Spatial Correlation Between Average Fracture Spacing (AFS) in the Lower Burro Canyon Formation and the GTO Fault, Lisbon Valley, UT, USA

by

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Abstract

The Burro Canyon Formation in Lisbon Valley, UT forms excellent reservoirs and pathways for fluid storage and transport. Rock permeability is an important metric for geologists and society alike, as it controls the distribution of important resources like metals, petroleum, and water. Chief among these factors that determine permeability are the fractures within a rock. The spatial distribution of fractures is imperative in understanding how fluids flow through the Lisbon Valley District.

The Lisbon Valley District is localized on a NW-trending, doubly plunging anticline. A normal fault (GTO Fault) on the anticline’s southwest flank has a 1000 feet of vertical offset. This fault has acted as a primary pathway for hydrothermal copper-bearing fluids that produced the ore deposits. The influences on localized fracture networks in the area are still relatively understudied and have yet to be quantified. A further investigation of Average Fracture Spacing through outcrop and core analysis is necessary in determining the controls on damage zones and how that relates to permeability and fluid flow at the Lisbon Valley Mine.

A total of six cores were collected from the Lisbon Valley Mining Company and were systematically examined to determine AFS based on proximity to the fault. Parameters described in each core include: number of fractures, upper/lower terminus depth, length, aperture, dip relative to core axis, and cementation. This quantitative data was inserted into an Excel calculator using the calculation methods of Narr (1996) to obtain AFS measurements within a given core.

AFS values vary from as low as 4.48 ft near the fault, up to 22.14 ft further from the fault. The distribution of fractures theoretically should be more intense closer to the normal fault. However, the additional structures in the area could be influencing the fracture networks in a way that contradicts this.

Results from this analysis can be used to plan for in-situ recovery of copper at the Lisbon Valley Mine. The data received from the AFS calculations can be used by the geologists and engineers at the mine site to create 3D/4D models to observe spatial distribution of fractures and estimate permeability and fluid flow. Existing permeability and porosity data at the mine can also be quantitatively compared to AFS values.

Introduction

Although we have considerable information on the qualitative properties of fractures, our quantitative knowledge is limited due to the difficult processes of properly collecting and analyzing fracture data, as well as the lack of awareness of the possible uses for said data (Narr, 1996). A comprehension of the spatial distribution of fractures is imperative in understanding how fluids flow through the Lisbon Valley District. The behavior of reservoirs or aquifers can be estimated with models; however, such models require quantitative information on fracture spacing prior to estimation. Various geological processes, for example pore-fluid overpressure, folding, and faulting, are all thought to influence the distribution of fracture networks. However, these influences can be difficult to constrain without a quantitative comparison of fracture spacing within different boreholes. The average fracture spacing (AFS) model created by Dr. Wayne Narr, is a method that pertains directly to this issue. This method allows quantitative data received from core to be integrated in the analysis and exploitation of naturally fractured reservoirs (Narr, 1996). In this paper is presented a core and outcrop-based analysis of AFS within the Burro Canyon Formation of Lisbon Valley, UT using the methods provided by Narr, (1996).

Background

Paradox Basin

The Paradox basin of the eastern Colorado Plateau Province is a paleotectonic depression of Late Paleozoic age. The boundaries of the basin are usually defined by the geographic extent of salt deposited during Middle Pennsylvanian time in the Paradox Formation. The basin is bounded on the northeast and east by the Uncompahgre uplift segment of the Ancestral Rockies orogenic system and is surrounded along the remainder of shallow-water deposits. The basin has a northwesterly orientation, extending from Durango, Colorado and Farmington, New Mexico on the southeast to Green River, Utah on the northwest (Baars and Stevenson, 1981). The Paradox basin formed adjacent to the southwestern bounding faults of the Uncompahgre uplift as a compliment faulted depression. The deepest part of the basin lies immediately adjacent to the uplift, having stepped down structurally in a series of half-grabens from the western and southwestern shelves, or structural hinge line (Baars and Stevenson, 1981). This structural complexity is related to the fault systems at Lisbon Valley.

