THE EVOLUTION OF FRACTURE SURFACE ROUGHNESS AND ITS
DEPENDENCE ON SLIP

A Thesis
Submitted to
The Temple University Graduate Board

In Partial Fulfillment
Of the Requirements for the Degree
MASTERS OF SCIENCE

by
Olivia L. Wells
July 2015

Thesis Approvals:
Dr. Nicholas C. Davatzes, Advisor, Earth and Environmental Science
Dr. David E. Grandstaff, Earth and Environmental Science
Dr Bojeong Kim, Earth and Environmental Science
ABSTRACT

Under effective compression, impingement of opposing rough surfaces of a fracture can force the walls of the fracture apart during slip. Therefore, a fracture’s surface roughness exerts a primary control on the amount of dilation that can be sustained on a fracture since the opposing surfaces need to remain in contact. Previous work has attempted to characterize fracture surface roughness through topographic profiles and power spectral density analysis, but these metrics describing the geometry of a fracture’s surface are often non-unique when used independently. However, when combined these metrics are affective at characterizing fracture surface roughness, as well as the mechanisms affecting changes in roughness with increasing slip, and therefore changes in dilation. These mechanisms include the influence of primary grains and pores on initial fracture roughness, the effect of linkage on locally increasing roughness, and asperity destruction that limits the heights of asperities and forms gouge. This analysis reveals four essential stages of dilation during the lifecycle of a natural fracture, whereas previous slip-dilation models do not adequately address the evolution of fracture surface roughness: (1) initial slip companied by small dilation is mediated by roughness controlled by the primary grain and pore dimensions; (2) rapid dilation during and immediately following fracture growth by linkage of formerly isolated fractures; (3) wear of the fracture surface and gouge formation that minimizes dilation; and (4) between slip events cementation that modifies the mineral constituents in the fracture. By identifying these fundamental mechanisms that influence fracture surface roughness, this new conceptual model relating dilation to slip has specific applications to Enhanced
Geothermal Systems (EGS), which attempt to produce long-lived dilation in natural fractures by inducing slip.
ACKNOWLEDGMENTS

I would like to thank the EGI core repository at the University of Utah, Salt Lake City for providing the Newberry Core used in this study, James Ladd for his technical support and services, Shelah Cox for her endless help and advice, David Grandstaff and Bojeong Kim for serving on my advisory committee, Nick Davatzes for serving as my advisor, providing me grants to fund this research and helping me through this process. Lastly, I’d like to thank my family, my friends, and my fellow graduate students for all of their help and support over the past few years. This study is based upon work supported by AltaRock and grants from the Department of Energy, Grant Numbers: DE-EE0002757 and DE-EE0002777.
# TABLE OF CONTENTS

Page

ABSTRACT ................................................................................................................................. i

ACKNOWLEDGMENTS ............................................................................................................ iii

LIST OF TABLES ....................................................................................................................... viii

LIST OF FIGURES .................................................................................................................. ix

CHAPTER

1. INTRODUCTION .................................................................................................................. 1

1.1 Background ....................................................................................................................... 5

1.1.1 Fracture Surface Roughness ....................................................................................... 5

1.1.2 Fracture Propagation, Interaction and Growth by Linkage of Fractures .................... 16

1.1.3 EGS ............................................................................................................................. 21

1.2 Geologic Setting .............................................................................................................. 26

1.2.1 Geothermal Potential ................................................................................................. 29

1.2.2 Geo N2 ....................................................................................................................... 30

2. METHODS .......................................................................................................................... 33

2.1 Fracture History and Surface Topography ..................................................................... 34

2.2 Power Spectral Density and Slope ............................................................................... 41

2.3 Dilation .......................................................................................................................... 43

2.4 Grain and Pore Size Correlations ................................................................................. 45

2.5 Slip History .................................................................................................................... 48
3. RESULTS ......................................................................................................................... 50

3.1 Thin Section Mineralogy ........................................................................................... 50
    3.1.1 N2-4338 .............................................................................................................. 51
    3.1.2 N2-3617FA ........................................................................................................ 52
    3.1.3 N2-3617FB ......................................................................................................... 53
    3.1.4 N2-3937FB ........................................................................................................ 54
    3.1.5 N2-4267 ............................................................................................................ 55
    3.1.6 N2-4125 ............................................................................................................ 56
    3.1.7 N2-3937FA ........................................................................................................ 57

3.2 Fracture History and Statistics of Surface Topography ............................................. 58
    3.2.1 N2-4338 .............................................................................................................. 59
    3.2.2 N2-3617FA ........................................................................................................ 60
    3.2.3 N2-3617FB ......................................................................................................... 61
    3.2.4 N2-3937FB ........................................................................................................ 62
    3.2.5 N2-4267 ............................................................................................................ 64
    3.2.6 N2-4125 ............................................................................................................ 67
    3.1.7 N2-3937FA ........................................................................................................ 69

3.3 Power Spectral Density and Slope ........................................................................... 71
    3.3.1 N2-4338 .............................................................................................................. 71
    3.3.2 N2-3617FA ........................................................................................................ 72
    3.3.3 N2-3617FB ......................................................................................................... 73
    3.3.4 N2-3937FB ........................................................................................................ 74
    3.3.5 N2-4267 ............................................................................................................ 75
3.3.6 N2-4152 ................................................................. 77
3.3.7 N2-3937FA ............................................................ 78

3.4 Dilation .................................................................. 80
3.4.1 N2-4338 ............................................................... 81
3.4.2 N2-3617FA ............................................................. 82
3.4.3 N2-3617FB ............................................................. 84
3.4.4 N2-3937FB ............................................................. 86
3.4.5 N2-4267 ............................................................... 89
3.4.6 N2-4152 ............................................................... 91
3.4.7 N2-3937FA ............................................................. 94

3.5 Grain and Pore .......................................................... 96
3.5.1 N2-4338 ............................................................... 96
3.5.2 N2-3617FA ............................................................. 98
3.5.3 N2-3617FB ............................................................. 99
3.5.4 N2-3937FB ............................................................. 100
3.5.5 N2-4267 ............................................................... 101
3.5.6 N2-4152 ............................................................... 103
3.5.7 N2-3937FA ............................................................. 104

3.6 Slip ........................................................................ 106
3.6.1 N2-4338 ............................................................... 106
3.6.2 N2-3937FB ............................................................. 106
3.6.3 N2-4152 ............................................................... 107
3.6.4 N2-3937FA ............................................................. 107
4. ANALYSIS................................................................................................. 109
   4.1 Topography ............................................................................................ 109
      4.1.1 History of Fracture Roughness ......................................................... 109
      4.1.2 Tortuosity .......................................................................................... 113
   4.2 Power Spectral Slope ............................................................................... 115
   4.3 Power Spectral Slope of Apertures ......................................................... 118
   4.4 Grain and Pore Correlations ................................................................. 120
   4.5 Slip and Dilation .................................................................................... 123
5. DISCUSSION ............................................................................................... 125
   5.1 Interpretation of Results and Analysis ................................................... 125
      5.1.1 Fracture History as a Function of Smoothing .................................... 125
      5.1.2 Grains and Pores .............................................................................. 130
      5.1.3 Slip and Dilation .............................................................................. 131
   5.2 The Evolving Role of Fracture Surface Roughness ................................. 137
      5.2.1 Results Relative to Literature ............................................................ 137
      5.2.2 Conceptual model ............................................................................ 139
   5.3 Implications to EGS ................................................................................ 141
   5.4 Summary ................................................................................................ 142
6. CONCLUSIONS .......................................................................................... 146
REFERENCES CITED ...................................................................................... 147
APPENDIX
A. MATLAB SCRIPTS AND FUNCTIONS ..................................................... 154
B. SUPPLEMENTAL DATA COLLECTED ....................................................... 218
LIST OF TABLES

Table 5.1: Table of possible combinations of fracture surface roughness characterization methods with corresponding descriptions and an example surface………………..129
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Idealized depiction of different sources of roughness</td>
<td>4</td>
</tr>
<tr>
<td>1.2</td>
<td>Standard shape profiles and corresponding JRC values</td>
<td>8</td>
</tr>
<tr>
<td>1.3</td>
<td>Graphs showing the relationship between permeability and slip distance</td>
<td>12</td>
</tr>
<tr>
<td>1.4</td>
<td>Example power spectral density procedure</td>
<td>13</td>
</tr>
<tr>
<td>1.5</td>
<td>Cartoon illustrating of linkage structures and related failure mode</td>
<td>18</td>
</tr>
<tr>
<td>1.6</td>
<td>Cartoon illustrating the growth of faults through linkage</td>
<td>20</td>
</tr>
<tr>
<td>1.7</td>
<td>Definitions and conditions of different geothermal resources</td>
<td>22</td>
</tr>
<tr>
<td>1.8</td>
<td>Varying stimulation techniques</td>
<td>23</td>
</tr>
<tr>
<td>1.9</td>
<td>Map of Newberry Volcano</td>
<td>27</td>
</tr>
<tr>
<td>1.10</td>
<td>East West cross section of Newberry Geothermal Field with locations of stimulation well 55-29 and Geo- N2</td>
<td>28</td>
</tr>
<tr>
<td>1.11</td>
<td>Locations of minerals at depth from Geo-N2 with the depth interval corresponding to the sample highlighted in yellow</td>
<td>32</td>
</tr>
<tr>
<td>2.1</td>
<td>Example delineated surfaces</td>
<td>35</td>
</tr>
<tr>
<td>2.2</td>
<td>Process for monotonic resampling shows a fracture surface intersection a pore that results in a large embayment in the fracture surface</td>
<td>37</td>
</tr>
<tr>
<td>2.3</td>
<td>Comparing resampling techniques</td>
<td>38</td>
</tr>
<tr>
<td>2.4</td>
<td>Resampled point spacing</td>
<td>39</td>
</tr>
<tr>
<td>2.5</td>
<td>Fracture cross section illustration of sample N2-3617FA</td>
<td>41</td>
</tr>
<tr>
<td>2.6</td>
<td>Graphs comparing statistics of the upper, lower, and aperture surfaces</td>
<td>43</td>
</tr>
<tr>
<td>2.7</td>
<td>Example slip indicators</td>
<td>49</td>
</tr>
<tr>
<td>3.1</td>
<td>Photomicrographs of sample N2-4338 taken under plane polarized light at 4x optical zoom</td>
<td>51</td>
</tr>
</tbody>
</table>
Figure 3.2: Photomicrographs of sample N2-3617FA taken under plane polarized light at 4x optical zoom.................................................................................................................. 53

Figure 3.3: Photomicrographs of sample N2-3617FB taken under plane polarized light at 4x optical zoom.................................................................................................................. 54

Figure 3.4: Photomicrographs of sample N2-3937FB taken under plane polarized light at 4x optical zoom.................................................................................................................. 55

Figure 3.5: Photomicrographs of sample N2-4267 taken under plane polarized light at 4x optical zoom.................................................................................................................. 56

Figure 3.6: Photomicrographs of sample N2-4152 taken under plane polarized light at 4x optical zoom.................................................................................................................. 57

Figure 3.7: Photomicrographs of sample N2-3937FA taken under plane polarized light at 4x optical zoom.................................................................................................................. 58

Figure 3.8: Fracture surface statistics for sample N2-4338...................................................... 60

Figure 3.9: Fracture surface statistics for sample N2-3617FA.................................................. 61

Figure 3.10: Fracture surface statistics for sample N2-3617FB............................................. 62

Figure 3.11: Fracture surface statistics for sample N2-3937FB............................................. 63

Figure 3.12: Fracture surface statistics for sample N2-4267.................................................. 66

Figure 3.13: Fracture surface statistics for sample N2-4152.................................................. 68

Figure 3.14: Fracture surface statistics for sample N2-3937FA............................................. 70

Figure 3.15: Power spectral density analysis of sample N2-4338 for each surface and its corresponding slope values................................................................. 72

Figure 3.16: Power spectral density analysis of sample N2-3617FA for each surface and its corresponding slope values................................................................. 73

Figure 3.17: Power spectral density analysis of sample N2-3617FB for each surface and its corresponding slope values................................................................. 74

Figure 3.18: Power spectral density analysis of sample N2-3937FB for each surface and its corresponding slope values................................................................. 75

Figure 3.19: Power spectral density analysis of sample N2-4267 for each surface and its corresponding slope values................................................................. 76
Figure 3.20: Power spectral density analysis of sample N2-4152 for each surface and its corresponding slope values. ................................................................. 78

Figure 3.21: Power spectral density analysis of sample N2-3937FA for each surface and its corresponding slope values. ................................................................. 79

Figure 3.22: Aperture distributions for sample N2-4338........................................ 81

Figure 3.23: Power spectral density analysis of sample N2-4338 for each aperture and its corresponding slope values. ................................................................. 82

Figure 3.24 Aperture distributions for sample N2-3617FA........................................ 83

Figure 3.25: Power spectral density analysis of sample N2-3617FA for each aperture and its corresponding slope values. ................................................................. 84

Figure 3.26: Aperture distributions for sample N2-3617FB........................................ 85

Figure 3.27: Power spectral density analysis of sample N2-3617FB for each aperture and its corresponding slope values ................................................................. 86

Figure 3.28: Aperture and dilation distributions for sample N2-3937FB...................... 87

Figure 3.29: Power spectral density analysis of sample N2-3937FB for each aperture and its corresponding slope values. ................................................................. 88

Figure 3.30: Aperture and dilation distributions for sample N2-4267......................... 90

Figure 3.31: Power spectral density analysis of sample N2-4267 for each aperture and its corresponding slope values. ................................................................. 91

Figure 3.32: Aperture and dilation distributions for sample N2-4152......................... 92

Figure 3.33: Power spectral density analysis of sample N2-4152 for each aperture and its corresponding slope values. ................................................................. 93

Figure 3.34: Aperture and dilation distributions for sample N2-3937FA..................... 94

Figure 3.35: Power spectral density analysis of sample N2-3937FA for each aperture and its corresponding slope values. ................................................................. 95

Figure 3.36: Grain and pore comparison for sample N2-4338................................. 97

Figure 3.37: Grain and pore comparison for sample N2-3617FA.............................. 98

Figure 3.38: Grain and pore comparison for sample N2-3617FB............................. 100
Figure 3.39: Grain and pore comparison for sample N2-3937FB. ........................................... 101

Figure 3.40: Grain and pore comparison for sample N2-4267. ............................................. 102

Figure 3.41: Grain and pore comparison for sample N2-4152. .............................................. 104

Figure 3.42: Grain and pore comparison for sample N2-3937FA. ......................................... 105

Figure 3.43: Slip and related opening for sample N2-3937FA. .................................................. 108

Figure 4.1: Topographic relief in relative age order for all seven samples. ........................... 110

Figure 4.2: Tortuosity in relative age order for all seven samples. ........................................... 114

Figure 4.3: Power spectral slopes for all samples in relative age order...................................... 116

Figure 4.4: The affects of cumulative slip on PSS of individual surfaces. ................................. 117

Figure 4.5: Power spectral slopes of apertures for all samples in relative age order............... 119

Figure 4.6: The affects of cumulative slip on PSS of apertures. .............................................. 120

Figure 4.7: Comparing grain size to asperity heights for all the surfaces............................... 121

Figure 4.8: Comparing pore size to asperity heights for all the surfaces............................... 122

Figure 4.9: Comparison of slip and cumulative dilation for all the samples. ......................... 123

Figure 5.1: Comparing slip-dilation models. ................................................................. 134

Figure 5.2: Compilation of results for Figure 4.7 and the Lee and Cho data for experiments preformed at 3 MPa of effective pressure. ............................................... 138
CHAPTER 1
INTRODUCTION

Natural fractures provide a significant source of porosity and permeability in rock. However, in reactive environments dissolution and precipitation limits this porosity which can then be renewed by repeated fracturing. Under effective compression, separation of the fracture walls results from the slip along the naturally rough surfaces, thus resulting in increased porosity. Initially, when slip is small relative to the size of the asperities the pair of fracture surfaces is nearly mated, and their separation is small. As slip continues, the resulting mismatch of the surfaces reduces the contact area between the fracture walls to a few contact points where asperities with a positive relief force the fracture walls apart. Since the fractures remain in contact at the asperities on the fracture walls, the dilation induced by this slip produces a long-lived fracture aperture. In this circumstance, as the magnitude of slip approaches the height of the largest asperities, dilation reaches a maximum. Therefore, dilation should reflect the relative length-scale of the asperities defining the roughness of the surface and magnitude of accumulated slip.

However, this scenario presumes the roughness of the fracture surfaces is static. While the slip is necessary to produce dilation, large or repeated slip can act to grind away or break asperities (e.g., Paterson and Wong, 2005), which can reduce asperity height and increase the contact area between the opposing surfaces resulting in a smaller aperture (Lee and Cho, 2002). Pressure solution produced from high pressures can also reduce the size of the asperities, but is not a result of increasing slip. This process also potentially fills the fracture with free moving fault rock that modifies the interaction of
asperities on opposing fracture surfaces, as well as filling areas of negative relief. In the time between slip events, alteration of the minerals lining the fracture walls or the fault rock can occur as well as precipitation of pore-filling cement along the fracture. Cementation reduces aperture and can reduce the connectivity of pores, which in combination reduce permeability. In addition to modifying the established fracture surface, slip eventually causes the fracture to grow providing new, fresh fracture surfaces and the potential to acquire new, possibly larger, asperities.

Understanding the complicated feedback in which fractures sustain repeated slip, grow, and dilate is critical to understanding the long-term permeability of the deep crust, seismic behavior influenced by dilatant-frictional failure in the presence of fluids, and the potential relationship between earthquake magnitude and permeability gain on faults (Lockner and Beeler, 2002; Patterson and Wong, 2005). In addition, the relationship between slip and dilation has practical implications for Enhanced Geothermal Systems (EGS) where slip is intentionally induced on natural fractures by injecting fluid in an attempt to cause fractures to dilate and thus increase permeability that can be maintained even after fluid pressure is reduced.

This work investigates the sources of fracture surface roughness and its evolution as a function of repeated slip to assess the dilation potential of in situ natural fractures. Initially, when fractures first propagate, the dominant mechanical heterogeneities in the rock are the grains and pores. Thus, the grains and pores should strongly influence the path of the fracture due to contrasts in elastic properties that locally alter stress, such as grain and contact strength (Brown, 1995) and free surfaces along pore boundaries. This implies that the dimensions of grains and pores should correlate with initial fracture
topography (Figure 1.1a). The unevenness of the topography of each of the two fracture surfaces defines a population of asperity heights relative to a flat best fitting reference plane (Figure 1.1c).

Once established, fractures are a dominant weakness in the rock and repeatedly exploited by subsequent deformation. As the fracture accumulates slip through additional slip events, a key mechanism of growth is through linkage to nearby fractures at a distance typically less than the length of the fracture (Martel and Pollard, 1989) (Figure 1.1b). This linkage step should introduce a new, potentially large and laterally extensive asperity that modifies the roughness and thus potential for dilation. In addition, linkage is a critical mechanism promoting a percolating fracture network.

These two sources of relief on fracture surfaces compete with modification of topography from wear and healing. Although slip leads to fracture growth, slip also promotes the production of fault rock by preferentially reducing the height of large asperities so that younger surfaces should have less topographic relief than older surfaces. Similarly, as zones of connected porosity, fractures preferentially host fluid flow that, in combination with freshly broken mineral surfaces and small grain sizes associated with fault rock, promote dissolution and precipitation reactions. Thus four distinct processes are anticipated during the life cycle of a fracture: (1) fracture initiation at small slip; (2) healing; (3) wear of the fracture surfaces; and (4) fracture growth through linkage.
Figure 1.1: Idealized depiction of different sources of roughness. (a) Small/initial slips propagate around grains and pores. (b) At larger slips, fractures will link and the separation distance determines the amount of linkage. (c) Profile of a pair of fracture surfaces where the aperture in the fracture is shaded in blue and aperture distribution graphed in red. Profile was taken from sample N2-3617FA.

These four processes are investigated by deducing the history of reactivation through detailed petrography of the fracture surfaces, grain breakage, and cement that preserve individual slip events. These analyses were conducted on fractures in similar rock type and depth from the GEO N-2 core hole in the west flank of the Newberry Volcano, Oregon, which implies a common stress and deformation history. The topography of individual pairs of fracture surfaces and the related apertures were
measured and characterized by the frequency distribution of topographic relief and the power spectral density (PSD) and power spectral slope (PSS) of the asperity size distribution. The topography of initial and evolved surfaces were compared to the measured grain and pore size distributions to test to what extent their dimensions influence asperity size. The evolution of fracture surface roughness and related dilation was assessed by examining the change in topographic relief as a function of relative age and slip deduced from petrographic relationships. The goal of the analysis is to provide valuable insight into the lifecycle of a fracture by defining the physical trade-off between slip, healing, wear, and linkage by carefully describing the fracture surface geometries through each of these stages during a complete history.

1.1 Background

1.1.1 Fracture Surface Roughness

Models of intact rock strength relate effective normal stress to shear stress necessary to induce failure using the linear Coulomb relationship:

\[ \tau = c + \sigma_n \tan \phi \]

Eqn. 1.1

where \( \tau \) is the peak shear strength, \( c \) is the cohesion (corresponding to the y-intercept), \( \phi \) is the friction angle, and \( \sigma_n \) is the effective normal stress (see for example Barton and Choubey, 1977, Lockner and Beeler, 2002; or Patterson and Wong, 2005). This equation emphasizes the sensitivity of inducing failure to effective normal stress, which can be interpreted to result from the tendency of brittle failure to be accompanied by dilation due to grain scale tensile failure. A similar relationship is applied to the strength of
established fracture, by dropping the cohesion term, which produces the familiar frictional failure criterion defined by:

$$\tau = \sigma_n \tan \phi$$  \hspace{1cm} \text{Eqn. 1.2}

The relationship implicitly neglects the influence of contact area between the opposing fracture walls in accordance with Amontons Law (1699) (Barton and Choubey, 1977).

However, the opposing surfaces of fractures subjected to compressive normal stresses and shear displacements typically only touch across 1 to 10% of their surface area (Dietrich and Kilgore, 1996), therefore concentrating normal stress to these contact points. The form of this equation is similar to Eqn. 1.1, but the cohesion of the intact rock (c) becomes the cohesion of the two surfaces in contact ($S_0$) and is highly sensitive to the magnitude of normal stress, thereby affecting the contact area of the surfaces (e.g., see summary in Jager et al., 2007). Another strong influence on $S_0$ is the interlocking of asperities which oppose slip and is determined by the topography of the two interacting fracture surfaces. This implies the fracture deformation behavior and shear strength strongly depend on the asperity characteristics (Barton and Choubey, 1977). For this reason, when the updated form of Eqn. 1.1 is applied to rough joints, like those found in nature, the values of peak shear strength can range over four orders of magnitude in otherwise similar materials, depending on the roughness characteristics (Barton and Choubey, 1977). In addition, experimental results yield a curved path for peak shear strength (Jaeger, 1959; Krsmanovic and Langof, 1964; Byerlee, 1967; Barton and Choubey, 1977) where the initial increase in shear strength is proportional to shear displacement until the peak shear strength is reached (e.g., see summary in Jager et al., 2007). Increasing shear displacement after the peak shear strength for a given material...
results in asperity destruction and shear softening. The curved path of shear strength and its scale dependence are therefore not accounted for by introducing a fracture cohesion term into the equation.

To capture these influences, an empirical equation describing shear strength was developed by Barton and Choubey (1977):

$$\tau = \sigma_n \tan \left[ JRC \log_{10} \left( \frac{JCS}{\sigma_n} \right) + \Phi_b \right]$$  \hspace{1cm} \text{Eqn. 1.3}

where $\tau$ is the peak shear strength, $\sigma_n$ is effective normal stress, JRC is the joint roughness coefficient, JCS is the joint wall compressive strength, and $\Phi_b$ is the friction angle. For this equation an average friction angle of 30° is assumed (Barton and Choubey, 1977). The JCS value is typically derived from the elastic rebound of the joint’s wall measured using a Schmidt hammer and converted to compressive strength (Miller, 1965). This leaves the JRC value as an empirical fitting variable. Initially it was back calculated from shear tests before being related to standard fracture surface topographic profiles (Barton and Choubey, 1977). In application, these profiles capture the essential roughness characteristics, which are strongly influenced by rock type and weathering, as well as deformation history (Barton and Choubey, 1977). From these standard profiles, JRC values were assigned ranging from 0-20 that could then be matched to field and lab samples (Figure 1.2). The roughest joints correspond to the highest values and more planar, smoother joints with little to no roughness correspond to values close to zero.
Since roughness influences dilation accumulated during slip, this roughness parameter should provide a measure of dilation potential. To measure this tendency, Barton and Choubey (1977) proposed taking the ratio of dilation (normal displacement of the fracture walls) to shear displacement (slip) to define the shear dilation angle of the fracture. The dilation angle is directly affected by the degree of roughness, where smoother surfaces dilate less compared to the rougher surfaces during shearing. Both experimental and calculated results yield dilation angles from $13^\circ$ to $27^\circ$ through the whole range of JRC values (Barton and Choubey, 1977). While these initial findings demonstrated the effects of roughness on shear strength and dilation, other factors that
evolve with slip such as degree of mating (alignment) between the surfaces, weathering or alteration, healing by mineral precipitation (Barton and Choubey, 1977), and large slips greater than 10 mm (Barton et al., 1985; Chen et al., 2000) were neglected. Essentially, the analysis captures the static characteristics of the fracture at relatively early stages of fracture formation and nominally predicts the effect of the next slip increment.

Nevertheless, the standard JRC values not only provide better estimates of rock strength and dilation, but also allow for the roughness parameter to be incorporated into equations for hydraulic conductivity (Scesi and Gattinoni, 2007). Early models of hydraulic conductivity of fractures assume laminar flow through a constant aperture between two parallel plates:

\[
\frac{Q}{\nabla h} = C(2b)^3
\]

Eqn, 1.4

where \( Q \) is discharge, \( b \) is aperture, \( C \) is a constant, and \( \nabla h \) is the hydraulic gradient (Witherspoon et al., 1980; Klimezak et al., 2010). This is clearly an idealized representation of rough fracture surfaces but captures the primary influence of the mechanical separation of the fracture walls of flow. However, asperities inhibit flow by creating turbulence (Scesi and Gattinoni, 2007). In most fractures sustaining slip, only a small proportion of the opposing fracture surfaces are in contact (Dieterich and Kilgore, 1995). The combination of large asperities and contact area increases the tortuosity of flow lines, which must bend around these obstacles. Thus, apertures with asperities increase the deviation in flow relative to the smooth walls of the cubic law (Barton et al., 1985). By neglecting these affects, the cubic law overestimates hydraulic conductivity (Scesi and Gattinoni, 2007). This shortcoming can be addressed by using the JCR
coefficient to characterize the mechanical aperture, which varies along the fracture surface, to derive an hydraulic aperture that predicts discharge (Witherspoon et al., 1980; Scesi and Gattinoni, 2007).

The mechanical aperture can be estimated from an empirical relationship using JRC values derived from the Barton shape profiles by:

\[ e_e \approx \frac{JRC}{5} \left( 0.2 \frac{\sigma_c}{JCS} - 0.1 \right) \]  \hspace{1cm} \text{Eqn. 1.5}

where \( e_e \) is the mechanical aperture and \( \sigma_c \) is the unconfined compressive strength (Barton et al., 1985). The hydraulic or conducting aperture, where the walls of the fracture can be approximated as smooth, can be related to the mechanical aperture by the empirical equation:

\[ e_e = JRC^{2.5} \left( \frac{e}{e_e} \right)^{2} \]  \hspace{1cm} \text{Eqn. 1.6}

where \( e \) is the hydraulic aperture (Bandis et al., 1985, Barton et al., 1985, Scesi and Gattinoni, 2007). This hydraulic aperture can then be substituted into preexisting equations for hydraulic conductivity where the influence of the asperities is accounted for and yields more accurate estimate (Scesi and Gattinoni, 2007).

However, the aperture is eventually modified by shear displacement through the grinding and breaking of asperities that smooths the fracture surfaces. Since asperities prop the fracture walls apart, this asperity destruction leads to an overall decrease in porosity and aperture that commensurately decreases permeability (Lee and Cho, 2002). Barton et al. (1985) modeled this smoothing effect using a modified cubic law that relates the roughness, dilation, and hydraulic conductivity. Their results demonstrate that increasing shear displacement after peak shear stress was reached reduces surface
roughness (Barton et al., 1985). This smoothing in turn decreases aperture and permeability. This violates the early characterization of a constant shear dilation angle that predicts a monotonic increase of aperture due to slip (Barton et al., 1985).

This model is verified by experimental results that measure permeability as a function of increasing shear displacement (Lee and Cho, 2002). In these experiments, artificial opening-mode fractures in granite and marble were subjected to shear displacement under a variety of normal stresses while the permeability of the fracture was measured (Lee and Cho, 2002) (Figure 1.3). Experiments yielded results identifying transitions in permeability depending on slip. At small slips, permeability gain is negligible. As cumulative slip increases, this stage is followed by a transition to rapid increases in permeability that only persists for a few additional millimeters of slip. This initial behavior implies that the mechanism causing the necessary dilation to increase permeability is length-scale dependent and primarily a result of the initial asperity size distribution. Subsequent slip produces negligible permeability gain. This leveling off is interpreted as reflecting gouge formation as a result of the destruction of interlocking, larger asperities that most oppose slip (Lee and Cho, 2002). Filling of the fracture aperture with this gouge also implies that even if dilation can still be increased, permeability will primarily depend on the properties of the gouge (Barton et al., 1985; Lee and Cho, 2002).
Figure 1.3: Graphs showing the relationship between permeability and slip distance in granite (a) and marble (b). Modified from Lee and Cho (2002).

Although powerful, the use of the JCR and “standard shape profiles” only provides a semi-quantitative basis for characterizing surface roughness and the resulting impact of slip on dilation and permeability. The development of high-resolution digital mapping (Roth, 2014) and profilometry of fracture surfaces using lasers (e.g., Light Distance and Ranging, LiDAR) (Mlynarczuk, 2010) provides a basis for highly quantitative analysis of the topography of surfaces. Perhaps the simplest summary of the statistical variation in the height of a surface is to calculate the difference between the surface and a best fitting plane in three dimensions or line in two dimensions. This provides a histogram of the deviation in topography as a function of the sample spacing that can in turn be summarized by the root of the mean of the squared residuals (RMS) (Thomas, 1982; Brown, 1995).
Figure 1.4: Example power spectral density procedure. (a) Example fracture surface and (b) corresponding composite representation as a summation of sine waves with distinct wavelength and amplitude. (c) Graph displaying the power or squared amplitude of each sin wave after the fractures deconstruction and plotted as frequency or the inverse of the wavelength. The vertical dashed lines indicate the lowest detectable frequency (blue) and maximum resolvable frequency (red). The slope of the PSD is 2, which falls within the self-similar fractal range. Modified from Brown (1995).

Another approach to characterizing the roughness of fractures is to model them as a series of superposed sine waves of specified wavelength and amplitude. The resulting distribution of contributing waveforms defines a PSD that measures how much a particular wavelength contributes to the topography of the surface, in this case, a fracture’s surface in profile (Power and Tullis, 1991). The Fast Fourier Transform (FFT) is used to break down the fracture into the series of superposed sinusoids of varying wavelengths and amplitudes (Figure 1.4). The power of each waveform is measured as
the squared amplitudes per wavelength, and the distribution of this power is described in a plot of log frequency versus log power summarizing the relative contribution of different sized asperities. Underlying this analysis is the assumption that each sinusoid is present throughout the surface (i.e., the distribution is stationary and thus independent of position or sub-segment sampled). By distinguishing the wavelength of asperities and their associated amplitudes (i.e., local heights on the fracture surface), PSD reveals whether a fracture surface is more jagged, such as surfaces related to grain and pore dimensions, or dominated by a few, large and wide asperities, such as those that could result from linkage.

Many studies of the power spectral distribution of fracture surface roughness suggest this topography is typically fractal, meaning asperity amplitude increases proportionally with the wavelength or equivalently decreases proportionally with the frequency (Power et al., 1987). This observation has two implications. First, it argues that the distribution of log frequency versus log PSD is linear and thus is primarily characterized by a slope called the PSS (Figure 1.4). Second, if this slope ranges between -2 and -3, then it corresponds to self-similar fractals in which relief on the profile is independent of the length scale of observation such that the relief appears constant for all length scales (Power and Tullis, 1991; Brown, 1995). In other words, if a small portion of the surface is magnified, it will be indistinguishable from the surface as a whole (Power and Tullis, 1991; Brown, 1995). However, other studies show that many natural fractures vary in slope depending on the length scale of observation and range of resolvable frequencies (Brown and Scholz, 1985; Power et al., 1987). In this alternate case, if the log frequency versus log PSD of the surface depends on the scale of magnification to be
statistically similar, then it is a self-affine fractal and has a power spectral slope outside the self-similar range (Power and Tullis, 1991; Brown, 1995).

The main advantage of this characterization is that one parameter, the PSS, summarizes the roughness and asperity content of the fracture surface(s). In addition, this provides a common basis for comparing fractures of different length scales, unlike root mean square (RMS) heights which are a measure of the deviation in topography (Sagy et al., 2007). RMS is highly sensitive to sample lengths where the RMS value will increase with the length of the sample (Brown and Scholz, 1985; Brown, 1995), whereas PSD looks at the relative contribution of each wavelength to calculate its power by considering the entire length of the fracture.

As fracture surface roughness is altered by slip, so is the surface’s PSD (Power et al., 1987; Sagy et al., 2007; Brodsky et al., 2011). Sagy et al. (2007) argued that surfaces that have sustained small slips will be largely dominated by more frequent, smaller wavelength asperities and thus have a lower power spectral slope. In contrast, surfaces that have experienced large cumulative slip events have broader and less frequent asperities due to asperity destruction and correspond to a higher power spectral slope (Sagy et al., 2007). These arguments neglect two critical aspects of the fracture life cycle. First, the analysis does not take into account the addition of roughness either through propagation or more dramatically through the potentially large (wavelength and amplitude) asperities due to linkage at various length scales. Linkage is a fundamental element of fracture growth (e.g., Myers and Aydin, 2004; Patterson and Wong, 2005) and has the additional complication that the resulting asperities are introduced at a discreet
point along the fracture. Second, healing of natural fractures commonly modifies fracture surfaces and alters gouge characteristics.

A similar analysis and results can be obtained for the aperture distribution of a natural fracture (Brown, 1995). This has the advantage that it directly characterizes the property most influencing flow through fractures. However, it obscures the dependence of mating (or conversely mismatch) between opposing fracture surfaces on the asperities and the slip that induces the mismatch.

1.1.2 Fracture Propagation, Interaction and Growth by Linkage of Fractures

An essential mechanism of fracture formation is through grain scale cracking, often in Mode I, followed by linkage of these small cracks to form a macroscopic fracture formation (see summary in Patterson and Wong, 2005). This model is called the crack coalescence model of fracture formation and is well documented using acoustic emission to monitor the accumulation of damage during triaxial rock mechanical experiments. It is clear, that once the macroscopic fracture is formed, that there is a transition toward growth by the periodic linkage among a population of macroscopic fractures in the rock mass.

In these macroscopic fractures, shear distorts the adjacent volume of rock, especially at the tips where gradients in slip are large (e.g., see summary in Lawn, 1993). This concentrated distortion corresponds to stress that breaks the rock just beyond the fracture tip, enabling propagation of the fracture and relieving the distortion. To maintain the gradient in slip at the tip that allows fracture propagation, the maximum slip on the fracture continues to increase. The maximum slip along a fracture scales linearly with the
length of the fracture, so that as fractures grow so does its displacement (Scholz et al., 1993). This is due to finite stress concentrations whereby the fracture’s energy increases with size allowing for the fracture to propagate further into the previously unfractured rock (Scholz et al., 1993).

This distortion can also induce macroscopic tensile stress near fracture tips causing the formation of opening-mode fractures (also known as joints or Mode I fractures) that emanate from near the tip of the slipping fracture (Figure 1.5a). Opening-mode fractures formed in this special circumstance are called splay fractures (e.g., Martel and Pollard, 1989; de Joussineau, et al., 2007). Alternatively, increased compression can lead to pressure solution or differential stress that promotes shear failure (also known as Mode II/III fractures) (e.g., Fletcher and Pollard 1981; Petit and Mattauer, 1995; Willemse et al., 1998).
(a) Distortaiton around slipping fracture

(b) Splay fracture linkage

(c) Shear Fracture, Ramp linkage

Figure 1.5: Cartoon illustrating of linkage structures and related failure mode. (a) Linkage between established fractures can occur by splay fracture or shear fractures which are initiated by the large concentration of stress at the tip of a slipping fracture. Overlapping distortions between nearby slipping fractures promote their linkage by formation of a fracture breaking the intervening rock and constituting large asperities on the composite fracture surface. Blue indicates open porosity. (b) Rocks are weak in tension, so splay fracture is favored if local tensile stresses are achieved through the combination of a relatively low, remote least compressive principal stress and the local stressing from fracture slip. Splay fractures promote a localized, linear dilation within the splay fracture with only a minor geometric impact on dilation on the established parent fractures. (c) Shear fracture linkage promotes an asperity that forces the walls of the established parent fractures apart, promoting more extensive dilation across the fracture.

