ABSTRACT

GARLINGTON, CHRISTOPHER ALAN. Relation of Well Yields to Fracture Patterns and Lineaments in the Rolesville Batholith, Wake County, North Carolina. (Under the direction of Dr. John C. Fountain).

In Wake County over 140,000 county residents (about 25% of the population) rely on groundwater resources for drinking and other everyday uses. The increasing population of the county is causing an increase in demand for water resources. As surface water supplies for the county reach maximum capacity, groundwater will become an increasingly important source of water.

Most drinking water supply wells in the county are completed in the crystalline bedrock. There is little matrix permeability in these rocks, therefore groundwater storage and flow is primarily through secondary fractures. The three goals of this study are 1) to determine via field study the primary surface fracture directions present at pavement outcrops within the Rolesville granite area of Wake County, 2) to perform a larger scale land-surface lineament analysis using aerial photographs and remote sensing data to compare with the field data results, and 3) to use available well yield data to correlate with the observed primary surface fracture directions to identify possible areas within the Rolesville granite of Wake County where the subsurface fracturing will allow for the construction of wells with higher than average yields.

A total of 151 individual joints and fractures were identified by field study and were recorded. A rose diagram of these fractures finds the primary fracture azimuth to be 90° ± 5°, with 30.67 % of all measured fractures falling in this range. The secondary fracture azimuth in the field is approximately 0° ± 5° (18 % of all fractures). The third

most common fracture azimuth is roughly 280°-290° (14 %), and the fourth most common azimuth is 10°-15° (8.67 %).

The computer program ENVI was used to identify a total of 2362 lineaments on aerial photographs of the same geographic area where the fractures were located in the field study. The rose diagram of these land-surface lineaments also supports the E-W trend (90° ± 5°) found in the fracture data measured in the field. Lineaments in this range account for 15.66 % of those found. The second most common direction amongst the computer lineaments is 0° ± 5°. The number of fractures in this direction is roughly half that found in the 90° trend, accounting for 7.28 % of all lineaments found.

The consistency between the results of the computer and field data confirm the validity of using the computer program ENVI for identifying lineaments in the Rolesville batholith portion of Wake County. This suggests that the directional filter of the program ENVI may be a useful tool in helping locate optimal sites for new high yielding wells.

RELATION OF WELL YIELDS TO FRACTURE PATTERNS AND LINEAMENTS IN THE ROLESVILLE BATHOLITH, WAKE COUNTY, NORTH CAROLINA

by
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BIOGRAPHY

I was born in Dayton, Ohio on September 12, 1979. I attended grade school in Silver Spring, Maryland and high school in Chapel Hill, North Carolina. I was an active member in the Boy Scouts of America, attaining the rank of Eagle Scout in May 1997. My Eagle Scout project foreshadowed my interest in the environment. The project involved planning and constructing a system to mitigate the erosive affects of storm water run-off at the beachfront area of Eastwood Lake in Chapel Hill, NC. In the spring of 1997, I graduated from Chapel Hill High with outstanding service honors and an interest in pursuing environmental issues.

I graduated magna cum laude from North Carolina State University in the fall semester of 2001 with a BS in Environmental Science with a Geology concentration. During my summer breaks, I worked at the US Environmental Protection Agency as a physical scientist and chemist.

In my free time I enjoy watching movies, lifting weights, bicycling, and spending time with my friends. I would like to thank my family and friends for all of the support they have provided to me during this project.

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Introduction and Problem Statement

In Wake County over 140,000 county residents (about 25 % of the population) rely on groundwater resources for drinking and other everyday uses. Two-thirds of these people obtain their water directly from private domestic wells, with the other one-third receiving groundwater from community water systems (CWS) (CDM, 2003) (Figure 1). CWS are public water systems that serve year-round residents of a community, subdivision, or mobile home park containing at least 25 year-round residents.

The water demands of Wake County, North Carolina are constantly increasing with population growth. As surface water supplies for the county are appropriated, groundwater will become an increasingly important water source (Welby, 1985).

Within the past decade Wake County has enacted three environmental initiatives (the 1998 Comprehensive Water/Sewer Plan, the Land Use Plan, and the Comprehensive Watershed Management Plan) that emphasize the importance of groundwater for current and future water supplies for the county (CDM, 2003). The recent droughts leading to surface water shortages and dropping water levels in the Falls Lake reservoir may also cause an increased demand for developing groundwater resources in Wake County.

There is no productive surficial aquifer in eastern Wake County, as a relatively thin veneer of saprolite covers the crystalline bedrock. “The thickest soils are found capping the upland surfaces but are seldom more than 30 feet thick. A much thinner soil veneer is found on the slopes of draws and valleys where un-weathered granite usually crops out. Exfoliated boulders of granite are common. Floodplains are narrow and thin and un-weathered granite is commonly exposed in stream channels” (May and Thomas, 1968). Thus most drinking water supply wells in the county are completed in the

