LIDAR BASED FRACTURE ANALYSIS IN OUTCROPS OF CHATTANOOGA SHALE

ALONG THE WILLS VALLEY ANTICLINE, NORTHEASTERN ALABAMA

by

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ABSTRACT

Unconventional reservoirs produce gas and/or oil from fracture porosity and permeability. Therefore, understanding natural fracture patterns is important for effective production from unconventional gas-shale reservoirs in that natural fractures influence reservoir behavior and performance as they play vital roles in the movement of fluids such as oil and gas.

Understanding natural fractures within gas-shale reservoirs is also a critical factor in the distribution of hydraulic fracture treatment design. The objective of this investigation is to perform outcrop scale evaluation of fracture intensity by LIDAR (Light Detection and Ranging) survey on organic rich Chattanooga Shale. Evaluation of fracture intensity is done by determining the Fracture Spacing Index (FSI) of the shale at given stratigraphic intervals.

Organic rich Chattanooga Shale, a black shale formation, outcrops in several locations in Northeastern Alabama. Two outcrops, of this study, are located along the backlimb of the Wills Valley Anticline. During this investigation several close-up laser-scanned images of the shale were collected across the outcrops using LIDAR. The outcrops are similar in their stratigraphy and lithology; the base of the Chattanooga formation at both locations unconformably overlies the Red Mountain formation. Its lower part is ductily deformed, while the upper units of the shale at each outcrop become brittle and well-jointed with vertical fractures.

LIDAR provides highly accurate, representative data of natural fractures at the surface that can improve subsurface models leading to more realistic reservoir characterization. Laser scanned images at each outcrop provided highly accurate and precise digitized data which was analyzed
to determine the relationship between bedding thickness and fracture spacing. The FSI, determined from bed thickness/fracture spacing relationships, varies from 1.09 to 1.53 within the brittle part of the Chattanooga Shale in both outcrops, implying a measure of heterogeneity. Analysis of petrographic thin sections indicates that the brittle unit, with a high index, is rich in quartz content with correspondingly larger grain sizes. This suggests that there is a positive correlation between brittleness of a shale unit and its Fracture Spacing Index.
DEDICATION

This work is dedicated to... ‘the shoulders of giants.’
LIST OF ABBREVIATIONS AND SYMBOLS

AL-OGB State Oil and Gas Board
BRO Big Ridge Outcrop
$B_t$ Bed Thickness term in Correlation Equation
BRO Big Ridge Outcrop
CSD Cross Strike Discontinuity
FPF Fault Propagation Fold
FPO Fort Payne Outcrop
FSI Fracture Spacing Index
FTB Fold Thrust Belt
K Proportionality Constant in Correlation Equation
LIDAR Light Detection and Ranging, Instrumentation
mya million years ago
$P_f$ Pore Fluid Pressure
S Spacing term in Correlation Equation
SEM Scanning Electron Microscopy
TZ Transverse Zone
USGS United States Geological Survey
WVA Wills Valley Anticline
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CHAPTER I

INTRODUCTION

The southern Appalachian fold-thrust belt in Alabama contains organic-rich shale units in Cambrian and Devonian strata. One of these shale units is the Devonian Chattanooga Shale (Figure 1). Outcrops of Chattanooga Shale in Northeastern Alabama contain well developed natural fractures. During this study, two outcrops of the Chattanooga Shale along the backlimb of the Wills Valley Anticline in Northeastern Alabama (Figure 2) were imaged with Terrestrial Laser Scanning, commonly referred to as LIDAR (Light Detection and Ranging). The natural fractures occurring in these outcrops were evaluated in order to quantify relationships between bedding thickness and fracture spacing. Variations in fracture intensity, a measure of relative density of fractures, was also evaluated with respect to brittleness change vertically within each outcrop.

Figure 1. Outcrop of Chattanooga Shale in Fort Payne, Alabama.
Figure 2. Location Map of Study Area. Sedimentary Basins and Shale Plays across Alabama are indicated, including prospective shale plays within the Chattanooga Shale formation. The excerpt from the Geologic Map of Alabama has been modified and indicates outcrop locations.
STATEMENT OF PURPOSE

The main purpose of this investigation is to conduct outcrop scale evaluation of fracture intensity and fracture density with respect to bedding thickness and brittleness variation in the Chattanooga shale outcrops using images provided by a LIDAR survey. For this purpose, LIDAR images of the two Chattanooga Shale outcrops along the Wills Valley Anticline, in Northeastern Alabama, were obtained and studied in detail.

Previous studies on fracture analysis involved conventional field measurement techniques using a measuring tape to measure representative and accessible areas along outcrops within defined squares or circles. For example, Ataman (2008) studied natural fractures in Devonian Woodford shale outcrops in the Arbuckle Mountains of Oklahoma.

He used traditional methodology in which a limited area of accessible and representative rock at an outcrop is outlined and measured for bed thickness and fracture frequency (Figure 3). During this investigation, quantitative evaluation of fracture density has been made possible by high precision LIDAR images. The LIDAR images provided high precision measurements of fracture length, fracture spacing and bedding thickness along with the ability to scan and quantitatively analyze larger and inaccessible areas for greater representation. The results of LIDAR imaging demonstrate
improvements in the measurement of the quantitative relationship between the fracture
spacing and bedding thickness as the measurements are not only more precise but also have
the benefit of facilitating the measurement of larger inventory squares which becomes
impractical by hand measurement.
Quantitative evaluation of natural fractures is important to enhance gas production in
unconventional shale-gas reservoirs as effective production models rely on accurate
representation of the density of fractures within the conduit which provides for fluid flow and
the reservoir permeability. Effectiveness of reservoir models can be improved by the input of
data from more accurate, higher resolution fracture relationships. Quantitative analysis of
natural fractures in two Chattanooga outcrops may be used for a better estimate of reservoir
permeability of potential Chattanooga shale unconventional reservoirs.

IMPORNTANCE OF OUTCROP SCALE FRACTURE ANALYSIS
Stresses on the Earth’s crustal rocks create natural fractures as well as control their orientation.
Fracture frequencies and spatial distributions directly impact permeability and thus the fluid
flow in hydrocarbon reservoirs is, in part, controlled by fracture populations and their
connectivity (Gabrielsen, 1998). These natural fractures are often made up of genetically
different fractures sets which are commonly influenced by bed thickness, grain size,
compositional variation, fluid pressure, as well as influences from changes in local stress field
and temperature from burial and uplift which are associated with the tectonic regime. Variation
in production from shale gas units often can be tied to changes in the stress-dependent
fracture permeability (Bustin, et al., 2012; Ai, et al., 2014) which points toward the need to
consider both natural and induced fractures as the reservoir stress changes impact conductivity (Lorenz, 1999). Quantification of fracture relationships, such as fracture spacing and fracture density, aids in both assessment of hydrocarbon flow (Rohrbaugh Jr., 2002) and potential enhancement (Bustin, et al., 2012, Lorenz, 1999). The linear relationship between fracture spacing and bed thickness (Ladeira and Price, 1981) which is tied to lithological variation is reflected in the Equation below, usually referred to as the Correlation Equation.

\[ S = K \cdot Bt \]

Correlation Equation

Where

- \( S \) is the spacing between fractures,
- \( Bt \) is the bed thickness and
- \( K \) is the constant, strongly tied to differences in mechanical properties from lithological/compositional differences in the rock unit.

