USING STREAMS AND FAULTS AS LINEAMENTS TO DELINEATE AQUIFER CHARACTERISTICS

By

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USING STREAMS AND FAULTS AS LINEAMENTS
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CHARACTERISTICS

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VARIABLE	DEFINITION
α	rank of stream length
l_s	line segment length [L]
L_T	total length [L]
L_i	line segment length for i*th* grid cell
r	constant of proportionality
s	fracture length [L]
t	exponent of the power law
θ	orientation (0-180) (degrees)
θ_i	line segment orientation (degrees)
θ_L	length weighted orientation (degrees)
θ_φ	strength of orientation
θ_s	raw orientation (degrees)
x_m	x direction midpoint (easting)
x_n	cartesian coordinates in the x-direction (easting)
y_m	y direction midpoint (northing)
y_n	cartesian coordinates in the y-direction (northing)

CHAPTER I

INTRODUCTION

The hydraulic characteristics of fractured rock have been difficult to study, due to the heterogeneous nature of fractured aquifers. Others have also studied fractured rock characteristics to determine hydraulic properties of the aquifer which include: Zimmerman and Bodvarsson (1995), Wanfang et al. (1997), Leveinen et al. (1998), Or and Tuller (2000). Fractures are known to modify both the flow velocity and direction and are critical to understanding flow at many scales.

Lineaments have been studied to delineate subsurface characteristics, which are known to correlate with surface patterns (Blanchet, 1957; Mollard, 1957; Rumsey, 1971; Parizek, 1975). Many fractures and faults are exposed at the surface creating lineaments (Mabee and Hardcastle, 1997). A number of different methods are employed to analyze lineaments and their effect on subsurface characteristics and influence on ground water flow. Lineaments have also been used in ground water research to determine where the best location would be for a competent well (Lattman and Parizek, 1964; Sander et al., 1997; Magowe, 1999; Moore et al., 2002). Lineament studies have also been used by the petroleum industry to improve well siting (Blanchet, 1957; Mollard, 1957, McQuillan, 1986; Evenson, 1989; Friesatz, 1991; Terech, 2005).

Many of the investigations conducted on lineaments have used aerial photographs (Sander et al., 1997; Magowe, 1999; Mabee et al., 2002; Moore et al., 2002). The use of LANDSAT and side-looking aerial radar has been the most common methods used. Various scales of the images are also used when trying to determine regional lineament characteristics.

Geographical Information Systems (GIS) has become widely used in the geological sciences. GIS coverages are easily available for most areas, or data layers can easily be created by digitizing maps. Aspect, hillslope, and degree slope change can be readily analyzed if a topographic map is available. GIS has become an important aid for mapping geology and rock properties in regions with subtle topography (Belt and Paxton, 2005).

Evidence has shown that a correlation can be made between surface lineaments and subsurface fractures. Lineaments that have a permeable overburden have been found to correspond to higher flows (Mabee et al., 2002). Surface water near lineaments has also been found to produce higher flow (Mabee et al., 2002). Streams and faults are lineaments that have not been fully utilized to assess subsurface characteristics. Developing a quantitative understanding of aquifer characteristics can be a time consuming and costly task, however, stream beds can be recognized easily around the world and are perhaps the most unbiased and cost effective lineament type available to researchers. The use of GIS data sets allows for a significant increase in the amount of data that can be analyzed quantitatively. The methods introduced in this study should be applicable to studies of fractured aquifers in most geological settings.

The hypothesis that was tested for this study is that stream and fault characteristics (orientation, length, and density) will correlate to subsurface fracture characteristics which will help determine hydrogeological control over the aquifer. In order to test this hypothesis, a method to analyze polymodal data from GIS layers was developed. Field data was collected to confirm interpretations from the GIS streams and faults layers. The data was evaluated in a geologic context using the structural history of the area and current stress fields. The analysis of the combined data could help make flow direction predictions from potentiometric data.

This study uses the Arbuckle-Simpson aquifer in south-central Oklahoma as a field test area. The assessment of the Arbuckle-Simpson aquifer was made based on the stream and fault data collected using GIS and outcrop data collected in the field. Two different GIS data grid sizes were used over the study area for a more detailed analysis of stream and fault characteristics and subsurface fracture patterns over different lithologies.

CHAPTER II

REVIEW OF LITERATURE

Understanding how lineaments can aid in understanding aquifer characteristics was important to this study. Lineaments have been studied for many years and have been proven to be an effective tool for geologists. A general discussion of history of lineaments and how they are being used scientifically is provided in this chapter. The fluvial geomorphology influence on lineament studies is also discussed and an overview of how lineaments and structural geology have been analyzed is presented. Previous work on the connections between hydrogeology and lineaments follows. In order to evaluate the methods developed as part of this thesis, a brief review of statistical methods that have been used to analyze orientations is provided. Finally, a site description of the study area provides background information on the Arbuckle-Simpson aquifer.

Lineament Studies

Many studies have been conducted using lineaments as exploration tools to locate oil, gas, and water. Lineament studies date as far back as the 1950’s (Blanchet, 1957; Mollard, 1957; Kupsch and Wild, 1958) and conducted globally. The oil and gas industry was the first to study lineaments as an exploration method, using aerial photographs to identify lineaments and aid in the search for petroleum (Blanchet, 1957; Mollard, 1957; Ray and Fischer, 1960).

One of the major difficulties with lineament analysis is the reproducibility of the results. Lineament data is limited because lineament locations and orientation vary when different observers analyze the trends. The difficulty in identifying lineaments has been realized since the earliest studies. Mollard (1957) noted that the analyst only sees what has meaning based on his or her own experience. When using digital satellite imagery the perception of each individual person was different (Sander et al.,1997). Identifying lineaments usually required many observers working at different scales and required multiple trials (Mabee et al., 2002; Moore et al., 2002).

Fluvial Geomorphology

The relationship between surface water and lineaments was studied in Bolivia by Pflaker (1964), who analyzed the relationship between oriented lakes and lineaments. He studied the relationship of lineaments on the surface to fractures in the basement. Pflaker (1964) study concluded that the lineaments oriented in the Beni basin correlated to oriented fractures in the crystalline basement. Strong evidence for this correlation was found in the preferred orientation that could be detected on a regional scale.

Lithology is an influencing factor of drainage density that has been correlated to drainage density characteristics. Day (1980) looked at the variation of flowing stream length. The study analyzed stream density in granite and sedimentary lithology. Day (1980) found that high frequency of jointing and thick granitic soils caused rapid infiltration and larger groundwater storage of rainfall. Day (1980) also found that each basin has distinctive flow characteristics and varies with rock type.

Hillslope processes and drainage density have been studied. A study conducted by Montgomery and Dietrich (1989) examined drainage density and source area. The source areas for channel network were believed to be linked to drainage density characteristics. They found that an inverse relationship exists between source-basin length and drainage density. The study found a link between hillslope and drainage density. Many channels in the study area did not connect with drainage networks downslope. This indicated that hillslope processes controlled the channel head locations rather than headward network extensions.

Another study conducted by Tucker and Bras (1998) studied this relationship and derived expressions for the relationships between drainage density, rainfall, relief, and mean erosion rate. The found that drainage density and factors such as climate, geology, and relief will vary in a predictable way due to the characteristics of the geomorphic processes. On the basis of different threshold theories, Tucker and Bras (1998) derived relationships between drainage density and environmental factors such as rainfall, relief, and mean erosion rate. In conclusion, their models provided a framework for understanding geomorphic processes and drainage density. Their models considered only equilibrium landscapes that had sufficient time to adjust to differing environmental conditions and cannot necessarily describe what might happen to drainage density under different environmental conditions.

Research has also been conducted on drainage density and climate (Gregory and Gardiner, 1975; Rodriguez-Iturbe and Escobar, 1982; Moglen et al., 1998). The studies indicate that climate of an area can impact drainage density. Relationships have been established between climate and drainage density. However, each study noted other factors that influence drainage density and indicated they cannot be ignored.

Structural Controls on Lineaments

Rumsey (1971) studied the relationship of fractures in unconsolidated superficial deposits to subsurface characteristics. The study also concluded with a correlation between linear traces and subsurface fracture characteristics. The fractures on the surface were caused by the underlying bedrock. In southeastern Oklahoma, lineaments have been analyzed with LANDSAT data (Walsh and Vitek, 1981). They found that a strong correlation exists between geologic lineaments detected by LANDSAT images and geologic trends.

Another method used to study lineaments was gravity surveying. In South Florida, gravity surveys were used to determine if lineaments can give researchers insight about the geologic history and tectonic framework of an area (Culbreth, 1988). The lineaments mapped for this study were straight stream segments, tonal variations, linear water bodies, and aligned water bodies. The study found that geologic structures oriented parallel to preferred orientation were more likely to be found at the surface because they are parallel to stress fields.

Hydrogeology and Lineaments

Lineaments have been studied in the past by many researchers for groundwater exploration. Lattman and Parizek (1964) found a relationship between the occurrence of groundwater and fracture traces for carbonate aquifers. They found that fracture traces are found in zones of increased permeability and porosity. Fracture traces and lineament analysis in carbonate and other terrains were conducted by Parizek (1975), who aimed at finding a relationship between fracture traces and major lineaments to delineate zones of increased permeability and porosity.

Cotton (1964) also studied the control on drainage density. It was believed at the time that permeability of the terrain was the most important control (Carlston, 1964). However, Cotton believed the climate of each region affected drainage characteristics and argued that rainfall was an important control in drainage density. Assuming drainage density were only a function of the permeability of the terrain was shown to be incorrect because runoff characteristics were also an important factor.

Mabee and Hardcastle (1997) analyzed outcrop-scale fractures to investigate aquifer characteristics in the subsurface. They compared surface fracture data with orientation data collected from boreholes using acoustic televiewer logs. Mabee and Hardcastle (1997) discovered that analysis of fracture domains on the surface can provide information on fractures in the subsurface.

A study by Magowe (1999) that was completed in Botswana also correlates lineaments to groundwater occurrences. Magowe found that fracture density and high well-yields have a positive correlation. A similar field study in New Hampshire looked at factors related to well yield in a fractured bedrock aquifer (Moore et al., 2002). The study found that lineaments identified using aerial photographs can be correlated with the primary fracture direction of the aquifer. They also found that wells within 100 ft of a lineament had higher than average well-yields.

Mabee et al. (2002) correlated lineaments to groundwater inflows in a bedrock tunnel. The study was carried out to compare water producing structures that were observed in a tunnel with lineaments identified using various scales of aerial photographs. The analysis, which was executed in glaciated metamorphic rock, and they found a good correlation between lineaments and inflows.

Remote sensing data has been used to derive lineaments for groundwater exploration (Sander et al., 1997). The goal of this research was to increase the confidence in mapped lineaments and production wells. The reproducibility tests conducted showed that each interpreter identifies different lineaments based on their perception. The method used to define lineaments can produce conflicting results. Sander (1997) concluded that a detailed field analysis is necessary to identify lineaments.

Previous investigations that involved using streams as lineaments to delineate the subsurface fracture characteristics are minimal and only a single reference was located. Halihan et al. (1999) found the method was useful and that high creek density correlated with high well yields.

Lineaments can be used to determine the potential effects anisotropy will have on ground water flow direction. On some scales aquifer materials can be isotropic, showing little variation in hydraulic properties with any given direction. However, in many fractured aquifers, fracture orientation can induce anisotropy and influence flow path orientation (Fitts, 2002). Fitts (2002) also states that the orientation of joint sets often govern the large scale anisotropy in crystalline rocks. The variation in hydraulic properties due to anisotropy can vary from small percentages to orders of magnitude

(Weight and Sonderegger, 2001). Figure 1-1 is a schematic of the potential influence anisotropy will have on flow for different orientations of anisotropy.

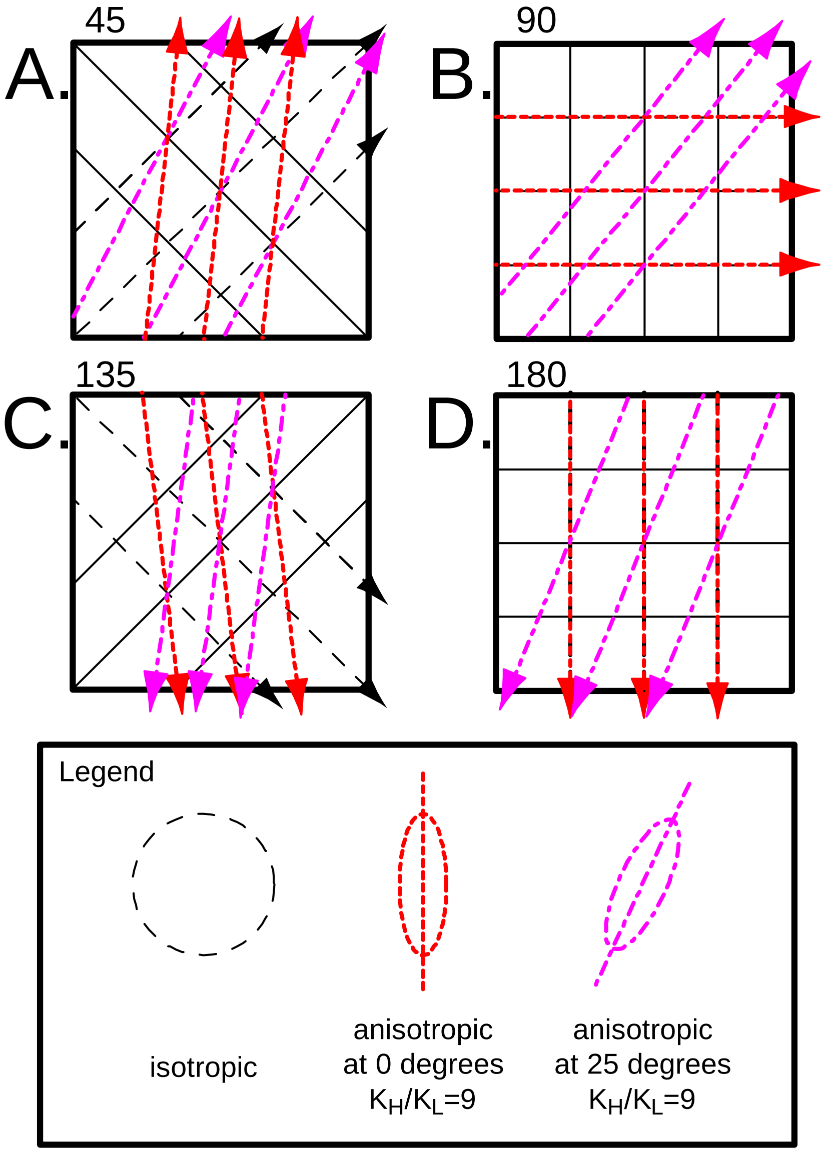


Figure 1-1. Influence of anisotropy on flow direction for different orientations of the hydraulic gradient. Isotropic flow directions of A) 45°, B) 90°, C) 135°, and D) 180°.

Statistics

The earliest published studies of the statistics of oriented data began with Rayleigh (1880) who analyzed sound vibrations. The distribution of sound waves was found to be more complex than just taking an average, and the Rayleigh method of orientation analysis was developed as a result.

Pincus (1951) investigated distributions of orientations in the earth sciences. Periodic and non-periodic characteristics in collecting data both proved to create error in the data collected. Statistical methods such as the circular normal theory, the chi-square test, and linear normal method were discussed. Pincus (1953) also conducted a quantitative analysis of fracture orientation collected from Precambrian gneisses and overlying lower Paleozoic sedimentary rocks in northern New Jersey. The data were plotted on rectangular coordinates and the Schmidt equal area net. Frequency and mean orientation were used to determine dominant trends. Deviations from normal were tested by using the Poisson exponential binomial limit.

Methods to evaluate the statistics of orientation data were studied by many other researchers (Gumbel et al., 1953; Watson, 1966; Anderson and Stephens, 1972; Downs, 1972; Mardia, 1975; Khatri and Mardia, 1977). These papers discussed methods for describing orientation data. Formal statistical methods are introduced and described in each paper. Emphasis on assumptions is crucial because the technique for collecting data ultimately controls statistical variance in the data. The methods introduced in these papers were only helpful for unimodal data.

Other disciplines in science also have an interest in studying orientations. Bird nest orientations have been extensively analyzed to determine any possible trends in animal behavior. Bergin (1990) studied the nest orientations in Western Kingbirds. To statistically characterize the behavior of bird nest orientations, Bergin analyzed four statistical methods. The chi-square method, Watson, Rayleigh, and Rao statistical methods were used to study the data set. Each method was compared to determine which method described the data set the best. The Rao method was the most efficient in detecting significant patterns, but none of the methods could account for polymodal data.