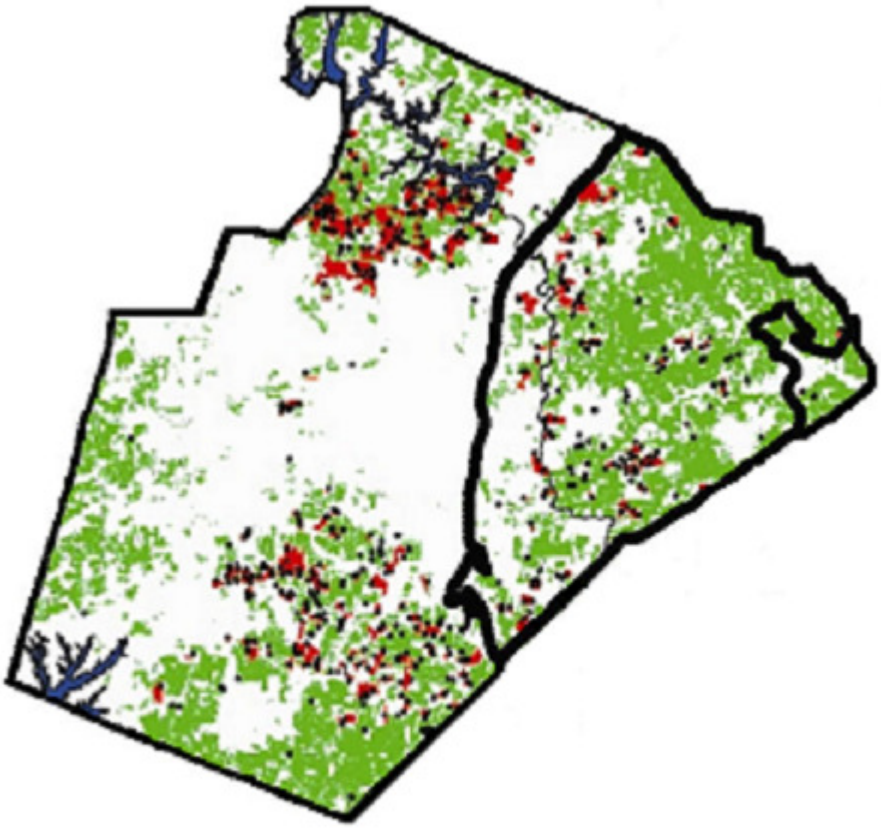


Figure 1. The distribution of groundwater use in Wake County, North Carolina.

Green Areas = Land parcels containing private wells
Red Areas = Land parcels served by CWS'
Black Dots = CWS well locations
Thick Black Outline = Rolesville Batholith

Modified from CDM 2003

crystalline bedrock. There is little matrix permeability in these rocks, therefore groundwater storage and flow is primarily through secondary fractures. The relatively small storage capacity of fractured bedrock (1-3%) makes it important to identify areas in the county where the bedrock fracture conditions favor increased well yields (CDM, 2003). Two aspects that affect groundwater utilization in crystalline rocks are (1) the actual volume of groundwater available (inventory); and (2) the production aspect, or the

rate at which water can be withdrawn from any given point (Welby, 1984). The areas in Wake County where increased yields are most likely to occur are those areas where fractures or fracture systems are better developed (May and Thomas, 1968). This hypothesis is again supported by a study of Wake County that determined; "The characteristics of the fracture system are the most important factors affecting well yield, but are difficult to measure directly" (Wilson, 1982).

The purpose of this study is to use a combination of field data and remote sensing data (aerial photographs, topographic maps, LIDAR elevation data), and directional filtering software (the Environment for Visualizing Images, or ENVI)) to locate areas within the Rolesville batholith that have a higher fracture density. Identifiable surface features that represent zones of increased porosity are fracture traces, fracture intersections, zones of shearing, and concentrated zones of fracturing. Siddiqui and Parizek (1971) determined that wells located in a fracture trace, or especially at the intersection of two traces in a carbonate terrane, have statistically significant higher well yields than wells not located on a fracture trace.

The three goals of this study are 1) to determine via field study the primary surface fracture directions present at pavement outcrops within the Rolesville granite area of Wake County, 2) to perform a larger scale land-surface lineament analysis using aerial photographs and remote sensing data to compare with the field data results and results of previous geologic studies, and 3) to correlate available well yield data with the observed primary surface fracture directions in order to identify possible areas within the Rolesville granite of Wake County where these subsurface fractures might allow for the construction of wells with higher than average yields.

Background

Wake County Geology

There are two major geologic units that cover roughly 50 percent of Wake County, North Carolina. These geologic units are the igneous felsic intrusives (the Rolesville granite), and the Triassic sedimentary rocks. In Figure 2, the mint-green bands in the westernmost portions of Wake County represent the Triassic sedimentary rocks. The orange colored area outlined with a bold black line represents the felsic intrusive rocks of the Rolesville batholith. The remaining rock units are diverse metamorphic rocks that occur as north-south trending bands of varying sizes, and are located in between the two major geologic units (CDM, 2003). This study will focus exclusively on the igneous felsic intrusive rocks that comprise the Rolesville batholith.

