Linear Trend Analysis: Implications for a Structural Fracture System and Applications of Subsurface Fluid Migration, Northwest Arkansas and Eastern Oklahoma

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Linear Trend Analysis: Implications for a Structural Fracture System and Applications of Subsurface Fluid Migration, Northwest Arkansas and Eastern Oklahoma

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geology

by

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University of Arkansas
Bachelor of Science in Geology, 2010

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This thesis is approved for recommendation to the Graduate Council.

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Abstract

Lineaments are mappable, simple or composite linear or curvilinear features of the Earth's surface longer than one mile, which differ from the patterns of adjacent features and are presumed to reflect subsurface phenomenon such as faults and fractures. The usage of the term refers to the description Lattman published in 1958 and was the foundation for work by MacDonald in 1977, which is the basis for this project. Remote sensing techniques have provided a valuable means to analyze lineaments on a large scale in a relatively short time in comparison to field mapping methods. The products of such fracture studies have been used in exploration for groundwater and may also have implications for other subsurface fluid migration pathways. Cost-benefit evaluations of employing remote sensing techniques have found that this method took less time and saved on costs of drilling. Published work completed by MacDonald included a compilation of lineament maps for 13 counties in Northwest Arkansas. The maps were published on county highway basemaps and prepared using LANDSAT imagery that was later transferred. Quality of remotely sensed imagery has increased exponentially since the time of the original production and in 2006 the map was digitized by a group of NSF Research Experience for Undergraduate students. Comparison of the digital lineament data to more modern imagery allowed a check on accuracy and extension or modification where appropriate. The final products include a compilation of all relevant literature and data sources related to water quality investigations in mantled karst and fractured rock areas of Arkansas including the Ozark Dome area and Arkoma basin to the western border and east to the Fall Line. As well as digitization of a lineament map containing the 27 counties based on the most current Digital Elevation Models (DEMs) and satellite imagery available.
Acknowledgements

Firstly, I would like to express my sincere gratitude to Dr. Ralph K. Davis for the guidance and continuous support that made this thesis possible. A special thanks also goes to committee members Dr. Doy L. Zachry and Dr. Gregory Dumond for their constructive comments and contributions which prompted me to widen my research perspective. My sincere gratitude goes to the Arkansas Department of Health, Source Water Assessment and Protection Program for funding the original research upon which this thesis is based and The Arkansas Water Resource Center at the University of Arkansas for granting access to resource archives. I would also like to thank Dr. Van Brahana who greatly inspired me to follow my geological passion and always take every opportunity to see and learn. Last but not least, I would like to thank my family for their unfailing support and encouragement.
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I. Introduction

Remote sensing techniques have provided a valuable means to analyze and map lineaments on a large scale in a relatively short time in comparison to field mapping methods. The products of fracture studies have been used in exploration for groundwater such as with Lattman and Parizek (1964) in which fracture traces were compared to the occurrence of groundwater. Their study found that in areas of intersecting fracture traces wells produced ten to one hundred times the yield as opposed to wells drilled off of fracture traces (Lattman & Parizek, 1964). In another rural water-supply project, an economic analysis was conducted on a 500-well program to evaluate the cost-benefit of employing remote sensing techniques and found that this method took less time and saved on costs of drilling (Sander, 2007).

Utilizing lineament mapping to determine concentrations of fault traces can ultimately lower uncertainty in well drilling and may thereby cut costs of exploration. These methods may also be applicable for fields other than hydrology, such as mineral and petroleum exploration.

More recently, lineament mapping has become more popular with many published papers on the topic with regard to different applications. This study continues on lineament data published by MacDonald, et al., 1977. The maps were published on county base maps for better clarity during reproduction. The resources available at the time required that the maps be hand drawn which was a lengthy and tedious process. In addition, the work constructed from aerial photography and Landsat images had to be transferred to the working maps. Since the time of the MacDonald publication, aerial and satellite imagery has become readily available in digital format. In conjunction with advancements in computer science and mapping software, another view of the data with the most current imagery is warranted. Higher resolution satellite images and Digital Elevation Models (DEM's) which were not available for analysis in 1977 have also become available which further aid in lineament interpretation.

The fragile and complex nature of groundwater resources in the study area require that investigations into aquifer delineation and recharge be conducted. In addition to locating wellsites with higher yield, lineament data may aid in recognition of potential aquifer contaminant source areas. These areas include sinking streams, open sinkholes, and other features that allow direct interaction with groundwater. Source and non-source point contamination is a concern as the demands for water resources rises due to increased human population and activity. The lineament work provided in this
study can aid in research of groundwater migration as subsurface fluid tends to follow faults and fractures that can manifest in surface features interpreted as lineaments.

A. **Purpose and Objectives**

The purpose of this investigation was to assess previous lineament maps for accuracy to be digitally incorporated into an expanded and updated lineament map. Lineament map data and knowledge of the structural geology of the area can allow for further analyses such as lineament orientations, groundwater occurrences, and qualities. The goal is to provide new and updated lineament data for the 27 county study area as well as preliminary lineament orientation data. Lineaments represented on these maps have been delivered to the Arkansas Department of Health for incorporation into the current source water assessment data-base as a new GIS layer.

Working with the most current satellite image and Digital Elevation Models (DEM) in GIS software allows us to utilize geoprocessing tools beyond the capabilities of aerial and satellite imagery alone. The ability to analyze large datasets efficiently and view data in varying color and layer combinations allows us greater ability to interpret and share lineament data that can be exported and used for further research. Checking accuracy of previously mapped lineaments with the higher resolution images and DEM data allows for modification or extension where appropriate. One product of this is a combined lineament data set that allows for seamless viewing with many applications for further research.

Carbonate sections of the area are at higher probability of solutioning as groundwater flows along fracture traces. The dissolved voids in these fractures can continue to grow and provides storage for groundwater resources. The implications are that higher yield wells can be obtained through wells drilled along lineaments, and save time and therefore expense in groundwater exploration. Proper lineament mapping is crucial to understanding subsurface structure and hydrogeology. Used as a guide to relate lineaments to areas of higher fracture trace concentrations and well placement, lineament mapping can increase groundwater yield. A lineament trend analysis of these datasets was conducted to provide general lineament orientation and trends. The orientation of lineaments and knowledge of general structure of the region provides data on both vertical and horizontal groundwater pathways.
B. Location

The study area includes 23 counties in Northwest Arkansas and 4 in Eastern Oklahoma for a total of 27 counties as seen in Figure 1. The original working maps from MacDonald (1977) covered 13 counties in Northwest Arkansas including Baxter, Benton, Boone, Carroll, Fulton, Izard, Madison, Marion, Newton, Searcy, Sharp, Stone, and Washington. The expanded study area includes Cleburne, Crawford, Figure 1- Location Map. The study area comprising 27 counties in northwest Arkansas and eastern Oklahoma.

Conway, Franklin, Independence, Johnson, Lawrence, Pope, Randolph, and Van Buren counties in Northwest Arkansas and Adair, Cherokee, Delaware, and Sequoyah counties in Eastern Oklahoma. The complete 27 county study area encompasses 18,365 square miles.

A fall line separates a relatively hard bedrock, highland region, and a lower-lying region usually composed of softer sedimentary units. In Arkansas, the Fall Line separates the Interior Highlands and the Gulf Coastal Plain, or Atlantic Plain. The latter is a depositional region of unconsolidated sand, silt, and clay of alluvial origin. In contrast, the Interior Highlands are primarily erosional surfaces of Paleozoic
sedimentary rocks exposed at the surface. It is across the hard rock terrain that fracture traces can be identified at the surface and studied by remote sensing practices.