Figure 4 shows a hypothetical example where bed thickness directly correlates to the spacing between fractures, with generic measurements of bed thickness and fracture spacing. The greater the bed thickness the greater the separation between fractures. The linearity and slope of this relationship is dependent on compositional consistency and other factors which contribute to heterogeneity within the rock, such as the degree and type of cementation present. The data can be illustrated in a variety of ways including plots of bed thickness to fracture spacing and plots of fracture density to bed thickness (Figure 4).
This equation is a generic relationship which reflects the tendency for a fracture, once formed, to impact subsequent fractures in a fashion where separation is regular, given a specific lithology and consistent stress. Literature for several decades have pointed to the shortcomings of the relationship resulting from competency contrast in adjacent beds (Rijken and Cooke, 2001; Ji and Saruwatari, 1998), the strain rate (Mandal, et al., 1994), fluid pressures, stress shadows (Gross, et al., 1995), joint saturation (Tan, et al., 2014) and the impact of time in terms of changes in the state of stress (Tuncay, Park, and Ortoleva, 2000; Olson, 2003) including those derived from fluid pressures changing from thermal maturation of organic matter (Engelder, 2009). While the equation may not hold in all cases, the empirical relationship is valid (Ladiera and Price, 1981) and can provide useful insight.

Analysis of bed thickness relative to fracture spacing is a measure of fracture density. This can be measured across an outcrop and is useful in evaluating the adherence to the linear relationship from the Correlation Equation. Descriptions of density relationships at given stratigraphic intervals, at the surface, are often used in subsurface reservoir characterization. Digital outcrop information can be extracted from LIDAR images. With the inherent high resolution and precision available by laser scanning of outcrops, as well as the ability to measure beds inaccessible by conventional field methods, the wealth of data within the images can be statistically analyzed to extract the relationship between bedding thickness, fracture spacing and fracture density precisely.
Figure 4. Measurements of Fracture Density within Inventory Squares. A window (or square) of given dimensions is used to take inventory of the thickness of each bed as well as the spacing between fractures. The data can be represented in a variety of ways including the two above (Fracture Spacing to Bed Thickness and Fracture Density to Bed Thickness) as well as Bed Thickness to Number of Fractures or even more elaborate relationships such as Number of Fractures per Area of Plane or Length of Fractures per area of Plane. Data collection from inventory squares at varying stratigraphic levels within an outcrop provide the means to evaluate changes in populations of fractures.
Modelling fracture networks in reservoirs by extrapolating parameters such as fracture density, which has historically been derived from borehole image logs (Ma, et al., 1993; Kubik and Lowry, 1993; Caramanica and Hill, 1994; Narr, 1996) or outcrop measurements, can improve reservoir models by reducing uncertainty both in conventional and unconventional reservoirs (Barthelemy, et al., 2008). Conventional workflow for constraining fracture information such as fracture density into such models involves identifying fracture domains or networks within a given area or sector followed by upscaling the data to populate the geological models (Boro, et al., 2014). Fracture density data, which is rarely observable on cores, can effectively be obtained from outcrop studies, especially with highly accurate and precise digital data produced by LIDAR images (Gale, et al., 2014). Predicting zones for successful stimulation and production is an essential goal (Glaser, et al., 2013) especially when seeking ‘Sweet Spots’ within Unconventional Reservoirs.

Outcrop studies, including fracture density evaluation, are seeing a resurgence (Martinsen, et al., 2011) as technological improvements in imaging provide high-resolution data can further development of fracture network models with accurate representation being made on a meter scale. LIDAR imaging generating highly accurate and precise digital records of outcrops is providing much of the impetus behind the resurgence.

RESEARCH QUESTIONS

This investigation addresses the following research questions:

1) Can the application of LIDAR surveying be effective in the study of natural fractures within outcrops of potential shale gas units such as the Chattanooga Shale?
2) What relationship exists between fracture spacing and bed thickness within the Chattanooga Shale?

3) How do two outcrops of Chattanooga Shale, separated by 40 kilometers (Figure 2), along the backlimb of the Wills Valley Anticline vary in fracture intensity? Are controls of fracture intensity variation evident?

4) What granular or compositional differences can be observed by microscopic study of thin sections of the Chattanooga Shale within the outcrops? How do these variations affect brittleness of the Chattanooga Shale and formation of natural fractures.

METHODOLOGY

During this study the RIEGL VZ-400 Laser Scanning System (LIDAR) at the Big Ridge Outcrop (BRO) and the Fort Payne Outcrop (FPO) of Chattanooga Shale (Figure 2), provided rich detailed images of scanned areas which are evaluated for bed thickness and fracture spacing (Figure 5). The images facilitated fracture analysis as the digitization of the spatial information leads to a data rich point cloud which can be analyzed and evaluated at a workstation with RIEGL’s proprietary software, RiSCAN Pro.
The method used for analyzing fracture intensity within the outcrops of Chattanooga Shale involved marking representative areas within each formation with a 1 x 1 meter square to inventory fracture relationships (Figure 6). Once an inventory square was delineated on the formation at stratigraphic intervals which had notable lithologic or mechanical changes, LIDAR imaging of the target area on the outcrop surface commenced. Workup and Analysis involved measurements of bed thickness and spacing between fractures within each inventory square and representing the data through plots showing the relationship between bed thickness and fracture spacing, such as those presented in Figure 4.

Figure 6. LIDAR scanning of the pre-marked inventory square leads to a digitized point cloud rich with spatially resolved information enabling fracture analysis with high measures of accuracy and precision. Chattanooga Shale, FPO.
USE OF LIDAR IN OUTCROP SCALE FRACTURE ANALYSIS

LIDAR techniques operate by spatially resolving points across a surface referencing position and distance relative to the imaging system. The functionality is tied to laser pulses sent from the LIDAR system to a surface and reflected back, where travel time is the key factor in establishing position and distance. With a terrestrial laser scanning system using a near infrared laser with pinpoint accuracy detailed information of surficial features can be resolved. Appendix A is a short summary of the RIEGL Laser Measurement System used during this study. Appendix B provides the workflow of the LIDAR imaging of outcrops.