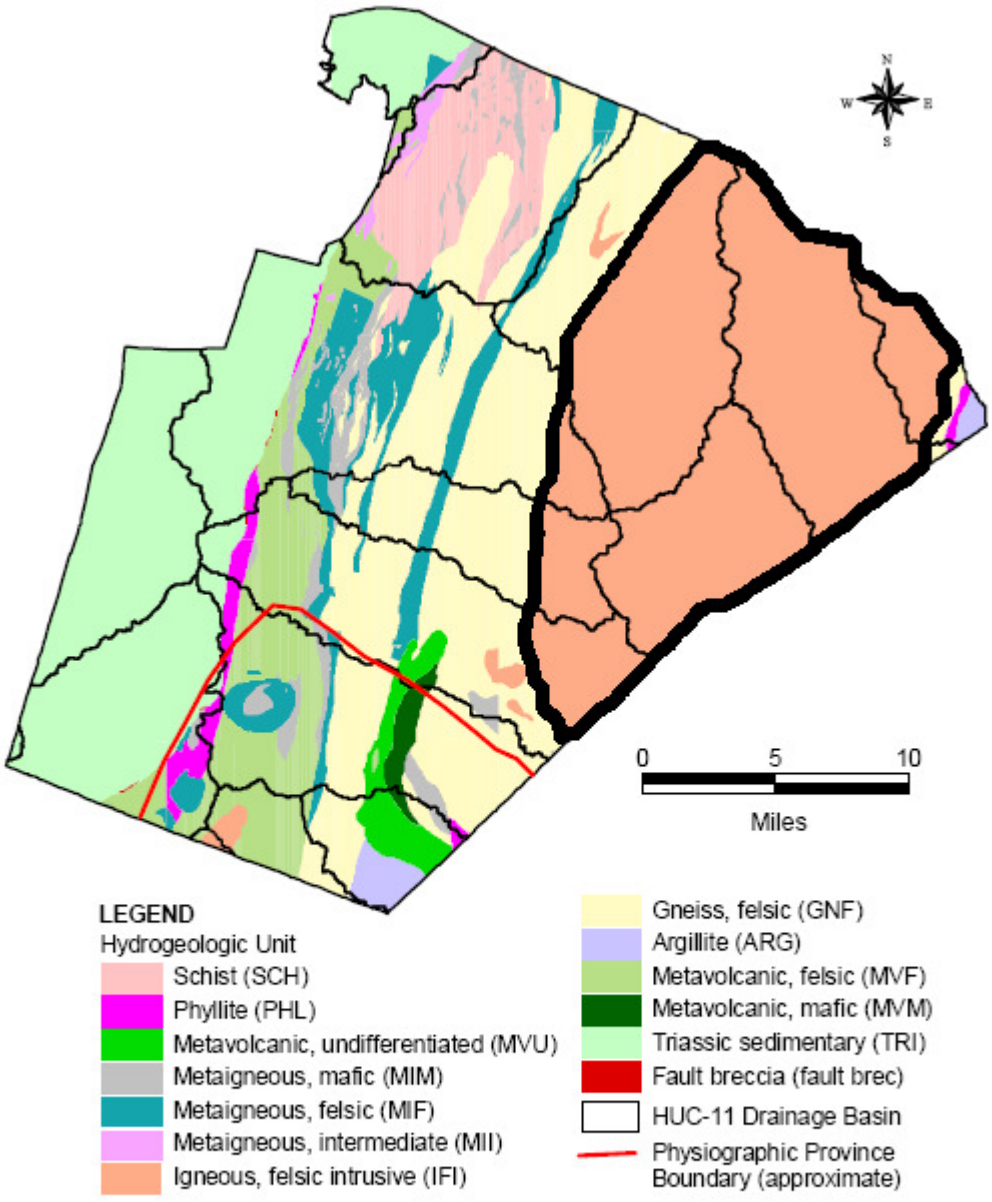


Figure 2. Hydrogeologic Units of Wake County

The Rolesville Batholith is outlined in black

(Modified from CDM, 2003)

Study Area

The study area of this report is limited to those areas of the Rolesville batholith that are contained within Wake County, North Carolina. This area covers roughly 628.59 square kilometers (242.7 square miles), or ~ 28 % of Wake County's total land area.