Polymodal Data

Much statistical uncertainty is present when orientation data becomes bimodal. Two preferred directions are present and averaging is affected. Curray (1955) studied bimodal orientation data. Two distributions were taken from sand grain orientations studies. The study found that the best fits appear to be circular normal distribution and a distribution found by wrapping an unlimited linear normal curve to the center point of a polar coordinate. The Rayleigh test was modified for two-dimensional data (Durand, 1958). The effectiveness of the Rayleigh test was examined to determine uniformity in the data set when bimodal distributions are present. Another study of bimodal orientation conducted by Jones (1969) also uses circular normal distributions to describe bimodal orientations. The study indicates that a meaningful analysis of bimodal orientation largely depends on analyzing each orientation individually. They believed that the mixed circular model presented in the paper is a general model for most geologic problems that have bimodal distributions.

Length Statistics

The power law function will be used to describe the behavior of stream lengths in the data set. Previous work has found that natural fractures and faults become linear on a log-log graph indicating that the power law best describes the distribution (Cladouhos and Marrett, 1996; Marrett, 1996; Marrett et al., 1999; Ortega et al., 2006). Since streams are lineaments similar to faults and fractures this method is the most appropriate to analyze the data.

Site Description

The Arbuckle-Simpson aquifer outcrops over an area of over approximately 500 mi^2 in southern Oklahoma (Fairchild et al., 1990). It lies beneath parts of Murray, Carter, Johnston, and Pontotoc Counties; and a small portion of western Coal County (Figure 2-1). The Arbuckle-Simpson aquifer includes formations from the Arbuckle Group (Upper Cambrian to Lower Ordovician) and the Simpson Group (Middle Ordovician). The aquifer is composed of mostly limestone, dolomite, and sandstone. The formations have been folded and faulted due to major uplifts in the area during Early to Late Pennsylvanian time (Fairchild et al., 1990). Secondary porosity is created by fractures, joints, and solution channels (Fairchild et al., 1979). Many of the springs in the area supply the perennial streams (Fairchild et al., 1990).

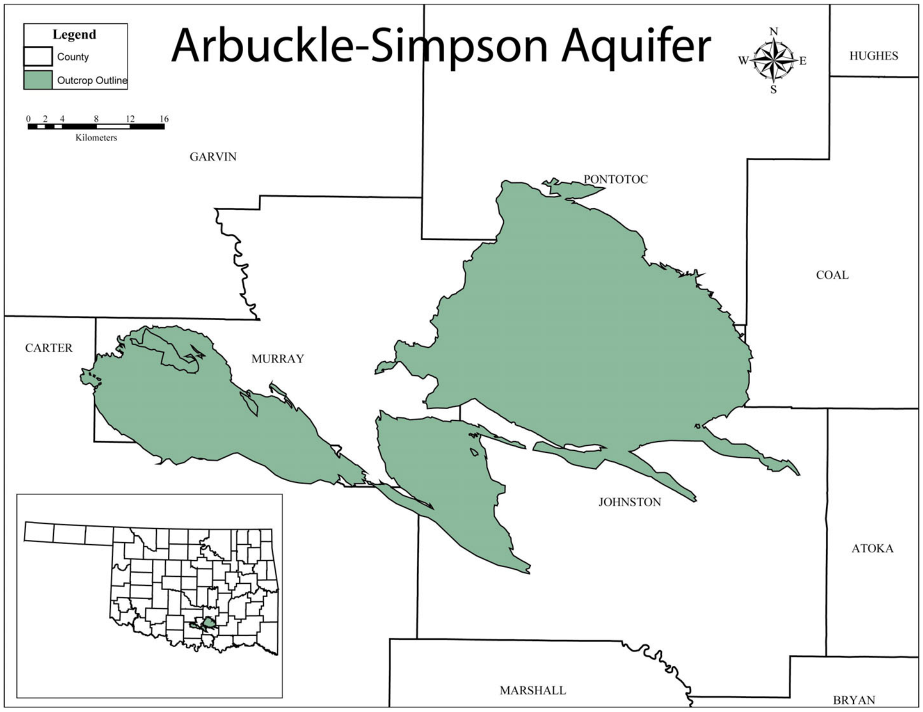


Figure 2-1**.** Regional map showing the location of the Arbuckle-Simpson aquifer.

The structural history of the region is one that has been extensively studied (Decker and Merritt, 1931; Dott, 1933; Dott, 1934; Ham, 1955, Ham et al., 1964; Johnson, 1991a; Johnson, 1991b). The Arbuckle Mountains are part of the southern Oklahoma Aulacogen (Wickham, 1978). A brief description of southern Oklahoma's structural history can be broken into three stages based on the work of Wickham (1978). First, a rifting state occurred, which was a period of uplift. Both intrusive and extrusive activity was present. Sedimentation was of a continental scale during this time. During the second state subsidence occurred. A formation of a passive continental margin, marine transgression, and rapid subsidence occurred. Thick sedimentary sequences were being formed. The final stage was the deformation stage. Reactivation of old fault trends occurred with strike-slip and dip-slip displacements being the dominant fault activity.

Local basins and uplifts were formed. Due to the orogenic activity within the region, conglomerates were formed.

Some dominant fault trends can be seen as a result of this failed rift zone. During the Paleozoic, an inversion of the rift began during the Late Mississippian and continued to the early Permian. During this process a belt of west–northwest trending uplifts and faults were created (Marshak et al., 2003). Inversion of the aulacogen shortened orientations perpendicular to the rift axis in an East - SE direction (Marshak et al., 2003). Many faults during the aulacogen began to change. Normal faults became reverse faults, and during times of compression, folds began to form. Left and right lateral, strike-slip faults, normal faults, and reverse faults characterize the area, as well as some flower structures (Marshak et al., 2003). In the Tishimingo-Belton anticline, lineament orientations were found to be dominantly N50^{o}-60^{o}W (Denison, 1995).

CHAPTER III

METHODOLOGY

The GIS methods introduced in this thesis allow for an efficient means of data analysis by processing GIS data layers of streams and faults into data for individual line segments. Length, density, and orientation are calculated from the data. A hillslope, aspect, and shaded relief map were created for the study area. A general lithology map for the 10 km grids was also created. Outcrop data collections were conducted in the field. Length, density, and orientation of fractures were recorded. Statistical methods are used to determine the significance of length and orientation data of the stream and fault data. A comparison of all the data sets was then conducted to determine if correlations exist.

GIS Data Processing

GIS stream and fault layers were converted to line segments to study length, orientation, and density. The stream and fault layers were sent to the Department of Primary Industries and Resources in South Australia to be processed. They created the nodes in GIS with ArcInfo Workstation and used the commands SHAPEARC and UNGENERATE to acquire Northings and Eastings of beginning and ending nodes of each line segment in the x (easting) and y (northing) direction in the data layers. The study area was overlaid by 77, 10 km grid cells (Figure 3-1). A set of higher resolution grids was created to help determine the relationship between stream characteristics and lithofacies. The higher resolution grid contained 304, 2.5 km grid cells (Figure 4-7). The size of the grid cells was determined by the data density of stream and fault data in the area. In the x-direction (easting) the study was approximately 11,000 meters long and in the y-direction (northing) the length was approximately 7,000 meters. Each 10 km grid cell contains between 260 to 1500 stream segments and 0 to 100 fault segments.

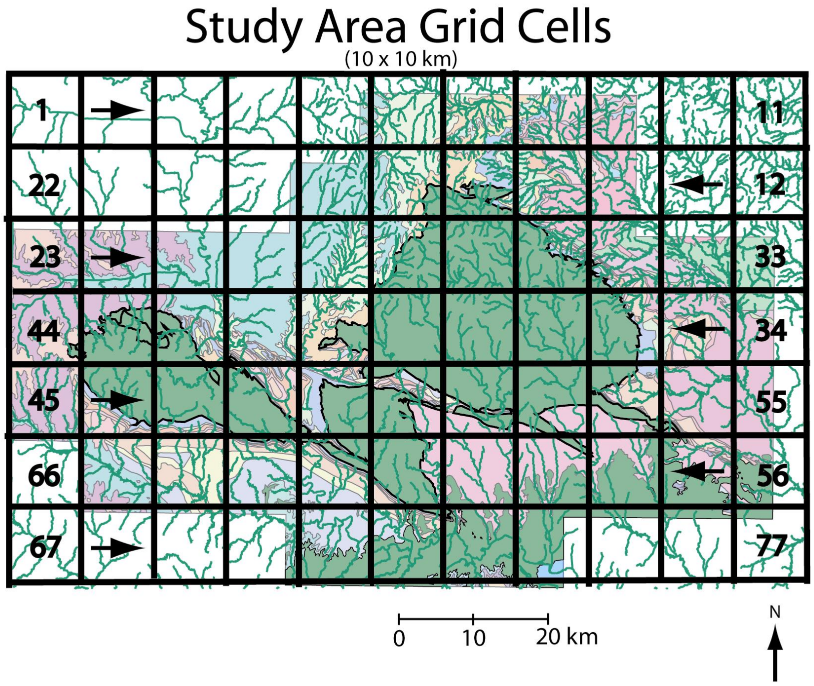


Figure 3-1. The Arbuckle-Simpson study area over laid by 10 km grid cells. Each grid cell has a 100 km^2 area.

A point halfway between the endpoints of a line segment was called a midpoint (Figure 3-2). Midpoints of each stream segment were obtained to determine the cell position of each stream segment.

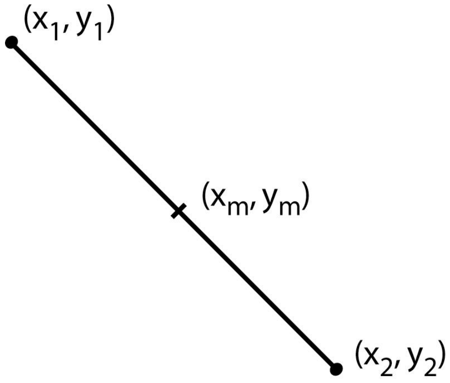


Figure 3-2. This figure illustrates where the midpoint was located on a line between two data points.

This allowed for an analysis of each grid and eliminates segments crossing multiple grid cells. Midpoints were found using basic algebra (Equation 1).

$$(x_m, y_m) = \left(\frac{x_1 + x_2}{2}, \frac{y_1 + y_2}{2} \right). \tag{1}$$

The lengths of each line segment were found by using equation 2 (Figure 3-3).

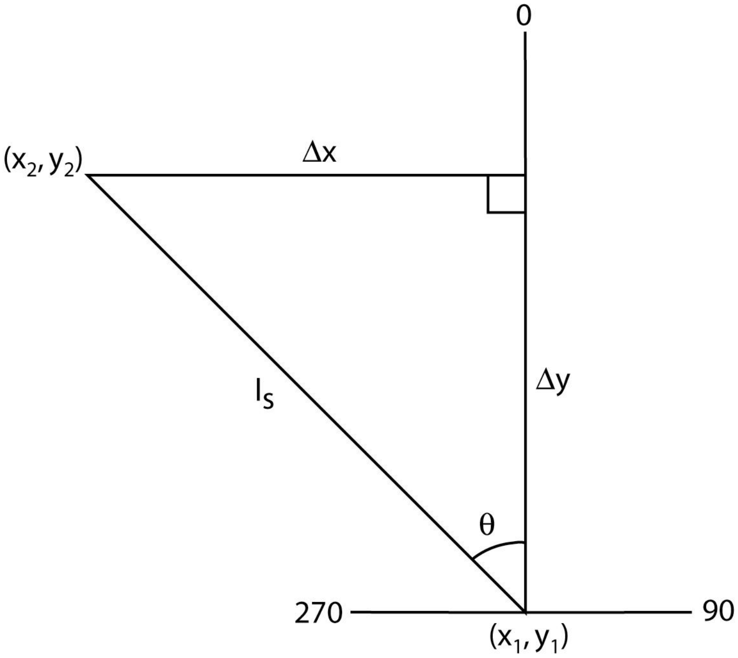


Figure 3-3. Geometry defining the distance and angles used to find lengths and orientations of streams and faults.

The formula to find lengths was known as the distance equation (Equation 2),

$$l_s = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \ . \tag{2}$$

By rearranging the formula, orientation was found using:

$$\theta_s = \sin^{-1}\left(\frac{x_2 - x_1}{l_s}\right). \tag{3}$$

Since the orientations were analyzed between 0^o-180^o, negative values were corrected using:

$$\theta = \theta_s + 180 \, . \tag{4}$$

The density of each grid cell was analyzed by obtaining the total length of the streams in the grid and dividing that number by the area of the grid. A density map was only created for the 10 km grid cells, which equals a total area of 100 km^2 for each grid cell. A smaller grid was constructed over the study area to acquire a better resolution of trends over the Arbuckle-Simpson aquifer. It enables a better analysis of stream characteristics in different lithologies. The smaller grid that was created contained 2.5 km sized cells. Each 2.5 km grid cell contained approximately 100 streams.

The smaller grids allowed for a detailed view of orientation trends to give a better resolution and help strengthen the correlation between the lineaments and subsurface characteristics. The 10 km grid resolution combined with the 2.5 km resolution strengthened observations by providing a better view of which lithologies were affecting each grid cell. This data, combined with field work and potentiometric maps over the area allowed for aquifer characteristics to be better understood. The trends observed in the small grids indicated which lithologies are creating certain behaviors in stream characteristics.

GIS and Geomorphology

A shaded relief and hillslope map was used to study the geomorphology over the study area. This will be aided by also creating an aspect map for the study area. The aspect map will allow for a visual aid to determine if the direction of the slope is affecting the orientations observed in the streams and faults GIS layers. A general lithology map will also be created to help better understand stream and fault characteristics in different lithologies.

Field Data Collection

Field work was conducted at four different locations where exposed bedrock with fractures was present. The locations were chosen based on availability of bedrock exposure over the Arbuckle Mountains. Locations that were near streams were preferable. However, there are limited outcrops over the study area. The four locations were: Site 1 in Connerville, Oklahoma (upstream of Blue River), Site 2 in Connerville, Oklahoma (downstream of Blue River), Site 3 in Devil's Den, and Site 4 at Turner Falls, near Davis, Oklahoma.

Field work was conducted in the study area to correlate fracture characteristics seen in the field to stream characteristics. Exposed bedrock along streams enabled a scan line to be created perpendicular to prominent fracture orientations (Figure 3-4).

Figure 3-4. A scan line taken across fractures was used to gather data. One dominant trend is seen perpendicular to the scan line. A second fracture set can be seen parallel to the tape and has grass growing in one of the fractures in the set.

Location, length, and orientation of each fracture that crosses the scan line was determined. Length was measured using a 12 inch ruler for small fracture lengths. A tape measurer was used if the fracture length was longer than 12 inches. Orientation was observed using a brunton azimuthal compass. A magnifying glass was used to increase fracture visibility and determine if the fracture was open or closed. If the fracture was closed, the fill material was analyzed to make a field determination of the composition of the fill.

Statistical Analysis of Orientation

Along with standard rose diagram analysis, an unbiased statistical polymodal orientation method to analyze stream and fault data was developed to determine preferred orientations. Circular statistics were not sufficient in correctly determining dominant orientations; this lead to a new method created for this thesis. The lack of confidence in existing circular statistics was due to the fact that they do not account for length weighted data and polymodal data. A stream segment that is long in length in a particular orientation must be considered a stronger signal. Figure 3-5 is an example of this scenario.

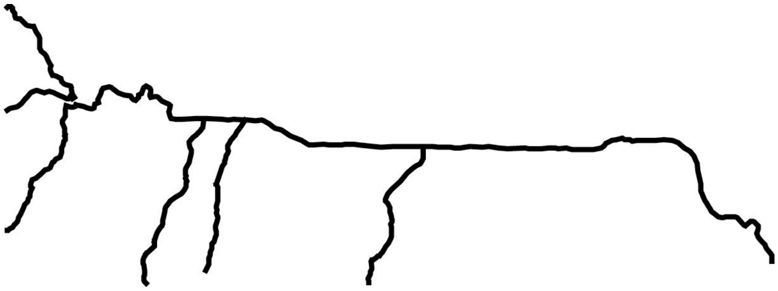


Figure 3-5. This stream segment has a preferred orientation towards the east-west, but traditional statistical methods would determine the north-south orientation was dominant.