These structures occur in all rock types and other natural and engineered materials including sandstones (Myers and Aydin, 2004), granites (Martel and Pollard, 1989), limestone (Fletcher and Pollard, 1981; Petit and Mattauer, 1995; Willemse et al., 1998), and ice (Wilson, 1960). The far field stress determines, (1) whether true tension can be
achieved in the typically compressive earth, and (2) the extent of the volume subjected to tension. The length of the splay crack is heavily dependent on the length of the “parent” fracture undergoing slip, represented as a power law equation in the form of:

\[
msl = 0.53pfl^{0.95}
\]

Eqn. 1.7

where \( msl \) is the maximum length of the splay crack and \( pfl \) is the parent fault length (de Joussineau et al., 2007). This equation was determined from the best fit line of 135 sets of parent faults and corresponding splay fractures where the average splay was found to be 60 percent of the maximum fault length (de Joussineau et al., 2007).

As fractures slip the distortion impacts the behavior of other nearby fractures. In most cases, this effect inhibits fractures from significantly overlapping where their spacing is less than the length of the slipping facture (Cartwright et al., 1996). Instead, the buildup of the displacement gradients results in the rotation of the propagation front and a locally very intense distortion. That intense distortion promotes failure of the intervening rock, leading to a linking fracture (Martel, 1990; Cartwright et al., 1996). Where the sense of slip and step sense between the fractures match, the intervening volume is preferentially extended, promoting formation of splay fractures that can bridge the intervening rock (Figure 1.5b), linking two fractures into a single discontinuity in the rock mass (2001Cartwright et al., 1996; Acocella et al., 2000; Mansfield and Cartwright, 2001). Alternatively, where slip sense and the step sense of fracture is different (Figure 1.5c), both compression and differential stress may be enhanced ultimately leading to linkage by shear fracture (Myers and Aydin, 2004).
Figure 1.6: Cartoon illustrating the growth of faults through linkage. (a) Before linkage where the length of the fault \((L)\) is a small fraction of the maximum displacement along the fault \((D)\) but lacks linkage related to the elasticity of the rock. The distortion of the adjacent rock is directly related to the scaling of the slip to the fracture length. (b) After linkage, the length of the fault will have increased unproportionally to the amount of displacement and the linkage step \((LS)\) will be no greater than the length of the fault before linkage. (c) As the linked fault continues to slip, the maximum displacement increases, distorting the region around the “composite” fracture until linkage occurs again. Modified from Cartwright et al. (1996).

Since the volume distorted is proportional to the length of the slipping fracture, the spacing and size of linkage fractures increase in length as the fracture grows suggesting a self-similar, scale invariant process (Martel and Pollard, 1989; Cartwright et al., 1996) (Figure 1.6). This means that as the fracture grows through linkage, the total length of the fracture increases allowing for increased interaction distance with nearby fractures, thus larger linkage distances (Cartwright et al., 1996). In this way, splay
fractures occur at all length scales and display consistent geometry. In particular, splay fractures also characteristically form an acute angle between 45° to 70° to the main fracture depending on the remote stress tensor and strength distribution along the slipping fracture (Martel and Boger, 1998; de Joussineau et al., 2007).

1.1.3 EGS

The average temperature gradient in the Earth is 30°C/km. This heat is transferred from the Earth’s interior to the surface primarily by means of convection and conduction as a result of leftover energy from planetary accretion as well as continued radioactive decay (Barbier, 2002). This heat flow from the Earth averages 82 mW/m² and amounts to a total output of 4x10¹³ W, which is four times greater than the global energy consumption of 10¹³ W (Barbier, 2002). In many locations, the temperature gradient and associated heat flow is significantly higher. This heat provides an abundant, consistently available, clean energy alternative for societal use.

To access this heat for use as an energy source requires three elements: (1) the heat source close enough to the surface to access through wells, (2) permeable or porous volume connected to the heat source, and (3) fluid. The combination of permeability and fluid allows this heat to be efficiently moved from the rock to the well and brought to the surface for use. There are only a few places on Earth where all three of these elements are readily accessible to this energy source in the form of a viable and cost efficient geothermal system (Barbier, 2002; Jung, 2013) (Figure 1.7). Geothermal systems occur in areas of high heat flow where permeable rocks at depth act as reservoirs for circulating
water that are heated from the surrounding rock (Barbier, 2002). Convection through this permeable network brings the heat to the near surface. In many cases, these reservoirs are connected to the surface by fractures and tend to, but not always, have surface expressions in the form of hot springs, fumaroles, and geysers (Barbier, 2002). The high heat flow is most often the result of either young volcanism occurring near plate boundaries, or regions of large crustal extension that thin the crust and are punctured by faults that extend to great depth limiting their existence to a few localities around the world (Barbier, 2002). In these areas, the permeability of the fractures and host rock can be reduced by active precipitation of secondary minerals promoted by convective fluid

Figure 1.7: Definitions and conditions of different geothermal resources. Modified from Huenges (2010).
circulation across large temperature and pressure gradients, further limiting potential geothermal reservoirs (Fetterman, 2010).

![HDR Model and EGS Model](image)

**Figure 1.8:** Varying stimulation techniques. (a) Original HDR design for unfractured rock and well placement. (b) EGS design for fracture stimulation and well placements. The red and blue wells correspond to the stimulation and producing wells. Modified from Jung (2013).

In an attempt to access more of the earth’s vast energy potential, the concept of hot, dry rock (HDR) reservoirs was developed in the 1970s. Assuming that the crystalline basement was unfractured, areas that hosted high geothermal gradients could be artificially fractured to improve the permeability of the rock mass, and created a heat exchanger extract that heat through a circulating fluid (Figure 1.8) (Jung, 2013). This negates the need for a large geothermal reservoir because water would be injected and then produced as either steam or water. If viable, this technology could radically increase the number of locations that could host an HDR system (Tester et al., 2006). An ideal
location would need temperatures from 150\(^\circ\)C to 500\(^\circ\)C occurring at depths no greater than 5 or 6 km with an average flow rate of 265 l/s (Potter et al., 1974), but could potentially be as deep as 10 km.

For the HDR system concept, sets of parallel tensile fractures are created perpendicular to the least compressive stress and both the pumping and production wells are drilled through this fractured zone (Figure 1.8) (Jung, 2013). Effective tension is generated by high rate injection of fluid at high pressure. However, early work revealed that the crystalline basement is naturally, and heavily fractured, thus limiting the need to create new fractures using hydraulic fracturing (Jung, 2013). If the naturally low permeability of these fractures could be improved, this would provide the necessary heat exchange manifold. Importantly, these fracture systems are also naturally complex, and thus provide the potential for large areas of heat exchange along a tortuous flow path that would promote transfer of heat from the rock mass into a circulating fluid. It was also recognized that on geologic time scales the basement typically displays normal fluid pressure gradients throughout the seismogenic crust attributed to the generation and maintenance of permeability along natural fracture networks (Barton et al., 1995; Townend and Zoback, 2000; Sibson, 2004). The ability for such natural fracture networks to cycle between low and high permeability is also demonstrated by ore deposits such as gold (Mickelthwaite and Cox, 2004; Sibson, 2004). Thus, this recognition and supporting insights caused a shift in goals to improve the low permeability of the preexisting fractures in the crystalline basement (Tester et al., 2006).

One strategy to engineer an enhanced geothermal systems (EGS) is to inject fluid under pressure to reduce the effective normal stresses resolved on them, thus reducing the
frictional resistance to slip. The presumption is that slip will be induced, and the natural roughness of the fracture will cause long-lived dilation. This type of hydraulic stimulation has been dubbed “hydro shearing” (Jung, 2013). In this model, preferential growth of the stimulated volume is expected along intermediate principle stress direction (coinciding with the intersection lineation of conjugate shear faults) (Heffer, 2002; Huenges, 2010, Jung, 2013).

The intentional inducement of slip is on natural fractures during hydraulic stimulations has been documented by the associated seismicity. When this induced seismicity has a moment magnitude less that 3.5 on the Richter scale it is referred to as a microseismic event (MEQ) (Breede et al., 2013). MEQs are used to track the stimulation of the reservoir and the quantify changes in the rock volume such as the size of fractures and their orientation (Huenges, 2010). Most EGS sites have recorded MEQs with a typical value less than 3.5, with the largest MEQs around 4.6 (Breede et al., 2013). These MEQs are of great concern to the surrounding community and have affected operations at locations such as Geysers geothermal field, while other communities such as those around St. Gallen geothermal field have chosen to go ahead with drilling despite 3.6 magnitude seismicity events (Breede et al., 2013).

To date, there are over 31 EGS projects worldwide with an average flow rate of 40 l/s (Breede et al., 2013). The Desert Peak Geothermal Field in Nevada is the most successful EGS project in the United States and has an estimated flow rate of 100 l/s and an estimated capacity of 1.7 MW (Breede et al., 2013). In addition, the EGS stimulation method has been used to improve well performance within established geothermal fields such as the Geysers (Tester et al., 2006). EGS is still within the learning phase and
Despite the microseismic events as a result of successfully induced slip, production remains low on average (Breede et al., 2013; Jung, 2013). An unresolved critical issue is the detailed relationship between microseismic events, porosity production, and the generation of a permeable fracture network.

1.2 Geologic Setting

The Newberry shield volcano is located 60 km east of the Cascade Range, at the intersection of three fault zones–Sisters Fault Zone in the north, Walker Rim Fault Zone in the southwest, and Brother’s Fault Zone in the east (Fitterman, 1988; Cladouhus et al., 2011)–causing it to elongate in the NW direction (Keuhn, 2002) (Figure 1.9). The summit is 5 by 7 km wide, standing about 1100m at its highest and covering an area of 1300 km$^2$ (Keuhn, 2002). It is home to over 400 cinder cones, fissure vents, rhyolitic domes, flows, and pyroclastic deposits, as well as two lakes residing within the caldera (Bargar and Keith, 1999). There have been 25 eruptions distinguished spanning from 1.3 Ma to 0.4 ka based on radiometric dating of volcanic material and cross-cutting relationships from intervening structures (Bargar and Keith, 1999). In addition, ring faults are associated with multiple episodes of caldera collapse dating from 0.5 to 0.3 Ma (Bargar and Keith, 1999).
The youngest stratigraphic formation exposed at the study site is the Newberry Formation and is comprised of the 25 eruption events. Eight of which are associated with obsidian flows, including the youngest Big Obsidian Flow erupting 1.3 ka (Keuhn, 2002). There have also been over ten tephra deposits in the last 1.5 ka (Keuhn, 2002). Other layers include basaltic, siliciclastic, and rhyolitic flows (Jensen et al., 2009). The older and younger events are separated by a 7.7 ka layer from the eruption and collapse of Mount Mazma, which formed Crater Lake, Oregon (Donnelly-Nolan, 2011) (Figure 1.10).
Below the Newberry Formation is the John Day Formation that is composed of older volcanic material dating as far back as 37 Ma and is associated the creation of the Cascade Range (Robinson et al., 1984) (Figure 1.10). It is mostly a pyroclastic sequence consisting of tuffs with intervening lava flows (Robinson et al., 1984). Both formations are underlain by intrusive rocks, which are also volcanic in origin (Roth, 2014). The core used in this study comes from the Newberry Formation while the stimulation well penetrates into the intrusive layer.

Figure 1.10: East West cross section of Newberry Geothermal Field with locations of stimulation well 55-29 and Geo- N2. The black box represents the depth interval where the samples were taken from. Modified from Sonnenthal et al., 2012.
1.2.1 Geothermal Potential

Starting in 1976 and extending through 1986, twenty geothermal wells were drilled in the area surrounding the caldera to assess the geothermal potential (Bargar and Keith, 1999). One such well, USGS-N2, is the hottest well relative to its depth in the country reaching temperatures up to 270°C at the shallow depth of 932 m due to high-temperature gradients (Bargar and Keith, 1999); deeper wells exceed 350°C. However, despite being heavily fractured and hot, these wells have low porosity and low permeability which is interpreted to result from pore and fracture filling cement (Bargar and Keith, 1999; Davatzes and Hickman, 2011; Fetterman and Davatzes, 2011; Cladouhos et al, 2013). Currently, well 55-29 on the west flank of the Volcano is the site of an Enhanced Geothermal Systems demonstration project, and was subjected to stimulation in 2012 (Cladouhos et al., 2013) and again in 2014 (Cladouhos et al., 2015). The well extends to a depth of 3066 m and experiences temperatures up to 315°C (Sonnenthal et al., 2012) (Figure 1.9).

Image logs for well NWG 55-29 reveal fractures that dominantly strike N-S and have dips consistent with normal faults (Davatzes and Hickman, 2011), which mimics surface fault traces, fissures, and alignments of cinder cones visible in detailed LiDAR topography (Cladouhos et al., 2011) in the vicinity. These structures appear well oriented for slip in the modern stress state as indicated by breakouts in NWG 55-29, which indicate that $S_{Hmax}$ is oriented approximately N-S and an inferred normal faulting stress regime (Davatzes and Hickman, 2011). Core from around the volcanic system (Bargar and Keith, 1999; Fetterman and Davatzes, 2011) and image log analysis from well NWG 55-29 on the west flank of the volcano (Davatzes and Hickman, 2011) document a high
degree of fracturing but pervasive fracture healing limiting fluid flow (Bargar and Keith, 1999).

1.2.2 Geo N2

The core in this study was obtained from well GEO-N2, the nearest corehole to stimulation well 55-29, located approximately 0.5 km to the east toward the caldera (Figure 1.8b). This core is comprised of basaltic to rhyolitic flows with intervening breccias, lithic tuff, and volcanic sandstone with minimal to moderate hydrothermal alternation (Bargar and Keith, 1999) (Figure 1.10). The well was first drilled in 1986 and reaches a depth of 1,337 m. This well represents the deepest core available at Newberry and reaches temperatures of 150°C at the bottom of the hole (Bargar and Keith, 1999).

Samples used in this study are from the deepest section of the approximately vertical well, from 1160-1337 m measured depth. These samples are comprised of mafic to siliciclastic tuffs with abundant phenocrysts of plagioclase (Bargar and Keith, 1999) (Figure 1.11). Vesicles are common, but pores are typically small (Fetterman and Davatzes, 2011; Roth et al., 2013). The cement found in healed fractures is dominated by calcite, quartz, or chalcedony with minor chlorite and hematite (Bargar and Keith, 1999; Fetterman and Davatzes, 2011). The majority of matrix and fracture porosity is healed (Bargar and Keith, 1999; Roth, 2014), which likely accounts for the overall low permeability in the geothermal system. These samples represent similar rock types as those found in portions of the NWG 55-29 well and have experienced the same tectonic history.
Stress conditions leading to formation of fractures in the core of GEO N-2 for the depth interval of the samples can be obtained from the nearby study of well NWG 55-29 (Davatzes and Hickman, 2011), and from details of the GEO N-2 well. Davatzes and Hickman (2011) infer a normal faulting dominated system based on the fracture population encountered and breakout formation. In GEO N-2, based on density logs, a representative density of the rock is 2200 kg/m³, suggests a vertical stress of 21 to 29 MPa, corresponding to depths between 1000 and 1350 meters. For a normal hydrostatic gradient with water table at the surface, this corresponds to effective stresses on the order of 11 to 19 MPa. In a normal faulting environment this corresponds to the maximum compressive principle stress, rather than confining pressure. Assuming stress is limited by the frictional strength of the rock mass and a reasonable coefficients of friction of 0.6, at the low end for the rock forming minerals and fracture filling minerals, suggest that during frictional slip on optimally oriented fractures the confining pressure was in the range of 13.5 to 16 MPa, or an effective confining pressure of 3.5 to 6 MPa.
Figure 1.11: Locations of minerals at depth from Geo-N2 with the depth interval corresponding to the sample highlighted in yellow. Modified from Bargar and Keith (1999).
CHAPTER 2

METHODS

The core seven samples collected from GEO-N2 span a range in early fracture development from newly formed fractures characterized by a single discernible slip event to fracture with multiple slips, growth through linkage, and development of gouge. More advanced fracture development is generally associated with formation of breccia and complex fault architecture including development of a distinct damage zone and fault core in these rocks, which is the subject of the study by Fetterman and Davatzes (2011). Details of the fracture topography and slip history were derived from petrographic relationships revealed in thin section.

Thin sections were cut perpendicular to the fracture plane and coinciding with the slip vector, which was generally along the dip of the fracture apparent in the near-vertical core. As a practical matter, only fractures at least half the length of the thin section were studied to provide a sufficient sample length for reliable statistical analysis. Samples of this minimum length sustained a total slip of less than 1 cm. Examples were chosen so that mineralogy among the samples is similar, although grain size distribution does vary. The core samples are also obtained from a narrow depth range from 3617 ft to 4338 ft, implying they experienced similar stress and temperature conditions. Thus, the primary difference between the fractures is the number of slip events, the magnitude of slip, and the grain and pore size distributions. In each thin section, the series of fracture surfaces representing distinct slip events were interpreted and then digitized. From these base maps, the surface topography and associated history of slip and dilation discerned from relative timing relationships and offset markers were quantified.
2.1 Fracture History and Surface Topography

A series of photo-micrographs along the fracture in each thin section were taken with 1x optical zoom in plane polarized light. They were then stitched together in Adobe Photoshop to create a single high-resolution photograph of the thin section with a pixel size of approximately 2-3 microns. The photographs were printed out at 100 times exaggeration where they were used in tandem with a Nikon DS-Fi1 petrographic microscope to hand trace the paired surfaces of individual fractures. Mapping was supported by petrographic relationships of the surface texture and mineralogy available from the combined use of polarization, the gypsum plate, and high resolution in the microscope. After the surfaces had been delineated, they were paired to define the opposing faces of distinct fracturing events. In most of these cases, each of these surface pairs is associated with younger precipitated cement that healed the fracture prior to a subsequent slip event. The relative age order of the paired surfaces were deduced from petrographic relationships such as abutting, cross-cutting, inclusion, and superposition relationships between fractures, cement, and grains. The high-resolution photographs were imported into DigitizeIt where the fracture maps could be digitized within axes corresponding to the thin section edges (Figure 2.1). The surfaces are digitized to approximate point spacing along each fracture surfaces between 0.005 and 0.01 cm (50 to 100 microns). Care was taken to capture key topographic features. Thus, although the spacing is dense, it is not initially uniform. Since the reference frame in DigitizeIt corresponds to the real dimensions of each thin section with axes oriented along the thin section, one axes also corresponds to the measured depth of the core, with positive
Figure 2.1: Example delineated surfaces. (a) Thin section in cross polarized light (b) with digitized surfaces (c) and a close up section defining a mismatched grain slip indicator and dilation perpendicular to the surfaces. The single and double notches in the thin section correspond to formation dip and up-well direction, respectively. The naming convention of thin section samples corresponds to the “well name – measured depth.” Where there are multiple thin sections from the same depth interval, the samples have been distinguished by either an “FA” or a “FB” following the depth.
numbers corresponding to the up direction of the core and the radial direction of the core parallel to the dip direction of the fracture.

Once fully digitized and interpreted, the resulting maps were imported into MATLAB (Figure 2.2a) (using MATLAB script RoughnessCalculations3_F, Appendix A). Digitized points defining each surface were sorted to ensure a consecutive distribution along the fracture surface (Figure 2.2b) (using MATLAB function ReorderByNearestNeighbors_F, Appendix A) and monotonically resampled at a constant spacing along a least squares best fit line (using MATLAB function MonotonicReSample_F, Appendix A) (Figure 2.3). An ordered, monotonic (Figure 2.2c and 2.2d), and equally spaced distribution (Figure 2.2e) is necessary to enable spectral characterization of the topography. In addition, this choice also reflects an emphasis on portions of each fracture surface that can interact with the opposing fracture face. Finally, pairs of surfaces are resampled along the same local x-positions to measure their separation which corresponds to the aperture of the fracture generation defined by the paired surfaces. Interpolation schemes including linear, spline, and cubic spline were evaluated. Linear interpolations provided the simplest scheme and minimum estimates of length along the fracture surface corresponding to the sum of separates between adjacent points (which can be taken as an estimate of fracture surface “area”), but introduced sharp corners and locally deviated from the fracture surface evident in thin section where the spacing of the digitized points was relatively large. The spline algorithm in MATLAB resulted in locally extreme deviations from the fracture surface where the spacing of manually digitized points suddenly changed. Cubic spline interpolation provided the best match to thin sections; the somewhat smoother interpolation followed the curvature in the
fracture surface evident in thin section. Consequently, resampling was accomplished using a cubic spline interpolation. In most cases the difference between the linear and cubic spline interpolations are not significantly different (Figure 2.3). The local x-spacing of the interpolation points is determined to be one fifth of the 25\textsuperscript{th} percentile of the initial spacing of digitized points defining the fracture surface.

Figure 2.2: Process for monotonic resampling shows a fracture surface intersection a pore that results in a large embayment in the fracture surface. (a) The initial digitation of the fracture surface where digitized points are not necessarily sequentially distributed along the surface. (b) Re-ordered sample points. (c) Search for points that overlap along the local x-direction is conducted in both the positive and negative. (d) Determination of points constituting a monotonic distribution by only retaining points common to both the positive and negative local x-direction search in (c). (e) Final interpolated monotonic distribution.
After monotonic resampling, the resolution of the original digitized surfaces are preserved as information is neither added or lost (Figure 2.3a). However, the monotonic resampling does increase the resolution in the y direction compared to the x direction (Figure 2.4). Also, due to the necessity that each x position is larger than the previous, portions of the fracture that represent embayments are eliminated, thus decreasing overall path length (Figure 2.2e and 2.3b).

![Figure 2.3: Comparing resampling techniques.](image)

(a) Box plots of the spacing of samples based on initial digitization and re-sampling. (b) Distance along fracture surface compared to linear fit for different sampling schemes. The reduction in estimated fracture surface length between original and re-sampled surfaces is primarily a result of the enforced monotonic distribution that removes length associated with overlapping surface such as in the embayment.
Figure 2.4: Resampled point spacing. (a) Box plots showing resampled spacing of points defining the fracture surface and (b) normal and cumulative distributions of sample spacing.

The surfaces were then evaluated relative to the best fitting line as the local x-axis and the data translated so that the lowest y-point of the fracture surface has a y-position of 0 in order to calculate the topographic relief along the fracture. In this reference frame, the topography of each surface is plotted for inspection and the frequency of topographic
relief evaluated as box plots in relative age order (MATLAB script RoughnessCalculations3).

The roughness of the fracture can also be evaluated by its total, piece-wise length relative to a straight line (Figure 2.5). This comparison reveals the relative amount of surface area available for chemical interaction with pore-filling fluid. Similarly, it approximates the tortuosity of the flow-path, or, in other words, the actual distance a partial of fluid must traverse to progress throughout the fracture in the x-direction, and thus relates to fracture permeability. Tortuosity is the ratio of path length (L_{\text{path}}) to the shortest distance (L_{\text{min}}) between two points and was calculated for each rotated and resampled surface (Figure 2.5) (MATLAB script RoughnessCalculations3). In this approach, the sum of distances between points defines a fracture surface divided by the sum of the x-components since the local x-axis coincides with the best-fit line (Figure 2.3). Therefore, as a fracture surface becomes smoother and thus flatter, the length of L_{\text{path}} approaches L_{\text{min}} and value for tortuosity goes to one. The average path length for all the fractures in the sample (L_{\text{avg}}) was calculated, and the ratio of individual L_{\text{path}}’s to L_{\text{avg}} was found as a way of comparing path lengths between surfaces. This is used to determine how path length influences tortuosity, i.e. whether tortuosity is affected by path length, much like RMS, or if it is a distinct indicator for roughness.
Figure 2.5: Fracture cross section illustration of sample N2-3617FA. The upper surface is delineated in orange, and the bottom is delineated in red after being rotated and monotonically resampled. An example height (H) and width (W) of an asperity is denoted. The shaded light orange region corresponds to the separation of the two surfaces, or its aperture, where it is re-plotted on the x-axis. The difference between \( L_{\text{path}} \) and \( L_{\text{min}} \) is illustrated. Lastly, the amount of slip is marked as it relates to offset between the matching surfaces.

### 2.2 Power Spectral Density and Slope

From the resampled data, the PSD was calculated using the Fast Fourier Transform and multitaper methods (Thomson, 1982; Percival and Walden, 1993) for each of the surfaces (see Figure 2.6 as an example). This approach establishes the relative contribution of different wavelength asperities to the overall roughness; in other words the relative importance of small-scale, high-frequency asperities, as compared to large-scale, low-frequency asperities is defined by their relative power (Figure 2.6b). Once the PSD was calculated, the absolute values of the slope of each surface were determined by linear regression using the equation:

\[
\logPower = -\beta \log(Frequency) + \log(C)
\]

Eqn. 2.1
where $\beta$ is the slope of the best-fit line and $C$ is the intercept (Figure 2.6c) (Power and Tullis, 1991). This function is fit via least squares regression to the PSD between $1/3$ the sample length (low frequency) and 3 times the median sample spacing (high frequency) (Figure 2.6b and 2.6c) for each generation of surface associated a fracture. This interval represents the range of frequencies reliably and sufficiently sampled to fit the sinusoids without significant error, aliasing, or frequency leakage that produce edge effects evident in the graph as a break in slope or high scattering (Nyquist, 1928). Each slope value has error bars corresponding one standard deviation (Figure 2.6d). The error in the slope, as opposed to the combined error related to both the slope and intercept parameters, is isolated by translating the data so that its centroid coincides with the $y$-axis before the regression is determined (Lyons, 1993). To evaluate whether the frequency content of the fracture evolves due to repeated reactivation, the PSS represented by $\beta$ is plotted in relative age order.
Figure 2.6: Graphs comparing statistics of the upper, lower, and aperture surfaces. From left to right: (a) Box plots summarizing frequency distribution of topographic relief or aperture; (b) Power Spectral density (the vertical dashed lines indicate the lowest detectable frequency (blue) and maximum resolvable frequency (red) and sample spacing (magenta)); (c) Linear least squares fit to power spectral density of the upper and lower surfaces of the fracture and aperture to determine spectral slope. (d) Spectral slope (yellow region corresponds to range for self-similar fractal characteristics) and relative path length of each distribution. Data generated in Dilation_F, Appendix A.

2.3 Dilation

Each fracture is comprised of multiple pairs of fracture surfaces that document its slip and dilation history. To deduce the dilation associated with each pair of surfaces, a procedure similar to the analysis of topography is followed. However, the relative position of each surface pair must be preserved. Therefore, a best-fit line to the oldest pair of fracture surfaces is defined as a new basis and all surfaces are then rotated relative to this basis with the initial position of the longest surface translated to the y-axis. The
surfaces are then reordered into a monotonic series and resampled at common x-positions along the basis at a spacing one fifth of the length of the 25\textsuperscript{th} percentile of the sample spacing for the surfaces (Figure 2.3).

The separation between each surface pair at common x-positions defines the mechanical aperture distribution (Figure 2.5) along the basis which can be related to the hydraulic aperture that controls permeability. In this approach, the separation between fracture surfaces represents the accumulated aperture, or dilation, since that surface formed. In other words, younger fracturing events, if present, modify the separation of these surfaces. To determine the aperture of any single event requires subtraction of the contribution of younger events (using MATLAB script Dilation3937FA_F, Appendix A). It is also important to note that the aperture measured along the basis does not necessarily capture the minimum or maximum aperture, and related dilation, of the three-dimensional fracture since it is limited to a two-dimensional sampling profile. Nevertheless, the statistical characteristics of the aperture in the direction of slip should be captured, and in most cases a small number of contact points between opposing surfaces is evident.

The incremental aperture and cumulative dilation are then analyzed in two ways. First box plots are used to summarize the variability in aperture, and when plotted in relative age order, to evaluate the evolution of the aperture distribution (using MATLAB script Dilation3937FA_F, Appendix A). The box plot series reveals the impact of repeated slip on the persistent aperture of the fracture, i.e. how the potential for dilation changes as slip is accumulated across multiple fracturing events. Second, the PSD analysis and derived PSS is used to evaluate how aperture evolves with repeated slip (using MATLAB script PSDAp_F, Appendix A). Both characterizations can be evaluated
in terms of the relative age order, the cumulative slip, and the inferred incremental slip of the fracture.

2.4 Grain and Pore Size Correlations

Initial formation of fracture surfaces should be influenced by the natural variability in mechanical properties such as rock strength. If true, it is expected that fractures propagate around grains and pores, which provide the mechanical heterogeneity in the rock, and thus the size and orientation of the grains and pores should contribute roughness to the fracture surface. This implies that the grains and pores not only account for initial topography heights, but also provide the basis for initial dilation. Thus, to test the effect of intrinsic rock properties on initial asperity heights requires a detailed measurement of the grain and pore distributions.

Determining the grain and pore distributions in the thin sections is necessarily two dimensional and in this application serves to characterize their shape in the plane parallel to slip. However, due to the small area of the thin section, grain and pore sizes are often underestimated as the slice of the thin section is unlikely to intersect the true diameter of the particle (Goldsmith, 1967). To correct for this, analyses requiring the use of a representative grain or pore size are performed with the 75th percentile size, rather than the median.

To account for variability perpendicular to slip, in the plane of the fracture serial thin sections were cut from sample N2-3617, separated by a small displacement perpendicular to slip. This provides both a re-sampling of grain and pore size in the strike
parallel direction and a test of the repeatability of the statistical characteristics of the relief of the fracture surfaces and related aperture.

The grain size distribution in each thin section was measured via a 600-point count on a regular sample grid consistent with standard point counting techniques (Ingersoll et al., 1984). The grid did not take the location of the fracture into account, instead starting at the corner of the thin section since grains are evenly distributed. Broken grains and grains that interacted with the fracture were counted along with intact grains. Inspection of the thin sections shows that two distinct grain size populations exist in the rock: the groundmass consisting of grains less than 0.002 cm and larger grains. For the >0.002 cm size fraction, the long and short axes of each grain were measured. For the groundmass, its relative abundance as compared to the larger grains is derived from the number of counts and individual matrix grain dimensions were not quantified.

Pores are less abundant in the samples and required a different measurement technique. The entire thin section was scanned, and any detectable pore, corresponding to pores with widths greater than 0.0016 cm was measured. These pores included filled, partially filled, open, and broken. Pores that intersected the fracture were also counted, as their influence on the path of the fracture can be explicitly seen. The long and short axis of the grains and pores were recorded similarly to the grain dimensions.

Based on the qualitative evaluation, there is no preferential orientation of grains in the thin section or relative to fractures the distributions of the long and short dimensions of the grains and pores are stacked. The stacked distributions are then compared with the frequency of asperity heights. In this analysis only the asperity height, as defined in the analysis of topography, and not their width, is considered. Only accounting for height in
the y-direction represents a major limitation because the widths of asperities were not readily resolvable. This approach also neglects positional dependence, thus assuming a homogeneous distribution of both characteristics in space (akin to the assumption underlying the power spectral analysis). The influence of the grains and pores should be evident from correlations between their size distribution and that of topography. First the grain and pore size distributions are simply compared to the topography of asperity heights of the oldest surfaces, since initial fracture surfaces should show this influence most strongly by having the least modification due to subsequent slip or dissolution and precipitation. The comparison is also made to younger surfaces to determine if such a correlation persists despite wear accompanying slip.

To determine whether there is such a correlation, histograms for each of the datasets (grain size, pore size, initial asperity heights, and younger asperity heights) are constructed (using MATLAB script GPACorrelation_F, Appendix A). The binning for the data is based on the mean asperity size divided by ten over a range between zero and the maximum feature size plus the bin spacing. In this way, all the datasets were binned on a consistent basis and the grain size intersects the y-axis at 0.001 cm. This reveals the fraction of the proportion of the thin section that is matrix. The histograms for each of the datasets were then divided by the total number of data points per set to determine the normalized (i.e., fractional) frequency. In addition, the corresponding cumulative frequency distribution is plotted. For further comparison the four dataset are summarized as box plots to facilitate the evaluation of different generations of fracture surfaces. The box plots clearly define the distribution and outliers that represent each dataset. To test for a pervasive relationship evident in all samples, the representative grain or pore size is
plotted against median asperity height (using MATLAB script CrossPlotAll_F, Appendix A) with error bars corresponding to the interquartile span from the 25\textsuperscript{th} to the 75\textsuperscript{th} percentiles.

2.5 Slip History

There were several different criteria used to measure slip in thin section, but vary based on the amount of ambiguity (Figure 2.7). The most reliable slip indicators that clearly quantify separation are from broken grains (Figure 2.7a), which serve as offset markers on either side of the surface, and wrench faults (Figure 2.7b). However, broken grains that can be easily matched across the fracture are rare. In addition, such grains most often document the cumulative slip rather than the incremental slip. The most common slip indicator is matching surface topography (Figure 2.7c) between the two opposing fracture faces. Higher quality is assigned to this interpretation where extensive portions of surfaces match and where the interpretation is independently supported by kinematic indicators including the thickness/width of cement, small faults such as reidel shears within the fracture (Figure 2.7d), or splay fractures (Figure 2.7e).

Thus slip was measured from petrographic analysis, or, in some cases, using the matching surface in the digitized profiles from the dilation analysis. This approach yielded both estimates of total slip and incremental slip (e.g. matching surfaces or broken cement). In both cases, slip values for younger events were subtracted as appropriate to reveal the incremental slip for each fracture surface pair were appropriate (using MATLAB script Slip3937FA_F, Appendix A). The incremental slip distances were plotted versus the incremental aperture to test the dependence of dilation on slip
distances. In addition, the cumulative slip was derived and added in appropriate age order and plotted against cumulative dilation for a complete history of the fracture. The representative grain sizes for each sample was plotted as horizontal and vertical bars on the slip dilation graphs. The representative grain size was chosen to be the 75\textsuperscript{th} percentile as the larger size faction of the grains, and thus presumably the initial asperities, controls the dilation of the fracture. This is due to larger asperities providing the maximum relief and therefore the separation of the opposing surfaces.

Figure 2.7: Example slip indicators. (a) Broken grain. (b) Wrench fault. (c) Matching surfaces. (d) Reidel shears. (e) Splay fractures.
CHAPTER 3

RESULTS

3.1 Thin Section Mineralogy

All seven samples are siliciclastic tuffs obtained from a depth interval from 3617 ft to 4338 ft. Due to the same rock type, samples have similar grain size distributions and mineralogy. There is variation in the pore size distribution and the amount of open porosity. The samples have been organized based on increasing degree of complexity, i.e. the number of fracture generations and features such as gouge formation and linkage. Each fracture generation is comprised of a pair of surfaces that is either the top or bottom of the fracture generation and represents a single slip event. The top surface is the hanging wall and is denoted as a solid line. The bottom surface is the footwall and is denoted as a dashed line. All surfaces are arranged in relative age order with the top surface coming before the bottom surface. The samples have been named based on the depth they were taken. If there are two samples from the same depth, the letters ‘FA’ or ‘FB’ follow the depth interval.

The first step in characterizing each sample and understanding the fracture behavior is provided by a mineralogic description. Each sample was point counted to reveal the total area of grains, pores, matrix, and fractures in the thin sections. Interesting features were identified, such as linkage structures and gouge layers. The amount of alteration was noted, as well as the mineralogy of the cement healing the fractures, if any, and the pores.
3.1.1 N2-4338

Sample N2-4338 contains 57% matrix, 24% pores, 19% phenocrysts, and 2% fractured area. The phenocrysts are highly altered but consist of predominately plagioclase, with small amounts of clinopyroxene (Figure 3.1). The plagioclase phenocrysts are small, but their Carlsbad twinning and prismatic shape are preserved despite the alteration. Pores are highly amorphous with rugose margins and are infilled with quartz, opal, or calcite. The fracture has no cement healing, despite the infilled pores.

![Figure 3.1: Photomicrographs of sample N2-4338 taken under plane polarized light at 4x optical zoom. (a) Uninterpreted thin section identifying the lack of cement and an amorphous pore. (b) Interpreted thin section showing delineated fracture surfaces. The yellow arrow corresponds to the up well direction.](image-url)
3.1.2 N2-3617FA

Sample N2-3617FA is comprised of 73% phenocrysts that are mostly small, uniform and interlocking plagioclase grains (Figure 3.2a). Other phenocryst mineralogy includes clinopyroxene and magnetite but only account for 2% of the thin section. The sample has 19% matrix and 3% pores. The pores tend to be small, amorphous and infilled, but there is one large pore present in the sample with a size of 0.41 cm (Figure 3.2a). The small pores are infilled with calcite while the mineralogy of the large pore is obscured by diagenetic iron staining that also stained the area of the thin section surrounding the fracture. The fracture has been healed by both quartz and calcite cement, but only one fracture generation could be delineated. The quartz cement appears to be younger as it occurs as lenses within the calcite cement. Secondary fractures are present on either side of the fracture that either formed as part of the damage zone or as splays.
Figure 3.2: Photomicrographs of sample N2-3617FA taken under plane polarized light at 4x optical zoom. (a) Uninterpreted thin section with alteration staining and large pore identified. (b) Interpreted thin section showing delineated fracture surfaces. The yellow arrow corresponds to the up well direction.

