Investigating the Volume and Structure of Porosity in Fractured and Unfractured Rock From the Newberry Volcano, Oregon, USA: Evaluation of Two- and Three-Dimensional Methods

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ABSTRACT
Porosity is a fundamental characteristic of rock critical to its mechanical and hydrologic behavior, yet a study of the open and accumulated healed porosity measurements of nine core samples from Newberry Volcano shows that different measurement methods produce significantly different estimates of pore volume and structure. We compare traditional 2D point count, petrographic image analysis, and 3D micro X-Ray Computed Tomography (micro CT). This comparison reveals that detailed petrographic mapping provides the most accurate characterization of fracture porosity, and its history of development, owing to its high spatial resolution and accuracy of phase identification as well as insights afforded from mineralogic and textural relationships. However, this analysis lacks the three-dimensional characterization necessary to determine pore shape and interconnectedness, especially in highly anisotropic and heterogeneous fracture porosity. Thus micro CT, although it consistently underestimates porosity, can usefully augment the petrographic analysis.

High resolution mapping of petrographic thin sections also provides a means to characterize the roughness of fracture surfaces associated with repeated slip that generates porosity recorded by the development of healed porosity. Analysis of 19 slip events on a small, early stage fracture experiencing ≤ mm-scale slip, indicates that this roughness is preserved across multiple slip events and is consistently associated with dilation. Characteristic length scales intrinsic to rock such as the primary grain and pore size distributions of the > 0.2 mm size fraction primarily influence the roughness of fractures until the mechanism of fracture growth transitions to linking among macroscopic fractures. This correlation among primary rock characteristics such as grain size, fracture roughness, repeated fracture slip, and dilation suggests that these key attributes for successful stimulation to generate an Enhanced Geothermal System might be readily assessed.

1.0 Introduction
Porosity in rock is a critical control on the storage and flow of fluid in the subsurface and is thus fundamental to the study of hydrologic, petroleum, and geothermal systems (Ingebritsen and Sanford, 1998). Accurate measurements of pore volume and structure, defined as the shape, size, attitude, and distribution of pores, are therefore necessary to model fluid storage, fluid flow, and the surface area exposed to fluids during flow under natural flow, production, injection, and stimulation conditions. In addition, porosity structure plays an important role in determining the failure mode of geologic materials (Paterson and Wong, 2005). For instance, large pore volume or size tends to promote porosity loss during shearing, whereas very low porosity can lead to high strength and low permeability, but tends to promote dilatant failure. Similarly, porosity between fracture surfaces is related to surface roughness and contact area and could impact the slip behavior of the fracture including its potential for dilation. In addition, the pore structure in the volume adjacent to these surfaces can influence the stiffness of asperities and local stresses (e.g., Paterson and Wong, 2005). Thus characterizing the true structure of pores is integral for fully understanding hydrologic, petroleum, and geothermal systems.

Porosity is derived from and modified by a wide variety of processes including sedimentation, lithification, alteration and deformation that result in a variety of pore shapes and size distributions, as well as textural and mineralogic changes (Crawford et al., 2002; Krauskopf and Bird, 1995). In geothermal systems in particular, porosity is primarily added through fracture formation and slip. The history of recurrent fracture slip and porosity production in fractures is evident from the varying amounts of open, healed, and skeletal (open + healed) porosity present. The proportions of these pore types varies by position relative to the fracture surface, as well as with the maturity and apparent surface roughness of the fracture. In the determination of this porosity, there is a trade-off between the time it takes to perform the analysis, the cost of the analysis, and the accuracy of the method. Consequently, these trade-offs limit the number of analyses that can be performed. In addition, deformed and fractured rocks intro-
duce anisotropic grain and pore geometry and heterogeneous pore distribution attributed to the deformation and fracturing process. The result is preferentially oriented, highly elongated pores whose volume and structure will be portrayed differently depending on which technique is chosen for analysis and the relative size of the volume measured. In the first part of this contribution we investigate the porosity structure as portrayed through three different measurement techniques and in the second part we investigate the relationship between dilation during slip to the evolving roughness of multiply slipped fractures.