Imaging of outcrops by LIDAR provides opportunity for fractures within geologic bodies to be measured and evaluated with precision. Fracture attributes characterizing clusters, intensity, tracelengths, or orientations make outcrop analogues viable for improving reservoir models (Watkins, et al., 2015). Fracture spacing, commonly represented by fracture density or intensity, is known to correlate with bed thickness (Ladeira and Price, 1981; Wu and Pollard, 1995; Ji and Saruwatari, 1998; Schopfer, et al., 2011). Many recent studies have sought to model the mechanics when the relationship holds in a rigorously linear fashion (Mandal, et al., 1994; Gross, et al., 1995; Tan, et al., 2014) while some studies propose perspectives as to why a linear relationship is, in principle, too generic (Narr and Lerche, 1984; Dershowitz and Herda, 1992; Narr, 1996; Rohrbaugh, et al., 2002). Ideally, the relationship holds true within a homogeneous body (bed) of rock free from defects or flaws including cracks, irregular and variable grain size, fractures, impurities, or fossils, which effectively reduce stress locally.
CHAPTER II

GEOLOGIC OVERVIEW

The Appalachian foreland basin formed during a series of collisional orogenies over a span of geologic time. The major orogenic events impacting the basin were the Taconic Orogeny (ca. 430 mya), the Acadian/Neo-Acadian Orogeny (ca. 360 mya), and the Alleghanian Orogeny (ca. 320 mya) (Hatcher, 2005). The tectonic dynamics throughout the multiple orogenic events affected sedimentary patterns and drove the distribution of accumulated sediments (Ettensohn, 2008).

The Devonian Chattanooga black shale was deposited in the retroarc foreland basin (Ver Straeten, 2009) formed during the Acadian Orogeny (Figure 7). Chattanooga Shale is common in the Southern Appalachian Fold-Thrust Belt (FTB) in Alabama in Northeast Alabama. The FTB lies within the Valley and Ridge province and part of the Appalachian Plateau, spanning from the Black Warrior Basin, the western boundary, to the Piedmont Metamorphic Belt to the east at the Talladega Fault (Thomas, et al., 1984; Thomas and Neathery, 1980).

Within the elongate Northwestern domain of the FTB the Paleozoic rock units are deformed into synclines and anticlines, including the Wills Valley Anticline area of study (Figure 8). The Rising Fawn Cross Strike Discontinuity (CSD) or transverse zone can be found on the Northwest end of the Wills Valley Anticline and the Anniston CSD is found on the Southeast end. Two outcrops of the organic rich Devonian Chattanooga black shale are readily accessible along the
backlimb of the thrust sheet ramping from the sole detachment within the Rome-Conasauga Shale with mid-level decollement within the Chattanooga (Coleman, et al., 1988).

Figure 7 A.) Idealized cross section of the retro-arc foreland basin during the Acadian. Black Shale deposition occurs cratonward from the orogeny (from Ver Straeten, 2009). B. Schematic of thrust belt orogenic elements which impact sediment deposition within the foreland. (from Johnson and Beaumont, 1995).
Figure 8. Structural Variability within the Appalachian Thrust Belt.
A) Simplified geologic map showing the location of the study area.
B) The structural suggesting that the Wills Valley anticline is the result of Trishear Fault Propagation Folding occurring from a thrust sheet splaying from a decollement surface in the Conasauga. The figures are modified from (A) Thomas and Bayona, 2005, and (B) Robinson, et al., 2012.
Figure 9 indicates the location of the outcrops, of this study, in DeKalb and Etowah Counties. The outcrops at Fort Payne (FPO) and Big Ridge (BRO) are indicated on the section of the Geologic Map. A representation of the outcrops along the backlimb of the thrust sheet in the Wills Valley Anticline is illustrated. Both outcrops have been detailed in guidebooks released by the Alabama Geological Society (Coleman, et al., 1988; Thomas and Pashin, 2011) and represent locally thick sections of Late Devonian Chattanooga Shale disconformably overlying the sandstone of the Silurian Red Mountain Formation and capped by a thin bed of distinctly green Maury Shale (Mississippian) followed by thick beds of Fort Payne Chert. The location furthest to the
north can be found near Fort Payne, Alabama, roughly 1.5 miles east of exit 218 on Interstate 59 (N 34° 28.229' and W 85° 42.193') and, to the south, the locality designated as Big Ridge can be found along Interstate 59 at mile marker 193 (N34° 07.884 and W85° 59.191). At these outcrops, the Chattanooga Shale ranges from 10 to 13 meters, and consists of black shale with well-developed natural fractures within the upper, more brittle, section, whereas more ductile deformation characterizes the lower section (Figure 1). The natural fractures within the upper section of the shale provide the opportunity to evaluate fracture density using LIDAR imaging, as well as to draw comparisons between the outcrops along strike.

The Chattanooga Shale is rich in organic material and often contains well-developed natural fracture networks in many outcrops. Conant and Swanson (1961) and Pashin, et al., (2011) proposed that in the southern Appalachians, the Chattanooga Shale was deposited in a dysoxic environment. Organic material within the shale is preserved with the limited presence of oxygen, contributing to the organic richness of the Chattanooga Shale. With the onset of the Alleghanian orogeny, the fold thrust belt of the foreland basin migrated northwestward with compressional forces being mitigated by decollement, duplexing, thrusting, folding and fracturing (Thomas and Neathery, 1980; Thomas, et al., 1984; Thomas and Neathery, 1982; Pashin, et al, 2011). Much of structure within the Appalachian thrust belt in Alabama is the result of thin-skinned thrusting, common within ductile shale, which facilitated decollement surface development (Thomas and Bayona, 2002; Hatcher, 2004; Thomas, et al., 2007). Robinson, et al., 2009 and Robinson, 2012, interpreted the Wills Valley Anticline as a Trishear Fault Propagation Fold (FPF) with two subsequent breakthrough thrusts developing from motion along the basal decollement in the Rome-Conasauga unit as it ramps upsection.
Trishear FPF settings demonstrate decreased displacement along faults being accommodated by deformation in shear zones radiating from tip lines (Hardy and Allmendinger, 2011). Within the Rising Fawn CSD the McLemore Cove, Wills Valley, and Lookout Valley Anticlines all sole within a lower decollement in the Conasauga Formation and are capped by roof thrust within the Chattanooga Shale. These are thought to derive from the decollements in the Chattanooga Shale propagating northwest in advance of the Conasauga decollement (Chowns, et al., 2004).
CHAPTER III

NATURAL FRACTURES

Natural fractures within shale units are strongly linked to rock strength and their growth within the rock occurs by mechanisms such as differential compaction, changes in tectonism, and strain accommodation (Gale, et al., 2014). One current motivation for the study of natural fractures is their role in gas and oil production in unconventional shale reservoirs. LIDAR analysis of natural fractures in surface exposures of fine grained rocks offers the potential to use this information to refine and enhance reservoir models and provide positive impacts on production.