The Interior Highlands in Arkansas is further divided into more specific physiographic regions. The northernmost section, the Ozark Plateau extends into eastern Oklahoma and southern Missouri with the Salem being the northernmost plateau surface. These are erosional remnants that have in some areas been deeply cut and been mistakenly called “mountains”. The Paleozoic rock sequences are characterized by relatively flat cap rock of Pennsylvanian sandstone underlain by limestones and shales deposited upon an igneous basement. The sandstone caprock is well-lithified and has preserved much of the underlying limestone units from erosion with the exception of fractured areas where surface water can easily penetrate the caprock. The study area encompasses portions of the Arkoma basin, Boston Mountains, and Springfield and Salem plateaus.

II. Regional Geology
A. Regional Structure

The study area is comprised of portions of the Springfield and Salem Plateaus, the Boston Mountains and the Arkansas Valley. This area is located in the foreland of the Ouachita-Appalachian
orogenic belt, deformation of which occurred in the late Paleozoic era. Also called the Ozark dome, the region is a geologic uplift characterized by a stratigraphic dome with the igneous core in the St. Francois Mountains in southeastern Missouri. The topographic axis of the anticline runs from northwest Arkansas to the St. Francois Mountains. Although more complex in certain localities, regionally the units dip gently (1-2 degrees) southward at the Missouri border and steepen (up to 5 degrees) towards the southern flank of the plateaus province (Croneis, 1930). The beds are broken by a series of normal faults downthrown to the south, which dissect the plateaus surface across the area. The Boston Mountains is the highest of the plateaus, and has been uplifted to elevations exceeding 2000 feet and interrupt the symmetry of the dome (Imes & Emmett, 1994).

The stresses that accommodated the uplift of the area as well as the majority of faulting and fracturing of the area have been attributed to the Ouachita orogeny. Foreland deformation associated with the Ouachita orogeny is more complicated than a simple dome dipping south-southwestward in Arkansas. Normal faults are dominant although strike-slip faults and monoclinal folds have also been acknowledged. Hudson’s (2008) work in the Buffalo River area of the Boston Mountains described northeast striking dextral faults and east striking normal faults formed from north-south extension and north strike slip faulting due to east-west shortening. The extension was related to flexure in the foreland of the Ouachita orogenic belt, which closed obliquely to the area (Hudson, 2008).

The complexity of the deformation related to late Paleozoic orogenic activity compelled a kinematic analysis of mesoscale structures in the Ozark Plateaus to determine paleostress fields. Cox et. al. (2009) concluded that large-scale deformation happened during four major events although they have not been incorporated into a unified tectonic model. The approach of the Ouachita terrain marks event 1 and is associated with joints and northwest striking normal faults. The docking of the northwest moving Ouachita terrain in event 2 was accompanied by significantly stronger north-south compression and a set of high-angle fault zones with a shift from north/northeast in the west and east/northeast. During event 3, reverse faults and folds are most common. Cox suggests that the relatively uniform northeast compression is not consistent with Ouachita convergence but rather agrees with shortening of the late Paleozoic Ancestral Rockies deformations. Event 4 marks a return to northwest convergence with late stage deformations congruent with the Ouachita orogeny.
Horizontal compression associated with the closure of the Ouachita terrain alone does not explain high-angle reverse faults within the Ozark Plateaus therefore an accompanying variable must be identified. An increase in pore pressure created by tectonic pulses driving fluid migration toward the craton interior could reduce the stress required for reactivation of basement faults, which caused high angle reverse faults (Sibson, 1985). Paulsen and Marshak (1994) suggested that hot brines migrated through the midcontinent, this would account for the weakened frictional strength of faults. Increased pore fluid pressures within fault zones originating in the basement is consistent with structures found within the study area (Cox, 2009). In addition to pore fluid pressure aiding the reactivation of faults during the late Paleozoic, the lack of regional fluid pulses previous to the Pennsylvanian may account for the limited distribution fractures prior to the Ouachita orogeny.

B. **Regional Stratigraphy**

The Precambrian crystalline basement is of granitic composition determined from the few wells in the area that are drilled to that depth (Frezon & Glick, 1959). The basement is not exposed in the study area and the surface is irregular due to exposure and erosion prior to deposition of Cambrian system. The strata overlying the basement in the study area is composed of Paleozoic sequences of sandstones, shales, limestones, cherts, dolostones and siltstones. Sedimentation occurred during the Cambrian, Ordovician, Mississippian and Pennsylvanian periods. Shallow seas with a gentle slope allowed for the accumulation of sediments in the area. Occasional periods of exposure generated disconformities at certain horizons and not all units are continuous throughout the study area (Caplan, 1960). A summary of the lithologies corresponding to Figure 3 is described in order of depositional history.

**Cambrian System**

**Lamotte Formation** - The oldest Cambrian formation is often described as an arkosic sandstone due to the fragments of feldspar originating from the Precambrian basement. The Lamotte sandstone is fine to coarse-grained and white to yellow or red-stained, loosely cemented subangular to rounded quartz grains. Occasionally dolomitic in the few wells that have penetrated to that depth, the thickness ranges from 35 to 60 feet (Caplan, 1960).
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Figure 3- Generalized Stratigraphic Column (modified from (McFarland, 1998) and (Frezon & Glick, 1959)). Trellis pattern correlates to unconformities between formations. Chart does not imply relative unit thickness.

**Bonneterre Formation**- The Bonneterre is a light gray, finely granular to medium-crystalline, pyritic dolomite. Where the Bonneterre dolomite is present, it’s thickness ranges from 60-71 feet although the
unit is considerably thicker on the west flank of the Ozark Dome in Missouri. In some instances, may be glauconitic, and shale or chert may be present (Caplan, 1960).

**Potosi-Eminence Formations** - Undifferentiated in Arkansas, the Potosi-Eminence Formation is a light-colored, fine to coarse crystalline dolomite. The combined unit thickness ranges from 307-384 feet and contains white to light gray chert, sometimes containing siliceous oolites. Occasional traces of green shale and glauconite and very thin sandstone lenses in the upper section may be present (Caplan, 1960).

**Ordovician System**

**Gasconade Formation** - The Gunter member of the Gasconade Formation is the oldest rock in the Ordovician system. The Gunter member is approximately 40 feet thick and is a loosely cemented, white to gray sandstone. The 319-600 feet of overlying Gasconade section is light-colored, finely granular to medium crystalline, vuggy, dolomite. Occasionally oolitic, chert of white, light-gray, or blue-gray color may be present in the lower part of the section (Caplan, 1960).

**Roubidoux Formation** - Ranging from 132-455 feet thick in the study area the Roubidoux Formation unconformably lies above the Gasconade and consists of dolomite, sandstone, and chert. The dolomite is light in color, fine to medium crystalline, and may be sandy or contain chert in some areas. Thin shale units may also be present within the dolomite. The light gray sandstone sections are fine to medium, angular to rounded, loosely to well cemented, frosted quartz grains. Sandstone in the Roubidoux formation makes up 48 percent of the total section towards the eastern part of the study area. The cherts are also light colored, although blue-gray and black cherts have been recorded (Caplan, 1960).

**Jefferson City Formation** - The Jefferson City Formation is the oldest rock that crops out in Fulton, Marion and Sharp counties in Arkansas. The lower contact is unexposed in the area and the unit ranges from 100-500 feet in thickness. Ooliths are common in the light to medium gray, fine to medium crystalline, sandy, dolomites (Caplan, 1960).

**Cotter Formation** - The Cotter Formation is commonly undifferentiated from the Jefferson City formation in areas that lack the discontinuous sandstone or sandy dolomite basal section due to similarities of the lithologies (McFarland, 1998). The Cotter Formation is approximately 200 feet thick but
up to 500 feet has been reported. Present in the majority of the study area, the dolomite unit includes pyritic chert which aids in differentiation from the Powell formation (Caplan, 1960).