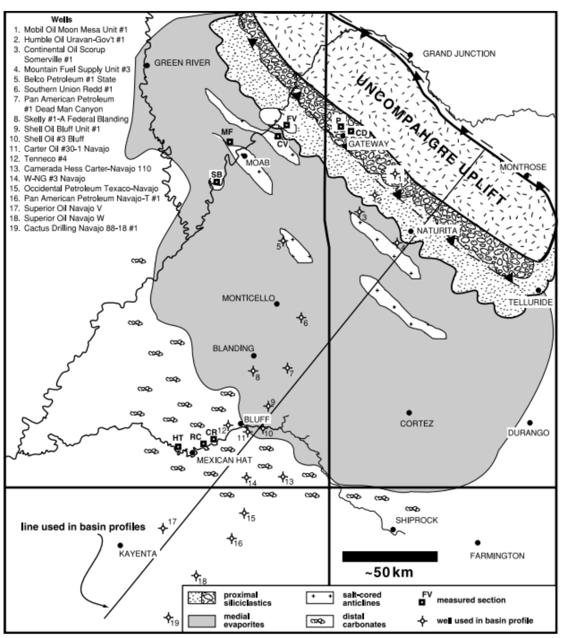

Figure 1): A Geologic Map of the Paradox Basin (modified from Baars and Stevenson, 1981)

Lisbon Valley District and Fluid Flow

The Lisbon Valley district is localized on a northwest-trending, doubly plunging anticline. A normal fault on the anticline's southwest flank (GTO Fault) has roughly 1000 feet of vertical offset, down to the northeast. This fault has acted as a primary pathway for hydrothermal copper-bearing fluids that produced the deposits. Bleached sandstones of the Cretaceous Burro Canyon Formation host the typical Lisbon Valley Mine's copper ore body, with subsidiary mineralization in the overlying Dakota Sandstone. Copper minerals occur in pore spaces and fractures in the medium- to coarse-grained, bleached sandstones. The Paradox Basin and the Lisbon Valley District are dominated by porous and permeable sandstones near the surface (as well as siltstones, mudstones, and shales), and thus form excellent reservoirs and pathways for fluid storage and transport. Rock permeability is an important metric for geologists and society alike, as it controls the distribution of important resources like metals, petroleum, and water. The rock permeability (matrix) depends on lithology, while the overall system permeability depends on stratigraphic architecture and structure, including fractures. The spatial distribution of these fractures is imperative in understanding how fluids flow through a body of permeable rock.