### 3.1.3 N2-3617FB

Sample N2-3617FB is a serial thin section from cut parallel and adjacent to N2-3617FA and thus shows the same mineralogy, grain textures, and pore characteristics (Figure 3.3a). The phenocrysts account for 72%, the matrix account for 21%, the pores account for 4%, and the fracture account for 3% of the thin section area. The large pore present in this sample is the same pore seen in sample N2-3617FA (Figure 3.2a).
Figure 3.3: Photomicrographs of sample N2-3617FB taken under plane polarized light at 4x optical zoom. The dark color of the thin section is a result of the thin section making process (a) Uninterpreted thin section identifying the staining and the large pore. (b) Interpreted thin section showing delineated fracture surfaces. The yellow arrow corresponds to the up well direction.

3.1.4 N2-3937FB

Sample N2-3937FB is comprised 30% phenocrysts and 35% matrix (Figure 3.4a). The phenocrysts are primarily comprised of plagioclase grains with 3% of the phenocrysts being clinopyroxene and magnetite. The sample contains 2% pores and can be divided into two categories based on size. The larger pores over 2 mm in size (Figure 3.4a) have a broad range of shapes from spherical to amorphous and are infilled with quartz or calcite. The pores less than 2 mm tend to be spherical and either completely infilled with calcite or partially infilled representing geopetal indicators. The cement healing the fractures are predominantly calcite with some quartz lenses.
Figure 3.4: Photomicrographs of sample N2-3937FB taken under plane polarized light at 4x optical zoom. (a) Uninterpreted thin section with a large pore identified. (b) Interpreted thin section showing delineated fracture surfaces. The yellow arrow corresponds to the up well direction. (c) Idealized generations of fracture surfaces active during each time period. The light blue lines indicate the active surfaces whereas the dark blue indicate the prior generations of fracture surfaces.

3.1.5 N2-4267

Sample N2-4267 consists of small, uniform, and highly altered plagioclase grains that comprise 42% of the thin section area (Figure 3.5a). Other phenocrysts include clinopyroxene and magnetite and comprise 8% of the thin section. Alternation obscured the Carlsbad twinning but not the prismatic shapes of the crystals making the identification of the plagioclase possible. The matrix material has a red color throughout the thin section and accounts for 24% of the thin section. The pores vary in size and are both elliptical and amorphous. The pores are 13% of the thin section and are either in filled with quartz, calcite, or open. The fracture is healed by both quartz and calcite and
has incorporated a large pore (Figure 3.5a). There is also a visible linkage structure in this fracture (Figure 3.5a).

![Figure 3.5: Photomicrographs of sample N2-4267 taken under plane polarized light at 4x optical zoom. (a) Uninterpreted thin section with large pores, the linkage structure, and uniform grains identified. (b) Interpreted thin section showing delineated fracture surfaces. The yellow arrow corresponds to the up well direction. (c) Idealized generations of fracture surfaces active during each time period. The light blue lines indicate the active surfaces whereas the dark blue indicate the prior generations of fracture surfaces.]

3.1.6 N2-4125

Sample N2-4152 is comprised of 40% phenocrysts, 47 % matrix, and 3% pores (Figure 3.6a). The phenocrysts are prismatic plagioclase and magnetite grains. The pores are generally larger than 2 mm and tend to be elliptical in shape with a random orientation. Pores have been infilled with calcite and quartz cement, but there is also open porosity. The fracture has been healed mostly by calcite, but the there is a layer of gouge material that is composed of quartz. There is also a splay fracture located on the right side of the fracture (Figure 3.6a).
Figure 3.6: Photomicrographs of sample N2-4152 taken under plane polarized light at 4x optical zoom. (a) Uninterpreted thin section with the gouge layer, splay fracture, and open porosity identified. (b) Interpreted thin section showing delineated fracture surfaces. The yellow arrow corresponds to the up well direction. (c) Idealized generations of fracture surfaces active during each time period. The light blue lines indicate the active surfaces whereas the dark blue indicate the prior generations of fracture surfaces.

3.1.7 N2-3937FA

Sample N2-3937FA has phenocrysts of primarily plagioclase with some calcite and magnetite grains. Together the phenocrysts comprise 46% of the thin section (Figure 3.7a). The matrix accounts for 40% of the thin section. All the pores for this sample are small, spherical, and infilled with calcite, and account for 2% of the thin section. The fracture is healed with primarily calcite and small bands of quartz. There is a linkage structure evident in this sample, and there is also evidence of hydrothermal alteration to the thin section due to dark red staining of one-half of the rock (Figure 3.7a).
3.2 Fracture History and Statistics of Surface Topography

A detailed fracture history is obtained through careful delineation of cement layers through the use of petrographic information and reveals the process of fracture growth. The upper and lower surfaces of the individual cement layers preserve the topography and tortuosity of the fracture as it slips and dilates. By distinguishing these different surfaces, the associated cements, and the relative timing of fracture surfaces and cement, the entire lifecycle of the fracture can be deduced. In this way, the fracture surfaces can be mapped to reveal the evolution of the topography and tortuosity along the fracture through time or as a function of the slip history (addressed in a subsequent section). Several distinct stages are evident and used as a basis to guide later
interpretation in the Analysis and Discussion chapters. These stages include the earliest formed initial surfaces (showing only a single fracturing event and which typically have the simplest morphology), surfaces associated with linkage (which are affected by the separation distance), and surfaces associated with gouge (which indicates wear associated with fracture slip).

3.2.1 N2-4338

Sample N2-4338 has one pair of fracture surfaces that was not cemented before the sample was obtained (Figure 3.1b). As evident from the lack of healing, sample N2-4338 only slipped once and is the youngest sample of the ones analyzed. The single fracture has a slight s-curve shape, and the opposing surfaces are in contact at certain points near the middle of the fracture. There is a damage zone in the rock mass around the points of contact that has been interpreted from several smaller fractures that are parallel to the main fracture. However, few of the smaller fractures in the damage zone are connected to the through going fracture. Therefore, while they contribute to the overall permeability of the rock, the smaller fractures were not digitized because their role in accommodating slip and roughness is uncertain. The fracture then widens away from the middle of the fracture, towards the edges of the thin section.

When the two surfaces are compared, the footwall (1.B) has a slightly larger maximum topographic relief of 0.15 cm and a negative skew (Figure 3.8a). The hanging wall (1.T) has a normal distribution for topography, meaning the footwall has a higher abundance of larger asperities as compared to the hanging wall. The 95th % confidence intervals around the medians do not overlap revealing the two surfaces appear statistically
distinct. Both tortuosity values for the two surfaces vary less than ten percent from $L_{\text{min}}$, with the footwall varying the most at 1.086 (Figure 3.8b). However, this variation is not meaningful and the surfaces can be approximate as the same length. The hanging wall is also the shorter of the two surfaces but this difference is not meaningful either (Figure 3.9c).

**Figure 3.8:** Fracture surface statistics for sample N2-4338. (a) Box plots summarizing topographic relief of each fracture surface listed from oldest to youngest. Pairs of surfaces constituting a single fracture surface generation share the same number and their relative position distinguished as T = top and B= bottom. (b) Calculated tortuosity of each surface. (c) Ratio of path length of each surface to average path length for all the surfaces in the sample plotted in relative age order.

### 3.2.2 N2-3617FA

Sample N2-3617FA contains one main fracture that was digitized and several secondary fractures that were not (Figure 3.2b). The secondary fractures were not digitized for the same reasons mentioned for sample N2-4338. The sample is interpreted to have only slipped once, but is cemented and therefore older than N2-4338.
Of the two surfaces, the footwall (1.B) has a larger maximum topographic relief of 0.096 cm and a positive skew (Figure 3.9a). The hanging wall (1.T) has a maximum topographic relief of 0.0758 cm and a normal distribution. The skew of the two surfaces are different and indicate a different abundance of larger asperities for the hanging wall. The 95\textsuperscript{th} percent confidence intervals around the medians do not overlap, meaning the surfaces appear statistically different. Both surfaces have tortuosity values less than one percent larger than $L_{\text{min}}$, but the difference in tortuosity (Figure 3.9b) and path length (Figure 3.9c) between the surfaces is not significant.

![Figure 3.9: Fracture surface statistics for sample N2-3617FA. (a) Box plots summarizing topographic relief of each fracture surface listed from oldest to youngest. Pairs of surfaces constituting a single fracture generation share the same number and their relative position distinguished as T = top and B= bottom. (b) Calculated tortuosity of each surface. (c) Ratio of path length of each surface to average path length for all the surfaces in relative age order.](image)

\subsection*{3.2.3 N2-3617FB}

Much like sample N2-3617FA, sample N2-3617FB has only one main fracture that is interpreted to have slipped only once (Figure 3.3b). The thin section contains many
secondary fractures around the main fracture, but less than its sister sample. The secondary fractures were not digitized.

Both the hanging wall (1.T) and the footwall (1.B) for sample N2-3617FB have the same maximum topographic relief of 0.13 cm and positively skew (Figure 3.10a). The hanging wall has a higher tortuosity value than the footwall, but only by 0.1% and can therefore the surfaces can be approximated as the same (Figure 3.10b). The path lengths of the two surfaces also do not vary meaningfully (Figure 3.11c).

![Figure 3.10](image.png)

Figure 3.10: Fracture surface statistics for sample N2-3617FB. (a) Box plots summarizing topographic relief of each fracture surface listed from oldest to youngest. Pairs of surfaces constituting a single fracture generation share the same number and their relative position distinguished as T = top and B= bottom. (b) Calculated tortuosity of each surface. (c) Ratio of path length of each surface to average path length for all the surfaces in relative age order.

3.2.4 N2-3937FB

The fracture in sample N2-3937FB extends across the majority of the long axis of the thin section until it intersects a large pore (Figure 3.4b). The opposing walls of the
fracture pinch together at several discrete points, representing contact between asperities. These pinching points act to obscure surfaces within the fracture so that only a few can be traced. The fracture has also incorporated a large pore located on the edge of the thin section that was not digitized because surfaces could not be distinguished inside the pore. There are no splays or evidence of linkage within the thin section.

![Image of fracture surface statistics](image)

Figure 3.11: Fracture surface statistics for sample N2-3937FB. (a) Box plots summarizing topographic relief of each fracture surface listed from oldest to youngest. Pairs of surfaces constituting a single fracture generation share the same number and their relative position distinguished as T = top and B= bottom. (b) Calculated tortuosity of each surface. (c) Ratio of path length of each surface to average path length for all the surfaces in relative age order.

Three generations (i.e., three pairs of surfaces) have been identified in sample N2-3937FB (Figure 3.4b). The oldest fracture generation is on the margin, adjacent to the host rock (Figure 3.4c, part 1). The second oldest generation spans the entire length of the oldest surface (Figure 3.4c, part 2). The top and bottom layer of this surface is interpreted to be the same because they share similar cement extinction angle in cross-polarized light indicating they are crystallographically continuous on opposite sides of a fracture and the
obstruction of cross-cutting relationships from the pinching points. Therefore, there was no aperture measured for this fracture generation. Instead, this fracture generation likely caused asperity destruction, or insufficient slip to create offset. The youngest fracture generation only reoccupied a portion of the previous fracture (Figure 3.4c, part 3). This fracture generation is broken by a small thrust fault.

The maximum topographic relief for the first pair of fracture surfaces is 0.21 cm (Figure 3.11a). Despite this similar range and negative skews, the 95\(^{\text{th}}\%\) confidence intervals around the medians do not overlap, and, therefore, are statistically different. The second pair of surfaces has the same maximum topographic relief of 0.22 cm, as well as similar skews and medians. The second pair of surfaces is also statistically similar to the footwall (1.B) of the first fracture generation. The third pair of surfaces is statistically similar to each other with a maximum topographic relief of 0.09 cm. The topographic relief of the third surface pair is less than the 25\(^{\text{th}}\) percentile for all the previous surfaces or approximately half of the maximum relief of the initial four surfaces.

The tortuosity values for the first pair of surfaces are 1.07 and 1.08. These are the highest tortuosity values for all the fracture generations (Figure 3.11c). The final four surfaces have similar tortuosities of approximately 1.05. As for the path length, the youngest two surfaces are the shortest, and the initial four surfaces are of similar length (Figure 3.11c).

3.2.5 N2-4267

Sample N2-4267 is a complicated fracture that underwent linkage and incorporated several large pores into the fracture (Figure 3.5b). The sample can be
divided into three segments. The first segment is the oldest fracture generation and is two-thirds the length of the whole thin section (Figure 3.5c, part 1). This pair of surfaces extends along the margin of a large pore, whose incorporation into the fracture constitutes a large embayment on the fracture surface and significant addition of surface area and tortuosity. The pore coincides with the edge of that fracture generation, and the accumulation of cement is significantly thicker along the portion of the fracture down-dip from the pore. Only a single phase of calcite cement is present in the pore, and this cement is continuous with the cement in the fracture. Therefore this surface pair only slipped once and the pore was open before fracturing. Part of the oldest cement layer was then abandoned so that only a portion of the fracture was reactivated in slip. Slip along this reactivated fracture created the second fracture generation (Figure 3.5c, part 2). As the second fracture generation was forming, another fracture was propagating towards it (Figure 3.5c, part 3). This is the third fracture generation, which also incorporated a large pore. These two fractures linked during the fourth slip event and formed the final fracture generation (Figure 3.5c, part 4). The large pore on the second fracture generation segment has multiple, continuous cement layers, meaning after the initial incorporation of the pore into the fracture, it was not completely infilled with cement until the final slip event. However, neither incorporated pore influenced the dilation of the fracture because they were located on the outside of the fracture where it slipped with the surface instead of acting as an asperity.

The topographic distributions for the oldest four surfaces are similar with 95% of the relief less than 0.2 cm (Figure 3.12a). However, only the medians for the surfaces 1.B, 2.B and 3.T appear statically similar. Also, of the eight surfaces, all are negatively
skewed with the exception of 1.T, which is positively skewed. Surfaces 3.B and 4.B have a large increase in topographic relief where the 5th percentile of these surfaces is above the 95th percentile of the other seven surfaces. The topographic distribution for the Surface 4.B also contains the linkage step and has a maximum topographic relief of 0.44 cm.

Figure 3.12: Fracture surface statistics for sample N2-4267. (a) Box plots summarizing topographic relief of each fracture surface listed from oldest to youngest. Pairs of surfaces constituting a single fracture generation share the same number and their relative position distinguished as T = top and B= bottom. (b) Calculated tortuosity of each surface. (c) Ratio of path length of each surface to average path length for all the surfaces in relative age order.

The tortuosity values yield a trend much like that of topographic relief where the largest tortuosity values belong to surfaces 3.B and 4.B (Figure 3.12b). However, surface 3.B has the largest tortuosity of 1.67 despite not having the highest topographic relief. The first four surfaces and surface 4.T have tortuosity less than 1.4 and variable path length (3.12c). The variation in path length comes from the segmented growth of the fracture where the initial surface is close to the average surface length, and the final surfaces are almost twice its length.
3.2.6 N2-4125

Sample N2-4152 is the flattest fracture. This relative lack of relief is associated with two characteristics: (1) a lack of linkage surfaces; (2) the presence of gouge consistent with wear of the fracture surfaces (Figure 3.6b). Aside from the surfaces formed from the accumulation of gouge, which is the youngest fracture generation, the oldest pair of fracture surfaces is on the margin, adjacent to the host rock (Figure 3.6c, part 1). There is a splay fracture on the hanging wall of this pair that is consistent with the sense of slip but was not digitized due to its short interval. The second fracture surface extends across the whole length of the initial fracture generation (Figure 3.6c, part 2). The same is true for the third oldest fracture generation, which also contains Riedel shears towards the edge of the thin section (Figure 3.6c, part 3). Riedel shears are where conjugate shear fractures form synthetic or anthetic to the fracture (Twiss and Moores, 1992). They are the result of parallel shear along the boundaries of the layer where the conjugates form at an angle 30° from the maximum stress, consistent with Coulomb theory (Twiss and Moores, 1992). For this sample, the shears are anthetic, meaning they have an opposite sense of shear to the layer in which they occur.

The maximum topographic relief for all the surfaces belongs to surface 1.T and is 0.12 cm (Figure 3.13a). Surface 1.B has the next highest relief. The second and the third pairs of surfaces have similar topographic reliefs with a maximum of 0.08 cm and statistically similar medians. All topographic distributions for the initial three generations are positively skewed. Surfaces formed from the accumulation of gouge correspond to
the lowest topographic relief with the over 95% of the topography less than 0.03 cm. This is less than the 25th percentile for all preceding surfaces (Figure 3.19a).

Figure 3.13: Fracture surface statistics for sample N2-4152. (a) Box plots summarizing topographic relief of each fracture surface listed from oldest to youngest. Pairs of surfaces constituting a single fracture generation share the same number and their relative position distinguished as T = top and B= bottom. (b) Calculated tortuosity of each surface. (c) Ratio of path length of each surface to average path length for all the surfaces in relative age order.

The tortuosity associated with each surface does not reveal the general decrease seen in the topographic relief (Figure 3.13b). All the surfaces except, for 1.B, have tortuosities around 1.03 and 1.04. Surface 1.B has the highest tortuosity of 1.05 despite a lower topographic relief than surface 1.T, and the gouge surfaces have similar tortuosity to the preceding surfaces despite much lower topographic relief. The length of the surfaces cannot explain this variation because all except the gouge surfaces are similar lengths (Figure 3.19c).
3.1.7 N2-3937FA

Sample N2-3937FA is the most complicated fracture and contains linkage surfaces and ten fracture generations (Figure 3.7b). From the petrographic analysis, it is inferred that the first two fracture generations were propagating towards each other but failed to connect through linkage (Figure 3.7c, part 1). Instead, part of the oldest fracture generation was abandoned as part of the fracture was reactivated, creating the third fracture generation (Figure 3.7c, part 2). This third fracture generation linked to another nearby fracture, adding length and becoming the fourth fracture generation (Figure 3.7c, part 3). After the onset of linkage, the fifth fracture generation propagated throughout the entire length of the fracture. There were four more slip events that resulted in new fracture generations, but only occurred through part of the total fracture that did not include the linkage step (Figure 3.7c, part 4). The last slip event created a fracture in the opposite part of the fracture from the preceding four surface pairs. This slip event, fracture generation ten, cuts across previous fracture generations, and is therefore interpreted as the youngest (Figure 3.7c, part 5).

The first six surfaces all have a maximum topographic relief less than 0.10 cm (Figure 3.14a). There is variability among these initial surfaces where the 25\textsuperscript{th} percentile for surface 2.B is larger than the interquartile range for the other five surfaces. The fourth and fifth pairs of surfaces occupied the linkage structure and have a maximum topographic relief of 0.22 cm with a negative skew. The topographic increase corresponds to doubling the relief from the initial surfaces through linkage. The remaining five pairs of surfaces have maximum topographic reliefs less than 0.11 cm, with some surfaces (9.T, 9.B, and 10.B) have maximum topographic relief less than 0.04
cm. The narrow range of topography for the final surfaces is consistent with the expected smoothing of the surfaces over time.

![Diagram](image.png)

**Figure 3.14:** Fracture surface statistics for sample N2-3937FA. (a) Measured topography of each surface in relative age order. (b) Calculated tortuosity values for each surface in relative age order. (c) Ratio of path length of each surface to average path length for all the surfaces in relative age order.

The tortuosity analysis also shows the general decrease in roughness with the initial surfaces having an average tortuosity of 1.06, the surfaces sustaining linkage having an average tortuosity of 1.1, and final surfaces having an average tortuosity of 1.01 (Figure 3.21b). Overall there is a correlation between high topographic relief and increased tortuosity, as well as with path length (Figure 3.14c). The surfaces with the longest paths correlate to the surfaces with the highest topographic relief, except for surface 2.B.
3.3 Power Spectral Density and Slope

For each surface, the PSD and PSS are calculated from the digitized surfaces. The evolution of these parameters with successive slip events are evaluated based on relative age from youngest to oldest as in the descriptions of topographic relieve above. For ease of comparison between sections, the same color codes are used for both sections.

3.3.1 N2-4338

The two fracture surfaces in sample N2-4338 have overlapping PSD distributions, implying similarity (Figure 3.15a). This is due to insignificant differences variation between the upper and lower surfaces of the fracture as seen from the similar ranges in topographic relief. The interval of frequencies sampled for the PSS corresponds to wavelengths from 0.06 cm to 0.79 cm. The spectral slope of the upper surface was found to be $2.4 \pm 0.18$ deviation, while the bottom slope was $2.5 \pm 0.18$ (Figure 3.15b). Both of these spectral slopes are within the self-similar fractal range, as well as the error bars, which are narrow and vary less than 0.1 from the PSS.
Figure 3.15: Power spectral density analysis of sample N2-4338 for each surface and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to $\log_{10} (\text{frequency})$ versus $\log_{10} (\text{power})$. The errorbars correspond to one standard deviation.

3.3.2 N2-3617FA

The two surfaces of sample N2-3617FB have almost identical PSD distributions but vary based on length of the interval used to calculate PSS (Figure 3.16a). There are no linkage steps in this sample, nor large pores that interacted with the fracture to cause larger discrepancies between surfaces. The total interval of frequencies sampled for the PSS corresponds to wavelengths from 0.06 cm to roughly 1.00 cm. Both spectral slopes are $2.8 \pm 0.18$ and within the self-similar fractal range (Figure 3.16b). However, the error
bars for each surface are different and fall outside the self-similar fractal range for the lower surface.

Figure 3.16: Power spectral density analysis of sample N2-3617FA for each surface and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to \( \log_{10}(\text{frequency}) \) versus \( \log_{10}(\text{power}) \). The errorbars correspond to one standard deviation.

### 3.3.3 N2-3617FB

Both surfaces for sample N2-4338 have similar PSD distributions, with most of the variability towards the higher frequencies (Figure 3.17a). The interval of frequencies sampled for the PSS corresponds to wavelengths from 0.06 cm to 0.89 cm for the surfaces. The spectral slope of the upper surface was found to be \( 2.3 \pm 0.20 \), and the bottom slope was \( 2.4 \pm 0.23 \) (Figure 3.17b). Both of these spectral slopes are within the self-similar fractal range, as well as the narrow error bars.
Figure 3.17: Power spectral density analysis of sample N2-3617FB for each surface and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to $\log_{10}$ (frequency) versus $\log_{10}$ (power). The errorbars correspond to one standard deviation.

### 3.3.4 N2-3937FB

The six surfaces for sample N2-3937FA all span a frequency interval from 0.03 cm to 0.80 cm (Figure 3.18a). The PSS slopes fall between 2.80 and 3.85, and all error bars are narrow, less than 0.20 in width (Figure 3.18b). The first two surfaces, corresponding to the first slip event, have variable slopes with surface 1.B having the lowest spectral slope for the sample. The middle two surfaces have the same spectral slope because they are the same surface. This is also the highest slope for the all of the surfaces. There are no linkage steps in this sample and the large pore that interacts with
the fracture was not digitized. For these reasons, the high spectral slope for the middle layer cannot be accounted for by these processes. The final two surfaces have decreased PSS. This layer is also the shortest layer, about half the length of the oldest layer. Of the six surfaces for sample N2-3937FB, only surface 1.B falls within the self-similar fractal range. However, the upper error bars for this surface extend outside the 2-3 fractal range.

Figure 3.18: Power spectral density analysis of sample N2-3937FB for each surface and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to log_{10} (frequency) versus log_{10} (power). The errorbars correspond to one standard deviation.

### 3.3.5 N2-4267

The eight surfaces for sample N2-4267 span different frequencies that were used to calculate PSS (Figure 3.19a). The broad interval is from 0.03 cm to 0.63 cm, but some
surfaces only extend to 0.50 cm. The initial surfaces for this sample have the highest PSS and decrease with increasing age (Figure 3.19b). The ranges of slopes fall between 2.20 to 3.25, with all but one surface, 1.B, lying outside the self-similar fractal range. Also, as age increases, so does the width of the error bars.

![Power spectral density analysis](image)

Figure 3.19: Power spectral density analysis of sample N2-4267 for each surface and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to $\log_{10}$ (frequency) versus $\log_{10}$ (power). The errorbars correspond to one standard deviation.

This sample has sustained linkage and interacted with large pores that were then incorporated into the fracture. When compared to topographic relief, the PSS tend to be inversely related. The surfaces with high relief due to the pore’s effect (1.T, 3.B, and 4.B) have lower slopes than the surfaces with no pore influence. This pattern also holds for the
youngest surface that sustained linkage. These two surfaces have lower slopes than the preceding surfaces despite the additional length and roughness.

**3.3.6 N2-4152**

For sample N2-4152, the majority of the surfaces have a consistent range of frequencies from 0.06 cm to 0.85 cm that were used to calculate the slope (Figure 3.20a). However, the two youngest surfaces, which correspond to fracture generation formed by gouge, have a PSD y-intercept much less than the other six surfaces. The PSSs for the sample are between 1.85 and 3.75, with four of the middle surfaces having very similar spectral slopes (Figure 3.20b). This lack of variability is consistent with the sample having a straight fracture with surfaces of the same length. The highest spectral slopes belong to the surfaces formed from the accumulation of gouge, which is also the shortest surface with the least topographic relief. Of the eight surfaces, seven are within the self-similar fractal range, and all but two of the seven have error bars that extend outside of this range.
Figure 3.20: Power spectral density analysis of sample N2-4152 for each surface and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to log_{10}(frequency) versus log_{10}(power). The error bars correspond to one standard deviation.

### 3.3.7 N2-3937FA

Sample N2-3937FA has the most variability between surfaces when it comes to path length, and the amount of linkage sustained. This is evident in the PSD as different sampled intervals were used to calculate PSS for each surface (Figure 3.21b). Each surface also has a different y-intercept. The PSSs vary from 2.42 to 4.45, a broader range than any other sample (Figure 3.21b). Of the twenty surfaces, eight are within the self-similar fractal range, but only five also have error bars within the range.
Figure 3.21: Power spectral density analysis of sample N2-3937FA for each surface and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to $\log_{10}$ (frequency) versus $\log_{10}$ (power). The errorbars correspond to one standard deviation.

However, much like the graph of topographic relief, the trend of PSS shows a change from lower spectral slopes to higher spectral slopes in the middle surfaces, followed by lower PSS (Figure 3.21b). The high middle spectral slopes of surfaces 4.T, 4.B, 5.T, and 5.B correspond the surfaces that sustained linkage. However, the surface corresponding to the highest slope of around 4.30 ± 0.24 is not a linkage surface. Instead, it corresponds to a surface after the linkage stage that does not occupy the entire length of the fracture or linkage pathway. After the surfaces of higher spectral slope, there is a decrease, consistent with a smoothing trend as also seen in topographic relief. Also, the
final surfaces have higher slopes than the initial surfaces whereas there was an overall topographic decrease.

3.4 Dilation

The fractures reveal the accumulated separation of the host rock across the fracture normal to the fracture surfaces. It is presumed that this dilation is the sum of the apertures associated with each fracturing event. Thus, the incremental apertures represent the separation normal to the paired surfaces that constitute a single generation of fracture slip and opening. Determining this separation immediately following a particular slip and dilation event requires removal of all contributions from other generations of fractures. The cumulative dilation history is then revealed by the sum of the incremental apertures in time order. Example aperture plots for each sample can be found in Appendix B.

Both the incremental apertures and the progressive dilation are used as metrics to show how the distribution of aperture changes with age and slip. The incremental aperture has the advantage that it documents the dilation potential associated with any particular slip event of a given magnitude. In contrast, the cumulative dilation emphasizes the dependence of dilation potential on the entire history of deformation. In the Analysis section, both metrics will be compared with the incremental and cumulative slip to fully explore this dependence.

For simplicity in the subsequent text, the term “aperture” always indicates the incremental aperture introduced by a single fracture generation whereas as “dilation” indicates the cumulative dilation owing to the progressive contribution from all fracture generations.
3.4.1 N2-4338

The distribution of aperture associated with the pair of surfaces in sample N2-4338 ranges from 0 to 0.16 cm and has a positive skew (Figure 3.22). Since there is only a single generation of fracture, the incremental aperture and cumulative dilation distributions are equivalent. The largest apertures are found towards the ends of the fracture and have a maximum width of 0.15 cm. This is consistent with the thin section, where the middle of the fracture has very little aperture and is close to 0 at several points. The PSS of the aperture has a value of 3.1 ± 0.09 (Figure 3.23b), which is calculated from the PSD ranging from 0.01 cm to 0.80 cm (Figure 3.23a) and is slightly outside the range of self-similar fractals from 2-3, although the lower error bar does extend below 3.

Figure 3.22: Aperture distributions for sample N2-4338. (a Top and Bottom) The measure of the individual aperture along the surface path.
Figure 3.23: Power spectral density analysis of sample N2-4338 for each aperture and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to $\log_{10}(\text{frequency})$ versus $\log_{10}(\text{power})$. The errorbars correspond to one standard deviation.

3.4.2 N2-3617FA

The single aperture distribution for sample N2-3617FA ranges from 0 to 0.06 cm with a positive skew (Figure 3.24). The points of low and high apertures occur at intervals throughout the length of the sample, except at the ends where the aperture varies over a narrower range from 0.01 cm to 0.03 cm. These intervals are similar to the curved shape of the fracture. The PSS of the aperture has a value of $3.4 \pm 0.19$ (Figure 3.25b), taken from a PSD corresponding to frequencies ranging from 0.01 cm to 1.00 cm (Figure 3.25a). This is outside the self-similar fractal range.
Figure 3.24 Aperture distributions for sample N2-3617FA. (a Top and Bottom) The measure of the individual aperture along the surface path.
3.4.3 N2-3617FB

The single aperture distribution for sample N2-3617FB ranges from 0 to 0.052 cm (Figure 3.26). The 95 percent confidence interval has a slight positive skew that is more pronounced after outliers are included. There are no obvious intervals between low and high apertures despite the curved fracture geometry. The areas of zero aperture indicate that the two surfaces are in contact at one location. The PSS of the aperture is $3.6 \pm 0.40$ (Figure 3.27b) and corresponds to a PSD frequency interval of 0.003 cm to 0.630 cm (Figure 3.27a). This is outside the self-similar fractal range.
Figure 3.26: Aperture distributions for sample N2-3617FB. (a Top and Bottom) The measure of the individual aperture along the surface path.
Figure 3.27: Power spectral density analysis of sample N2-3617FB for each aperture and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to $\log_{10}$ (frequency) versus $\log_{10}$ (power). The errorbars correspond to one standard deviation.

3.4.4 N2-3937FB

Sample N2-3937FB only has two fracture generations with measurable apertures due to the second fracture generation occupying the same surface (Figure 3.28a). The largest aperture is from the first slip event that represents the oldest cement layer and has a distribution from 0.02 cm to 0.10 cm. The third fracture generation has a lower aperture distribution than the oldest fracture generation that is between 0 cm, where the surfaces come in contact, and 0.04 cm. Both apertures have a slight positive skew. Along the fracture, there are two areas where low aperture of the oldest layer corresponds to low
aperture of the youngest layer, meaning they are in contact or close to contact at these points.

The cumulative dilation reveals an overall increase from oldest to youngest fracture generations (Figure 3.35b). However, while the overall dilation increases, so does the range of the distribution which extends from 0.01 cm to 0.11 cm with the addition of the youngest event. This is due to the contact points of the youngest layer that retains narrow apertures despite additional cement growth at other points along the fracture. Therefore, while the dilation is increasing, it is not doing so homogeneously.

Figure 3.28: Aperture and dilation distributions for sample N2-3937FB. (a Top and Bottom) The measure of the individual aperture along the surface path. (b Top and Bottom) The measure of cumulative dilation of each surface.
The PSD for the two fracture generations that have measureable apertures have the same range of frequencies sampled from 0.01 cm to 0.80 cm for PSS (Figure 3.29a), but different slopes (Figure 3.29b). The spectral slope for the oldest aperture is 2.00 ± 0.10, and the youngest aperture has a slope of 2.9 ± 0.23. This is an increase in slope of 0.9 from the prior generation, which is inconsistent with the PSS of the individual surfaces which lacked a definitive trend or pattern due to the oldest surface pair having spectral slopes similar to the youngest surface pair.

Figure 3.29: Power spectral density analysis of sample N2-3937FB for each aperture and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to $\log_{10}$ (frequency) versus $\log_{10}$ (power). The errorbars correspond to one standard deviation.
In the oldest fracture generation, 95% of the aperture variation is symmetrically distributed between 0.01 and 0.05 cm. (Figure 3.30a). However, the majority of the outliers constituting the remaining 5% are skewed toward larger apertures. This trend is present in all four aperture distributions as a result of the discrete oversized pores incorporated into the fracture. The second oldest aperture varies from a minimum of 0.02 cm to a maximum 0.10 cm. This is less than the oldest aperture, but has a wider 95% interval. The third aperture has a distribution from 0.03 cm to 0.39 cm. The youngest aperture has the most extensive distribution from 0.01 cm to 0.42 cm due to the inclusion of a large pore and linkage, which adds to its topography.

For the cumulative dilation plots, the mean for the first three generations increase almost linearly until an exponential increase with the addition of the fourth generation (Figure 3.30b). This trend is similar to the trend of the topographic profiles. This is due to the infilling of the large pore and the linkage separation which increases the dilation. This trend is similar to the trend of the topographic profiles.
Figure 3.30: Aperture and dilation distributions for sample N2-4267. (a Top and Bottom) The measure of the individual aperture along the surface path. (b Top and Bottom) The measure of cumulative dilation of each surface.

The highest PSS for the aperture is $3.5 \pm 1$ standard deviation and corresponds to the third generation. This fracture generation contains a pore, but no linkage (Figure 3.31b). There are large error bars associated with this PSS, but it is still outside the range of self-similar fractals and do not overlap with the other three apertures. The final fracture generation includes both the large pore and linkage and has the lowest spectral slope of $2.3 \pm 0.10$. The oldest generation has a spectral slope of $2.6 \pm 0.14$. If the third generation were ignored, then there would be a trend of decreasing slope as the fracture continued to slip. This is not reflected in the topographic profiles.
Figure 3.31: Power spectral density analysis of sample N2-4267 for each aperture and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to log10 (frequency) versus log10 (power). The errorbars correspond to one standard deviation.

3.4.6 N2-4152

The oldest surface for sample N2-4152 has the largest aperture distribution ranging from 0.01 cm to 0.11 cm with a positive skew (Figure 3.32a). The remaining three generations all have aperture distributions between 0.07 and 0.01 cm. While these apertures come close to zero, there is no point where the opposing surfaces are in contact. Generations two and three have alternating periods of high and low separations that are further expressed as opposite skews. The youngest generation is the one formed from the
accumulation of gouge and only extends over part of the sample, but increases in separation towards the edge of the thin section.

The cumulative dilation box plots show the large initial increase from the oldest fracture generation, as well as additional increases with time (Figure 3.32b). Each time the dilation increase is less than the time before, but the width of the distribution remains consistent over the 95% interval. The youngest dilation event increases the positive skew of the distribution with several outliers. This event is associated with the gouge accumulation generation.

Figure 3.32: Aperture and dilation distributions for sample N2-4152. (a Top and Bottom) The measure of the individual aperture along the surface path. (b Top and Bottom) The measure of cumulative dilation of each surface.
When plotted PSD (Figure 3.33a) and PSS (Figure 3.33b), the layers of sample N2-4152 reveal a trend opposite to the spectral analysis of the individual surfaces. For this sample, the highest slope of $3.8 \pm 0.38$ belongs to the initial generation while the final generation has a slope of $2.4 \pm 0.19$ and is the lowest spectral slope for the sample. When plotted as individual surfaces, the gouge surfaces have the highest slopes for the sample. This cannot be explained by the aperture distribution since the youngest three surface pairs all vary over the same range- but the gouge layer is also the shortest fracture generation for the sample.

Figure 3.33: Power spectral density analysis of sample N2-4152 for each aperture and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to log10 (frequency) versus log10 (power). The errorbars correspond to one standard deviation.
3.4.7 N2-3937FA

Sample N2-3937FA has the most fracture generation and the most variability among aperture distributions (Figure 3.34a). The first three generations occurred prior to linkage and their widths of distribution decrease with increasing age. The oldest generation has a distribution from 0.01 cm to 0.83 cm with no points of contact. Generations four and five contain the linkage step with a maximum width of 0.12 cm and are both positively skewed. The remaining five fracture generations do not include the linkage step and have aperture distributions less than 0.03 cm.

