Proposal: Creating a 4D model of Fracture and Fault Development within the Arbuckle Mountains

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Abstract

Fractures, faults, and fault zones are ubiquitous features in regions of folded and uplifted rocks. Their occurrence is relevant to hydrocarbon reservoir and water aquifer studies, as well as seismic hazard analysis. The Arbuckle Mountains, in south-central Oklahoma, provides an excellent natural laboratory to study the spatial and temporal evolution of fractures and faults over a varying range of scales from kilometers to micrometers. The proposed research has three objectives: 1) construct a digital fault and fracture map based on aerial imagery (Google Earth) and field geology that will enable detailed field studies to evaluate the distribution, density, and style of these features along the southern flank of the Arbuckle anticline, a major geologic feature in the southern mid-continent; 2) integrate these data sets into a geo-referenced ARCGIS database that may then be visualized using 3D ARCSCENE software; and 3) use this data set to test the following hypotheses: i) Fracture sets within the Arbuckle mountains predate the folding and faulting associated with the main phase of orogenesis in the region (e.g., the Ouachita Orogeny); ii) fracture characteristics are a function of rock type and may be correlated by rock type across the anticline; and, iii) tectonics associated with the Ouachita orogeny reactivated the preexisting fractures as a function of proximity to regional faults.

Faults and naturally occurring fractures play a fundamental role in increasing permeability whether it be in a hydrocarbon reservoir or in an aquifer. The morphology and density of these structures controls how effectively fluids can move through the subsurface and the rate at which they can be extracted or injected. Hydraulic fracturing, or “fracking” in the modern vernacular, is a technique used to extract hydrocarbons by
injecting over-pressured fluids into the subsurface thus enabling existing or new fractures to form, allowing the release and migration of hydrocarbons into a well bore. Such a process is also used to re-inject waste water into the subsurface. Critical data that can help in evaluating the nature of permeability pathways in the subsurface include detailed analysis of the spatial distribution and characteristics of fractures as observed in natural outcrops. The Arbuckle Mountains, south-central OK provide an excellent natural lab to evaluate the 4D evolution of fault and fracture networks.
Introduction

Associations between large-scale, geographical folds and fracture network distributions within them have not been completely modernized based on recent discoveries of correlations between fracture systems and folds. Fractures are ambiguous features within regional folds yet still the correlation between a fold and a fracture’s intensity or orientation has yet to be fully developed. This study will break down the individual controls in regards to this relationship and begin to decipher the most prominent constraints on the fractures found within the large, comprehensive folds.

Five major controls will be separated within this investigation and analytically correlated using a wide range of data sets. The five major controls on fracture networks within regional folds are: 1) the geographical geometry of the fold 2) the brittleness/hardness rock mechanics of the formations that construct the fold 3) the bedding thickness of the formations that construct the fold 4) the location of faults within the regional fold along with an understanding of their kinematics 5) the pre-existing stress field and pre-exist structures within the research area.

Control 1: The geometry of a large, regional fold can greatly impact the fracture network distribution throughout it. In terms of orientation, connections have been made which show an angular relationship between the alignment of the axial plane of the fold, and the position of the mode 1 and mode 2 fracture sets. (Figure 1) The correlation presents that mode 1 fracture sets, a contractional fracture, will be oriented perpendicular to the axial plane of the fold with an opening direction parallel to the axial plane. Mode 2 fracture
sets, an extensional fracture, will have an attitude parallel to the axial plane with an opening direction perpendicular to the axial plane. Most fold and fracture models do not encompass further fracture sets beyond mode 2 even though it is possible for other fracture sets to exist. Other fracture network orientations could also be found within the regional folds but are not a feature of the fold, and are formed from another existing controls. With regard to fracture density, models depicting the distributions of fracture densities have been constructed. (Figure 2) These models predict the most dense fracture networks to be found within the core of the fold, and fracture densities dissipating into the limbs of the folds. Other models show fracture densities, considerably larger, on the overturned side of a fold compared to the non-overturned side. (Watkins, 2015) A range of contractional, extensional, and transverse forces can construct a wide variety of fold geometries, therefore, the structural domain of the area must be understood before attempting to predict fracture distributions based solely off of fold geometries.
**Fig 1 Model showing Mode 1 Fractures**
perpendicular to the fold axial plane
with Mode 2 fracture parallel to the
axial plane. (Reference)