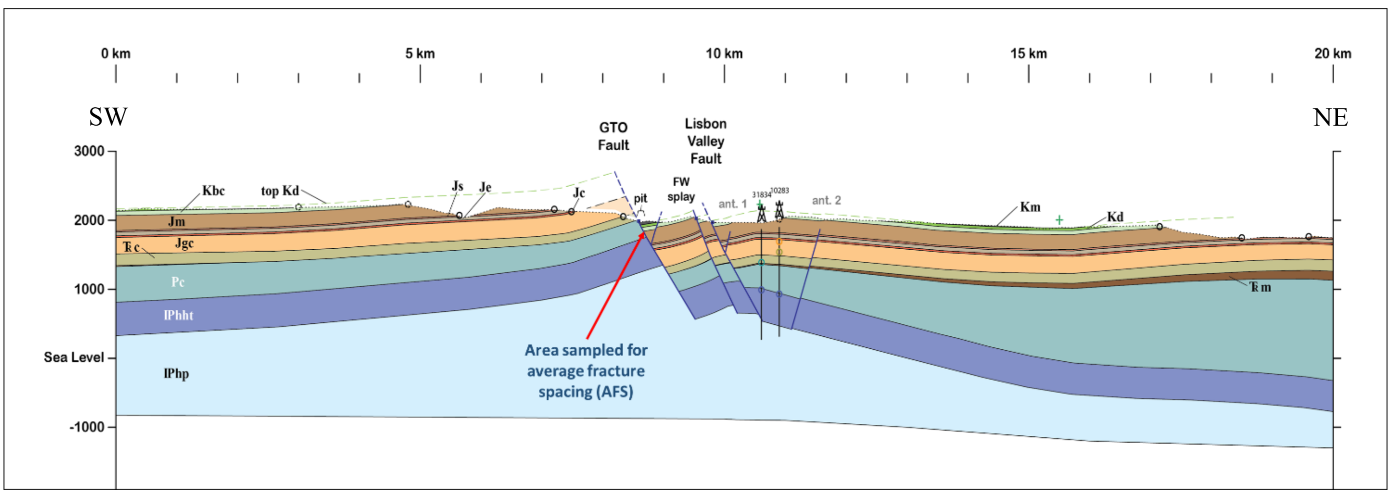

Figure 2 – Cross section of modern day Lisbon Valley highlighting the structural complexity of the area. Area sampled for average fracture spacing is on the right of the GTO fault (footwall). Unit Abbreviations: Kd = Dakota SS, Kbc = Burro Canyon Formation, Jm = Morrison Formation, Jc = Carmel Formation, Jgc = Glen Canyon Group, Trc = Chinle Formation, Pc = Cutler Formation, Phht = Honaker Trail Formation, Php = Paradox Formation (Lingrey, personal communication).

Damage Zones

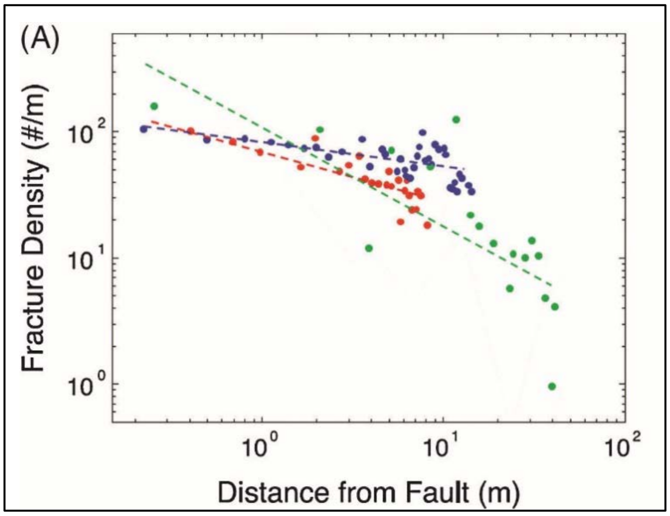

Figure 3) Decay of fracture density in damage zones with distance from a main fault. The colors represent three transects across (damage zones around the Punchbowl fault (an inactive trace of the San Andreas fault system) (Modified from Johri, et al. 2007)

A fault consists of two architectural elements; an interior fault core and an enveloping fault damage zone (Moustafa et al., 2016). The damage zone's intensity is mainly dependent on fault displacement and lithology. In a typical scenario, an isolated fault will create damage zones that dissipate as they advance further away from the fault (Chester and Logan, 1986). Unfortunately, there is no systematic classification of fault damage zones (Kim et al., 2004) in terms of fracture intensity around faults and in relation to lithology and displacement. Therefore, quantifying a damage zone proves to be a challenge and certain variables must be analyzed individually to get quantifiable data. In this scenario, the average fracture spacing (AFS) is quantified within the damage zone of the GTO fault through a core-based analysis. Understanding the structure of fault damage zones is important for a variety of applications including accurate flow models for hydrocarbon exploration, seismic hazard assessment, CO2 storage, contaminant transport and ground water flow models (Moustafa et al., 2016). These types of flow models will assist in the planning of in-situ recovery at Lisbon Valley Mine.

Importance of Damage Zones at Lisbon Valley Mine

The existing structures in Lisbon Valley have had significant impacts on fracture intensity and distribution. However, the influences on localized fracture networks in the area are still relatively understudied. The fault systems in the Lisbon Valley district almost certainly have some effect on fracture distribution and the extent of the damage zone (which is dependent on distance from the normal fault on the anticlines southwestern flank and the surrounding lithology). A further investigation of fracture spacing through outcrop and core analysis is necessary in determining the intensity of damage zones surrounding the GTO fault and how that relates to permeability and fluid flow at the Lisbon Valley Mine. Understanding the spacing of fractures in the subsurface can help facilitate the assessment of the Burro Canyon Formation's potential production characteristics during in-situ recovery.

