Examining microroughness evolution in natural pseudotachylyte-bearing fault surfaces, Gole Larghe Fault Zone, Italy

by

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Table of Contents:
I. Introduction
II. Geologic Background
   IIa. Wavy Fault
   IIb. Gole Larghe Fault Zone, Adamello
III. Data Collection and Analysis
   IIIa. Microscopy
      IIIa.i. Optical Microscope
      IIIa.ii. Differences between OM and CT observations
      IIIa.iii. Scanning Electron Microscope
   IIIb. CT
   IIIc. Fault extraction
      IIIc.i. Avizo®
      IIIc.ii. MATLAB®
   IIIId. Roughness analysis
      IIIId.i. PSD (power spectral density)
      IIIId.ii. Biotite elevation
IV. Results
   IV.a. Visuals
   IV.b. PSD plots
   IV.c. Biotite elevation statistical analysis and histograms
   IV.d. Stress modeling adaptation
   IV.e. Error
V. Discussion
VI. Conclusions
VII. Works Cited
VIII. Appendices
   A. Field notes
   B. MATLAB scripts
   C. Sample details
FIGURES:
Figure 1: Sample location map
Figure 2: L05-06
Figure 3: L05-07
Figure 4: Overview outcrop photo
Figure 5: Precursor joints, pseudotachylyte, and cataclasite
Figure 6: Geologic location map
Figure 7: L12-05 photomicrographs
Figure 8: L12-06 photomicrographs
Figure 9: L12-07 photomicrograph
Figure 10: L12-07 fault photomosaic
Figure 11: L12-08 photomicrographs
Figure 12: SEM images of L12-06
Figure 13: Linear attenuation curve
Figure 14: CT visualization process
Figure 15: Biotite elevation workspace in ArcGIS
Figure 16: L12-05
Figure 17: L12-06
Figure 18: L12-07
Figure 19: L12-08
Figure 20: PSD plots, N/S sides of fault
Figure 21: PSD plots, by fault orientation
Figure 22: Biotite elevation histograms, by fault orientation
Figure 23: Model of maximum compressive stress for the fault

TABLES
Table 1: wt% composition from SEM analysis
Table 2: P-values from rank sum analysis
Fault surfaces are rough at all wavelengths, and power dissipation is therefore also likely to be highly heterogeneous during seismic slip along a single fault. In this thesis I explore the relationship between the evolution of fault surface microroughness and power density, the product of slip rate with shear stress, by 3D imaging of intact pseudotachylyte-bearing fault surfaces along a wavy fault surface where fault normal stress is inferred to vary with local fault orientation. Natural pseudotachylyte-bearing faults preserve a record of roughness and, potentially, processes of wear and roughening during earthquake slip. By studying a fault with a relatively uniform slip magnitude but different orientation we can approximate the controlled conditions of dynamic friction experiments. In order to quantify fault surface microroughness and understand its evolution during slip we have examined the 3D geometry of samples from a single fault with approximately 110-200 mm of slip from within the Gole Larghe Fault Zone, Italy. At the outcrop scale, this fault is distinctly wavy with contractional and extensional fault bends as well as relatively straight sections. We quantified the micro-scale roughness for six samples from a range of geometric positions along the fault that we infer to have experienced different fault normal stress during slip. High-resolution x-ray computed tomography (CT) was used to image the internal geometry of the intact sample cores (2-3.5 cm in diameter, 4-6 cm in length). The surfaces of the fault zone were then extracted from the CT volume using an edge detection algorithm. The microroughness (sub mm to 10 cm scale) of the surfaces was then quantified using a Fourier spectral analysis and was also analyzed by comparing topography to mineral location. Identifying the mineral topography was done to pinpoint sources of roughness on the fault surface. Samples from relatively planar sections of the fault show less wear, but do have evidence of preferential melting of biotite. Samples from contractional bends have evidence of the most wear and the highest levels of preferentially melted biotite. Samples from extensional bends, however, display distinctly different microroughness on each surface. Thus, samples from natural faults show an evolution of microroughness in response to changing conditions along the fault.
I. Introduction

Natural faults can be rough on a variety of scales, a variable that describes the geometry of the fault (Power, 1987; Power, 1988; Griffith, 2010; Candela, 2009). The friction on a fault surface during earthquake rupture and propagation is controlled to some extent by the geometry of the fault zone (Scholz, 2002; Griffith, 2010). Quantifying the roughness of a fault surface in relation to the stress present on that surface during faulting is a step towards determining specific control of friction during earthquake slip.

High levels of stress in Earth’s upper crust cause brittle deformation, manifested in the creation of fractures and earthquake faulting (Scholz, 2002). The stored potential energy released as a fault slips is released as either radiated, fracture, or frictional energy; this is commonly referred to as the earthquake energy budget (McGarr, 1999; Shearer, 2009). Seismic waves, the radiated energy can be quantified relatively easily and accounts for approximately 6% of the earthquake energy budget (McGarr, 1999). Fracture and frictional energies are known as the dissipative or non-radiated energy (Kanamori and Rivera, 2006). The exact partitioning of the non-radiated energy during earthquake slip is unknown; fault roughness and its relationship to the friction present during slip is one of few measurable variables related to this section of the earthquake energy budget (See Shipton, 2006 “The missing sinks”; Kanamori and Rivera, 2006; Hirose and Shimamoto, 2003).

Roughness of a fault surface can be quantified by measuring the offset of a given point from a mean reference plane representing the mean fault surface (Power, et al 1988). An individual fault surface’s roughness is proportional to the length and
exhibits fractal, now described as self-affine, qualities (Power et al., 1988). The most widely accepted mathematical methods of calculating roughness are Fourier power spectrum methods (Sagy, 2007; Candela, 2009). These methods are recognized for their “robustness” in portraying self-affine fault surfaces because they characterize the surface at multiple wavelengths or scales (Bistacchi, 2011).

Changes in roughness have been specifically related to shifts in several controlling earthquake parameters. After earthquake nucleation, changes in rupture velocity have been linked to roughness as well as shifts in stress experienced on the fault surface, rupture velocity, kinetic shear resistance, slip weakening distance, dynamic friction during slip and slip fracture energy (Sibson, 1980; Marone, 1998; Chester and Chester, 2000). One possible method of constraining some of the parameters listed above is through study of ancient seismic faulting.

Pseudotachylytes are the most widely accepted record of ancient seismic faulting (Cowan, 1999). Pseudotachylytes (PT) form when the heat produced by friction during fault slip melts the wall rock and is solidified; it is composed of wall rock clasts suspended in an extremely fine-grain crystalline matrix (Spray, 1992; Shand, 1916; Sibson, 1975). This preserves an exact record of the fault surface at the time of rupture and faulting through the contact between the pseudotachylyte and the host rock (Spray, 1995). Average formation depth has been estimated by several papers with a range of 3-11 km, which means exhumed faults zones are the only way to study natural pseudotachylyte (Kirkpatrick, 2012; Di Toro and Pennacchioni, 2005).
Hirose and Shimamoto (2003) used experimental pseudotachylyte to infer slip weakening distance values, an important earthquake source parameter in governing fault instability immediately after rupture. Pseudotachylyte has also been used to constrain the earthquake energy budget (Pittarello, 2008), the rupture velocity and fracture energy (Di Toro, 2005a) and the slip rate (Nielsen, 2010).

One significant relationship is that of stress and fault roughness. In experimental work, this is constrained by testing samples at a variety of normal stresses and the same slip distance (Niemeijer, 2012). To replicate this in nature, we studied a wavy fault with contractional, extensional, and neutral fault sections, each with their own inferred normal stress and roughness. The friction dissipated along a fault is proportional to both the slip rate and the inferred normal stress of the fault, which varies based on the type of bend (Nielsen, 2010). Therefore, each section of a wavy fault will theoretically have a different normal stress and consequently a different roughness. To estimate the past friction along a fault, as well as the slip weakening distance and velocity, one can quantify the roughness and normal stress. Ultimately, a greater understanding of the relationship between friction, roughness and earthquake propagation will lead to a greater understanding of major faulting events and earthquakes (Di Toro, 2005a).

We studied a pseudotachylyte-bearing wavy fault in the Gole Larghe Fault Zone with extensional, contractional, and neutral sections. Samples were taken from each section to compare the shifting normal stress with the roughness measured from the pseudotachylyte surface, a record of the fault surface. CT scans of samples were analyzed for the roughness of the entire fault surface, and these surfaces are used to
calculate both the power spectral density and the changing mineralogy of the fault at each orientation.

II. Geologic Background

IIa. “Wavy” Fault

To best quantify microroughness over a variety of stresses, we sought a fault with changing orientations along its length. Our study area is a sample way fault strand from the Gole Larghe Fault Zone (GLFZ) of the southern Italian Alps. To ideally compare the fault to experimental samples in later work, the fault needed to have the least number of independent variables. This fault was chosen for study because it exhibited an assumed uniform slip, a single faulting event, a variety of fault orientations creating extensional, contractional and neutral segments and no evidence of cataclasite (which causes difficulty in analyzing CT scans) (Griffith, 2010).

The fault, like all faults in the GLFZ, is a right lateral strike-slip fault. The fault trace is approximately 5 meters long; however, the true fault length is not known because neither fault tip can be seen. The outcrop surface is orthogonal to fault dip and therefore assumed to be parallel to fault slip (Griffith, 2010). Both extensional and contractional bends are filled with pseudotachylyte. Injection veins are seen along the fault, primarily along the southern side. The fault is assumed to represent a single slip event because there are no overprinting relationships indicating multiple generations seen on the fault trace (Griffith, 2010).