A variety of techniques including the analysis of thin sections and, more recently, studies including X-Ray Computed Tomography (CT) imaging are currently used to measure porosity structure. These techniques balance practicality against the goals of accuracy and precision. Thin sections provide an insightful means of directly integrating the measurement of porosity with textural and mineralogic evidence of porosity evolution. However, critical properties of pores, including their connectedness and their 3D size, are not completely revealed by thin section analysis in 2D. Conversely, X-Ray CT characterizes a volume providing insights into the fully 3D structure and connectedness of pores, but is limited by non-uniqueness in the identification of minerals from their attenuation of x-rays, especially in the presence of very small pores less than ~1 μm or very thin micro-crack pores. These differences lead to potential inconsistencies in characterizing the porosity structure and its development that are necessary to understand the permeability of fractured rock, its ability to be stimulated by increasing fluid pressure to induce shearing accompanied by dilation, and the likelihood of seismic energy release. Thus a careful study of the relative compatibility of 2D and 3D methods in intact rocks as well as rocks fractured to different levels of development needs to be conducted. These techniques have been employed over decades, generating large amounts of data. In order to use this data in an appropriate and self-consistent manner this study establishes how these different measurements correspond in the case of fracture porosity. In this contribution, we investigate the porosity of naturally fractured volcanic rocks at the Newberry Volcano, Oregon, USA, where an EGS demonstration intended to stimulate porosity and permeability in an initially low permeability fracture network is currently underway.

Fracture surface roughness can be defined in terms of the topographical relief of a fracture surface relative to a flat line or plane fit to the surface. The character of surface roughness is important to geologists for a number of reasons. The size, shape, and curvature of asperities that are in contact across the surfaces affect the stiffness and strength of the rock (Brown and Scholz, 1985a, 1986; Barton, 1986), influencing the mechanical properties of the rock mass (e.g., Power and Tullis, 1992; Jaeger et al., 2007; Barton, 2007). The size and complexity of the apertures between the surfaces affects the ability of a fracture to transport fluids (Long et al., 1985; Brown, 1987), thus controlling the transport properties of the fracture, and both the permeability and storativity of the rock mass in otherwise low porosity rock. High porosity in slipped fractures (and therefore the potential for natural or stimulated permeability) can be maintained when the surface roughness is high enough, in combination with sufficient strength, to actually prop the two fracture surfaces apart during slip. If roughness is initially influenced by the characteristic length scales of the rock mass associated with grain and pore size and the evolving distribution of cracks, then the potential for dilation during induced slip in EGS systems could be partly assessed a priori through characterizing these attributes. In addition, secondary processes such as mineralization, dissolution, mineral alteration, and repeated opening or slip modify the topography of the fracture surface and the strength of the asperities influencing dilation potential (e.g., Crawford et al., 2002). Thus as a secondary focus of this paper, we investigate the history of surface roughness and the corresponding history of dilation and healing in a natural fracture experiencing repeated failure.

2.0 Field Site

Newberry Volcano is located in Oregon, USA approximately 60 km east of the north-south trending crest of the Cascade Range (Barger and Keith, 1999). The bedrock at Newberry Volcano is subjected to a high, conductive temperature gradient, thus reaching high temperatures at relatively shallow depth. Thus the region has the potential to be geothermally viable, but although naturally fractured (e.g., Davatzes and Hickman, 2011), the bedrock surrounding the central caldera contains low permeability. Currently, a multi-million dollar Enhanced Geothermal Systems (EGS) demonstration project is underway by AltaRock supported by private investment and the Department of Energy (DOE) (e.g., Cladouhos et al., 2012). Following a long period of pre-stimulation characterization, the first step in stimulation of EGS well NWG 55-29 was implemented in October 2012 (Cladouhos et al., 2013; Petty et al., 2013).

The core used in this study comes from the Geo-N2 well, located ~0.5 km east of the approved NWG 55-29 stimulation well. The Geo-N2 well is the deepest core in Newberry (1337 m) and consists of basaltic to rhyolitic lava flows with intervening flow breccias, lithic tuff, and volcanic sandstone (Bargar and Keith, 1999). As confirmed by powder X-Ray Diffraction (XRD) and petrography, the mineralogy of the core studied in this contribution is dominated by plagioclase; also present are magnetite, clinopyroxene, quartz, potassium feldspar, and chalcopyrite (Bargar and Keith, 1999; Fetterman and Davatzes, 2011). Phenocrysts of plagioclase are abundant as are vesicles. Pore-filling minerals are dominantly chalcedony, quartz, and calcite, with minor amounts of chlorite (Fetterman and Davatzes, 2011; Bargar and Keith, 1999).