**Fig 2 Model showing fracture densities**
greatest with the core of the fold and
dissipating outward.

*Control 2:* The brittleness and hardness of the rock within formations that construct the large-scale, geographical fold can impact the supply of fracture networks throughout the structure. (James, et al, 2017) Concerning orientation, links have not yet been discovered that model fracture orientations changing as they cross from one formation with one hardness into another formation with a different hardness. Theoretically, fracture orientations could change and refract as the fracture propagates into a new medium of rock hardness, but this has not been evaluated within a geological study. With regards to
intensity/density of fracture set, strong correlations have been made between rocks hardness and the intensity of fractures within the rock. The correlation is simple; rocks hardness is directly proportional to the fracture density within the rock. For example, a piece of Plato is much hard, in not impossible, to crack than apiece of glass. Studies show that this relationship is due to the volume of clays within a rock. The higher the volume of clay, the more ductile or less brittle, the rock will be. This relationship is a function of the rocks lithology. For example, a clay mineral such as smectite can increase the rocks flexibility and consequently, the rock does not easily fracture. Therefore, rocks cannot be evaluated on their fracture density if the lithology of the rock is unknown. Fracture densities can change due to the mineral crystal structures, grain distribution, and secondary digenetic features within the rock.

Control 3: Bedding thickness of a formation can have an impact on the distribution of fracture networks. In terms of orientation, similar to brittleness, relationships have not been developed that show a strong correlation between bedding thickness and fracture orientations. Correlations have not shown that a fracture will propagate in different directions as it travels in a rock with a different bed thickness. Changes in bedding are defined as a change in lithology. Once again, theoretically, fractures could refract as they propagate through different bed thickness mediums, although geological studies have not developed this phenomena. As to fracture densities, correlations have been made that show fracture densities changing as they cross bedding thickness mediums. (Spence, 2014) The relationship has been described as an inverse relationship. As the bedding thickness decreases, the fracture density increases. Therefore, theoretically, thinner
bedding would be denser with fractures compared to thicker beds of similar lithology. Bedding thickness depicts a relative energy regime where the formation was deposited. Thinner beds depict a depositional environment with rapid energy changes, where as thick deposits correlated to a steady depositional environment in terms of energy.

Control 4: The proximity of fault within fracture networks can change the distribution of the fracture networks. In terms of orientation, fracture can be propagated from faults although the orientations are very diverse due to the many varieties of faults. Also, it can be difficult to distinguish if the folding causes a fracture set or faulting because in many cases the two are orientated the same. In terms of fracture intensity and density, correlations have been made which link the two. (Caetano, 2014) Relationships show that the fault’s size in terms of displacement is directly correlated to the intensity of fractures near the fault zone. Therefore, in very large fault zones, fracture densities can increase dramatically as they venture towards the faults zone, where smaller faults could only change the fracture density slightly. Other models have been constructed that show fracture densities changing from the footwall to the hanging wall. (Hamahashi, 2013) The model shows an increase of fracture on the hanging wall side of the fault compared to the footwall side. These models greatly depend on the type of fault being analyzed. As a result, the kinematics of the fault must first be distinguished before fracture predictions can be made.

Control 5: Pre-existing stress fields and structures can play a major role in fracture distributions within regional folds. Studies show that before fold and thrust begin, as the
foreland begins to arc, a fracture network can develop and then be folded afterwards. This fracture network would greatly depend on the pre-existing fracture network and other existing structures before folding occurred.

While analyzing fracture networks in the field, topography and vegetation must be considered because they can drastically impact the exposure of the fractures within the research area. Weathering can be more prominent in high topological areas where fracture sets can seam to pop out to the eye more, and be easier to see, although this does not mean the fractures are not as prominent in less exposed areas, they are simply harder to see. This relationship is the same with regards to vegetation, and areas with concentrated vegetation can make it difficult to see the fault sets. Vegetation can be correlated to lithology types, which was previously depicted as a large control on fracture sets. Also, fractures caused by un-roofing processes must be analyzed in the field. As a formation is uplifted to the surface, a large amount of lithostatic load is released from the rock causing it to fracture. Therefore, formation studies at the surface may have more fractures within them compared to the same formation in the sub-surface.

**Research Objectives**

1) Analyze fracture orientations and densities within the Arbuckle Mountains.
2) Fully develop the trend and plunge of the axial plane in the Arbuckle Anticline.
3) Analyze rock hardness as it changes across the anticline and how that correlates to the rock’s lithology.
4) Measure bed thickness changes across the anticline.