Fault thickness varies slightly along the fault from less than a millimeter to 12 mm, with an average thickness of 7 mm (Griffith, 2010). In contractional bends, the pseudotachylyte thickness is closer to 1 mm. In extensional bends, the thickness can
be up to 12 mm. There is no visible zoning in the pseudotachylyte at the fault surface. Cataclasite is not visible to the naked eye or with a hand lens on or around the fault surface. Grains in the wall rock surrounding the fault are not visibly deformed, fractured, or altered in any other way.

Because there are no offset markers on this particular fault, slip must be estimated via other means. Griffith, 2010 approximated slip of 30 to 100 cm based on two methods. First, other pseudotachylyte-only faults (no cataclasite) in the GLFZ with known slip plot linearly on graphs of slip vs. corresponding length (Di Toro, 2005). This fault, with an average thickness of 7 mm, would be expected to have 100 cm or less of slip. Also, dilational jogs are hypothesized to be the length of slip on faults with a single slip event (Griffith, 2009). The dilational jog seen in the sample location map below (located at sample L05-07) is approximately 30 cm, suggesting the slip is hypothetically around that value (Griffith, 2010).

Fig 1: Location of samples used for this study along a wavy fault in the GLFZ. Photomosaic and drawing adapted from Griffith 2010.

A previously published photomosaic (Griffith, 2010) is used as the base of the sample location map (Fig. 1). Two samples, L05-06 and L05-07 were taken in 2005 and previously studied in Griffith, 2010 by taking 1D roughness profiles from thin sections and have been re-analyzed in this work (Fig. 2, 3).
Fig. 2: oriented L/R:N/S  a. slip parallel photomicrograph  b. slip parallel CT slice  
c. volume rendering of sample core, fault in purple  
d. southern fault surface  e. southern fault surface mineralogy. Scale of d: 700/-1000 microns

Fig. 3: oriented L/R:N/S  a. slip parallel photomicrograph  b. slip parallel CT slice  
c. volume rendering of sample core, fault in purple  
d. southern fault surface  e. southern fault surface mineralogy. Scale of d: 5000/-1000 microns
Four samples, L12-05-08 were taken in August 2012 and are covered in this work for the first time. L05-07, L12-05, and L12-06 are from a single extensional jog. L05-06 and L12-07 are from a single contractional bend. L12-08 is from a straight fault section.

IIb. Gole Larghe Fault Zone

The retreat of the Lobbia Glacier in the Adamello region of the Alps over the past ten years has exposed and polished the Gole Larghe Fault Zone (GLFZ) (Fig. 4) (Di Toro and Pennacchioni, 2005). The GLFZ cuts a 550-meter wide swath east-west across the characteristic tonalite of the region and consists of a series of sub-parallel interconnected strike-slip faults (Di Toro and Pennacchioni, 2004). All summed, the GLFZ accommodated 1.1 km of slip on its approximately 200 exposed faults (Di Toro and Pennacchioni, 2005). Because of the “undulating topography typical of glacier-polished roches moutonnée” faults are essentially exposed in 3 dimensions; fault traces can be chosen for study with outcrop surfaces orthogonal to the fault
surface, and therefore parallel to slip, making it an ideal natural laboratory for roughness studies (Bistacchi, 2011).

The faults and fault strands cut the Avio pluton, which, at approximately 34-32 Ma, cooled and developed two sets of joints, trending NNE-SSW and ESE-WNW (Fig. 5) (Di Toro and Pennacchioni, 2005). Mineralogical composition of the pluton is characteristic of a hornblende-free medium grained tonalite, with 45-50% plagioclase, 25% quartz, 15-20% biotite, and 1-5% k-feldspar. The ENE-WSW joints were then exploited by brittle deformation and became the base for the series of strike-slip faults that are now referred to as the GLFZ (labeled GLF in Fig. 6). Fault roughness of the fault surfaces in the GLFZ originated from the roughness of the ENE-WSW joints. Pseudotachylyte dating from the fault zone places their formation at approximately 29.8 +/- 0.4 Ma, which most likely means that the deformation along the faults in the GLFZ was occurring at the time of slip along the Tonale line to the north (labeled TO in Fig. 6) and the cooling of the Presanella pluton to the east.

Fig. 5: Geologic characteristics of the fault zone, CW from left: joints, pseudotachylyte, cataclasite.
(4 in Fig. 6) (Di Toro and Pennacchioni, 2005). Both pseudotachylyte and cataclasite were formed as a part of this deformation process (Fig. 5).

Fig. 6: Geologic map of the Adamello batholith, from Di Toro and Pennacchioni 2004. Of interest: GLF is the Gole Larghe Fault Zone; TO is the Tonale Line; 4 is the Presanella pluton.

The approximately 200 sub-parallel faults of the GLFZ have an anastomose pattern (Griffith, 2010). Faults and fault traces are spaced approximately 1-6 meters apart (Di Toro, 2009). The slip on a single fault or fault trace varies from 10-100 cm on average but can be up to 20 m (Di Toro, 2005b). Fault thickness varies from less than 1 mm to 35 mm (Di Toro and Pennacchioni, 2005). Faults have both cataclasite and pseudotachylyte, both singly and in combination. Exclusive pseudotachylyte usually indicates a fault trace with only a single slip event (Griffith, 2010). The pseudotachylyte occasionally overprints the cataclasite, while in other locations within the fault zone, the pseudotachylyte and cataclasite are mutually crosscutting.

Studies on pseudotachylyte from this zone indicate that the pseudotachylyte formed at 9-11 km depth at 250-300°C (Di Toro and Pennacchioni, 2004, 2005).
Temperature and pressure estimates of 250-300°C and .25-.36 GPa, respectively, were deduced by using the mineralogical characteristics of the pseudotachylyte, such as the crystal plasticity of the quartz, the epidote veining in association with PT and cataclasite, and the lack of amygdules. The pressure estimate was, in turn, then used to estimate a depth of 9-11 km using expected geotherms. Pseudotachylyte dating via $^{40}\text{Ar}/^{39}\text{Ar}$ dating gives an approximate time of faulting 29.8 ± 0.4 Ma. The faulting is assumed to have occurred directly after the cooling of the tonalite intrusions because of its exploitation of the preexisting joints (Di Toro and Pennacchioni, 2004).

Di Toro, 2005b hypothesized that one could use the pseudotachylyte thickness and its associated fault orientation to determine the stress normal to the fault plane by manipulating the typical stress tensor of a strike-slip system. The stress normal to the fault plane was approximated to be around 112 MPa for the GLFZ as a whole, though this value is dependent on the pore pressure of the system at the time of faulting, which is unknown (Di Toro, 2005b).
III. Data Collection and Analysis

IIIa. Microscopy

Mineralogy and observations of microstructures were analyzed using both optical and scanning electron microscopes. Mineralogical analysis of L05-06 and L05-07 was done in Griffith, 2010.

III.a.i. Observations, OM

The mineralogical composition of the wall rock was fairly consistent with other samples from the fault zone, with 45-50% plagioclase, 25% quartz, 15-20% biotite, and 1-5% k-feldspar (Di Toro and Pennacchioni, 2004). No sample, including the ones studied in Griffith 2010 (L05-06 and L05-07) has a mineral composition that varies significantly from Di Toro and Pennacchioni’s assessment in their 2004 paper.

L12-05 is representative of an extensional jog, though the sample decreases in thickness with depth. The first thin section is from approximately 4 mm underneath

Fig. 7: A full photomicrograph and zoom of the injection vein are shown. Note the clear zoning between the spherulitic interior zone and microlitic exterior zone.
the surface with 7.5 mm thick pseudotachylyte, while the second section is from 30 mm underneath the surface with 5 mm thick pseudotachylyte. L12-05-1 has three zones within the pseudotachylyte (Fig. 7). The core (6.5 mm) is an extremely fine-grained, aphanitic yellow-brown crystalline matrix with suspended well rounded to rounded clasts of quartz and feldspar representing a spherulitic texture. The core has a less-defined inner core with a slightly darker matrix containing a higher proportion of clasts and a higher proportion of larger clasts than the outer core. The exterior zone (.2 mm on one side, .8 mm on the other) is an orange-brown crystalline matrix, with slightly larger grains representing a microlitic texture. The clasts are well-rounded to rounded quartz and feldspar, with some biotite. An injection vein is observed very clearly (Fig. 7). L12-05-2 has the same pseudotachylyte composition, but with no inner core.

The zonation is expected in this sample because of its location on the fault. There are two explanations for the zones in this sample- one, the transformation of the pseudotachylyte occurred after the melt was crystallized; or two, because of the characteristics of the zonation, the melt occurred in multiple pulses during the same slip event and thus still represents a singular slip event. The latter is the explanation used by Griffith, 2010 to explain the zoning in L05-07 and is the most likely explanation for the zoning in this sample.

One difference indicative of the formational orientation is within the quartz grains. As observed in Griffith, 2010, samples from extensional bends (like L12-05) have quartz grains with micro cracks both sub parallel and orthogonal to the fault. This observation is consistent with the quartz grains seen in this sample. The feldspar
grains show little sign of damage. Samples from contractional bends (i.e. L12-07, described later within this section) have cracks orthogonal to the fault but not parallel. Griffith, 2010 hypothesized this could show a record of the static stress perturbation due to the fault geometry.

Biotite is embayed within the pseudotachylyte surface on both sides of the fault, something that is quantitatively explored in later sections. The embayment is likely due to the preferential melting of biotite and contributes to the roughness on the fault surface. The edges of the fault with no biotite embayment are significantly straighter. Section III.a.iii details the SEM analysis of the edge of the pseudotachylyte vein within L12-06.