IMPORTANCE OF NATURAL FRACTURES IN UNCONVENTIONAL RESERVOIRS

Natural fractures within the shale play vital roles in the movement of fluids, such as oil, gas, and water, through the rock and an understanding of these fractures is critical in designing and implementing hydraulic fracture treatments of unconventional gas-shale reservoirs. Therefore, understanding the natural fracture patterns within the shale is essential for unconventional gas-shale reservoir production. Many early detailed fracture descriptions, crucial to proper reservoir modelling, were made in the subsurface via borehole or core analysis (Kubik and Lowry, 1993; Caramanica and Hill, 1994; Ma, et al, 1993; Narr and Lerche, 1984; Narr, 1996). When possible, correlation between fractures in outcrops and those in the subsurface are of
great interest (Watkins, et al, 2015) in that key fracture attributes, such as spatial arrangements and length, are only effectively measured in outcrops (Gale, et al., 2014). Mapping trends of high fracture incidence or fracture density facilitates enhanced productivity (Narr and Lerche, 1984). With improvements in the ability to discern outcrop details from the highly accurate LIDAR images, reservoir uncertainty can be reduced (Hodgetts, 2013; Seers and Hodgetts, 2014) and production can be further improved.

FORMATION OF NATURAL FRACTURES
Lithologic characteristics from environments of deposition, as well as diagenesis and fluid pressure during the thermal maturation play very important roles in the formation of natural fractures within shale units. Devonian black shale units within the Appalachian Basin, including the Chattanooga Shale, have natural fractures which were impacted by abnormal fluid pressures generated during thermal maturation of the organic matter (Engelder, et al., 2009; Lash and Engelder, 2009; Lash, et al., 2004). Figure 10 illustrates the change in fracture stability associated with increasing pore pressure as the Mohr circle shifts from a stable applied normal stress to an effective normal stress. If the pore pressure is sufficiently high, the shift within the envelope of stability can lead to a critical point beyond which fractures can occur. Natural fracture systems within shale beds can provide enhanced permeability or storage capacity and improve the efficiency of gas production (Gale, et al., 2007). Production performance of shale gas wells is heavily influenced by the fabric of the rock (Bustin and Bustin, 2012) in which the fracture networks, heavily impacted by rock heterogeneity, play a large role. The fabric effectively controls the permeability through the fractures as well as the microporous rock matrix. Gale, et
al. (2014) point to the variability in fractures, and their growth, due to several possible mechanisms (e.g. differential compaction, local and regional stress changes, strain accommodation), as well as mechanical properties tied to the depositional, diagenetic, and structural setting. Variability in fractures and jointing within a rock fabric is also connected to structural deformation history, including potentially poly-phase deformation which effectively reorients the local stress field (Engelder, 1987).

Figure 10. Mohr Circle Diagram illustrating the effect of Pore Fluid Pressure (Pf) on stability. The applied stress Mohr Circle well within the Mohr Stability Envelope is typical for stable rock in the earth having low differential stress (small diameter). Presence of fluids, such as hydrocarbons or injected water during hydraulic fracturing, effectively shift the circle to the left by reducing all applied normal stresses by the amount equivalent to the Pf. The effective stress Mohr Circle, as illustrated is at the bounds of the stability envelope which defines the point of cohesive failure and fracturing. (Twiss and Moores, 2007)
LIDAR IN OUTCROP SCALE FRACTURE ANALYSIS

Within the last 10 years, there have been many studies using LIDAR images to study natural fractures for outcrop scale reservoir characterization. Appendix C provides a short summary of the major fracture analysis studies conducted in recent years using LIDAR images to better understand natural fractures in the surface. These studies provided better reservoir permeability models for reservoirs.
CHAPTER IV

FRACTURE ANALYSIS IN SELECTED CHATTANOOGA OUTCROPS

During this study, LIDAR images have been obtained from two Chattanooga Shale outcrops along the backlimb of the Wills Valley Anticline in the Southern Appalachian FTB in order to characterize the relationships of bedding thickness and fracture spacing in each outcrop along the outcrop belt as well as stratigraphically at each locality. The FPO is located in DeKalb County while the BRO is located to the southwest in Etowah County (Figure 9).

At the BRO the bedding within the well-jointed, brittle Chattanooga Shale strikes N44°E and dips 18° SE. One set of systematic fractures strike approximately N 70° W. A cross-joint set of fractures strike about N40°W. At the FPO the lower part of the formation strikes between N20°E and N45°E and dips between 5 - 10° SE. In the more brittle upper section, the beds strike N10°W and dip 08° SW. Some of the variability in orientation within the FPO might have resulted from localized stress, not occurring on a regional scale and probably due to the ductile deformation at the base of the formation which plays a role in frictional sliding during the compressional tectonism and causes local structural thickening (Figure 8).

STRATIGRAPHY OF THE CHATTANOOGA SHALE IN FPO AND BRO

The Wills Valley Anticline formed as a Fault Propagation Fold (Robinson, et al., 2009) (Figure 8). The natural fractures along the Wills Valley Anticline formed in response to stress mitigated by lithologic variation. The BRO and FPO of Chattanooga Shale both exhibit a well-developed
system of fractures within the upper brittle part of the section. The shale is more ductile and does not fracture well in the lower part of the section which is associated with a decollement surface.

In Central Tennessee, the United States Geological Survey recognizes distinct members of the Chattanooga Shale (Figure 11). The shale outcrops at the BRO and FPO in Northeastern Alabama contain the top of the Dowelltown Member, Frasnian-Famennian (Devonian) in age, and the Gassaway Member (Lu, 2015). The upper, more brittle part, the Gassaway Member, is better suited for LIDAR based fracture intensity studies because of its thick bedded brittle mechanical stratigraphy which gave way to formation of well-developed natural fractures.

Correlations between bed thickness and frequency of fractures can provide stratigraphically-defined relationships between bedding thickness and fracture density in the well fractured beds of the Chattanooga Shale. Compositionally, the shale is predominantly mixtures of clay and quartz (Lu, 2015) and the siliciclastic content increases upsection, with a notably distinct upper section behaving in a more brittle fashion than the more ductily deformed lower section, as seen at the FPO (Figure 1).

Lu (2015) divided the two outcrops into lithological subgroups with fissile shale at the base and blocky shale at the top (Figure 12). The BRO contains distinct jointing in the upper 20 feet of the in the formation (Pashin, et al., 2011). High resolution LIDAR images of predefined inventory

<table>
<thead>
<tr>
<th>System</th>
<th>Formal name</th>
<th>Informal name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Mississippi \n Upper Devonian</td>
<td>Maury formation</td>
<td></td>
</tr>
<tr>
<td>Gassaway member</td>
<td>Upper unit</td>
<td>Upper black shale</td>
</tr>
<tr>
<td></td>
<td>Middle unit</td>
<td>Upper gray beds</td>
</tr>
<tr>
<td></td>
<td>Lower unit</td>
<td>Middle black shale</td>
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<tr>
<td>Dowelltown member</td>
<td>Upper unit</td>
<td>Middle grey beds</td>
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<tr>
<td></td>
<td>Lower unit</td>
<td>Lower black shale</td>
</tr>
</tbody>
</table>
squares have been acquired along the outcrops at each location. Two inventory square images at both FPO and BRO provide fracture intensity data of the more brittle shale which has been identified as the upper Gassaway Member (Lu, 2015). While four inventory squares were imaged at FPO, two are from the more ductile section in the lower part of the outcrop which is the low to middle units of the Gassaway Member of the Chattanooga Shale (Lu, 2015).