5) Analyze faults within the Arbuckle anticline in terms of kinematics and how fracture network interact near and away from the fault zone.

6) Use field observations to describe the pre-exist structure domain before folding.

7) Take data sets from the 5 controls of fractures within folds of anticlines and correlate the data to the fracture orientation and density data using ARCGIS.

Case Study: Arbuckle Mountains, Oklahoma

The Arbuckle Mountains are an ideal field laboratory to study fracture networks within regional folds. The Arbuckle Mountains are located in southern Oklahoma, 20 miles north of Ardmore, Oklahoma. (Figure 3) These mountains exhibit multiple outcrops featuring fracture systems. Within the Arbuckle Mountains lies a large-scale regional fold named the Arbuckle Anticline. The anticline’s axial plane plunges to the southeast while the northeast limb is overturned. Outcrops that transect along interstate I-35 exhibit formations within the core and both limbs of the anticline. These outcrops allow the viewer to see examples of each of the 5 controls on fracture network distributions within regional folds. These outcrop examples can then be used to correlate large-scale, regional structures.
Geologic Setting of the Southern Oklahoma

Formations exposed within the Arbuckle Mountains are Cambrian-Devonian in age. (Figure 4) The thickest carbonate build-ups within the Arbuckles occurred within the Ordovician. The Ordovician period lies within a greenhouse cycle along with relative sea level rise. During the lower and middle Paleozoic, the Arbuckle Mountains lay within a stable platform along the southern margin of Luarentia. The paleoclimate was warm and humid and carbonates existed in the shallow marine realm. Sea level was on a relative slow rise and was transitioning from calcite seas to aragonite seas. This stable platform is the site of thick Cambrian through Mississippian shallow marine deposits (Fritz, et al., 2012). These Sedimentary formations deposited include the Upper Cambrian Timbered Hills Group, Upper Cambrian through Early Ordovician carbonates of the Arbuckle
Group, and Middle Ordovician through Mississippian mixed siliciclastic and carbonate rocks including the Simpson and Hunton Groups and the Woodford Shale (Ham 1973).

**Regional Tectonics of Southern Oklahoma**

Shortly after deposition within the Arbuckle Mountains, major tectonic events uplifted the area creating regional scale folding and faulting. This deformation correlates to the Marathon-Ouachita orogeny that occurred around 200 Ma. (Thomas 1991, Thomas 2006) This deformation has drastically folded and faulted the strata within and area and any depositional analysis of the area must recalibrate for the major tilting of the previous horizontal bedding. Southern Oklahoma is composed of 3 different uplifts all related to the Marathon Ouachita which are made up of the Wichita Mountains, Ouachita Mountains, and the Arbuckle Mountains (Ham 1973). All three uplifts have a strongly different geologic emphasis even though they are geographically close and all related to the same mountain building event (Ham 1973).

**Geology of the Arbuckle Anticline**

The Arbuckle Anticline gently plunges to the SE and the NE Limb is overturned. The axial plane is oriented approximately 127 degrees and plunges slightly to the SE. Both limbs strike SE and dip to SW at around 40-50 degrees. The core of the anticline consists of several smaller scale folds with the same structural domain as the large-scale, regional fold. Fractures are found within the anticline in form of two modes. Mode 1 is perpendicular to the axial plane and mode 2 is parallel to the axial plane. Faults related to
the previous Southern Oklahoma Aulacogen are within the core and limbs of the fold.
The fold is well exposed within its core and within its limbs.

**Fig 4. Regional Map of the Cambrian through Ordovician Great Carbonate Bank**

**Arbuckle Anticline Core Facies**

The core of the anticline exposes thick deposits of Cambrian-Ordovician aged carbonates. These carbonates are a part of the Great Carbonate Platform and consist of the Timbered
Hills Group and the Arbuckle Group, Simpson Group, Viola Limestone, Sylvan Shale, and the Hunton Group.

Timbered Hills Group

The Timbered Hills Group is at the bottom of the section and immediately follows the great unconformity (~500Ma) where large felsic granite bodies were eroded into quartz rich sandstones. (Gilbert and McConnell, 1991) These sandstones, known as the Reagan Sandstones, are equivalent to Hickory Sandstones found within the Llano Uplift. This unconformity documents 500 Ma of missing time. Overlying the Reagan Sandstones is the Honey Creek Formation, described as a thin, trilobite rich limestone, which grades into a sequence of sandy dolomites. The Timbered Hills Group is Cambrian in age. The Timbered Hills Group is approximately 584 feet thick. The Honey Creek Limestone is a 124 feet carbonate within the Timbered Hills Group. Its depositional environment is described as a shallow marine, reef environment along a stable margin where trilobites were abundant (Fortey, 2004). It is the first small carbonate growth within the very late Cambrian and marks the start of the great carbonate growth period throughout the Ordovician.