To statistically analyze this stream reach, each orientation (θ) of the segment is weighted by the length (L) of a segment,

$$\theta_L = L_i \times \theta_i \quad . \tag{5}$$

All the length weighed orientations (θ_L) are summed in 10 degree bins. The sum of the θ_L is then divided by the total length in that orientation (L_T),

$$\theta_\varphi = \frac{\sum L_i \theta_i}{L_T} = \frac{\sum \theta_L}{L_T} \, . \tag{6}$$

By determining the mean and standard deviation of lengths in a grid cell, strong and weak orientations were identified using equation 6. If θ_φ was one standard deviation above the mean of all 18 θ_φ values, it was considered a weak signal; two standard deviations above the mean were considered strong signals. There were more than one strong signal in some grid cells. Strong signals indicated a preferred orientation of streams and faults in a particular grid cell. Weaker signals indicated that other orientations are present in the grid cell but may not be geologically significant.

To determine which orientations were preferred for the streams and faults GIS layer on a regional basis, histograms of the grid signals were created for the each datasets. A histogram of the sum of strong and weak signals for the binned orientations was observed for the 10 km and 2.5 km grids. The mean and standard deviation of the sums is used to delineate preferred regional orientations for each GIS layer. The GIS faults layer was the layer used to determine if a correlation can be made between orientation signals and fractures in the subsurface. The GIS faults layer should limit stream data biases because the faults are digitized off of a fault map. Again in this case, two standard deviations above from the mean indicated a preferred orientation.

Power Law Statistics for Length

The power law between two scalar quantities can be written as

$$\alpha = rs^{t} . \tag{7}$$

The variable α was the rank of the length of the stream, with α=1 corresponding to the longest fracture. The two variables r (constant of proportionality) and t (the exponent of the power law) were determined from the slope of a line using Excel.

When equation 7 was rearranged to solve for *s*, the predicted length of the longest fracture was determined. By allowing α to equal 1, the longest fracture length was found by carrying out these steps,

$$1 = rs^{t}, \tag{8}$$

divide by *r*,

$$\frac{1}{r} = s^{t}. \tag{9}$$

To solve for *s* we must take the log of both sides

$$\log\frac{1}{r} = t\log s, \tag{10}$$

and taking the exponent of both sides rearranges the equation to

$$10^{\log\frac{1}{r}} = 10^{t\log s}. \tag{11}$$

By solving for *s* the length can be determined

$$s = 10^{\frac{1}{r}}. \tag{12}$$

The power law was used only to model stream lengths above 100 meters. The resolution from the GIS stream layer does not allow a precise determination of actual stream lengths below 100 meters. Previous work conducted on fractures supports this method (Cladouhos and Marrett, 1996; Marrett, 1996; Marrett et al., 1999; Ortega et al., 2006). They found that there is a minimum measurable length for fractures. Below a certain length, fracture lengths cannot be correctly measured and errors will be introduced into the data set

Data Comparison

One factor that is taken into consideration in this project was the affect geomorphology had on the stream orientations. A shaded relief map was used to study the influence hillslope had on stream density and orientation. An aspect map was also created to determine if the direction the slope was facing had an influence on the direction that the streams were oriented in a particular grid cell. The characteristics of stream density over the study area were observed by creating a map in GIS of the degree of slope change for the study area. By combining all of these maps and correlating them to the preferred orientations for the study area, an unbiased analysis of stream lengths, orientations, and densities was conducted.

Two potential sources of bias were in the stream data. First, the digitizing of the layer may include more streams by one algorithim or person doing hand digitizing. Second, at lower resolutions, a pixilation bias may results in extra north-south or east-west segments. These were examined in the datasets by separating areas with higher apparent stream density if they appeared to be induced during digitizing. In orientation data, pixilation bias could be observed by extra signal strength at 0 or 90 degrees. This bias is not expected in the fault dataset.

CHAPTER IV

RESULTS

The comparison between surface geomorphology and stream and fault data is presented. The results of stream and fault orientations were discussed based on standard rose diagrams and the polymodal orientation method. Stream and fault length and density results were also presented. Field data was compared to the GIS streams and faults data. A figure was created to better visualize the relationships.

Geomorphology and Stream Orientations

The shaded relief map for the Arbuckle-Simpson Mountains indicated very little slope change over the Hunton Anticline (Figure 4-1). To analyze the influence surface geomorphology processes may have on stream orientations an aspect map for the study area (Figure 4-2) and a hillslope map (Figure 4-3) are used.

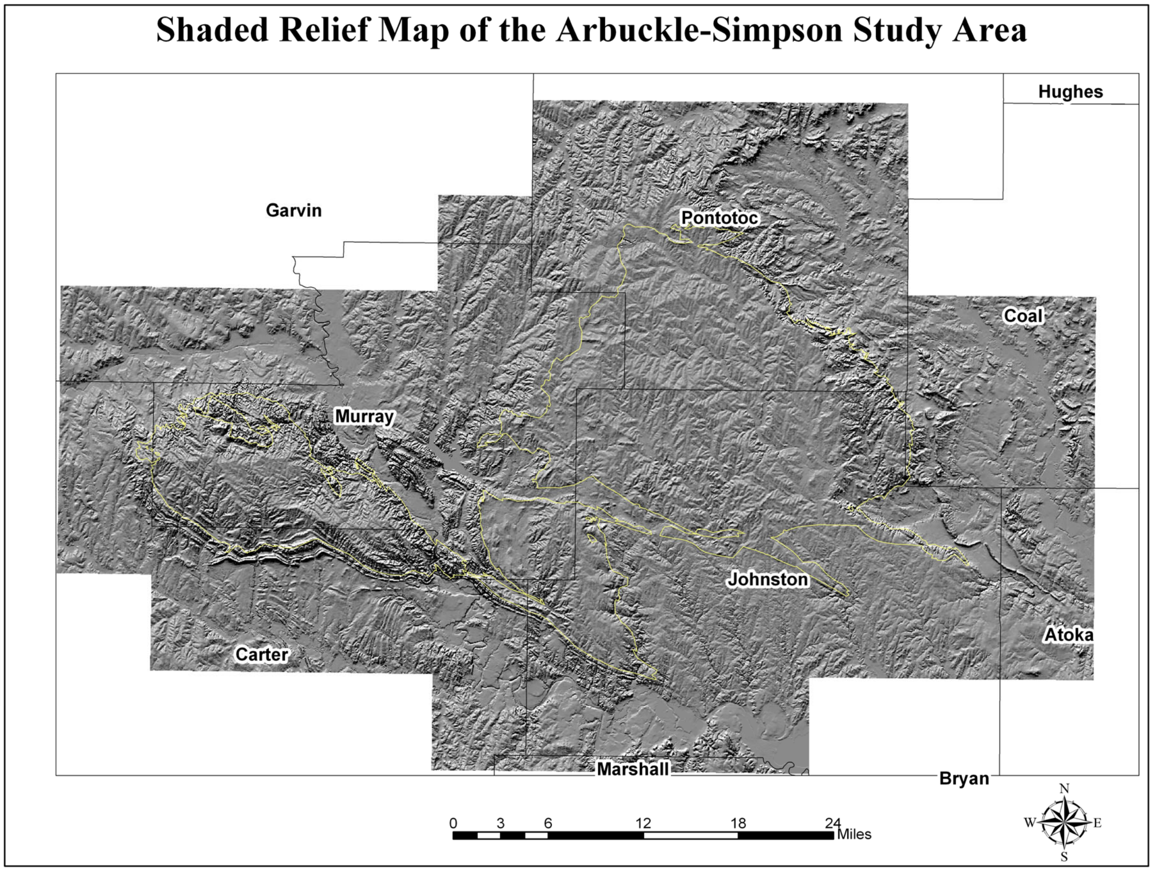


Figure 4-1. The shaded relief map for the Arbuckle-Simpson Mountains shows very little change in slope over the Hunton Anticline. The aquifer area is outlined by a faint yellow line to better visualize the boundary.

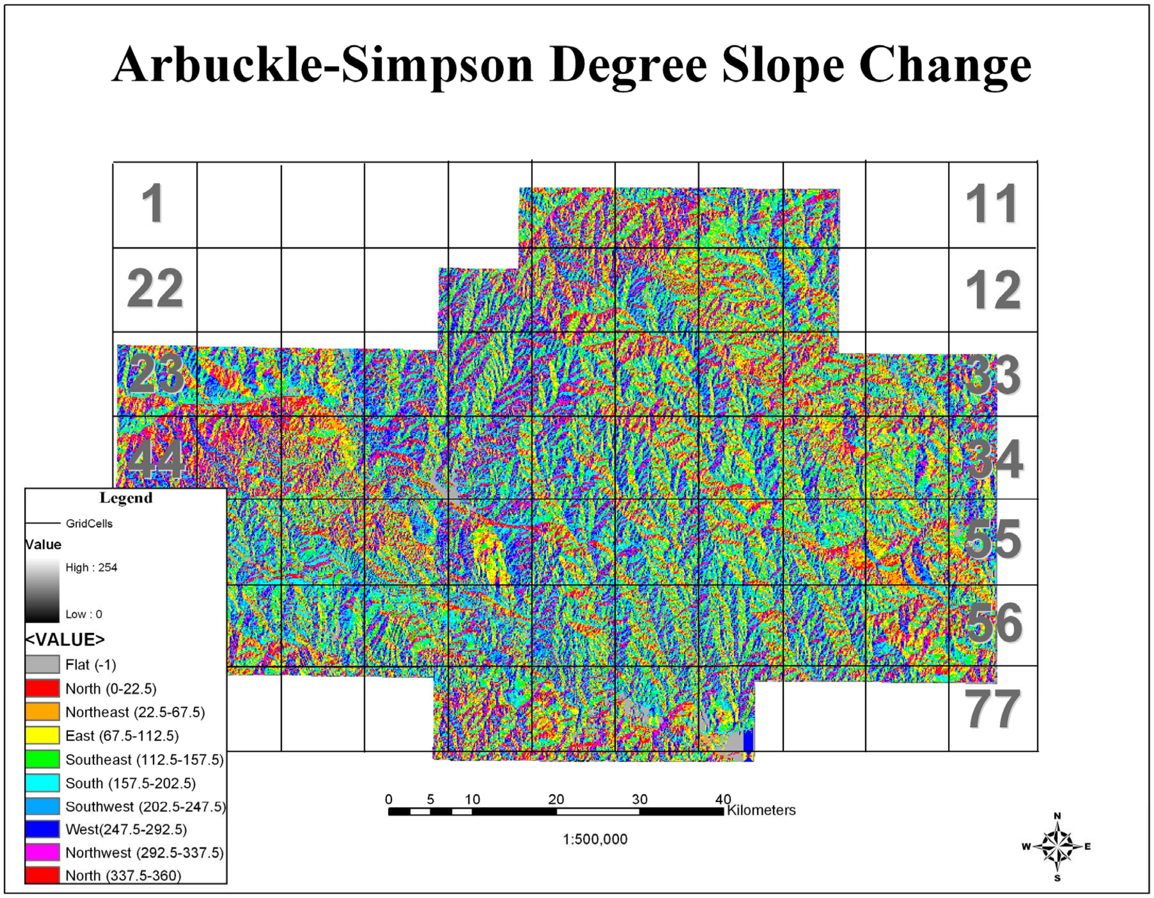


Figure 4-2. The aspect map for the Arbuckle-Simpson Mountains does not show an obvious preferred hillslope direction.

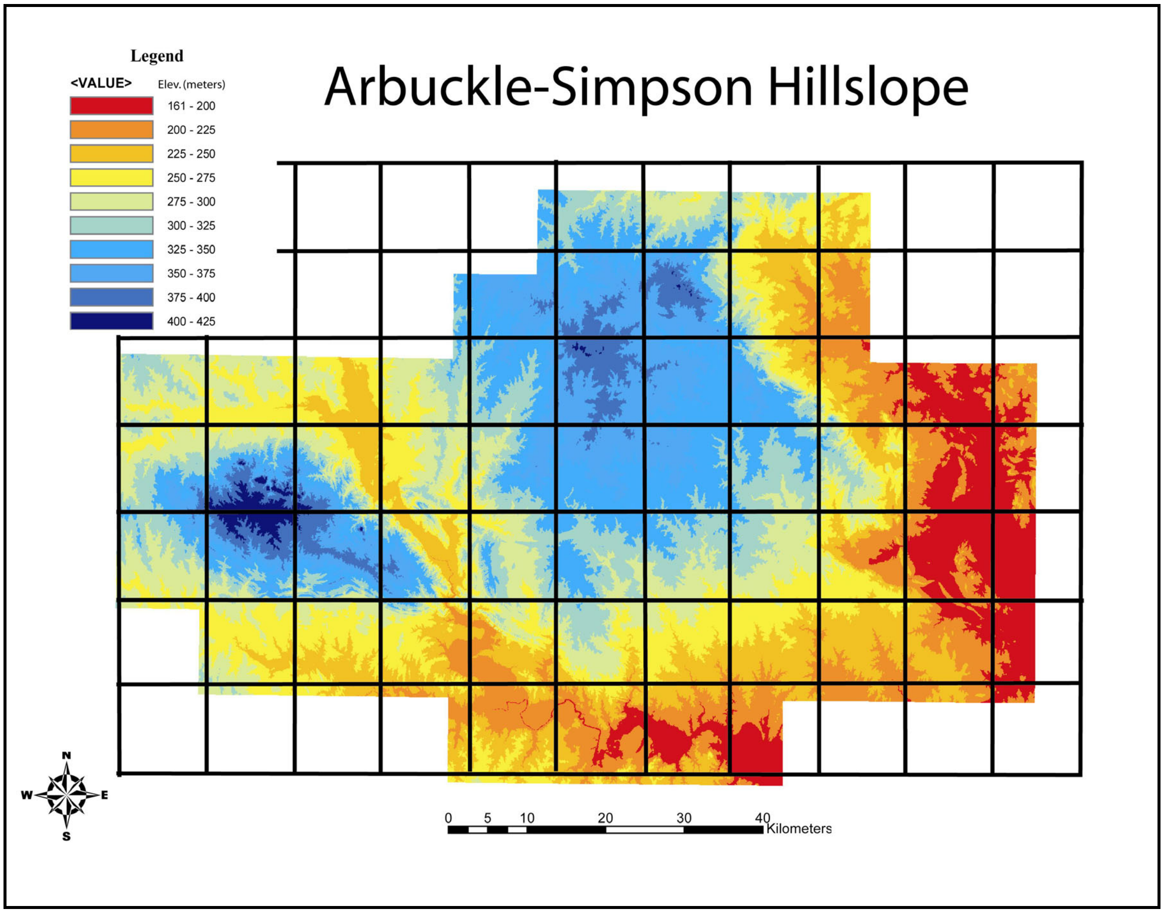


Figure 4-3. The hillslope map for the Arbuckle-Simpson shows very little change in elevation over the Arbuckle-Simpson Mountains.

A more general geological map was created to determine if lithology may explain differences in stream orientations (Figure 4-4).

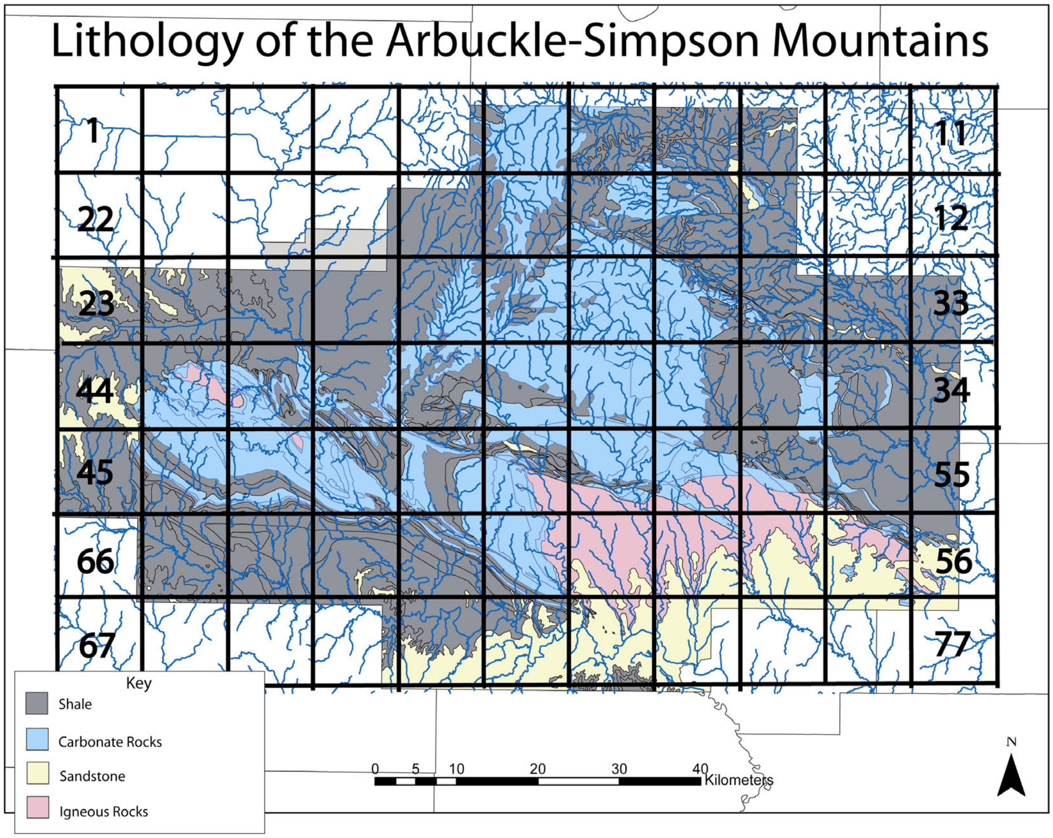


Figure 4-4. A general lithology map over the Arbuckle-Simpson Mountains indicates a mostly carbonate aquifer with surrounding shales and granites.