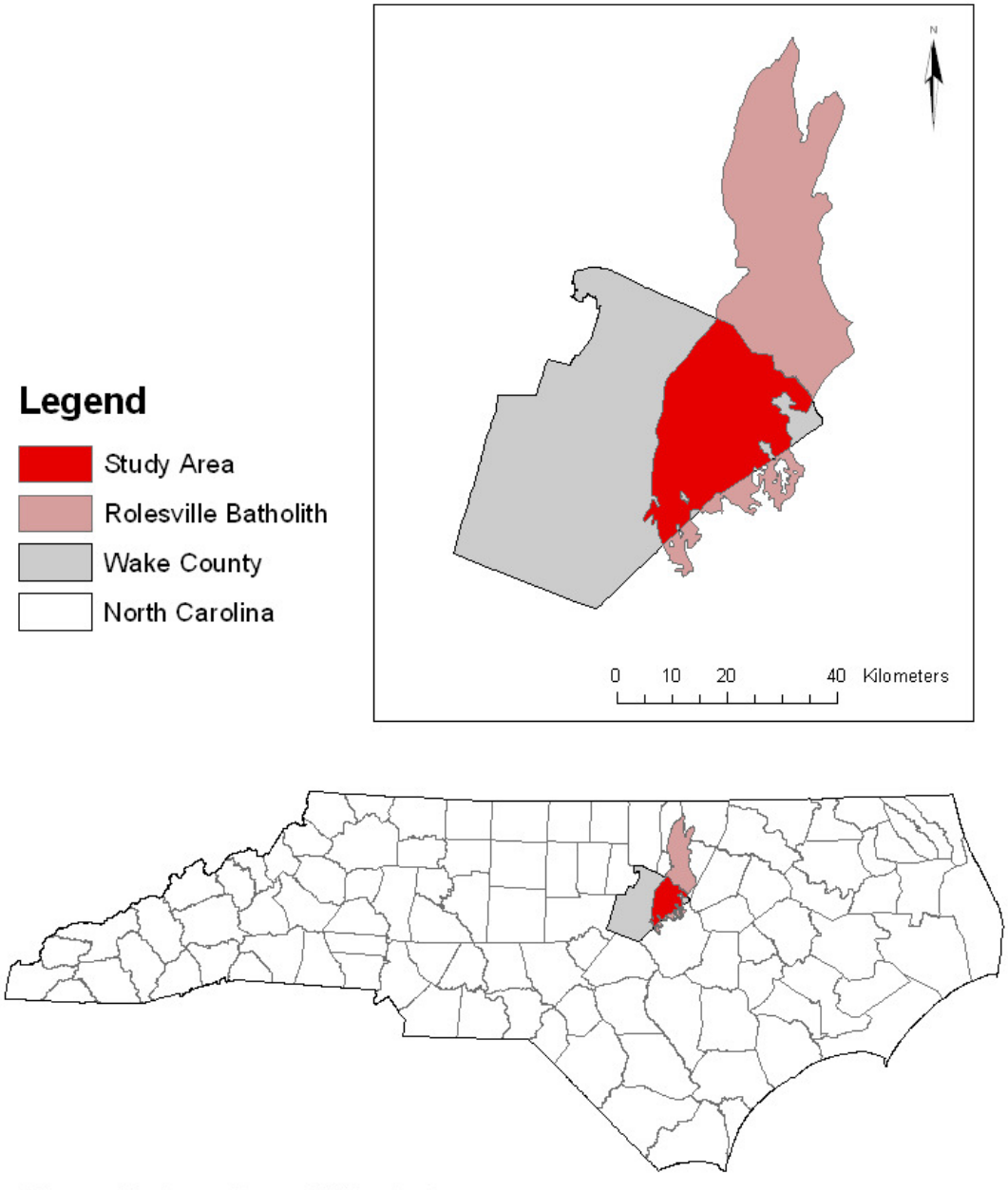


Figure 3. Location of Study Area

The Rolesville batholith

The Rolesville batholith is the largest intrusive body in the southern Appalachians (Speer, 1994). This large Carboniferous granitic mass occupies much of the eastern third of Wake County, North Carolina (Parker, 1979). It occupies the core of the southern Raleigh belt, roughly along the north-northeast-south-southwest trending hinge zone of the Wake-Warren antiform (Stoddard et al., 1991). The granitiod Rolesville batholith was formed as part of a larger group of plutons during the Late Paleozoic Alleghanian orogeny of the southern Appalachians (Farrar, 1985 a, b). (Figure 4) Its size and range of granitiod rock types make it likely that the batholith is comprised of multiple magmatic pulses (Speer et al., 1994). Zircon and monazite U-Pb age dating performed on samples taken from the batholith have concluded that it was likely emplaced ca. 298 Ma (Schneider and Sampson, 2001).

The Rolesville batholith has approximate dimensions of 24 km x 80 km (14.9 miles x 49.7 miles). It is marked by a gravity low, suggesting a thick section of the less dense granitic rock. A gravity study (Stephens, 1988) suggests that the batholith thickens toward the east and southeast, reaching depths of up to 20 km (12.43 miles). The Rolesville batholith is predominately bounded by the Raleigh terrane on the west and by the Spring Hope terrane to the east. (Figure 5)