L12-06 is also an example from an extensional bend and increases in thickness with depth from 5 mm to 6.5 mm (Fig 8). L12-06-1 was taken closer to the surface and the pseudotachylyte is slightly thinner, while L12-06-2 was taken 30 mm from the surface. The interior of the pseudotachylyte is quite similar to L12-05 in both sections, with a core of extremely fine-grained yellow-brown matrix and an exterior zone with an orange-brown matrix with larger clasts present. Clast size is

![Fig. 8: full photomicrograph and two levels of magnification; note the flow structures; the far right is the area used for later SEM analysis.](image)
more varied in this sample, though the largest clasts are less than 1% of the clasts observed and are an anomaly. Clast size variation is from 1 mm to 30 µm. Injection veins are seen on one side of the fault and are extremely small (<.5 mm long).

Flow structures are present in both sections within the pseudotachylyte. This implies that the melt did not originate in the extensional jog and was instead carried from point of high stress (contractional sections) to the extensional jog. These structures are curved and folded, implying that the zonation in this sample was most likely caused by heterogeneous melt (shown in detail in Fig. 8)(Griffith, 2010).

Micro cracks both orthogonal to and subparallel to the fault are observed in quartz grains from these thin sections as well, consistent with the observations from L12-05 as well as Griffith’s observations from L05-07.

Fault edges are qualitatively described as straight, except when biotite grains are in contact with the fault surface. Biotite grains are embayed in the fault surface on both sides, leading to the qualitative conclusion of higher roughness in these sections.

Fig. 9: Full photomicrograph of L12-07; height of section is 3.2 cm.

L12-07 is from a contractional fault bend, and therefore the pseudotachylyte in this section is extremely thin (Fig. 9). Thickness varies from .2 mm – 1 mm. L12-07-1 has the largest variety in thicknesses, due to its interaction with another small fault and other fractures present. There is little zoning in the pseudotachylyte at any point, except at one location where a fracture cuts
through the fault orthogonally and a miniature reservoir is formed. Flow structures are observed within this reservoir. The pseudotachylyte composition is microlitic, like the composition of the exterior zones in other samples.

L12-07-1 is more complex than L12-07-2 due to its interactions with fractures and another fault. A photomosaic of the fault zone within this sample has been included (Fig. 10). This sample seems to be appreciably rougher than other samples, with kinks in the pseudotachylyte as well as bends on the edges that approach right angles. The fractures crosscutting the pseudotachylyte do not always affect the pseudotachylyte or the fault surface. Some are seemingly filled with pseudotachylyte.

![Photomosaic of the fault at L12-07](image)

Fig. 10: photomosaic of the fault at L12-07; top right edge and bottom left edge connect. a. reservoir formed by orthogonal fracture b. fault kink/bend at almost right angle c. fracture with no effect on fault geometry d. embayed and recessed biotite

The biotite, quartz and feldspar grains located near the fault all show signs of damage. The quartz grains have microcracks subparallel to faulting, without the orthogonal cracks seen in the samples near extensional bends. This is consistent with observations from Griffith, 2010 on sample L05-06. The feldspar and biotite grains
fracture along cleavage planes and seem to have been compressed because their shape is significantly less rounded than grains within the same section that are further from the fault. The biotites have also experienced an enhancement of their streakiness in coloration and seem to be striped brown and white instead of brown with small white areas.

Biotites are embayed on both sides of the fault, and a quartz grain appears to be embayed as well. Unlike other samples with examples of biotite embayment, there are clearly clasts from the embayed grain within the pseudotachylyte and fractures within the grain implying a high level of stress. The biotites correspond with qualitatively determined higher levels of roughness. Grains not embayed within the fault surface with fractures appear to have small amounts of pseudotachylyte or another dark mineral within the fractures.

However, there are also striking examples of roughness along the fault surface that are not associated with biotite embayment. The waviness seen on one side of the fault surface seems to be approximately the same wavelength, with recessions every ~1mm for half of the fault seen in the section.

L12-08 is an example from a neutral section of the fault. The pseudotachylyte is 1 mm thick in both thin sections and the thickness is consistent across the entire section in both cases. The matrix is exactly the same as observed in L12-05 – an inner section of yellow-brown crystalline and an outer section of an orange-brown slightly larger grain (Fig. 11). The zoning is less clear in this sample, with undulations at the contact between the two types of matrices. One side of the fault is seemingly qualitatively rougher than the other. Biotites are embayed on both sides of the fault,
but there is little damage to the embayed grains.

![Image of embayed grains]

**IIIa.ii. Differences between CT and OM observations**

One of the main inquiries when considering the CT imagery was an unknown substance within the PT vein that appeared to be a pale grey to white in the gray scale – half way between the values for pseudotachylyte and biotite. However, this unknown substance did not appear in the thin sections at any point, and may simply correspond to a slight density difference that was amplified by the x-ray energy levels set for the CT scanner. The substance was also not visible in SEM images.

**IIIa.iii. SEM**

![Image of SEM study area]

**Fig. 11:** L12-08. Magnification of the straight fault surface with embayed biotite seen.

**Fig. 12:** Full SEM study area with magnification of region 1 (microlitic composition test), region 2 (spherulitic composition test and clast test) and region 3 (control biotite grain).
Sample L12-06, from the extensional jog of the fault, was chosen to be analyzed under the scanning electron microscope (SEM) as well because it contained lithological features present in all samples: two distinct matrix types, varieties of clast sizes and possibly compositions, embayed biotite grains, and an unknown substance from the CT images. Six spots were chosen for analyses (Fig. 12). The first was an easily identified biotite grain as a control (a), the second two were chosen from the orange-brown microcrystalline matrix (b, c), the fourth as a part of the inner spherulitic matrix (d), and the fifth and sixth as representations of various clasts within the spherulitic matrix (e, f). The wt% element values are shown for all samples in Table 1; samples are arranged in the table with increasing distance from the southern surface of the fault.

Table 1: Elemental Composition of Pseudotachylyte Vein

<table>
<thead>
<tr>
<th>Element</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>29.49</td>
<td>28.87</td>
<td>29.35</td>
<td>32.41</td>
<td>30.22</td>
<td>30.49</td>
</tr>
<tr>
<td>Na</td>
<td>0.27</td>
<td>0.00</td>
<td>1.25</td>
<td>0.22</td>
<td>0.19</td>
<td>0.38</td>
</tr>
<tr>
<td>Mg</td>
<td>5.71</td>
<td>6.52</td>
<td>3.31</td>
<td>3.60</td>
<td>2.07</td>
<td>2.19</td>
</tr>
<tr>
<td>Al</td>
<td>11.28</td>
<td>11.87</td>
<td>12.78</td>
<td>15.27</td>
<td>9.61</td>
<td>7.03</td>
</tr>
<tr>
<td>Si</td>
<td>21.64</td>
<td>22.34</td>
<td>29.38</td>
<td>26.36</td>
<td>23.41</td>
<td>20.52</td>
</tr>
<tr>
<td>K</td>
<td>9.11</td>
<td>8.89</td>
<td>8.06</td>
<td>8.91</td>
<td>5.54</td>
<td>3.10</td>
</tr>
<tr>
<td>Ca</td>
<td>0.16</td>
<td>0.49</td>
<td>3.04</td>
<td>1.18</td>
<td>11.63</td>
<td>15.80</td>
</tr>
<tr>
<td>Ti</td>
<td>2.07</td>
<td>1.99</td>
<td>1.19</td>
<td>0.77</td>
<td>10.01</td>
<td>12.58</td>
</tr>
<tr>
<td>Fe</td>
<td>18.92</td>
<td>18.18</td>
<td>11.00</td>
<td>10.16</td>
<td>5.94</td>
<td>6.92</td>
</tr>
</tbody>
</table>

The biotite used as a control plotted as expected with distinctive peaks of Mg, Al, Si, K, Ti, and Fe (a in Table 1). The first sample from the microcrystalline matrix is nearly touching the contact between the pseudotachylyte and host rock, while second sample from the microcrystalline matrix is further from the contact between the two (b, c in
Table 1). The contact at this point is between a slightly embayed biotite grain and the pseudotachylyte. These samples both have comparable levels of titanium to the sample biotite grain. This suggests that the composition of the microlitic matrix is derived from the preferential melting of biotite grains on the surface of the fault. The titanium composition of the yellow-brown spherulitic matrix (d in Table 1) is less than half that of the titanium composition of b, the first microlitic sample, suggesting a decrease in titanium and therefore a decrease in biotite contribution to the melt as one moves further away from the surface. This accounts for the differing coloration of the two matrices as well. The biotite and b both contain almost double the amount of iron as c and d, which accounts for the gradual shift in coloration from orange-brown to yellow-brown.

The second use of the SEM was to explore the clastic composition beyond the quartz and feldspar clasts found under the optical microscope. Three other types of clasts were found (two are shown in table 1); all of these are from the spherulitic matrix. First, a zircon grain was found. Second, two grains with an interesting and not immediately identifiable composition were found, shown on the table as e and f. Both seem to have a similar composition to that of sphene, but with much higher aluminum content than typically seen in sphene composition (Welton, 1984). Under the optical microscope, these spots appear to be green.
High-resolution x-ray computed tomography (HRXCT) produces contiguous images incrementally throughout a volume to create an essentially 3-dimensional visualization of a sample (Ketcham and Carlson, 2001). Because x-rays are used to image the sample, the technology is non-destructive and preserves the sample for alternative uses such as thin-sections for mineralogical analysis. The gray-scale image produced is a map of the varying x-ray attenuations, which strongly correlate with density values (Ketcham, 2005). This makes the image essentially a density map.