3.0 Methods

Techniques: To investigate both the modern porosity and its evolution through geologic history, we carefully distinguish the current open porosity, the healed porosity, and the total skeletal porosity structures. We integrate the 2D and 3D measurement with point counts of porosity from 2D thin section analysis to: (1) evaluate the differences in porosity estimated through these techniques; (2) interpret the process of porosity creation and destruction in the volcanic rocks at Newberry. Whereas the connected porosity is critical for fluid flow and might be measureable in core plugs through porosimetry techniques, the total porosity including isolated pores is critical for mechanical failure and accompanying dilation relevant to EGS applications. 2D methods lack the ability to assess such connections. In addition, the healed pore structure
provides insights into the in situ accumulation and loss of porosity due to dilation, dissolution, and healing. We investigate this complete pore structure history using non-invasive, 3D micro CT imaging with a resolution of ~26.7 μm.

First, we obtain porosity measurements using point counts of thin sections and automatically-thresholded images of thin sections to explore differences, advantages, and disadvantages between the two techniques. Second, we then carefully map the pore structure in high resolution images of sub-regions within the thin sections that have pixel dimensions of ~1.2 μm; this approach provides both higher resolution imaging and critical qualitative contextual information on the mineral structure, mineral dissolution and replacement textures, and consequently the history of healing in the sample. Third, we investigate pore structure using non-invasive, 3D micro CT imaging with a resolution of ~26.7 μm. We evaluate the 3D measurement technique, which is presumed to better characterize anisotropic porosity structure that is expected of fractured rock volumes. Finally, we examine the differences in porosity measurements between these techniques including the dependence of these measurements on the relative maturity of the fracture.

**Geologic Implications:** Documentation of the history of porosity production establishes the most basic necessary criteria for EGS development via hydro-shearing. In addition, assessment of porosity associated with different levels of fault zone development evident from the formation and accumulation of fault gouge provides a 1st order insight into the ability of faults and fractures to dilate during natural or induced slip (e.g., Fetteman and Davatzes, 2011). Second, careful roughness measurements of the surfaces defining an early stage fracture that has sustained multiple dilation events are also conducted. We take advantage of the repeated failure to assess: (1) dilation accompanying multiple slip events; (2) how dilation is related to roughness, (3) how roughness is related to initial rock characteristics such as primary grain and pores size, and (4) how surface roughness evolves over the short slip distances expected in most of the fractures stimulated during a low pressure EGS injection stimulation.

### 3.1 Point Counts

Point counts were conducted on thin sections using a Nikon Eclipse LV 100 petrographic microscopic in combination with a Pelcon Automatic Point Counter. The automatic point counter not only allowed for automatic movement along the thin section while point counting, but also kept track of the designated category and Cartesian coordinates of each point, allowing the construction of porosity maps. Each observation point was classified as either: (1) groundmass (original rock), (2) healed porosity, or (3) open porosity. For the samples used in this study, the blue color of the impregnated epoxy clearly identifies the open porosity. Healed porosity, whether from crack fill or dissolution re-precipitation, is interpreted from mineralogy, texture, and relative age relationships.

### 3.2 Automated Image Analysis

Scans of thin sections were obtained using a flatbed scanner. The resulting TIF files were imported into MATLAB® for automated analysis. Each pixel in these images is 20.7 μm and contains combinations of RGB color values between 0 and 255. Pixels correlating to the colors of the range of blue epoxy and to the range of colors indicating the healing minerals were isolated for analysis. For each thin section, the lower and upper limit of the range of these colors is manually determined. In general, the blue of the open pore space is unequivocal; however the color ranges corresponding to the minerals healing the fracture can be non-unique on a sample-by-sample basis. The healed minerals from Newberry are predominately chalcedony, quartz, and calcite, and are therefore displayed in the image by various shades of white. For instance, plagioclase, abundant in these rocks and unstained in analyzed thin sections, also appears as a range of white.