**Powell Formation**: With thickness up to 223 feet, the Powell is a light to dark-gray or brown to black, granular to medium crystalline, silty, shaly, dolomite. In addition, thin layers of green, pyritic shale and dark oolitic chert may be present (Caplan, 1960). Significant outcrops of Powell dolomite are exposed in Benton, Carroll, Boone, Marion, Newton, Fulton, Izard, and Sharp counties (MacDonald, Steele, & Gaines, 1977).

**Smithville Formation**: At approximately 65-150 feet thick and only cropping out in Lawrence, Randolph, and Sharp counties, the Smithville is not an extensive unit in the study area. The Smithville consists of gray, finely granular dolomitic limestone. Occasionally sandstone and lead-zinc minerals may be present towards the base of the unit (Caplan, 1960).

**Black Rock Formation**: The Black Rock Formation is slightly more widespread than the Smithville identified in outcrop in Independence County in addition to Lawrence, Randolph, and Sharp counties. The unit thickness ranges from 55-200 feet and is a similar finely granular, dolomitic limestone to the Smithville. Although in lesser concentration, lead and zinc minerals have been noted (Caplan, 1960).

**Everton Formation**: Ranging from 300-650 feet, changes in rock type and facies are common in the Everton formation. The various dolostones, limestones, and sandstones also contain traces of conglomerate, shale, and chert. The occasionally sandy dolostones are light to dark gray and can be limy and sandy. The light gray to brownish gray limestones may be dolomitic or sandy. The friable sandstones in the upper section tend to be thick and are sometimes confused with the overlying St. Peter sandstone (McFarland, 1998).

**St. Peter Formation**: Ranging from very thin up to 175 feet thick, the St. Peter sandstone is massive, well-rounded, medium to fine grained, friable white sandstone. Often cemented by large calcite crystals, the unit readily forms bluffs. Minor beds of shale, limestone, or dolostones have been recorded (Caplan, 1960). The unit is either undifferentiated from the Everton formation or pinches out in northwest Arkansas (Frezon & Glick, 1959).
Ordovician- Post-St. Peter Sandstone

Formations of Ordovician age, deposited post-St. Peter sandstone range from nearly absent to more than 500 feet in thickness and crop out discontinuously across the study area. The Joachim Dolomite, Plattin Limestone, Kimmswick Limestone, Fernvale Limestone, and Cason Shale represent a relatively short interval of deposition followed by a short erosional period and are each lithologically unique despite their discontinuities. The Joachim dolomite conformably overlies the St. Peter sandstone while the remaining formations are separated by unconformities (Frezon & Glick, 1959).

Silurian

The maximum combined thickness of the three Silurian age formations is 254 feet in Franklin county. The Brassfield, St. Clair, Lafferty formations are limestones of varying extent with the St. Clair limestone being the most extensive in outcrop, present in discontinuous outcrops from Newton county eastward, and the Brassfield being the most restricted in outcrop, present in Searcy county alone. Silurian age rocks are thickest in the western portion of the area, thinning to the north and east (Frezon & Glick, 1959).

Devonian

Penters Formation- The Penters Formation is mainly composed of light gray to black chert but contains varying concentrations of sand west of Pope county. The thickness decreases northward where truncates to an edge, in Madison and Washington counties in the northwest and Independence county in the eastern portion of the study area thin narrow fingers of the formation reach northwest of the more linear limit in surrounding counties (Frezon & Glick, 1959). The Penters formation ranges from 25-90 feet thick and in some locations a thick bed of chert breccia is present at the upper portion of the unit (McFarland, 1998).

Clifty Formation- Up to 4 feet thick but only averaging 2 feet, the Clifty is unconformably overlies the Everton Formation and is sometimes mistakenly included with the Sylamore sandstone member of the Chattanooga formation. At the type locality in Carroll county the Clifty is a very sandy limestone with a few fossils present, although outside the type locality area sandstones are dominant (McFarland, 1998).
Chattanooga Formation- Deposition of the Chattanooga Formation began during the late Devonian and continued into the early Mississippian. The formation averages 30 feet but ranges from 0-85 feet. The white to dark gray phosphatic quartz Sylamore sandstone member is the base of the formation and also may dominate the interval in some location. The Chattanooga shale is a fissile, pyritic, black clay shale usually displaying prominent orthogonal jointing (McFarland, 1998).

Mississippian

St. Joe Member (Boone Formation)- Although there have been suggestions for the Formation status of the St. Joe, it is considered a member of the Boone Formation. The unit is a fine grained fossiliferous limestone with smooth bedded chert in some locations. Crinoids, brachiopods, bryozoan, conodonts, blastoids, ostracods and rugose coral are among fossils found in the St. Joe limestone. The base is typically discernable by a phosphatic, greenish shale or conglomerate and ranges from very thin to 110 feet in thickness (McFarland, 1998).

Boone Formation- One of the most extensive units in the area, the Boone Formation is a gray, fine to corase grained, fossiliferous limestone 300-350 feet thick. Interbedded sequences of dark colored chert may be present and the quantity of which varies greatly. Most prominent in northwest Arkansas, the Boone is a major karst forming unit with numerous sinkholes, caves and enlarged fissures. Among the fossils in the unit crinoids are most abundant but brachiopods, bryozoan, mollusks, corals, shark material, trilobites, conodonts, and others are present (McFarland, 1998).

Moorefield Formation- The thickness of the Moorefield ranges from barely there up to 300 feet and is a sparsely fossiliferous limestone. Cephalopods and brachiopods can be found in irregular concentrations. The lower section is a black calcareous shale and siliceous limestone with the upper section consisting of a dark fissile clay shale referred to on the Arkansas geologic map as the Ruddell Shale member of the Moorefield formation (McFarland, 1998).

Batesville Formation- The base of the Batesville is the sandy, occasionally fossiliferous Hindsviile member of the Batesville Formation. The cream to brown, fine to coarse grained sandstone of the Batesville contains thin shales. The combined thickness ranges from thin to over 200 feet with the
thickest sections in Independence County. In the western portion of the area, the Batesville strata may be absent with only the Hindsville member present (McFarland, 1998).

**Fayetteville Formation** - Black, fissile, concretionary, clay shale commonly interbedded with dark gray, fine grained limestones, dominate the Fayetteville Formation. The Weddington member most common in west Arkansas consists of gray to brown, fine grained, occasionally calcareous sandstone. In certain locations pyritic fossils are abundant and septarian concretions are common (McFarland, 1998). The thickness of the Fayetteville Formation ranges from 10-400 feet and varies greatly in thickness irregularly across the area (Croneis, 1930).

**Pitkin Formation** - The last deposited rock of Mississippian age is a fine to coarse grained, oolitic, bioclastic limestone. Sequences of interbedded black shale more prominent in the south, and minor chert at the top and bottom of the section may be present. Fossils include crinoids, brachiopods, bryozoans, corals, bivalves, gastropods, cephalopods, trilobites, conodonts, and shark teeth. Archimedes are of abundance to be a marker fossil of the unit. The average thickness is 50 feet in the west and 200 feet in the east (McFarland, 1998). Erosion prior to Pennsylvanian deposition was extensive and has completely removed the Pitkin in many locations (Croneis, 1930).

**Pennsylvanian**

**Hale Formation** - At the type locality in Fayetteville, Arkansas the Hale Formation is divided into the Cane Hill and Prairie Grove members. The Cane Hill consists of dark gray silty shale with interbedded siltstone and thin bedded, fine grained sandstone which may be locally calcareous. Mollusks and brachiopods may be present in the calcareous sections. The Prairie Grove member is light gray to dark brown, limy sandstone with lenses of highly fossiliferous limestone and oolitic limestone. Crinoids, bryozoans, brachiopods, algae, corals, trilobites, mollusks, and microfossils are present and generally fragmented. Thickness of the Hale Formation ranges from thin to more than 300 feet (McFarland, 1998).