Figure 13 provides the relative stratigraphy for each outcrop and also indicates the approximate Dowelltown-Gassaway boundary. The ductile shale is towards the base of the formation while the brittle, well-jointed shale is found upsection within the Gassaway member.

LIDAR imaging of outcrops provided precise data for analysis. High resolution, spatially resolved images are made with laser precision leading to 3D data which lends itself to fracture intensity analysis from each outcrop (Figure 14). During this study, LIDAR images were captured to provide 3-D perspective to quantitatively study the relationships between fracture spacing and bedding thickness. Images of one meter by one meter squares across the formation have been
Figure 13. Relative generalized stratigraphy between each outcrop. The approximate boundary between the ductile Dowelltown and the brittle Gassaway member is indicated. Studies (Lu, 2015) show that Quartz to Clay ratios, determined by X Ray Diffraction, increase significantly from an average of 1.2 within the Dowelltown to an average of 3.4 within the Gassaway.
made to ‘inventory’ the intensity of fractures at relative stratigraphic levels. For example at the BRO (Figure 14), the lower of the two inventory squares (1) along the highly deformed more ductile base appears lithologically distinct from the upper inventory square (2) as the shale appears to become more brittle, blocky, and jointed upsection. Locations of inventory squares for imaging were determined by evaluating visible changes in lithological variation including changes in relative bed thickness and brittleness of the shale beds within each outcrop.

![Figure 14. Inventory Squares marked at different stratigraphic levels above the more ductile Chattanooga Shale. High Resolution LIDAR images for each inventory square are illustrated with (1) being along the base of the highly deformed ductile shale and (2) at a stratigraphically higher level.](image-url)
At the FPO inventory squares were imaged at four stratigraphically distinct areas (Figure 15).

Two of the squares within the more deformed shale, near the basal contact with the Red Mountain Formation, were of limited utility as fractures were sparse and irregular (Figure 16). Further upsection the outcrop becomes notably brittle in nature and representative inventory squares provide measurable well-developed natural fractures. Figure 17 provides the location of the inventory squares, as well as the LIDAR images of the well jointed shale at each outcrop.

Figure 15. LIDAR images of Chattanooga Shale, FPO. From Inventory Squares across the formation. Squares (1) and (2) fall within the more ductile base and are of limited utility. Inventory Square (4) is a high resolution image of the more blocky, well jointed upper section.
Figure 16. LIDAR images of Chattanooga Shale within the highly deformed ductile section from the near the base of the formation along the contact with the Red Mountain Formation (1) and further upsection (2).
Figure 17. High Resolution LIDAR images from the brittle lithology at the BRO and the FPO.
Correlations between bed thickness and joint spacing yield indexes of fracture spacing (Fracture Spacing Index, FSI) which are representative of localized strata and offer potential insight into vertical and lateral variability. Appendix D includes data extracted from the LIDAR images and processed data used to determine the FSI. The LIDAR images, which provide 3-D spatially resolved data, facilitate point-to-point measurements of distance/separation enabling determination of bed thickness and fracture spacing. For the Chattanooga Shale in this study, FSI variation ranges from 1.09 to 1.53 and these values are essentially determined from the slope of the plots of bed thickness to joint spacing. FSI measurements within each outcrop demonstrate differences in fracture frequency suggesting lithologic variation and bedding thickness exert a strong control.

Thin section analysis from four areas across the shale from the FPO provides opportunity for insight into variability as changes in grain size and/or quartz content often correspond to changes in brittle response. Thin sections and SEM micrographs illustrate the variability (Figure 18). Transmitted light in the microscopic analysis is useful for samples from the highly deformed base of the Chattanooga Shale, proximal to the Red Mountain Formation, as well as at the top of the formation near the contact with the overlying Maury Shale (18a and 18c). However, with high concentrations of organics within the middle part of the shale section, using transmitted light in microscopic imaging was limited necessitating the use of reflective light in the petrographic work (Figure 18b) as well as wavelength dispersive backscattered SEM (18d) on polished slides. The shale at the base (18a) of the formation, having experienced intense deformation, appears to have large quartz grains that may represent alteration and growth from greater temperature and pressures experienced along decollement horizons. The shale at
near the top of the formation (18c) might best be described as sandy shale with particles commonly greater than 63 microns. Although reflective light microscopy of the black shale within the formation (18b) provides a general image of the fabric, detail such as pyrite framboid sizes and distributions (4 – 12 microns), are much more accessible by SEM (18d). Given that the pyrite framboids range in diameter from those under 5 microns to those on the order of 10 microns, suggestive of mixed oxidation levels, the organic rich shale of the Chattanooga Shale appears to have been deposited in an environment in which oxygen richness varied over time.

FORT PAYNE OUTCROP (FPO) – FRACTURE ANALYSIS

At the FPO, the Chattanooga Shale is bounded at the base by the Silurian Red Mountain Formation and above by a thin bed of Mississippian Maury Shale which is overlain by the Mississippian Fort Payne Chert. The LIDAR image at the top of Figure 15, across the FPO was made by imaging quadrants at several Scan-Positions (specific vantage points at which the LIDAR images are obtained). Where stratigraphic levels within the outcrop were notably distinct with respect to bed thickness as well as fracturing, inventory squares were marked for imaging and analysis. Four Inventory Squares (1 m²) were marked along the FPO of Chattanooga Shale. The upper two inventory squares, within the brittle Gassaway member, yielded viable data for fracture analysis. See Appendix D for Fracture Data from LIDAR images of Chattanooga Shale at BRO and FPO.
Figure 18. Polished thin sections from FPO Chattanooga Shale.
a.) Large Quartz Grains near base of the Chattanooga Shale in the FPO using a Transmitted Light Petrographic Microscope. b.) Organic Rich Shaly Fabric using Reflected Light Petrographic Microscope. c.) Sandy Shale near top of the formation using Transmitted Light. d.) SEM image of Chattanooga Shale approximately 1 meter above the Red Mountain Sandstone with notable pyrite frambooids.
Measurements of bed thickness and fracture separation, often seen as systematically spaced jointing within the rock, were made manually on the Inventory Square images. With the use of a workstation, the colored image and point cloud of spatially resolved data from LIDAR imaging, facilitated the measurement of bed thickness and fracture separation. Plots of thickness relative to spacing were generated from measurements within the LIDAR image by evaluating the distance between selected points. Bed thickness measurements are tabulated and within a given bed the spacing between fractures is cumulated and averaged. Fracture Density (or Intensity) is similarly calculated by assessing the number of fractures per given length. Plots of Fracture Density, in fractures per centimeter, relative to bed thickness are generated. Figure 19 presents plots of thickness relative to spacing and the density relationships to bed thickness from data extracted from Inventory Square #4. In the plot of spacing to thickness the R² value at 0.73 suggests deviation from the expected linear correlation. For a given homogeneous lithology, spacing is expected to be uniform with a uniform application of stress. Deviations from linearity, as mentioned earlier, are worth noting as they suggest the system is more complex, e.g., fractured beds might exhibit more than one fracture. Similarly the curve-fit of fracture density relationship to thickness is not ideal with an R² of 0.77.