The basic mechanism in any x-ray CT scanner is the same in all scanners. A scanner must have an x-ray source and detectors to distinguish the varying attenuations of the x-ray signal. The x-ray source produces an x-ray signal, which hits the sample and is absorbed, scattered, or transmitted. The detector records the transmitted signal and calculates attenuation along the x-ray path. By combining multiple paths with differing orientations one can tomographically reconstruct 3D distribution of attenuations within the sample (Ketcham and Carlson, 2001). In industrial scanners, which are used for non-medical (therefore scientific) imaging, the detectors and signal are stationary while the sample rotates to multiple angles. The
tomographic volume is stored as a set of 2-dimensional stacked images, individually known as slices.

The x-ray signal for volume imaging is typically a cone beam, which can collect data for multiple slices at a time (Ketcham and Carlson, 2001). The x-ray signal efficiency is dependent on the size of the focal spot as well as the spectrum and intensity of the energy produced. Adjusting any of those three parameters will adjust the resolution of the scan produced and can be shifted to optimal levels for different rock types and materials. Higher-energy x-rays are better for denser materials, but result in less clear definition of density change boundaries (Fig. 13).

Our samples were scanned with the xRadia microxCT scanner at the University of Texas at Austin High-Resolution X-Ray Computed Tomography Facility. UTCT does the necessary preparation of samples, then calibrates the detectors for the ideal collection of each individual sample, and mathematically reconstructs the x-ray signal detected to a series of 2-D slices (Ketcham and Carlson, 2001). Typically, rock samples require little preparation beyond a cylindrical core shape. The detectors must be calibrated for rock type, as well as the number of rotations (i.e. views) the sample will undergo. Reconstruction is the most complex step of the process, as the values used change based on the material scanned and the overarching goal of the scan (Ketcham and Carlson, 2001).

L05-06 and L05-07 were scanned at a resolution of 32.09 µm, while L12-05-08 were scanned at a resolution of 36.09 µm. This means that each pixel in an individual slice is, for example, 32.09 µm x 32.09 µm while the individual slices are 32.09 µm apart. The main phases of the sample cores in this work are
pseudotachylyte, quartz, feldspar, and biotite. Quartz and feldspar have similar attenuations beams at an energy of 70 kV (the scan energy of all of our samples) so they are not always distinguishable from one another. However, pseudotachylyte, biotite and quartz/feldspar (as a pair) have significant enough differences that they are easily identifiable.

Even with this enhanced calibration for individual samples, the system is not foolproof. Three types of artifacts are common: beam hardening, ring, and starbursts. The resultant scans have some artifacts, most notably, beam hardening and starburst – however, these have little significance on our work because our area of interest is the pseudotachylyte surface. Beam hardening lightens the edges of the sample, but does not change its essential composition, which means it has no effect on visualizing the fault surface. The starbursts, or individual bright spots with a star-like shape, are sporadic and only infrequently come near the fault surface, so very rarely affect the interpretation of the fault surface. Ring artifacts, or concentric rings of light, are minimized in these samples because of the use of a light filter.

Before segmenting the pseudotachylyte, images are preprocessed to reduce noise in later analyses. Full sets of slices were loaded into the program ImageJ (freeware from NIH). The scans were cropped to the smallest possible size that still contained the full core volume. Scans were then processed with a median filter set to radius 3. A median filter processes the image pixel by pixel, replacing the value within each pixel by a median of the pixels within a set radius. Median image filters are ideal for this study because they reduce noise while still maintaining the integrity
of edges within the image (Arias-Castro and Donoho, 2009). The scans are then ready to be segmented to extract an interpolation of the fault surface.

**IIIc. Fault Extraction**

![Fig. 14](image)

Fig. 14: 1. Original sample core 2. CT scan of sample core 3. PT segmentation within CT scan of core 4. Segmented PT, ready for analysis.

To analyze the microroughness of the fault, we need to extract the fault surface from the CT data. The fault surface is the contact between the pseudotachylyte and the wall rock. Accurately identifying the edge of the pseudotachylyte within the CT volume gives a map of the location of the fault edge within the volume. A visualization of the steps to process the sample up to and including this point is shown in figure 14.

**IIIc.i. Avizo®**

The first pass analysis of the fault surface was done qualitatively by hand through the program Avizo Fire® (for this work, edition 7.1 was used). Avizo Fire® is designed to visualize 3-dimensional materials structures (Avizo). The scans were loaded into the program and then segmented using the edit label field function. Manual segmentation was done every 20 slices in the X-Y plane.
A combination of the blow tool and the brush tool from the Avizo® segmentation editor was used to segment the pseudotachylyte from the surrounding host rock. The brush tool is a manual tool that allows you to “paint” voxels in to add to the material selection. The blow tool functions as a combination of an automatic and manual tool. One selects the region, and increases the size of the selected polygon. However, the tool itself selects only voxels with a similar gray-scale to the initial region while avoiding selecting voxels with significantly different values. The blow tool starts as a circular shape and is designed to expand to a larger degree when further from the initial selection point or when selecting homogeneous gray scale values. Because our data is a long, thin rectangle, the blow tool worked best when used multiple times (~20) along each edge. The brush tool could then be used to fill in any pseudotachylyte that was not selected between the two edges.

The advantage of using the blow tool as a part of the manual first-pass analysis is that it uses thresholding to decide which voxels it is going to select. This enhances the accuracy of the manual segmentation, and leads to less error when using the manual segmentation as a basis for the mathematical segmentation in later steps.

Once the entire volume has been segmented every 20 slices in the XY plane, one creates an approximation of the entire fault surface. Clasts were included as a part of the pseudotachylyte when segmenting unless the clast was embayed in the fault surface. This was done to avoid error in edge interpretation in later steps. All the segmented sections are selected and the Avizo® command “fill holes” is run. This fills any holes in the interpretation, which prevents accidental errors of edge detection within the volume. Next, the Avizo® command “interpolation” is run to connect the
slices and create a 3D volume of the pseudotachylyte. The interpolation of the pseudotachylyte is saved as a “.labels” file, which is a 3-D binary file with a “0” every voxel when there is no segmented PT and a “1” every voxel when there is segmented PT.

Ideally, after this step, every voxel within the volume with pseudotachylyte has been identified and labeled as such. To refine the edge identification, the label map and image are exported to MATLAB to be run through a custom script to determine the most likely location of the edge.

IIIc.ii. MATLAB

The MATLAB script (Appendix B) is designed to use the Avizo interpolation of the pseudotachylyte surface as a base for an edge detection algorithm to determine the edge of the pseudotachylyte. The output is the surface of each side of the pseudotachylyte, as well as a map of the mineralogical composition of each surface. These pieces of data will then be used to analyze the roughness of the fault surface using two methods, which will be covered in the next section of this work.

The script includes the following steps: 1. data pre-processing (reshaping from 4-D to 3-D, defining dimensions); 2. identify the top and bottom edge of the pseudotachylyte from the initial Avizo® interpolation; 3. use the Canny edge detection algorithm to identify edge pixels in 2D slices; 4. find the difference between the two edge interpretations and reject all edges beyond a certain threshold – this step creates a best-fit surface for the top and bottom edges; 5. identify the mineral composition of the top and bottom surfaces based on mineralogy; and lastly, 6. find the best fit plane and subtract it from the surface DEM.
The data exported from Avizo® is in 4-D and needs to be in 3-D for our calculations. The first step is to reshape the data to 3-D. The dimensions of the data are defined in this section of the script, as well as the threshold for maximum distance between the initial edge and the Canny edge detection.

The Avizo® label map is then read in to identify the edges of the manual interpretation by finding the first non-zero voxel in each column. The data is then flipped to do the same for the bottom edge of the pseudotachylyte. The edges created by the first non-zero voxel are used as the initial guess for the edge of the pseudotachylyte. At this point, any zero voxels are converted to NaN values.

The image matrix is then run through a Canny edge detection filter, which was developed to be the “optimal” edge detector algorithm, especially for noisy data (Canny, 1986). MATLAB has a pre-written Canny edge detection algorithm that was used on our data (Mathworks, 2013). The data is first processed to reduce noise by using a Gaussian filter, which creates a slightly blurrier image. The Gaussian filter can be adjusted; smaller filters “smear” a lesser number of pixels. MATLAB® picks an automatic filter size, but one’s own parameters can be used as well. We used MATLAB’s preselected parameters because we found after testing there was no significant difference between a number of input values for the size of the Gaussian “smear” and their default values. The filter size used by MATLAB was √2 pixels.

After smoothing, the edge and edge direction are found by using four filters to detect intensities in the horizontal, vertical and diagonal directions. The edges are traced throughout the volume, selecting all points above a certain threshold. The threshold is another value that is either automatically chosen by the MATLAB
function or can be input by the user. Again, seeing no significant difference between the default values and test values, we used the MATLAB default value of 0.1563. The result was several clear edges.

The location of the edges from Canny and the edge of the pseudotachylyte from our initial interpolation were then subtracted from each other to find the most likely location for the pseudotachylyte edge. We set a threshold value of five pixels and any point in the edge that returned a value of greater than five pixels of difference between our interpretation and MATLAB’s interpretation were discarded. The resulting slice-by-slice edges are combined to create the DEMs of the PT-fault boundary surfaces.