The lithology of the aquifer is mostly massive limestone and dolomites. It is difficult to find fractures outcropping on the surface as determined by many attempts to conduct field work in the area. No significant patterns are evident for the area showing significant trends for hillslope relative to aspect and geology. A more rigorous statistical analysis of aspect may provide additional information.

Field Data

At the four field sites a total of 8 lines were run. At site 1, at Connerville, Oklahoma, the combined length of both lines measured 6.6 meters. A total of 72 fractures were intercepted by the scan lines. Site 2 was also located at Connerville, Oklahoma. The combined length of both lines measured 1.3 meters. A total of 57 fractures were intercepted by the scan lines. Scan lines for Site 3, at Devil's Den, had a combined total length of 3.6 meters. A total of 114 fractures were intercepted by the two scan lines. The final site was located at Turner Falls, near Davis Oklahoma. The scan lines for site 4 combined for a total length of 1.8 meters. 61 fractures were intercepted by the two scan lines.

Orientation Analysis

The scale created for the rose diagrams was determined by the maximum stream length in any orientation in the GIS stream data set. Grid Cell 31 had a maximum length of 17,078 meters and controlled the scale created for the grid. A complete map of all the rose diagrams over the study area is shown in Figure 4-6.

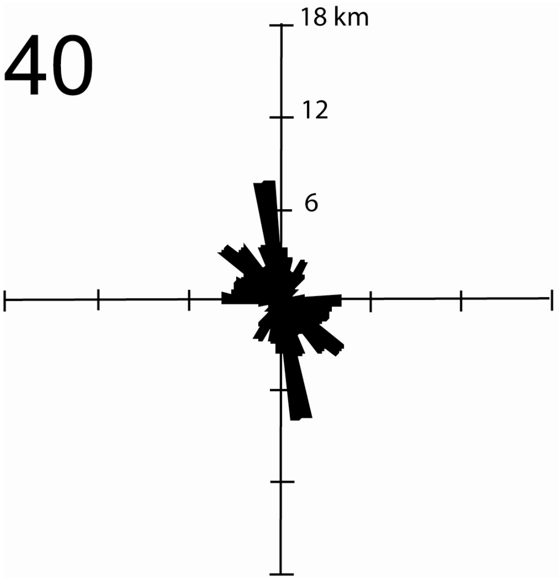


Figure 4-5. Rose diagram for streams in grid cell 40.

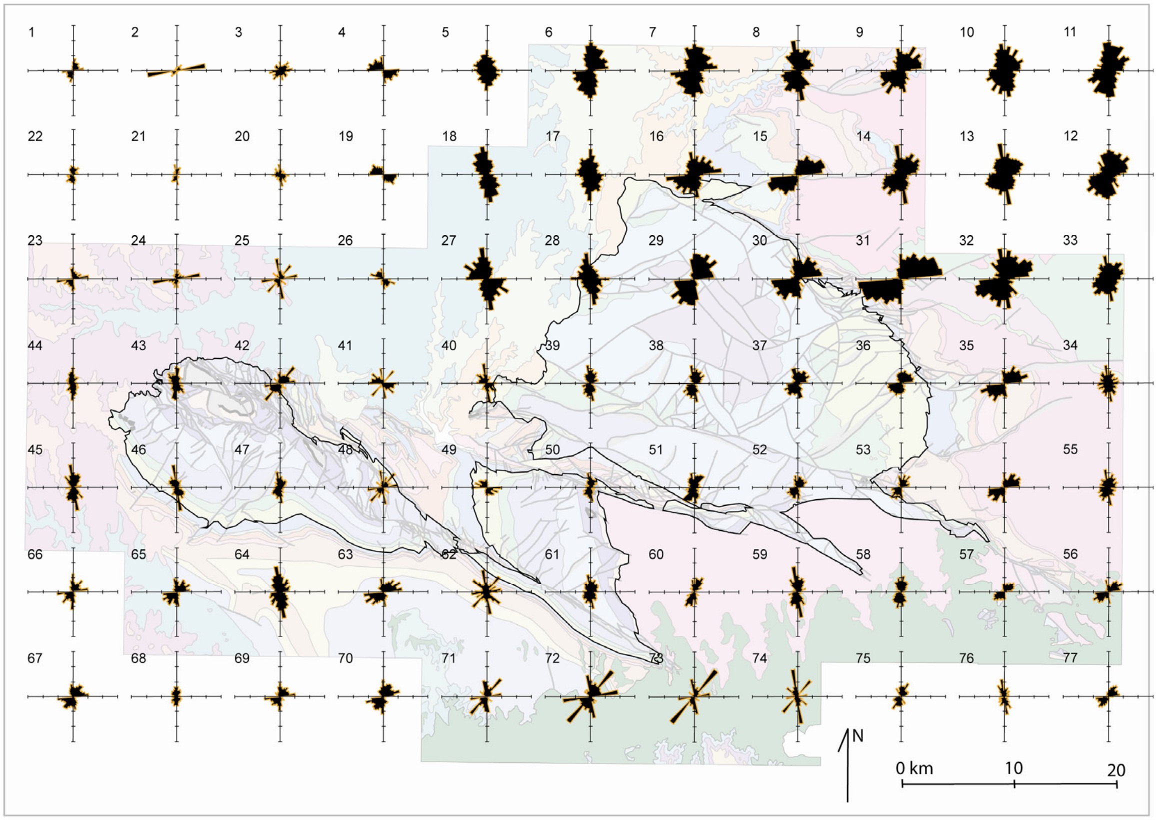


Figure 4-6. The 10 km grid cells with rose diagrams for each grid cell allow a visual aid to analyze stream orientations over the study area.

The 2.5 km rose diagrams were also created over the Hunton anticline. Figure 4-6 overlays the rose diagrams onto the study area. It is difficult to determine trends using this figure, the statistical analysis of the 2.5 km rose diagrams will provide another visual aid to help delineate preferred orientations.

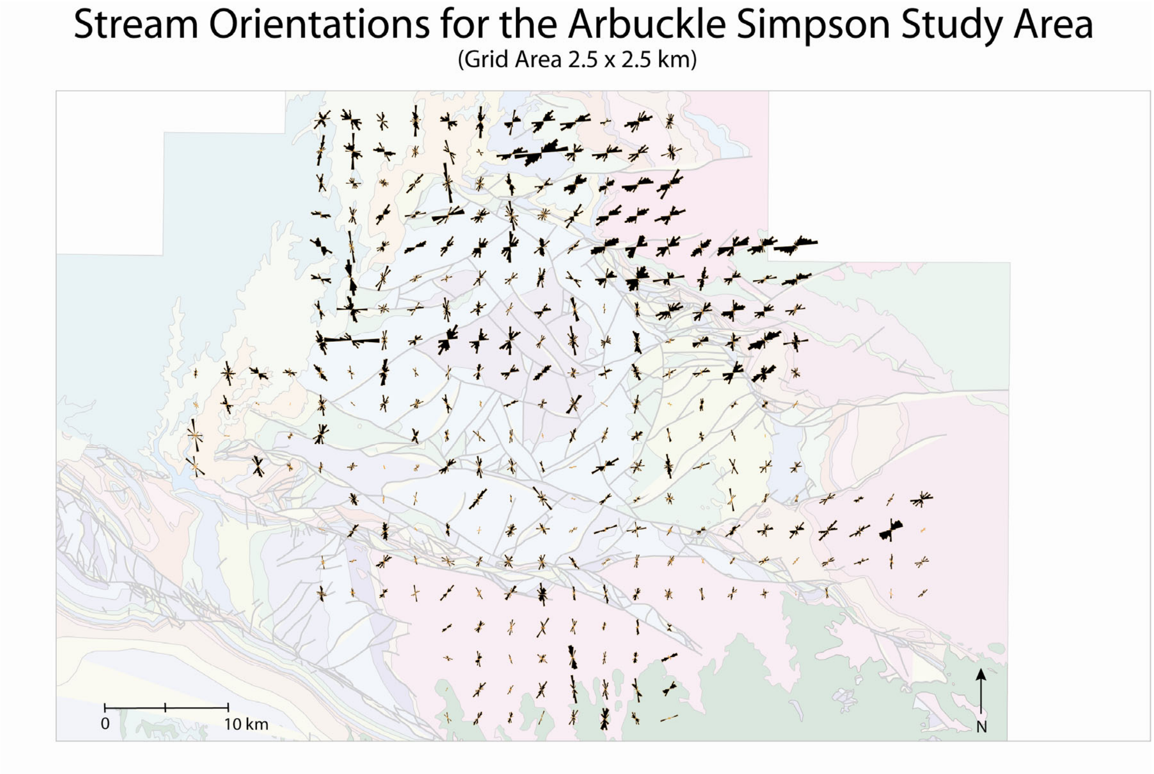


Figure 4-7. Rose diagrams for streams were created for 2.5 x 2.5 km grid cells for a more detailed interpretation over the Hunton Anticline.

By using the mean and standard deviation of the orientations for each grid cell it was possible to determine if preferred orientations existed using the polymodal orientation method. Figure 4-8 indicates that each grid cell is unique and is better characterized by using this method. The preferred orientations predicted by this method vary in strength for all three grid cells (Figure 4-8).

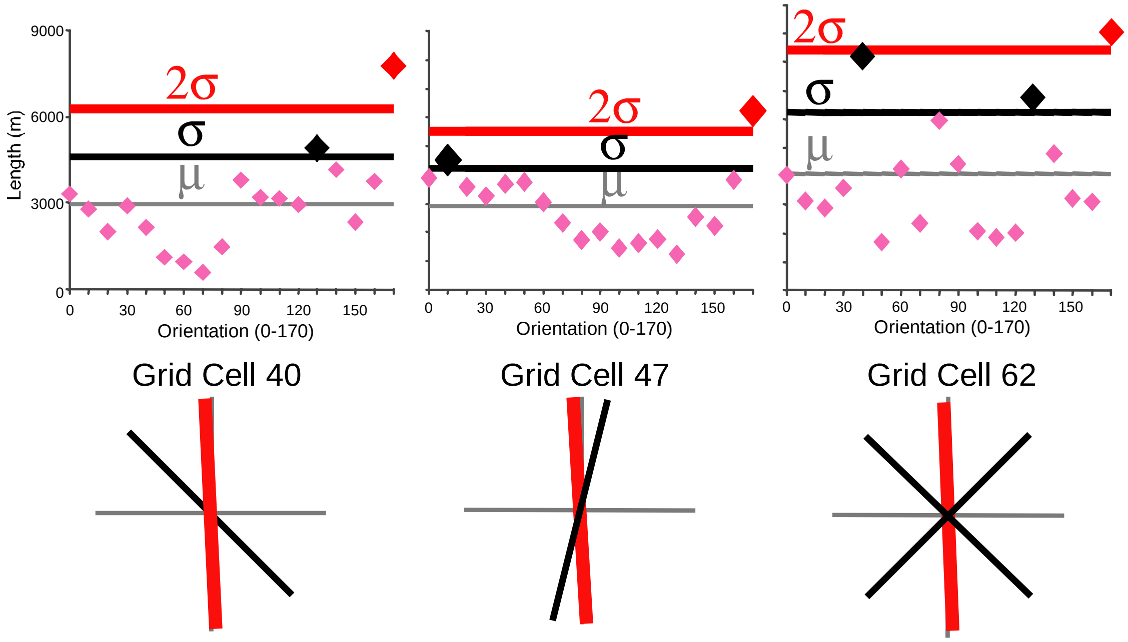
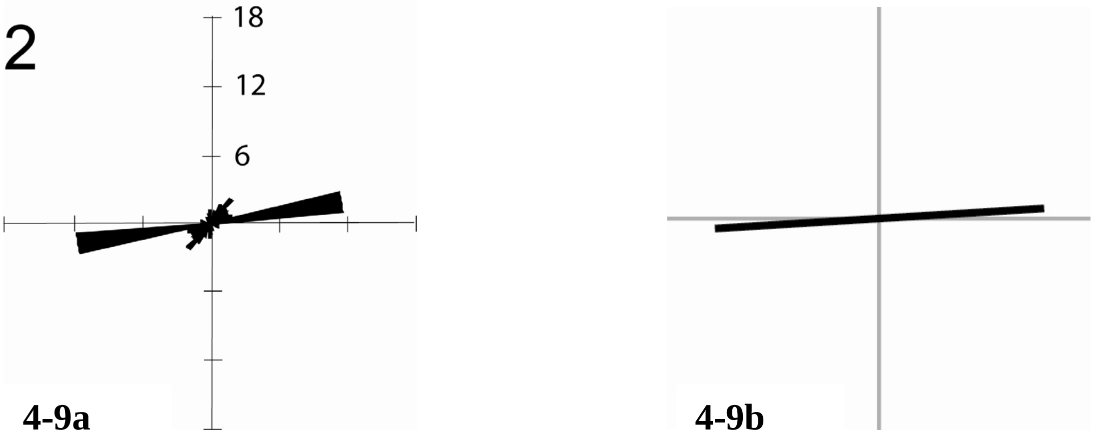


Figure 4-8. This figure shows that the statistics used to define preferred orientations allows for a better understanding of grid cell characteristics. The strength in the method is that is allows each grid cell to uniquely define preferred orientations.

Unimodal

Unimodal orientations indicate the streams are dominantly oriented in one direction (Figure 4-9). After statistically analyzing the data, it was evident that grid cell 2 was unimodal. Only one dominant orientation was present and no weak signals were present (Figure 4-9). 4 cells had unimodal orientations for 10 km stream grids, 24 cells had unimodal orientations for 2.5 km stream grids, and 8 cells had unimodal orientations for fault data. This accounts for 5 %, 8%, and 16% of the grids, respectively.

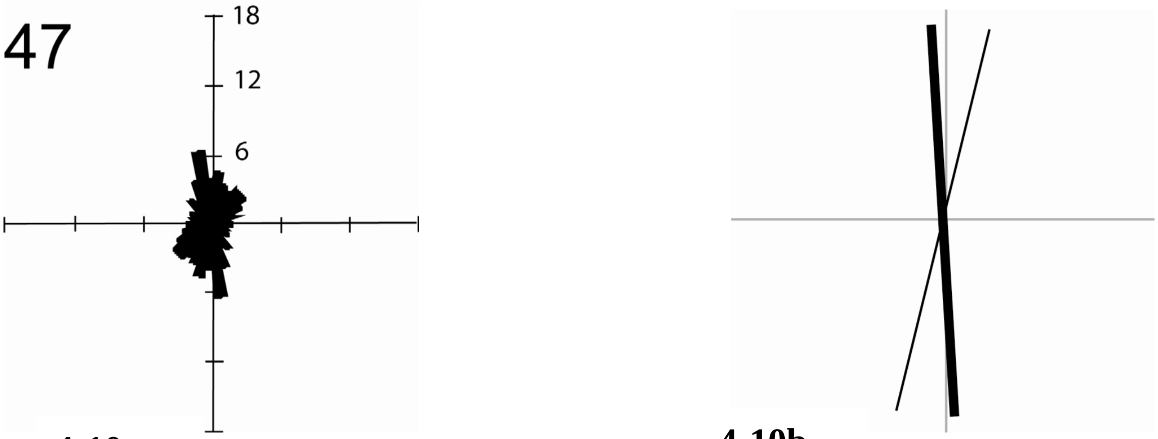


4-9a **4-9b**

Figure 4-9. Grid cell 2 is an example of unimodal orientation. 4-9a is the rose diagram for grid cell 2. After statistically analyzing grid cell 2, one orientation is preferred (4-9b).