Methods

Core Analysis

The core samples at the Lisbon Valley Mine provide excellent exposure of fractures that exist within the subsurface. Naturally induced fractures are exposed within Bed 15 (Burro Canyon Formation) which allows for fractures to be quantitatively measured for a variety of characteristics. Size characteristics such as length and aperture are perhaps the most significant aspects in this core analysis. These determine the overall spatial abundance or distribution of fractures within the subsurface. A fracture logging sheet containing all the necessary parameters (number of fractures, upper/lower terminus depth, length, aperture, dip relative to core axis, type, and cementation) used to record data from certain boreholes. The cores available at the mine are also organized by location and depth. This provided information on where the cores were drilled from and how deep in the subsurface the core came from. With this known, fractures can be analyzed with respect to spatial distribution, depth, and lithology. This provides an opportunity to model fractures in 3-dimensions to observe spatial patterns, depth, and rock type in which the fractures exist in. These boreholes were strategically chosen based on lateral proximity to the GTO fault in order to observe how fracture spacing is distributed throughout the damage zone.

Boreholes Selected for Analysis

The following boreholes were selected for interpretation from the GTO pit at Lisbon Valley Mine (LVM): GTO 221, GTO 224, GTO 229, GTO 230, GTO 232, and GTO 233. This six-core transect was strategically chosen for analysis due to its variety of distances from the GTO fault. Each of these cores become increasingly distant from the fault trace (Figure 4), thus being ideal for interpreting how average fracture spacing (AFS) is changing with respect to the proximity of the fault. The location of these cores is also important due to its economic potential. In-situ recover efforts being conducted at LVM include the exploration of this area for its permeability properties. Quantifying average fracture spacing assisted these efforts.

The map below displays the selected boreholes sampled for AFS:

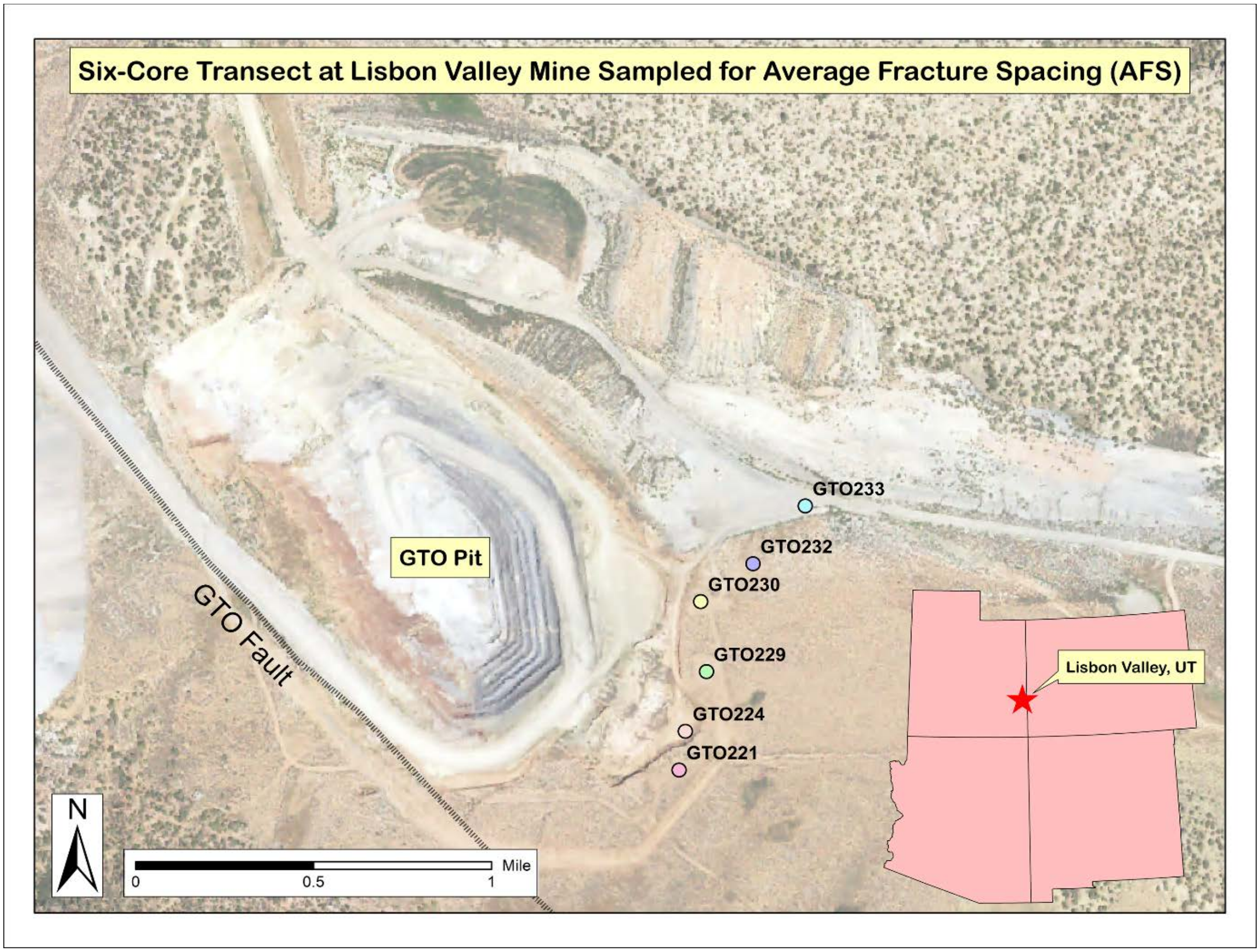

Figure 4) Map displaying the six-core transect at Lisbon Valley Mine (LVM) sampled for average fracture spacing (AFS). Distance of borehole to the GTO fault was measured using this map and assisted in the AFS correlation. Data sources: Esri Inc., NAIP, and Lisbon Valley Mine

Natural vs. Induced Fractures

A major challenge in this analysis was establishing the distinct differences between natural and induced fractures. Induced fractures are breaks or discontinuities caused by the drill bit during coring or from being mishandled during core storage. Natural fractures can be identified by the following characteristics: Vertical fractures against bedding, mineralization or cementation fillings, and a relatively straight or natural shape/orientation. Induced fractures can be identified by the following characteristics: rough and irregular shape, conchoidal chipping, and no evidence of mineralization or cementation (Kulander et al., 1990). Figure 5 shows visual examples of both types of fractures.

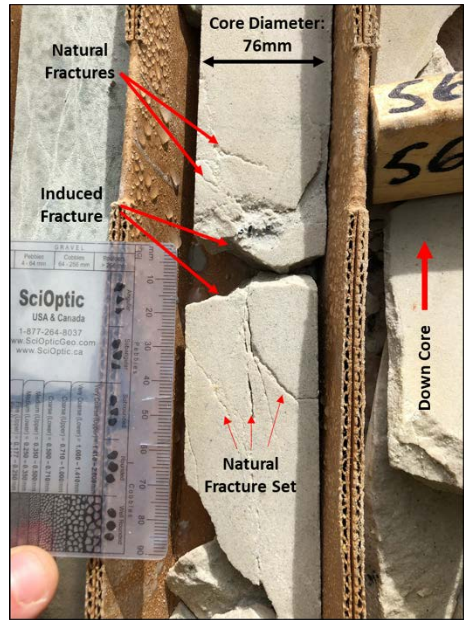

Figure 5) Image of core displaying natural fractures that were confidentially logged and the induced fractures that were disregarded.

Average Fracture Spacing (AFS) Calculations

Calculating average fracture spacing in the subsurface has always proved to be a challenge in the past. Using the methods of Narr (1996), fracture spacing can be quantified by using a statistical method to estimate fracture spacing from the limited spatial information available in cores. The basis of the AFS method is to equate fracture porosity measured in core with fracture porosity defined for the reservoir, which leads to average fracture spacing (Narr, 1996). There are two different approaches to calculating average fracture spacing (AFS) in core. One using the apertures given and another excluding aperture. Both use the same general formula modeled as: [Core Diameter x Core Height/ Summed Fracture Height in Core] (Narr, 1996).

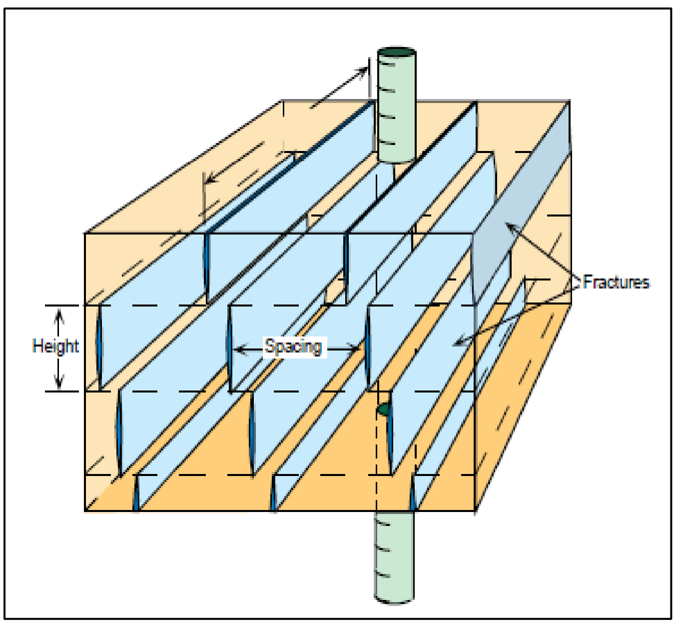

Figure 6) Borehole of finite diameter passing through rock volume with set of uniformly distributed fractures having equal spacing and height. (Narr, 1996).