The next step is determining the mineral present at each point of the contact between the fault surface and the wall rock. This was done by identifying each point in the image volume immediately adjacent to the fault surface and then identifying the gray scale value at that point. For 8-bit gray scale images, values above approximately 140 are labeled “2” for biotite, values below approximately 95 are labeled “1” for quartz/feldspar and values not within those parameters are labeled as “0.”

Finally, the surfaces are detrended by calculating the best-fit plane and then subtracting that value from the surface matrix. The top surface is multiplied by -1 and the bottom surface is flipped left-right so that both surfaces are oriented looking towards the fault. The CT volume is read into MATLAB with the vertical axis parallel to the edge of the core, not the edge of the fault. Therefore, we also calculate the angle of the dip of the surface as well.
IIIId. Roughness analysis

After the surface and the mineral identification matrices are created, the data is ready to be analyzed for its roughness. This is done using two techniques. First, power spectral density is calculated using the Thomson Multi-Taper method, which is ideal for fault surfaces because it characterizes the surface at multiple wavelengths or scales. Second, the relationship between the biotite elevations in comparison to the elevation of other minerals contacting the fault surface is analyzed.

IIIId.i. MATLAB® - PSD

Power spectral density is a description of how the power of a signal – in our case, the roughness – is distributed over different scales (Thomson, 1982). Because faults exhibit roughness at different scales, PSD is a useful method to examine the roughness of a fault surface across many magnitudes of scale (Power, 1987; Power, 1988; Candela, 2009). We chose the Thomson Multi Taper Method of calculating PSD because it has been used before successfully to identify fault roughness with the least amount of noise (Bistacchi, 2011). The data produced at the end of the last MATLAB script is ready to be analyzed using PSD because it has been fit to a best-fit reference plane. One further step to avoid distortions in the data was masking each size sample (with the exception of L12-06, which had a smaller mask due to an injection vein) with the same size mask so PSD plots would plot all data on the same range of wavenumbers.

The script used for the PSD analysis prepares the data to be interpreted in both the x and y directions. These roughly correspond to the slip-parallel and the slip-perpendicular directions on the fault surface, respectively. The multi taper method is
used first column-by-column and then row-by-row, outputting slip parallel and perpendicular plots.

The multi taper method works by adapting the traditional method of Fourier transform to prevent data bias by providing multiple tapers to prevent leakage (Lee and Parks, 1995). The data is divided into individually tapered overlapping sets and Fast Fourier Transform is applied to each set; all sets are combined for the final approximation. The tapers are orthogonal and are the Slepian sequences of K number of tapers. Slepian sequences were developed as a family of window functions used in multitaper analysis if one could expand the main lobe (the window), which in filter construction means $2\pi /\text{the width in samples}$, an amount n (Slepian, 1983). These sequences are calculated to be the best possible fit for the length of the input signal and the change in lobe size (n); the corresponding eigenvectors (orthogonal to each other) compute independent estimates that are then averaged together (Press, 2007).

The multi taper method is implemented in MATLAB as the built-in function `pmtm`, where the input is the signal (x), time half bandwidth product (nw), which controls the frequency resolution of the estimate because $2\text{nw} - 1$ Slepian tapers are used, and the number of points in the transform (nfft). The maximum is 256. We used nw = 4 and nfft=256 which are the default and maximum, respectively.

The output is plotted on a log-log graph and represents the grain-scale roughness at approximately x=log10³, centimeter scale at x=log10⁴, and outcrop scale at x=log10⁵ when the units are in microns.

IIIId.ii. Biotite elevations
Biotite, along with other mafic minerals, has been observed to preferentially melt during non-equilibrium melting such as the pseudotachylyte formation process while other minerals present in host rock (ie, quartz and feldspar) resist melt and become clasts (Sibson, 1975; Maddock, 1983; Spray, 1992, 1993; Di Toro and Pennacchioni, 2004). Therefore, areas of the pseudotachylyte surface with embayed or recessed biotite grains relative to the surrounding material are hypothesized to be areas of melt production. Our samples come from a variety of fault orientations, and are expected to have differing levels of recessed biotites. To analyze the elevation of biotite in comparison to the elevation of other minerals present on the fault surface, we used a series of steps in ArcGIS.

The mineral identification map and the surface data are converted from the .asci file to raster data. The mineral map is converted from raster to polygon. Then, a series of buffers are applied to 1. Isolate the polygons identified as biotite; 2. Buffer – 3 to rid the data set of all polygons smaller than 6 in diameter and reduce edge effects; 3. Buffer by 3 to include the edges of the grains while reducing edge effects, which may not have been identified because of lower gray scale values; 4. Buffer 5 out to create a buffer of the outside realm; 5. Clip this buffer by the +3 buffer to get rid of overlap; 6. Input the DEM of the surface and the biotite regional polygons to zonal statistics as a table; Re-run with the outside realm polygons (Fig. 15). The output is two tables, one with the elevations of all the biotite grains and one with the relative elevation surrounding each biotite grain. Each surface has between 20-120 individual biotite grains.
At this point, paired topographical/mineralogical maps for each N/S surface of every sample can be produced, indicating the surface mineralogy and its equivalent topography. These show the biotite grains and their relationships with recessions and valleys in the topography of the fault surface. However, the elevation differences can also be quantified by comparing the mean elevation value from the interior of a biotite grain with the mean elevation value of the outside realm adjacent to the grain. The ID field from the biotite elevation table and the surrounding elevation table are matched, and the surrounding elevation mean is subtracted from the biotite elevation. A negative value represents a recessed biotite, while a positive value represents a raised biotite grain. To visualize the mean elevations, we displayed the difference values in histograms for each surface.

However, to accurately decide if surfaces had significantly different median biotite elevations, we turned to the Wilcoxon rank-sum test, a statistical test hypothesizing the median of the two populations is equal (Mann and Whitney, 1947).

Fig. 15: The ArcGIS workspace after buffering for the interior of biotite grains (purple) and the exterior realm (yellow) for elevation comparisons.
Wilcoxon rank-sum is ideal for this data set, because the distribution of the data does not need to be known and the number of input values for population x and population y does not need to be equal (Fay and Proschan, 2010). It also is less likely to be distorted by noise because the test is based on the rank of the individual values found by putting them in ascending order. Wilcoxon rank-sum is equivalent to the Mann-Whitney U test. The test is a part of the MATLAB ® statistics toolbox, and the input is the two populations to be compared and the output is a p value. We accepted the hypothesis as true at the 70% level to allow for fluctuations due to error in data processing.
IV. Results

IV.a. Visuals

As a part of the analysis process, each sample was visualized in a variety of ways. Slip parallel thin sections were taken from representative spots within the sample core for microscopy work (a in all figures). Slip parallel CT scans are provided for comparison between CT and thin section perspectives (b in all figures). The CT scans are used to segment out the fault, seen in purple, as well as create a volume rendering of the core (c in all figures). The north and south fault surfaces are determined from the MATLAB script and projected as a DEM to show the overall surface topography (d, S in all figures). These surfaces, with masks, were used as the base for the PSD plots presented in IV.b. Representative areas from the DEM surfaces paired with a mineral identification map to show the elevation relative to the mineralogical composition at various points (e, S in all figures). The paired plots were used as the basis of the biotite elevation analysis presented in IV.c.

L12-05 is representative of the extensional section of the fault, and this is clear by looking at the thin section, CT slice, and volume rendering simply due to the thickness of the vein within the sample (Fig. 16). One does see the need for masks within the PSD plot because of the distortion at the edges of the southern surface of the sample. This is due to the angle at which the vein edge was cut at the base of the sample.

L12-06 is also representative of the extensional section of the fault, though this is not immediately clear (Fig. 17). As the volume rendering of the sample shows, the fault at the surface is much thinner and almost looks contractional, but expands
quickly in the dilational zone. The DEM surface of the fault shows areas that need to be masked, specifically the dark blue (representing a valley) injection vein. This sample also has distortion around the edges of the DEM.

Fig. 16, above (scale for d: 7000/-1000 microns) and Fig. 17, below (scale for d: 2000/-2500 microns): a. slip parallel photomicrograph b. slip parallel CT slice c. volume rendering of sample core, fault in purple d. southern fault surface e. southern fault surface mineralogy
L12-07 is a classic contractional example, with a fault vein so thin there are no data points in places where it cannot be identified in the volume (Fig. 18). The surface also reflects a large crack orthogonal to the fault plane, which was masked during analyses. The mineralogical map shows signs of biotite recession. There is little distortion around the edges of the DEM, so a large part of the surface can be used for PSD analysis.

Fig. 18: a. slip parallel photomicrograph b. slip parallel CT slice c. volume rendering of sample core, fault in purple d. southern fault surface e. southern fault surface mineralogy. Scale for d: 1500/-600.
L12-08 is from the neutral section of the fault (Fig. 19). Volume rendering shows a consistently wide, medium thickness fault. The mineralogical/topographical map exhibits recessed biotites very clearly on this surface, which is confirmed by quantitative analysis in section IV.c.

Fig. 19: a. slip parallel photomicrograph b. slip parallel CT slice c. volume rendering of sample core, fault in purple d. southern fault surface e. southern fault surface mineralogy. Scale of d: 1400/-700
IV.b. PSD plots

Power spectral density is plotted for the north and south surfaces of every sample, represented with solid and dotted lines, respectively. The y-axis is the power, while the x-axis is the wavenumber. Wavenumber is \(2 \pi / \lambda\). Samples from contractional bends are warm colors (red/orange), extensional bends cool colors (purple/blue/green) and the neutral sample is grey. PSD was calculated in the slip parallel and slip perpendicular directions, represented with thin and thick lines, respectively.