<u>Bimodal</u>

Bimodal orientations indicated the presence of more than one significant orientation. Bimodality may have had more than two strong orientations, two weak orientations, or a strong and a weak orientation. Grid Cell 47 had bimodal stream orientations over the study area. Figure 4-10a was the rose diagram for grid cell 47. After statistical analysis one preferred orientations and one weak orientation was found (Figure 4-10b). 25 cells had bimodal orientations for 10 km stream grids, 104 cells had bimodal orientations for 2.5 km stream grids, and 10 cells had bimodal orientations for fault data. This accounts for 33 %, 34%, and 20% of the grids, respectively.



4-10a

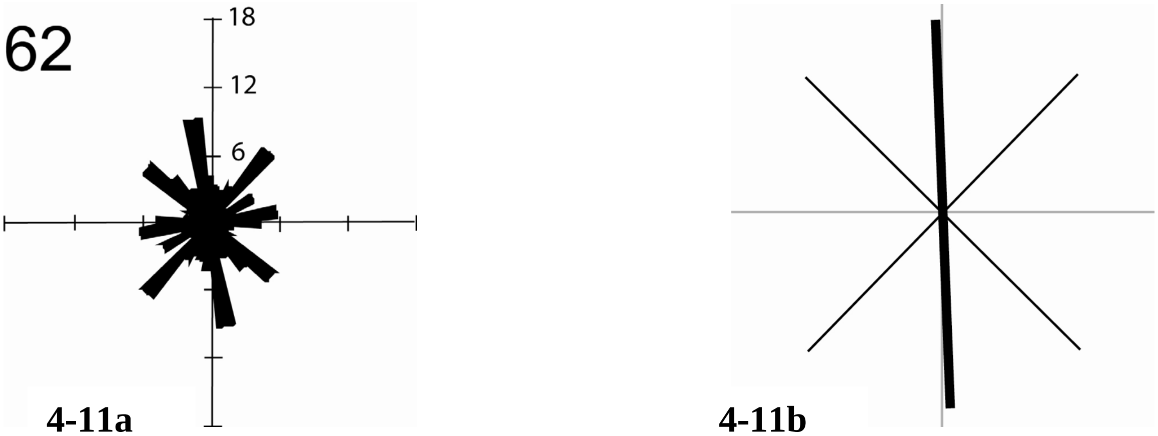
4-10b

Figure 4-10. Grid Cell 47 is an example of bimodal stream orientations over the study area. Figure 4-10a is the rose diagram for grid cell 47. After statistical analysis one preferred orientations is found and one weak orientation (4-10b).

<u>Polymodal</u>

Polymodal behavior is a distinctive behavior in which many dominant orientations are distinguishable. After conducting the statistics on grid cell 62 we found that it is polymodal (Figure 4-11). One strong orientation was present and two weak orientations were orthogonal to the strong signal. 42 cells had polymodal orientations for 10 km stream grids, 176 cells had polymodal orientations for 2.5 km stream grids, and 32 cells had polymodal orientations for fault data. This accounts for 62 %, 58%, and 64% of the grids, respectively.

The areas that show polymodal orientations were dominantly in highly faulted areas. Faults and fractures were influencing the polymodal characteristics. Both open and closed faults and fractures were present and were creating conduits and barriers to flow. A more detailed analysis of each grid using water chemistry and electrical conductivity methods will be help determine more detailed flow paths within a grid cell.



4-11a

4-11b

Figure 4-11. Grid Cell 62 is a good example of polymodal stream orientations. In Figure 4-11a it is difficult to determine if a preferred orientation exists. After calculating the statistics it is evident that it is polymodal (4-11b).

Regional Analysis

All rose diagrams for streams were statistically analyzed for both the 10 km grid cells and the 2.5 km grid cells. The faults were analyzed only at the 10 km scale because at a higher resolution there would be a lack of sufficient data for analysis (Figure 4-14). After completing the statistics on each of the rose diagrams, the strong and weak orientations were plotted over the study area (Figure 4-12).

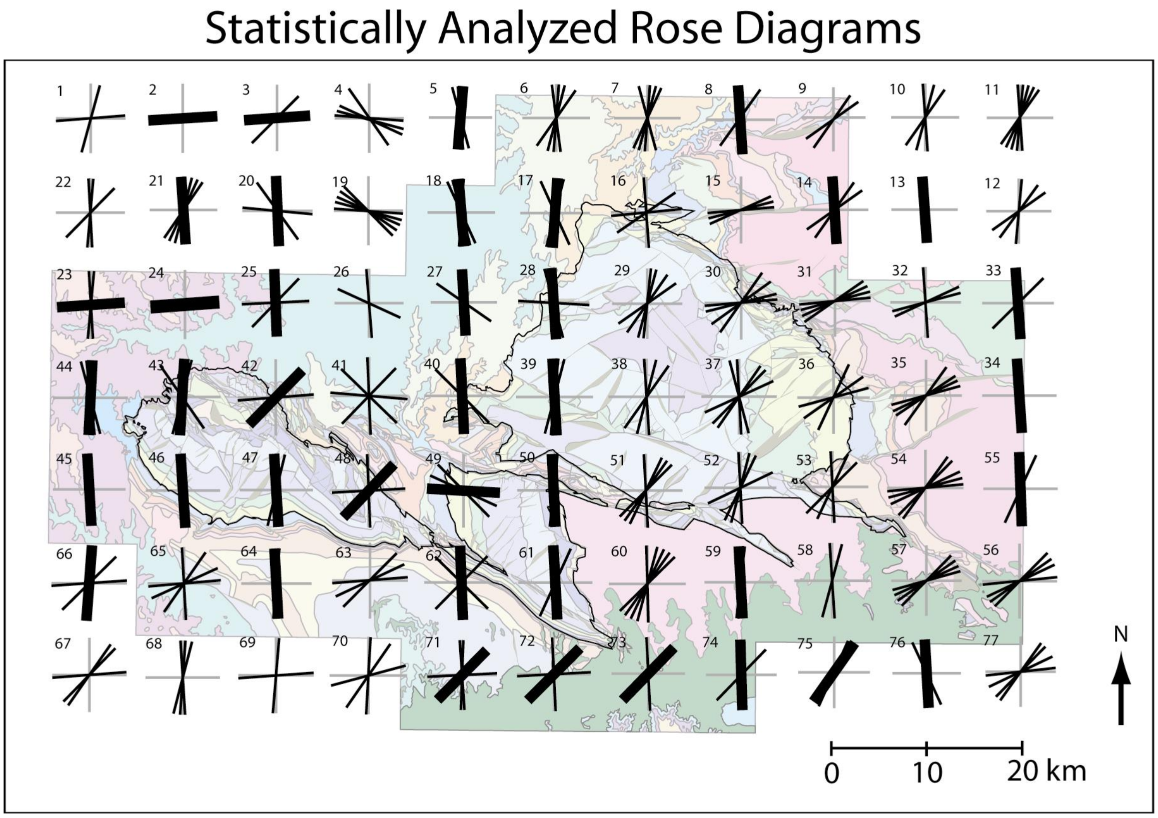


Figure 4-12. The 10 x 10 km streams grid cells map for streams are statistically analyzed and plotted over the study area. Strong signals are indicated by the dark black line, and weaker signals are indicate by a thinner black line.

A more detailed statistical analysis over the Hunton Anticline using the 2.5 km grid cells shows some interesting features (Figure 4-13). The higher resolution grid cells support the N-S trends being seen in the streams and faults.

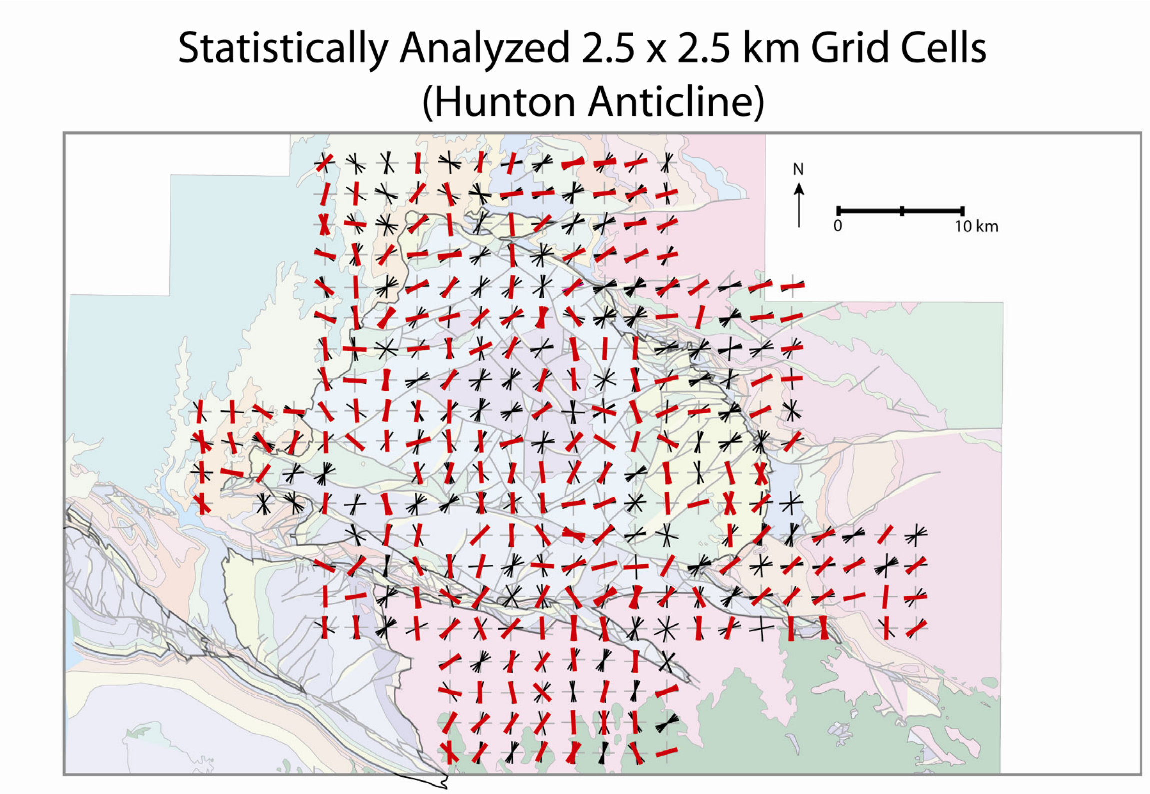


Figure 4-13. Statistically analyzed 2.5 x 2.5 grid cells over the Hunton Anticline. The thick red lines indicate strong signals, the black lines indicate weak signals.

In the Oil Creek formation (Ooj), streams are not present. The lithology of the Oil Creek formation is a sandstone, which is very friable, porous, and permeable. There may be fewer streams in this area due to these characteristics.

The GIS faults layer was studied to determine what preferred orientations can be seen (Figure 4-14). The data layer for the faults is much smaller than the streams due to the number of faults in the study area. This explains why some grid cells do not have any data.

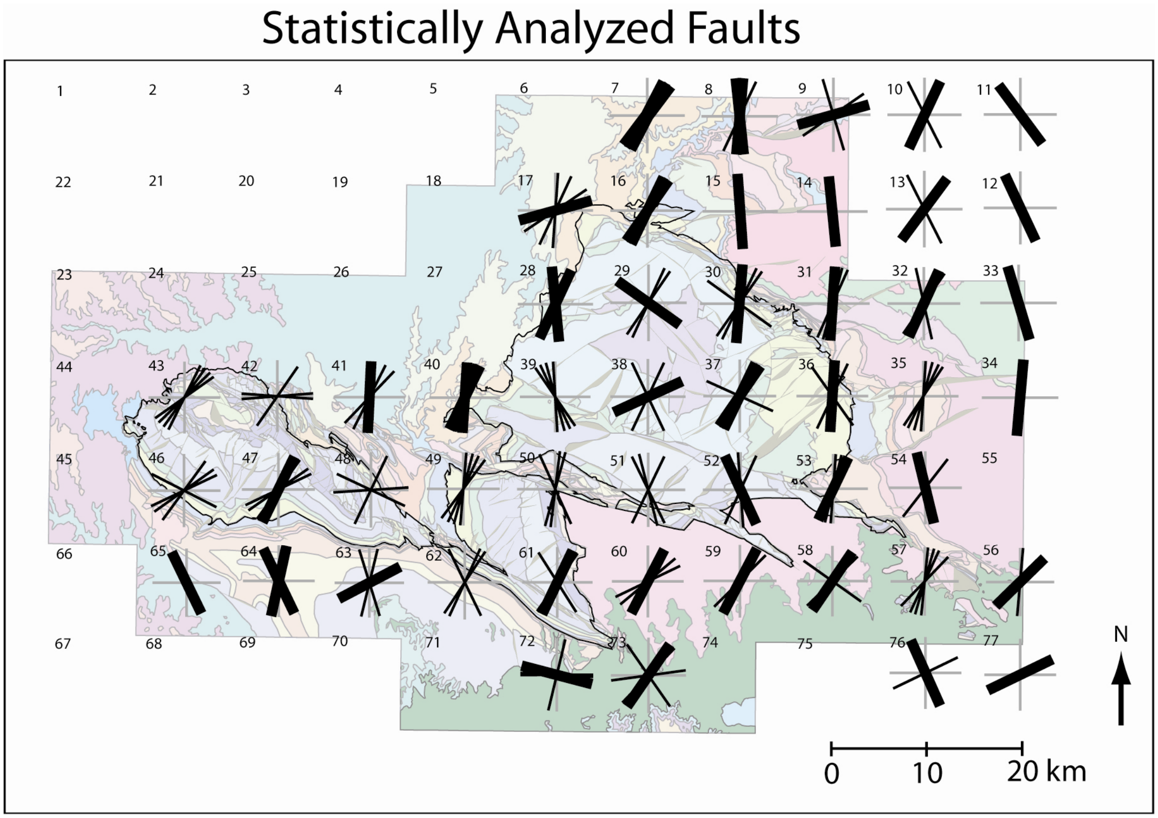


Figure 4-14. The preferred fault orientations can be seen. The preferred orientations are much more difficult to see using this map, however they do not follow the preferred orientation found by Marshak (2003) of W-NW, but instead are generally orthogonal to this direction.