Correlating AFS and Distance from GTO Fault

Quantitative AFS data from the core can be used to spatially correlate the fracture spacing to the relative distance of borehole location to the fault trace. This is imperative in understanding the control and impact the GTO fault has on the intensity of the damage zone.

Each borehole's distance from the fault was measured via ArcMap (Figure 4) and was recorded for statistical interpretation.

Field Investigation

In addition to the core, it is useful to visit the areas surrounding Lisbon Valley to qualitatively observe the fractures visible in outcrops (Figure 7). Outcrops can display certain spatial orientations of fractures that might not be visible in core and provide useful information on characterizing fracture networks. The orientation of the fractures displayed in outcrop can also be compared to the orientation of the GTO fault to determine the influence or source of the network.

Results

Qualitative Observations in Core

The Burro Canyon Formation at this depth in Lisbon Valley is composed of medium to coarse grained bleached sandstones. Fractures in these sandstones are primarily vertical or near vertical (60-90° dip) and intersect bedding perpendicularly. The vertical orientation of these fractures suggests that they are a part of the vertical fracture sets extending laterally from the GTO fault. A small portion of the fractures observed were open mode with little to no cementation, however, the remaining natural fractures were filled and cemented with either quartz, barite, or calcite. The cementation fillings in the fractures suggest that this is secondary mineralization and provides supporting evidence that they have a natural origin (Kulander, 1990). Overall, the fracture intensity varied throughout the core with particular intervals containing little to no natural fractures and other intervals with high fracture intensity and evidence of mineralization. Areas of high fracture intensity were noticeably more frequent in cores within close proximity to the trace of the GTO fault. On a different note, identifying natural vs. induced fractures was a challenge in this analysis, however, induced fractures appeared quite obvious in core and were not recorded in the logging process. The rough and irregular shape the drill bit makes when inducing a fracture in core made it relatively simple to rule out for logging purposes (Figure 5) (Kulander, 1990).

Figure 7) Outcrop to the North of the Lisbon Valley Mine displaying large fractures with similar NW orientation to the GTO fault.

Qualitative Observations in Outcrop

A field investigation was conducted in the Burro Canyon Formation outcrop just north of Lisbon Valley Mine. Orientation and approximate spacing was recorded in the outcrop for qualitative comparisons to what was observed in core. These large vertical fractures exhibited a similar N-W strike to that of the GTO fault (Figure 7) which is supportive evidence of this network being influenced by the movement and displacement of the fault. The network had an approximate spacing of 10 ft between each significant fracture. This spacing compared to the measurements in the core is lower than expected, however, the outcrop only displays the vertical fractures in 2-D and does not account for the fractures in the subsurface.

AFS Values and Borehole Distances

AFS values the results varied significantly from 4.68 ft to 22.14 ft. Distances of each borehole to the fault were measured via ArcMap and varied from 600 ft to 1450 ft. Each borehole was assigned the following AFS values: GTO 221 – 4.68 ft, GTO 224 – 9.95 ft, GTO 229 – 22.14 ft, GTO 230 – 9.90 ft, GTO 232 – 13.57 ft, and GTO 233 – 18.29 ft. (Table 8) The distance from each borehole to the fault is as follows: GTO 221 – 600 ft, GTO 224 – 700 ft, GTO 229 – 875 ft, GTO 230 – 1000 ft, GTO 232 – 1450 ft. (Table 9)

AFS of Each Core in Transect	
GTO 221 – 4.68 ft	GTO 230 – 9.90 ft
GTO 224 – 9.95 ft	GTO 232 – 13.57 ft
GTO 229 – 22.14 ft	GTO 233 – 18.29 ft

Table 8 – Table showing the average fracture spacing (AFS) for each sampled borehole.