The Arbuckle Group

The Arbuckle Group Overlies the Timbered Hills Group in a gradational manner. Arbuckle group is mostly fossiliferous, shallow marine limestones. The Arbuckle group consists of mostly interbedded mudstones, intraclast, oolitic sands, stromatolites, and
laminated dolostones. Most of the carbonates within the Arbuckle Group have been
dolomitized. The Arbuckle group is 6,700 feet thick making it one of the great carbonate
sequences of the world. The Arbuckle group is regionally known as the Ellenberger
Formation where it outcrops in the Llano Uplift and is found in the sub-surface within the
Permian Basin (Fritz 2012). Most of the outcrops seen in the Arbuckle Mountains are that
of the Arbuckle Group. The Arbuckle group is early Ordovician in age. (Ham 1973)
Depositional environments of the Arbuckle group consist of sub, intra, and supra tidal
sequences. Subtidal sequences are very thin within the Arbuckle group and tend to crop
out within the Arbuckle Mountains. The intra and supratidal sequences are thicker and
document sea level drop and low stands. These cycles form parasequences showing sea
level drop. Rock types found within the subtidal facies consist of hummocky bedding,
silicified oolites and carbonate sands, fine laminations, storm layers, and burrowed layers.
The supratidal facies are relatively very thin created by times of rapid sea level drop,
making sub and intra tidal sequences more dominate. Sub tidal facies consist of
hummocky cross stratifications, burrows and shoaling sands. Intra tidal Facies within the
Arbuckle group consist of millimeter scale laminations and birds eye stromatilites.
Bioclastic material and tidal channels are also found within the intertidal facies. The
intratidal facies are relatively thin and grade quickly into supratidal facies. Supratidal
facies consist of desiccations, laminated anhydrite, and anhydrite nodules. (Ham 1973)

**Simpsons Group**

The Simpsons group represents a large change in depositional environment from that of
the Arbuckle Group. The Simpsons group consists of the first thick deposits of quartz
rich sandstones along with greenish gray shale, skeletal carbonates, and algal mats. Crinoids and bryozoans are common within the Simpson Group. Large ranges of diverse brachiopods are also common within the Simpson group along with mollusks, sponges, and trilobites. The Simpsons Group is approximately 2,300 feet thick. (Ham 1973)

Viola Limestone

Above the Simpsons group is the Viola Limestone. The Viola Limestone is approximately 900 feet thick within the Arbuckle Mountains. The Viola group is separated in a low, middle, and upper group. The lower group consists of silica rich carbonates, the middle unit consists of skeletal mudstones, and the upper unit consists of carbonate sands. These carbonate types show a sea level rise and an increase in energy. The base and top of the Viola Limestone are unconformities. The Viola Limestone is middle Trenton in age. (Ham 1973)

Sylvan Shale

The Sylvan Shale is a greenish-gray, finely laminated shale which overlays the Viola Limestone. The Sylvan Shale is late Ordovician in age, is approximately 325 feet thick. The Sylvan Shale is rich in chitinozoans fossils. Deep-water sediment. The Formation extends all the way from Texas to Iowa and is equivalent to the Maquoketa Shale. (Ham 1973)

Hunton Group

Youngest rocks of the early Paleozoic sequence in southern Oklahoma are those of the Hunton Group. The Hunton Group is late Ordovician, Silurian, and Devonian in age. The Hunton Group is approximately 350
feet thick. At the top of the Hunton Group are several unconformities. (Fay, 1989, Al-Shaieb and Puckette, 2000) The base of the Hunton Group is composed of oolitic carbonates and grades upwards into skeletal carbonate sands. The Hunton group is thinly bedded due to rapid regional subsidence. The Hunton Group is a large petroleum source rock throughout Oklahoma. (Ham 1973)

**Arbuckle Anticline Limb Facies**

The limbs of the Arbuckle anticline consist of thinly bedded shale, Mississippian in age. The end of the Devonian marked the end of the dominance of carbonate rocks. Mostly clastics were deposited in Southern Oklahoma after the Devonian. The main division can be describes as a transition from shallow marine carbonates to deep marine carbonates. This abrupt change is tectonically driven. Due to the start of major uplifts, the carbonate sedimentation period of southern Oklahoma was closed and blanketeted by dark shales. The most dominant formations of this time were the Woodford Shale, Sycamore Formation, Caney Formation, and the Springer formation.