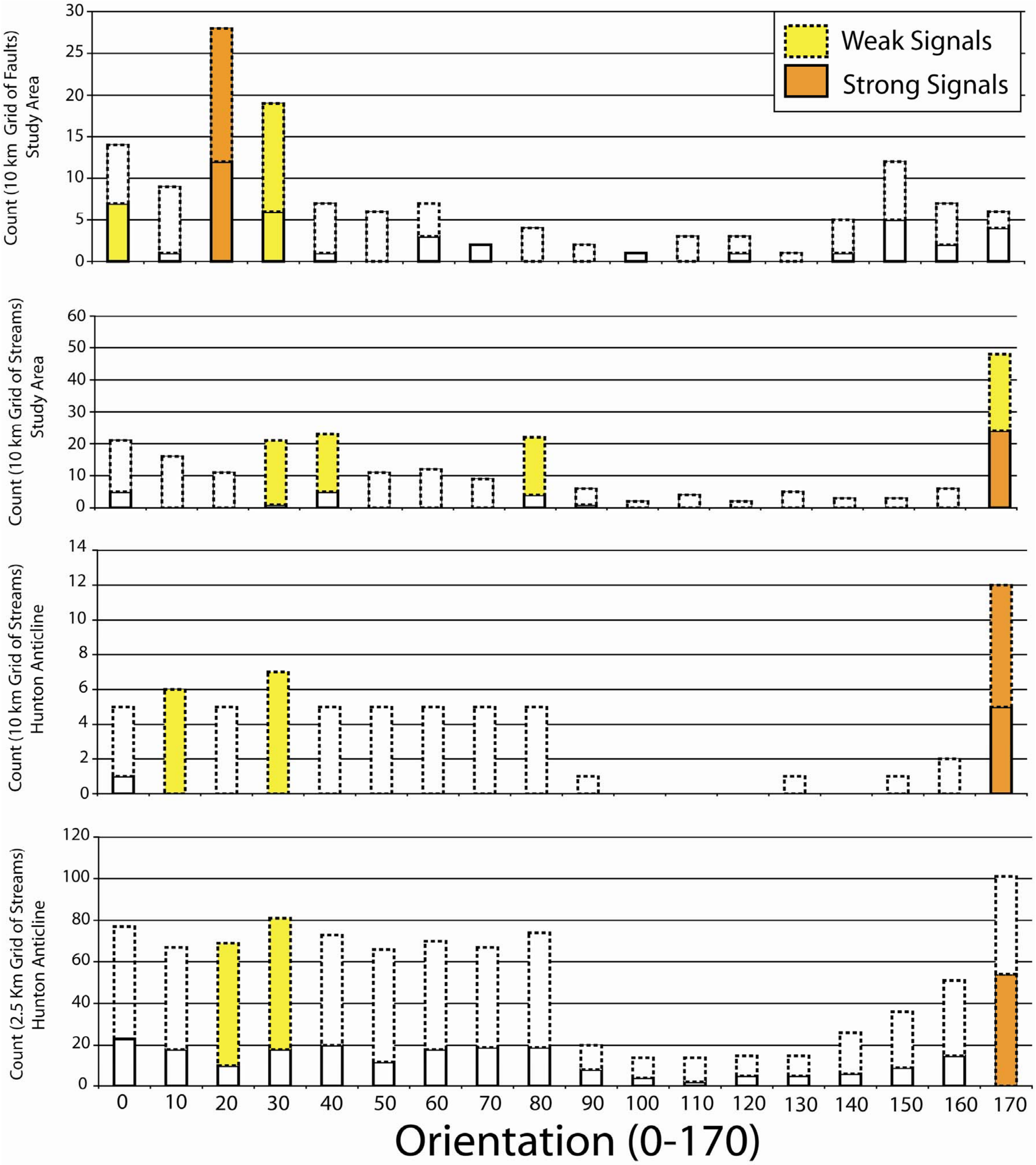


Figure 4-15. A histogram of the 10 stream orientations shows a preferred orientation of 0° and 170° and a 20° and 30° trend. Other orientations are present but are not as dominant this would be expected in an area with a complicated structural history such as the Arbuckle Mountains. The orientations of the 2.5 km streams and faults also indicate a preferred orientation similar to the 10 km stream layer.

By creating a histogram of the streams and faults it is evident that the streams and fault have similar trends. Figure 4-16 and 4-17 are used to better visualize the extent the preferred orientations over the aquifer. The grid cells are colored for strong and weak orientations of 0° and 170°. Figure 4-17 grid cells are colored for 20° and 30° orientations. Potential flow lines for the aquifer can be determined by observing these trends and using the potentiometric map of the area to aid in the analysis.

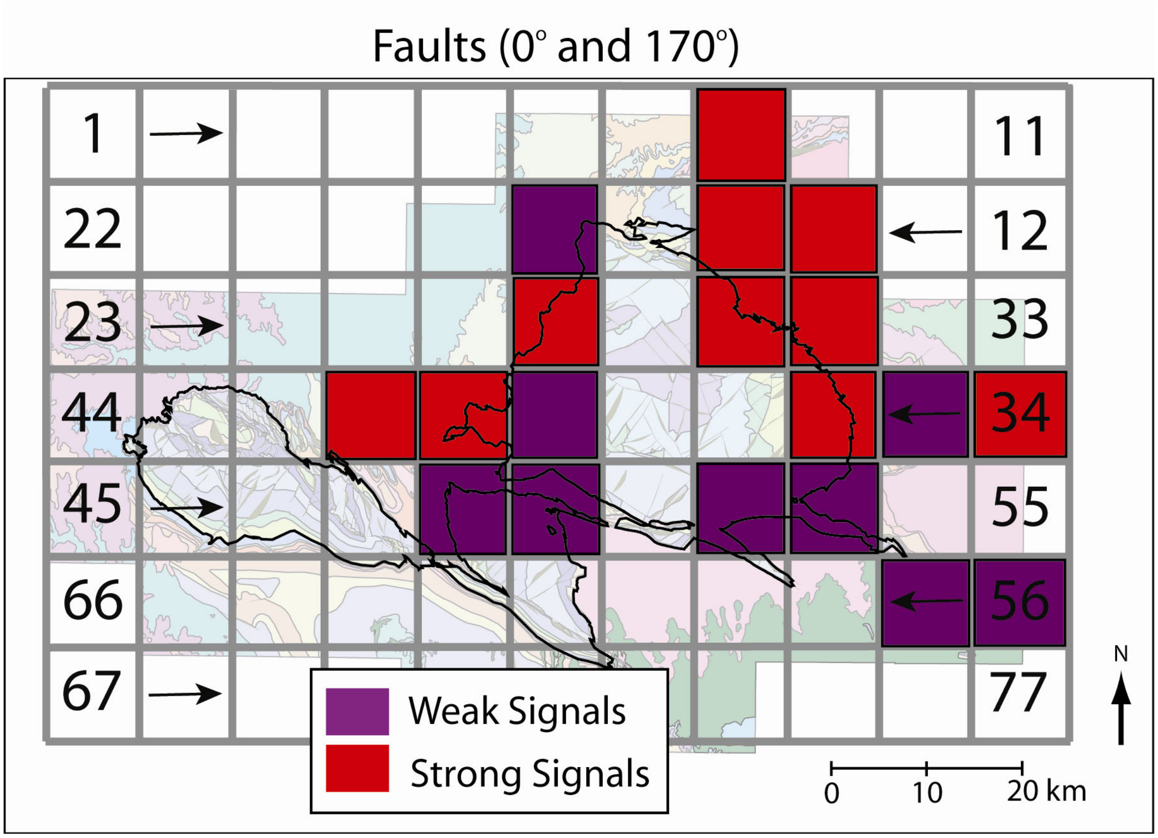


Figure 4-16. The GIS fault layer is used to determine if a correlation exists between streams and faults. The GIS fault layer has less bias than the streams layer due to digitizing techniques.

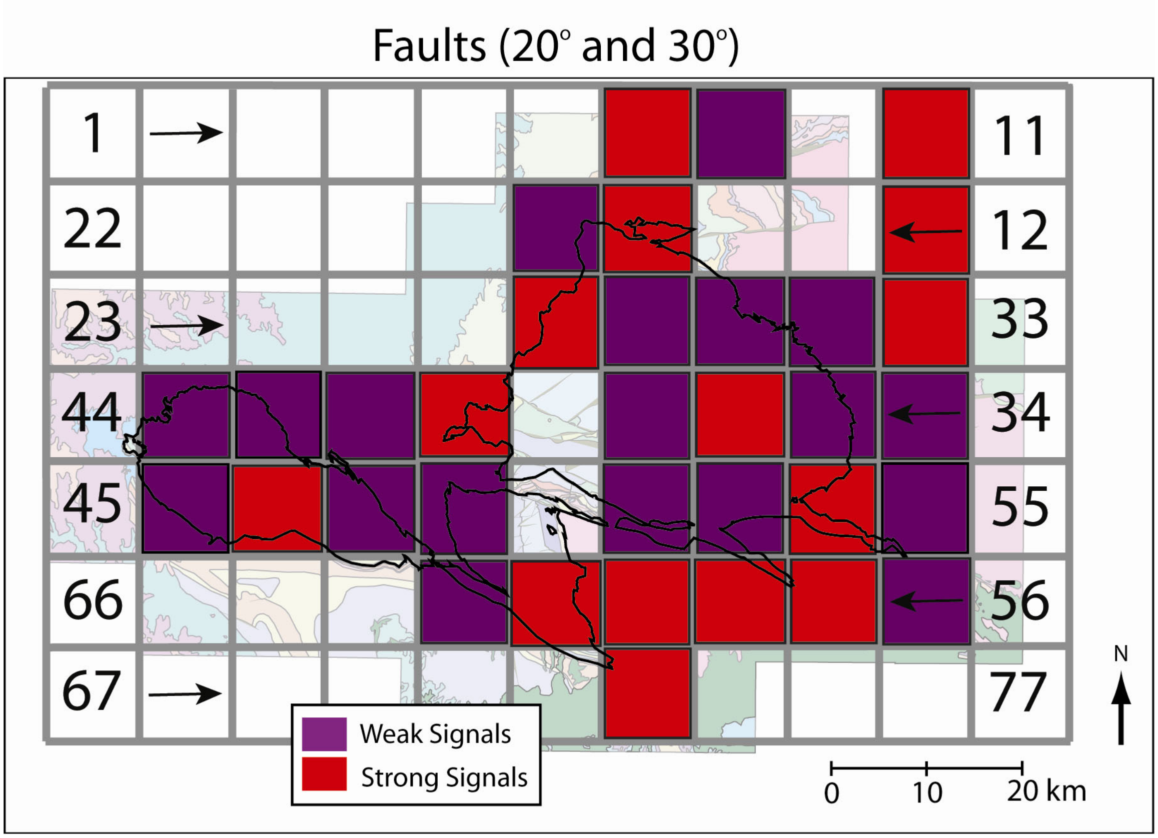


Figure 4-17. The GIS fault layer is used to determine if a correlation exists between streams and faults. This map is for strong and weak signals at 20 and 30 degrees.

The GIS streams layer is also analyzed and 0 and 170 degrees (Figure 4-18).

Another map for orientations of 20 and 30 degrees is observed (Figure 4-19)

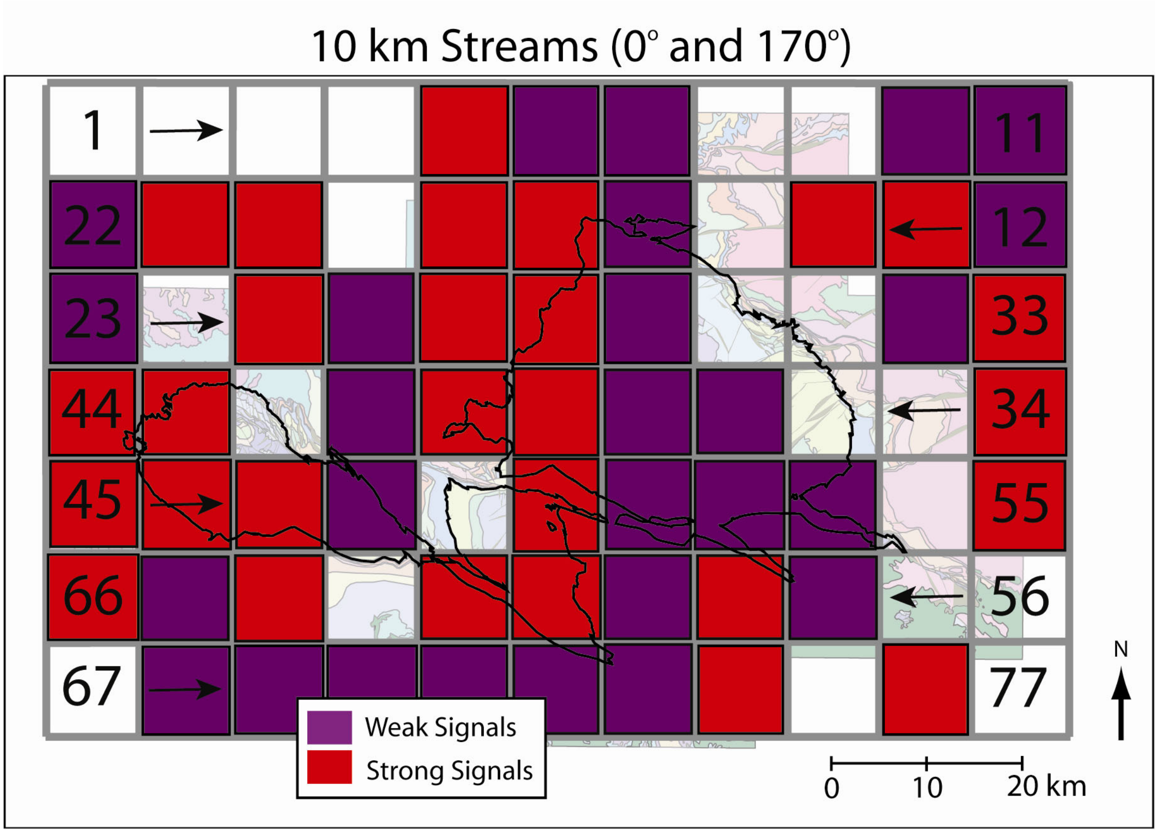


Figure 4-18. The GIS stream layer is used to determine if a correlation exists between streams and faults. This map is for strong and weak signals at 0 and 170 degrees.

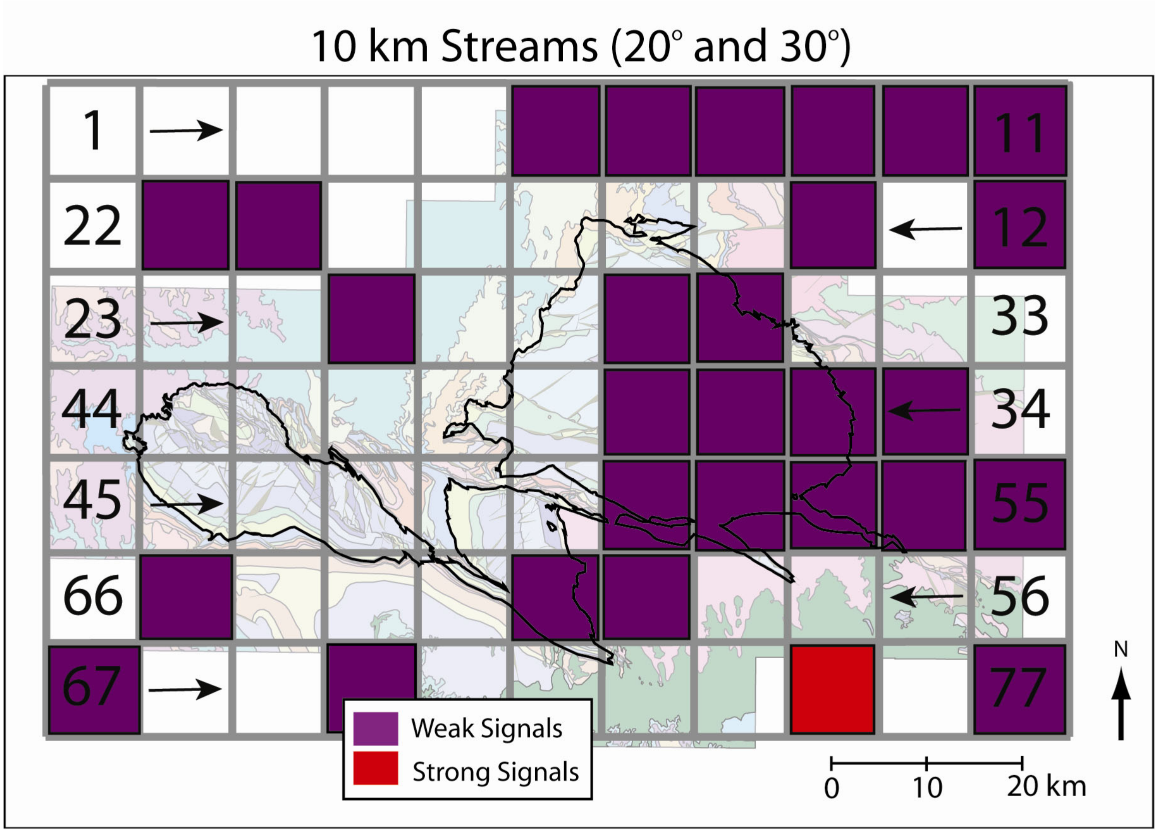


Figure 4-19. The GIS stream layer is used to determine if a correlation exists between streams and faults. This map is for strong and weak signals at 20 and 30 degrees.

Field Work and Stream Data Correlation

The field work conducted over the study area was compared to stream and fault data in that grid cell. The grid cells field work was conducted in was 37, 59, and 47.