Figure 3.34: Aperture and dilation distributions for sample N2-3937FA. (a Top and Bottom) The measure of the individual aperture along the surface path. (b Top and Bottom) The measure of cumulative dilation of each surface.
When added together as cumulative dilation through time, the box plots show an S-shaped curve (Figure 3.34b). There is little dilation gain between the first two generations, as they occupy different parts of the sample. The third dilation event increased the overall dilation of the sample to 0.10 cm, as well as the width of the distribution as the aperture of the surfaces remains narrow. Dilation is then dramatically increased to 0.16 cm for the fourth generation, then again to 0.19 cm for the fifth generation. This is consistent with the topographic profiles that also show a large increase associated with the surfaces that sustained linkage. The remaining five generations fail to increase the overall dilation of the sample. This is a result of narrow apertures and failure to occupy the linkage pathway.

Figure 3.35: Power spectral density analysis of sample N2-3937FA for each aperture and its corresponding slope values. (a) Periodogram of the frequency distribution of power. (b) Power spectral slope inferred from linear least squares fit to \( \log_{10} \) (frequency) versus \( \log_{10} \) (power). The errorbars correspond to one standard deviation.
All apertures share a range of sampled frequencies but vary based on y-intercept, therefore creating variability in their spectral slopes (Figure 3.35a). In general, the PSS of the apertures decrease with additional slip events, with the exception of the third and tenth generations (Figure 3.35a). This trend does not reflect the topographic reliefs or the PSS of the individual surfaces which show an increase in value for the surfaces that sustained linkage.

3.5 Grain and Pore

The grain and pore dimensions were measured and assessed to see how they contributed to the topography of the initial surfaces. The initial surfaces are those that interact directly with the surrounding rock without modification by cement, alteration or wear. Topography is as described in Section 3.2. The cumulative frequency distributions for the grains and pores sizes intersects the bin size axis at 0.001 cm.

3.5.1 N2-4338

Despite the large matrix component and heavy alteration in sample N2-4338, there are large grains present, with the largest being 0.125 cm in size (Figure 3.36b). The 95 percent interval for the grains is narrow and extends to 0.049 cm. There are no large pores that directly interact with the fracture and the 95 percent interval is similar to the grain distribution but extending to 0.068 cm. The largest pore within the thin section is 0.35 cm.
Figure 3.36: Grain and pore comparison for sample N2-4338. (Top) Graph showing the distribution of different features in both normalized frequency and cumulative frequency. (Bottom) Box plots of topographic distributions of different features.

Both the grain and pore distributions are positively skewed towards the small size fraction (Figure. 3.36a). The asperity distribution is more evenly distributed, with a slight negative skew towards the large size fraction, with the largest asperity height of 0.144 cm. However, this maximum asperity size is less than maximum pore size but larger than the maximum grain size as seen from the cumulative frequency curve (Figure 3.36a).
3.5.2 N2-3617FA

Aside from two large pores, the grain and pore distributions for sample N2-3617FA vary over the same range of sizes. The largest pore is 0.420 cm while the largest grain is 0.073 cm (Figure 3.37b). The 95% interval for the pore distribution is from 0.003 cm to 0.070 cm and for the grain distribution is from 0.002 cm to 0.032 cm.

Figure 3.37: Grain and pore comparison for sample N2-3617FA. (Top) Graph showing the distribution of different features in both normalized frequency and cumulative frequency. (Bottom) Box plots of topographic distributions of different features.

All three distributions are similar but vary based on the skew (Figure 3.37b). The two surfaces have a normal distribution, whereas both grain and pore distributions have a positive skew towards smaller sizes. The asperity heights range from 0 to 0.096 cm. This
is larger than the maximum grain size by 0.023 cm but less than the maximum pore size by 0.320 cm and shows that the asperity heights occur within the range of grains and pores as seen from the cumulative frequency curves (Figure 3.37a).

3.5.3 N2-3617FB

Much like sample N2-3617FA, the distributions of the grains and pores are very similar, except for a few large pores (Figure 3.38b). The grains vary over 0.002 cm to 0.061 cm. The pores vary over 0.003 cm to a maximum of 0.230 cm with a 95th percentile interval between 0.003 cm and 0.060 cm.

The only two surfaces present in sample N2-3617FB have asperities that range from 0 cm to 0.137 cm. The distributions are bimodal with concentrations around 0.035 cm and 0.120 cm. This is outside the 95th percentile interval for both the grain and pore distributions but less than the maximum pore size by 0.090 cm.
Figure 3.38: Grain and pore comparison for sample N2-3617FB. (Top) Graph showing the distribution of different features in both normalized frequency and cumulative frequency. (Bottom) Box plots of topographic distributions of different features.

### 3.5.4 N2-3937FB

Sample 3937FB has a few outsized pores, some of which interacted with the path of the fracture. The 95\% interval of the pores range from 0.003 cm to 0.033 cm, but the largest pore is 0.290 cm (Figure 3.39b). The grains present in the thin section are mostly prismatic plagioclase grains. The maximum and minimum grain sizes are from 0.001 cm to 0.170 cm. Both grain and pore distributions are positively skewed.

The initial surface data set consists of the oldest pair of surfaces and the remaining surfaces consists of the youngest two pairs of surfaces. The asperity heights for
the initial surfaces are less than 0.208 cm (Figure 3.39b). This asperity maximum exceeds the grain distribution but not the maximum pore size. The asperity data sets have a similar shape in cumulative and normalized frequency with a positive skew, except there is a larger proportion of smaller asperity heights for the younger surfaces data set (Figure 3.39a).

Figure 3.39: Grain and pore comparison for sample N2-3937FB. (Top) Graph showing the distribution of different features in both normalized frequency and cumulative frequency. (Bottom) Box plots of topographic distributions of different features.

3.5.5 N2-4267

Sample N2-4267 has two pores incorporated into the fracture. The maximum pore value is 0.673 cm (Figure 3.40b). The 95% range is also large, extending to 0.302 cm.
The grain distribution, on the other hand, is quite narrow with a maximum size of 0.089 cm. This sample contains the smallest grains as seen by a positive skew. The pore distribution also has a positive skew towards smaller sizes.

Figure 3.40: Grain and pore comparison for sample N2-4267. (Top) Graph showing the distribution of different features in both normalized frequency and cumulative frequency. (Bottom) Box plots of topographic distributions of different features.

The initial surfaces for this sample are the first three pairs of surfaces, as they all interacted with the rock mass. These layers contain pores but no linkage. The analysis of both data sets show the asperities well exceed the grain distribution but are less that the maximum pore size (Figure 3.40a). The initial asperity heights strongly correlate with pore size because a hundred percent of the initial asperities occur over the 95% interval
from 0 to 0.300 cm. However, the shape of the initial surfaces’ cumulative frequency curve strongly resembles the shape of the grain distribution but vary based on the amount of skew towards smaller sizes. The pore distribution more closely resembles the remaining surfaces curve.

3.5.6 N2-4152

Both the grain and pore distributions for N2-4152 are very similar, except for one outsized pore. The grains range from 0.001 cm to 0.071 cm with 95 percent of the grains falling between 0.001 cm and 0.031 cm (Figure 3.41b). The pores range from 0.002 cm to 0.175 cm with 95 percent of the data falling between 0.002 cm and 0.033 cm.

The initial surfaces for this sample are solely the oldest pair of surfaces as all other surfaces occur inside the oldest fracture generation. This is true except for the fracture generation associated with gouge which is between the rock mass and the fracture, but represents extensive wear as opposed to an initial surface. However, the initial surfaces and the remaining surfaces all occur within the same span of 0 to 0.121 cm when the outliers are included and have a positive skew. The main difference between the two asperity data sets is the frequency of heights within the range where the other surfaces have a higher contribution of smaller sized asperities (Figure 3.41a). Both asperity data sets extent past the 95th% confidence interval for the grain and pore distributions, but due to the outsized pore, no asperity exceeds this maximum value. Neither of the cumulative frequency curves for the asperity data sets resemble the grain or pore cumulative frequency curves, but the majority of the asperities occur where the distributions of the grains and pores diverge (Figure 3.41a).
3.5.7 N2-3937FA

Sample N2-3937FA has the smallest pore size distribution with a size range from 0.001 cm to 0.020 cm (Figure 3.42b). The grains are prismatic plagioclase grains with a size range from 0.001 cm to 0.170 cm. This maximum grain size is over five times larger than the maximum pore size range. N2-3937FA is the only sample to have all the pores less than the grains. Both the grain and pore distributions are positively skewed.
Figure 3.42: Grain and pore comparison for sample N2-3937FA. (Top) Graph showing the distribution of different features in both normalized frequency and cumulative frequency. (Bottom) Box plots of topographic distributions of different features.

The initial surfaces separated for analysis include the first two pairs of surfaces. The remaining surfaces are the youngest eight pairs of surfaces which include the surfaces that sustained linkage. When plotted as cumulative frequency curves, the range of sizes for the remaining surfaces extends well beyond the maximum grain and pore size (Figure 3.42a). The remaining surfaces data set is bimodal and has a negative skew. The largest asperity height for this data set is 0.240 cm, almost 0.100 cm larger than the maximum grain size and over 0.200 cm larger than the maximum pore size. However, the maximum asperity height for the initial surfaces is 0.070 cm. This is well within the
range of grain sizes, but much larger than the pore distribution. The initial surfaces are positively skewed with a unimodal distribution

3.6 Slip

Slip was measured to assess how the amount of dilation changes with slip over the life of a fracture. Incremental slip for a single fracture generation was measured and related to the incremental aperture on an individual basis to show if there are any direct correlations between aperture and slip. The cumulative slip was then calculated by adding sequential slip values in relative age order and related to cumulative dilation. This correlation was used to put aperture and slip into the context of the overall fracture history by seeing how the trends in dilation changed with time. A table of slip values and corresponding surfaces is available in Appendix B.

3.6.1 N2-4338

Sample N2-4338 has only one fracture generation and slip was measured from this layer using matching surfaces. The slip was measured at multiple locations for consistency and found to be 0.015 cm. An annotated image of where slip was measured on N2-4338 can be found in Appendix B.

3.6.2 N2-3937FB

Only one fracture generation for sample N2-3937FB was measured using a broken grain on the outside of the oldest surface. The slip was measured to be 0.057 cm.
An annotated image of where slip was measured on N2-3937FB can be found in Appendix B.

### 3.6.3 N2-4152

The oldest generation for sample N2-4152 was measured for slip. The slip indicator used was matching surfaces from the dilation profiles and measured to be 1 cm. This is the maximum amount of slip achieved on any sample. An annotated image of where slip was measured on N2-4152 can be found in Appendix 3.B.

### 3.6.4 N2-3937FA

Slip was measured on six of the ten fracture generations for sample N2-3937FA, making it the best-documented sample for slip. Slip indicators included broken grains and matching surfaces. There were no wrench faults, and splays only occurred on surfaces where more reliable slip indicators were present. The two initial surfaces had both slipped around 0.045 to 0.050 cm, which were the largest slip distances. The other four generations are the third, fourth, fifth, and seventh pairs and slipped between 0.009 and 0.018 cm, including surfaces that occupied the linkage structure.

The plot of incremental aperture and slip reveals different zones based on age (Figure 3.43b). The aperture of the initial surfaces follows a one to one linear increase with slip. The other surfaces show almost no correlation between slip and aperture, meaning very little slip was needed to increase aperture. Only the oldest surfaces are associated with apertures greater than the grain size and this is associated with incremental slips that are likewise greater than the grain size. The cumulative dilation and
slip plot shows an S-shaped curve, much like the plot of cumulative dilation for this sample (Figure 3.43a). There is an immediate onset of dilation from the very first slip, followed by a period of little increase, until the linkage stages where there is an increase in dilation produced from little slip. The 75th percentile grain size was chosen as a reference due to the larger grain and asperity size control the dilation potential of a fracture and was plotted. It is shown that linkage occurs after cumulative dilation well exceeds the representative grain size. An annotated image of where slip was measured on N2-3937A can be found in Appendix B.

Figure 3.43: Slip and related opening for sample N2-3937FA. (a) Cumulative slip and dilation for sample. (b) Incremental slip and apertures with a one to one line. In both plots, the horizontal error bars reflect the uncertainty of the slip measurement based on available geologic indicators and pixel size which is ±0.003 cm. The vertical error bars represent the 25-75 percentile of the dilation distribution for the paired fracture surfaces. The colored dashed line represents the median grain size for the sample. Note that slip for some surface pairs could not be independently determined and thus 6 out of 10 fracturing events are plotted.
CHAPTER 4
ANALYSIS

4.1 Topography

4.1.1 History of Fracture Roughness

The evolution of surface roughness is compared by juxtaposing boxplots, which summarize the distribution of roughness on each fracture surface, as a function of their relative age (Figure 4.1). Generally, early-formed fracture surfaces are characterized by unimodal distributions. This comparison of initial surface relief reveals that although most of the distributions overlap to some degree, many of these distributions appear statistically different at the 95% confidence level. Despite these differences in the initial roughness, all of the samples analyzed document the progressive development of fractures from initial surfaces, recurrent slip, healing, propagation, linkage, and the formation of gouge and show a general trend of topographic relief decreasing with decreasing slip. This finding documents the potential for variability in relief despite consistent rock type, mineralogy and depth. In the majority of cases, the frequency distribution of asperity height is either symmetric or skewed toward smaller asperity height.
Figure 4.1: Topographic relief in relative age order for all seven samples. Surfaces associated with growth by linkage of fractures or the presence of gouge is highlighted as yellow and red respectively. As before, pairs of surfaces resulting from a single slip event are numbered their generation as T or B corresponding to top and bottom, respectively. Horizontal dashed lines represent the 75th percentile grain size for each of the samples.
The surfaces with the lowest relief belong to the youngest generation of fractures in sample N2-4152 and N2-3937FA (Figure 4.1). In the case of sample N2-4152’s, this relative lack of relief is associated with the presence of gouge. In sample N2-3937FA, gouge is not evident, but this fracture has accumulated several layers of well-distributed cement. This suggests two distinct mechanisms that can reduce fracture roughness and potentially influence subsequent dilation during slip.

The formation of a gouge layer in sample N2-4152 is the product of extensive wear and breaking of asperities. This gouge layer is located between the host rock and the earlier fracture generations, instead of within, and, though continuous, is only a third of the length of the previous fracture generation. Broken grains are not visible in this layer; instead the material has been precipitated as quartz. The cement mineralogy is unique to this layer, for all other cement healing the fractures are calcite. The gouge is characterized by an over-all reduction in asperity height and a reduction in the variability of asperity heights relative to earlier fracture generations. Prior to the appearance of gouge, prior generations are characterized by a constant width of the relief distribution.

The highest relief is found in sample N2-4267 and is associated with a large pore that introduces an embayment, and with a linkage structure associated with a large positive relief asperity. The large pore and the linkage both represent localized effects confined to small portions of the fracture. Sample N2-3937FA also underwent linkage and, similarly to N2-4267, these linkage surfaces are also the only surfaces to have a negative skew. The linkage that joins two non-coplanar (i.e., offset) fractures necessarily produces two distinct populations of asperity height if the common reference is parallel to the oldest fracture as introduced here to provide uniformity across all fracture
generations. In the boxplots, this bimodal distribution is evident as a much broader inter-quartile width. Locally, the asperity height populations on the formerly isolated fractures on either side of the linkage structure are similar. However, the offset represented by the linkage structure that causes the bimodal distribution is mechanically significant as it introduces an asperity that could strongly influence dilation and the resistance of the fracture to slip by either introducing an obstruction or opening structure (Figure 1.5). After the fracture has linked, subsequent reactivation continues to decrease topographic relief of the fracture surfaces.

During reactivation, the portion of the fracture experiencing slip varies. Both samples N2-3937FA and N2-4267 abandoned parts of the oldest surface as they developed and accumulated slip. In particular, in sample N2-3937FA the portions of the older fracture surfaces that overlap the region of linkage with an adjacent fracture did not participate in subsequent slip and dilation. In sample N2-4267, although the slip event associated with linkage is the youngest evident fracture generation, the overlapping region nevertheless did not participate. In both cases, the linkage occurred after several slip events. Samples N2-4152 and N2-3937FB also have multiple slip events, and examples of partial reactivation of surfaces, but neither resulted in linkage. Unlike the reactivation in samples N2-4152 and N2-3937FA, these reactivated portions occurred along older fractures and did not propagate into to host rock. Therefore, reactivation of only a portion of a fracture is a common feature of fracture growth that can occur in varied situations.

As for the serial thin sections N2-3617FA and N2-3617FB, their maximum topographic reliefs differ by 0.04 cm (Figure 4.1). Their medians do not appear to overlap
at the 95\textsuperscript{th} confidence interval. Thus the fracture generations are significantly different, though only by 0.01 cm. These serial thin sections were cut from the same fracture and significantly overlap in area as can be seen from the common oversized pore they share. Therefore, the slight differences in topography statistics are related to their position on the fracture, similar to varying slip gradients along a fracture.

4.1.2 Tortuosity

Tortuosity of the fracture can evolve as it propagates, grows by linkage between fractures, and as the asperity population is modified by mechanical wear or dissolution and precipitation. If fractures decrease in relative abundance of small wavelength asperities as slip progresses, then the relative surface area should also decrease leading to lower tortuosity. This is only true in the absence of significant propagation and linkage, which adds to path length and creates a new source of roughness. Therefore, the initial tortuosity calculated for the surfaces becomes the basis for whether subsequent surfaces are increasing or decreasing in roughness.
Figure 4.2: Tortuosity in relative age order for all seven samples. All surfaces have been rotated individually. Surfaces corresponding to linkage and gouge have been highlighted.

With the initial surfaces acting as the reference, trends in tortuosity between samples can be assessed. The initial surfaces pairs are as they are defined from the grain and pore correlations. From Figure 4.2, it can be seen that, with the exception of surfaces that underwent linkage or incorporated large pores, tortuosity decreases with additional slip events. The surfaces that include linkage and large pores have higher tortuosity than previous samples. However, these trends do not correlate perfectly with topographic relief. In many cases, the surface with the highest relief is not the surface with the highest tortuosity, for example, surface 4.B for sample N2-4267. The opposite is also true, for
example, surface 4.T for sample N2-4152. This surfaces was formed from the accumulation of gouge and have little topographic relief, but tortuosity similar to the other surfaces in this sample. Thus, this demonstrates that low topographic relief does not mean a straight surface.

4.2 Power Spectral Slope

A critical threshold for PSS is whether the surface is self-similar fractal, which implies scale-independent roughness. In other words, the roughness of the fracture at any length-scale of observation is indistinguishable from the roughness at a different length-scale, which means that self-similar surfaces posses the same proportion of wavelengths through all scales. In this way, the amplitude is directly related to the wavelength so that the height to width ratios are constant (Turcotte, 1997). Self-similar fractal behavior is associated with a spectral slope between 2 and 3. If the slope lies outside this range, the contribution of different frequencies is scale dependent; in other words, the ratio of asperity height to width is no longer constant and is considered self-affine. In fractures, this dependence could result from the mechanisms controlling fracture shape such as grain or pore size, smoothing by wear that produces gouge, or acquisition of asperities through linkage. For instance, wear could preferentially remove tall, short wavelength asperities increasing the relative proportion of broad wavelengths asperities.
Figure 4.3: Power spectral slopes for all samples in relative age order. Surfaces corresponding to linkage and gouge have been highlighted in yellow and red. The errorbars correspond to one standard deviation.

Nearly all samples show the first two surfaces have spectral slopes between 2 and 3 representing self-similar fractal behavior, with the exception of samples N2-4267 and N2-3937FB (Figure 4.3). In subsequent generations, results diverge and few surfaces fall within the fractal range. The highest spectral slopes are found in samples N2-4152 and N2-3937FA, which are comprised of surfaces with low maximum topographic relief and a narrow range of asperity heights. This is most extreme in N2-4152, where gouge is present presumably as a result of wear of asperities. However, sample N2-3937FA has surfaces with relief similar to gouge surfaces that do not high spectral slopes that would...
be expected for surfaces with low relief. As for the surfaces with high topographic relief, such as surfaces that underwent linkage in samples N2-3937FA and N2-4267, their spectral slopes are higher than the preceding surfaces, meaning a large wavelength asperity was added. In the case of sample N2-4267, the spectral slope for the surfaces that underwent linkage only increased slightly from previous surfaces because the linkage separation was minimal. For sample N2-3937FA, the increase in spectral slope for the surfaces that underwent linkage was more significant as is the separation distance of the linked fractures. Both linkage surfaces for N2-4267 are within the self-similar fractal range while only half of the linkage surfaces for N2-3937FA are inside this range. The comparison of the PSSs reveal a trend of overall increase in spectral slope with increasing age associated with the accumulative of slip, indicating the dominance of large wavelength asperities (Figure 4.4).

![Figure 4.4: The affects of cumulative slip on PSS of individual surfaces. Surfaces corresponding to linkage have been highlighted in yellow. The errorbars correspond to one standard deviation. Data generated in PSSvSlip_F, Appendix A.](image-url)
An important aspect of the periodogram method of testing fractal behavior is the assumption of a stationary distribution. In other words that there is no positional dependence on frequency content so that all frequencies contribute the same to all parts of the fracture surface. This assumption also implies continuity of the contribution as represented by the superposed sine waves in the Fast Fourier derivation of the periodogram. The discrete distribution of both outsized pores and linkage structures provide important contributions to roughness that clearly violates this rule at small length-scales of observation. However, as fractures grow, and the intersection/occurrence between these structures and fractures increase more numerous, it is expected that this conflict will likely be resolved.

4.3 Power Spectral Slope of Apertures

The PSS of apertures describes how the two opposing fracture surfaces are related to each other due to differences in geometry and their relative offset related to slip. It is presumed that at zero slip, the two surfaces should match, resulting in negligible variation in aperture, and small apertures overall, except where pores or other inherited primary structures lead to mismatch. Slip results in limited points of contact, as discussed above, that become the lows in aperture. The remaining variation in aperture should reflect the complex interaction of the roughness of the fracture walls, slip, and modifications resulting from wear or chemical processes including dissolution and precipitation.
For the seven samples, the calculated spectral slopes for the apertures range from 2 to 4.2, with most of the variability in the oldest fracture generation (Figure 4.5). Three out of the four samples with documented repeated slip show an overall decrease in spectral slope as slip continues (Figure 4.6), where the youngest apertures are within the self-similar fractal range. The evolution of PSS in N2-3937FA, which has the most extensive slip history, implies a leveling off in the PSS as slip continues. Even the
surfaces that sustained linkage in samples N2-3937FA and N2-4267 decrease in spectral slope when compared to preceding apertures. The apertures that deviate from this trend, such as the third aperture for samples N2-3937FB, N2-4267, and N2-3937FA, represent reactivation of only small portions (typically about a third shorter) of these fracture compared to the other generations. The general decrease in PSS for apertures with increasing age is opposite to the trend of the individual surfaces (Figure 4.6).

![Figure 4.6: The affects of cumulative slip on PSS of apertures. Apertures corresponding to linkage have been highlighted in yellow. The errorbars correspond to one standard deviation.](image)

### 4.4 Grain and Pore Correlations

The influence of grain and pore size on the topography of the surfaces are assessed by comparing the 75\textsuperscript{th} percentile of the grain and pore sizes to the 75\textsuperscript{th} percentile of asperities for the initial surfaces and the remaining surfaces. The asperities for the
initial fracture generation and the subsequently, remaining, or reactivated, generations are the same as previously defined, as well as the grain and pore size distributions. All samples have similar grain size between 0.02 cm and 0.04 cm but vary based on asperity heights (Figure 4.7a). For the initial surfaces, the asperities are as much as an order of magnitude larger than the grain size. This does not include the size variation of the error bars which represent one standard deviation. Only sample N2-3937FA has an asperity size almost proportional to the grain size. All other samples seem limited by grain size, with no dependence on matrix due to lack of asperities smaller than grain size. For the reactivated surfaces, the asperities can be as much as an order of magnitude to twenty times larger than the grain size (Figure 4.7b).

![Figure 4.7: Comparing grain size to asperity heights for all the surfaces. (a) Grain and asperity size of the initial surfaces for all the samples with error bars of one standard deviation. (b) Grain and asperity size of reactivated surfaces for all the samples with error bars of one standard deviation. The relief added to the samples that underwent linkage is plotted on the graphs as dashed line. The colors of these lines correspond with the color of the sample.](image)
The pore size distributions are much more variable between samples than the grain size distributions and reveal a stronger correlation. In the initial surfaces, as pore size increases so does the asperity size, with the exception of sample N2-3937FB (Figure 4.8a). However, several of the pore sizes and error bars representing one standard deviation are either close or past the one to one line. This means that despite the positive correlation there are asperities less than the pore sizes. Given the relatively infrequent distribution of pores, this is consistent with the influence of the smaller and more pervasive grains. This holds true when the pore distribution is compared to the asperities for the reactivated surfaces (Figure 4.8b). Over the lifespan of the fracture, rather than providing strong direct correlation, the influence of grains and pores appear to be closer to a lower bound on roughness.

Figure 4.8: Comparing pore size to asperity heights for all the surfaces. (a) Pore and asperity size of the initial surfaces for all the samples with error bars of one standard deviation. (b) Pore and asperity size of reactivated surfaces for all the samples with error bars of one standard deviation. The relief added to the samples that underwent linkage is plotted on the graphs as dashed line. The colors of these lines correspond with the color of the sample.
4.5 Slip and Dilation

The dilation accumulated during reactivation shows a strong positive correlation to the cumulative slip. However, the evaluation of the incremental accumulation of slip on a sample N2-3937FA through seven generations (Figure 3.50), and the aggregation of data from all samples suggests the accumulation of dilation is strongly non-linear (Figure 4.9). For small cumulative slip, such as sample N2-4338 and the initial slip event for N2-3937FA, the increase in dilation is proportional to the magnitude of slip. These two surfaces also lie close to the 75\textsuperscript{th} percentile grain size for sample N2-3937FA. As slip increases to become larger than the grain size, the amount of dilation decreases. This behavior persists until sample N2-3937FA acquires the linkage structure, and the dilation is once again proportional to cumulative slip. During this interval of slip, large dilations are gained from small slip. However, with additional slip, the dilation ceases to increase further, as seen for sample N2-4152. This result is influenced by the presence of gouge derived from wear of asperities that inhibits gains of additional dilation.

Figure 4.9: Comparison of slip and cumulative dilation for all the samples. Error bars are representative of the 25\textsuperscript{th} and 75\textsuperscript{th} percentiles for dilation. The sequence of points for sample N2-3937FA is the same as Figure 3.43.
This return to a more direct scaling between slip and dilation is consistent with two commonly recognized behaviors of elastic fracture: (1) that the interaction distance between fractures that can link is proportional to the length of the slipping fracture (see Figure 1.6 and supporting discussion); (2) that the maximum slip is also proportional to the length of the fracture as scaled by the frictional strength of the fracture and the elastic properties of the material. This suggests that growth of the fractures through linkage produces asperities of a scale that is limited by fracture length. As a result, the linkage structure is capable of reintroducing dilation at scales that depend on the fracture length, and thus also maximum slip. Consequently, these structures should allow the dilation potential of fractures to be regenerated at least for a time.
CHAPTER 5
DISCUSSION

5.1 Interpretation of Results and Analysis

5.1.1 Fracture History as a Function of Smoothing

The modification of fracture surface roughness accompanying slip occurs in distinct developmental stages. When cumulative slip is small, roughness is generally uniform across multiple slip events and is several times larger than the grain size. When fracture surface roughness is uniform so is the total surface area of the fracture, as inferred by its path length despite cement precipitation along the fractures. At larger slip, surface roughness is modified by linkage to nearby fractures and the formation of gouge. These two processes have conflicting effects on surface topography and dilation despite their similar dependence on large cumulative slip (Figures 3.50 and 4.7) and their similar reduction in PSS to values consistent with self-similar fractal characteristics (Figure 4.4).

The first process, linkage, is anticipated to be self-similar because of the scaling relationship between fracture length, slip, and the maximum size of a linkage separation (Martel and Pollard, 1989; Cartwright et al., 1996). This process can occur several times throughout the life of a fracture, each time providing an additional and localized source of roughness proportional to the separation distance that also increases the path of the fracture. For sample N2-3937FA, over 1.2 mm in topographic relief was added to the sample through linkage (Figure 3.1b and 4.1g) in addition to the gain in length resulting from combining two formerly isolated fractures. The topographic relief added by linkage
is less obvious for sample N2-4267 due to a separation distance smaller than the initial topography of the surface prior to linkage (Figure 3.4a&b and Figure 4.1e). Surfaces that underwent linkage typically have steeper spectral slopes than the older surfaces (Figure 4.4). This appears to be the result of introducing a large, long wavelength asperity equivalent to the separation distance between the fractures joined through linkage that therefore minimizes the relative power of the smaller wavelength asperities relative to the length of each surface.

Unlike linkage of macroscopic fractures, which occurs intermittently during fracture growth, asperity destruction is an ongoing process that starts once peak shear strength of the rock is surpassed (e.g., see summary in Jager et al., 2007). This can occur with the first slip event as observed from the general and gradual decrease in topographic relief with increasing surface age. Asperity destruction reduces both the height of the largest asperities and the diversity of asperity heights, leading to a decrease in surface area. Therefore the influence of longer wavelengths increases as shorter wavelength asperities are worn away to form gouge (and the small grain size, larger surface area, and freshly broken surfaces promote dissolution and re-precipitation) (Fetterman, 2011). This process leads to steeper spectral slopes, and is associated with surfaces of low topographic relief, such as sample N2-4152 for example. However, this increase in spectral slope could also be partially the result of short surface lengths, which limits the measurement of long wavelengths.

Both gouge and linkage are capable of producing steeper spectral slope, which qualitatively indicates the dominance of long wavelength features. However, these processes are critically different. The formation of gouge, or the process of smoothing
rougher surfaces, is associated with decreasing the contribution of small wavelength asperities, while linkage introduces a localized large wavelength asperity. Because of the relative size of the linkage separation, it can skew the PSD to steeper spectral slope, even though the diversity and magnitude of relief increase. In the application to dilation, gouge appears to minimize dilation and needs not be associated with fracture growth, whereas linkage will promote dilation, extend the fracture, and promote connectivity of the fracture pore space. This indicates that for the purposes of predicting dilation potential as well as for use in assessing EGS stimulation potential, PSS is a potentially misleading parameter as it does not distinguish between processes that prohibit versus promote storativity (porosity) and permeability (connectedness and size of pores) in the rock volume. Similarly, the resistance to slip on a fracture is strongly influenced by the strength of interlocking asperities (e.g., Lockner and Beeler, 2002). So it is expected that fractures with larger asperity diversity due to linkage and surfaces smoothed and coated by gouge will have significantly different frictional properties.

The problem then becomes how to uniquely characterize surface roughness in terms of parameters that tend to be ambiguous about both processes and implications for key characteristics such as permeability or fracture strength. A surface can have high topographic relief without the influence of linkage, such as surface 3.B for sample N2-4267 that has incorporated a large pore. Similarly, surface 4.B for sample N2-4267 has both a large pore and a linkage structure. Much like linkage, a pore incorporated into the fracture acts as a large wavelength asperity that can affect the PSD. Therefore, it can be unclear how much the pore or the linkage attributed to the steeper spectral slope for this surface, as they are both long wavelength features. Surface 3.B has higher tortuosity over
surface 4.B implying surface 3.B is rougher, but the surface also has a slightly steeper
PSS implying the opposite. Other surfaces displaying discrepancies include the surfaces
associated with gouge in sample N2-4152. Both of these surfaces have low topographic
relief and high PSS, implying a smooth surface, but the tortuosity for these surfaces are
comparable to the initial surface’s tortuosity. Therefore, in order to accurately describe
the geometry of a fracture surface, all three methods of analysis have to be considered
where all three describe aspects of the surface (Figure 5.1).
Table 5.1: Table of possible combinations of fracture surface roughness characterization methods with corresponding descriptions and an example surface. Table aims to explain how the three metrics of fracture geometry can be used to describe the fracture surface by combining the non-uniqueness attributes that the metrics have when applied individually. High or low tortuosity is relatively based on the initial tortuosity values for each sample. High PSS are spectral slopes more than a spectral slope of 3, and low PSS are spectral slopes less than 3.
5.1.2 Grains and Pores

Grain size appears to determine the minimum asperity height along these fractures. However, the samples have a relatively narrow range in grain size, which limits the insight into this dependence. The strongest correlation between grain size distribution and asperity height distribution occurs in sample N2-3937FA, which also lacks large pores. In addition, there seems to be a negligible effect from the matrix on the initial asperity sizes even in samples with forty percent matrix. The relative lack of influence of grains in the matrix can be explained by the strength of the phenocrysts that cause the fracture to propagate around them rather than through (Kitey and Tippur, 2005). The grains are largely comprised of feldspar, calcite, and pyroxenes, which are typically high friction and relatively high strength materials and thus not easily broken, especially in low mean stress environments such as shallow depth and normal faulting stress regimes (Lockner and Beeler, 2002). There is also the potential for a slight bias from the minimum resolution in the digitization of the fracture surfaces, which may prevent resolving a matrix contribution to roughness.

There is a broad, direct correlation between pores and asperity heights where the largest asperity size is often less than the largest pore. In addition, anecdotally it appears that large pores strongly influence fracture nucleation and thus potentially also fracture spacing which ultimately influences linkage. This association is common in both the field examples discussed here as well as in laboratory experiments of the Geo N-2 core examined at Newberry (Li et al., 2012; Ghassemi personal communication, 2012) where they likely act as stress concentrators that initiate the fracture. Where the pores interact
with the fracture, they correlate to locally large, negative relief (embayment) asperities on the fracture surface and are thus less likely to promote dilation.

5.1.3 Slip and Dilation

All fracture generations are characterized by pairs of surfaces that are locally in contact and show offset markers documenting slip. In general, in these two-dimensional profiles, only a small fraction of the fracture surfaces are in contact in each generation. This is consistent with a variety of two- and three-dimensional experimental evaluations (e.g., Dieterich and Kilgor, 1996) on a large variety of materials. This, together with incremental dilation remaining less than the available topographic relief (Figure 4.1 and Appendix 3.12), confirms that Mode II-III frictional slip is the driving mechanism for fracture re-activation and dilation in these samples. Dilation through Mode I opening and mixed Mode I and II-III require effective tension and would result in a lack of contact between surfaces inconsistent with these samples.

The characterization of each surface, together with its corresponding fracture generation, reveal that when slip reactivates a fracture, the whole fracture does not need to be involved. This manifested in two ways that can be documented in the samples. The first example was partial reactivation along or within older fractures where new propagation remained juxtaposed next to the older fractures. The second example was when partial reactivation of older surfaces occurred on the margin between the older fracture generation and the host rock. This led to the abandonment of the un-reactivated older fracture generation, where the reactivated portion led to linkage to nearby fractures.
Thus, not only do fractures grow from the accumulation of slip, but they also do so heterogeneously without involving the entire fracture.

The Mode II-III fractures sampled here have incremental and cumulative slip less than 1 cm (Figure 4.9). For sample N2-3937FA, the largest values of incremental slip, with magnitudes similar to the grain size (within the 25th to 75th percentile), belong to the first two fracture generations (Figure 3.50). The relief of these early surfaces correlates with the grain and pore size distribution (Figure 4.7 and 4.8) and is characterized by a relatively steep spectral slope (Figure 3.28). The associated dilation similarly scales with the accumulation of slip, resulting in high PSSs for initial apertures (Figure 3.42). This is due to the relatively well-matched surfaces at small cumulative slip that will result in relatively few small wavelength features. As the fracture is repeatedly reactivated, and slip continues to accumulate, the PSS of fracture surfaces generally increases (Figure 4.4) and the PSS of apertures generally decreases (Figure 4.6) as more offset and mismatch is accumulated and increases the abundance of small wavelength features to the apertures (Figure 3.28 and 4.3). This trend is evident in all samples, despite differences in the mechanisms of fracture growth (linkage versus wear and gouge).

The cumulative and incremental dilation plots for sample N2-3937FA (Figure 3.50) reveal distinct domains of slip induced dilation corresponding to pre- and syn- or post-fracture linkage. Initial fracture formation is associated with an immediate dilation approximately proportional to the slip and grain size. Additional slip events produce small additional dilations but largely preserve this scaling. A second stage is characterized by large dilation per slip increment accompanying and immediately following linkage. These large gains in dilation persist until the slip approaches the size...
of the asperity introduced by linkage. As slip approaches the size of the asperity, dilation and slip return to rough proportionality (Figure 3.50a).