Figure 20 illustrates similar data extracted from Inventory Square #3. The R² values from the graphs are reasonable, but a larger set of data might provide a more holistic picture of the shale at this stratigraphic level. A FSI of 1.473 is seen at FPO within Inventory Square #3. A FSI of 1.086 is recorded at FPO within Inventory Square #4, though the measure of linearity, R², is 0.73.
Figure 19. (a) Plots of Spacing to Bed Thickness and (b) Density to Bed Thickness. FPO Inventory Square #4. The slope provides a Fracture Spacing Index of 1.086.
BIG RIDGE OUTCROP – FRACTURE ANALYSIS

At the BRO (Figure 14) two Inventory Squares were imaged in the more brittle lithology (the Gassaway member) above the ductile shear zone. Plots of Fracture Spacing to Bed Thickness exhibit linear relationships with high $R^2$ values, (Figure 21). Of note between the two inventory squares, however, is the change in the value of the slope of the lineations. Slope in plots of spacing to bed thickness essentially represents and index for fractures where facies changes are occurring. The upper Inventory Square has a distinctly higher slope suggestive of a lithologic change considering both data sets are consistently linear in nature. The higher slope corresponds to a greater spacing

Figure 20. Plots of Spacing to Bed Thickness and Density to Bed Thickness. FPO Inventory Square #3. The slope provides a Fracture Spacing Index of 1.473.

Figure 21. Plots of Fracture Spacing to Bed Thickness. BRO Inventory Squares #1 and #2. FSI value of 1.17 and 1.53, respectively.
between fractures for a given bed thickness. Lu (2015) records an increase in oxicity in tandem
with quartz influx as deposition continued throughout the Late Devonian, the change within the
depositional environment leading to more quartz rich beds of Chattanooga Shale correlates
with the observed brittle tendency and fracture response.

LIDAR APPLICATION RANGE LIMITS

With respect to LIDAR application, a ranging study was done to evaluate what data collection
parameters were viable to resolve bedding and fractures on the order of centimeters. The use
of LIDAR to evaluate features on the order of centimeters necessitated establishing actualistic
boundaries. The RIEGL VZ-400 has a defined step width of 7 cm at 100 meters distance with a
setting of 0.04° angular resolution (RIEGL, 2015), meaning that a measured surface point has a
nearest neighbor at that distance. In practicality, for mapping and measuring surfaces of shale
for bed thickness and joint spacing the point-to-point separation must be at least an order of
magnitude lower than the distances being measured. Application of the RIEGL VZ-400
Terrestrial Laser System for imaging Chattanooga Shale beds on the order of centimeters,
required that angular resolution relationships be taken into consideration.

Images of a well-jointed face were done with incrementally increased step-widths (Figure 22),
and fixed distance from the outcrop. Figure 22a is an image made at 0.06° resolution. Note the
meter stick scale bar along the wall at the bottom left. The image is greatly enhanced at 0.01°
resolution and the window for visual evaluation is improved. In terms of analysis this means
that one can pan in on the image up to the point of degraded visual quality. Two aspects of
collecting highly resolved images are important in planning the LIDAR survey. The areal extent
of the surface being imaged and the desired resolution are intrinsically tied together. Colorized LIDAR images are created upon the conclusion of the scan as photographs from the attached camera are used to colorize the laser scanned data. The photorealistic LIDAR images which provide access to point-to-point distance measurements used for fracture spacing evaluation impact the manual collection of spatially relevant data from outcrop features. The image in Figure 22c was made at 0.007° step-width resolution. Note that as the resolution changes, although the visual details of the outcrop are improved, the window of visualization decreases.

The ability to measure smaller separation distances is improved at the cost of area being imaged, with constraints on data management, time for data acquisition, as well as the demand for advanced photographic means. The rich details which are provided within the point cloud of data from close-proximity LIDAR scanning of fractured surfaces comes at the expense of system data management as the amount of data the LIDAR system can actively buffer limits the scope of the project. The system will stop scanning the surface if a large amount of data from close-up imaging exceeds the data management capacity for the device. Field results of LIDAR imaging suggest that attempting to acquire a highly resolved image (centimeter resolution) across a broad surface (> 3 m²) will result in cessation of the laser scanning during data collection.

Acquisition time is of concern if large surface areas are being imaged. A 1 m² inventory square of a surface imaged at centimeter resolution takes approximately one hour once the system has been set up, with larger surfaces more significant time demands will result. Consideration of the photographic equipment used to colorize the LIDAR scans is necessary when taking close up images as the colorization requires the digital photographs taken by the camera during the project scanning to be of substantially high resolution (centimeters). Successful project
planning for LIDAR surveying of close-up surfaces involves consideration of these aspects as the area to be studied is intrinsically tied to image resolution.

If very fine, detailed resolution is desired, the window for imaging needs to be correspondingly decreased to mitigate workstation processor demands as well as optical limitation from the attached camera which colorizes the LIDAR images. The present study involved step widths ranging from 0.003 – 0.005° resolution, approaching the lower limit of the instrument, with area scan windows set to best represent the inventory squares and a minimal area of adjacent rock.

Figure 22. Images of FPO Chattanooga Shale made at fixed distance with variable step-width for resolution evaluation. a.) larger window - low resolution image (0.06°), b.) moderate window – moderate resolution (0.01°), c.) small window – higher resolution (0.007°).
CHAPTER V

CONCLUSION

This study has shown that LIDAR imaging of outcrops can be effectively applied towards determining the positive correlation between fracture spacing and fracture intensity variation with bedding thickness in brittle shale units. LIDAR images obtained from two Chattanooga Shale outcrops along the backlimb of the Wills Valley Anticline were evaluated for fracture intensity variations within the brittle shale lithology. The two outcrops (Figure 9) were named BRO (Big Ridge Outcrop) and FPO (Fort Payne Outcrop). At the BRO, a linear correlation between bed thickness and fracture spacing was clearly established based on the statistical analysis of high resolution LIDAR image data. The Fracture Spacing Index (FSI) notably varied stratigraphically within the outcrop. The lower inventory square (Figure 17) yielded a FSI value of 1.17. With increasing quartz content and bedding thickness upsection the FSI increased to 1.53 within the upper part of the formation (the Gassaway member). The Fracture Spacing Index (FSI), a function of fracture intensity, is determined by measuring the slope of the Bed Thickness-Fracture Spacing plot (Figure 21). Variation from 1.17 to 1.53 suggests that the shale fracturing is not homogeneous within the Chattanooga. A first order observation would indicate that mechanically distinct stratigraphic intervals exist within the BRO, which is not surprising as the lithology, especially the quartz content (Figure 23), has been shown to vary upsection (Lu, 2015).
Plots of Thickness to Spacing for the BRO and FPO have been constructed. The Plots of Thickness to Spacing for BRO were consistently linear with high $R^2$ values (> 0.98). Plots of Thickness to Spacing for FPO were of limited linearity for measurements made within the brittle lithology inventory squares in Fort Payne Outcrop with the stratigraphically higher (Gassaway Member) inventory square section having an $R^2$ of 0.77 and the stratigraphically lower inventory square (the Dowelltown member) section having a slightly better value at an $R^2$ of 0.917.