A MATLAB® algorithm was written which automatically imported the thin section images and thresholded for the desired color ranges of both open and healed porosity for each sample via user input. To determine the relative abundances of porosity, the algorithm divided the number of pixels selected for each category by the total number of pixels in the image. Similarly, a porosity map was generated by replacing the thresholded pixels representing open and healed porosity with solid colors of blue and green, respectively.

### 3.3 High Resolution Image Analysis

Photomicrographs of thin sections magnified at 4x were taken in plane-polarized light using a Nikon Eclipse LV 100 petrographic microscopic in combination with a high-resolution digital camera attachment. Each picture contained approximately 2 mm x 2.5 mm of thin section area and had a resolution of 2560x1920 pixels and a pixel size of ~1.04 μm. Overlapping pictures were taken in 1 mm increments across features of interest with the aid of a thin section stage mount. The photographed transect was chosen such that it encompassed varying porosity types, as well as at least one of the following: isolated host rock, damage zone, and/or fracture.

The series of transect photographs were then stitched using Adobe Photoshop and saved as TIF files (Figure 1a, b). Again the impregnated blue epoxy was represented by pixels containing open porosity, which could be automatically selected using tools in Photoshop to create a blue-color overlay that represents a high-resolution map of open porosity. In plane-polarized light, mineral colors that represent healed porosity do not strongly contrast the mineral color of the host rock, so healing minerals were manually thresholded and mapped in detail. These interpretations were benchmarked petrographically for quality assurance. Thus, the Photoshop tools, in combination with petrographic data and researcher-decision, generated a high-resolution map of the pixels that correlate directly to healed porosity. Once completed, a green color overlay was constructed that represents a high-resolution map of healed porosity in the image. These overlays provide the basis for binary image maps of the open and healed porosity (using either Photoshop or ImageJ), which can be subsequently analyzed via scripts in MATLAB® (Figure 1c, d).

The fractional porosity is then evaluated within the whole image or within sub-regions to evaluate spatial variation in pore structure, size, or anisotropy of the pore structure. For instance, in the simplest approach a moving window measures porosity along a transect across the image (Figure 1e) revealing the variation of porosity in the vicinity of a fracture including damage adjacent to the fracture and the current open and healed porosity of the fracture itself.
To obtain three-dimensional porosity data, Newberry sub-cores were scanned on the Temple University School of Medicine’s SkyScan 1172 high-resolution micro CT scanner. Scans were taken with aluminum and copper filters at the machine’s highest resolution (26.7 μm) and power (100 kV and 100 μA) settings in an attempt to resolve the smallest pores possible allowed by this method and to account for the large attenuation in rock. Upon scan completion, which can take up to 4 hours, the 3D images were reconstructed using the program NRecon, which reconstructed the scanned data into a 3D image consisting of thousands of horizontal 2D bitmap images. These images are comprised of 26.7 μm pixels, each with grayscale values correlating to a tomographic inversion for x-ray attenuation (which correlates with material density). The program CTan was then used to post-process the data.

CTan has numerous tools for post-processing the bitmaps that allow: (1) correlating attenuation to density, and (2) isolating attenuation or density values to produce 3D porosity maps. The thresholding tool allows for pixels of desired grayscale values to be selected, binarized, and isolated from the rest of the image. Materials in the samples that have a higher density than the host rock (i.e. calcite) are represented by pixels with grayscale values that are lighter than the uniform background of the host rock. Materials with lower densities than the host rock (i.e. open space) are represented by pixels with grayscale values that are darker than the uniform background of the host rock. By thresholding the grayscale values that correlate to the x-ray attenuation for open space and specific minerals of known density, we were able to identify open and healed porosity, respectively. The density contrast between the healed minerals in the Newberry rock and the host rock is not prominent enough to be fully resolved by thresholding alone. In addition, many of the mineral grains comprising the matrix are smaller than a single pixel, complicating the correlation of attenuation with mineral density. The despeckle tool available in CTan was used to filter out unwanted pixels that were selected for, but not representative of healed minerals. This processing results in three sets of binary images: (1) open porosity; (2) pore-filling minerals less dense than the matrix; (3) pore-filling minerals more dense than the matrix.