**Bloyd Formation** - The Bloyd Formation is a 200 feet thick series of shale, limestone, and sandstone units with a thin seam of coal. The basal sequence of limestones separated by thick intervals of dark shale are part of the Brentwood member. The next depositional sequence of dark-gray fissile shale often interbedded with thin siltstones is termed the Woolsey member. The Baldwin Coal occurs as a
thin layer in the upper section of the Woolsey. The Dye Shale member is a dark gray shale with occasional calcareous concretions. The Kessler Limestone is either a single unit or a sequence of interbedded limestone and shale. The Trace Creek Shale is commonly considered a part of the Atoka formation and is composed of dark gray shales with few thin beds of sandstone with thicken upsection. Fossils may be present in the limestone and calcareous sandstones throughout the Bloyd formation (McFarland, 1998).

**Atoka Formation** - Atoka Formation has the greatest areal extent of the Paleozoic rock sequence in the study area with the largest areas of outcrop in Washington, Crawford Madison, Franklin, Newton, Johnson, Pope, Searcy, Stone, Van Buren, Cleburne, Conway, White, and Independence counties. The unit thickens southward to approximately 2000 feet between the Boston Mountains and Arkansas Valley. Considered a caprock in the Boston Mountains it conformably overlies the Bloyd and rests on high ridge exposures in the north (Frezon & Glick, 1959). The Atoka formation consists of medium-grained, tan to gray or brown, silty sandstones and grayish black shales are rarely calcareous. Discontinuous beds of coal and coaly shale and poorly preserved plant fossils are present in the Boston Mountains (McFarland, 1998).

**III. Water Resources**

**A. Surface Water**

The Ozark Plateaus has abundant surface water features with several major rivers and reservoirs in the area. The rivers that originate in the study area tend to flow radially away from the relatively high elevation near Red Star in the Boston Mountains. This includes the Illinois, White, and Buffalo Rivers with many smaller drainages flowing into these systems. The Illinois River flows west into Oklahoma forming Tenkiller Ferry Lake before emptying into the Arkansas River and flowing east, back into Arkansas, to run along the south side of the study area. The White River is the longest river originating in the study area. The headwaters flow east before turning northward into Missouri and then south again crossing the Arkansas state line. The White River has several dams which regulate streamflow and form a series of lakes that are popular recreation areas. All of the surface water in the area flows into either the Arkansas or White Rivers and contributes to the Mississippi River watershed in Southeastern Arkansas.
Figure 4- Surface Water System
In Arkansas, an estimated 11,300 million gallons per day (Mgal/d) were withdrawn from surface and groundwater sources during 2010. Surface water contributes 31% or 3,540 Mgal/d with the largest withdrawals in Pope, Arkansas, Benton, Hot Springs, and Lonoke counties. Beaver Lake along with the Arkansas and White Rivers produce the largest amount of surface water resources in the state. Thermoelectric power generation was the dominant category of surface water use followed closely by irrigation (Pugh & Holland, 2015).

B. Ground Water

Major groundwater sources are located in various Quaternary deposits in eastern Arkansas as well as Paleozoic rock formations of the Interior Highlands in north and northwest Arkansas. Groundwater contributed 69% or 7,790 Mgal/d of the total water used in 2010. The largest percentage of withdrawals from groundwater are in eastern Arkansas. The top five counties for groundwater usage are Poinsett, Arkansas, Cross, Jackson and Clay with irrigation being the dominant purpose for withdrawal (Pugh & Holland, 2015).

The amount of interaction between the surface water and groundwater systems can differ considerably between basins and physiographic areas depending on variables such as geology, soil type and topography. Contact between the systems is greater in the Springfield and Salem Plateaus than in the Osage or Atlantic plains. Surface and groundwater interaction can be characterized by flow-duration curves, dye-tracing and seepage-run studies, and groundwater level information. Streams with continuous base flow have a large groundwater contribution to streamflow and streams with little or no base flow receive relatively little groundwater and in some instances lose water to the groundwater system. (Adamski, Petersen, Freiwald, & Davis, 1995)

Many factors can directly and indirectly contribute to the quality of the water resources in the area including climate, geology, physiography, soils, population, and land use. Population density and agricultural activities are higher in the Springfield Plateau and Osage Plains determining that streams in these areas are more affected by human activities than streams in other areas. Seasonal precipitation and evapotranspiration greatly influences stream flow and aquifer recharge rates which in turn affect water quality. Steeper topography can intensify surface runoff leading to erosion and higher sediment and surface contaminant input than in areas of low relief. Concentrations of suspended constituents are
generally higher during times of high flow as the turbulence allows for constant resuspension along the flow path. The opposite is true of dissolved constituents due to the higher contribution of groundwater. (Adamski, Petersen, Freiwald, & Davis, 1995)

Areas in farther proximity from the lakes along the Arkansas-Missouri border do not consistently have large amounts of surface water. Seasonal changes in base flow affect the availability of surface water as a main supply source. Consequently, municipalities in these areas need to look towards groundwater to meet supply demands. Lineament analysis can help determine placement of wells to achieve higher yield although depending on usage, water quality from wells on lineaments may not be pure enough and can pose potential problems. MacDonald (1977) found that a statistical comparison of yields in wells on and off lineaments proved that wells located on lineaments showed significantly higher yields. The study also analyzed the water quality of wells both on and off lineaments. In more densely populated areas shallow groundwater already has shown signs of severe degradation. Water quality analysis found higher concentrations of chloride, total hardness, and total dissolved solids in wells located on lineaments with the higher probability of combined calcium and magnesium concentrations (MacDonald, Steele, & Gaines, 1977).

C. Karst Aquifer

The Ozark Plateaus is characterized by mantled karst aquifers. Karst refers to a landscape containing extensive underground water systems that are developed in especially soluble areas such as carbonate rock sections found within the study area. Faults and fractures represent zones of secondary porosity which is of importance in settings where primary porosity is often eliminated during lithification. These fractures allow surface and groundwater to penetrate confining units and can be broadened further by the processes of circulating groundwater (Ford & Williams, 2007). Springs, caves, sinkholes, and sinking streams, are common indicators of karst terrain and are abundant across the Springfield and Salem Plateaus as well as the Boston Mountains.

Hypogenic karst forms from artesian conditions driving aggressive groundwater upsection. Erosional features and deposits found within caves indicate a history of thermal groundwater circulation. This indicates that hypogenic formations may have initiated karst in the area. A study of hypogene speleogenesis within the Ozark Plateaus concluded that reactivation of basement faults associated with
the Ouachita orogeny extended into the brittle overlying Paleozoic rocks and that these faults served as flow conduits. Although origin has not been precisely identified, the study credits tectonic pulses for driving fluid migration from the Arkoma basin northward into the Ozark Plateaus. Stable isotope analysis of dogtooth spar crystals show the formation is incongruent with meteoric origin supporting the hypogenic karst hypothesis (Tennyson, Terry, Brahana, Hays, & Pollock, 2008).