*Woodford Shale*

The Woodford Shale was the first formation to be deposited on top of the Hunton Group. The Woodford Shale is 400 feet thick and consists of dark, fissile shale, chert, siliceous shale, and, in its upper part, chert nodules. The woodford shale is thinly bedded with a low volume of clays. (Ham 1973)

*Sycamore Formation*

The Sycamore Formation is described as a poorly fossiliferous, silty limestone with inner bedded shales which overlays the Woodford shale. Due to the lack of fossils, the
sycamore formation has been poorly dated but it is estimated to be early Mississippian. The upper Sycamore formation grades into the Caney and Springer shales. (Ham 1973)

*Caney and Springer Shales*

The Caney shale is a dark, fissile shale with chert nodules, and limestone and sandstone are absent. The Springer shale and Caney shale contact is defined by the presences of siderite clays because the Caney shale is free from siderite while the Springer shale is siderite rich. The Springer shale grades into sandstone at the top of the formation. The Springer and Caney Shales range in thickness from 350 feet to 4600 feet consisting of Pennsylvanian dark shales and sandstones, thin marine limestones, and local conglomerates. (Ham 1973)

**Methods and Preliminary Analysis**

The geology within the Arbuckle Mountains will be analyzed in terms of controls in fracture networks within regional folds. As discussed, 5 controls on fractures within folds will be analyzed and quantitative data will be collected using a variety of methods to be able to correlate the data. The data will then be put into an ARCGIS database and a 4D model will be created. A wide variety of laboratory methods will be used to extract bias from field data. Each control requires a different method to produce adequate results, free from field observations and bias.

**Measuring Fracture Networks**

Fracture orientations will be measured in the field of study using a Brunton Compass. This data will then be compiled with previous measures fractures, while other fracture
sets will be measured using ARCGIS. (Figure 5) Most areas within the Arbuckle
Mountain fracture sets can be seen from areole photo. The photos can then be analyzed
d and rose diagrams depicting fracture orientation can be deduced from the photo. (Figure
7) The fieldwork measured fracture sets and areole photo measured sets will then be
compared and a overall fracture network will be produced using over a thousand data
points.

Fracture Densities will be measured in the field of study, by computer calculations
similar to fracture orientation measurements, and by using ARCGIS and areole photos.
(Figure 5) In the field, fractures within measured areas will be counted and measured
using a measuring tape. This process will deduce the number of fractures per measured
area and a length of fractures per measured area. A similar process will be done using a
computer. A scaled picture will be taken of the outcrop using a GIGAPAN which can
produce up to a 1cm resolution. The photo will then be analyzed for fractures using
Geomatic Software and a fracture density will be produced. These computer-driven data
sets will then be compared to the ones taken in the field and a final fracture density will
be produce in several spots along the anticline. The third method of analyzing the fracture
densities will come from using ARCGIS. The same fractures that were mapped using
ARCGIS and the orientation that was deduced will be used to create a spatial model of
the fracture densities across the anticline. (Figure 6) This method will then be compared
to the other sets of data collection.
Fractures will be measured in terms of orientation and density, at approximately 20 outcrops within the core and limbs of the anticline. This data will then be entered into ARCGIS to be correlated with data from the 5 controls of fracture networks within regional folds.
Fig 6. Model shows preliminary analysis of fracture densities within the Arbuckle Anticline. Fracture densities calculated by satellite imagery.

Fig 7 shows fracture orientations calculated by satellite imagery across the Arbuckle Anticline.
Analyzing the 5 controls on Fracture Systems within the Arbuckle Anticline

Control 1: Fold Geometry

The fold geometry of the Arbuckle Anticline will be analyzed using pre-existing geologic maps, newly created geologic maps, fieldwork, and areole photos. Mapping the axial plane within the Arbuckle Mountains can be difficult because it cannot be seen in outcrop. Using strike and dips from each limb of the fold will allow the trend and plunge of the axial plane to be deduced. This method will allow calculations of small, local changes in the axial planes orientation, but will be sufficient enough to compare to the fracture data. Data collect from the axial plane will be correlated to mode 1 and mode 2 fracture sets and relationships between the two will be developed.