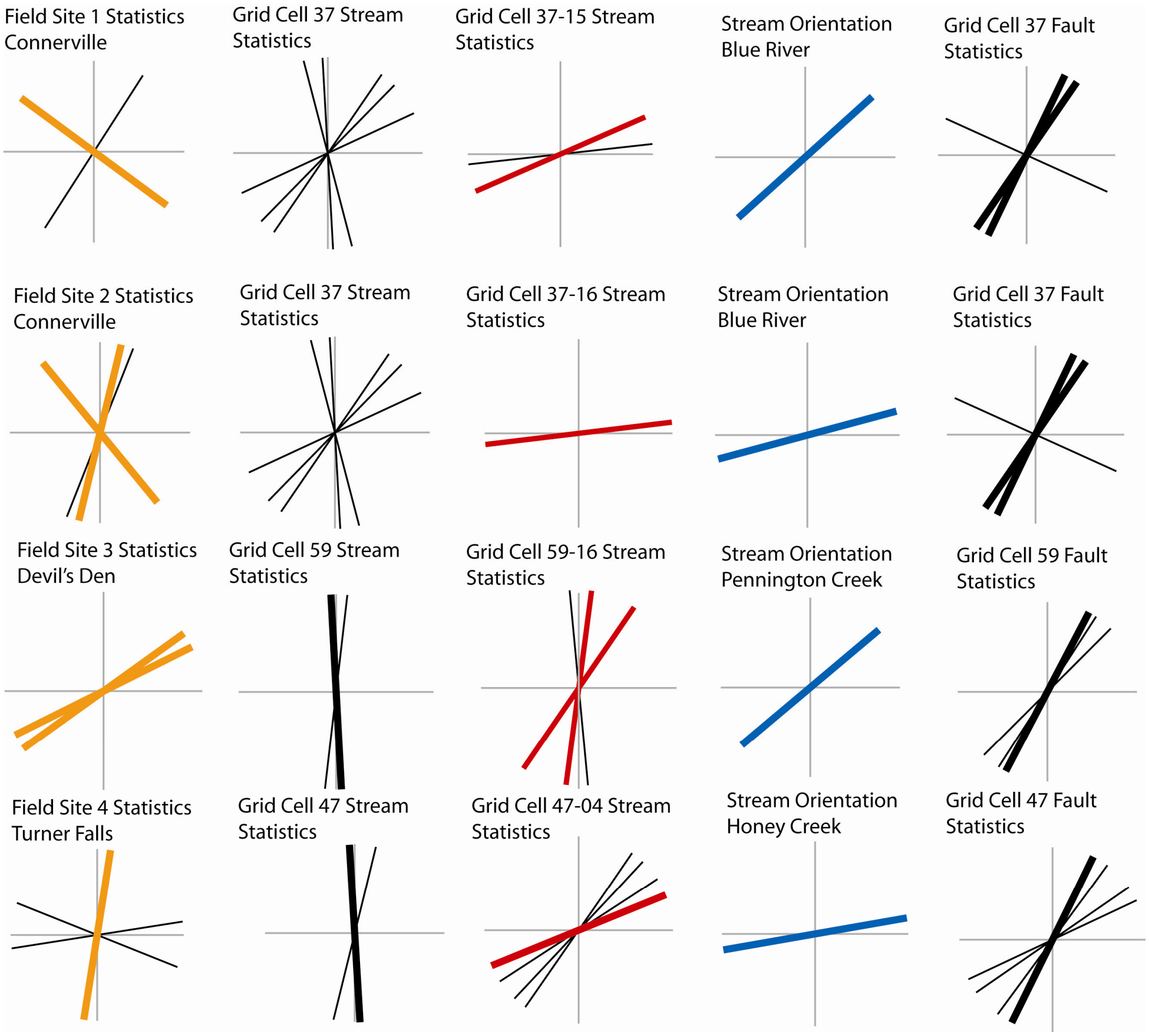


Figure 4-20. A comparison between field work, streams, and faults are made using this figure.

There is a correlation between field work and stream data for grid cells 37 and 47.

Though a direct correlation cannot be made between stream and faults using figure 4-20, a histogram of orientations for streams and faults indicates a correlation between the two using figure 4-15.

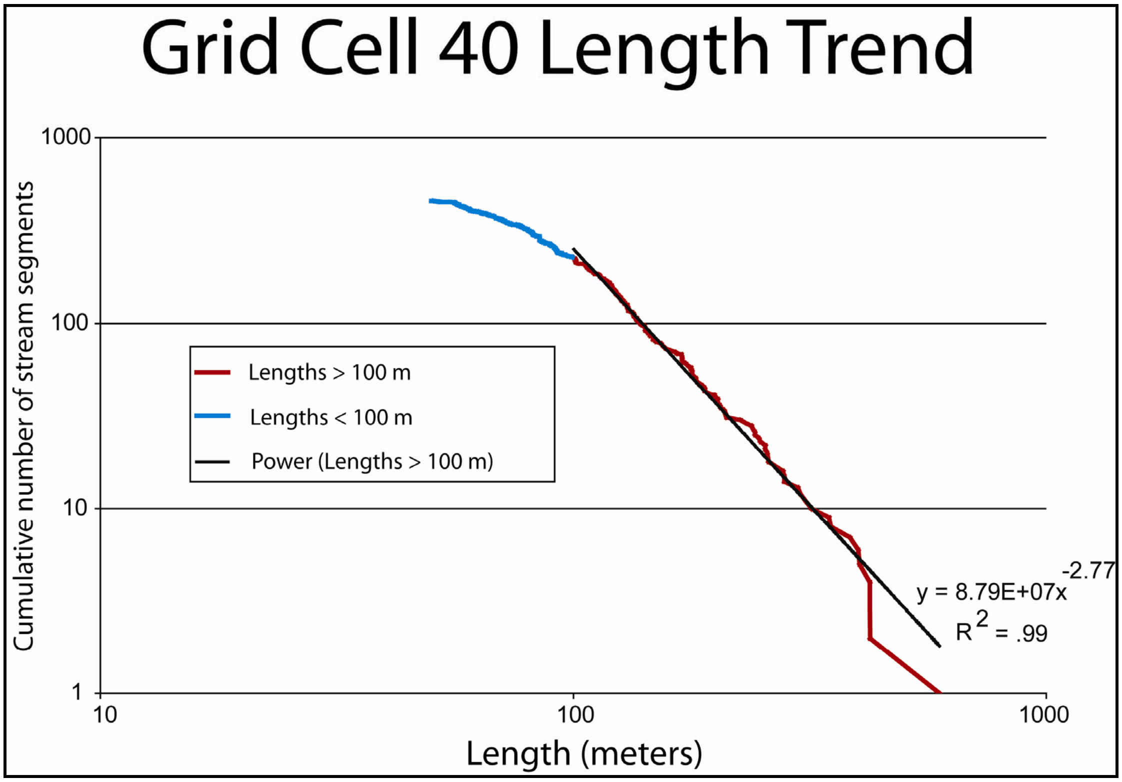


Figure 4-21. The stream length trend of grid cell 40 shows the power law function has a fit with an R^2=99% for length data greater than 100 meters.

Length trends for each formation were analyzed for the 2.5 km grid cells. Figure 4-22 shows the formation vs. length without the greater density bias removed. Figure 4-23 is a modified version with the greater density area removed.

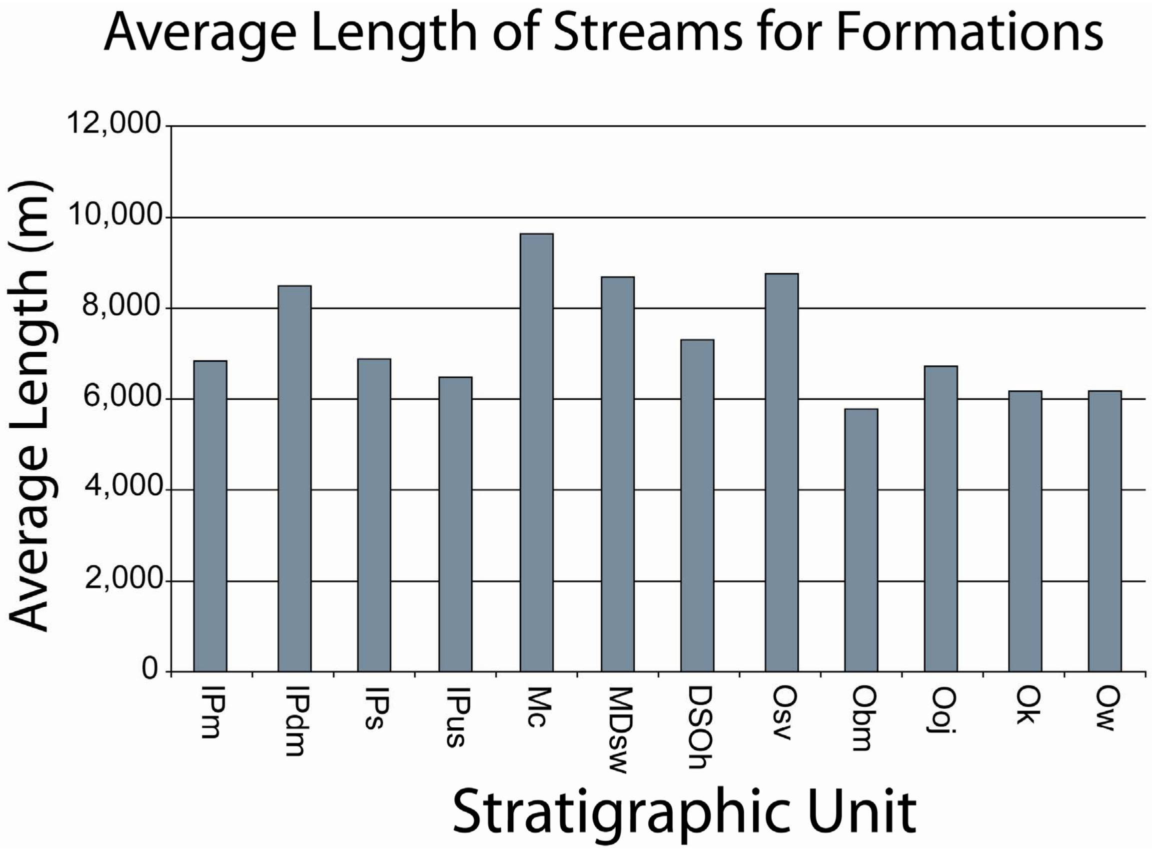


Figure 4-22. The average length of each formation for the 2.5 km grid cells is plotted as a bar graph to better visualize formation characteristics.

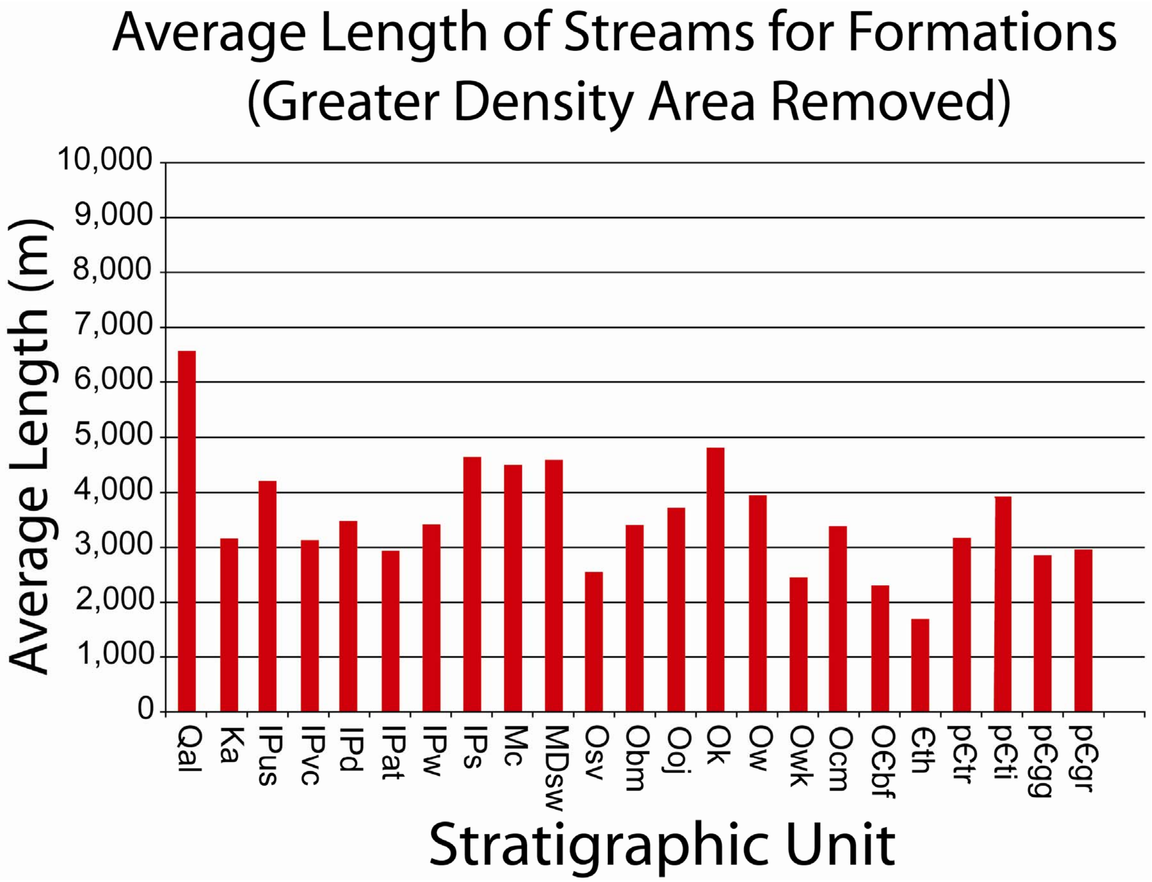


Figure 4-23. After the greater density area is removed the characteristics of each formation can be better analyzed.

The results from the GIS streams layer allowed for orientations to be plotted on rose diagrams. The rose diagram created for grid cell 40 is an example of one of many created over the study area (Figure 4-5).

The density map (Figure 4-24) which is created indicates which portions of the study area contain more streams. The top right portion of the study area contains a greater density of streams, which will be discussed in more detail later.

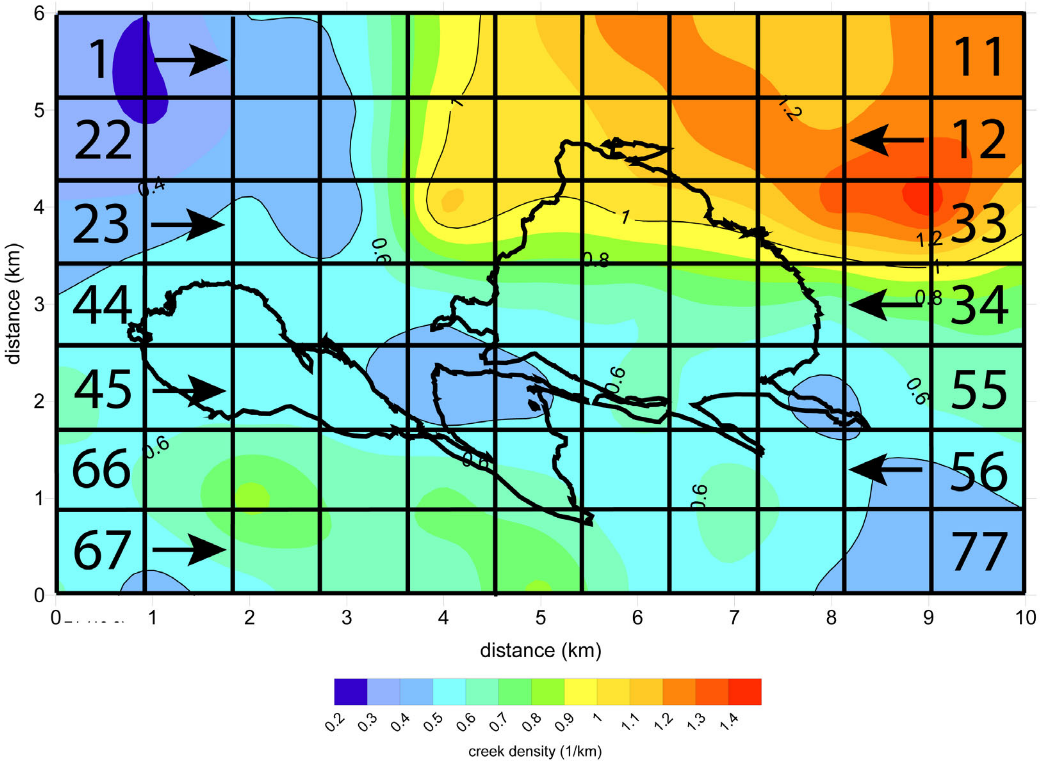


Figure 4-24. The density map over the study area indicates that there is a greater density of streams near grid cells 13 and 32. This is due to bias in the GIS stream created by human factors.

To fully understand the characteristics of different formations their densities were plotted on a bar graph (Figure 4-25 and 4-26). Due to the bias in GIS layer of stream density two different graphs are created. Figure 4-25 shows the density of streams for formations before the greater density area was removed from the data. Figure 4-26 shows densities after the greater density area is removed from the data.