Currently karst processes within the study area are considered epigenetic in nature, solutioning from meteoric water infiltrating through fractures at the surface. The mixing of precipitation with carbon dioxide produces a carbonic acid solution. As the water migrates downward through fractures in the rocks influenced by gravity, the acid dissolves calcite creating and enlarging conduits and cave systems. In these areas, surface contaminants can also be readily flushed into the aquifer with little to no filtration impacting groundwater quality. Bacterial loading during storm pulses significantly affects the water quality of karst springs (Davis & Brahana, 2000). Additionally, caves systems allow groundwater to cross into adjacent surface watersheds making point source detection of contaminants more difficult to determine in karst aquifers (Adamski, Petersen, Freiwald, & Davis, 1995)

The karst terrain of the study area is important to the hydrology of the area and require consideration when utilized as a source of groundwater for agricultural, suburban, and commercial applications. Springs sampled by Davis and Brahana (2000) found each to be impacted by external sources of contaminants. The contamination of these aquifers by fecal coliform and Nitrates have serious negative implications for health (Davis & Brahana, 2000). Nitrate concentrations above 2 milligrams per liter provide a good indicator of human impact on groundwater (Gillip, Hays, & Galloway, 2008). Background nitrate levels in unimpacted areas are less than 0.2 milligrams per liter (Steele, 1983). Best Management Practices (BMPs) to prevent non-point source contamination include timing and rate of poultry litter dispersal, as well as waste, nutrient, and compost management. Evaluation BMPs found that variability of precipitation was greater than any benefits gained from the implementation of BMPs (Davis & Brahana, 2000).

IV. Literature Review
A. Lineament Definition

To begin the study a clear definition of the term lineament needed to be acquired through a literature review of past meanings to modern definitions to ensure the term is understood and proper procedure is performed during mapping. The foundation of this analysis was a study conducted in the 1970s by MacDonald which used Lattman’s definition of a lineament. By this definition a lineament is considered a natural linear feature more than one mile in length, features less than one mile in length are considered fracture traces. MacDonald interpreted lineaments from forms such as topographic sags, aligned segments in water-courses, vegetation alignments, and linear soil tonal anomalies, which are most easily appreciated from a broadened view acquired by remote sensing techniques (Lattman, 1958). These features commonly manifest due to faults, folds and fractures and can thereby aid in the identification of subsurface fluid migration. Previous studies have concluded that analysis of fractures can aid in understanding the structural and stratigraphic characteristics of an area (Blanchet, 1957).

The terms lineament and lineation are not interchangeable. A paper published in 1976 by O’Leary, Friedman, and Pohn details 26 instances of how the term lineament has been used and intended to clarify the standard definition. The paper concluded that a lineament is “a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon.” The word had taken on a relaxed usage that could be misinterpreted as lineations which are purely petrologic features (O’Leary, Friedman, & Pohn, 1976).

Review of the term lineament has shown that Lattman’s definition is appropriate for this analysis although O’Leary’s definition expounds upon that to indicate subsurface structure. Lattman’s usage is applied to the methodology here as the scale of the map produced is small enough that only lineaments will be mapped and not fracture traces to ensure visibility and functionality of the final product.

B. Water Quality Data

A compilation of all relevant literature published by the Arkansas Water Resource Center (AWRC) and data sources related to water quality, lineament and fracture trace analysis was generated. The material covers mantled karst and fractured rock areas of Arkansas and includes the Ozark Dome area in
northern Arkansas and the Ouachita area in west-central Arkansas. The publications are available in
digital pdf form from the AWRC website. This research provides a comprehensive listing of literature and
data sources for the water quality of bedrock aquifers and lineament data in the western and northern
portions of Arkansas west and northwest of the Fall Line.

V. Previous Work

A. Landsat and Aerial Photography

In 1977, a lineament map published by MacDonald, Steele, and Gaines through the Arkansas
Water Resources Research Center provides data for 13 counties in Northwest Arkansas. Utilizing both
LANDSAT images and A.S.C.S. (Agricultural Stabilization and Conservation Service) photo indexes of
the study area were analyzed using Lattman's technique to identify lineaments. LANDSAT images are
taken from a space borne platform orbiting at an altitude of 565 miles and provide clear definition of long
regional lineaments which because of sheer size may not be visible on larger scale images. Enlarging the
LANDSAT image to eight times its normal size blurred the drainage features used to align the image and
the map, also increased the width of the lines drawn on the acetate to mark the lineaments on the
LANDSAT image. Consequently, transfer of the LANDSAT lineaments was not exact and introduced a
margin of location error of about one quarter mile (MacDonald, Steele, & Gaines, 1977).

The lineament basemap published by MacDonald includes only those features longer than 1 mile
(as defined by Lattman, 1958) those shorter than 1 mile, fracture traces, would degrade the clarity of the
map and therefore were not included in the original map. The working map was published on county
highway basemaps and prepared using LANDSAT imagery that was later transferred. The hand drawn
maps were available in 8.5”x11.5” format at a scale of about four miles per inch in a report by MacDonald,
AWRC Publication No. 49. These working copies were prepared on county highway base maps and
copies are available in the Department of Geosciences at the University of Arkansas.

B. Geographic Information Systems (GIS)
Quality of remotely sensed imagery has increased exponentially since the time of the original production. GIS software provides powerful computing abilities to analyze datasets such as digital elevation models that weren’t available at the time MacDonald published the original lineament data. The first digital format of the MacDonald publication was produced in 2006 by a group of NSF REU students. The students scanned the working maps to digital format and imported the data into ArcGIS mapping software. The digitized lineaments were analyzed digitally for the first time resulting in some movement and/or connection of lineaments. The finished product included digital files for each of the 13 counties in Northwest Arkansas covered by the MacDonald working maps. These files can be opened to create a seamless lineament map for the study area.

This study utilized ESRI’s ArcMap program to create a seamless layer that can be viewed on varying basemaps. As with the 2006 NSF student group, the 2013 analysis utilized the most current satellite imagery available from ESRI as well as Arkansas Digital Elevation Models (DEMs) available online from GEOSTOR. The elevation models are available by county and were later joined to create a single, seamless mosaic for the Arkansas portion of the map area. Digital elevation models were not available for the Oklahoma portion of the map.

VI. Methods
A. Digital Elevation Model

One of the most important aspects of the lineament map was the ability to visualize the topography of the area in the form of a Digital Elevation Model (DEM). This raster format assigns an elevation value to each pixel and can be then associated with a specific color, or as with this study, varying shades within a black and white spectrum.

The DEM data are available from National Elevation Dataset (NED), the primary elevation dataset distributed by the USGS. While available in a few different resolutions, this study utilized the 1/3 arc second (approximately 10 m) data. Smaller scale resolution may not have enough definition to determine smaller, more obscure lineaments. Data available in 1/9 arc second resolution would have more detail than needed and would be difficult to process for larger datasets such as the one used here.
Figure 5- Digital Elevation Model. Values represent elevation above mean sea-level

B. **Hillshade**

Hillshade projection can illuminate topographic features and aid in determining more obscure lineaments. In addition to merely studying the image from directly above, viewing DEM data using a hillshade technique allows clearer recognition of linear surface trends and aided in the detection of lineaments. Across the region, specific areas of the final map appeared to have particular trends among the lineaments. For example, a hillshade projection from 0° N at an altitude of 20° will highlight East-West trending lineaments and may obscure North-South trending features. Altitude of the projection and shadow length have an inverse relationship; lower altitudes of projection will lengthen hillshade effect. Height of landforms in the area determines altitude needed to view hillshade with less obtrusive features requiring lower altitude. If illumination source is from directly above, hillshade will not be apparent in features of any height. For the purpose of this study, hillshade from varying angles was used to emphasize lineaments of differing trend orientations.
Figure 6- Hillshade Illuminated from 0° due north at an altitude of 20°.