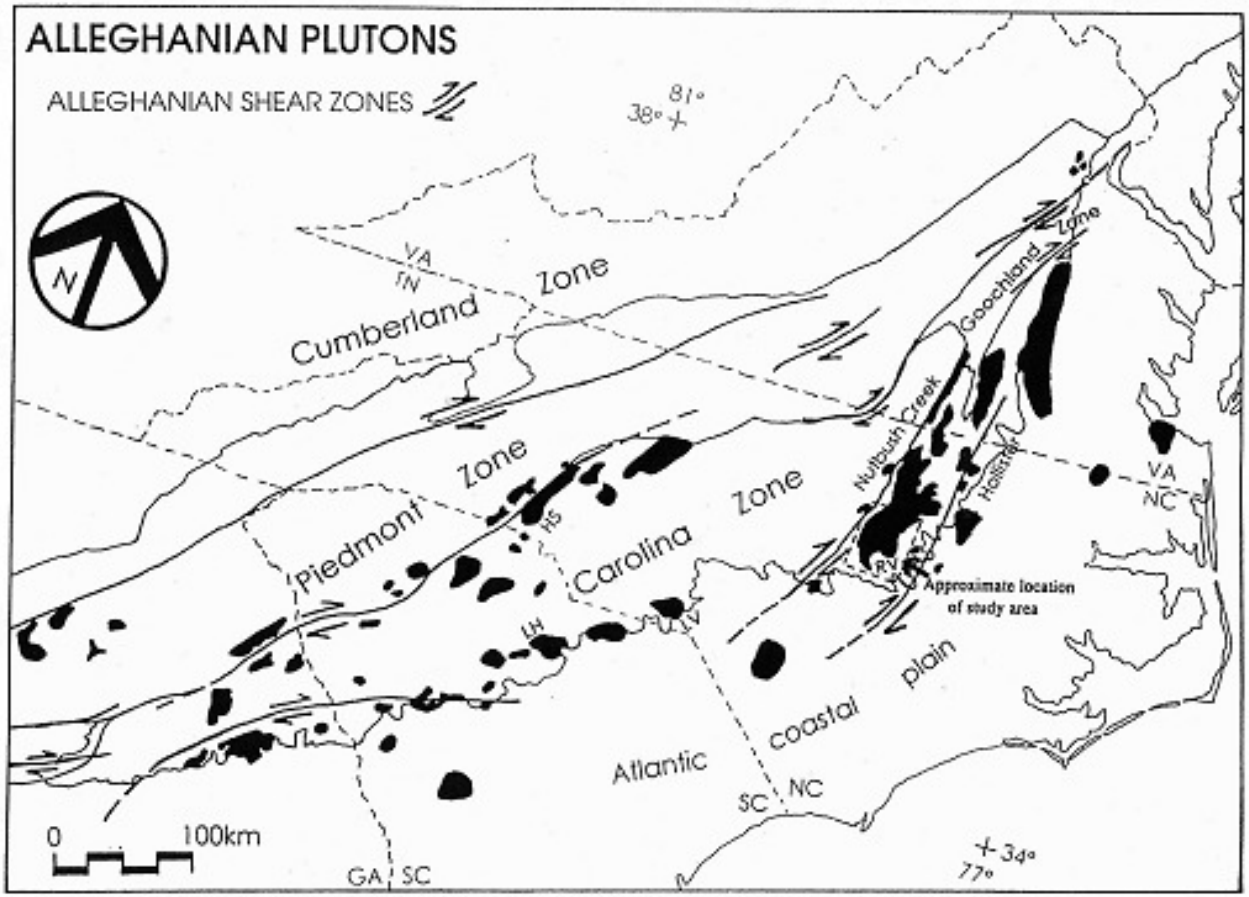


Figure 4. Alleghanian plutons in the Southern Appalachians (in black). Plutons are spatially and temporally related to Alleghanian ductile shear zones (e.g. Nutbush Creek fault zone, Hollister shear zone; after Horton et al., 1989; Speer et al., 1994; Hibbard and Samson, 1995; Coler et al., 1997). RV = Rolesville batholith; HS = High Shoals pluton; LV = Lilesville pluton; LH = Liberty Hill pluton.
(Image from Gaughan, 1999)