Two aspects of this data can be addressed. The first is the limited utility of the FSI when the plots are not linear and the second is the utility of LIDAR digitized data. Minimally, the limited FSI suggests that within the outcrop at different stratigraphic levels and between the outcrops along the backlimb there exists dissimilarity in fracture response to stress. Correlating stratigraphic levels across the backlimb would be difficult to impossible given the tectonic thickening (Coleman, et al., 1988) which may be present in the atypically thick outcrops of Chattanooga Shale.

Noting the low $R^2$ in the plot of Bed Thickness to Fracture spacing in Figure 24a, even more evident in the plot of Fracture Density to Bed Thickness (24b), suggests that outliers exist within the expected correlation. If the data point at 7 cm bed thickness with a fracture density of 0.2 $F/cm.$ were removed from the data an improved $R^2$ of 0.9296 results (24c). The goal is not to
dismiss outliers from statistical analysis but to consider that re-evaluation of the digital data might provide evidence that the outlier does not belong in the fracture set (i.e., a second fracture set or non-natural fractures might exist). The data from the fracture spacing/density analysis from LIDAR images suggests that fracture density variation exists both within each outcrop at varying stratigraphic levels and along the backlimb. Given the proximity of the inventory squares within each formation, the variation in fracture intensity is derivative of lithologic variation.

Figure 24. Inventory Square #4, FPO Chattanooga Shale outcrop. a.) low $R^2$ value (0.7304) evidences non-linearity, b.) Outliers are notable in curve, c.) Improvement in linearity, $R^2$ of 0.9296.
CONCLUDING REMARKS

Literature reviews of the current state of LIDAR imaging together with the images obtained during this study suggest that carefully planned survey programs will deliver optimal results. Highly accurate, highly resolved images of surfaces can be made with the laser scanner, but as the data volume grows workstation processing demands can easily become unmanageable. Software developments in academic and industrial groups with focus on application to geosciences are facilitating point cloud data processing, image interpretation, and incorporation into models (Rarity, et al., 2014). Workflow in outcrop selection, choice in scanning locations, and choice of resolution specific to the representative feature(s) still remains the key element in LIDAR surveys. User-oversight in data processing and interpretation is essential to incorporation of the spatially resolved data into 3D models.

During this study, the opportunity to collect high resolution digital images of inventory squares at outcrops of Chattanooga Shale along the backlimb of the Wills Valley Anticline served to prove the concept of application of LIDAR imaging for determining fracture density relationships. In shale units, provenance studies would be of interest to potentially tie stratigraphic variation and lithologic variation associated with changes in brittleness. The development of a cellular model from the laser scanned images would improve the accuracy of models with more realistic representation of fracturing as well as an improvement on fluid flow parameters. With the LIDAR imaging one can expect to collect highly accurate, representative attributes, such as fracture spacing or intensity that are useful for incorporation into reservoir models for estimating the flow of fluids during the production.
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APPENDIX A

RIEGL LASER MEASUREMENT SYSTEMS

RIEGL Laser Measurement Systems GmbH, headquartered in Austria, is recognized locally as RIEGL USA an industrial leader in performance of their 3D Laser Scanners offering variety in Terrestrial LIDAR Systems. The LIDAR system used in this work is the VZ-400 with a functional range roughly between 2 to 500 meters and accuracy with respect to laser imaging of roughly

<table>
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<th>VZ-4000</th>
<th>VZ-2000</th>
<th>VZ-1000</th>
<th>VZ-400</th>
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<td>Long range, very high speed</td>
<td>Long range, accurate, extra high speed</td>
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<td>0.002°</td>
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<tr>
<td>Horizontal Angular Stepwidth</td>
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<td>0.002°</td>
<td>0.0024°</td>
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Differences in LIDAR laser scanners. Data from currently available systems from RIEGL. (RIEGL, 2015)
0.5 cm. Images acquired from this system, for this study, were typically done between 5 to 15 meters from the outcrop surface. LIDAR imaging systems operate on a speed of light, typically an infrared laser, in combination with travel time from the fixed LIDAR system to a remote surface and back allowing for distance determination. As the laser scans, both vertically and horizontally across a surface, 3-D spatialization is realized. The resolution of the 3-Dimensional spatial relationships is derived from the step-widths both horizontally and vertically as the laser steps across the surface, and is subject to user-control with a limit of 0.0024° for the VZ-400. The high resolution images can be further enhanced with corresponding camera images imparting essentially true color to the spatial data-set.

The Principles of Operation illustration maps out the essential elements of a typical terrestrial LIDAR imaging system as produced by RIEGL. The cylindrical operating unit has local control through a keypad (element 4) although a field laptop (element 10) equipped with the LIDAR system facilitates many aspects of data collection. The key operational components are the optical head (element 3) allowing 360° horizontal scanning, the mirror (element 2) which provides for vertical scanning, and the image calibrated camera (element 9) for high resolution coloration of the laser generated spatially resolved images.
Principle of Operation Detail. Elements of a typical terrestrial laser scanner are outlined. The pictured model is of the RIEGL VZ-400 high accuracy LIDAR scanner.

This illustration is used with permission from RIEGL Laser Measurement Systems. (RIEGL, 2015)
The laser scanning units are portable facilitating field use and imaging spatially complex features from multiple perspectives. Multiple scan-positions can be used to image complex geologic outcrop features which can be combined into a 3-D view within RIEGL’s proprietary RiSCAN PRO software. Within the software the data rich point-cloud can be used to measure point to point distances or derivatives e.g. area, perimeter. Some current technological limitations are from issues resulting from demands on computer processing abilities. Large data-sets from high resolution images lead to heavy demands on power, memory, and processing ability.
APPENDIX B

LIDAR IMAGING OF OUTCROPS – WORKFLOW

Preparation for use of the LIDAR imaging system involves placement of the system, including the mounted camera, laptop, and power source, at an appropriate distance and orientation to the outcrop and identification of other scan-positions to ensure full coverage of surface being imaged. Placement of reflector targets is done for internal control (tie points) for registration from multiple scan-positions.