C. Satellite Imagery

Satellite Imagery provides an invaluable resource in determining lineament location and orientation. Although lineaments may prominently appear on satellite imagery, precaution must be taken to determine that linearity is not associated with features other than faults or fractures. Certain sections of highways or shorter stream segments appearing on imagery may be falsely interpreted as lineaments. In areas of high relief, shorter stream segments may be influenced by gravity causing stream direction to travel downhill and give the perception of linearity. In many cases these are erosional landforms and not representative of faults or fracture traces (Gaines, 1978). Furthermore, larger lineaments may not be apparent on larger scale maps and can be better viewed by a smaller scale perspective. Viewing of satellite imagery in conjunction with DEMs or hillshade projections proved particularly helpful in determination of lineaments.
D. **Linear Trend Analysis**

The study area was divided into 4 regions by visually determining the most apparent linear trends. These regions were further analyzed by creating rose diagrams of lineament data orientation. The ArcGIS attribute tables were uploaded into Rockworks 17 as excel files containing geospatial information. The beginning and ending points of lineaments were utilized to determine length and orientation. This method assumed that lineaments are straight and would not take into consideration any curvilinear characteristics. Lineaments in the study area are of a linear nature and therefore can be analyzed by the endpoint method. Since lineament data does not contain a direction of flow or dip all diagrams were bidirectional with lineaments being represented in 2 bins with each bin containing half of the lineament data. The two bins containing a particular lineament’s data are located ±180 degrees from each other. Each bin is representative of 10 degrees for a total of 36 bins for a full compass rotation. Petal color is a visual aid and categorized on a cold-to-hot monochromatic scale Blue colored petals indicate background frequency or length while red petals correspond to bins with the most lineament data. A black line representing the vector mean of each calculation is included and oriented accordingly.
The lineaments were plotted with respect to both length and frequency to determine the overall trends in the data. Length type analysis produced diagrams based on the sum of combined lineament lengths within a particular bin. Petal length of length-based diagrams indicate the percent of total lineament length. Utilizing total lineament length would have produced illegible diagrams as major trends would have overwhelmed less dominant trends. Alternatively, analysis of the lineaments by frequency resulted in diagrams based on the sum of lineaments in a particular bin. Petal length of frequency-based diagrams indicate the percent of total lineament occurrence.

VII. Results
A. Lineament Maps by County

The lineament maps produced by this study have been assembled by county with county and state boundary basemaps. Using imagery or DEM data layers in combination with lineaments muddy the appearance and cause difficulty distinguishing features and therefore have not been included in the final lineament maps. Furthermore, data has only been acquired for features that manifest at the surface where they can be detected visually by DEM, hillshade, satellite imagery, or a combination thereof. Some counties appear to lack lineament data, which in some cases is due to physiographic boundaries crossing county lines. The plains areas contain loose sediment that covers underlying structure making analysis of lineament data difficult or impossible to detect with remote sensing practices. Major construction or large population areas may also hinder the ability to verify the presence of lineaments. Lineament maps that were digitized from the original MacDonald publication and checked for accuracy are given in the Appendix.
Figure 8- Lineament map of Adair County, Oklahoma
Figure 9 – Lineament map of Baxter County, Arkansas
Figure 10 - Lineament map of Benton County, Arkansas
Figure 11 - Lineament map of Boone County, Arkansas

Explanation

Lineaments interpreted from DEM and satellite imagery
Figure 12: Lineament map of Carroll County, Arkansas

Explanation

Lineaments interpreted from DEM and satellite imagery
Figure 13- Lineament map of Cherokee County, Oklahoma
Figure 14 - Lineament map of Cleburne County, Arkansas
Figure 15- Lineament map of Conway County, Arkansas
Figure 16- Lineament map of Crawford County, Arkansas
Figure 17- Lineament map of Delaware County, Oklahoma

Explanation

Lineaments interpreted from DEM and satellite imagery
Figure 18- Lineament map of Franklin County, Arkansas
Figure 19- Lineament map of Fulton County, Arkansas
Figure 21- Lineament map of Izard County, Arkansas
Figure 22: Lineament map of Johnson County, Arkansas

Explanation
Lineaments interpreted from DEM and satellite imagery

Miles
Figure 23- Lineament map of Lawrence County, Arkansas
Figure 24- Lineament map of Madison County Arkansas
Figure 25- Lineament map of Marion County, Arkansas
Figure 26- Lineament map of Newton County, Arkansas
Figure 27 - Lineament map of Pope County, Arkansas
Figure 28 - Lineament map of Randolph County, Arkansas
Figure 29- Lineament map of Searcy County, Arkansas
Figure 30 - Lineament map of Sequoyah County, Oklahoma
Figure 31 - Lineament map of Sharp County, Arkansas
Figure 32- Lineament map of Stone County, Arkansas
Figure 33- Lineament map of Van Buren County, Arkansas
Figure 34- Lineament map of Washington County, Arkansas
B. **Linear Trends**

The lineament map produced by this study was compared with USGS fault data and found that the largest, most prominent lineaments correlated with large faults particularly with those that trend NE-SW across NW Arkansas. This is in agreement with the previously discussed tectonic models that propose major basement faults of the same NE-SW orientation that extend into the overlying Paleozoic strata. The study area was then divided into 4 sections of an approximate equal area in which general lineament trends appeared visually similar to determine if general orientations vary across the study area. Further linear trend analysis provided rose diagrams of lineament orientations for the complete study area, the 4 visually delineated areas, and of each county (Appendix B). The resulting rose diagrams both length- and frequency-based provide orientation data and can be compared to determine variations across the study area.

The results of the complete area diagrams match the visually acquired hypothesis of a dominant NE-SW trend with a less dominant NW-SE. The 1,230 lineaments in the study area represent 8,601 miles of faults and fracture traces although additional, undetected lineaments may be present. Lineaments were represented in every bin although mostly in background lengths frequencies as compared to major trends. The 4 areas of interest show that longer and fewer lineaments in Area 1 give way to shorter more densely located lineaments progressing up to the Fall line where detection was no longer possible.

All 4 areas independently exhibit major NE-SW trends with a less prominent NW-SE trends. Area 1 contained a population of 262 lineaments, 2041 miles in length. With an exceptionally dominant NE-SW trend, Area 1 seems to show no indication of N-S trending lineaments seen in other areas. Area 2 has 347 lineaments with a total length of 2262 miles. The dominant NE-SW trend remains although Area 2 also indicates higher concentrations of orientations of a definite trend in N-S orientations. Area 3 has population of 350 with 2054 miles and displays the characteristic NE-SW dominant trend. Area 4 contains a population of 373 for a total of 2242 miles. A N-S orientation trend is observed in Area 4 although to a lesser degree than Area 2 and of a concentration just higher than background levels.
Figure 35 - Regional lineament orientation areas
Figure 36 - Lineament orientation of Area 1

<table>
<thead>
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<th>Calculation Method</th>
<th>Length</th>
<th>Calculation Method</th>
<th>Frequency</th>
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<tr>
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<td>59.6°/239.6°</td>
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Figure 37 - Lineament orientation of Area 2

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<td>Mean Bin Population</td>
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</tr>
<tr>
<td>Vector Mean</td>
<td>57.0°/237.0°</td>
<td>Vector Mean</td>
<td>67.3°/247.3°</td>
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Figure 38- Lineament orientation of Area 3

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<td>Vector Mean</td>
<td>88.2°/268.2°</td>
<td>Vector Mean</td>
<td>96.0°/276.0°</td>
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Figure 39- Lineament orientation of Area 4

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</table>
VIII. Conclusions

The Ozark Plateaus has abundant surface and groundwater resources with several major rivers and extensive karst aquifers in the area. In Arkansas, an estimated 11,300 million gallons per day (Mgal/d) were withdrawn from surface and groundwater sources during 2010. Surface water contributed 31% or 3,540 Mgal/d while groundwater contributed 69% or 7,790 Mgal/d of the total water used in 2010. Springs, caves, sinkholes, and sinking streams, are common indicators of karst terrain and are abundant across the Springfield and Salem Plateaus as well as the Boston Mountains. The karst terrain of the study area is important to the hydrology of the area and requires consideration when utilized as a source of groundwater for agricultural, suburban, and commercial applications. Springs sampled by Davis and Brahana (2000) found each to be impacted by external sources of contaminants. Source and non-source point contamination is a concern as the demands for water resources rises due to increased human population and activity. The contamination of these aquifers by fecal coliform and Nitrates have serious negative implications for health.
A digital 27 county lineament map of Northwest Arkansas and Eastern Oklahoma was created using satellite imagery, DEMs, and hillshade projection. The map contained 13 counties originally covered by the 1977 MacDonald investigation and expanded the study area south, east, and west from 13 to 27 counties. The current study reanalyzed the 1977 map using the latest satellite imagery and DEM data available. Utilizing the digital elevation models with varying degrees of transparency and hill-shade allowed for the greatest distinction of the lineaments. The lineament map produced was then compared with USGS fault data and found that the largest, most prominent lineaments correlated with large faults particularly with those that trend NE-SW with less dominant NW-SE trend. These trends are consistent with the previous tectonic models that propose major basement faults of the same NE-SW orientation that extend into the overlying Paleozoic strata. A lineament trend analysis of this dataset was conducted to provide general lineament orientation and trends.