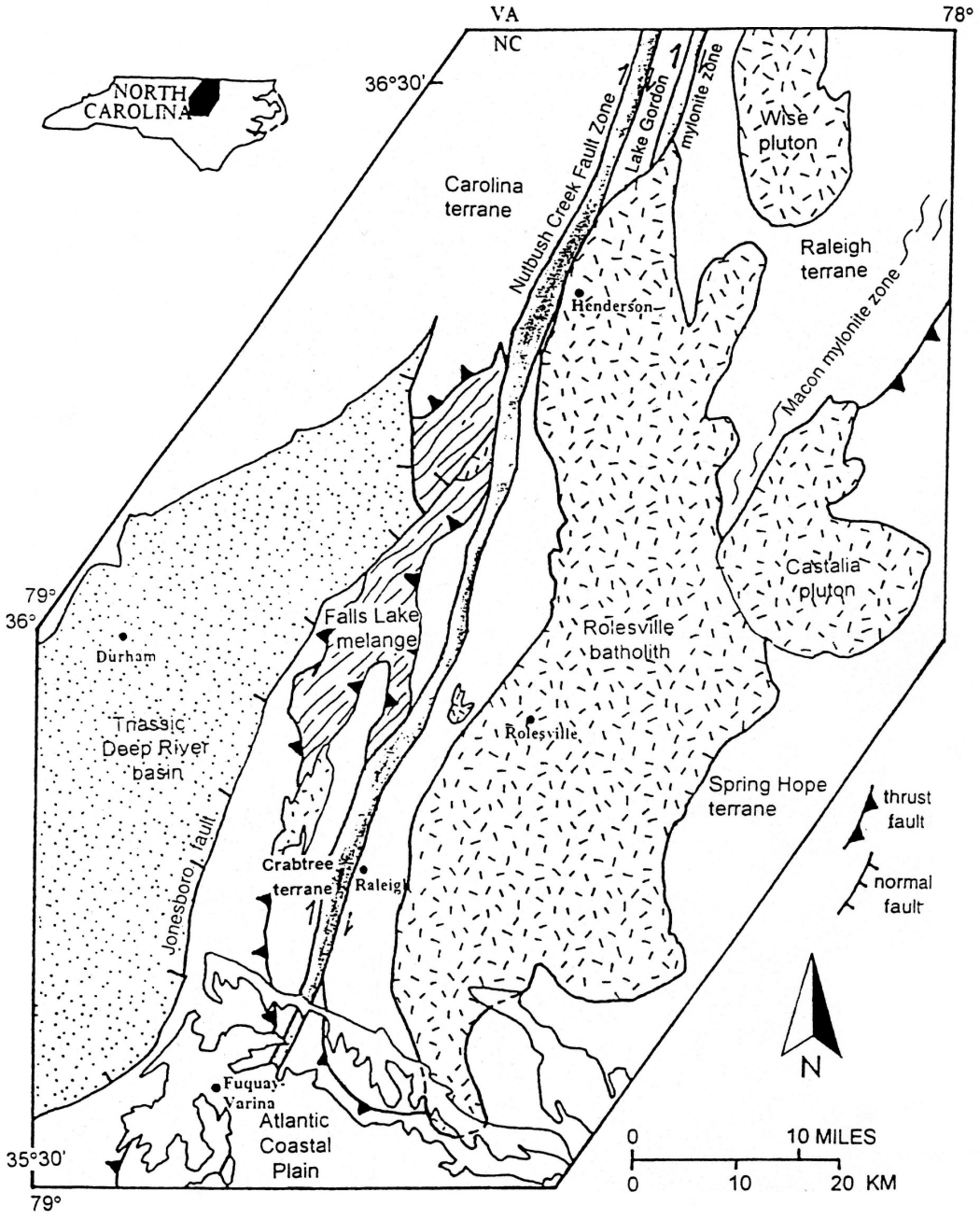


Figure 5. Tectonic map of the eastern North Carolina Piedmont.
(after Stoddard et al., 1991; Horton et al., 1994)

(Modified from Gaughan, 1999)

Fractures

Fractures are mechanical breaks in rocks. They form from various processes including response to tectonic, thermal, and lithostatic stresses, as well as high fluid pressures. Fractures occur at a wide variety of scales, from microscopic to continental in extent. Hydraulically significant fractures provide conduits for fluid flow and are connected to other hydraulically conductive fractures to form systems or networks. Due to the irregular distribution of porosity within fractured rock bodies, flow systems through fractures can have complex geometries (NRC, 1996). As a result, these intricate systems exhibit often-irregular distribution of groundwater, which must be taken into account in the construction of water supply wells in Wake County (Welby, 1984).

Fractures represent the concentration of void space in rocks. Groups of closely spaced and interconnected fractures are referred to as fracture zones. Fractures with little to no offset are commonly referred to as joints, and groups of these fractures are called joint sets. "Joints commonly cluster in groups oriented around one or more preferred directions" (Daniel, 1987).

Igneous, metamorphic, and consolidated sedimentary deposits all tend to be fractured to some extent when they occur within hundreds of meters of the land surface. Some fractures may extend to considerable depths, but generally fractures decrease in size and number with increasing depth (LeGrand, 1979). Fracturing in a rock body exists both vertical and horizontally, yet a major component of flow must be through horizontal fractures or no depth dependant relationship would exist.

Therefore, the permeability, well yield, and specific capacity in a fractured crystalline aquifer will decrease with well depth (Wilson, 1982). However, Daniel (1987)

reports that maximum well yields in North Carolina are obtained at much greater depths than the previously reported maximum well depth of about 300 feet. Using a statistical analysis, he found that the average yield for 6" diameter wells located in draws or valleys reaches a maximum yield of roughly 45gal/min at depths of 500-525 feet. Similarly, the average yields of 12" diameter wells located in draws or valleys reaches a maximum yield of about 150 gal/min at depths of 700 to 800 feet. This study was conducted on wells constructed in crystalline rocks in the Piedmont and Blue Ridge provinces of North Carolina.

Joints and Dikes

In the Rolesville Batholith, the two prominent structural features are jointing and sheeting. It is common to find at least two primary joint sets intersecting at nearly right angles (May and Thomas, 1968).

The oldest joints in Wake County are those filled by quartz veins. These joints trend parallel to foliation, although some are oblique or at right angles (Parker, 1979). In the Raleigh area, quartz veins are generally more fractured than the surrounding rock. Generally these veins are vertical or dip at nearly vertical angles (May and Thomas, 1968).

The later joints are those that have been filled by pegmatite. In the Rolesville batholith, vertical joints striking N80°-90°E are the most prominent. Relatively less common but widespread scattered joints strike near northeast or northwest with varying dips (Parker, 1979). The youngest joints are filled by diabase dikes, which are considered Jurassic in age (Speer, 1994).

Dikes are tabular igneous rock bodies that cut through the existing rock structure. In Wake County, diabase dikes fill fractures that are generally not parallel to the local joints. They record an episode of crustal fracturing due to extension, and a subsequent intrusion of basic magma. The diabase dikes show little consistent relation to ductile structures, but they do relate to brittle structures (Parker, 1979). In the Raleigh area dikes are usually not good aquifers. However, the host rock adjacent to these dikes has often been made more permeable due to fractures caused by the force of intrusion and heat (May and Thomas, 1968). The most common joints in the igneous rocks of the Rolesville batholith strike near east-west, while most dikes strike north-northwest (Parker, 1979). (Figure 6)

Faults

Faults are planes along which the continuity of a rock formation is broken. Wake County contains both ductile faults (mylonite zones, shear zones, etc.) and brittle faults (the Jonesboro fault (roughly NNW trend)).

The brittle faults and cataclastic zones mapped by Heller (1998) near the Rolesville batholith may be grouped into three sets based upon their strike and dip attitude. The first set consists of two cataclastic zones that trend N5°E to N10°E, with unknown dips. The second set consists of two faults that are moderately N-dipping (50° to 60°), and can be observed in outcrops. The third set consists of six faults and one cataclastic zone. Four of these faults lie in the vicinity of Lake Wheeler while two others are located near the city of Cary. The structures near Lake Wheeler trend N70°W to east-west and are sub-vertical (Heller, 1998). This study infers that similar brittle faults are

likely to exist elsewhere in the Rolesville batholith, even though detailed geologic mapping has not been performed on this area.

Lineaments

Lineaments are defined as topographic features having a linear configuration; they generally range in length from 2-100 km. Lineaments are commonly expressed as depressions, valleys, or as an alignment of features such as streambeds or vegetation. Spanjers (1983) reported a major lineament trend of N5° - 25°E within the Raleigh belt.