Thus dilation appears to be directly influenced by the relative size of asperity heights on the fracture surface and the slip. In the early stages, where slip is close to the grain size, dilation is limited to this size range (Figure 5.1b). When the surface is modified by linkage, this new, larger asperity size mediates dilation. In both cases, the dilation is limited by the asperity size and where slip exceeds the size of these asperities, little additional dilation is achieved. Since new asperities could be gained through linkage, and the distance of linkage increases as a function of fracture length, this implies a kind of “stair-stepped” variation in slip versus dilation (Figure 1.6), where the upper limit on dilation corresponds the largest asperity heights. Eventually, this relationship is modified by wear and gouge as in sample N2-4152 (Figure 4.9) that further inhibits dilation. In larger faults, brecciation also plays a role in mediating the interaction of asperities on opposing fault surfaces (Myers and Aydin, 2004; Fetterman and Davatzes, 2011).

Also, the apparent, progressive changes in fracture surface topography could actually result from partial reactivation of the surfaces that is biased to exclude larger asperities. In many of the fractures investigated, such as N2-3937FA, fracture generation may correspond to slip on only a portion of the fracture (rather than the entire fracture slipping in each generation). This is consistent with the behavior of larger seismogenic faults, although not as commonly encountered in laboratory settings where samples are very small. In this explanation, larger asperities act as strong points that separate reactivated regions, and are thus preferentially excluded from some generations, therefore
emphasizing smaller asperities and resulting in both lower relief and a narrower distribution of relief. It is presumed that as these “patches” are slipped, the intervening larger, stronger asperities will eventually be reactivated as well. Thus apparent variation in roughness between generations at least partly reflects how slip heterogeneously accumulates on the fracture.

![Figure 5.1: Comparing slip-dilation models. (a) Two commonly employed models relating dilation to slip. The shear dilation angle model proposes a simple linear relationship between slip and dilation (blue line). The Lee and Cho model describes an evolution of dilation with slip from zero dilation prior to a critical slip to a rapid transition to maximum dilation coinciding with the onset of gouge production (green line). (b) The conceptual model presented in this paper where the transitions of the shear dilation behavior are controlled by the rock properties.](image)
During the interseismic periods between slip events, fluid flow along the connected pores of the fracture and the interaction of asperities and gouge with fluid, or material removed through pressure solution promotes precipitation of secondary minerals along the fracture surface (Renard et al., 2000). Precipitation of cement reduces porosity, isolates pores, and thus reduces permeability of the fractures. In the case of the samples analyzed, most of the cementation is quartz and/or calcite, both high frictional strength minerals (Davatzes and Hickman, 2010; Fetterman, 2011). High frictional strength minerals maintain brittle properties that are similar to the host rock (Davatzes and Hickman, 2010; Fetterman and Davatzes, 2011). In this way, continued slip causes fracturing along the cement layers, that are similar to the original surfaces and preserves slip history as well as the potential for dilation.

Other common secondary minerals include phyllosilicates with lower frictional strength and typically very small grain size (Fetterman and Davatzes, 2011). These minerals are able to ductily flow more readily around asperities due to low strength, therefore limiting dilation while reducing the frictional contact between the two surfaces (Fetterman and Davatzes, 2011). These minerals cause the fracture to behave more ductile (Lockner and Beeler, 2002), thus reducing permeability (Crawford et al., 2002; Davatzes and Hickman, 2010). Therefore, fractures with these minerals will develop and evolve surface roughness distinctly different from the analysis presented here. However, at the high temperatures in 55-29 and the bottom of Geo-N2, the weakest of these minerals, smectites, are unstable and fractures have a higher abundance of quartz and calcite (Figure 1.11).
The majority of fractures demonstrate accumulations of cement that are at least partially broken during subsequent reactivation. Several of these fractures, such as N2-3937FA, exhibit progressive reduction and narrowing in the distribution of roughness consistent with wear, but without the expected accumulation of gouge. This implies that healing, in addition to wear and linkage, can alter surface roughness and dilation during the fracture life cycle. Several possible mechanisms are likely: (1) Coating the surfaces with cement could alter the surface roughness and would reflect the initial topography of the fracture walls as modified by the mineralogy and competition of crystals growing from them. If subsequent reactivation occurs either prior to complete healing or in the interior of the fracture within the cement instead of the interface between the host rock and cement, the cement will influence the roughness of the new fracture surfaces. (2) Alternatively, wear during slip should produce small, detached fracture-bounded particles characterized by large surface areas as in sample N2-4152. The relative solubility of these particles is enhanced by these characteristics, and in conjunction with their exposure to the fluid in or moving through the connected porosity of the fracture, could lead to preferential dissolution and subsequent re-precipitation to form the observed cement. In this way, wear would have been active in modifying the fracture surface topography, but its effects obscured. (3) In a related mechanism, gouge formed during slip can provide nucleation points for cement growth after slip (Renard et al., 2005). In this case, the gouge would be difficult to detect although ghost textures of the gouge could be preserved and detectable in plane polarized light or under cathodoluminescence.

Each of these processes is consistent with a trend of decreasing topographic relief as the fracture repeatedly slips. Thus, any of these three mechanisms could explain the
progressive changes in surface relief in N2-3937FA, which has multiple layers of cement but lacks gouge.

5.2 The Evolving Role of Fracture Surface Roughness

5.2.1 Results Relative to Literature

Of the forty-eight surfaces analyzed, twenty-seven fall within the self-similar fractal range as described by Power and Tullis (1991) and Brown (1995), who argue fractures have a consistent, unchanging PSD throughout their development. Yet, this leaves twenty-one surfaces with slopes characterized as self-affine. Also, Figure 4.3 does demonstrate that PSS changes significantly as a function of slip (Power et al., 1987; Sagy et al., 2007; Brodsky et al., 2011) and that there are several mechanisms that can cause the change including wear, linkage, and healing. Previously, Sagy et al. (2007) and Sagy and Brodsky (2009) argued that surface roughness “smoothes” to favor the long wavelength content as faults grow and slip accumulates.

Unlike these studies, which compare separate fractures of different length (and from a range of different field sites), the analysis presented here records the evolution of fracture surface topography in single fractures subjected to repeated slip under consistent conditions. It was found that (1) unchanging PSD is associated with short fractures of small cumulative slip (prior to macroscopic linkage or formation of gouge) and (2) additional sources of roughness can increase PSS so that it is not a unique result of ‘smoothing.’
Lee and Cho (2002) performed experiments in marble and granite to explore the evolution of roughness and dilation at confining pressures similar to this field study that also relate dilation and permeability to slip (Figure 5.2). Fracture permeability is measured in m$^2$ or the square of the aperture areas and is therefore very sensitive to changes in dilation. The seven samples show that due to the inherent roughness of fractures, dilation is immediately gained even at small cumulative slips. This contradicts the Lee and Cho experiments which show that there are negligible gains in dilation at small slips. However, their results are similar to our assessment of linkage, except the dilation increase occurs at different cumulative slip and their experiment ranged over slip distances of up to 15 mm while the natural fractures analyzed only have slip distances up to 10 mm. Also, the experiments performed involved creating tensile fractures in marble and granite slabs that were then positioned and slipped and the natural process of fracture growth through linkage was neglected. Instead, the onset and effects of gouge were expressed by the leveling off of permeability past a critical slip distance, indicating that permeability is not infinitely increasing like the concept of dilation angle might suggest.
5.2.2 Conceptual model

Two models are commonly employed to relate dilation and roughness to slip. The first model developed by Barton and Choubey (1977) defines a dilation angle which relates the amount of dilation to the amount of shear displacement relative to the size of the asperities according to Barton shape profiles (Figure 5.1a). A key assumption of this model is that the dilation angle is fixed, i.e. it does not include an evolution in the relationship between slip and dilation. Through their analysis, most fractures have a dilation angle between 13°-27°, providing a way to calculate hydraulic conductivity of a certain fracture by assuming an unchanging roughness. The second model is proposed by Lee and Cho (2002) which described dilation and permeability as a non-linear function of shear displacement (Figure 5.1a). The model is characterized by a lower and upper limit on dilation/ permeability gain due to slip. The lower limit represents a threshold that needs to be overcome before there can be any measurable permeability. The upper limit represents the formation of gouge where permeability is no longer increased.

Both of these models attempt to quantify the role of fracture surface roughness and find similarities between modeled results and natural examples. The shear dilation angle model appears to accurately describe the dilation, but only for small cumulative slip that remains less than the asperity size. Thus, it neglects the changes in roughness accompanying slip through either healing, wear, or linkage that imply the dilation angle must change at a critical slip magnitude. The Lee and Cho permeability model describes the evolution of fractures by defining transitions between high permeability and low permeability which neglects the propagation and linkage of finite fractures, as well as
healing. Thus, while these experiments demonstrate key behaviors of fractures in natural materials and sensitivity to confining pressures, they do not account for natural fracture growth through linkage, only the effects of wear and asperity/surface matching or healing.

This analysis, however, accounts for natural propagation of fractures that underwent repeated slip and reveals separate phases of fracture dilation related to three distinct mechanisms influencing dilation: (1) asperity mismatch, (2) asperity damage and gouge formation, and (3) linkage (Figure 5.1b). The first phase encompasses initial fracture propagation at small cumulative slip just before linkage and depends on initial fracture geometry. A key control on this at Newberry appears to be the presence and distribution of large pores. How long this phase persists should depend on the density of small fractures in the rock mass that controls the separation to be bridged during linkage. The second phase is dominated by linkage to nearby fractures and, again, depends on the separation distance of fractures. In this case, the separation must be less than 1x to at most 3x the fracture length, and will be most effective at shorter distances, so as the fracture grows, its ability to link to other fractures occurs at wider and wider separation (Martel and Pollard, 1989; Myers and Aydin, 2004; de Joussineau, 2007). Thus, in rocks with a high density of fractures, these additional asperities, that are the result of the linkage separation, and their accompanying contribution to dilation would be small.

The third phase of fracture evolution involves two possible paths representing either a fracture dominated by linkage or gouge. If the fracture is gouge dominated, then the wearing of the asperities prohibits increased dilation, similar to sample N2-4152 and the Lee and Cho (2002) experiments. If the fracture is linkage dominated, then there will
exist a zone dominated by gouge formation before the fracture is able to link again and increase dilation/permeability. The size interval of this phase would be determined by the fracture and depend on how many cycles of linkage or how long permeability stays constant with gouge. The final phase is where the two paths in phase three converge with the development of a complex fault zone with core comprised of distinct fault rock and breccia as described by Caine et al., (1996) and Fetterman and Davatzes (2011).

5.3 Implications to EGS

The goal of any EGS system is to supply sufficient permeability, porosity, and saturation to extract heat from hot rocks (Barbier, 2002). One mechanism to accomplish this goal is to induce slip on naturally rough fractures that dilate and then remain propped open by their asperities. It has been shown that the most effective way to increase permeability is with the propagation of splay fractures (Jung, 2013). Older fractures would incorporate clay minerals, for instance due to alteration of the abundant plagioclase phenocrysts, as permitted by the local temperature conditions. It has been suggested that younger, smaller fractures are better for EGS stimulation for this reason (Fetterman, 2010).

This has important implications to EGS where effectively modeling dilation due to slip on natural fractures is needed to characterize, and later manage, the EGS reservoir. During EGS, pumping of water into stimulation wells to induce slip results in small earthquakes (MEQ), typically much less that 3.5 $M_W$ (Breede et al., 2013) as discussed in the Introduction. The seismic moment of an earthquake is proportional to the amplitude of a long period wave and represents the total energy measured from a seismogram.
(Kanamori and Anderson, 1975, Chen et al., 2007). The magnitude of an earthquake is the amplitude of a certain frequency measured from a seismogram (Kanamori and Anderson, 1975) and is recorded for each event. Thus, from the measured magnitude of the earthquake, the static moment released can be derived which better represents the energy involved in the earthquake (Hanks and Kanamori, 1979). The relationship between static seismic moment, $M_o$, slip area, $A$, and the slip, $s_{avg}$, is:

$$M_o = \mu A s_{avg}$$

where $\mu$ is the shear modulus of the rock mass (Aki, 1967; Hanks and Kanamori, 1979; Beeler et al., 2003). Therefore, if the size of an earthquake can be related to a slip area and slip, then this proposed model allows for the prediction of resulting dilation, and thus permeability on individual fractures, the hypocentral positions, and areas, as well as focal mechanisms could be used to infer the likelihood of intersection necessary for a percolating fracture network and also representing linkages that would influence subsequent deformations and dilation potential.

5.4 Summary

Fracture surface roughness is characterized by the qualitative petrographic analysis and the quantitative statistical variation in topographic relief, tortuosity, and power spectral slope of small fractures with up to a centimeter of cumulative slip. These parameters evolve as slip accumulates and the fractures repeatedly slip. Individually, these metrics fail to adequately distinguish the mechanisms modifying fracture roughness and the key structures that reveal the influence of roughness on permeability and strength of fractures. The characterization of topography quantifies the distribution of asperity
heights along the fracture surface that reveals that stages key processes including linkage, gouge, and healing, but neglects the width of the asperities. In contrast, power spectral slope accounts for relative contribution of different sized asperities characterized by a width and height based on an idealized sinusoidal form. However, the power spectral slope that summarizes the relative influence of asperities of different wavelengths does not distinguish the competing mechanisms modifying roughness. Although linkage adds large asperities and wear decreases asperity height producing gouge, surfaces modified by these processes have similar power spectral slope that express a dominance of large wavelengths. These processes contribute to an evolution in roughness characterized by power spectral slopes that are initially self-similar (2 to 3 m²) to self-affine (>3 m²) as slip accumulates and results in apertures that follow the opposite evolution. Tortuosity as approximated by the piecewise path-length normalized to the best fitting linear length, indicates whether surface area is increasing or decreasing between fracture generations, but is unclear in distinguishing different fracture stages or specific mechanisms such as the incorporation of a pore. However, when all three metrics are considered, the characteristics of the fracture surface can be accurately described and related to the mechanisms of asperity modification, especially where supported by petrographic relationships between fracture surfaces, cements and alteration, and gouge.

The initial fracture surfaces have a wide range in roughness in part due to different grain and pore size distributions, though the variation in grain size is from 0.01 to 0.06 cm. Initially, fracture propagation is strongly influenced by nucleation at and incorporation of pores and by preferential propagating around grains. The largest grain size fraction appears to more strongly influence initial roughness than the presence and
proportion of matrix. However, the grains provide positive relief asperities that interact with the opposing fracture surface. The influence of pores is stronger but results in negative relief embayments along the fracture surface that do not contribute to dilation. Thus, the grain distribution of the rock mass limits the maximum apertures for the initial surfaces and results in an immediate dilation at cumulative slips. The result is that the population of asperities on the oldest fracture surfaces vary between these two distributions, and the minimum dilation is most strongly influenced by grain size.

Linkage is most likely as cumulative slip exceeds the grain distribution and the fracture length exceeds the spacing of early formed fractures in the rock mass. During linkage, or when the fracture surfaces active in slip span the linkage structure, small incremental slips produce large dilations. If the step sense and sense of shear match, dilation is localized at the linkage structure and the remainder of the surface should continue to experience dilation consistent with the earlier stage and the grain size. In this case, the distribution of dilation could become bimodal. Alternatively, if the step sense and sense of shear are opposite, the fracture surfaces are forced apart as they override this new asperity. As a result, the new asperity is the primary point of contact between the surfaces and rest of the fracture dilates. After the cumulative slip exceeds the size of the linkage structure, dilation is again small. In addition, as slip accumulates asperity destruction, and the formation of gouge is expected, dilation will be inhibited. It is likely that the necessary amount of slip is complexly related to the stress boundary conditions, and the mineralogy and shape of the asperities that influence their strength so that this transition is highly variable. This pattern of slip and dilation, with intervening periods of healing, is cyclical and defines the complete life cycle of natural fractures. Thus, unlike
previous models that do not account for natural fracture growth and reactivation, this slip-dilation model can be discretely inferred from the primary properties of the rock and the spacing of fractures which influences linkage.
CHAPTER 6
CONCLUSIONS

Fracture surface roughness changes as a function of slip. This has been determined from the combination of different metrics, such as power spectral density and topography, which describe the geometry of a fracture’s surface roughness. Aided by successive cement layers that preserve multiple slip events, their associated dilation, and individual surfaces, a new conceptual model has been proposed that relates the changes in fracture surface roughness and the resulting dilation as a function of slip to discrete mechanism that affect roughness throughout the lifecycle of the fracture. It was found that (1) initial fracture surface roughness is strongly influenced by the grain and pore sizes of the rock mass, (2) once the accumulated slip exceeds the size of the asperities on the fracture surface, linkage occurs and provides a new source of roughness, (3) slip results in asperity destruction as the two opposing surfaces grind past one another and creates gouge, and (4) the healing of fractures that also limits the aperture of the fracture.
REFERENCES CITED


APPENDIX A
MATLAB SCRIPTS AND FUNCTIONS

RoughnessCalculations_4

function [MySurfaces, mc] = 
RoughnessCalculations_F(fimagename,DP,fdigitname,fname,Vis);

%TITLE: RoughnessCalculations_F.m

% Author: NC Davatzes and Justin Roth
% Later edited by: Olivia Wells
% Date: last modified 5/1/2015
% Plot of surface topography, statistics of surface length and
% topography
% Power Spectral Analysis of surface topography
% CRITICAL CALLED FUNCTIONS:
% QUARTILE
% ScaleImage
% ReorderByNearestNeighbor
%
% Purpose:
% This script imports digitized fracture surfaces in order to
% calculate
% and visualize the topographic relief.
% INPUTS:
% Photograph of thin section from sample 3937FA
% Digitized interpreted fracture surfaces from sample 3937FA
% OUTPUTS:
% Plot of fracture surfaces colored by age
% NOTES:
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
%%                   SECTION 0: Import using filenames
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
close all;
Image=imread([fimagename,'.jpg']);
Traces=load([fdigitname,'.m']);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
%cLEAR all, close all

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
% Section 1: Import and Visualization

% Definition Variables:
%DP = 1125; %dots per cm
% Load the JPEG of the thin section image
%TSi = imread('Image');
%TScl = imread('Image');
TSi = Image;  %supposed to be for CL image
image(TSi), axis equal, axis tight

% Section 1.2: SCALE DATA
[Xtsi,Ytsi] = ScaleImage(TSi,DP);
[Xtscl,Ytscl] = ScaleImage(TScl,DP);

% Section 1.3: Plot scaled image
figure(1);
subplot(1,2,1)
image(Xtsi(1,:),Ytsi(:,1),TSi); % TS image
xlabel('X-position [cm]')
ylabel('Y-position [cm]')
title('Thin Section Image')
set(gca, 'YDir', 'normal') % set axis properties within figures
axis equal, axis tight, grid on

% SECTION 2: Visualizing the digitized fracture surfaces:

% SECTION 2.1: Load and Organize Data
% data = load('RoughRoughnessData.txt');
data = Traces;
% NOTE:
% Column 1 = x
% Column 2 = y
% Column 3 = surface index pairs(color)
% Column 4 = 1 or 2 corresponding to top or bottom

% For proper analysis and plotting, it is necessary to make the order of
% the points defining each surface approximately monotonic within each
% combined data set. The original data was not systematically digitized
% from one end of a fracture to another in order to take advantage of the
% clearest surfaces first, then infill.
% --> A goal here is to always start from one extreme end of the data
% set.
% OPTION 1:
data = sortrows(data,[3,4]);

% OPTION 2:
% ReorderByNearestNeighbor
% this assumes that a search for the radially
% closest digitized point determines the order. This is only viable
if
% the data is digitized at a spacing smaller than the distance
between
% faces patches of the surface at bends.

X  = data(:,1);  %#loads the master x-coordinate data
Y  = data(:,2);  %#loads the master y-coordinate data
Si = data(:,3);
Stb= data(:,4);
mc = max(Si);

% % Use this section if re-scaling of digitized data is necessary
% because of
% % problems with the axes defined during original digitization:
% %
% % The thin section image has an origin. The digitized fracture
% surface has
% % an origin. These two origins might coincide. If they do not share
% the
% % same reference frame, then for the purpose of plotting the
% digitized
% % surfaces onto the images or next to them in corresponding position
% % requires a position transformation (i.e., a translation and/or
% rotation).
% % transform coordinate system due to wrong origin during digitization
% % account for offset of y-origin
% % yoffset = 0;
% %yoffset = 157*(1/DP); % difference between image and digitized data
% origin
% % realy = ((Y - (max(Y))).*1);
% % X = X.*(1/DP);
% % Y = realy.*(1/DP)+yoffset;

% Set color scale for plotting each digitized surface with a unique
% color:
MyColor = jet(2*mc);

% SECTION 2.2: Divide data set into cells by surface number and top or
% bottom and make sure the data is a sequential order along the surface
% (path order and not necessarily monotonic in x)
MySurfaces.obs = cell(2*mc,1);
% upper surfaces are always the odd numbered elements, bottom surfaces
are
% in the even numbered elements

for i = 1:mc;
    for j = 1:2;
        I = find(Si==i & Stb == j);
        x = X(I);
```matlab
y = Y(I);
if j==1;
    TB='T';
    Vis='N';
    [XII,YII,II,P,MaxGap,XI,YI,I] = ReorderByNearestNeighbor3(x,y);
else j==2;
    TB='B';
    Vis='N';
    [XII,YII,II,P,MaxGap,XI,YI,I] = ReorderByNearestNeighbor3(x,y);
end
XR=XII;
YR=YII;
MySurfaces.re{2*(i-1)+j,1} = [XR,YR];
end
end
for i = 1:mc;
    for j = 1:2;
        I = find(Si==i & Stb == j);
        x = X(I);
        y = Y(I);
        if j==1;
            TB='U';
            Vis='N';
            [XPYP,XMYM] = MonotonicReSample2(x,y,TB,Vis);
        else j==2;
            TB='L';
            Vis='N';
            [XPYP,XMYM] = MonotonicReSample2(x,y,TB,Vis);
        end
        XI=XPYP(:,1);
        YI=XPYP(:,2);
        XM=XMYM(:,1);
        YM=XMYM(:,2);
        MySurfaces.obs{2*(i-1)+j,1} = [XI,YI];
        MySurfaces.obss{2*(i-1)+j,1} = [XM,YM];
    end
end

% SECTION 2.3: Plot surface traces
subplot(1,2,2)
dummy = [1;2];
for i = 1:mc-1;
    dummy = [dummy;1;2];
end
MyLine = {'-','--'};
for i = 1:2*mc
    hold on
    % plot(MySurfaces.obs{i}(:,1),MySurfaces.obs{i}(:,2),...%
    % 'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
    plot(MySurfaces.re{i}(:,1),MySurfaces.re{i}(:,2),...%
        'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
end
```
% SECTION 2.4: Quality Assessment: Many results depend on the ordering
% of points defining the surface (they are path-dependent)
% --> Plot Test of the ordering of the points defining the surface
figure
subplot(1,2,1)
i = length(MySurfaces.obs); % 4; % 14; % 12 % 14 % 34;
I = [1:1:length(MySurfaces.obs{i}(:,1))];
x = MySurfaces.obs{i}(:,1);
y = MySurfaces.obs{i}(:,2);
plot3(x,y,I,'k-');
hold on
scatter(MySurfaces.obs{i}(:,1),MySurfaces.obs{i}(:,2)+yoffst,...
ones(size(MySurfaces.obs{i}(:,1)))*4,I);
scatter3(x,y,I,...
one(size(MySurfaces.obs{i}(:,1)))*8,I);
grid on, box on
view([0,90])
hc = colorbar;
set(get(hc,'ylabel'),'String','Path Sorted Index Position',...
'FontSize',12,'FontName','Helvetica');

% Reorder by nearest neighbor (careful for "flat, "crack-like"
% protrusions from the surface
% [XI,YI] = ReorderByNearestNeighbor(x,y);
% [XI,YI] = ReorderByNearestNeighbor3(x,y);
plot(XI,YI,'r-','LineWidth',1.5);
xlabel('X-component [cm]')
ylabel('Y-component [cm]')
title('Example surface path colored by row position')

subplot(1,2,2)
horder = nan(1,2*mc);
htitle = cell(1,2*mc);
hold on
for i = 1:2*mc
    horder(i) = plot(MySurfaces.obs{i}(:,2),',o-',...
    'Color',MyColor(i,:),'MarkerSize',5);
    htitle{i} = num2str(i);
end
xlabel('Index Position []
ylabel('y-component [cm]')
legend(horder,htitle{:})
grid on, box on
title('Quality Assessment of Surface Path')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

SECTION 3: Import and Visualization

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

SECTION 3.1: Solve for Least Squares Best Fits to Each Surface

MySurfaces.model = cell(2*mc,3);
% structure of cell array:
%   column 1: [X,Y]
%   column 2: P (the constants in the polynomial fit)
%   column 3: S
% --> every row of the cell array corresponds to a different surface
% To query data:
% 1st: use curly brackets to grab the appropriate cell in the
% cell
%   array, e.g., MySurfaces{5,2} ==> cell at row 5, column 2
% 2nd: use normal brackets to query a position in the matrix
% contained in the cell, e.g., MySurfaces{5,2}(1,2)
% ==> element of matrix at row 1, column 2 in the cell at row 5
% column 2

% APPROACH: Polyfit for each surface using the slope and intercept of
% the
% oldest surface to determine rotation.

% SECTION 3.1a: Fit each surface independently
N = 1; % polynomial fit degree
for i = 1:2*mc
  x = MySurfaces.obs{i}(:,1);
  y = MySurfaces.obs{i}(:,2);
  [x,I] = sortrows(x);
  y = y(I);
  [XI,YI] = ReorderByNearestNeighbor(x,y);
  [MySurfaces.model{i,2},MySurfaces.model{i,3}] =...
  polyfit(XI,YI,N);
  [MySurfaces.model{i,2},MySurfaces.model{i,3}] =...
  polyfit(MySurfaces.obs{i}(:,1),MySurfaces.obs{i}(:,2),N);
  ymodel = m * Xobs + b
  ymodel = MySurfaces.model{i,2}(1)*MySurfaces.obs{i}(1,:1) + ...
    MySurfaces.model{i,2}(2);
  MySurfaces.model{i,1} = [MySurfaces.obs{i}(1,:1),ymodel];
end
% SECTION 3.1b: Fit oldest surface to define reference frame and distribute
% into structure array (just so all arrays are the same shape even though
% it is redundant).
MySurfaces.old.model=cell(2*mc,1);

% Least Squares fit using polyfit
% Oldest surface first:
[P,S] = polyfit(MySurfaces.obs{1}(:,1),MySurfaces.obs{1}(:,2),N);
for i = 1:2*mc
    MySurfaces.old.model{i,2} = P;
    MySurfaces.old.model{i,3} = S;
    % ymodel = m * Xobs + b
    ymodel = MySurfaces.old.model{i,2}(1)*MySurfaces.obs{i}(:,1) + ...
            MySurfaces.old.model{i,2}(2);
    MySurfaces.old.model{i,1} = [MySurfaces.obs{i}(:,1),ymodel];
end

%============================================

%%% 3.2.1: Rotate individual surface data set to slope = 0
MySurfaces.obsP = cell(2*mc,1);
for i = 1:2*mc
    t = -atan(MySurfaces.model{i,2}(1));
    ROT = [cos(t),sin(t);-sin(t),cos(t)];
    MySurfaces.obsP{i} = ROT'*MySurfaces.obs{i}';
    % rotated observed data by polyfit line
    MySurfaces.obsP{i} = MySurfaces.obsP{i,1}';
    % Sort the data along X to ensure monotonic increase in [x,y]
    MySurfaces.obsP{i} = sortrows(MySurfaces.obsP{i},[1,2]);
    % MySurfaces.obsP{i} = unique(MySurfaces.obsP{i},'rows');
end

% Plot the rotated data
figure
hold on
h = zeros(size(MySurfaces.obsP));
for i = 1:2*mc
    h(i) = plot(MySurfaces.obsP{i}(:,1),MySurfaces.obsP{i}(:,2),...
                'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
end
xlabel('Xp-position [cm]')
ylabel('Yp-position [cm]')
box on, grid on

% SECTION 3.2.2: Rotate by Individual YModel and calculate residual
MySurfaces.modelP  = cell(2*mc,1);
MySurfaces.residual= cell(2*mc,1); % topography
MySurfaces.residual0=cell(2*mc,1); % topography where the lowest point is 0
MySurfaces.gradient= cell(2*mc,1); % numerical first derivative of residuals (i.e., topography)
for i = 1:2*mc
    t = -atan(MySurfaces.model{i,2}(1));
end

160
ROT = [cos(t),sin(t);-sin(t),cos(t)];
MySurfaces.modelP{i} = ROT'*MySurfaces.model{i}';
MySurfaces.modelP{i} = MySurfaces.modelP{i}';

% [X, Yobs - Ymodel]
MySurfaces.residual{i} = [MySurfaces.modelP{i}(1,:),1,...
    MySurfaces.obsP{i}(2,:) - MySurfaces.modelP{i}(2,:)];

% Calculate slope (taken to coincide with midpoint of x-values
% --> Note this approach does not achieve even spacing between data
% points nor does it attempt to evaluate the wavelength dependence
  
  % slope
  [m,n] = size(MySurfaces.residual{i}(1,:));
  MySurfaces.residual0{i} = [MySurfaces.model{i}(1,:),1,...
    MySurfaces.residual{i}(2,:) - min(MySurfaces.residual{i}(2,:))];
  MySurfaces.gradient{i}(1,:) = MySurfaces.residual{i}(1:m-1,1) + ...
    diff(MySurfaces.residual{i}(1:m-1,:));
  MySurfaces.gradient{i}(2,:) = diff(MySurfaces.residual{i}(2,:)) ./
    diff(MySurfaces.residual{i}(1,:));
end

%------------------------------------------------------------------------

%%% SECTION 3.3: Rotate by Oldest (i.e., first) YModel & calculate
residual
MySurfaces.old.modelP = cell(2*mc,1);
MySurfaces.old.residual = cell(2*mc,1); % topography
MySurfaces.old.residual0 = cell(2*mc,1); % topography where lowest point
  is 0
MySurfaces.old.gradient = cell(2*mc,1); % numerical first derivative of
  % residuals (i.e., topography)
MySurfaces.old.obsP = cell(2*mc,1);

t = -atan(MySurfaces.model{1,2}(1));
ROT = [cos(t),sin(t);-sin(t),cos(t)];
for i = 1:2*mc
    MySurfaces.old.obsP{i} = ROT'*MySurfaces.obs{i}';
    MySurfaces.old.obsP{i} = MySurfaces.old.obsP{i,1}';

    MySurfaces.old.modelP{i} = ROT'*MySurfaces.old.model{i}';
    MySurfaces.old.modelP{i} = MySurfaces.old.modelP{i}';

    % [X, Yobs - Ymodel]
    MySurfaces.old.residual{i} = [MySurfaces.old.modelP{i}(1,:),1,...
        MySurfaces.old.obsP{i}(2,:) - MySurfaces.old.modelP{i}(2,:)];

    % Calculate slope (taken to coincide with midpoint of x-values
    % --> Note this approach does not achieve even spacing between data
    % points nor does it attempt to evaluate the wavelength dependence
    % of
    % slope

[m,n] = size(MySurfaces.old.residual{i}(1,:));
MySurfaces.old.residual0{i} = [MySurfaces.old.model{i}(1,:),
    MySurfaces.old.residual{i}(1,:),
    min(MySurfaces.old.residual{i}(1,:))];
MySurfaces.old.gradient{i}(1,:) = ...
    MySurfaces.old.residual{i}(1:m-1,1) + ...
    diff(MySurfaces.old.residual{i}(1,:));
    % deltaX./deltaY
    MySurfaces.old.gradient{i}(2,:) = ... %
    diff(MySurfaces.old.residual{i}(1,:))./...
    diff(MySurfaces.old.residual{i}(1,:));
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
%%                 Section 4: Basic Surface Roughness
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
% SECTION 4.1a:
figure
xmin = 0;
xmax = 3.2;
% use tight subplot instead of subplot
% Data rotated individually
subplot(3,2,1)
hold on
h = zeros(size(MySurfaces.obsP));
for i = 1:2*mc
    h(i) = ...
    plot(MySurfaces.residual{i}(1,:),MySurfaces.residual{i}(2,:),
        'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
end
title('Individually Evaluated 2D Surfaces')
box on, grid on
% xlabel('Xp-position [cm]')
ylabel('Topography [cm]')
xlim([xmin xmax])
ylim([-0.3 0.2])

% SECTION 4.2a: Slope variation by position; individually rotated data
subplot(3,2,3)
hold on
for i = 1:2*mc
    plot(MySurfaces.gradient{i}(1,:),MySurfaces.gradient{i}(2,:),
        'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
%    semilogy(MySurfaces.gradient{i}(1,:),MySurfaces.gradient{i}(2,:),
%        'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
end
ylabel('dTopo/dx []')
xlabel('Xp-position [cm]')
xlim([xmin xmax])
% SECTION 4.3a: Data statistics of topography for individually rotated data
subplot(3,2,5)
hold on
s = 0.001;
bins = [0:s:0.25];
MySurfaces.hist = cell(2*mc,1);
MySurfaces.hist = zeros(2*mc,length(bins))*nan;
for i = 1:2*mc
    MySurfaces.hist{i} = hist(MySurfaces.residual{i}(:,2) + ...
        min(MySurfaces.residual{i}(:,2)),bins);
    MySurfaces.hist{i} = hist(MySurfaces.residual0{i}(:,2),bins);
    % 'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
    semilogy(bins,MySurfaces.hist{i},...
        'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
end
ylabel('log(10)Frequency')
xlabel(['Topography [cm]: bin size = ',num2str(s)])
box on, grid on
xlim([0,max(bins)])

% SECTION 4.1b: Data rotated by lsq derived from oldest surface
subplot(3,2,2)
hold on
h = zeros(size(MySurfaces.old.obsP));
for i = 1:2*mc
    h(i) = plot(MySurfaces.old.residual{i}(:,1),...
        MySurfaces.old.residual{i}(:,2),...
        'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
end
title('Relative to Oldest Evaluated 2D Surfaces')
box on, grid on
% xlabel('Xp-position [cm]')
ylabel('Topography [cm]')
xlim([xmin xmax])
ylim([-0.3 0.2])

% SECTION 4.2b: Data statistics for lsq to oldest surface
subplot(3,2,4)
hold on
for i = 1:2*mc
    plot(MySurfaces.old.gradient{i}(:,1),...
        MySurfaces.old.gradient{i}(:,2),...
        'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
    semilogy(MySurfaces.gradient{i}(:,1),MySurfaces.gradient{i}(:,2),...
        'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
end
ylabel('dTopo/dx []')
xlabel('Xp-position [cm]')
xlim([xmin xmax])
ylim([-10 10])
grid on, box on

% SECTION 4.3b: Slope variation by position; lsq to oldest surface
subplot(3,2,6)
hold on
% MySurfaces.hist = cell(2*mc,1);
MySurfaces.old.hist = zeros(2*mc,length(bins))*nan;
for i = 1:2*mc
  % MySurfaces.hist{i} = hist(MySurfaces.residual{i}(:,2) + ...
  %   min(MySurfaces.residual{i}(:,2)),bins);
  % semilogy(bins,MySurfaces.hist{i},...
  %     'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
  MySurfaces.old.hist(i,:) =
  hist(MySurfaces.old.residual0{i}(:,2),bins);
  semilogy(bins,MySurfaces.old.hist(i,:),...
    'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
end
ylabel('log(10)Frequency')
xlabel(['Topography [cm]: bin size = ',num2str(s)])
box on, grid on
xlim([0,max(bins)])

% % SECTION 4.4: Position versus standard deviation of topography within bin

%------------------------------------PLACEHOLDER-----------------------------------


# SECTION 5: Relative Surface age versus roughness

% SECTION 5.1a: Surface age versus roughness statistics in box plots
figure
subplot(4,1,1)
hold on
% Surfaces are ordered from oldest to youngest (best to do in reference to
% original fracture plane???)

% Transform data back into a simple two column vector for use with
boxplot
% group functionality
MySurfaces.boxplot.data = [];
MySurfaces.boxplot.group= [];
for i = 1:2*mc
dummyD = MySurfaces.residual0{i}(:,2);
[m,n] = size(dummyD);
MySurfaces.boxplot.data = [MySurfaces.boxplot.data;...
dummyD];
MySurfaces.boxplot.group = [MySurfaces.boxplot.group;...
one(m,n)*i];
end

MySurfaces.boxplot.labels=cell(1,2*mc);
dummyL = ['T';'B'];
for i = 1:2*mc
  if mod(i,2) == 0
    j = 2;
  else
    j = 1;
  end
  MySurfaces.boxplot.labels{i} = [num2str(ceil(i/2)),'.',dummyL(j)];
end

h = boxplot(MySurfaces.boxplot.data,MySurfaces.boxplot.group,...
  'notch',on,'colors',MyColor,...
  'labels',MySurfaces.boxplot.labels,'labelorientation',inline',...
  'outliersize',4,'symbol','k+');
ylabel('Topographic Relief [cm]')
xlabel('Surface in age order Oldest to Youngest')
box on, grid on
title('Analysis of independently evaluated surfaces')

%------------------------------------------------------------------------------------

% subplot(4,1,2)
hold on
% Surfaces are ordered from oldest to youngest (best to do in reference to
% original fracture plane???)