Linear trend analysis provided rose diagrams of lineament orientations for the complete study area, the 4 visually delineated areas, and of each county. The 1,230 lineaments in the study area represent 8,601 miles of faults and fracture traces although additional, undetected lineaments may be present. The density and length of lineaments appear to have an inverse relationship. That is, as lineament frequency increases eastward, lineament length increases westward. The results of the complete area diagrams match the visually acquired hypothesis of a dominant NE-SW trend with a less dominant NW-SE. In some areas a N-S trend was also observed although to a lesser degree than the NE-SW or NW-SE trends. The lineament work provided in this study can aid in research of groundwater migration as subsurface fluid tends to follow faults and fractures that can manifest in surface features interpreted as lineaments. Determining whether a water source is located on a lineament can be a subjective decision, because the actual width of the lineament often cannot be determined without field work.

IX. Further Research

The lineament data presented in this paper can be used to apply models to targeted public water supplies pending available data for each of the selected source water areas. A model based on existing available data can be developed to adequately delineate source water assessment and protection areas.
in the fractured rock and karst areas of Arkansas. While the end result of this process may not provide a one-size fits all model that can be applied unilaterally to all hydrogeologic settings in Arkansas, it will point to areas where data are insufficient. This will provide a mechanism to target future data acquisition efforts related to source water assessment and protection in Arkansas.
X. References


XI. Appendix A

Digitized lineament maps from MacDonald (1977)
Appendix B

Lineament orientation diagrams of study area by county
Lineament orientation of Adair County, Oklahoma

<table>
<thead>
<tr>
<th>Calculation Method</th>
<th>Length</th>
<th>Calculation Method</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>261.6 mi.</td>
<td>Population</td>
<td>52</td>
</tr>
<tr>
<td>Maximum Bin Length</td>
<td>30.3 mi. (11.6%)</td>
<td>Maximum Bin Population</td>
<td>5.5 (10.58%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>11.9 mi. (4.55%)</td>
<td>Mean Bin Population</td>
<td>2.2 (4.17%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>71.2°/251.2°</td>
<td>Vector Mean</td>
<td>82.3°/262.3°</td>
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</table>

Lineament orientation of Baxter County, Arkansas

<table>
<thead>
<tr>
<th>Calculation Method</th>
<th>Length</th>
<th>Calculation Method</th>
<th>Frequency</th>
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</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>491.5 mi.</td>
<td>Population</td>
<td>129</td>
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<tr>
<td>Maximum Bin Length</td>
<td>44 mi. (8.96%)</td>
<td>Maximum Bin Population</td>
<td>11 (8.53%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>13.7 mi. (2.78%)</td>
<td>Mean Bin Population</td>
<td>3.6 (2.78%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>78.6°/258.6°</td>
<td>Vector Mean</td>
<td>80.3°/260.3°</td>
</tr>
</tbody>
</table>
Lineament orientation of Benton County, Arkansas

- Calculation Method: Total Length
- Length: 294.9 mi.
- Maximum Bin Length: 44 mi. (22.55%)
- Mean Bin Length: 13.6 mi. (3.57%)
- Vector Mean: 47.3°/227.3°
- Calculation Method: Population
- Frequency: 50
- Maximum Bin Population: 5.5 (11%)
- Mean Bin Population: 1.8 (3.57%)
- Vector Mean: 60.2°/240.2°

Lineament orientation of Boone County, Arkansas

- Calculation Method: Total Length
- Length: 377.1 mi.
- Maximum Bin Length: 22.5 mi. (5.96%)
- Mean Bin Length: 10.5 mi. (2.78%)
- Vector Mean: 81.2°/241.2°
- Calculation Method: Population
- Frequency: 92
- Maximum Bin Population: 5.5 (5.98%)
- Mean Bin Population: 2.6 (2.78%)
- Vector Mean: 96.3°/276.3°
Lineament orientation of Carroll County, Arkansas

- Calculation Method: Total Length
- Length: 282.97 mi.
- Maximum Bin Length: 27.1 mi. (9.58%)
- Mean Bin Length: 8.3 mi. (2.94%)
- Vector Mean: 113.9°/293.8°
- Calculation Method: Population
- Frequency: 66

Lineament orientation of Cherokee County, Oklahoma

- Calculation Method: Total Length
- Length: 97.3 mi.
- Maximum Bin Length: 20 mi. (20.59%)
- Mean Bin Length: 6.9 mi. (7.14%)
- Vector Mean: 65.7°/245.7°
- Calculation Method: Population
- Frequency: 18
- Maximum Bin Population: 3 (16.67%)
- Mean Bin Population: 1.3 (7.14%)
- Vector Mean: 87.1°/267.1°
### Lineament orientation of Cleburne County, Arkansas

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<th>Calculation Method</th>
<th>Frequency</th>
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<tbody>
<tr>
<td>Total Length</td>
<td>184.4 mi.</td>
<td>Population</td>
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<td>21 mi. (11.39%)</td>
<td>Maximum Bin Population</td>
<td>3 (11.54%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>7.7 mi. (4.17%)</td>
<td>Mean Bin Population</td>
<td>1.1 (4.17%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>103.6°/283.6°</td>
<td>Vector Mean</td>
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### Lineament orientation of Conway County, Arkansas

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<th>Frequency</th>
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<tr>
<td>Total Length</td>
<td>64.1 mi.</td>
<td>Population</td>
<td>10</td>
</tr>
<tr>
<td>Maximum Bin Length</td>
<td>9.0 mi. (14.06%)</td>
<td>Maximum Bin Population</td>
<td>3.0 (10.0%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>5.3 mi. (8.33%)</td>
<td>Mean Bin Population</td>
<td>0.7 (7.14%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>92.6°/272.6°</td>
<td>Vector Mean</td>
<td>95.8°/275.8°</td>
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</tbody>
</table>
### Lineament Orientation of Crawford County, Arkansas

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<th>Length</th>
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<th>Frequency</th>
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</thead>
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<tr>
<td>Total Length</td>
<td>264.1 mi.</td>
<td>Population</td>
<td>52</td>
</tr>
<tr>
<td>Maximum Bin Length</td>
<td>27.9 mi. (10.58%)</td>
<td>Maximum Bin Population</td>
<td>6 (11.54%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>9.4 mi. (3.57%)</td>
<td>Mean Bin Population</td>
<td>1.9 (3.57%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>61.9°/241.9°</td>
<td>Vector Mean</td>
<td>63.4°/243.4°</td>
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### Lineament Orientation of Delaware County, Oklahoma

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<th>Length</th>
<th>Calculation Method</th>
<th>Frequency</th>
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<tr>
<td>Total Length</td>
<td>238.6 mi.</td>
<td>Population</td>
<td>40</td>
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<tr>
<td>Maximum Bin Length</td>
<td>29.0 mi. (12.14%)</td>
<td>Maximum Bin Population</td>
<td>4 (10.0%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>10.9 mi. (4.55%)</td>
<td>Mean Bin Population</td>
<td>1.7 (4.17%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>73.5°/253.5°</td>
<td>Vector Mean</td>
<td>65.3°/245.3°</td>
</tr>
</tbody>
</table>
Lineament orientation of Independence County, Arkansas