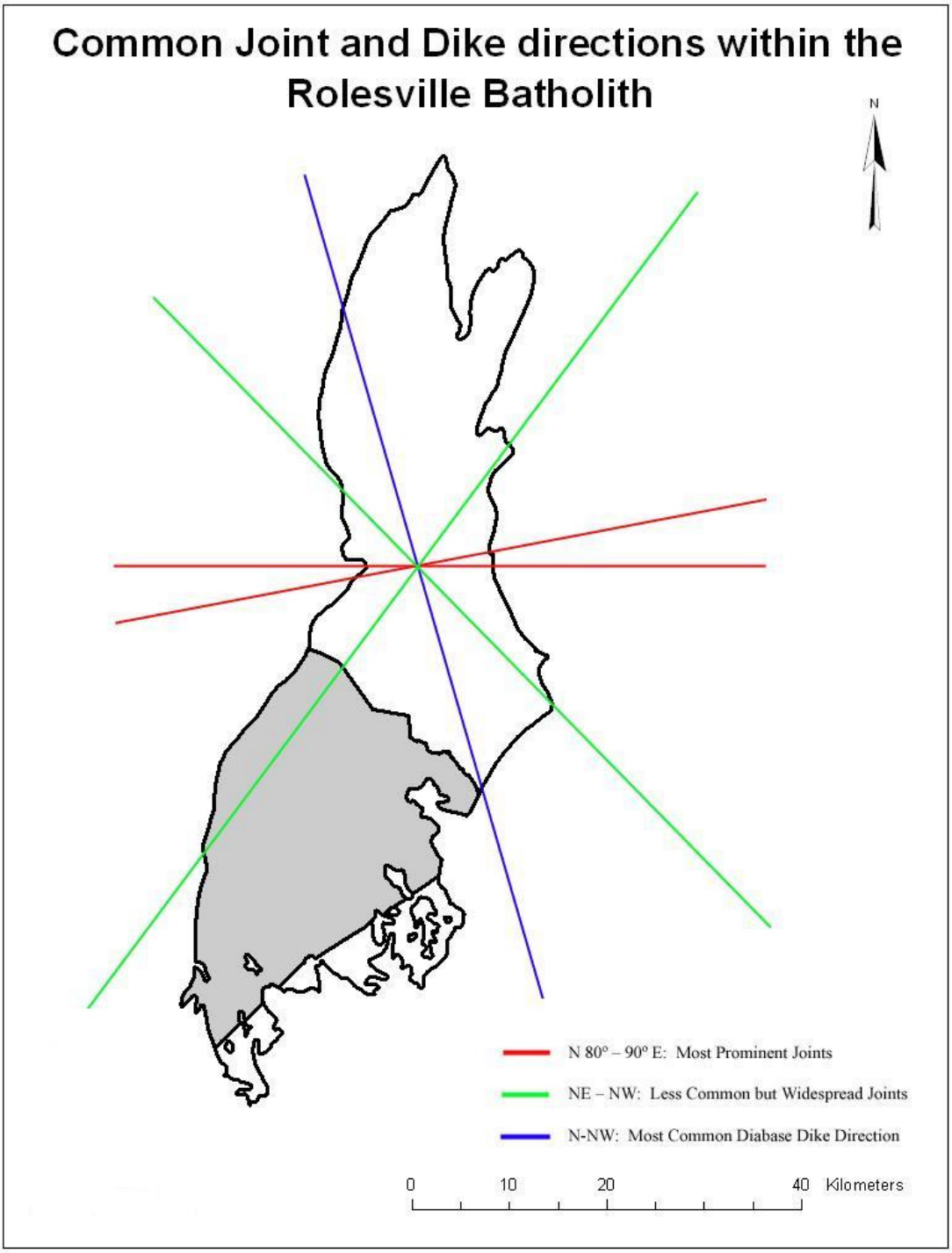


Figure 6. Common Joint and Dike Directions within the Rolesville Batholith.

The Wake County Aquifer System

An aquifer is a geologic formation capable of providing economic quantities of water to wells (Freeze and Cherry, 1979). Wake County's groundwater is primarily stored in the regolith and fractured crystalline rock aquifer system. (Figure 7) The regolith consists of all material (soil, saprolite, loose rocks) found above the fractured bedrock. The regolith is an important part of the aquifer system in that it stores groundwater while at the same time feeding water into the fractured bedrock below (CDM, 2003).