For the image analysis, scripts to automatically upload and process these data were similarly developed in MATLAB®. Variation in porosity is assessed within a moving cube with dimensions of set size that is moved along an established transect parallel to the z-axis of the sample. The intersection of the cube with each bitmap results in a square window at constant z-position, i.e., orthogonal to the transect, that sub-samples the porosity within each bitmap traversed and forms the basis for the volume average. Construction of parallel transects of equal window dimensions allows direct comparison of results from 2D and 3D methods. Figure 2 provides a direct comparison of core, CT image, computerized bitmaps, and the variation of healed, open, and skeletal porosity along an axis-parallel transect.
3.5 Measurements of Fracture Roughness

Thin sections aligned with the slip direction and orthogonal to the fracture surface were used to digitize the shape of the fracture surface. Textural relationships including cross-cutting, superposition, and continuity of materials between the host rock and layers of cements evident in petrographic analysis and cathodoluminescence (CL) allowed us to reconstruct the history of recurrent surface formation (Figure 5a). Thus we could measure the initial fracture surface roughness and its modification through repeated failure. After distinct fracture surfaces were identified, traced on paper, and grouped according to age, they were digitized using the software Digit. The statistical characteristics of the topography of these surfaces including the surface length, and the variation in wavelength, amplitude, and thickness/dilation were assessed using algorithms developed in MATLAB®. The statistical variations in the topography of these surfaces are compared to characteristic lengths in the rock associated with the grain and pore size distribution. Grain and pore sizes were measured within a roughly 1cm by 1cm square area of the thin section photographed at 4x. The long and short axes of all grains and pores >0.02 mm, which were resolvable at this scale, were then measured.

4.0 Results

4.1 Point Counts Versus Automated Image Analysis

Point count analyses and automated image analyses can be directly compared because the methods calculate the porosity across an identical area so that differences in sample size do not lead to false correlations. Both methods yield porosity maps that give insight into the 2D pore size and fracture shape. Point count porosity maps are pixilated and of lower resolution than the thin section image maps; however, the categorization of points is highly accurate and flexible. Fractional porosity values of identical samples significantly vary between the two methods. For the rocks at Newberry, we found that point counts typically yield skeletal porosity values that are 5-15% lower than the automated image analyses (Figure 3). We found the values of open porosity to be similar across the techniques, but healed and skeletal porosity values to be different. These differences unsurprisingly are attributed to the non-uniqueness in the automated image analysis.

4.2 High Resolution Image Versus X-Ray CT

The transect data for high-resolution images and micro CT scans can be directly compared because the moving windows along each transect are constrained to have the same dimensions and analyze moving regions of comparable sizes and sufficient pixel count.

As shown in Figure 4, in both methods skeletal porosity increases, peaks, and

![Figure 3](image-url) (a) Scanned thin section image; (b) Porosity map derived from point counts; (c) Porosity map derived from automated analysis; (d) Plot of fractional porosity vs. technique used.

![Figure 4](image-url) Top) Porosity transects for five high-resolution image analyses; Bottom) Comparable porosity transects for five micro CT analyses. Blue, green, and red lines refer to open, healed, and skeletal porosity, respectively. Dashed lines indicate an average value of fractional porosity.
decreases as the window approaches, coincides with, and moves away from the fractures of interest, respectively. Similar patterns in the transect data of both techniques were identified, but we found that the peak values of porosity are significantly different between the two techniques. In particular, micro CT scans produce consistently lower values of open and healed porosity along the transect. In some samples, the peak value across a fracture reached as little as one-fourth of the value obtained in the high resolution image analysis, despite the uniqueness of open-porosity identification in both techniques. The micro CT data also contains anomalously high measurements in the data towards the top and the bottom of the transects. In particular, open porosity is apparently amplified at the tops of transects whereas healed porosity is apparently amplified at the bottom of the transects.

4.3 Fracture Surface Roughness

Through careful study of relative age relationships, superposition, textural and mineralogic variation, and cathodoluminscence, 19 pairs of fracture surfaces were identified and differentiated into three groups (denoted Segments A-C) with distinct relative ages (Figure 5a, b). Segment C is linked to, but branches off from Segment B at a curved junction, while segment A is relatively linear. Independently rotating each trace map to visualize the topography along each surface (Figure 5c) reveals that Segment C has the greatest variation in along-fracture topography. A plot of the frequency of asperity amplitudes of each surface (Figure 5d) shows three distinct groups, one of which coincides with the long axis 2D grain size distribution of the host rock (Figure 5e). A box plot summarizing the variation in the topography of each surface (Figure 6a) and a plot of the ratios of piecewise fracture surface length, \( L_s \), to straight-line length, \( L_{min} \) reveals the variation in surface area and roughness associated with each break (Figure 6b) as a function of relative age.