The units are in microns, so that a wavenumber of \(10^3\) represents millimeter or grain scale, \(10^4\) represents centimeter or sample scale, and \(10^5\) represents meter or outcrop scale. Overall, PSD analysis of the samples plotted before \(10^{2.5}\) on the x-axis is unreliable because it is approaching the resolution of our data at several times the 32-36 micron voxel scale. PSD analysis above approximately \(10^{4.5}\), corresponding with 3.16 cm, is also out of our range, as our samples have a maximum diameter of 3.2 centimeters. The plots have lines with slope 1, 2, and 3 (3 is solid, the others are dashed) to compare differing slopes.

Figure 20 plots all the southern surfaces on one plot and all the northern surfaces on another; because there are 24 plotted surfaces (12 slip perpendicular, 12 slip parallel) it is difficult to view them easily on one plot. One can see that there is no data before \(10^{2.5}\), while the slope breaks after \(10^{4.5}\). A consistent trend on both the southern and northern plots over all plotted wavelengths is the slip perpendicular (thicker) PSD is higher on the plot. A surface that is rougher than another plots higher
on the PSD plot; therefore, we conclude that the fault at all locations is rougher in the slip perpendicular direction than in the slip parallel direction.

When considering just the scale $10^{2.5}-10^3$ wavenumber, it seems the extensional section is rougher than the neutral in both the slip perpendicular and slip parallel directions on both sides of the fault and the contractional in the slip parallel direction. Both the extensional and neutral sections have several peaks and inconsistent slope (a value a little less than 2) with the rest of the PSD plot, not seen in the contractional samples. Peaks in this range are only present in the slip perpendicular direction and not seen in the slip parallel direction. On the scale $10^3$-

![Fig. 20: Northern/Southern PSD plots: southern plot to the right and northern plot to the left.](image)
$10^{4.5}$ wavenumber, the contractional surfaces, specifically the contractional surfaces in the slip perpendicular direction, are rougher than any other surfaces and have a slope around 2 that decreases slightly as wavenumber increases. After $10^{4.5}$, the slope breaks in all samples because we have reached the diameter of the sample and, therefore, the maximum length in the x direction.

Other trends on the plots can be viewed more clearly when plots are separated into fault orientations. Figure 21 plots the PSD by extensional (a), contractional (b), and neutral (c) orientations. The graph properties are the same between figures 20 and 21 and are plotted on the same axes.

Fig. 21: Extensional (left), contractional (middle) and neutral (right) PSD plots.

In this plot, it is clear that between sub-grain scale and grain scale ($10^{2.5}$-$10^3$), the extensional samples are rougher in only the slip perpendicular direction with no easily fit slope because of multiple jagged peaks closest to a slope of 1 (a). The neutral samples exhibit the same trend, also exclusively in the slip perpendicular direction (c). The contractional samples do not; these avoid the tapering off in slope.
seen in the other two orientations as well and have the same slope, approximately 2, as seen in from $10^3$-$10^{4.5}$ (b).

From grain scale to sample scale ($10^3$-$10^{4.5}$), the extensional samples show a uniform slope across all variables, though slip perpendicular plots slightly above slip parallel. However, this surface is above, and therefore rougher than, the plot shown of the contractional samples in the slip parallel direction in (b). The green-grey plots are from sample L12-06, which has both a smaller diameter and a smaller masked area used for PSD analysis, breaks in slope earlier than the other samples. The neutral samples have a slope lower than 2, and therefore are less rough than the other two fault orientations.

IV.c. Biotite elevation statistical analysis and histograms

Our second method of quantifying the surface roughness produced two quantitative results: first, histograms of the mean elevation difference in microns between biotite grains and the plane surrounding; and second, a table of the rank sum analysis indicating which surfaces are statistically similar at the 70% level.

![Fig. 22: Biotite elevation histograms, extensional to the left](image)
Histograms are shown grouped by fault orientation – extensional (a), contractional (b) and neutral (c) (Fig. 22). Neutral and contractional samples have histograms centered in the negative mean elevation values, indicating that these samples have recessed biotite. Extensional samples are not clearly recessed and instead their histogram is centered, indicating these samples do not have significantly recessed biotite and instead have a distribution of both recessed and non-recessed grains. The extensional graph does not include the sample L05-07, because it contains cataclasite on one side of the surface, obscuring the biotite recession measurement.

Fig. 22: biotite mean elevation value histograms.
Table 2 displays the rank sum test; samples that are statistically similar at the 70% level (or a p-value of .7 or higher) are identified as statistically similar. Few samples were statistically similar on the north and south sides of the fault. Instead, samples within each fault orientation and on the same side of the fault experienced a similar biotite mean elevation if, in rare cases, a statistically similar mean biotite elevation distribution was found.

### Table 2

<table>
<thead>
<tr>
<th>Sample nos.</th>
<th>Comparison</th>
<th>p-value</th>
<th>Significantly similar?</th>
</tr>
</thead>
<tbody>
<tr>
<td>0506 N/S</td>
<td>Contractional, same sample</td>
<td>3.90E-04</td>
<td>No</td>
</tr>
<tr>
<td>1207 N/S</td>
<td>Contractional, same sample</td>
<td>2.27E-05</td>
<td>No</td>
</tr>
<tr>
<td>1205 N/S</td>
<td>Extensional, same sample</td>
<td>0.766</td>
<td>Yes</td>
</tr>
<tr>
<td>1206 N/S</td>
<td>Extensional, same sample</td>
<td>0.8683</td>
<td>Yes</td>
</tr>
<tr>
<td>1208 N/S</td>
<td>Neutral, same sample</td>
<td>0.556</td>
<td>No</td>
</tr>
<tr>
<td>0507/1205 N</td>
<td>Extensional, same side</td>
<td>0.93</td>
<td>Yes</td>
</tr>
<tr>
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<td>Contractional, same side</td>
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<td>No</td>
</tr>
<tr>
<td>1208/0507 N</td>
<td>Neutral vs. extensional</td>
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<tr>
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<td>Extensional vs. contractional</td>
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</tr>
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</table>

Table 2 shows that statistical similarity of medians of mean biotite elevation differences is not common.

### IV.d. Stress modeling adaptation

Griffith, 2010, modeled the maximum compressive stress on this fault at a frictional coefficient of 0, indicative of a lubricated slip surface. Our samples are projected onto this model (Fig. 23). The modeled stress values are representative of
this fault after pseudotachylyte was produced, as melt is hypothesized to cause slip lubrication (Di Toro, 2009). One consideration when viewing our samples on this model is the location of L12-05 and L12-06 and their respective stresses; the model parameters were determined from the geometry present at the surface. Both of these samples entered a dilational zone representative of an extensional jog just below the depth of the surface. These samples should then be assumed to have the lowest level of compressive stress due to their location, a value of approximately 100 MPa rather than the value plotted in the model, which is approximately 300 MPa.

\[ \mu = 0.0 \]

Fig. 23: maximum compressive stress model adapted from Griffith, 2010.

The neutral fault section plots with PSD at the lowest slope of any of the orientations with a slope of less than 2, signifying that it is measurably less rough than the other samples. This is despite having a higher level of compressive stress (~200 MPa, Fig. 25) and a negatively trending mean biotite elevation histogram (Fig. 23). There is no similarity between these biotite elevation values and any others on the fault.

The extensional fault section experiences the lowest level of compressive stress, at ~100 MPa, but its roughness on PSD graphs plots higher than samples from the neutral section with a slope of slightly higher than 2. The results of the biotite
mean elevation values statistical test led to very little similarity between values for any pair of sample surfaces, except homogeneity across the extensional jog. Biotite does not show a trend of recession or non-recession on the extensional jog fault surface.

Contractional samples experience the highest compressional stress, between 500-700 MPa. These samples have a PSD slope close to 3 and the most marked trend in negative values on the biotite elevation histograms, though there is no statistical similarity between the biotite mean elevations between any of these surfaces.

Therefore, samples undergoing higher levels of compressive stress (above ~100 MPa) have evidence of preferential melting of biotite, but the roughness of the surface varies from a PSD with a slope of close to 3 for contractional to less than 2 for neutral. However, samples undergoing the least amount of compressive stress, the extensional samples, have a higher PSD roughness, but no marked evidence for preferential biotite melt.

IV.e. Error

In any scientific analysis, there is a likelihood of error. In this particular study, a few limitations to consider when evaluating the work as a whole are: the masks used on the topographical surfaces, the size of the buffers used to calculate the biotite elevation difference, the method of identifying the mineralogy in the MATLAB script, and the cataclasite on the southern surface of L05-07.

However, error was reduced as much as possible via a few differing techniques. The masks were all the same size for samples with the same diameter except for L12-06, which was noted above. The biotite elevation buffers erred on the
side of conservative rather than liberal and were clipped to avoid overlap. The threshold values for mineralogy were changed sample-to-sample; any other method of identification would significantly increase the calculation time. The southern side of L05-07 was ignored in biotite elevation results to avoid possibly inaccurate values.
V. Discussion

The roughness found on the micro scale (sample surface, rather than full fault surface) in past work was based on 1D fault traces from single slices of thin section for each sample. Essentially, CT analysis is the same – fault trace on a slice- but each sample has 800-1300 fault traces generating much more data than is possible via thin section analysis. Any distortion due to interpretive error or fault slice selection is reduced because of the significantly greater sample size. The previous PSD work in Griffith, 2010 calculated lines that were much less smooth, with jagged peaks. Best-fit lines placed the slope of samples from this fault close to 1 when measured locally; this is a bit lower than our projected slopes of approximately 2. The difference between data sets can be explained in two ways: first, the best fit line offers a better, more specific approximation of slope, and second, the noise in the thin section data is reduced when approximately 5,500 fault traces are used for PSD instead of 5. A combination of these explanations most likely accounts for this difference in data.