Approximate Distance from Fault	
GTO 221 – 600 ft	GTO 230 – 1000 ft
GTO 224 – 700 ft	GTO 232 – 1200 ft
GTO 229 – 875 ft	GTO 233 – 1450 ft

Table 9 – Table showing the distance of each borehole to the GTO fault. Measured using ArcMap.

Discussion

Applications and Importance of AFS Methods

Understanding fracture spacing in the subsurface has always proved to be a challenge in the past. Conducting a 2-D scanline survey on a fracture network can be useful and can provide qualitative data about the orientation of the fractures (Figure 7). However, assumptions must be made with little confidence about the spacing in the subsurface. For the sake of this analysis, a 2-D sampling method was not sufficient enough on its own. The methods of Narr, 1996 allows this fracture network to be analyzed in three dimensions with respect to core volume and total fracture height using core sampled from the Burro Canyon Formation. This method also reduces statistical bias because the fracture network in the subsurface is not visible, meaning the boreholes serve as random sample points for fracture spacing.

AFS Cons

The orientation of fractures is difficult to constrain when observing core samples. Measuring strike and dip of the bedding relative to the orientation of the fracture(s) is problematic when the core sample is not in its place of origin. This is unfortunate because fluid flow behavior can be dependent on the orientation of these fractures. Additionally, recording the aperture (width) of the fractures proved to be a challenge. The apertures ranged from 0.5mm – 2.0 mm, 0.5mm being the smallest aperture that can be confidently measured and logged with a handheld ruler. For the scope and time constraint of this analysis, apertures were not logged for every fracture and were not accounted for in the AFS calculations. This was due to the difficulty of confidentially measuring them with a ruler. Nonetheless, this method still proved to be useful for estimating average fracture spacing with respect to the damage zone of the GTO fault.

AFS vs Distance from GTO Fault Interpretation

As hypothesized, the AFS values increased with distance from the fault. A normal fault will typically produce high fracture intensity in close proximity and will dissipate as distance from the fault increases laterally (Chester and Logan, 1986). The figure below (Figure 10) displays this expected relationship and confirms that there is a strong positive correlation between distance and AFS. Thus, the fracture intensity decreases with lateral distance from the GTO Fault. AFS values even further away from the GTO fault would theoretically not be measurable in core due to the absence of significant fractures that were structurally induced by the fault. Additional structures in the greater Lisbon Valley area could have produced fracture networks that would contradict that idea, and AFS values would then be measurable and significant. Given the structural complexity of the Paradox Basin in conjunction with the collapsed salt anticline in the Lisbon Valley district, there is most likely a base level of fracture development and AFS in this region.