5.0 Discussion

The porosity associated with fractured rocks from Newberry Volcano depends on both the measurement technique employed and the development of the fracture contained within the sample. Thin sections provide the only means of clearly integrating the measurement of porosity with textural and mineralogic evidence of porosity evolution. However, critical properties of pores, including their connectedness and their size, are not clearly or directly revealed by thin section analysis. Direct 3D methods such as micro CT scans can be used to reveal pore shape, size, and porosity magnitude, as well as the spatial distribution of those pores. Large open pores are well characterized by this technique. However, this technique typically suffers from the non-uniqueness of mineral densities in healed pores, attenuation shadows from high-density minerals such as pyrite, and resolution limitations.

5.1 Point Counts Versus Automated Image Analysis

While point counts of thin sections provide point-by-point observations of minerals and textures in thin section, they take significant time, require constant researcher-decision, and result in pixilated porosity maps that lack detail. An automated process that can save time and improve resolution is often desired. In this study, the automated thin section method that we investigated constructs detailed porosity maps in a matter of seconds, but drastically overestimates healed porosity when compared to point counts (Figure 3). The healed minerals in the Newberry samples are predominantly calcite and silica. In transmitted light, these minerals share the same shades of white as the ubiquitous plagioclase of the host rock. The automated algorithm appropriately categorizes the healed minerals as healed porosity, but in doing so incorrectly includes the plagioclase grains. Staining the samples for plagioclase is a logical
solution to the problem and is likely a future step in this research. We conclude that while the automated process saves time and improves resolution of porosity maps, it neglects to incorporate the conscious researcher decisions that improve the uniqueness of phase identification, which depending on rock type, may lead to a large discrepancy in fractional porosity values.

5.2 High Resolution Image Versus Micro CT

Constructing porosity maps from high-resolution stitched images is very time consuming and can take up to a full day or longer for each sample. Because researcher decision is used to manually map contiguous pixels defining pore structures on such a high resolution, the porosity maps that result are highly detailed and reliable. These maps, however, lack insight into the 3D size and connectivity of pores since they are only a 2D slice of a 3D material. Micro CT scans can fill in this gap, but we found this method to have disadvantages of its own.

Micro CT imaging ultimately results in a 3D porosity map that provides insight into the size, shape, and connectedness of pores. Each scan takes up to 4 hours and can be relatively expensive depending on the desired number of samples. Because micro CT scans rely on material density, rock types that lack sufficient density contrasts are difficult to successfully post-process. We found the density contrast between the host rock minerals (mainly plagioclase) and the healed minerals (calcite and silica) at Newberry to be relatively low. When thresholding for healed porosity, the non-uniqueness of the healed mineral densities causes a significant portion of host rock to be incorrectly included in the healed mineral component. To deal with this over-estimation of healed porosity, the selected host rock grains were despeckled out of the dataset, but so too were some healed grains. Because of this overlap, it is nearly impossible to successfully differentiate between healed minerals and host rock. A best-guess method needs to be employed, and even that, we found, results in gross underestimations of healed porosity.

On every micro CT transect, the skeletal porosity is amplified at the top and bottom of the sample. This results from an over-estimate of open porosity due to the proximity of the top of the sample and of dense healing minerals at the bottom due the proximity of the brass sample holder at the bottom. The impact at the top of the sample extends over a much larger distance (up to a few cm) than at the bottom.

5.3 Fracture Surface Roughness

The geometry of the fracture surfaces and its correlation with dilation accompanying repeated slip reveals 19 dilatant slip events resulting in 38 surfaces. These surface are differentiated into three distinct groups, A-C, that suggest 3 distinguishable episodes (ages) of fracture growth, each of which sustained multiple slip events. We interpret segment A to represent an initial series of fracturing events that continued to dilate and eventually give rise to segment B, as suggested by layering and cross-cutting relationships visible petrographically and by distinct color variation under the cathodoluminescence. Segment B continues to slip and dilate until Segment C forms and links to Segment B. Taking into account this relative timeline, we document the evolution of surface roughness as a function of fracture development including linkage of fracture segments. Figure 6a suggests that surface topography decreases after the initial break and remains relatively constant as slip recurs. The linkage of fractures, however, introduces greater topography, which gradually decreases as the linked fractures continue to slip.