% transform data back into a simple two column vector
MySurfaces.old.boxplot.data = [];
MySurfaces.old.boxplot.group = [];
for i = 1:2*mc
  dummyD = MySurfaces.old.residual0{i}(:,2);
  [m,n] = size(dummyD);
  MySurfaces.old.boxplot.data = [MySurfaces.old.boxplot.data;...
dummyD];
  MySurfaces.old.boxplot.group = [MySurfaces.old.boxplot.group;...
one(m,n)*i];
end

h = boxplot(MySurfaces.old.boxplot.data,MySurfaces.old.boxplot.group,...
  'notch',on,'colors',MyColor,...
  'labels',MySurfaces.boxplot.labels,'labelorientation',inline',...
  'outliersize',4,'symbol','k+');
ylabel('Topographic Relief [cm]')
xlabel('Surface in age order Oldest to Youngest')
box on, grid on
title('Analysis of surfaces relative to oldest surface')

%--------------------------------------------------------------------------
%% SECTION 5.1b: Find ratio of straight line length and surface length
% SECTION 5.1b-1: Find ratios for individually analyzed surfaces
subplot(4,1,3)
MySurfaces.Ltotal = cell(2*mc,1);
MySurfaces.Lmin   = cell(2*mc,1);
MySurfaces.Lratio = cell(2*mc,1);
MySurfaces.xmax   = ones(2*mc,1)*nan;
for i = 1:2*mc
    xdummy = MySurfaces.obsP{i}(:,1);
    ydummy = MySurfaces.obsP{i}(:,2);
    xdummy = MySurfaces.residual0{i}(:,1);
    ydummy = MySurfaces.residual0{i}(:,2);
    MySurfaces.Ltotal{i} = sum(sqrt((diff(xdummy)).^2+(diff(ydummy)).^2));
    MySurfaces.Lmin{i}   = max(MySurfaces.modelP{i}(:,1)) - min(MySurfaces.modelP{i}(:,1));
    MySurfaces.Lratio{i} = MySurfaces.Ltotal{i}/MySurfaces.Lmin{i};
hold on
    h3 = plot(i,MySurfaces.Lratio{i},'
    % To calculate the length between adjacent points (should really be its
    % own function)
    MySurfaces.Lavg=mean(MySurfaces.avg);
    for i=1:2*mc;
        %MySurfaces.Lrel{i}=MySurfaces.Lmin{i}/MySurfaces.Lmin{1};
        MySurfaces.Lrel{i}=MySurfaces.Ltotal{i}/MySurfaces.Lavg;
    end
% % SECTION 5.1b-2: Find and plot ratios using oldest surface as reference
MySurfaces.old.Ltotal = cell(2*mc,1);
MySurfaces.old.Lmin   = cell(2*mc,1);
MySurfaces.old.Lratio = cell(2*mc,1);
MySurfaces.old.xmax   = ones(2*mc,1)*nan;
for i = 1:2*mc
    xdummy = MySurfaces.old.obsP{i}(:,1);
    ydummy = MySurfaces.old.obsP{i}(:,2);
    % To calculate the length between adjacent points (should really be its
    % own function)
    MySurfaces.old.Ltotal{i} = sum(sqrt((diff(xdummy)).^2 + ...}
MySurfaces.old.Lmin{i}   = max(MySurfaces.old.modelP{i}(:,1)) - min(MySurfaces.old.modelP{i}(:,1));
end
MySurfaces.old.Lratio{i} = MySurfaces.old.Ltotal{i} /...
     MySurfaces.old.Lmin{i};

hold on
    h4 = plot(i,MySurfaces.old.Lratio{i},...
        '^','MarkerFaceColor',MyColor(i,:), 'MarkerEdgeColor','k',...
        'MarkerSize',9);
    MySurfaces.old.xmax(i) = max(MySurfaces.old.modelP{i(:,1)});    
end

%h1 = plot([1:2*mc]',cell2mat(MySurfaces.old.Lmin),'-k');
%h2 = plot([1:2*mc]',cell2mat(MySurfaces.Lmin),'-r');
% legend([h1 h3],'Lmin of surface/Lmin of reference ',...%
%    'Lf/Lmin: Individually evaluated');

set(gca,'XTickLabel',MySurfaces.boxplot.labels,'XMinorTick','on')
set(gca,'XTick',1:length(MySurfaces.boxplot.labels));
grid on, box on
xlabel('Surface in age order Oldest to Youngest')
ylabel('L(path)/L(min) [cm]')
title('Comparison of Individually Rotated Surface Length to Straight Line Length')

subplot(4,1,4)
    h1 = plot([1:2*mc]',cell2mat(MySurfaces.Lrel),'-k');
    set(gca,'XTickLabel',MySurfaces.boxplot.labels,'XMinorTick','on')
set(gca,'XTick',1:length(MySurfaces.boxplot.labels));
grid on, box on
xlabel('Surface in age order Oldest to Youngest')
ylabel('Lpath/Laverage [cm]')
title('Comparison of Path length')

set(gcf,'PaperPositionMode','auto')
fig_name = 'FIG - Boxplots';
print(gcf,'-dpng','-r300',[fdigitname, fig_name, '.png'])
print(gcf,'-dpdf','-r300',[fdigitname, fig_name, '.pdf'])
save([fname,'_Boxplots.mat'],'-mat')

%-------------------------------

%%% SECTION 5.2: Plot in image fracture length versus ratio of
% Ltotal/L(linear)
% --> once fracture links the total length jumps and the roughness
%     suddenly
% becomes small relative to the new greater length in the plot
% --> possibly add second axis with lengths to previous plot above

% should use originally smapled data as opposed to monotonic sampling data
% when comparing Lpath to Lmin

%-------------------PLACEHOLDER------------------
% SECTION 5.3: Age versus standard deviation of topography for each surface

%-------------------------------PLACEHOLDER-------------------------------

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
% SECTION 6: Anaylsus of Wavelength and Power
%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Surfaces roughness (same could be performed on thickness distribution)

% SECTION 6.1: Data Preparatio: Resample rotated data
% --> resampling to produce a monotonic progression could obscure some path-dependent features of the surface texture.
MySurfaces.residualInt = cell(2*mc,1);
MySurfaces.unique.residual = cell(2*mc,1);
% int = 0.001;
int = 0.0005;
MySurfaces.XI = [0:int:max(MySurfaces.old.xmax)]';
% ***** FUTURE IMPROVEMENT: rebuild this to make it more flexible by determining the xmax above in the rotated data above
for i = 1:2*mc
% Sort the data along X to ensure monotonic increase in [x,y]
MySurfaces.unique.residual{i} = sortrows(MySurfaces.residual{i},[1,2]);

% There might be some degredation of the surface since this step % enforces a monotic function
[A,IA] = unique(MySurfaces.unique.residual{i}(:,1));
MySurfaces.unique.residual{i} = ...
    [MySurfaces.unique.residual{i}(IA,1), ...
    MySurfaces.unique.residual{i}(IA,2)];

Y2 = interp1(MySurfaces.unique.residual{i}(:,1), ...
    MySurfaces.unique.residual{i}(:,2),...
    MySurfaces.XI,'linear',nan); % spline smoother, but produces some
% perturbations, linear for simplest
MySurfaces.residualInt{i} = [MySurfaces.XI,Y2];
end

% Example plot of Original Surfaces and resampled surfaces
figure
for i = 1:2*mc
    h1 = plot(MySurfaces.XI,MySurfaces.residualInt{i}(:,2),...
            'Color',MyColor(i,:));
    hold on
h2 = plot(MySurfaces.unique.residual{1}(1,:), ... 
MySurfaces.unique.residual{1}(2,:), 'o', ... 
'Color', MyColor(1,:), 'MarkerSize', 4);
end

title('Interpolation Test')
xlabel('x-position [cm]')
ylabel('Topography [cm]')
grid on, box on
legend([h1 h2], 'Fit', 'Obs')

%-------------------------------------------------------------------------%

% SECTION 6.2a: Calculate Power Spectral Density Distribution

figure
for i = 1:2*mc;

var1{i,1}=PointDist(MySurfaces.re{i,1}(1,:),MySurfaces.re{i,1}(2,:));
% makes PointDist into a cell array so I can call between two

var2{i,1}=PointDist(MySurfaces.obs{i,1}(1,:),MySurfaces.obs{i,1}(2,:));
N{i,1}=length(MySurfaces.obs{i,1}(2,:));
fs=N{i,1}/var2{i,1}.Lxmin;
[p,freq]=pmtm(MySurfaces.obs{i,1}(2,:), [],
'onesided', N{i,1}, fs);

MySurfaces.p{i,1}=p; %the {} will put all sets next to each other
and () will keep track
MySurfaces.freq{i,1}=freq;
MySurfaces.fs{i,1}=fs;

fmin(i)= 1/((1/5)*var2{i,1}.Lxmin); %
1/((1/3)*Surfaces.dp5.Lxmin);
fmax(i)= 1/((3)*var1{i,1}.Median); %fmax = 1/(3*dx5);

%xp5,yp6
I = find(MySurfaces.freq{i,1}(1)>=fmin(i) &
MySurfaces.freq{i,1}(1)<=fmax(i));
xfreq{i} = log10(MySurfaces.freq{i,1}(I));
ypower{i} = log10(MySurfaces.p{i}(I));

% [lsq6] = polyfit(xfreq,ypower,1);
[a,b,alpha,pdummy,c
hiopt,Cab,Calphap] =
wtls_line(xfreq{i},ypower{i},ones(size(xfreq{i}))), ...
ones(size(ypower{i}))); % ones enforce equal weighting of points
xfit= xfreq; %linspace(fmin,fmax,4);
MySurfaces.a{i}=a;
MySurfaces.b{i}=b;
yfit{i} = MySurfaces.a{i}*xfit{i} + MySurfaces.b{i};
sigma{i} = sqrt(1/(length(xfit{i}))*sum((ypower{i}-yfit{i}).^2)));

MyXlabel = ['log10(Frequency) [1/cm]'];
MyYlabel = ['log10(Power) [m^2/(1/cm)]'];
MyXrange = [1/var2{i,1}.Lxmin 1/var2{i,1}.Median];
MyYrange = [min(MySurfaces.p{i,1}) max(MySurfaces.p{i,1})];
MyFormat = {'grid on, box on, '};

subplot(1,2,1);
   h_psd = loglog(MySurfaces.freq{i,1},MySurfaces.p{i,1},'-',
                  'LineWidth',2,'MarkerSize',3,...
                  'LineStyle',MyLine{dummy(i),:},'Color',MyColor(i,:));
   hold on
   plot lsq fit line
   loglog(10.^xfit{i},10.^yfit{i},'k-', 'LineWidth',2);
   %loglog(10.^xfit{i},10.^{(yfit{i}+sigma{i})},'k--', 'LineWidth',0.5);
   %these are error bar lines
   %loglog(10.^xfit{i},10.^{(yfit{i}-sigma{i})},'k--', 'LineWidth',0.5);

   % Plot Referene Lines
   h_psdmedian = loglog([1/var1{i,1}.Median; 1/var1{i,1}.Median],
                        MyYrange,'--r','LineWidth',1);
   h_psdmin3x = loglog([1/var2{i,1}.Lxmin; 1/var2{i,1}.Lxmin]*(3),
                        MyYrange,'--b','LineWidth',1);
   xlim(MyXrange), ylim(MyYrange);
   hold on

end
% Plot Referene Line
%  h_psdmedian = loglog([1/var1{1,1}.Median; 1/var1{1,1}.Median],
%                        MyYrange,'--r','LineWidth',1);
%  % I might need to take an average of the medians and the mins to
%  % make
%   h_psdmedian = loglog([1/var1{1,1}.Median; 1/var1{1,1}.Median],
%                        MyYrange,'--r','LineWidth',1);
%  % it better
%   h_psdmin3x = loglog([1/var2{1,1}.Lxmin; 1/var2{1,1}.Lxmin]*(3),
%                        MyYrange,'--b','LineWidth',1);
%   xlim(MyXrange), ylim(MyYrange);
%   eval(MyFormat{:}); set(gca, 'XTick',10.^(1:1:4));
%   %set(gca,'YTickLabel','') %might not need this
%   title('Spectral Analysis';['Sample:',fname,'']);
   xlabel('log10(Frequency) [1/cm]')
   ylabel('log10(power) [m^2/(1/cm)]')

for i = 1:2*mc
   subplot(1,2,2) % Power Spectral Slope
   hfractal = fill([0 i i 0],[1 1 3 3 1],'w');
   %set(hfractal,'LineStyle', '-')
   h1= errorbar(i,abs(MySurfaces.a{i}),
                -sigma{i},sigma{i},'kd',...}
      'LineWidth',1.5,'MarkerFaceColor',MyColor(i,:),
      'MarkerSize',10,'LineStyle',MyLine{dummy(i),:});
   set(gca, 'XTick',1:length(MySurfaces.boxplot.labels));
   set(gca, 'XTickLabel',MySurfaces.boxplot.labels,'XMinorTick','on')
   hold on
end
grid on
xlabel('Relative Surface Age')
ylabel('Power Spectral Slope \((m^2/(1/m))/m\)')
title('(b)')
%title('Power Spectral Slope')
ylim([0 6])
xlim([0 (mc*2+1)])

set(gcf,'PaperPositionMode','auto')
fig_name='FIG-PSD';
print(gcf,'-dpng','-r300',[fdigitname, fig_name,'.png'])
print(gcf,'-dpdf','-r300',[fdigitname, fig_name,'.pdf'])
save([fname,'_PSD.mat'],'-mat')

%%% Analysis of Slip & Dilation history (Paired Surfaces Separation) %%%
% Dilation history analysis of paired surfaces
% --> Use resamples surfaces from wavelength analysis samples at the same x-positions
% -->

%---------------------------------PLACEHOLDER---------------------------------
%% Comparing the monotonic data to the monotonic resampled data
%% Ploting the monotonic unresampled data for all the data sets next to the monotonicly resampled data

if nargin <5
    Vis = 'N';
end
if Vis=='Y'
    for i=1:1:2*mc
        figure
        %set(gcf,'Units','Inches','Position',[2 1 11 8.5])
        % Common Formatting
        s.dx = (max(X)-min(X))*0.1;
        s.dy = (max(X)-min(Y))*0.1;
        MyXlim = [min(X)-s.dx max(X)+s.dx];
        MyYlim = [min(Y)-s.dy max(Y)+s.dy];
        commonf = {axis equal, grid on, xlim(MyXlim),ylim(MyYlim)};

        x1= MySurfaces.obss{i}(:,1);
        y1=MySurfaces.obss{i}(:,2);
        x2=MySurfaces.obs{i}(:,1);
        y2=MySurfaces.obs{i}(:,2);
        h1 = plot(x1,y1,'**'); % x and y are the sorted data but not resampled
        set(h1,'LineWidth',0.5);
        hold on
        h2 = plot(x2,y2,'k.);
        title('Comparison of Paths')
eval(commonf{;})

end
legend([h1 h2], 'Ordered Surface', 'Monotonically Resampled Surface')
end

Vis2='Y';
[Grain, Pore] = Distribution(mc, MyColor, fgrain, fpore, ... 
MySurfaces.boxplot.data, MySurfaces.boxplot.group, MySurfaces.boxplot.labels, Vis2);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%                   Save data uniquely by file name               %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
save([fname, '_analyzed.mat'], '-mat')

ReOrderByNearestNeighbor

function [XII, YII, II, P, MaxGap, XI, YI, I] = 
ReorderByNearestNeighbor_F(x, y)

% AUTHOR: N.C. Davatzes
% DATE CREATED: 2013-04-30
% DATE MODIFIED: 2013-05-01
% VERSION: 2

% PURPOSE
% Reorder data points by nearest neighbor. Assumes that the closest spacing is along the path...

% INPUTS
% x
% y
% Data is assumed to be distributed most widely along x-axis

% SYNTAX
% [XI, YI, I, P] = ReorderByNearestNeighbor2(x, y)

% OUTPUTS
% XII ordered x-component, data points whose position cannot be determined have been edited out
% YII ordered y-component
% XI un-edited ordering
% YI un-edited ordering
% I Index order
% P symetric matrix of distance between paired points

% NOTE:
% - Problem: If data is not regularly spaced or in non-monotonic data paths and the sample spacing of the paths is less than the spacing of data points intended to defin the path,
--> then this formulation could either (1) prevent convergence to a
solution or intersperse the data

- APPROACH:
  (1) Use MaxGap Criterion
  (2) Define path
  (3) Identify segments that exceed criterion
  (4) Modify series
    (a) Identify sub-series of data separated by distances greater
    (b) Calculate the series length
    (c) Identify the largest continuous series of data meeting the
    (b) For separate segments of path data where the length is
greater than two, L>=2, split matrix and concatenate in
     a
     (a) For isolated data points, L==1, within the span of the
data
     series Insert data violating MaxGap into nearest path
      position based on a dist2 calculation
- ALTERNATE APPROACH
  - Look into meshing algorithms such as delaunay or interpolation...

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% 1.0 Organize Data and I/O Check
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
%% 1.1 Variable matrix shape
[m,n] = size(x);
if n>m
  x = x';
end
[m,n] = size(y);
if n>m
  y = y';
end

%% 1.2 I/O Check
% Input arguments: Test for existence, if do not exist set to default
if nargin < 2
  error('too few input parameters')
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% 2.0 Compute matrix of distances between points in each array
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

173
data = [x,y];
% dist = pdist2(data,data,varargin{:});
dist = dist2(data,data);
span = max(max(dist));
[StartI,StartJ] = find(dist == span);

% Define maximum allowable gap between data points
w = 10;
MaxGap = min([w*span/length(x); span/w]);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%
%%%%
%%% 3.0 USE DIST and DIST2 To Develop Ordering of Points
%%% 
%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Basic ordering algorithm based on output from DIST2
% --> very sensitive to data spacing and start position
N = length(x); %size(data,1);
result = NaN(N,1);
result(1) = StartI(1); % first point is first row in data matrix

for i=2:N
    dist(result(i-1),:) = Inf;
    [~, closest_idx] = min(dist(:,result(i-1)));
    result(i) = closest_idx;
end

% Index order of original: rows of I correspond to the ordered indices
% of x and y by nearest neighbor distances
I = result;

% Ordered data output
XI = x(I);
YI = y(I);

% find distance between adjacent points:
dx = diff(XI);
dy = diff(YI);
d  = sqrt(dx.^2 + dy.^2);
II = find(d<MaxGap);
II = [1;II+1];
XII = XI(II);
YII = YI(II);

if XII(1) > XII(length(XII)) %without uncertain points
    XII = flipud(XII);
    YII = flipud(YII);
    II = flipud(II);
end
P  = pdist2([XII,YII],[XII YII]);
function tf = isdefined(in_var_name)
%% tf = isdefined(in_var_name)
% Returns a logical indicating if the variable ?in_var_name? both exists
% and is not empty in the ?caller? workspace.
% ?in_var_name? is a text string that specifies the name of the
variable to
% search for.
% 
% AUTHOR: Kent Conover, 12-Mar-08

cmd_txt = ['exist('',in_var_name,','',var,'');'];
if evalin('caller', cmd_txt);
    cmd_txt = ['~isempty('',in_var_name, ')');'];
    if evalin('caller', cmd_txt);
        tf = true;
    else
        tf = false;
    end
else
    tf = false;
end
end

MonotonicReSample_F

function [XPYP,XMYM,out,hout] = MonotonicReSample(x,y,TB,Viss)

% AUTHOR: NC Davatzes
% DATE CREATED:
% VERSION: v2
%
% PURPOSE:Resamples surfaces so that the data points are evenly distributed
% and dense. This allows for better statistical characterization of each of
% the surfaces. Only uses values where the next x position is larger than
% the previous data point. Therefore, areas of the surface that double back
% are not accounted for. This sets up samples where apertures are easily
% calculated.
%
% INPUTS:
% x = vector of x coordinates
%% y = vector of y coordinates
%% UL = a variable equal to either 'U' for upper surface or 'L' for lower
%% surface (Example: >> UL = 'U';
%% Vis= a variable equal to eitehr 'Y' for plotting the figures or 'N' for skipping hte figure plotting and just generating the data from the analysis

%% OUTPUTS:

%% EXAMPLE:
%%   >> x = data(:,1); % x-coordinate that resides within the imported data
%%   >> y = data(:,2); % y-coordinate
%%   >> UL = 'L';
%%   >> Vis = 'Y';
%%   >> XPYP = MonotonicReSample(x,y,UL,Vis);

%% NOTES:
% - assumes data is roughly parallel to the x-axis, a rotation option could be incorporated after the re-ordering

%% Define basic x and y variables from the imported data set
%x= data(:,1); x = x - min(x);
%y= data(:,2);

%% I/O Check
% Check to see if x and y are column vectors: Forces a column vector format
% % to the input variables
[m,n] = size(x);
if n>m
    x = x';
end
[m,n] = size(y);
if n>m
    y = y';
end

if nargin < 3
    TB = 'T'; % define whether analyzing upper or lower surface
end
if nargin < 4
    Viss = 'N';
end

%% Rotate Data before Monotonic Resampling
x_centroid = mean(x);
y_centroid = mean(y);

xt = x - x_centroid; yt = y - y_centroid;
% Example of how to rotate data based on a linear least squares fit
npoly = 1;
myfit = polyfit(xt,yt,npoly);
theta = atan(myfit(1)); % myfit(1) is the slope, myfit(2) is the y-
intercept of the LSQ-fitting line
rot = [cos(theta) sin(theta); -sin(theta) cos(theta)];

% Example of how to rotate data based on a linear least squares fit
npoly = 1;
myfit = polyfit(xt,yt,npoly);
theta = atan(myfit(1)); % myfit(1) is the slope, myfit(2) is the y-
intercept of the LSQ-fitting line
rot = [cos(theta) sin(theta); -sin(theta) cos(theta)];
xryr = [xt,yt]*rot';
xout = xryr(:,1) - min(xryr(:,1));
yout = xryr(:,2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
%%          Organize Data: Order data points by nearest neighbors
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

[xp,yp,Ip,Pp,MaxGap,XI,YI] = ReorderByNearestNeighbor3(xout,yout);
[d] = PointDist(xp,yp);
% if length(x)>length(xp)
% display(['nearest neighbor analysis dropped data points because'
%   ',...
%   'spacing irregularities prevented determination of path

% Procedure for sampling along the path

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
%%          Procedure for sampling along the path
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Resample along path to make monotonic in x-dir
% Step 0: (above) sort the points into a nearest-neighbor based path
% order
% Step 1: sample from low to high x so each point in the distribution
% is
% always a greater x-value than previous x
% Step 2: sample from high to low x so each point in the distribution
% is
% always less than the previous x
% Step 3: Find the points common to two samplings

177
% Step 4: Interpolate this combined curve at the original x-coordinate positions
% Step 5 (final step):
% (a) For an upper surface retain all the points from the original digitized data where the y-coordinate is less than or equal the interpolated distribution
% (b) For a lower surface take the same approach but use an greater than or equal criterion

% Find indices from xp that correspond to each criterion

xp_n = flipud(xp); yp_n = flipud(yp);
Ip_p = ones(size(xp)); Ip_n = Ip_p;
for i = 2:length(xp)
    % Step 1. Sample from low x to high x
    p = max(xp(1:i-1));
    if xp(i)>p %>=p
        Ip_p(i) = 1;
    else
        Ip_p(i) = 0;
    end
    % Step 2. Sample from high x to low x
    p_n = min(xp_n(1:i-1));
    if xp_n(i)<p_n %<=p_n
        Ip_n(i) = 1;
    else
        Ip_n(i) = 0;
    end
end
% Step 3. all points in common are kept
% Criteria for combining two distributions
Ip_n = flipud(Ip_n);
dummy = (Ip_p + Ip_n)./2;
Ip2 = find(dummy==1); % points common to both sampling directions
Ip_all = find(dummy>0); % all points from both sample directions

% Determine line-of-site points with monotonic distribution
% Steps 4 and 5a. For an upper surface, find the points from either of the distribution that exist under the line from the positive and negative sampling run.
% This should work if the surface is not too complicated... if there are many points that have the exact same x-position it can cause problems so we need to edit those out of Ip_all

[xdummy,Idummy_unique] = unique(xp(Ip_all)); Ip_all = Ip_all(Idummy_unique);
if TB == 'T';
    [yp3I] = interp1(xp(Ip2),yp(Ip2),sort(xp(Ip_all)),'linear');
    Ip4 = find(yp(Ip_all)<=yp3I); % Captur points BELOW line connecting common points
    xp4 = xp(Ip_all(Ip4));
    yp4 = yp(Ip_all(Ip4));
% Useful testplot if problems
% axtest(1) = subplot(2,1,1); plot(x,y,'.-'); grid on
% axtest(2) = subplot(2,1,2); plot([x(1:length(x)-1)+diff(x)/2],diff(x),'r.'); grid on
% linkaxes(axtest,'x')
else
    [yp3I] = interp1(xp(Ip2),yp(Ip2),sort(xp(Ip_all)),'linear');
    Ip4 = find(yp(Ip_all)>=yp3I); % Capture points ABOVE line connecting common points
    xp4 = xp(Ip_all(Ip4));
    yp4 = yp(Ip_all(Ip4));
end

% Step 6: Resample for uniform, dense spacing
dx4 = PointDist(xp4,yp4);
n = ceil((max(xp4)-min(xp4))/(0.2*dx4.Q1)); % --> 0.2* the 25th-percentile of dx
% n = ceil((max(xp4)-min(xp4))/(0.5*min(dx4.d))); % --> 1/2 the minimum distance between two adjacent points
xp5 = linspace(min(xp4),max(xp4),n);
dx5 = xp5(2)-xp5(1);
yp5 = interp1(xp4,yp4,xp5,'linear');

MyInterpMethod = 'cubic'; % use 'cubic' or 'spline' or splines or pchip
%yp6 = interp1(xp4,yp4,xp5,'cubic'); % cubic or spline or pchip
yp6 = interp1(xp4,yp4,xp5,MyInterpMethod); % cubic or spline or pchip

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%% Visualization                                                    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if Viss == 'Y'
% Plot Results - Visual test of algorithm
% figure
% Common Formatting
s.dx = (max(x)-min(x))*0.1;
s.dy = (max(x)-min(y))*0.1;
MyXlim = [min(x)-s.dx max(x)+s.dx];
MyYlim = [min(y)-s.dy max(y)+s.dy];
commonf = {'axis equal, grid on, xlim(MyXlim), ylim(MyYlim)'};

% Plot unsorted data in order as read from the data file
ax(1) = axes('Position', [.1, .82, .8, .14]);

h1 = plot(x,y,'.-','Color',[0.7 0.7 0.7]);
set(h1,'LineWidth',0.5);
hold on
h2 = scatter(x,y,4^2,[1:1:length(x)],'o','filled');
colormap autumn(64)
colorbar('East')
title('Original digitized surface')
eval(commonf{:})
set(ax(1),'XTickLabel','')
% Plot sorted data and Sampling
ax(2) = axes('Position', [.1, .64, .8, .14]);
h3 = plot(xp,yp,'-','Color',[0.7 0.58 0.7]); % plot line to reveal order of x,y vector pairs
set(h3,'LineWidth',0.5);
hold on
h4 = scatter(xp,yp,3.3^2,[1:1:length(xp)],'o','filled'); % plot digitization points color coded by row
colormap autumn(64)
% colorbar('East')
Ip_p_index = find(Ip_p==1); Ip_n_index = find(Ip_n==1);
h5 = plot(xp(Ip_p_index),yp(Ip_p_index),'o','Color',[0.8 0.1 0.8],'MarkerSize',7); % plot data sampled in positive x-dir
h6 = plot(xp(Ip_n_index),yp(Ip_n_index),'s','Color',[0.1 0.2 0.2],'MarkerSize',8); % plot data sampled in negative x-dir
eval(commonf{:})
set(ax(2), 'XTickLabel', '')
title('Ordered Data Sampled in Positive and Negative x-directions')
legend([h3 h5 h6], 'Ordered Digitized Surface Path', 'Sampling in positive x-dir', 'Sampling in negative x-dir')

% Comparison of points sampled in the positive and negative x-dir
ax(3) = axes('Position', [.1, .46, .8, .14]);
h7 = plot(sort(xp(Ip_all)),yp3I,'.-','Color',[0.7 0.7 0.7]);
hold on
h8 = plot(xp(Ip_p_index),yp(Ip_p_index),'o','Color',[0.8 0.1 0.8],'MarkerSize',8);
h9 = plot(xp(Ip_n_index),yp(Ip_n_index),'s','Color',[0.1 0.2 0.2],'MarkerSize',8);
h10 = plot(xp(Ip2),yp(Ip2),'--ko','MarkerSize',8);
eval(commonf{:})
set(ax(3), 'XTickLabel', '')
title('Common Points: For Upper Surface Points below the common path are included')
legend([h7 h8 h9], 'Path defined by commonly sampled pts', 'Sampling in positive x-dir', 'Sampling in negative x-dir')

% Monotonically Resampled data
ax(4) = axes('Position', [.1, .28, .8, .14]);
h3 = plot(xp,yp,'-','Color',[0.7 0.7 0.7]);
set(h3,'LineWidth',0.5);
hold on
h4 = scatter(xp,yp,4^2,[1:1:length(xp)],'o','filled');
colormap autumn(64)
% colorbar('East')
h11 = plot(xp4,yp4,'--ko','MarkerSize',8);
eval(commonf{:})
set(ax(4), 'XTickLabel', '')
title('Final Sampling for "Line of sight" in y-dir (normal to fracture), monontic in x')
legend([h3 h11], 'Ordered Digitized Surface Path',...
% Resampled data to enforce monotonic, constant spacing in x-direction
ax(5) = axes('Position', [.1, .1, .8, .14]);
h3 = plot(xp, yp, '-', 'LineWidth', 0.5, 'Color', [0.7 0.7 0.7], 'Marker', 'o', 'MarkerSize', 5, 'MarkerFaceColor', [0.7 0.7 0.7]);

% plot original sorted points for reference
hold on
h13 = plot(xp5, yp6, '-', 'Color', [0.8 0.1 0.4], 'LineWidth', 0.5, 'Marker', 'd', 'MarkerSize', 4); % piecewise cubic, smoother shape

h12 = plot(xp5, yp5, '-ks', 'MarkerSize', 3); % linearly interpolated
xlabel('Position along fracture surface [cm]')
ylabel('Topography on fracture surface [cm]')
eval(commonf{:})
title(['Final sampling with uniform, monotonic x-spacing;
n(i)=' num2str(length(xp)) ', n(f)=' num2str(length(xp5))])

legend([h3 h12 h13], 'Ordered Digitized Surface Path', 'Resampled, linear interpolated', 'Resampled, cubic interpolated')
linkaxes(ax)
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%     Organize Outputs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% % Analysis results
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

XPYP = [xp5, yp6]; % linearly resampled data
XMYM = [xp, yp];
out.xp = xp; % reordered data
out.yp = yp;
out.xp4 = xp4; % subsample of monotonically distributed points from x,y
out.yp4 = yp4;
out.xp5 = xp5; % linearly interpolated points
out.yp5 = yp5;
out.xp6 = xp5; % cubic interpolated points
out.yp6 = yp6;
out.d = d; % statistics on point separation
out.dx4 = dx4; % statistics on point separation

if Viss == 'Y';
    % Figure handles
    hout.h1 = h1;
    hout.h2 = h2;
    hout.h3 = h3;
    hout.h4 = h4;
    hout.h5 = h5;
    hout.h6 = h6;
    hout.h7 = h7;
    hout.h8 = h8;
    hout.h9 = h9;
end
Dilation_F

%function [ aperture ] = DilationF(.fname,SurfaceN,fdigitname )
% Dilation.m
%
% AUTHOR: NCD
% DATE: 2014-08-20
% VERSION: v1
%
% PURPOSE:
% Load a PAIR of surfaces and calculate dilation. Then compare the
dilation
to the surface roughness
%
% Builds on MonotonicSampling5.m which includes additional scripting to
% visualize each step of the analysis.
%
% SPECIALTY SCRIPTS/FUNCTIONS CALLED:
%
% TO DO:
%
% clear all,
close all

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
% A: Import Data 1: File Definition and Method Specification
%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%-%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Part 1: File import and Surface within file:
% Define Data File Name and Surface within File
% Format of data file
% [x,y,SurfaceN,UL]; m x 4 matrix, SurfaceN= surface number (assumed
to
come in paris), UL designates upper ('U') or lower ('L') surface
% FName = 'N2_4267.txt'; SurfaceN = 4;
% FName = 'N2_3937FA_v20140724.txt'; SurfaceN = 4;
% FName = 'N2_3937FA.txt'; SurfaceN = 3; % Choose Surface
% FName = 'N2_4267_v20140725.txt'; SurfaceN = 3; %
% fdigitname = 'N2_4152.m'; SurfaceN = 1; %
% Part 2: Method for rotating data to parallel the x-axis
% Rotate Data based on one of four choices:
% 1. A manual rotation angle
% 2. Rotate via LSQ fit to top surface of pair
% 3. Rotate via LSQ fit to bottom surface of pair
% 4. Rotate via LSQ fit to combined top and bottom points
Rot_Method = 4;
Rot_Angle = 30; % only used if choose Method 1.

% Note: the same files run in MonotonicResample5 and in Dilation might
% yield different spectral slopes if the rotations angles used in each
% are different. For instance, if the rotation angles are derived from a
% lsq fit to the data in MonotnicResample5, the same rotation angle will
% only be reproded if Rotation Option 2 or 3 consistent with the surface
% run in MonotonicResample5 is implemented.