To sum the results found from our analyses, extensional faults show higher roughness, but no preferential melting of biotite. Neutral samples show lower roughness, with preferential melting of biotite. Contractional samples show the highest slip perpendicular roughness and most marked preferential melting of biotite.

The three different pairs of results show the evolution of microroughness across different stress levels on one fault surface. Roughness on the fault surface before slip originated from the roughness of the precursor joints in this fault zone (Bistacchi, 2011). After the initial fault slip, the friction produced by the initial roughness led to communution of the wall rock on the fault surface, which eventually
evolved into frictional melting. Melt production is interpreted to come from areas of the fault where there is evidence of biotite embayment, an artifact of preferential melting of biotite from non-equilibrium melting processes like friction-controlled fault slip (Nielsen, 2010). Geometry of the fault affected the stresses present on different sections of the fault. The fault has natural waviness, and consequently some bends pulled apart to create reservoirs that were filled with melt while others were compressed to create areas of high stress.

Samples from the extensional jog had the least frictional wear from fault slip because the fault pulled apart during slip and filled in with melt. The length of fault slip was approximately the length of the extensional jog, so samples from either side of the fault in this section likely spent little time under extreme compressive stress. One exception would be the southern surface at the western end of the extensional jog because the fault is right-lateral. Sample L05-07 is illustrative of the southern fault surface at this point and exhibits characteristics not representative of extensional samples. The northern surface of L05-07 is like the other extensional samples and has significantly statistically similar mean biotite elevations as L12-05.

The measurements of biotite elevation and PSD roughness reflect these claims about the extensional section. The PSD roughness is higher than that of a sample from the neutral section of the fault because there was little wear, so the roughness represents the roughness derived from jointing, not from friction on the fault surface. Biotite is at a similar elevation as the surrounding quartz and feldspar, suggesting melt was not produced within this area of the fault surface; the biotite elevations should be similar to their distribution before faulting on all extensional samples. It
seems this is the case, as there is statistical similarity of the biotite elevations in just extensional fault samples from both the north and south surfaces.

Directly adjacent to the extensional bend on the fault is a contractional bend, exemplified by higher roughness levels on PSD plots in the slip perpendicular direction, with smoother, lower roughness levels in the slip parallel and negative median biotite elevations. As the extensional bend pulled apart, compressive stress heightened on the contractional bend, leading to maximum compressive stress values of 700 MPa. No two surfaces from this section had statistically similar biotite elevation values but all had negative median biotite values, supporting that the bend was an area of high deformation and likely an area of melt production.

Slip perpendicular roughness is higher than slip parallel values for all contractual samples. Slip parallel values from extensional samples are higher than those of from contractual samples. Compressive stress was high enough to wear the surface of the fault in the slip parallel direction so it became more smooth than its original roughness, assumed to be represented in the extensional slip parallel surfaces. However, compressive stress was also enough to create fault striations that led to significantly higher roughness in the slip perpendicular direction.

The neutral section characterizes a balance of the two other fault orientations. Compressive stress was high enough to smooth the surface of the fault so the surfaces have a low slope and therefore are smoother at a longer wavelength when PSD is calculated, but high enough that the biotites have begun to preferentially melt and melting is produced in this area. Melt production further lubricates the fault, leading to a continually steady low level of stress.
V. Conclusions

Past studies of microroughness of pseudotachylyte-bearing fault surfaces on the micron to centimeter scale have relied on 1D fault traces to quantify the roughness of the surface. In this work, we attempted to expand the understanding of microroughness of fault surfaces by studying 3D DEMs of extracted fault surfaces. This method of quantifying roughness is advantageous because it uses approximately 1100 times more data than methods used in previous work (e.g. Griffith et al., 2010).

Changes in roughness on the fault surface seem likely to be correlated to the stress level reflective of the fault orientation at that point. The changing stress is reflected in the presence of evidence or lack of evidence of fault striations, fault smoothing, trends within one surface indicating preferential melting of biotite, and statistical similarity of biotite elevation across surfaces. The microroughness of the fault evolves as the fault orientations change in the fault zone.

There is strong evidence that preferential melting is one source of fault surface roughness. The significantly different roughnesses seen in contractional section samples in comparison with one another versus the similarity between extensional samples in comparison with one another suggests that the stresses control the preferential melting. One consideration is biotite recession appeared in both the roughest and least rough fault sections analyzed. Further investigation of the normal stress on the straight section, as well as assessing the possibility that fault wear is more significant in roughness production in straight sections, is needed to clarify this result.
Because the changing fault orientation is indicative of fault roughness on the outcrop scale, it seems fair to assess that the roughness on the outcrop scale controls the microroughness at sample scale. The evolution in microroughness can then be assumed to represent the impact of roughness on the outcrop scale on the events occurring on the fault surface during and immediately after slip. Models indicate that after melt lubrication occurs on the fault surface, the friction is reduced to a point where the fault behaves like a straight fault and fault geometry no longer has an influence on fault behavior (Griffith, 2010).

However, prior to and during the induction of melt lubrication, the fault geometry transforms separate sections of the fault surface in distinct ways. Microroughness in the contractional section in the slip parallel direction indicates high levels of wear, a direct effect of the overall fault geometry before weakening due to melt lubrication. Both neutral and extensional samples do not exhibit these characteristics. Small-scale microroughness, though not a control on the behavior of the fault as a whole, is evidence of the impact of the larger fault geometry on fault behavior in creating melt lubrication and inducing fault weakening after slip is initiated.
VII. References


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VIII. Appendices

Appendix A: Field notes

Wavy fault figure from Griffith 2010
Saturday, August 25, 2012
6:51 AM
Wavy fault sample L12-05

Friday, August 24, 2012
3:35 PM

Taken between L05 07 and L0506

L1205
Dip direction 111 dip 36 of outcrop
Fault 215 dip 67
Trend and plunge of hole 304 52
at cast at of extensional Jog
Thoughts 8/25 am
Saturday, August 25, 2012
6:40 AM

Status

Day 1 explored entire area
Day 2 returned to faults near path and determined that most, if not all, have too complicated histories including abundant cataclasite.

Samples collected so far:
2 broken samples from weathered fault
2 samples from faults with variable offsets that juxtapose aplite/tonalite
Started drilling wavy fault to capture location where south wall has just entered the pt reservoir and south side has always (?) Been in pull apart.

To do:
Return to sample location 1 to get GPS location, describe sample
Continue drilling at wavy fault to fill in details. Can we constrain the slip?

Where next?
Across river to find horsetails? Did Giulio find them?
Return to location 1 to sample entire slip distance on one fault?
L12-06
Saturday, August 25, 2012
11:45 AM

Dip direction 209  dip 74 north side of fault
Outcrop surface 111 36
Hole t&p 122 52

Just past extensional Jog
Surface 110 31
Fault 205 69
Core 274 74

Contractional bend in fault
Fault 211 72
Hole 275 53
Core below surface

Straight section of fault
We have 4 samples from the wavy fault ~5 cm x 2.5 to 3.5 cm. These cover the extensional jog, the contractional bend, and the straight section, as well as a second sample that is transitional from the extensional jog to the contractional bend. The thought is that these samples span a range of fault normal stress values and will thus have a range of friction/melting behaviors.

We have 2 (?) intact samples from location 1 on ~12 cm slip faults, ~10 degree variation in orientation. One is tonalite/tonalite, the other is tonalite/aplite.

Thought was to collect samples to quantify:
1. Change in microroughness with change in normal stress (as above in Niemeijer, 2011)
2. Change in microroughness with change in slip (ideally on a single fault from tip)
3. Total wear across 2x slip distance
Appendix B: Matlab scripts
1: Avizo_edge – find the edge of the PT and create fault surface
   % new script to load data from Avizo, convert to 3D, and find PT edges
   % note that matrix axes are transposed from image axes

   % set thresholds
   thresh = 5;
   mt = 5;
   bio = 115;
   qf = 95;
   CELLSIZE = 36.04;

   % load image and labels
   load('A.mat');
   load('B.mat');

   % find size
   [~, ydim, xdim, zdim] = size(Avizo_A_mat);
   y = 1:ydim;  % define vector of rows
   x = 1:xdim;

   % create output surface arrays
   topsurf = zeros(zdim, xdim);
   botsurf = topsurf;
   topmin = topsurf;
   botmin = topsurf;

   % convert 4D variables to 3D
   A = reshape(Avizo_A_mat(1,:,:,:), ydim, xdim, zdim);
   B = reshape(Avizo_B_mat(1,:,:,:), ydim, xdim, zdim);

   % create a matrix filled with row values (for distance calculation)
   row = repmat(y', 1, xdim);
% loop through x-y slices

for j=1:zdim

    img=reshape(A(:,:,j),ydim,xdim);
    lbl=reshape(B(:,:,j),ydim,xdim);
    edg=edge(img,'canny');
    edg=double(edg);
    edg(edg==0)=NaN;

    % find initial guess row indices by column
    % top
    idxt = mod(sum(cumprod(double(lbl ~= 1),1),1)+1,ydim+1);
    idxt(idxt==0)=NaN;