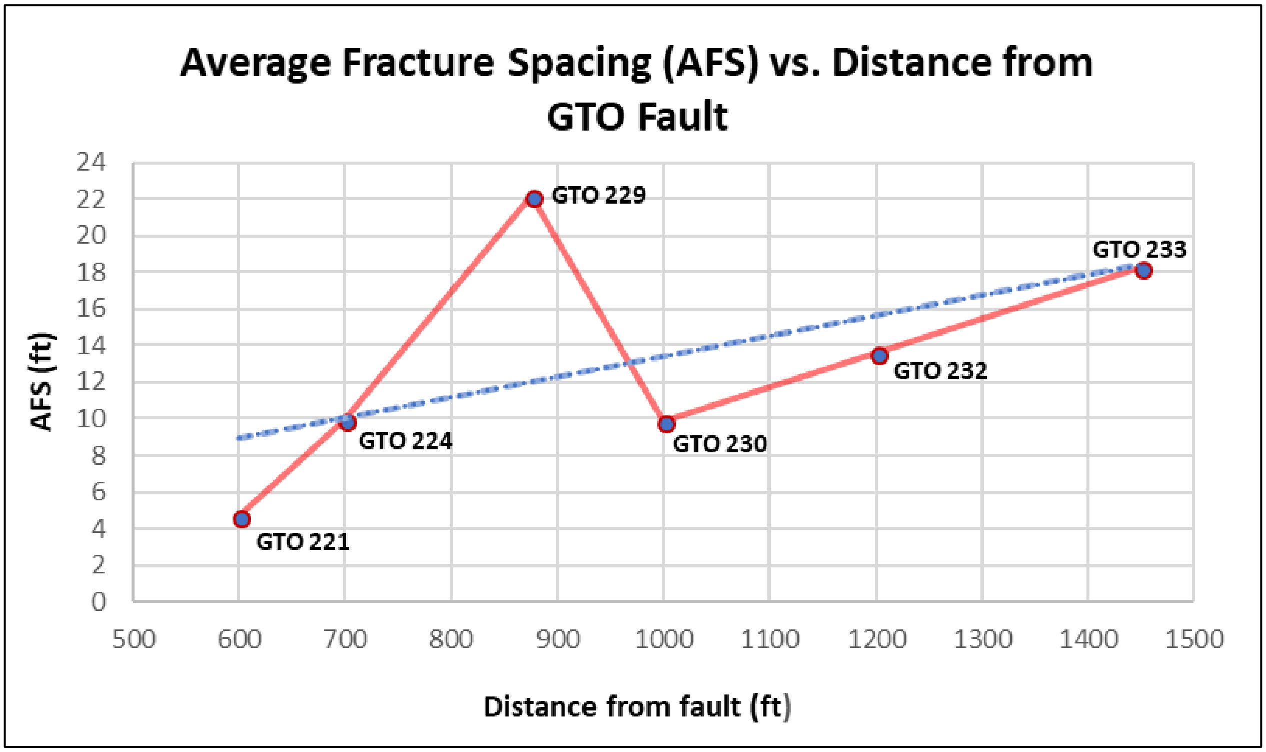

Figure 10) Graph displaying the strong positive linear correlation between AFS and distance from GTO fault.

In-situ Recovery Applications

The Lisbon Valley Mining Company is currently planning for their future in-situ recovery of copper. A critical aspect of in-situ recovery is understanding and quantifying permeability and fluid flow. Quantifying fracture networks is amongst some of the factors that will help facilitate assessing the behavior of a solution flowing in the sub-surface. Obtaining these AFS measurements in areas of exploratory interest has been beneficial to the mine. Permeability measurements taken via mercury injection can now be compared to the numerical AFS data to see if the fracture networks have significant affects. Fracture characteristics such as aperture, cementation, secondary mineralization, and orientation (not recorded in this analysis), can all have an impact on permeability and the chances of success for in-situ recovery. High fracture intensity could cause higher permeability parallel to the fault and this anisotropy should be considered while planning for in-situ recover at Lisbon Valley Mine. There is a possibility that the increased permeability due to fractures could cause the acid solution used in in-situ recovery to by-pass the rich ore deposits. It is possible that the ore grade increases closer to the GTO fault, meaning that the combination of high ore grade and high permeability could be problematic and needs to be assessed before in-situ recovery.

Hydrologic Modeling and the Paleo-fluids Project

Fractures contribute to the overall permeability of the system which is also analyzed with respect to hydraulic engineering and complex flow modeling. This type of analysis was beyond the scope of this research. However, the Hydrology Department at the University of Arizona is in the process of conducting a paleo-fluids research project within the Paradox Basin. This project will consider the regional fracture developments role in how fluids move throughout the basin and the impact that fracture orientation has on preferred flow directions.

Future Work

Additional borehole analyses could potentially be conducted if allotted a time extension for this investigation. At the Lisbon Valley Mine there is additional core available that has been sampled in close proximity to the GTO fault. This core would be ideal for an AFS analysis to confirm that fracture intensity remains high along the fault trace and if the AFS measurements are similar to that of the boreholes that have already been sampled. Additionally, the fracture distribution could be more heavily analyzed with respect to depth. Damage zones are dependent not only the lateral distance from the fault, but the depth in the sub-surface.

Conclusion

Estimating and quantifying fractures within a borehole can be difficult. However, the average fracture spacing (AFS) method used in this analysis is easy to use and is widely applicable in the deep subsurface, even where the borehole is parallel to the fractures (Narr, 1996). This method has proven to be effective in analyzing the fracture networks in the Lower Burro Canyon Formation. and has been able to produce meaningful quantitative information about the spatial distribution of fractures in respect to the location of the GTO fault. The results produced from this analysis conclude that the AFS increases laterally from the fault. If AFS measurements concur with permeability and porosity data from the Lisbon Valley Mine, then fracture networks can now be recognized as an important metric for in-situ recovery planning.

Acknowledgments

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