%% A: Import Data 2: Import and Variable Definition
%%
% Data Import
data = load('N2_4338F.m');
data = load(fdigitname); % Tracea=load([fdigitname,'.m']);
data = Traces;
S  = data(:,3);
TB = data(:,4); % designation as 1=top or 2=bottom
% Define basic x and y variables from the imported data set
% to change surface, change I; to change top versus bottom change TB to 1 or 2
SurfaceN=1;
I  = find(S==SurfaceN & TB==1);
U.xin  = data(I,1); %x = x - min(x);
U.yin  = data(I,2);

I  = find(S==SurfaceN & TB==2);
L.xin  = data(I,1); %x = x - min(x);
L.yin  = data(I,2);

%% B: Organize Data 1: Rotate Data Parallel to x-axis using LLSQ fit %
% Rotate Data based on one of four choices:
% 1. A manual rotation angle
% 2. Rotate via LSQ fit to top surface of pair
% 3. Rotate via LSQ fit to bottom surface of pair
% 4. Rotate via LSQ fit to combined top and bottom points

if Rot_Method == 1
    thetad = Rot_Angle;
    theta = deg2rad(thetad);
    xin = [U.xin;L.xin];
    yin = [U.yin;L.yin];
    x_centroid = mean(xin);
    y_centroid = mean(yin);
else
    if Rot_Method == 2
        xin = [U.xin];
        yin = [U.yin];
    elseif Rot_Method == 3
        xin = [L.xin];
        yin = [L.yin];
    elseif Rot_Method == 4
        xin = [U.xin;L.xin];
        yin = [U.yin;L.yin];
    end
    x_centroid = mean(xin);
    y_centroid = mean(yin);
    % Determine rotation angle from linear least squares fit
    npoly = 1;
    myfit = polyfit(xin,yin,npoly);
    theta = atan(myfit(1)); % myfit(1) is the slope, myfit(2) is the y-intercept of the LSQ-fitting line
end

% Translate Data
% First, useful to translate 1st data point to the origin
% Use the centroid of the data set to determine the translation parameters
% which when calculated from the origional data set should correspond to
% the pivot point of the least squares fit.
% the centroid of the data to the origin, which
% for equally weighted data is just the mean of the components
U.xout = U.xin-x_centroid; U.yout = U.yin-y_centroid;
L.xout = L.xin-x_centroid; L.yout = L.yin-y_centroid;
% Rotate Data set
rot   = [cos(theta) sin(theta); -sin(theta) cos(theta)]; % Rotation Matrix
% Upper Surface
xryr  = [U.xout,U.yout]*rot';
U.xout = xryr(:,1); U.yout = xryr(:,2);
% Lower Surface
xryr = [L.xout,L.yout]*rot';
L.xout = xryr(:,1); L.yout = xryr(:,2);

% Translate one more time so that the minimum x-coordinate of the pair
% surfaces is 0
x_trans = min([U.xout; L.xout]);
U.xout = U.xout-x_trans;
L.xout = L.xout-x_trans;

%----------------------------------------------------------------------

% Visualize original and rotated + translated data
figure
xmodel = linspace(min([0;min(xin)]),max(xin),10);
ymodel = xmodel*myfit(1) + myfit(2);
ht.model = plot(xmodel,ymodel,'g--','LineWidth',2);
hold on

ht.U = plot(U.xin,U.yin,'ks',U.xout,U.yout,'bo','MarkerSize',4);
ht.L = plot(L.xin,L.yin,'rs',L.xout,L.yout,'mo','MarkerSize',4);
legend([ht.U ht.L ht.model'],'Upper: original','Upper: rotated','Lower: original','linear LSQ fit')
axis equal, grid on
title({'Rotate data to parallel x-axis';...['Sample: ',fname,', Surface: ',SurfaceN]})

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %%     B: Organize Data 1: Resample surfaces at common points in x
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

UL = 'U';
MyInerpMethod = 'linear';
[U.YI,U.XI,outU] = MonotonicSampling5_Function(U.xout,U.yout,UL,MyInerpMethod);
UL = 'L';
[L.YI,L.XI,outL] = MonotonicSampling5_Function(L.xout,L.yout,UL,MyInerpMethod,U.XI);

% To visualize resampling
% MonotonicSampling5_Visualization(outU)
% MonotonicSampling5_Visualization(outL)

aperture = [U.YI-L.YI];
% Visualize Results
figure
D_fig=gcf;
set(D_fig,'PaperOrientation','landscape');
set(gcf,'Units','Inches','Position',[2 1 11 8.5]);
set(gcf,'Units','Inches','Position',[2 1 11 8.5]);

axp(1) = axes('Position', [.15, .5, .7, .3]);
    plot(U.xout,U.yout,'bo',L.xout,L.yout,'mo','MarkerSize',4);
    set(gca,'XTickLabel',''
    grid on
    title({['Fracture Surface Profiles';['Sample: ',fname,', Surface: ',SurfaceN]})

axp(2) = axes('Position', [.15, .15, .7, .3]);
    plot(U.XI,aperture,'dr-', 'MarkerSize',4);
    grid on
    xlabel('position along fracture [cm]')
ylabel('Aperture [cm]')

linkaxes(axp,'x')

figure
    plot(U.XI,aperture,'.r-', U.XI,U.YI,'.b-',U.XI,L.YI,'.m-')
    title({['Sample: ',fname,', Surface: ',SurfaceN]})
    ylim([-0.2 0.2])
    grid on

%set(gcf,'PaperOrientation','portrait');
set(gcf,'PaperPositionMode','auto')
fig_name = '_FIG-Sur+Ap';
print(gcf,'-dpng','-r300',[fdigitname, fig_name,'.png'])
print(gcf,'-dpdf','-r300',[fdigitname, fig_name,'.pdf'])
save([fname,'_Sur+Ap.mat'],'-mat')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
%%     C: Evaluate result:        %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
%--------------------------------------------------------------------------------
----
% Topographic Releive and Aperture Distribution: Statistics
%  1. Evaluate Topography on Upper Surface
%  2. Evaluate Topography on Lower Surface
%  3. Evaluate Dilation

U.relief = U.YI - min(U.YI);
% L.relief = -L.YI - min(-L.YI);
L.relief = L.YI - min(L.YI);

figure
    hr(1) = plot(U.XI,U.relief,'.b-');
    hold on, grid on
    ylabel('Relief [cm]'), xlabel('position along fracture [cm]')
    title('Relief = Y - min(Y)')
hr(2) = plot(L.XI,L.relief,'.m-');
% hr(3) = plot(L.XI,max(L.relief)-L.relief,'b--');
legend(hr,'Upper Surface','Lower Surface')

% Box Plot:
figure
set(gcf,'Units','Inches','Position',[2 11 8.5])
% subplot(1,2,1)
ax(1) = axes('Position', [.05, .1, .2, .7]);
boxplot([U.relief,...
    L.relief,aperture],...
    'notch','on',...
    'labels',{'Upper','Lower','Aperture'},...
    'labelorientation','horizontal',...
    'outliersize',4,'symbol','k+');
gold on
ylabel('Distance from Fracture Interior [cm]')
title({'Topographic Relief and Aperture';...'Relief is z(x) - min(z)';... ['Sample: ',fname,' Surface: ',SurfaceN]})

%------------------------------------------------------------------------
% Power Spectral Distribution
% PSD
%
% OPTIONAL Tools for calculating PSD from an observed signal:
% - Basic Calculation from Fast Fourier Analyssis (FFT)
% p   = abs(fft(y))/(N/2);  % absolute value of fft
% p   = p(1:N/2).^2;        % take the power of positive frequency half
% freq=[0:N/2-1]'/L;       % find the corresponding frequency in 1/cm
%
% - FUNCTION: SPECTRUM
% spectrum
% - FUNCTION: PERIODOGRAM
% [p,freq] = periodogram(y,[],'onesided',N,fs);   % periodogram
%
% - FUNCTION: MULTITAPER
% p = pmtm(x,nw) % multitaper
% [p,freq] = pmtm(y,[],nfft,fs,'onesided'); % multitaper
N = length(aperture);
span = (max(U.XI)-min(U.XI));
dXI  = abs(U.XI(1)-U.XI(2));
fs= N/span;
Inan = find(isnan(U.YI)==0); % multitaper
[pU,freqU] = pmtm(U.YI,[],'onesided',N,fs);
Inan = find(isnan(L.YI)==0); % multitaper
[pL,freqL] = pmtm(L.YI(Inan),[],'onesided',N,fs);
Inan = find(isnan(aperture)==0); % multitaper
[pA,freqA] = pmtm(aperture(Inan),[],'onesided',N,fs); % multitaper

%------------------------------------------------------------------------
% Fit slope
% Set bounds on range to fit
fmin = 1/((1/5)*span);  % 1/((1/3)*Surfaces.dp5.Lxmin);

% Evaluate high frequency limit due to spacing of original ordered data:
d = PointDist(outU.xp,outU.yp);
fmax = 1/((3)*dXI);  %fmax = 1/(3*dx5);
fmax = 1/((3)*d.Median);  %fmax = 1/(3*dx5);

% xpU, ypU
I = find(freqU>=fmin & freqU<=fmax);
xfreq = log10(freqU(I));
ypower = log10(pU(I));
[aU,bU,alphaU, pdummyU, chioptU, CabU, CalphapU] =
wtls_line(xfreq,ypower,ones(size(xfreq)),ones(size(ypower))); % ones
enforce equal weighting of points
xfitU = xfreq;  %linSpace(fmin,fmax,4);
yfitU = aU*xfitU + bU;
sigmaU = sqrt((1/(length(xfitU))*sum((ypower-yfitU).^2)));

% xpL, ypL
I = find(freqL>=fmin & freqL<=fmax);
xfreq = log10(freqL(I));
ypower = log10(pL(I));
[aL,bL,alphaL, pdummyL, chioptL, CabL, CalphapL] =
wtls_line(xfreq,ypower,ones(size(xfreq)),ones(size(ypower))); % ones
enforce equal weighting of points
xfitL = xfreq;  %linSpace(fmin,fmax,4);
yfitL = aL*xfitL + bL;
sigmaL = sqrt((1/(length(xfitL))*sum((ypower-yfitL).^2)));

% xpA, ypA
I = find(freqA>=fmin & freqA<=fmax);
xfreq = log10(freqA(I));
ypower = log10(pA(I));
[aA,bA,alphaA, pdummyA, chioptA, CabA, CalphapA] =
wtls_line(xfreq,ypower,ones(size(xfreq)),ones(size(ypower))); % ones
enforce equal weighting of points
xfitA = xfreq;  %linSpace(fmin,fmax,4);
yfitA = aA*xfitL + bA;
sigmaA = sqrt((1/(length(xfitA))*sum((ypower-yfitA).^2)));

% Visualize results of Spectral Analysis
figure
Hf_fig=gcf;
set(Hf_fig,'PaperOrientation','landscape');
set(gcf,'Units','Inches','Position',[2 1 11 8.5])

% Common Formatting
MyXlabel = ['log10(Frequency) [1/cm]'];
MyYlabel = ['log10(Power) [m^2/(1/cm)]'];
MyXrange = [1/span 1/dXI];
MyYrange = [min(min([pU;pL;pA])) max(max([pU;pL;pA]))];
MyFormat = {'grid on, box on, '};

axp(2) = axes('Position', [.30, .1, .2, .7]);
    h_psdU = loglog(freqU,pU,'-b','LineWidth',0.5);
    hold on
    h_psdL = loglog(freqL,pL,'-m','LineWidth',0.5);
    h_psdA = loglog(freqA,pA,'-r','LineWidth',0.5);

    % Plot Referene Lines
    h_psdmax = loglog([fmax; fmax]*3, MyYrange,'--m','LineWidth',1);
    % interpolated data spacing
    h_psdmedian3x = loglog([fmax; fmax], MyYrange,'--r','LineWidth',1);
    % median of original data spacing
    h_psdmin = loglog([1/span; 1/span], MyYrange,'--c','LineWidth',1);
    h_psdmin3x = loglog([1/span; 1/span]*(3), MyYrange,'--b','LineWidth',1);

    %Format plot
    eval(MyFormat{:}); set(gca,'XTick',10.^(-1:1:4));
    title('Spectral Analysis')
    xlabel('log10(Frequency) [1/cm]')
    ylabel('log10(Power) [m^2/(1/cm)]')
    axis tight

    legend([h_psdU, h_psdL, h_psdA], 'Upper', 'Lower', 'Aperture')

axp(3) = axes('Position', [.55, .6, .2, .2]);
    h_psdU = loglog(freqU,pU,'o','LineWidth',1,'MarkerSize',3);
    set(h_psdU,'Color',[0.6 0.6 0.6]);
    hold on
    % plot lsq fit line
    hfitU = loglog(10.^xfitU,10.^yfitU,'b-','LineWidth',2);
    loglog(10.^xfitU,10.^yfitU+sigmaU,'b--','LineWidth',0.5)
    loglog(10.^xfitU,10.^yfitU-sigmaU,'b--','LineWidth',0.5)

    % Plot Referene Lines
    h_psdmax = loglog([fmax; fmax]*3, MyYrange,'--m','LineWidth',1);
    % interpolated data spacing
    h_psdmedian3x = loglog([fmax; fmax], MyYrange,'--r','LineWidth',1);
    % median of original data spacing
    h_psdmin = loglog([1/span; 1/span], MyYrange,'--c','LineWidth',1);
    h_psdmin3x = loglog([1/span; 1/span]*(3), MyYrange,'--b','LineWidth',1);
    eval(MyFormat{:}); set(gca,'XTick',10.^(-1:1:4));
    % set(gca,'YTickLabel','')
    % set(gca,'XTickLabel', '')
    xlabel('log10(Frequency) [1/cm]')
    title({'LSQ fit +/- 1 Standard Dev';'from 1/3 sample length';'to 3x median sample spacing'})
    axis tight

axp(4) = axes('Position', [.55, .35, .2, .2]);
    % axp(3) = subplot(2,3,3);
    h_psdL = loglog(freqL,pL,'o','LineWidth',1,'MarkerSize',3);
```matlab
set(h_psdL,'Color',[0.6 0.6 0.6]);
hold on
% plot lsq fit line
hfitL = loglog(10.^xfitL,10.^yfitL,'m-','LineWidth',2);
loglog(10.^xfitL,10.^yfitL+sigmaL,'m--','LineWidth',0.5)
loglog(10.^xfitL,10.^yfitL-sigmaL,'m--','LineWidth',0.5)
% Plot Referene Lines
h_psdmax = loglog([fmax; fmax]*3, MyYrange,'--m','LineWidth',1); % interpolated data spacing
h_psdmedian3x = loglog([fmax; fmax], MyYrange,'--r','LineWidth',1);
% median of original data spacing
h_psdmin = loglog([1/span; 1/span], MyYrange,'--c','LineWidth',1);
h_psdmin3x = loglog([1/span; 1/span]*(3), MyYrange,'--b','LineWidth',1);
 eval(MyFormat{:}); set(gca,'XTick',10.^(-1:1:4));
% set(gca,'XTickLabel','')
set(gca,'XTickLabel',"")
xlabel('log10(Frequency) [1/cm]')
% title({'LSQ fit +/- 1 Standard Dev';'from 1/3 sample length';'to 3x median sample spacing'})
axis tight

axp(5) = axes('Position', [.55, .1, .2, .2]);
% axp(3) = subplot(2,3,3);
_h_psdA = loglog(freqA,pA,'o','LineWidth',1,'MarkerSize',3);
set(_h_psdA,'Color',[0.6 0.6 0.6]);
hold on
% plot lsq fit line
hfitA = loglog(10.^xfitA,10.^yfitA,'r-','LineWidth',2);
loglog(10.^xfitA,10.^yfitA+sigmaA,'r--','LineWidth',0.5)
loglog(10.^xfitA,10.^yfitA-sigmaA,'r--','LineWidth',0.5)
% Plot Referene Lines
h_psdmax = loglog([fmax; fmax]*3, MyYrange,'--m','LineWidth',1); % interpolated data spacing
h_psdmedian3x = loglog([fmax; fmax], MyYrange,'--r','LineWidth',1);
% median of original data spacing
h_psdmin = loglog([1/span; 1/span], MyYrange,'--c','LineWidth',1);
h_psdmin3x = loglog([1/span; 1/span]*(3), MyYrange,'--b','LineWidth',1);
 eval(MyFormat{:}); set(gca,'XTick',10.^(-1:1:4));
% set(gca,'XTickLabel','')
set(gca,'XTickLabel',"")
xlabel('log10(Frequency) [1/cm]')
% title({'LSQ fit +/- 1 Standard Dev';'from 1/3 sample length';'to 3x median sample spacing'})
axis tight

linkaxes(axp(2:5))
xlim(MyXrange), ylim(MyYrange);
legend([h_psdU h_psdL h_psdA h_psdmax h_psdmedian3x h_psdmin h_psdmin3x hfitA],...
     ['Upper Surface', ['MyInerpMethod',' interpolation'],...'
     'Lower Surface',...'
     'Aperture',...
     'median freq original data',...
min freq = length of sampled surface (Lxmin),
'LSQ Linear fit +/- 1 STdev; 1/3Lxmin to 3dx');

axp_slope = axes('Position', [.8, .5, .16, .3]);
% subplot(2,3,6) % Power Spectral Slope
hfractal = fill([0 4 4 0 0],[1 1 3 3 1], 'y');
set(hfractal,'LineStyle','--')
hold on
% Uncertainty in errorbars specific to the slope term from wtls_line
errorbar(1,abs(aU),-sigmaU,sigmaU,'kd','MarkerFaceColor','b','MarkerSize',10)
errorbar(2,abs(aL),-sigmaL,sigmaL,'kd','MarkerFaceColor','m','MarkerSize',10)
errorbar(3,abs(aA),-sigmaA,sigmaA,'kd','MarkerFaceColor','r','MarkerSize',10)
set(gca,'XTickLabel',{
    ' ';
    'Upper';
    'Lower';
    'Aperature'; ' '})
grid on
% xlabel('Data Set')
ylabel('Power Spectral Slope')
title('Power Spectral Slope')
ylim([0 6])

axp_L = axes('Position', [.8, .1, .16, .3]);

% Since Lpath is likely to involve NaNs owing to the fact that the start % and end points of the upper and lower surfaces do not perfectly coincide, % then we sum the non-NaN terms of the vector ApertD.d
I = find(isnan(U.YI)==0 & isnan(L.YI)==0);
U_length = PointDist(U.XI(I),U.YI(I));
L_length = PointDist(L.XI(I),L.YI(I));
A_length = PointDist(U.XI(I),(U.YI(I)+L.YI(I))./2);
yLxmin = [U_length.Lxmin;...
    L_length.Lxmin;...
    A_length.Lxmin];
yLpath = [U_length.Lpath;...
    L_length.Lpath;...
    A_length.Lpath];

xL = [1 2 3];
MyFormat = {'MarkerSize',8,'MarkerFaceColor'};
MyColor = [0 0 1;1 0 1;1 0 0];
for i = 1:length(yLxmin)
    hL(1) = plot(xL(i),yLxmin(i),'vk',MyFormat{:},MyColor(i,:));
    hold on
    hL(2) = plot(xL(i),yLpath(i),'k',MyFormat{:},MyColor(i,:));
    hL(3) = plot(xL(i),yLpath(i)./yLxmin(i),'kd',MyFormat{:},MyColor(i,:));
end
xlim([0 4])
set(gca,'XTick',[0 1 2 3 4])
set(gca,'XTickLabel',{' '; 'Upper'; 'Lower'; 'Aperture'; ' '})
grd on
ylabel('Lpath, Lxmin, Lpath/Lxmin')
title('Lengths along overlapping region')
legend(hL,'Lxmin', 'Lpath', 'Lpath/Lxmin')

% set(gcf,'PaperOrientation','portrait');
set(gcf,'PaperPositionMode','auto')
fig_name = '_FIG Compiled';
print(gcf,'-dpng','-r300', [fdigitname, fig_name, '.png'])
print(gcf,'-dpdf','-r300', [fdigitname, fig_name, '.pdf'])
save([fname,'_Compiled.mat'],'-mat')

% end

%%%%end%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%
%% Spectrograms
% savefile='Dialtion.mat';
% filename='SurfaceN';
% save([fname,'_analyzed','-struct',SurfaceN])
% %save([fname,'_analyzed','-struct', 'SurfaceN'])

Dilaiton3937FA_F

% AUTHOR:   Olivia Wells
% DATE:     Fall 2014
% VERSION:  v4
%
% PURPOSE:
% Script calculates the individual apertures by subtracting out other,
older % apertures and then adds the apertures in relative age order to reveal
the % history of dilation

clear all; close all;
load('N2-3937FA_analyzed.mat')
fname='N2-3937FA';

%% Find x value for all surfaces
clear Y; clear X;
data=MySurfaces.obs; %monotonic data from the roughness script
% gives better resolution of spacing since already resampled
n=length(data);
for i=1:n
    dummymin(i,1)=min(data(i,1)(:,1));
    dummymax(i,1)=max(data(i,1)(:,1));
end
minx=min(dummymin); %to find the entire range of the facture
maxx=max(dummymax);
s=((max(data{1,1}(:,1))-min(data{1,1}(:,1)))/length(data{1,1}(:,1)))*.5; %spacing of x so not arbitrary
X=[minx:s:maxx]';

%% Aperture
% Surface 1
Uy.s1=MySurfaces.re{1,1}(:,2); %reordered data from the roughness script
Ly.s1=MySurfaces.re{2,1}(:,2);
Ux.s1=MySurfaces.re{1,1}(:,1);
Lx.s1=MySurfaces.re{2,1}(:,1);
thetain=0;
x_cen=0;
y_cen=0;
x_trans=0;
[ out{1,1}, Aperture.time{1,1},thetaout1,x_cent1, y_cent1, xtrans1 ] =
Dilation_Fun4( Uy.s1, Ly.s1,Ux.s1, Lx.s1, fname,X, thetain, x_cen, y_cen, x_trans);

%Surface 2
Uy.s2=MySurfaces.re{3,1}(:,2);
Ly.s2=MySurfaces.re{4,1}(:,2);
Ux.s2=MySurfaces.re{3,1}(:,1);
Lx.s2=MySurfaces.re{4,1}(:,1);
thetain=thetaout1;
x_cen=x_cent1;
y_cen=y_cent1;
x_trans=xtrans1;
[ out(2,1), Aperture.time{2,1},thetaout2,x_cent, y_cent, xtrans ] =
Dilation_Fun4( Uy.s2, Ly.s2,Ux.s2, Lx.s2, fname,X, thetain, x_cen, y_cen, x_trans);

% Surface 3
Uy.s3=MySurfaces.re{5,1}(:,2);
Ly.s3=MySurfaces.re{6,1}(:,2);
Ux.s3=MySurfaces.re{5,1}(:,1);
Lx.s3=MySurfaces.re{6,1}(:,1);
thetain=thetaout1;
x_cen=x_cent1;
y_cen=y_cent1;
x_trans=xtrans1;
[ out(3,1), Aperture.time{3,1},thetaout3,x_cent, y_cent, xtrans ] =
Dilation_Fun4( Uy.s3, Ly.s3,Ux.s3, Lx.s3, fname,X, thetain, x_cen, y_cen, x_trans);

% Surface 4
Uy.s4=MySurfaces.re{7,1}(:,2);
Ly.s4=MySurfaces.re{8,1}(:,2);
Ux.s4=MySurfaces.re{7,1}(:,1);
Lx.s4=MySurfaces.re{8,1}(:,1);
thetain=thetaout1;
x_cen=x_cent1;
```matlab
y_cen=y_cent1;
x_trans=xtrans1;
[ out{4,1}, Aperture.time{4,1}, thetaout4, x_cent, y_cent, xtrans ] =
Dilation_Fun4( Uy.s4, Ly.s4, Ux.s4, Lx.s4, fname, X, thetain, x_cen, y_cen, x_trans);

% Surface 5
Uy.s5=MySurfaces.re{9,1}(::,2);
Ly.s5=MySurfaces.re{10,1}(::,2);
Ux.s5=MySurfaces.re{9,1}(::,1);
Lx.s5=MySurfaces.re{10,1}(::,1);
thetain=thetaout1;
x_cen=x_cent1;
y_cen=y_cent1;
x_trans=xtrans1;
[ out{5,1}, Aperture.time{5,1}, thetaout5, x_cent, y_cent, xtrans ] =
Dilation_Fun4( Uy.s5, Ly.s5, Ux.s5, Lx.s5, fname, X, thetain, x_cen, y_cen, x_trans);

% Surface 6
Uy.s6=MySurfaces.re{11,1}(::,2);
Ly.s6=MySurfaces.re{12,1}(::,2);
Ux.s6=MySurfaces.re{11,1}(::,1);
Lx.s6=MySurfaces.re{12,1}(::,1);
thetain=thetaout1;
x_cen=x_cent1;
y_cen=y_cent1;
x_trans=xtrans1;
[ out{6,1}, Aperture.time{6,1}, thetaout6, x_cent, y_cent, xtrans ] =
Dilation_Fun4( Uy.s6, Ly.s6, Ux.s6, Lx.s6, fname, X, thetain, x_cen, y_cen, x_trans);

% Surface 7
Uy.s7=MySurfaces.re{13,1}(::,2);
Ly.s7=MySurfaces.re{14,1}(::,2);
Ux.s7=MySurfaces.re{13,1}(::,1);
Lx.s7=MySurfaces.re{14,1}(::,1);
thetain=thetaout1;
x_cen=x_cent1;
y_cen=y_cent1;
x_trans=xtrans1;
[ out{7,1}, Aperture.time{7,1}, thetaout7, x_cent, y_cent, xtrans ] =
Dilation_Fun4( Uy.s7, Ly.s7, Ux.s7, Lx.s7, fname, X, thetain, x_cen, y_cen, x_trans);