Primary Scan – Steps in Data Acquisition

(1) Create New Project within RiSCAN Pro.
(2) Camera Setup and Configuration.
(3) Set Reflector Type
(4) Establish New Scan Position, Establish New Single Scan.
(5) Setup Panorama view for 360° imaging, set desired resolution via adjustment of step widths along both the horizontal and vertical.
(6) Initiate LIDAR Scanning along with Image Acquisition.
(7) Identify and Mark reflective tie points.
(8) Finescan tie points.
(9) Registration/Find Corresponding Points.
(10) Additional High Resolution Area of Interest Scan from same Scan Position is done by establishing a New Single Scan within a defined window adjusting step widths accordingly.

Use of additional Scan Positions involves repeating steps 4 – 9.
APPENDIX C

LIDAR BASED FRACTURE STUDIES

LIDAR is being used more frequently in outcrop studies because high-resolution surface representations can be used for geological constraints in reservoir modelling (Rarity, et al., 2014; Ahlgren and Holmlund, 2003; Buckley, et al., 2010; Hodgetts, 2013; Bellian, et al., 2005; Monsen, et al., 2006; Ahmadzamri, et al., 2014). Digital outcrop models, or virtual outcrops, developed from laser scanned images provide volumes of spatially resolved data which reduce model uncertainty and improve the reservoir characterization (Adams, et al., 2009; Ahmadzamri, et al., 2014; Minisini, et al., 2014) especially following a guided workflow (Enge, et al., 2008). The workflow typically consist of outcrop selection, data collection, and geological interpretation. Followed by the eventual construction and testing of a data-constrained geocellular model (Enge, et al., 2007). In the model, variability in reservoir zones can be accounted for by smaller area ‘cells’ representing significant differences within the rock. LIDAR imaging of outcrops provides many benefits, including surface area coverage which cannot be fully acquired by manual techniques (Monsen, et al., 2006). Moreover, digitized data can impart realistic geological heterogeneity into reservoir characterization models (Monsen, et al., 2011, Olariu, et al., 2008; Kurtzman, et al., 2009) and provide higher resolution of fracture details below than can be provided by conventional seismic techniques (Wilson, et al, 2011). In addition, acquisition of digital outcrop data allows automation in data processing and analysis (Assali, et al., 2014; Monsen, et al., 2006; Seers and Hodgetts, 2014; Monsen, et al., 2011).
Several studies have applied LIDAR in tandem with modelling techniques to characterize fractures: They focused on determining the relationship between a) orientation and spacing of fractures b) stratigraphy and lithologic variability in layers; and c) fold curvature and natural fractures (Pearce, et al., 2011; Olariu, et al., 2008; Zahm, et al., 2010; Wilson, et al., 2011). Each of these studies contribute insight into the application of the LIDAR surveys in fracture studies and reservoir models.

In recent years, there have been many studies using LIDAR images to study natural fractures for outcrops scale reservoir characterization. Olariu, Zahm, and Wilson have done fracture evaluation studies using LIDAR, over the past decade, providing much of the impetus for this body of research. Olariu, et al., 2008, characterized deep-water Pennsylvanian Jackfork sandstones by terrestrial laser scanned images of outcrops within the Big Rock Quarry, Arkansas. They focused on the application of an algorithm to extract surface orientations from point cloud data. The applied algorithm functions by pattern recognition done through successive analysis of clusters. They found that fracture planes from thicker beds with larger fracture spacing were easier to identify with larger numbers of data-points defining the surface, notably emphasizing that orientation was more difficult to recognize with thinner beds. Zahm, et al., 2010, evaluated fracture distributions resulting from stratigraphic architecture, and degree of faulting, within carbonate damage zone in the Balcones Fault Zone in central Texas by LIDAR survey. They determined that deformation was more intense in facies rich in mud, with thinner beds, which leads to reduction in rock strength. The LIDAR survey allowed Zahm, et al. (2010) to make surface measurements of strike and dip for faults, shear fractures, and joints within the outcrop. Fracture intensity was measured using a 0.5m x 0.5m grid
overlying the outcrop photo model. They determined fracture intensity within the grid by the

total trace length of fractures within the grid relative to the grid area. Grids in non-faulted
sections yielded deformation intensities roughly between 1 to 2 m/m². In grids within faulted
sections the distribution fell between 1 to 3 m/m². The thicker bedded, grain dominated, more
competent facies tended to have less deformation as measured by deformation intensity

squares.

Wilson, et al., 2011, used LIDAR surveying images of Austin Chalk fracture networks to extract
spatial relationships enabling the construction of discrete fracture network (DFN) models.
Manual and semi-automated methods were applied to frequencies and orientations of
fractures sets with variable results. The fracture data, derived from LIDAR images, was used to
construct a DFN model allowing flow simulations.
APPENDIX D

FRACTURE DATA FROM LIDAR IMAGES AT CHATTANOOGA SHALE OUTCROPS

Bed Thickness and Fracture Spacing measurements in pre-marked Inventory Squares have been made within the RiSCAN Pro software as the imaged surface is a point cloud constituted with positional information. Picking two points within the image enabled the determination of distance or separation. Measurements of Bed Thickness and Fracture Spacing within the given bed were made and recorded.

In general Bed Thickness varied within the Inventory Squares (#3 and #4) of Chattanooga Shale found in Fort Payne from roughly 1 to 10 centimeters though most commonly around 2 centimeters. The average thickness was 4.2 centimeters. The Bed Thickness varied within Inventory Squares (#1 and #2) of Chattanooga Shale found along the Big Ridge road cut from roughly 2 to 14 centimeters though most commonly around 7 centimeters. The average thickness was 5.5 centimeters. The following tables were derived from data collected from images made at each outcrop.

Fracture Spacing Index values range from 1.09 to 1.53 and are determined by determining the linear equation fitting plots of bed thickness to fracture spacing and solving for the slope. These values were determined for each inventory square and are descriptive at the respective stratigraphic intervals.
### FPO Inventory Square #3

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<th>Bed #</th>
<th>Thickness (m.)</th>
<th>Fracture Spacing (m.)</th>
<th>Fracture Spacing (m.)</th>
<th>Fracture Spacing (m.)</th>
<th>Fracture Spacing (m.)</th>
<th>Fracture Spacing (m.)</th>
<th>Fracture Spacing (m.)</th>
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<th>Fracture Spacing (m.)</th>
<th>Fracture Spacing (m.)</th>
<th>Fracture Spacing (m.)</th>
<th>Fracture Spacing (m.)</th>
<th>Density Fractures per cm.</th>
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Inventories of Fractures within the Chattanooga Shale in Fort Payne, Alabama.
Inventories of Fractures within the Chattanooga Shale along the Big Ridge Road Cut (I-59), Alabama.

<table>
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<th>Bed #</th>
<th>Thickness (m)</th>
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<th>Density Fractures per cm</th>
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