    % bottom
    idxb = ydim-mod(sum(cumprod(double(flipud(lbl ~= 1)),1),1)+1,ydim+1)+1;
    idxb = idxb.*(idxb<=ydim); % convert values greater than ydim to 0
    idxb(idxb==0)=NaN;

    % find nearest edge pixels
    % create matrices of top and bottom row indices repeating in columns and subtract from rows to get in-row distance
    top = repmat(idxt, ydim, 1);
    bot = repmat(idxb, ydim, 1);
    top = row-top;
    bot = row-bot;

    % find distance to edge pixels
    top = top.*edg;
    bot = bot.*edg;

    % find nearest non-zero value by column, calculate distance, reject edges > threshold away from initial, and add back to initial interp, then determine mineralogy
    [~, I] = min(abs(top),[],1);
temp = top(sub2ind([ydim,xdim],I,x));
temp(abs(temp) > thresh) = NaN;
tempsurf = temp+idxt;
topsurf(j,:) = tempsurf;
mintest=NaN(size(tempsurf));
mintest(~isnan(tempsurf)) =
img(sub2ind([ydim,xdim],tempsurf(~isnan(tempsurf)))-mt,x(~isnan(tempsurf))));
mineral=zeros(1,xdim);
mineral(mintest>bio)=2;
mineral(mintest<qf)=1;
topmin(j,:) = mineral;

[~, I] = min(abs(bot),[],1);
temp = bot(sub2ind([ydim,xdim],I,x));
temp(abs(temp) > thresh) = NaN;
tempsurf = temp+idxb;
botsurf(j,:) = tempsurf;
mintest=NaN(size(tempsurf));
mintest(~isnan(tempsurf)) =
img(sub2ind([ydim,xdim],tempsurf(~isnan(tempsurf)))+mt,x(~isnan(tempsurf))));
mineral=zeros(1,xdim);
mineral(mintest>bio)=2;
mineral(mintest<qf)=1;
botmin(j,:) = mineral;
end

% replace NaN values with -9999 for Arc and save min surface

topmin=fliplr(topmin);
topmin(isnan(topmin))=-9999;
botmin(isnan(botmin))=-9999;

save('./matlab_out/topmin.txt','topmin','-ascii')
save('./matlab_out/botmin.txt','botmin','-ascii')

% create new label map by creating 3D arrays of surface x coordinates and comparing to x coordinate matrix.

C=uint8(zeros(size(B)));
temp=topsurf';
DEM1 = temp(:,:,ones(ydim,1));
DEM1 = shiftdim(DEM1,2);

temp=botsurf';
DEM2 = temp(:,:,ones(ydim,1));
DEM2 = shiftdim(DEM2,2);

[~,Y,~] = meshgrid(x,y,[1:zdim]);
C(Y>=DEM1 & Y<=DEM2) = 1;
save('./matlab_out/C.mat','C')

%save raw version of topsurf/botsurf

rawtopsurf=topsurf;
rawtopsurf=rawtopsurf.*CELLSIZE;
rawtopsurf(isnan(rawtopsurf))=-9999;

rawbotsurf=botsurf;
rawbotsurf=rawbotsurf.*CELLSIZE;
rawbotsurf(isnan(rawbotsurf))=-9999;

save('./matlab_out/rawt.txt','rawtopsurf','-ascii')
save('./matlab_out/rawb.txt','rawbotsurf','-ascii')

%thickness, raw(S-N)

th= botsurf-topsurf;
th=th.*CELLSIZE;
th(isnan(th))=-9999;

save('./matlab_out/rawSN.txt','th','-ascii')

%thickness, raw (N-S)

th= topsurf-botsurf;
th=th.*CELLSIZE;
th(isnan(th))=-9999;

save('./matlab_out/rawNS.txt','th','-ascii')

% subtract best fit plane and calculate dip angle
[Zm, ~, YCoeff] = fitplane_mtrx(topsurf);
topsurf = topsurf - round(Zm);
topdip = atan(YCoeff) * 180 / pi

[Zm, ~, YCoeff] = fitplane_mtrx(botsurf);
botsurf = botsurf - round(Zm);
botdip = atan(YCoeff) * 180 / pi

topsurf = fliplr(topsurf);
botsurf = -1 * botsurf;

% replace NaN values with -9999 for Arc and save surface

topsurf = topsurf * CELLSIZE;
botsurf = botsurf * CELLSIZE;
topsurf(isnan(topsurf)) = -9999;
botsurf(isnan(botsurf)) = -9999;

save('./matlab_out/topsurf.txt', 'topsurf', '-ascii')
save('./matlab_out/botsurf.txt', 'botsurf', '-ascii')

% header values for esri ascii import

% NCOLS
% NROWS
% XLLCORNER 0
% YLLCORNER 0
% CELLSIZE
% NODATA_VALUE -9999
2: psd_work – calculate the PSD of the surface

% first-pass spectral analysis using multi-taper method

ptsurf=importdata('topsurf.txt', ' ',6);

% establish basic geometric parameters from header
% first replace inf with NaN;
expstr='([-])?([d])*([.])?([d])*$';
val=regexp(ptsurf.textdata,expstr,'match');
NCOLS=str2double(val{1});
NROWS=str2double(val{2});
XLLCORNER=str2double(val{3});
YLLCORNER=str2double(val{4});
CELLSIZE=str2double(val{5});
NODATA_VALUE=str2double(val{6});
ptsurf=ptsurf.data;
ptsurf(ptsurf==NODATA_VALUE)=NaN;

% read in mask and apply
mask=importdata('topsurfmask1.tif');
mask=double(mask);
[x1,y1]=find(mask,1,'first');
[x2,y2]=find(mask,1,'last');
ptsurf=ptsurf(x1:x2,y1:y2);

% interpolate data to prepare for analysis
NCOLS=y2-y1;
NROWS=x2-x1;
ptsurf_int=ptsurf;

% interpolate to full matrix
ptsurf_fill=inpaintn(ptsurf_int);

% create x y grids
x=XLLCORNER:CELLSIZE:XLLCORNER+(NCOLS-1)*CELLSIZE;
y=(YLLCORNER+(NROWS-1)*CELLSIZE:-CELLSIZE:YLLCORNER)';
[X,Y] = meshgrid(x,y);
% psd parameters

fs=1/CELLSIZE;
nw=4;
nfft = 2^nextpow2(NROWS); % Next power of 2 from length of vec

% initialize result variable

Pxx=zeros(nfft/2+1, NCOLS);

for l=1:NCOLS % take columns one at a time
    vec=detrend(ptsurf_fill(:,l));
    % nfft = 2^nextpow2(dim(1)); % Next power of 2 from length of vec
    [Pxx(:,l),fx] = pmtm(vec,nw,nfft,fs);
end

Pxx=sum(Pxx,2)/NCOLS;

ptsurf_fill=ptsurf_fill'; % transpose and calculate psd in y-dimension

Pyy=zeros(nfft/2+1, NROWS);

for l=1:NROWS % take columns one at a time
    vec=detrend(ptsurf_fill(:,l));
    % nfft = 2^nextpow2(dim(2)); % Next power of 2 from length of vec
    [Pyy(:,l),fy] = pmtm(vec,nw,nfft,fs);
end

Pyy=sum(Pyy,2)/NROWS;

wx=2*pi./fx;
wy=2*pi./fy;

clip1=1;
clip2=1;

figure;

loglog(wx(clip1:end-clip2),Pxx(clip1:end-clip2))
hold on
loglog(wy(clip1:end-clip2),Pyy(clip1:end-clip2),'r')
xlabel('log10(wavenumber (k))')
ylabel('log10(Power)')
axis([(10^2.5) (10^7.5) (10^3.5) (10^8.5)])

xLimits = [(10^2.5) (10^5.5)];    %# Limits for the x axis
yLimits = [(10^3.5) (10^8.5)];    %# Limits for the y axis

logScale = diff(yLimits)/diff(xLimits);  %# Scale between the x and y ranges
powerScale = diff(log10(yLimits))/...    %# Scale between the x and y powers
diff(log10(xLimits));
set(gca,'Xlim',xLimits,'Ylim',yLimits,...  %# Set the limits and the
'DataAspectRatio',[logScale/powerScale 1]);

set(gca,'XTick',[(10^3) (10^4) (10^5)]);
Appendix C

Figures are: overall surface, north mineralogy, south mineralogy

*Note- in degrees

<table>
<thead>
<tr>
<th>Sample</th>
<th>Top Dip</th>
<th>Bottom Dip</th>
<th>Top</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>L05-06</td>
<td>-5.5446</td>
<td>-5.4924</td>
<td>N</td>
<td>S</td>
</tr>
<tr>
<td>L05-07</td>
<td>-8.7373</td>
<td>4.487</td>
<td>S</td>
<td>N</td>
</tr>
<tr>
<td>L12-05</td>
<td>-11.8168</td>
<td>-13.961</td>
<td>N</td>
<td>S</td>
</tr>
<tr>
<td>L12-06</td>
<td>13.4179</td>
<td>17.9022</td>
<td>N</td>
<td>S</td>
</tr>
<tr>
<td>L12-07</td>
<td>18.732</td>
<td>18.8984</td>
<td>S</td>
<td>N</td>
</tr>
<tr>
<td>L12-08</td>
<td>13.6306</td>
<td>12.8666</td>
<td>S</td>
<td>N</td>
</tr>
</tbody>
</table>

This is a table of the dip correction made in MATLAB so the surface representation was even.
LO5-06 Surface

SOUTH

NORTH
L12-06 Surface

NORTH

SOUTH
L12-08 Surface

SOUTH

NORTH

LL2-08 Surface