The along-surface length of the fracture surfaces ($L_s$) was compared to a straight-line length ($L_{\text{min}}$) (Figure 6b). Surface length relates to the tortuosity of the void space within the fracture—that is, the physical length that fluid would take when traveling through the fracture—and the surface area available to sustain dissolution/precipitation reactions. After the initial break, the ratios of $L_s$ to $L_{\text{min}}$ spike and gradually decrease as slip continues. Once fracture linkage occurs, the $L_s/L_{\text{min}}$ ratio begins to increase, and continues to do so as the linked surface continues to break. We note here that variation in $L_{\text{min}}$ results from the fact that during most fracturing events only a portion of the fracture breaks open. Lastly, because asperity frequency and grain size share a common length scale, it may be possible to predict the dilating effects of induced fractures on an otherwise unfractured rock. 

![Figure 6](image-url)

Figure 6. (a) Variation in topographic relief of the individually analyzed fracture surfaces. The boxes span the 25th to 75th percentiles, with the inner, horizontal line corresponding to the median. The notch indicates the 95% confidence interval of the median; other median values outside this notch are statistically different populations to 95% certainty. The whiskers indicate the 2 sigma confidence range and the plus symbols are outliers; (b) Ratio of piecewise fracture surface length, $L_s$, to straight-line length, $L_{\text{min}}$, as a measure of surface roughness for individually evaluated surfaces (circles) and surfaces evaluated in references to the oldest surface (triangles). Notice that since not all of the fracture is reactivated during each slip and dilation (see reference in Figure 6b), successive surfaces are not all the same length. The minimum straight line length of these surfaces is recorded by the red and red dashed lines which make reference to the right-side y-axis, also in red.
5.4 Future Directions

In future contributions we will similarly analyze the porosity structure of experimentally fractured rock volumes and include additional measurements including the QEMScan of thin sections (e.g., Ayling et al., 2012) and analyses of 2D and 3D pore shape and size distribution. QEMScan in particular offers an alternative to the manual image mapping that more uniquely defines the pixel-by-pixel variation in mineralogy (and porosity) automatically inferred from correlating the measured semi-quantitative Energy-dispersive X-ray spectroscopy (EDS) spectrum obtained in a Scanning Electron Microscope (SEM) to a minerals reference table.

Analysis of roughness will be applied to additional fractures and power spectral analysis will be used to assess the relative contributions of different asperity wavelengths to the overall roughness of the fracture surface. Initial analysis indicates that the power spectral slope, which is correlated with the fractal dimension: (1) is not uniform but has a distinct break in slope at a characteristic length-scale and (2) does not vary significantly between different aged fractures.

6.0 Conclusion

The pore volume and structure of naturally fractured rock from the Newberry Volcano, Oregon differs significantly between techniques. This discrepancy is greatest for analyses of healed porosity and becomes exacerbated for more highly fractured rock. At Newberry, the amount of healed porosity significantly exceeds open porosity. Automated thin section thresholding tends to over-estimate healed porosity when compared to thin section point counts conducted on the same sample because of transmitted light color similarity. Detailed analysis of high-resolution images of petrographic thin-sections provides the most accurate means of porosity characterization, but should be augmented with data from micro CT scans, which although were found to consistently underestimate porosity because of the non-uniqueness of material density, provide insight into the 3D size, connectivity, and distribution of pores.

Fracture roughness measurements from Newberry show that even simple fractures sustain multiple opening events accompanying shearing. The size distribution of the >0.2mm size fraction of primary grains and pores strongly correlates with the roughness of fracture surfaces. Thus fundamental characteristic length scales associated with host rock (grain size and pore size, vesicles in this case) influence the potential for dilation through their control on fracture surface roughness. Preliminary findings suggest that this roughness directly influences dilation and progressively evolves both as a function of repeated slip and the linkage of cracks that occurs as a function of fracture development.

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7.0 References