% Surface 8
Uy.s8=MySurfaces.re{15,1}(::,2);
Ly.s8=MySurfaces.re{16,1}(::,2);
Ux.s8=MySurfaces.re{15,1}(::,1);
Lx.s8=MySurfaces.re{16,1}(::,1);
thetain=thetaout1;
x_cen=x_cent1;
y_cen=y_cent1;
x_trans=xtrans1;
```
\[
\text{out}(8,1), \text{Aperture.time}(8,1), \text{thetaout8}, x\_\text{cent}, y\_\text{cent}, x\_\text{trans} = \text{Dilation\_Fun4} (Uy.s8, Ly.s8, Ux.s8, Lx.s8, f\text{name}, X, \text{thetain}, x\_\text{cen}, \text{y\_cen}, x\_\text{trans});
\]

\% Surface 9
\begin{align*}
Uy.s9 &= \text{MySurfaces.re}(17,1)(:,2); \\
Ly.s9 &= \text{MySurfaces.re}(18,1)(:,2); \\
Ux.s9 &= \text{MySurfaces.re}(17,1)(:,1); \\
Lx.s9 &= \text{MySurfaces.re}(18,1)(:,1); \\
\text{thetain} &= \text{thetaout1}; \\
x\_\text{cen} &= x\_\text{cent1}; \\
y\_\text{cen} &= y\_\text{cent1}; \\
x\_\text{trans} &= x\_\text{trans1}; \\
\text{out}(9,1), \text{Aperture.time}(9,1), \text{thetaout9}, x\_\text{cent}, y\_\text{cent}, x\_\text{trans} &= \text{Dilation\_Fun4} (Uy.s9, Ly.s9, Ux.s9, Lx.s9, f\text{name}, X, \text{thetain}, x\_\text{cen}, \text{y\_cen}, x\_\text{trans});
\end{align*}

\% Surface 10
\begin{align*}
Uy.s10 &= \text{MySurfaces.re}(19,1)(:,2); \\
Ly.s10 &= \text{MySurfaces.re}(20,1)(:,2); \\
Ux.s10 &= \text{MySurfaces.re}(19,1)(:,1); \\
Lx.s10 &= \text{MySurfaces.re}(20,1)(:,1); \\
\text{thetain} &= \text{thetaout1}; \\
x\_\text{cen} &= x\_\text{cent1}; \\
y\_\text{cen} &= y\_\text{cent1}; \\
x\_\text{trans} &= x\_\text{trans1}; \\
\text{out}(10,1), \text{Aperture.time}(10,1), \text{thetaout10}, x\_\text{cent}, y\_\text{cent}, x\_\text{trans} &= \text{Dilation\_Fun4} (Uy.s10, Ly.s10, Ux.s10, Lx.s10, f\text{name}, X, \text{thetain}, x\_\text{cen}, \text{y\_cen}, x\_\text{trans});
\end{align*}

%% Dilation history

\begin{verbatim}
a=length(Aperture.time); 
for i=1:a; 
  dummy0=Aperture.time{i}(:,1); 
  dummyd=isnan(dummy0); 
  dummy0(dummyd)=0; 
  Aperture.time0{i,1}( :,1) = dummy0; 
end 
\end{verbatim}

\% Need to subtract out fractures inbetween other fractures to get
\% individual apertures for each event
\begin{align*}
\text{Aperture.time0}(4,1) &= \text{Aperture.time0}(4,1) - \text{Aperture.time0}(7,1) - \text{Aperture.time0}(6,1); \\
\text{Aperture.time0}(5,1) &= \text{Aperture.time0}(5,1) - \text{Aperture.time0}(10,1) - \text{Aperture.time0}(3,1); \\
\end{align*}

\% Sum Dilation quick and dirty
\begin{align*}
\text{Dilation.time}(1,1) &= \text{Aperture.time0}(1,1)(:); \\
\text{Dilation.time}(2,1) &= \text{Aperture.time0}(2,1)(:)+\text{Aperture.time0}(1,1)(:); \\
\text{Dilation.time}(3,1) &= \text{Aperture.time0}(3,1)(:)+\text{Dilation.time}(2,1); \\
\text{Dilation.time}(4,1) &= \text{Aperture.time0}(4,1)(:)+\text{Dilation.time}(3,1); \\
\text{Dilation.time}(5,1) &= \text{Aperture.time0}(5,1)(:)+\text{Dilation.time}(4,1); \\
\end{align*}
Dilation.time{6,1}=Aperture.time0{6,1}(:,1)+Dilation.time{5,1};
Dilation.time{7,1}=Aperture.time0{7,1}(:,1)+Dilation.time{6,1};
Dilation.time{8,1}=Aperture.time0{8,1}(:,1)+Dilation.time{7,1};
Dilation.time{9,1}=Aperture.time0{9,1}(:,1)+Dilation.time{8,1};
Dilation.time{10,1}=Aperture.time0{10,1}(:,1)+Dilation.time{9,1};
Dilation.sum{1,1}=Dilation.time{10,1};

for i=1:a;
    dummy=Dilation.time{i}(:,1);
    I=find(dummy==0);
    dummyd=dummy(I);
    Dilation.time0{i,1}(:,1)=dummyd;
end

Aperture.boxplot.data=[];
Aperture.boxplot.groups=[];
for i = 1:a
    dummyD =Aperture.time{i}(:,1);
    [m,n] = size(dummyD);
    Aperture.boxplot.data= [Aperture.boxplot.data;...  
    dummyD];
    Aperture.boxplot.groups = [Aperture.boxplot.groups;...  
    ones(m,n)*i];
    Aperture.boxplot.labels{i,:} = ['Aperture' num2str(i)];
end
m=max(a,b)+1;
Color=jet(m);
b=length(Dilation.time);
Dilation.boxplot.data=[];
Dilation.boxplot.groups=[];
for i = 1:a
    dummyD =Dilation.time0{i}(:,1);
    [m,n] = size(dummyD);
    Dilation.boxplot.data= [Dilation.boxplot.data;...  
    dummyD];
    Dilation.boxplot.groups = [Dilation.boxplot.groups;...  
    ones(m,n)*i];
    Dilation.boxplot.labels{i,:} = ['Dilation' num2str(i)];
end
Dilation.boxplot.data=[Dilation.boxplot.data];
Dilation.boxplot.groups=[Dilation.boxplot.groups];
Dilation.boxplot.labels = [Dilation.boxplot.labels];

figure
set(gcf,'Units','Inches','Position',[2 1 11 8.5])
%subplot(4,1,1)
axp(3)=axes('Position', [.1, .55, .35, .35]);
for i=1:a
    plot(X,Aperture.time{i}(:,1),'color',Color(i,:))
    legendInfo{i,:}=[Aperture.boxplot.labels{i,:}];
    hold on
end
legend(legendInfo)
title('Individual Apertures')
ylabel('Aperture [cm]')
xlabel('Length Along Fracture [cm]')
xlim([0 3.1])

axp(2)=axes('Position', [.55, .55, .35, .35]);
for i=1:b;
    plot(X,Dilation.time{i}(1,:), 'color', Color(i,:))
    legendInfo2{i,:}=[Dilation.boxplot.labels{i,:}];
hold on
end
legend(legendInfo2)
title('Dilation Through Time')
ylabel('Dilation [cm]')
xlabel('Length Along Fracture [cm]')
xlim([0 3.1])

boxplot(Dilation.boxplot.data, Dilation.boxplot.groups, ...'
    'notch','on','color',Color,'labels',Dilation.boxplot.labels,'labelorien
tation','inline','...
    'outliersize',4,'symbol','k+');
title('Dilation Through Time')
ylabel('Dilation [cm]')
xlabel('Time Oldest--->Youngest')

axp(4)=axes('Position', [.1, .1, .35, .35]);
boxplot(Aperture.boxplot.data, Aperture.boxplot.groups, ...'
    'notch','on','color',Color,'labels',Aperture.boxplot.labels,'labelorien
tation','inline','...
    'outliersize',4,'symbol','k+');
title('Individual Apertures')
ylabel('Length Along Fracture [cm]')
xlabel('Time Oldest--->Youngest')
save([fname,'_dilation.mat'], '-mat')

linkaxes(axp,'y')
set(gcf,'PaperOrientation','portrait');
fig_name = '_FIG - Dilation';
print(gcf,'-dpng','-r300',[fdigitname, fig_name,'.png'])
print(gcf,'-dpdf','-r300',[fdigitname, fig_name,'.pdf'])
save([fname,'_Dilation.mat'], '-mat')

PSDAp_F

% AUTHOR:   Olivia Wells
% DATE:     Fall 2014
% VERSION:  v2
% PURPOSE:
% Uses the data from the dilation scripts to calculate the power
% spectral density and slope for each aperture and dilation

clear all; close all

load('N2-4267_Dilation2.mat')
n=length(Aperture.time0);
for i=1:n;
    PSD.ap{i,1}=Aperture.time0{i,1};
    PSD.x{i,1}=X;
end

MyColor = jet(n);
figure
for i = 1:n;
    varN{i,1}=PointDist(PSD.x{i,1},PSD.ap{i,1}(:,1)); % makes PointDist
    Nn(i,1)=length(PSD.ap{i,1}(:,1));
    fsn(i,1)=Nn(i,1)/varN{i,1}.Lxmin;
    [pn,freqn]=pmtm(PSD.ap{i,1}(:,1),[],'onesided',Nn(i,1),fsn(i,1));
    PSD.pn{i,1}=pn; %the {} will put all sets next to each other and () will keep track
    PSD.freqn{i,1}=freqn;
    PSD.fsn{i,1}=fsn(i,1);
    fminn(i)= 1/((1/5)*varN{i,1}.Lxmin);  % 1/((1/3)*Surfaces.dp5.Lxmin);
    fmaxn(i)= 1/((3)*varN{i,1}.Median);  % fmax = 1/(3*dx5);

    %xp5,yp6
    I = find(PSD.freqn{i,1}(:,1)>=fminn(i) & PSD.freqn{i,1}(:,1)<=fmaxn(i));
    xfreqn{i} = log10(PSD.freqn{i,1}(I));
    ypowern{i} = log10(PSD.pn{i,1}(I));
    % [lsq6] = polyfit(xfreq,ypower,1);
    [a,b,alpha,pdummy,chiopt,Cab,Calphap] = wtls_line(xfreqn{i},ypowern{i},ones(size(xfreqn{i})),...
        ones(size(ypowern{i}))),... one
    [a,b,alpha,pdummy,chiopt,Cab,Calphap] = wtls_line(xfreqn{i},ypowern{i},ones(size(xfreqn{i})),...
        ones(size(ypowern{i}))),... one
    xfitn= xfreqn; %linspace(fmin,fmax,4);
    PSD.an{i}=a;
    PSD.bn{i}=b;
    yfitn{i} = PSD.an{i}*xfitn{i} + PSD.bn{i};
    sigman{i} = sqrt((1/(length(xfitn{i}))*sum((ypowern{i}-
        yfitn{i}).^2)));

    MyXlabel = ['log10(Frequency) [1/cm]';
    MyYlabel = ['log10(Power) [m^2/(1/cm)]';
    MyXrange   = [1/varN{i,1}.Lxmin 1/varN{i,1}.Median];
    MyYrange   = [min(PSD.pn{i,1}(:,1)) max(PSD.pn{i,1}(:,1))];
    MyFormat = {'grid on, box on, '};

198
subplot(1,2,1);
h_psd = loglog(PSD.freqn{i,1},PSD.pn{i,1},'-'...,'LineWidth',2,'MarkerSize',3,...
'Color',MyColor(i,:));

hold on
plot lsq fit line
loglog(10.^xfitn{i},10.^yfitn{i},'k-',...,'LineWidth',2);
%loglog(10.^xfit(i),10.^(yfit(i)+sigma(i)),'k--','LineWidth',0.5);
%these are error bar lines
loglog(10.^xfit{i},10.^(yfit{i}-sigma{i})),'k--','LineWidth',0.5);

% Plot Referene Lines
h_psdmedian = loglog([1/var1{i,1}.Median; 1/var1{i,1}.Median],
MyYrange,'--r','LineWidth',1);
%h_psdmedian = loglog([1/varN{1,1}.Median; 1/varN{1,1}.Median],
%MyYrange,'--r','LineWidth',1);
%ylim(MyYrange);

% Plot Referene Line
h_psdmedian = loglog([1/varN{i,1}.Median; 1/varN{i,1}.Median],
MyYrange,'--r','LineWidth',1);
%ylim(MyYrange);
h_psdmedian = loglog([1/varN{i,1}.Lxmin; 1/varN{i,1}.Lxmin]*3,
MyYrange,'--b','LineWidth',1);
%h_psdmedian = loglog([1/varN{1,1}.Lxmin; 1/varN{1,1}.Lxmin]*3,
%MyYrange,'--b','LineWidth',1);

xlim(MyXrange),ylim(MyYrange);

end

% MyXlabel = ['log10(Frequency) [1/cm]'];
% MyYlabel = ['log10(Power) [m^2/(1/cm)]'];
% MyXrange = [1/varN{i,1}.Lxmin 1/varN{i,1}.Median];
% MyYrange = [min(min(PSD.pn{i,1})) max(max(PSD.pn{i,1}))];
% MyFormat = {'grid on, box on, '};
% Plot Referene Line
yrange=[10^-10 10^0];
h_psdmedian = loglog([1/varN{1,1}.Median; 1/varN{1,1}.Median],
1/varN{1,1}.Lxmin,ylim(MyYrange),...,'LineWidth',1);

% ylim(MyYrange);

for i = 1:n
    subplot(1,2,2) % Power Spectral Slope
    h1= errorbar(i,abs(PSD.an{i}),-sigman{i},sigman{i},'kd',...'
'LineWidth',1.5,'MarkerFaceColor',MyColor(i,:),...,'MarkerSize',10);
    set(gca,'XTick',1:length(PSD.ap));
    hold on
end

grid on
xlabel('Relative Surface Age')
ylabel('Power Spectral Slope [(m^2/(1/m))/m']
title('Power Spectral Slope')
ylim([0 6])

199
xlim([0 (n+1)])

set(gcf,'PaperPositionMode','auto')
fig_name = 'FIG - PSD Ap';
print(gcf,'-dpng','-r300', [fdigitname,fig_name,'.png'])
print(gcf,'-dpdf','-r300', [fdigitname,fig_name,'.pdf'])
save([fname,'_PSDAp.mat'],'-mat')

GPACorrelation_F

% AUTHOR:   Olivia Wells
% DATE:     Fall 2014
% VERSION:  v2
%
% PURPOSE: Script is used for all samples. Finds the grain, pore, and
% asperity distributions and uses different plots to compare the
different
% data sets.

close all; clear all;

%% load values
load('N2-4152_analyzed.mat');
data=load('Pore_4152.txt');
data1=load('Grain_4152.txt');
fname=fname;

%% Define Variables
%Grains
G.L   = data1(:,1)*0.1;%changes mm into cm
G.S   = data1(:,2)*0.1;
G.A   = [G.L;G.S];

%Pores
P.L   = data(:,1)*0.1;
P.S   = data(:,2)*0.1;
P.A= [P.L;P.S];

%A sperity Height Distribution
A.H   = MySurfaces.boxplot.data;
m=mean(A.H)*.1;
b= max(max([G.L;P.L;A.H]))+m;
bins = [0:m:b];

%Grains
[G.Lf, xbin] = hist(G.L,bins); G.Lf = G.Lf';
[G.Sf] = hist(G.S,bins); G.Sf = G.Sf';
[G.Af]= hist(G.A,bins); G.Af = G.Af';
G.Ln  = length(G.L);
G.Sn  = length(G.S);
G.Lfn = G.Lf./G.Ln; %normalized long axis
G.Sfn = G.Sf./G.Sn; %normalized short axis
G.An = length(G.A);
G.Afn = G.Af./G.An; %normalized all grains

% Pores
[P.Lf] = hist(P.L,bins); P.Lf = P.Lf';
[P.Sf] = hist(P.S,bins); P.Sf = P.Sf';
[P.Af] = hist(P.A,bins); P.Af = P.Af';
P.Ln = length(P.L);
P.Sn = length(P.S);
P.Lfn = P.Lf./P.Ln;
P.Sfn = P.Sf./P.Sn;
P.An = length(P.A);
P.Afn = P.Af./P.An;

% Asperity Height Distribution
A.Hf = hist(A.H,bins); A.Hf = A.Hf';
A.Hn = length(A.H);
A.Hfn = A.Hf./A.Hn;
A.sig = ones(size(xbin));

% for individual surfaces
for i=1:mc*2
  A.S.H{i}=MySurfaces.residual0{i,1}(:,2);
  A.S.Hf{i}=hist(A.S.H{i},bins); A.S.Hf{i}=A.S.Hf{i}';
  A.S.Hn{i}=length(A.S.H{i});
  A.S.Hfn{i}=A.S.Hf{i}/A.S.Hn{i};
end

% turn off and on for samples
A.S.intH=[A.S.H{1,1}(::);A.S.H{1,2}(::)]; % 3617 % 4338 % 4152 % 3937FB
A.S.intH=[A.S.H{1,1}(::);A.S.H{1,2}(::);A.S.H{1,3}(::);A.S.H{1,4}(::);A.S.
H{1,5}(::);A.S.H{1,6}(::)]; %4267
A.S.intH=[A.S.H{1,1}(::);A.S.H{1,2}(::);A.S.H{1,3}(::);A.S.H{1,4}(::)

% Cumulative Distributions

201
G.cum = cumsum(G.Afn);
P.cum = cumsum(P.Afn);
A.cum = cumsum(A.Hfn);
A.S.intcum = cumsum(A.S.intHfn);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
%% Visualize Basic Data Sets
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
% Plot 1: side-by-side plot

MyColor = [0 0 1; 1 0 0; 0 0 0; .5 .5 .5]; % blue, red, black, gray

figure
set(gcf,'Units','Inches','Position',[2 1 11 8.5])
subplot(2,1,1) %toggle for different files
    nG = plot(xbin,G.Afn,'.b-'); %plots normalized long and short
    hold on
   nP = plot(xbin,P.Afn,'.r-');
    hold on
    nint = plot(xbin,A.S.intHfn,'.k-','LineWidth',1.5);
    hold on
    nlin = plot(xbin,A.Hfn,'LineWidth',1.5,'Color',[.5 .5 .5]);
    hold on
    plot(xbin,G.cum,'b', xbin,P.cum, 'r', xbin,A.S.intcum, 'k',
        'LineWidth', 1.5)
    hold on
    plot(xbin,A.cum, 'Color', [0 0 1]);
set(gca,'FontSize',18)
ylabel({'Normalize', 'Frequency (freq/n)'});
xlabel({'bin size [cm]'})
grid on
legend([nG' nP' nint' nlin'],
    ['Grain All, n=',num2str(G.An)],...
    ['Pore All, n=',num2str(P.An)],
    ['Int Surf Heights, n=',num2str(A.S.intHn)]...
    ,['Other Surf Heights, n=',num2str(A.Hn)]
    title('Frequency for Heights for Different Stages')
xlim([0 max(bins)])
ylim([0 1])
grid on

%Boxplots using un-normalized data because boxplots already do that
Corr.data = [G.A;P.A;A.S.intH; A.H];
Corr.groups = [ones(size(G.A));2*ones(size(P.A));3*ones(size(A.S.intH));4
    *ones(size(A.H))];
Corr.labels = {'Grain All','Pore All','Int Surf','Remaing Surf'};

subplot(2,1,2)
set(gca,'FontSize',18)
    'labelorientation','inline','outliersize',4,'symbol','k+')
ylabel({'Topographic',' Relief [cm]'})
title('Surface Stages with Grain and Pore Distributions')
box on, grid on
set(gcf,'PaperOrientation','portrait');
fig_name = '_FIG - GPA';
print(gcf,'-dpng','-r300',[fdigitname, fig_name,'.png'])
print(gcf,'-dpdf','-r300',[fdigitname, fig_name,'.pdf'])
save([fname,'_GPA.mat'],'-mat')

% AUTHOR:   Olivia Wells
% DATE:     Fall 2014
% VERSION:  v4
%
% PURPOSE:
% Script plots the representative grain and pore size for each sample
% as compared to the representative asperity size. Shows the relation
% between % each variable to see how much one affects the other

clear all; close all;

%% A cross plot of grain/pore vs asperity heights using un-normalized
% data

load('N2-3937FB_GPA.mat')
Gc.q1=quartile(G.A); %raw data
Gc.m(1,1)=Gc.q1.Median;
Ac.q1=quartile(A.S.intH);
Ac.m(1,1)=Ac.q1.Median;
Pc.q1=quartile(P.A);
Pc.m(1,1)=Pc.q1.Median;
Gc.Q1(1,1)=Gc.q1.Q1-Gc.m(1,1);
Ac.Q1(1,1)=Ac.q1.Q1-Ac.m(1,1);
Pc.Q1(1,1)=Pc.q1.Q1-Pc.m(1,1);
Gc.Q3(1,1)=Gc.q1.Q3;
Ac.Q3(1,1)=Ac.q1.Q3;
Pc.Q3(1,1)=Pc.q1.Q3;
Aa.q1=quartile(A.S.linH);
Aa.m(1,1)=Aa.q1.Median;
Aa.Q1(1,1)=Aa.q1.Q1-Aa.m(1,1);
Aa.Q3(1,1)=Aa.q1.Q3;
Pc.max(1,1)=max(P.A);
Gc.max(1,1)=max(G.A);
Pc.sigma(1,1)=Pc.q1.sigma;
Gc.sigma(1,1)=Gc.q1.sigma;
Ac.sigma(1,1)=Ac.q1.sigma;
Aa.sigma(1,1)=Aa.q1.sigma;

load('N2-3937FA_GPA.mat')
Gc.q2=quartile(G.A); %raw data
Gc.m(2,1)=Gc.q2.Median;
Ac.q2=quartile(A.S.intH);
Ac.m(2,1)=Ac.q2.Median;
Pc.q2=quartile(P.A);
Pc.m(2,1)=Pc.q2.Median;
Gc.Q1(2,1)=Gc.q2.Q1-Gc.m(2,1);
Ac.Q1(2,1)=Ac.q2.Q1-Ac.m(2,1);
Pc.Q1(2,1)=Pc.q2.Q1-Pc.m(2,1);
Gc.Q3(2,1)=Gc.q2.Q3;
Ac.Q3(2,1)=Ac.q2.Q3;
Pc.Q3(2,1)=Pc.q2.Q3;
Aa.q2=quartile(A.S.linH);
Aa.m(2,1)=Aa.q2.Median;
Aa.Q1(2,1)=Aa.q2.Q1-Aa.m(2,1);
Aa.Q3(2,1)=Aa.q2.Q3;
Pc.max(2,1)=max(P.A);
Gc.max(2,1)=max(G.A);
Pc.sigma(2,1)=Pc.q2.sigma;
Gc.sigma(2,1)=Gc.q2.sigma;
Ac.sigma(2,1)=Ac.q2.sigma;
Aa.sigma(2,1)=Aa.q2.sigma;

load('N2-3617FB_GPA.mat')
Gc.q3=quartile(G.A); %raw data
Gc.m(3,1)=Gc.q3.Median;
Ac.q3=quartile(A.S.intH);
Ac.m(3,1)=Ac.q3.Median;
Pc.q3=quartile(P.A);
Pc.m(3,1)=Pc.q3.Median;
Gc.Q1(3,1)=Gc.q3.Q1-Gc.m(3,1);
Ac.Q1(3,1)=Ac.q3.Q1-Ac.m(3,1);
Pc.Q1(3,1)=Pc.q3.Q1-Pc.m(3,1);
Gc.Q3(3,1)=Gc.q3.Q3;
Ac.Q3(3,1)=Ac.q3.Q3;
Pc.Q3(3,1)=Pc.q3.Q3;
Aa.q3=quartile(A.S.linH);
Aa.m(3,1)=Aa.q3.Median;
Aa.Q1(3,1)=Aa.q3.Q1-Aa.m(3,1);
Aa.Q3(3,1)=Aa.q3.Q3;
Pc.max(3,1)=max(P.A);
Gc.max(3,1)=max(G.A);
Pc.sigma(3,1)=Pc.q3.sigma;
Gc.sigma(3,1)=Gc.q3.sigma;
Ac.sigma(3,1)=Ac.q3.sigma;
Aa.sigma(3,1)=Aa.q3.sigma;

load('N2-4267_GPA.mat')
Gc.q4=quartile(G.A); %raw data
Gc.m(4,1)=Gc.q4.Median;
Ac.q4=quartile(A.S.intH);
Ac.m(4,1)=Ac.q4.Median;
Pc.q4=quartile(P.A);
Pc.m(4,1)=Pc.q4.Median;
Gc.Q1(4,1)=Gc.q4.Q1-Gc.m(4,1);
Ac.Q1(4,1)=Ac.q4.Q1-Ac.m(4,1);
Pc.Q1(4,1)=Pc.q4.Q1-Pc.m(4,1);
Gc.Q3(4,1)=Gc.q4.Q3;
Ac.Q3(4,1)=Ac.q4.Q3;
Pc.Q3(4,1) = Pc.q4.Q3;
Aa.q4 = quartile(A.S.linH);
Aa.m(4,1) = Aa.q4.Median;
Aa.Q1(4,1) = Aa.q4.Q1 - Aa.m(4,1);
Aa.Q3(4,1) = Aa.q4.Q3;
Ac.max(4,1) = max(A.S.intH);
Aa.max(4,1) = max(A.S.linH);
Ac.sigma(4,1) = Ac.q4.sigma;
Aa.sigma(4,1) = Aa.q4.sigma;
Pc.max(4,1) = max(P.A);
Gc.max(4,1) = max(G.A);
Pc.sigma(4,1) = Pc.q4.sigma;
Gc.sigma(4,1) = Gc.q4.sigma;
Ac.sigma(4,1) = Ac.q4.sigma;
Aa.sigma(4,1) = Aa.q4.sigma;

load('N2-4338_GPA.mat')
Gc.q5 = quartile(G.A); % raw data
Gc.m(5,1) = Gc.q5.Median;
Ac.q5 = quartile(A.S.intH);
Ac.m(5,1) = Ac.q5.Median;
Pc.q5 = quartile(P.A);
Pc.m(5,1) = Pc.q5.Median;
Gc.Q1(5,1) = Gc.q5.Q1 - Gc.m(5,1);
Ac.Q1(5,1) = Ac.q5.Q1 - Ac.m(5,1);
Pc.Q1(5,1) = Pc.q5.Q1 - Pc.m(5,1);
Gc.Q3(5,1) = Gc.q5.Q3;
Ac.Q3(5,1) = Ac.q5.Q3;
Pc.Q3(5,1) = Pc.q5.Q3;
Gc.max(5,1) = Gc.q5.sigma;
Gc.sigma(5,1) = Gc.q5.sigma;
Ac.sigma(5,1) = Ac.q5.sigma;
Aa.sigma(5,1) = Aa.q5.sigma;

load('N2-4152_GPA.mat')
Gc.q6 = quartile(G.A); % raw data
Gc.m(6,1) = Gc.q6.Median;
Ac.q6 = quartile(A.S.intH);
Ac.m(6,1) = Ac.q6.Median;
Pc.q6 = quartile(P.A);
Pc.m(6,1) = Pc.q6.Median;
Gc.Q1(6,1) = Gc.q6.Q1 - Gc.m(6,1);
Ac.Q1(6,1) = Ac.q6.Q1 - Ac.m(6,1);
Pc.Q1(6,1) = Pc.q6.Q1 - Pc.m(6,1);
Gc.Q3(6,1) = Gc.q6.Q3;
Ac.Q3(6,1) = Ac.q6.Q3;
Pc.Q3(6,1) = Pc.q6.Q3;
Aa.q6 = quartile(A.S.linH);
Aa.m(6,1) = Aa.q6.Median;
Aa.Q1(6,1) = Aa.q6.Q1 - Aa.m(6,1);
Aa.Q3(6,1) = Aa.q6.Q3;
Pc.max(6,1) = max(P.A);
Gc.max(6,1) = max(G.A);
Pc.sigma(6,1) = Pc.q6.sigma;
Gc.sigma(6,1) = Gc.q6.sigma;
Ac.sigma(6,1) = Ac.q6.sigma;
Aa.sigma(6,1) = Aa.q6.sigma;

load('N2-3617FA_GPA.mat')

Gc.q7 = quartile(G.A); %raw data
Gc.m(7,1) = Gc.q7.Median;
Ac.q7 = quartile(A.S.intH);
Ac.m(7,1) = Ac.q7.Median;
Pc.q7 = quartile(P.A);
Pc.m(7,1) = Pc.q7.Median;
Gc.Q1(7,1) = Gc.q7.Q1 - Gc.m(7,1);
Ac.Q1(7,1) = Ac.q7.Q1 - Ac.m(7,1);
Pc.Q1(7,1) = Pc.q7.Q1 - Pc.m(7,1);
Gc.Q3(7,1) = Gc.q7.Q3;
Ac.Q3(7,1) = Ac.q7.Q3;
Pc.Q3(7,1) = Pc.q7.Q3;
Aa.q7 = quartile(A.S.linH);
Aa.m(7,1) = Aa.q7.Median;
Aa.Q1(7,1) = 0;
Aa.Q3(7,1) = Aa.q7.Q3;
Pc.max(7,1) = max(P.A);
Gc.max(7,1) = max(G.A);
Pc.sigma(7,1) = Pc.q7.sigma;
Gc.sigma(7,1) = Gc.q7.sigma;
Ac.sigma(7,1) = Ac.q7.sigma;
Aa.sigma(7,1) = Aa.q7.sigma;

%% Plotting data
n = length(Gc.m); %needs to change based on how many samples
MyColor = jet(n);
figure
set(gcf, 'Units', 'Inches', 'Position', [2 1 8.5 3.5])
ax(2) = subplot(1,2,1);
for i = 1:n;
    errorbar(Gc.Q3(i,1), Ac.Q3(i,1), Gc.sigma(i,1), Gc.sigma(i,1), 'k')
    hold on
end
for i = 1:n;
    errorbar(Gc.Q3(i,1), Ac.Q3(i,1), Ac.sigma(i,1), Ac.sigma(i,1), 'ks', ...
              'LineWidth', 1, 'MarkerFaceColor', MyColor(i,:), 'MarkerSize', 10)
    hold on
end
pts = linspace(0.001,.5,10);
hold on, plot(pts, pts, 'k-');
title('Grain Size vs Int Asperity Heigth')
xlabel('Median Grain Size [cm]')
ylabel('Median Asperity Size [cm]')
xlim([0 0.5])
```matlab
ylim([0 0.5])
axis equal

ax(1)=subplot(1,2,1);
for i=1:n;
    herrorbar(Gc.Q3(i,1),Aa.Q3(i,1),Gc.sigma(i,1),Gc.sigma(i,1),'k'
    hold on
end

for i=1:n;
    errorbar(Gc.Q3(i,1),Aa.Q3(i,1),Aa.sigma(i,1),Aa.sigma(i,1),'ks',...
        'LineWidth',1,'MarkerFaceColor',Mycolor(i,:),'MarkerSize',10)
    hold on
end
pts = linspace(0.001,.5,10);
hold on, plot(pts,pts,'k-');
title('Grain Size vs Remaining Asperity Height')
xlabel('Median Grain Size [cm]')
xlim([0 0.5])
ylim([0 0.5])
linkaxes(ax, 'xy')

set(gcf,'PaperPositionMode','auto')
fig_name = '_FIG - Cross GrainQ3';
print(gcf,'-dpng','-r300',[ fig_name,'.png'])
print(gcf,'-dpdf','-r300',[ fig_name,'.pdf'])
save(['GrainMM.mat'],'-mat')

figure
set(gca,'Units','Inches','Position',[2 1 8.5 3.5])
ax(2)=subplot(1,2,2);
for i=1:n;
    herrorbar(Pc.Q3(i,1),Ac.Q3(i,1),Pc.sigma(i,1),Pc.sigma(i,1),'k'
    hold on
end

for i=1:n;
    errorbar(Pc.Q3(i,1),Ac.Q3(i,1),Ac.sigma(i,1),Ac.sigma(i,1),'ks',...
        'LineWidth',1,'MarkerFaceColor',Mycolor(i,:),'MarkerSize',10)
    hold on
end
pts = linspace(0.001,.5,10);
hold on, plot(pts,pts,'k-');
title('Pore Size vs Int Asperity Height')
xlabel('Median Pore Size [cm]')
xlim([0 0.5])
ylim([0 0.5])
xlabel('Median Asperity Size [cm]')
ylabel('Median Asperity Size [cm]')
```

207
for i=1:n;
    errorbar(Pc.Q3(i,1),Aa.Q3(i,1),Aa.sigma(i,1),Aa.sigma(i,1), 'ks', ... 
        'LineWidth', 1, 'MarkerFaceColor', Mycolor(i,:), 'MarkerSize', 10)
    hold on
end
pts = linspace(0.001,.5,10);
hold on, plot(pts,pts,'k-');
title('Pore Size vs Remaining Asperity Height')
xlabel('Median Pore Size [cm]')
xlim([0 0.5])
ylim([0 0.5])
%axis equal
linkaxes(ax, 'xy')

set(gcf,'PaperPositionMode','auto')
fig_name = '_FIG - Cross PoreQ3';
print(gcf,'-dpng','-r300',[ fig_name,'.png'])
print(gcf,'-dpdf','-r300',[ fig_name,'.pdf'])
save(['PoreMM.mat'],'-mat')

% AUTHOR:   NCD
% DATE:     2014-08-20
% VERSION:  v1
%
% PURPOSE:
% Load a PAIR of surfaces and calculate dilation. Then compare the 
% dilation 
% to the surface roughness 
% 
% Builds on MonotonicSampling5.m which includes additional scripting to 
% visualize each step of the analysis.

clear all; close all;
load('N2-3937FA_Dilation2.mat')

% Dont need the NaNs or 0 for slip
a=length(Dilation.time);
for i=1:a;
    dummy=Dilation.time{i}(::,1);
    I=find(dummy~=0);
    dummyd=dummy(I);
    DilationS.time{i,1}(::,1)=dummyd;
end

% Surface 1
[Stat.d1] = quartile(DilationS.time{1,1}(:));
Cum.slip(1,1)=.0445;
Cum.dilation(1,1)=Stat.d1.Median;
Cum.Q1(1,1)=Cum.dilation(1,1)-Stat.d1.Q1;
Cum.Q3(1,1)=Stat.d1.Q3-Cum.dilation(1,1);
%the median is subtracted from the Q because of how errorbar script works

[Stat.d2] = quartile(DilationS.time{2,1}(:));
Cum.slip(2,1)=.0445+.049826;
Cum.Q3(2,1)=Stat.d2.Q3-Cum.dilation(2,1);

[Stat.d3] = quartile(DilationS.time{3,1}(:));
Cum.slip(3,1)=Cum.slip(2,1)+.015909;
Cum.Q3(3,1)=Stat.d3.Q3-Cum.dilation(3,1);

[Stat.d4] = quartile(DilationS.time{4,1}(:));
Cum.slip(4,1)=Cum.slip(3,1)+.018615-.009033;
Cum.Q3(4,1)=Stat.d4.Q3-Cum.dilation(4,1);

[Stat.d5] = quartile(DilationS.time{5,1}(:));
Cum.slip(5,1)=Cum.slip(4,1)+.013623;
Cum.dilation(5,1)=Stat.d5.Median;
Cum.Q3(5,1)=Stat.d5.Q3-Cum.dilation(5,1);

[Stat.d6] = quartile(DilationS.time{7,1}(:));
Cum.slip(6,1)=Cum.slip(5,1)+.009033;
Cum.Q3(6,1)=Stat.d6.Q3-Cum.dilation(6,1);

n=length(Cum.slip);
Mycolor = jet(n);
figure
set(gcf,'Units','Inches','Position',[2 1 8.5 3.5])
axe(1)=subplot(1,2,1);
for i=1:n;
    herrorbar(Cum.slip(i,1),Cum.dilation(i,1),.01,'k')
    hold on
end
for i=1:n;
    errorbar(Cum.slip(i,1),Cum.dilation(i,1),Cum.Q1(i,1),Cum.Q3(i,1),'kd',
    'LineWidth',1,'MarkerFaceColor',Mycolor(i,:), 'MarkerSize',10);
    hold on
end
title(['Slip and Dilation Correlation ',fname])
xlabel('Cumulative Slip Distance [cm]')
ylabel('Median Cumulative Dilation [cm]')

%% Incremental Slip and Dilation
% Dont need the NaNs or 0 for slip
for i=1:a;
    dummy=Aperture.time0{i}(:,1);
    I=find(dummy~=0);
    dummyd=dummy(I);
    ApertureS.time{i,1}(:,1)=dummyd;
end

%Surface 1
[Stat.a1] = quartile(ApertureS.time{1,1}(:));
inc.slip(1,1)=.0445;
Inc.dilation(1,1)=Stat.a1.Median;
Inc.Q1(1,1)=Inc.dilation(1,1)-Stat.a1.Q1;
Inc.Q3(1,1)=Stat.a1.Q3-Inc.dilation(1,1);

[Stat.a2] = quartile(ApertureS.time{2,1}(:));
inc.slip(2,1)=.049826;
Inc.dilation(2,1)=Stat.a2.Median;
Inc.Q1(2,1)=Inc.dilation(2,1)-Stat.a2.Q1;
Inc.Q3(2,1)=Stat.a2.Q3-Inc.dilation(2,1);

[Stat.a3] = quartile(ApertureS.time{3,1}(:));
inc.slip(3,1)=.015909;
Inc.dilation(3,1)=Stat.a3.Median;
Inc.Q1(3,1)=Inc.dilation(3,1)-Stat.a3.Q1;
Inc.Q3(3,1)=Stat.a3.Q3-Inc.dilation(3,1);

[Stat.a4] = quartile(ApertureS.time{4,1}(:));
inc.slip(4,1)=.018615-.009033;
Inc.dilation(4,1)=Stat.a4.Median;
Inc.Q1(4,1)=Inc.dilation(4,1)-Stat.a4.Q1;
Inc.Q3(4,1)=Stat.a4.Q3-Inc.dilation(4,1);

[Stat.a5] = quartile(ApertureS.time{5,1}(:));
inc.slip(5,1)=.013623;
Inc.dilation(5,1)=Stat.a5.Median;
Inc.Q1(5,1)=Inc.dilation(5,1)-Stat.a5.Q1;
Inc.Q3(5,1)=Stat.a5.Q3-Inc.dilation(5,1);

[Stat.a6] = quartile(ApertureS.time{7,1}(:));
inc.slip(6,1)=.009033;
Inc.dilation(6,1)=Stat.a6.Median;
Inc.Q1(6,1)=Inc.dilation(6,1)-Stat.a6.Q1;
Inc.Q3(6,1)=Stat.a6.Q3-Inc.dilation(6,1);

axe(2)=subplot(1,2,2);
for i=1:n;
%errorbar(Inc.slip(i,1),Inc.dilation(i,1),.01,'k')
hold on
end
for i=1:n;
errorbar(Inc.slip(i,1),Inc.dilation(i,1),Inc.Q1(i,1),Inc.Q3(i,1),'kd',
'LineWidth',1,'MarkerFaceColor',Mycolor(i,:), 'MarkerSize',10);
hold on
end

% Save Figure
set(gcf,'PaperPositionMode','auto')
fig_name = '_FIG - Slip';
print(gcf,'-dpng','-r300',[fdigitname, fig_name,'.png'])
print(gcf,'-dpdf','-r300',[fdigitname, fig_name,'.pdf'])
save([fname,'_slip.mat'],'-mat')

%% All slip for the samples; can only do final cum slip and dilation
load('N2-3937FB_Dilation2.mat')
a2=length(Dilation.time);
for i=1:a2;
dummy=Dilation.time{i}(:,1);
I=find(dummy~=0);
dummyd=dummy(I);
Dilation2.time{i,1}(:,1)=dummyd;
end

%Surface 1
[S3937FB.d1] = quartile(Dilation2.time{3,1}(:));
C3937FB.slip(1,1)=.057;
C3937FB.dilation(1,1)=S3937FB.d1.Median;
C3937FB.Q1(1,1)=C3937FB.dilation(1,1)-S3937FB.d1.Q1;
C3937FB.Q3(1,1)=S3937FB.d1.Q3-C3937FB.dilation(1,1);

load('N2-4338_Dilation2.mat')
a3=length(Dilation.time);
for i=1:a3;
dummy=Dilation.time{i}(:,1);
I=find(dummy~=0);
dummyd=dummy(I);
Dilation3.time{i,1}(:,1)=dummyd;
end

%Surface 1
[S4338.d1] = quartile(Dilation3.time{1,1}(:));
C4338.slip(1,1)=.021;
C4338.dilation(1,1)=S4338.d1.Median;
C4338.Q1(1,1)=C4338.dilation(1,1)-S4338.d1.Q1;
C4338.Q3(1,1)=S4338.d1.Q3-C4338.dilation(1,1);

load('N2-4152_Dilation2.mat')
a4=length(Dilation.time);
for i=1:a4:
    dummy=Dilation.time{i}(:,1);
    I=find(dummy~=0);
    dummyd=dummy(I);
    Dilation4.time{i,1}(:,1)=dummyd;
end

%S4152.d1 = quartile(Dilation4.time{4,1}(:,));
C4152.slip(1,1)=1;
C4152.dilation(1,1)=S4152.d1.Median;
C4152.Q1(1,1)=C4152.dilation(1,1)-S4152.d1.Q1;
C4152.Q3(1,1)=S4152.d1.Q3-C4152.dilation(1,1);

figure
herrorbar(C3937FB.slip(1,1),C3937FB.dilation(1,1),.0,'k');
hold on
herrorbar(C4338.slip(1,1),C4338.dilation(1,1),.02,'k');
hold on
herrorbar(C4152.slip(1,1),C4152.dilation(1,1),.02,'k');
hold on
e...
% All slip for the samples and Lee and Cho normal displacement values

load('Granite_Lc.m')
Gran.slip=Granite_Lc(:,1);
Gran.dilation=Granite_Lc(:,2);
load('Marble_Lc.m')
Marb.slip=Marble_Lc(:,1);
Marb.dilation=Marble_Lc(:,2);

figure
errorbar(C3937FB.slip(1,1),C3937FB.dilation(1,1),.01,'k');
hold on
errorbar(C4338.slip(1,1),C4338.dilation(1,1),.02,'k');
hold on
errorbar(C4152.slip(1,1),C4152.dilation(1,1),.02,'k');
hold on
errorbar(C3937FB.slip(1,1),C3937FB.dilation(1,1),C3937FB.Q1(1,1),C3937FB.Q3(1,1),...'
kd','LineWidth',1,'Marker','s','MarkerFaceColor','r','MarkerSize',10);
hold on
errorbar(C4338.slip(1,1),C4338.dilation(1,1),C4338.Q1(1,1),C4338.Q3(1,1),...'
kd','LineWidth',1,'Marker','o','MarkerFaceColor','g','MarkerSize',10);
hold on
errorbar(C4152.slip(1,1),C4152.dilation(1,1),C4152.Q1(1,1),C4152.Q3(1,1),...'
kq','LineWidth',1,'Marker','^','MarkerFaceColor','m','MarkerSize',10);
hold on
n=length(Cum.slip);
for i=1:n;
errorbar(Cum.slip(i,1),Cum.dilation(i,1),.01,'k');
hold on
end
for i=1:n;
    errorbar(Cum.slip(i,1),Cum.dilation(i,1),Cum.Q1(i,1),Cum.Q3(i,1),'kd',..
            'LineWidth',1,'MarkerFaceColor',Mycolor(i,:),'MarkerSize',10);
    hold on
end
hold on
plot(Gran.slip, Gran.dilation,'-k')
hold on
plot(Marb.slip, Marb.dilation,'--k')
pts = linspace(0.001,.16,20);
grid on
title('Slip and Dilation Across Samples')
xlabel('Total Slip Distance [cm]')
ylabel('Total Cumulative Dilation [cm]')

% Save Figure
set(gcf,'PaperPositionMode','auto')
fig_name = 'FIG - SlipCompared';
print(gcf,'-dpng','-r300',[fig_name,'.png'])
print(gcf,'-dpdf','-r300',[fig_name,'.pdf'])
save(['slipcomp.mat'],'-mat')

Remaining Scripts and Functions (1 of 1)

TopoComparisonF

clear all;close all;
load('N2-4338_Dilation.mat')
a=length(out);
for i=1:a;
    Uymin=min(out{i,1}.U.yout); %translation factor to 0 y so relief can be calculated
    Lymin=min(out{i,1}.L.yout);
    % Uxmin=min(aperture{i,1}.U.xout);
    % Lxmin=min(aperture{i,1}.L.xout);
    U.ytrans=out{i,1}.U.yout-Uymin; % subtracts ymin from all numbers in vector
    L.ytrans=out{i,1}.L.yout-Lymin; % to calculate topography from topo relief
    U.xtrans=out{i,1}.U.xout;%-Uxmin;
    L.xtrans=out{i,1}.L.xout;%-Uxmin;
    L.yout=out{i,1}.L.yout-Uymin; % keeps the Lower surface in reference to Upper
figure
D_fig=gcf;
set(D_fig,'PaperOrientation','landscape');
set(gcf,'Units','Inches','Position',[2 1 11 8.5])
axp(1) = axes('Position', [.1, .4, .43, .3]);
plot(U.xtrans,U.ytrans,'bo',L.xtrans,L.yout,'mo','MarkerSize',4);
hold on
plot(X,out{i,1}.aperture,'dr-', 'MarkerSize',4);

title({['Fracture Surface Profiles'; ['Sample: ',fname, ' Surface',' num2str(i)] ]})

%axis equal
grid on
xlabel('position along fracture [cm]')
ylabel('Aperture [cm]')

%ylim([-0.4 0.5]);
%xlim([0 (max(max([U.xtrans; L.xtrans]))+.1)]);
%xlim([(min(min([U.xtrans; L.xtrans]))-.1) (max(max([U.xtrans; L.xtrans]))+.1)]);
xbins=[(min(min([U.ytrans; L.ytrans]))):(max(max([U.ytrans; L.ytrans])))/10:(max(max([U.ytrans; L.ytrans])))];
xbins=10;
[h1 bins1]=hist(U.ytrans,xbins);
[h2 bins2]=hist(L.ytrans,xbins);
[h1 bins1]=hist(U.ytrans,10);
[h2 bins2]=hist(L.ytrans,10);

axp(2) = axes('Position', [.6, .4, .1, .3]);
width1=.8;
barh(bins1,h1,width1,'b');
hold on
width2=.6;
barh(bins2,h2,width2,'m');
title('Topography')
ylabel('Bins [cm]')
xlabel('Frequency')
[h3, bins3]=hist(out{i,1}.aperture,xbins);
[h3, bins3]=hist(out{i,1}.aperture,10);
axp(3) = axes('Position', [.8, .4, .1, .3]);
barh(bins3,h3,'r');
title('Aperture')
ylabel('Bins [cm]')
xlabel('Frequency')

end

set(gcf,'PaperPositionMode','auto')
fig_name = '_FIG-SidexSide';
print(gcf,'-dpng','-r300',[fdigitname, fig_name,'.png'])
print(gcf,'-dpdf','-r300',[fdigitname, fig_name,'.pdf'])
save([fname,'_SidexSide.mat'],'-mat')

PSSvSlip_F

%TITLE: PSSvSlip.m
%
% Author: Olivia Wells
close all; clear all;
load('N2-3937FA_analyzed.mat');
slip3937A = [0.045; 0.045; 0.05; 0.05; 0.016; 0.016; 0.019; 0.019; 0.014; 0.014; 0.009; 0.009];
PSS3937A = [2.76 2.53 2.75 2.55 3.27 3.33 2.98 3.60 3.60 2.78 4.23 3.61];

slip4338 = [0.0015];
PSS4338 = [2.42; 2.5];

slip3937B = [0.057; 0.057];
PSS3937B = [3.15; 3.2];

slip4152 = [1; 1];
PSS4152 = [2.9; 3.45];

m = length(PSS3937A);
MyColor = jet(m);
figure

clear all;
load('N2-3937FA_analyzed.mat');
slip3937A = [0.045; 0.045; 0.095; 0.095; 0.111; 0.111; 0.13; 0.13; 0.144; 0.144; 0.153; 0.153];
PSS3937A = [2.76 2.53 2.75 2.55 3.27 3.33 2.98 3.60 3.60 2.78 4.23 3.61];

slip4338 = [0.0015];
PSS4338 = [2.42; 2.5];

slip3937B = [0.057; 0.057];
PSS3937B = [3.15; 3.2];

slip4152 = [1; 1];
PSS4152 = [2.9; 3.45];

m = length(PSS3937A);
MyColor = jet(m);
figure

for i = 1:m
    h1 = errorbar(slip3937A(i), abs(PSS3937A(i)), -
    sigma{i}, sigma{i}, 'kd', 'LineWidth', 1.5, 'MarkerFaceColor', MyColor(i,:), 'MarkerSize', 10, 'LineStyle', MyLine{dummy(i),:});
    hold on
end
hold on
plot(slipa4338,PSS4338,'ko','LineWidth',1.5,'MarkerFaceColor','m','MarkerSize',10)
hold on
plot(slipa3937B,PSS3937B,'ks','LineWidth',1.5,'MarkerFaceColor','r','MarkerSize',10)
hold on
plot(slipa4152,PSS4152,'k^','LineWidth',1.5,'MarkerFaceColor','g','MarkerSize',10)
grid on
xlabel('Slip Distance')
ylabel('Power Spectral Slope [(m^2/(1/m))/m]')
title('(b)')
%title('Power Spectral Slope')
ylim([0 6])
clear all;
load('N2-3937FA_Dilation2.mat')

slipa3937A=[0.045;0.095;0.111;0.13;0.144;0.153];
PSSa3937A=[4.11;3.96;1.95;2.97;2.33;2.10];
n2=length(PSSa3937A);
MyColor2 = jet(n2);

slipa4338=[0.0015];
PSSa4338=[3.1];

slipa3937B=[0.057];
PSSaFB=[2.9];

slipa4152=[1;1];
PSSa4152=[2.5];

figure
    for i = 1:n2
        hl= errorbar(slipa3937A(i),abs(PSSa3937A(i)),-
           sigman(i),sigman(i),'kd',... 
           'LineWidth',1.5,'MarkerFaceColor',MyColor2(i,:),'
           'MarkerSize',10);
    end
hold on

plot(slipa4338,PSSa4338,'ko','LineWidth',1.5,'MarkerFaceColor','m','MarkerSize',10)
hold on
plot(slipa3937B,PSSaFB,'ks','LineWidth',1.5,'MarkerFaceColor','r','MarkerSize',10)
hold on
plot(slipa4152,PSSa4152,'k^','LineWidth',1.5,'MarkerFaceColor','g','MarkerSize',10)
grid on
xlabel('Slip Distance')
ylabel('Power Spectral Slope [(m^2/(1/m))/m]')
title('Power Spectral Slope')
ylim([0 6])
Table indicating the sample and fracture surface pair that a value of slip has been obtained for. The gray boxes indicate surfaces are present for that sample, and the dashed lines represent fracture surfaces pair that slip could not be measured for.
N2-4152

Position along fracture [cm]

Aperture [cm]

0.057 cm