Control 2: Rock Brittleness/Hardness

Rock brittleness or hardness will be calculated using a Schmitt Hammer. The Schmitt Hammer will use approximately 20 samples collected from the Arbuckle Mountains, within the core of the anticline and the limbs of the anticline, and drill into the sample in order to deduce a quantitative output of the sample’s hardness. (Avdin, et al, 2010) These data points will then be geo-located using ARCGIS and spatially analyzed across the anticline. (Figure 8) This model will then be compared to the fracture orientations and fracture densities to discover relationships between the two.
Fig 8 Model shows rocks brittleness observed in outcrop. Schmitt hammer will create quantitative results.

Control 3: Bedding Thickness

Bedding thickness will be measured from the outcrop using a measuring tape. The entire section of outcrop will be measured for bedding thickness and those data point will then be averaged into an overall average bed thickness for the outcrop. This process will be done approximately 20 times within the core and limbs of the anticline. The data will then be geo-located and spatially analyzed using ARCGIS. (Figure 9) The model of bed thicknesses across the anticline will be compared to the fracture density and fracture orientations and the relationship among the variables will be highlighted.
Fig 9. Model showing bedding thickness within the Arbuckle Anticline.

Control 4: Proximity to Faults

The impact of faults on fracture sets will be analyzed using ARCGIS and field observations. Using ARCGIS, faults will be located using Areole Photo, and fracture sets will be analyzed near and away from the faults location. (Figure 10) (Figure 11) The fracture data near fault zones will then be correlated to the faults location to see if a relationship exists between the two.
Fig 10. Model shows fault locations compared to fracture densities.

Fig 11. Geologic Map of faults within the Arbuckle Anticline and fracture orientations near fault zones.
Control 5: Pre-existing stress field and pre-existing structures

Control 5 can be observed in outcrop. If fractures were affected by a pre-existing stress field, the top 4 controls above will not have the same type of impact as the were hypothesized. The only known pre-existing structures within the Arbuckle Mountains are thought to be reactivated faults from the Southern Oklahoma Alacogen. Relationships between these faults and the fracture networks may be able to shed light on the pre-existing structures within the Arbuckle Mountains.

Proposed Outcomes

1) Fracture sets within Arbuckle Anticline predate the folding and faulting associated with the main phase of uplift in the region. (Ouachita Orogeny) A correlation between fractures orientation and/or density and the 5 controls on fractures within fold will link to fracture systems to the folding event. If no correlation is made, the fracture sets must be a result of previous deformation because the area is thought to be stable over the past 200 million years.

2) Fracture characteristics are a function of rock type and may be correlated by rock type across regional folds. A strong correlation between fracture orientation and/or density and control 2 and control 3 will develop this relationship. This association will then develop a correlation between reservoir properties and rock mechanical properties.

3) Tectonics associated with major Arbuckle uplift reactivated the preexisting fractures as a function of proximity to regional faults. A strong correlation to control 4 and fracture densities will develop this idea. If fractures are not heavily altered near fault zones it can
be concluded that the faults had little impact on the fractures found within the Arbuckle Anticline.

4) Future models will be created on other regional folds, including hydrocarbon-bearing folds, using the same principles of analysis. The working model conducted on the Arbuckle Anticline will then be able to be used to predict fracture networks within other folds.
### Schedule

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<tr>
<th>Date</th>
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<tr>
<td>By 2/1/2017</td>
<td>Submit Proposal to Graduate Committee</td>
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<tr>
<td>By 3/1/2017</td>
<td>Take trip to Arbuckle Mountains to collect fracture orientation data, fracture density photos, bed thickness measurements, analyze faults, and defined the axial plane of the anticli - Analyze rock hardness using Schmitt Hammer</td>
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<tr>
<td>By 3/1/2017</td>
<td>Correlate data from 5 controls into ARCGIS - Present correlation observations and data collection methods at SWAAPG</td>
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<tr>
<td>By 8/1/2017</td>
<td>Submit paper to SWAAPG Bulletin, AAPG Bulletin, and GSA Bulletin</td>
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<tr>
<td>By 9/1/2017</td>
<td>Present Talk at WTGS Fall Symposium - Present poster at Nation GSA in Seattle - Start developing Outline For Thesis</td>
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<tr>
<td>By 1/12018</td>
<td>Start writing thesis - finish all corrections to research methods</td>
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### Budget

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<td>Schmitt Hammer Analysis</td>
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**Total Cost = ???????**
References