- **Calculation Method**: Total Length
- **Length**: 159.6 mi.
- **Maximum Bin Length**: 23.8 mi. (14.93%)
- **Mean Bin Length**: 6.1 mi. (3.85%)
- **Vector Mean**: 80.1°/260.1°
- **Calculation Method**: Population
- **Frequency**: 24

Lineament orientation of Izard County, Arkansas

- **Calculation Method**: Total Length
- **Length**: 501.6 mi.
- **Maximum Bin Length**: 42.2 mi. (8.41%)
- **Mean Bin Length**: 14.7 mi. (2.94%)
- **Vector Mean**: 45.0°/225.0°
- **Calculation Method**: Population
- **Frequency**: 121
- **Maximum Bin Population**: 10 (8.26%)
- **Mean Bin Population**: 3.6 (2.94%)
- **Vector Mean**: 155.1°/335.1°
Lineament orientation of Johnson County, Arkansas

<table>
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<tr>
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<th>Length</th>
<th>Calculation Method</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>255.6 mi.</td>
<td>Population</td>
<td>44</td>
</tr>
<tr>
<td>Maximum Bin Length</td>
<td>22.44 mi. (8.78%)</td>
<td>Maximum Bin Population</td>
<td>3 (6.82%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>8.5 mi. (3.33%)</td>
<td>Mean Bin Population</td>
<td>1.6 (3.57%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>88.2° / 268.2°</td>
<td>Vector Mean</td>
<td>83.3° / 263.3°</td>
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</tbody>
</table>

Lineament orientation of Lawrence County, Arkansas

<table>
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<th>Calculation Method</th>
<th>Length</th>
<th>Calculation Method</th>
<th>Frequency</th>
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</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>124.2 mi.</td>
<td>Population</td>
<td>37</td>
</tr>
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<td>Maximum Bin Length</td>
<td>16.3 mi. (13.13%)</td>
<td>Maximum Bin Population</td>
<td>3 (17.57%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>6.2 mi. (5.0%)</td>
<td>Mean Bin Population</td>
<td>1.6 (5.0%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>55.2° / 235.2°</td>
<td>Vector Mean</td>
<td>83.3° / 263.3°</td>
</tr>
</tbody>
</table>
### Lineament orientation of Madison County, Arkansas

<table>
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<th>Calculation Method</th>
<th>Length</th>
<th>Calculation Method</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>537.8 mi.</td>
<td>Population</td>
<td>91</td>
</tr>
<tr>
<td>Maximum Bin Length</td>
<td>33.5 mi. (6.22%)</td>
<td>Maximum Bin Population</td>
<td>5.5 (6.04%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>15.8 mi. (2.94%)</td>
<td>Mean Bin Population</td>
<td>2.7 (2.94%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>25.7°/205.7°</td>
<td>Vector Mean</td>
<td>52.9°/232.9°</td>
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</tbody>
</table>

### Lineament orientation of Marion County, Arkansas

<table>
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<th>Calculation Method</th>
<th>Length</th>
<th>Calculation Method</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>447.9 mi.</td>
<td>Population</td>
<td>86</td>
</tr>
<tr>
<td>Maximum Bin Length</td>
<td>70.1 mi. (15.66%)</td>
<td>Maximum Bin Population</td>
<td>14 (16.28%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>16.0 mi. (3.57%)</td>
<td>Mean Bin Population</td>
<td>2.9 (3.33%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>80.2°/260.2°</td>
<td>Vector Mean</td>
<td>83.3°/263.3°</td>
</tr>
</tbody>
</table>
Lineament orientation of Randolph County, Arkansas

<table>
<thead>
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<th>Calculation Method</th>
<th>Length</th>
<th>Calculation Method</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>228.9 mi.</td>
<td>Population</td>
<td>44</td>
</tr>
<tr>
<td>Maximum Bin Length</td>
<td>23.1 mi. (10.09%)</td>
<td>Maximum Bin Population</td>
<td>4 (9.09%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>8.2 mi. (3.57%)</td>
<td>Mean Bin Population</td>
<td>1.7 (3.85%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>86.6°/266.6°</td>
<td>Vector Mean</td>
<td>62.5°/242.5°</td>
</tr>
</tbody>
</table>

Lineament orientation of Searcy County, Arkansas

<table>
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<th>Calculation Method</th>
<th>Length</th>
<th>Calculation Method</th>
<th>Frequency</th>
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</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>430.5 mi.</td>
<td>Population</td>
<td>70</td>
</tr>
<tr>
<td>Maximum Bin Length</td>
<td>24.7 mi. (5.73%)</td>
<td>Maximum Bin Population</td>
<td>5 (7.14%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>12.7 mi. (2.94%)</td>
<td>Mean Bin Population</td>
<td>2.2 (3.13%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>99.7°/279.7°</td>
<td>Vector Mean</td>
<td>105.7°/285.5°</td>
</tr>
</tbody>
</table>
Lineament orientation of Sequoyah County, Oklahoma

- Calculation Method: Total Length
- Length: 189.8 mi.
- Maximum Bin Length: 24.0 mi. (12.65%)
- Mean Bin Length: 7.9 mi. (4.17%)
- Vector Mean: 66.1°/246.1°

Lineament orientation of Sharp County, Arkansas

- Calculation Method: Total Length
- Length: 471.7 mi.
- Maximum Bin Length: 31.4 mi. (6.65%)
- Mean Bin Length: 14.7 mi. (3.12%)
- Vector Mean: 47.6°/227.6°

- Calculation Method: Population
- Frequency: 106

- Calculation Method: Maximum Bin Population
- Frequency: 7.5 (7.08%)

- Calculation Method: Mean Bin Population
- Frequency: 3.5 (3.33%)

- Calculation Method: Vector Mean
- Frequency: 45.6°/225.6°
Lineament orientation of Stone County, Arkansas

Calculation Method | Length | Calculation Method | Frequency
Total Length       | 380 mi. | Population       | 68
Maximum Bin Length | 47.2 mi. (12.42%) | Maximum Bin Population | 5.5 (8.09%)
Mean Bin Length     | 11.2 mi. (2.94%) | Mean Bin Population | 2.3 (3.33%)
Vector Mean         | 103.9°/283.9° | Vector Mean       | 109.7°/289.7°

Lineament orientation of Van Buren County, Arkansas

Calculation Method | Length | Calculation Method | Frequency
Total Length       | 269.1 mi. | Population       | 42
Maximum Bin Length | 37.9 mi. (14.08%) | Maximum Bin Population | 4.5 (10.71%)
Mean Bin Length     | 8.4 mi. (3.12%) | Mean Bin Population | 1.4 (3.33%)
Vector Mean         | 97.4°/277.4° | Vector Mean       | 123.4°/303.4°
### Lineament orientation of Washington County, Arkansas

<table>
<thead>
<tr>
<th>Calculation Method</th>
<th>Length</th>
<th>Calculation Method</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>545.8 mi.</td>
<td>Population</td>
<td>74</td>
</tr>
<tr>
<td>Maximum Bin Length</td>
<td>36.2 mi. (6.63%)</td>
<td>Maximum Bin Population</td>
<td>4.5 (6.08%)</td>
</tr>
<tr>
<td>Mean Bin Length</td>
<td>16.0 mi. (2.94%)</td>
<td>Mean Bin Population</td>
<td>2.2 (2.94%)</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>56.3°/236.3°</td>
<td>Vector Mean</td>
<td>64.6°/244.6°</td>
</tr>
</tbody>
</table>
