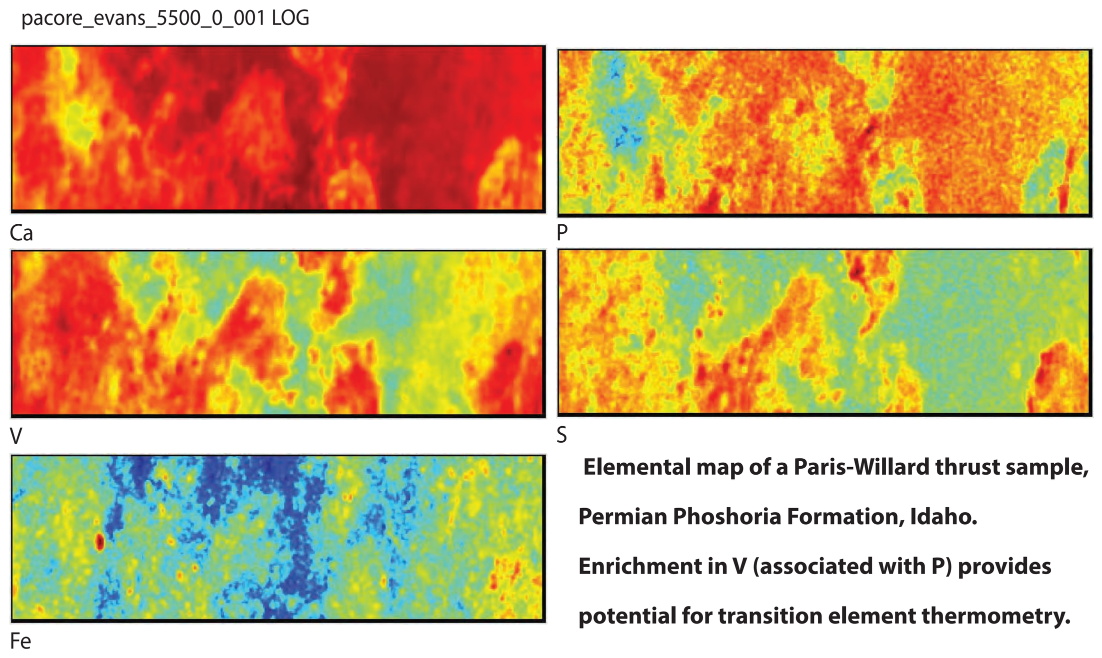
Elemental mapsof slip surface

sca03215_7200_0_001 LOG



Elemental map of slip surface from 'scary ladders' fault, Mecca Hills, CA. Spots may be asperities and sites that are datable with U-Th/He.

pacore_evans_5500_0_001 LOG



Elemental map of a Paris-Willard thrust sample, Permian Phoshoria Formation, Idaho. Enrichment in V (associated with P) provides potential for transition element thermometry.

We explore other applications of the method. In the case of faults of the San Andreas Fault sytem in the Mecca Hills (Moser et al., 2017: Ault et al., this meeting poster 111) no thermally activated iron reduction is seen. Moser et al. (2017) thus use the hematite coated fault surfaces and host rocks to determine thermal evolution of the faults and fault-bounded blocks with U-Th/He thermochronology. Future work with faults includes mapping th elocation of elements that are proxies for the location of U on the fault surfaces and systematically quantifying shear heat vs. other thermal processes. We will also examine other faults for transition element thermometry. Fe, Mn, Cr, Y, Mo, and V all have potential for fault surface thermometry. Cored samples of the Paris-Willard thrust have enriched V, and potential for thermometry.