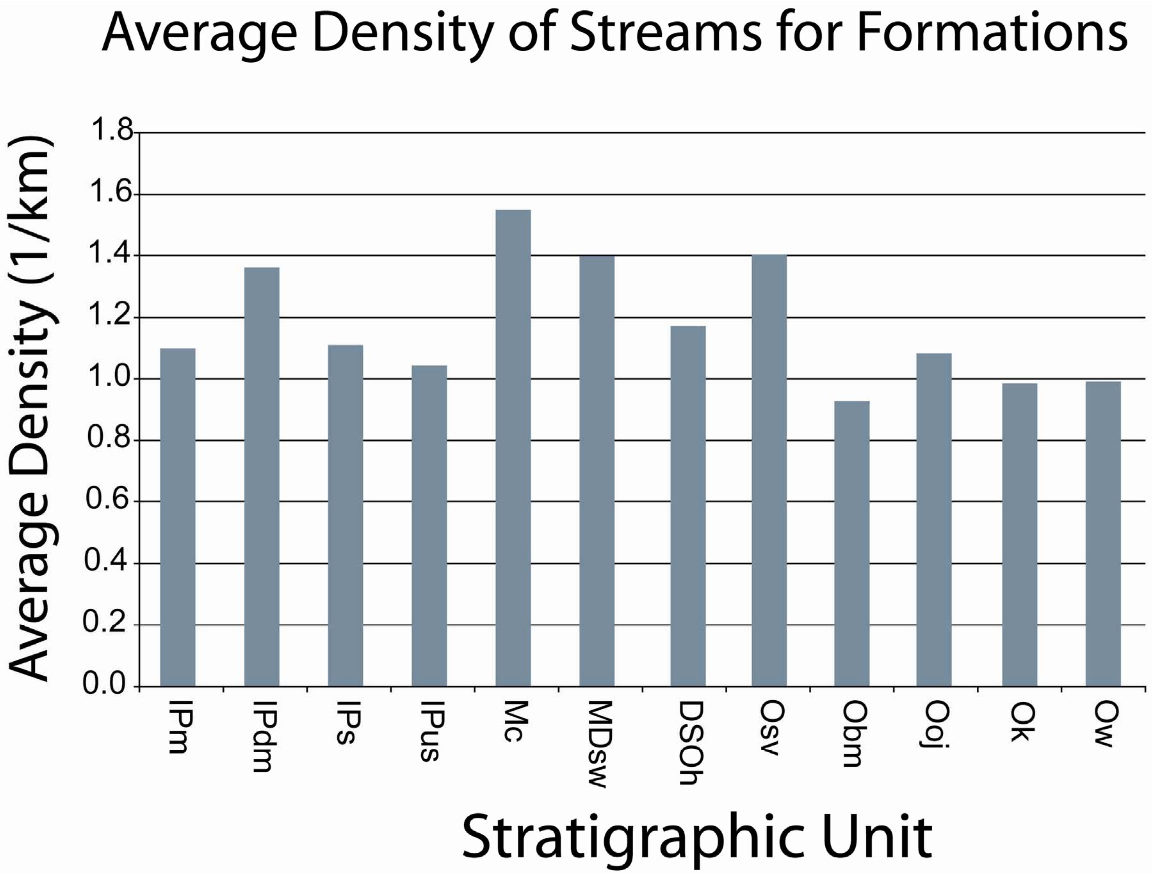


Figure 4-25. This bar graph shows that average density for each formation varies. The Caney Shale (Mc) has the greatest density of streams.

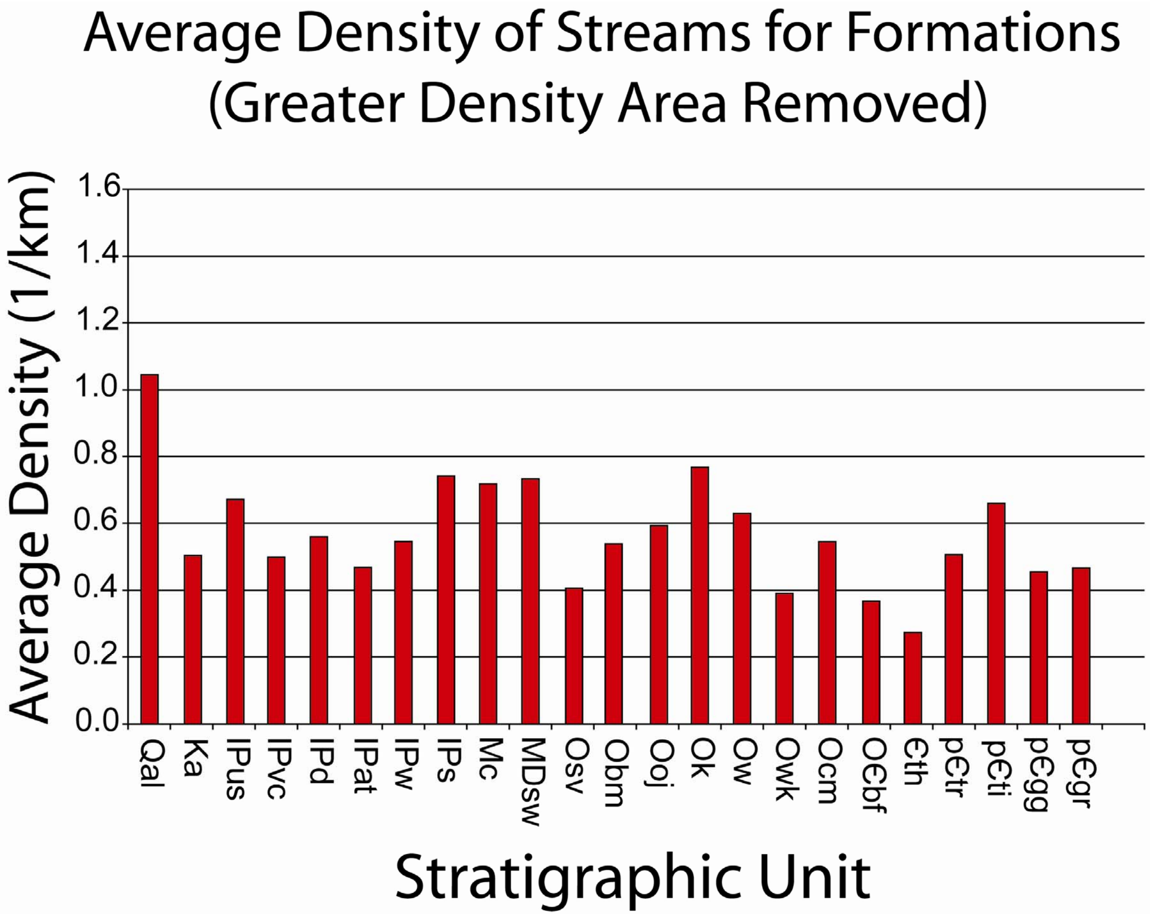


Figure 4-26. In this graph the Timbered Hills Group (Cth) has a low density of streams.

CHAPTER V

DISCUSSION

The length, orientation, and density maps compiled help better understand structural and hydraulic characteristics of the aquifer. Geomorphic influences are also important in understanding the data. The maps created using GIS allow for a more detailed analysis of stream characteristics with respect to geomorphic factors. The polymodal orientation method used to analyze orientation is a useful tool for helping better understand preferred orientations over the study area. The statistical method applied to the 10 km and 2.5 km grids over the study area are discussed. Field work and stream data correlations are discussed. Finally, the surface water and ground water interaction for the study area is interpreted using preferred orientations.

Geomorphology and Stream Orientations

The shaded relief map indicates that over the Hunton Anticline there is little relief (Figure 4-1). Changes in stream orientations would not be influenced strongly by the topography, especially over the Hunton Anticline. The aspect map does not appear to show any preferred orientation (Figure 4-2). To analyze the aspects in more detail to evaluate the trends quantitatively were beyond the scope of this study. The correlations observed between the data analyzed indicated that a significant geological influence is present in the data, and the influence of aspect was not analyzed more quantitatively.

The hillslope map (Figure 4-3) shows that elevation changes very little over the Hunton Anticline. This also may indicate that stream orientations are being influenced by the underlying lithological characteristics.

A general lithology map suggests that stream orientations must be explained by changes in subsurface fractures, as there are few to no changes in stream direction at lithologic contacts (Figure 4-4). The unique structural history of the Arbuckle-Simpson Mountains could explain the less dominant (20°-30°) orientation of streams that can be seen in the histograms. There are three events that occurred during the Oklahoma Aulacogen that could create different fault patterns over the study area (Wickham, 1978).

Field Work and Stream Data Correlation

Preferred orientations for GIS streams and faults, streams at field sites, and field fracture data all demonstrate preferred orientations (Figure 4-20). At different grid resolutions, and different scales, different orientation trends are present. However, it can be seen from Figure 4-15 that the streams have a preferred orientation of 170°-0^o and 20-30^o for the streams. The 10 km and 2.5 km grid cells both support this preferred orientation, as well as the faults, although the north-south orientation is not strong in the fault data.

Orientation Analysis

Orientations over the study area were difficult to analyze using basic rose diagrams. The polymodal orientation statistics allowed the dominant signals to be resolved although there was on 20 degrees difference between the dominant orientations.

Over the study area, three different modal characteristics were found. Unimodal, bimodal, and polymodal characteristics were all present. Some grid cells, such as grid cell 43 showed polymodal characteristics (Figure 4-12), but there was no preferred orientation in this grid, which was likely due to the structural complexity of the area that occurred in this region. Grid cell 62 also shows this same characteristic with no strong signal as well as few other grid cells. In regions with a complex structural history, such as the Arbuckle Mountains, it is expected to find such a behavior.

The polymodal orientation method enables preferred orientations to be seen, while also preserving less dominant signals. A N-S (0^o and 170^o) preferred orientation can be seen in the regional coverage of stream data, and also a second $20\text{-}30^o$ preferred orientation (Figure 4-12). This trend can be better seen using a histogram analysis (Figure 4-15). Marshak (2003) found dominant trending W-NW lineaments in the Arbuckle Mountains created by a failed rift zone. While there may be a few weak signals in that direction, the strong signals indicated most of the streams are oriented N-S and at $20\text{-}30^o$. The western portion of the Hunton Anticline is dominated by the N-S trending lineaments, while the central region contains less strength in that direction. Weak signals dominate the central portion of the Hunton Anticline, but still indicate the presence of a N-S orientation. The majority of grids for both stream and fault data did show a preferred orientation, which was not unexpected for this type of aquifer. What is unexpected is that none of the preferred orientation correlated with the strong northwest trend for the major faults in the area. The signal was instead orthogonal to this trend and correlated to the direction of minimum stress.

Further work on faults in the area is suggested by the stream analysis. The fault mapping that was performed was already difficult as most of the faults in the area are not readily apparent at the surface. The fault data does not have a significant number of north-south signals, but the streams see this orientation as the most dominant of the region. If streams in the area are following some north-south trending faults, they are likely more highly weathered and covered with some amount of alluvium. Thus it might be expected to find some north-south trending faults that were not mapped by previous workers.

Length and Density

The length trend for grid cell 40 indicated that the power law was a good fit for predicting stream lengths (Figure 4-21). The fit was similar for fault data. The length trends for each formation showed that the Caney shale (Mc) observes the longest length of streams (Figure 4-22). However, this trend was not statistically significant.

The less permeable shale could be allowing for longer stream lengths. After the stream density bias was removed from the dataset, the Caney shale was still indicative of the longer stream lengths (Figure 4-23). The Cambrian Timbered Hills Group (Cth) has a very low stream length. Again, this trend was not significant. The Timbered Hills Group, which includes the Reagan sandstone, was characterized by crystalline limestone and coarse grained sandstone. The higher permeability sandstone may be allowing for more infiltration and decreasing the stream length.

The density of streams over the study area (Figure 4-24) indicated that some bias was present in the data. An increase in the amount of streams in the upper right portion of the map over a very regular rectangular area was obvious. The boundary for this increase traveled from grid cell 5, south to grid cell 27, and east to grid cell 33. This increase in stream density was present in the density map (Figure 4-24). Some bias was introduced by the individual or algorithm that created the GIS stream layer. The advantage to this bias was that more data was available to analyze in the upper right corner of our study area. It was difficult to characterize trends for each formation using the density map. By trying to visualizing the density for each formation using it becomes evident that no trends existed for formations regarding stream density (Figures 4-25 and 4-26).

CHAPTER VI

CONCLUSIONS

The advantage of using a GIS layer of streams and faults to characterize subsurface aquifers is the amount of data available. Using streams and faults as lineaments to study subsurface characteristics is an underutilized, yet cost efficient tool. The results of this study indicate that 1) a dominant 170^{o}-0^{o} trend evident in stream data exists over the study area as well as a less dominant 20-30^{o} trend that exists in both stream and fault data. 2) The statistical analysis indicates stream and fault orientations correlate. 3) The correlation between the streams and faults can be used to infer subsurface characteristics as demonstrated by correlation with outcrop fracture data. 4) The stream density data indicate that no trends exist between density or length and stratigraphy. 5) Geological processes appear to have a significant influence on stream orientations in the study area. 6) The polymodal orientation method used in this thesis is an effective way to analyze orientations. The method allows for consistent orientation signals to become obvious even when there is little separation between signals. 7) The method used to study the aquifer is cost effective with limited bias in the studying aquifer characteristics. As GIS stream layers are readily available, it would be feasible to study streams as a preliminary analysis of the subsurface characteristics in most fractured aquifers.

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APPENDIX

Appendix 1 (Stratigraphic Units)

Abbreviation	Stratigraphic Unit
Qal	Quaternary Alluvium
Ka	Antlers Formation
IPvc	Vanoss Group
IPat	Atoka Formation
IPw	Wapanuck Formation
IPs	Springer Formation
IPus	Union Valley Formation
Mc	Caney Shale
MDsw	Sycamore Limestone, Welden Limeston, Woodford Shale
Osv	Sylvan Shale, Viola Group
Obm	Bromide, Tulip Creek, McLish Formation
Ooj	Oil Creek Formation
Ow	West Spring Creek Formation
Ok	Kindblade Formation
Owk	West Spring Creek and Kindblad Formation
Ocm	Cool Creek and McKenzie Hills Formation
OЄbf	Butterly Dolomite, Signal Mountain Formation, Royer Dolomite, Fort Sill Limestone
Єth	Timbered Hills Group
pЄti	Tishimingo Granite
pЄtr	Troy Granite
pЄgr	Grandiorite
pЄgg	Granitic Gneiss

VITA

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Title of Study: USING STREAMS AND FAULTS AS LINEAMENTS TO DELINEATE AQUIFER CHARACTERISTICS

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Scope and Method of Study: Lineaments are mappable features on the surface that can reflect subsurface characteristics. They can be created by topography, soil cover, vegetation, streams, and faults. An assessment of the Arbuckle-Simpson aquifer in south-central Oklahoma was made based on the stream and fault data collected using GIS. Lineaments have been studied for exploration of both oil and water. Studies have shown that the use of lineaments can be a useful tool in both cases. Streams are morphological features that are easy to detect but have not been fully utilized when analyzing subsurface fracture characteristics. GIS stream and fault properties of density, length, and orientation can be analyzed and compared with outcrop fracture data to correctly determine if a correlation can be made.

Findings and Conclusions: The advantage of using a GIS layer of streams and faults to characterize subsurface aquifers is the amount of data available. Using streams and faults as lineaments to study subsurface characteristics is an underutilized, yet cost efficient tool. The results of this study indicate that 1) a dominant 170^{o}-0^{o} trend evident in stream data exists over the study area as well as a less dominant 20-30^{o} trend that exists in both stream and fault data. 2) The statistical analysis indicates stream and fault orientations correlate. 3) The correlation between the streams and faults can be used to infer subsurface characteristics as demonstrated by correlation with outcrop fracture data. 4) The stream density data indicate that no trends exist between density or length and stratigraphy. 5) Geological processes appear to have a significant influence on stream orientations in the study area. 6) The polymodal orientation method used in this thesis is an effective way to analyze orientations. The method allows for consistent orientation signals to become obvious even when there is little separation between signals. 7) The method used to study the aquifer is cost effective with limited bias in the studying aquifer characteristics. As GIS stream layers are readily available, it would be feasible to study streams as a preliminary analysis of the subsurface characteristics in most fractured aquifers.

ADVISER'S APPROVAL: Todd Halihan