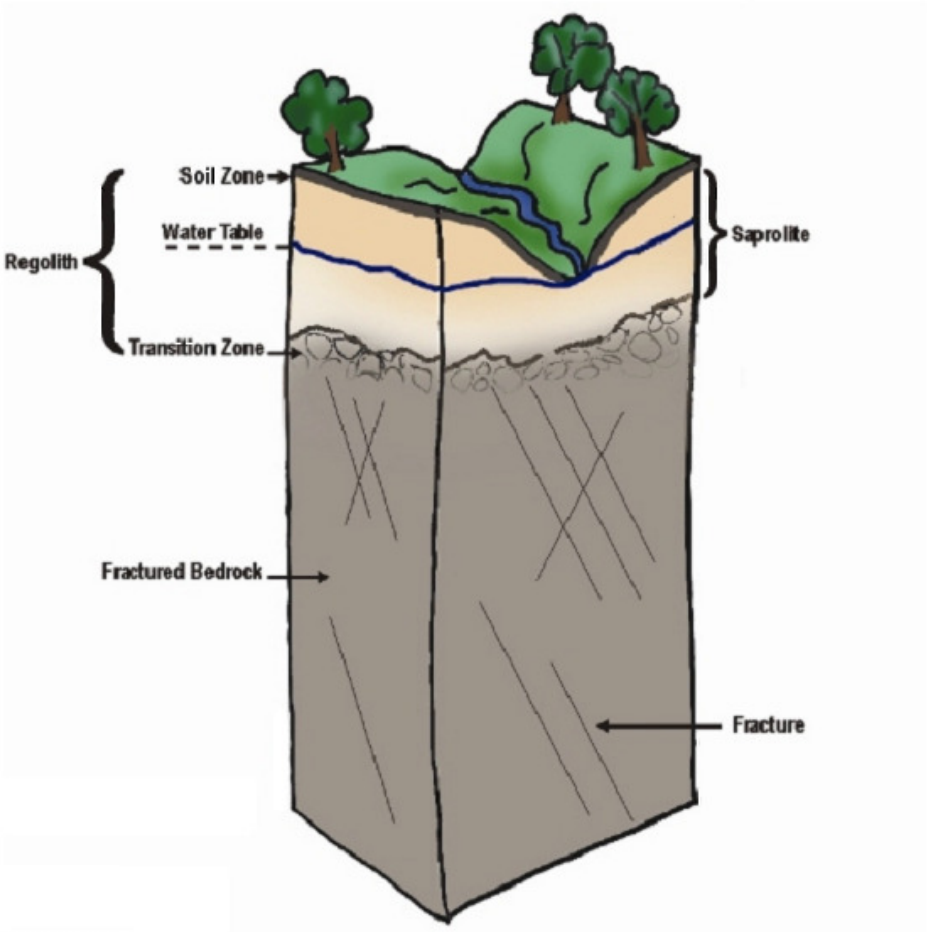


Figure 7.
Major Components of the Regolith-Fractured Crystalline Rock Aquifer System (adapted from Daniel and Dahlen, 2002) (From CDM, 2003)

The regolith is relatively thin in those areas of Wake County underlain by the Triassic sedimentary rocks and Rolesville granites. May and Thomas (1968) reported that the regolith is rarely thicker than 30 feet. A more modern estimate of regolith thickness in Wake County comes from Rick Bolich, a hydrogeologist with the NCDENR Division of Water Quality's Aquifer protection section, who writes, "a more appropriate estimate would be that there is seldom more than about 50 feet of saprolite/regolith in this area. Depth to rock is probably most highly variable in eastern Wake County due to the presence of the Rolesville granite, which has a highly variable weathering profile since it is a massive rock" (personal communication, 2006). The thin regolith in these areas provides little potential for water storage within this layer, increasing the importance of the fractured bedrock for water storage and retrieval. It also makes these areas more susceptible to reduced well yields and dry wells during periods of drought (CDM, 2003). Because the regolith is thin throughout the area of the study, the focus of this study will be on identifying those areas of the fractured rock aquifer system that have the potential for wells of higher than average yields.

Well Construction and Yields

The most common well construction method in Wake County is air-rotary drilling (R. Bolich, personal communication, 2006). Rotary drilling involves the use of drag or roller bits attached to the end of a rotating drill stem. Air-rotary drilling uses compressed air to cool the drill bit and to remove cuttings during well construction. This type of construction allows for well depths greater than 1000 feet and well diameters of 4 – 10 inches. This construction method is best suited for wells constructed in bedrock aquifers

(Huffman and Miner, 1996). In these wells, steel or PVC casing is installed a few feet into the bedrock, and the rest of the hole is left open to allow the water traveling through fractures to enter the borehole (R. Bolich, personal communication, 2006). In order to prevent surface contaminants from entering the well, North Carolina state well construction standards require that the annular space between the drilled well hole and casing be sealed with cement grout to a minimum depth of 20 feet below the land surface (Huffman and Miner, 1996). (Figure 8)

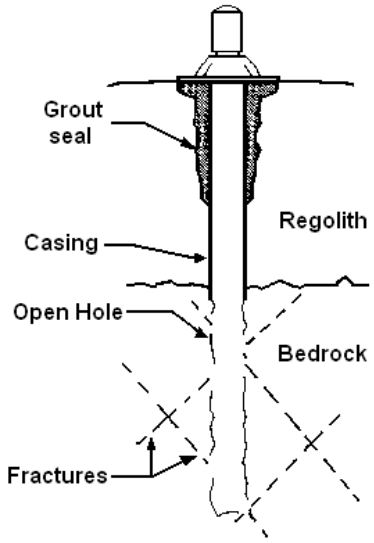


Figure 8. Typical drilled well in Wake County, North Carolina.
(Modified from Huffman and Miner, 1996)

The yield of a well is defined as the maximum pumping rate that can be supplied by a well without lowering the water level below the pump intake (Freeze and Cherry, 1979). The quantity and size of the water bearing fractures through which the well is constructed will ultimately control the yield of the well (NRC, 1996). In Wake County the most common method for estimating well yield is an educated guess by the driller

during well construction. “Obviously, this is not very accurate, but in my experience a good well driller who has been in the business for a few years will generally be able to estimate the yield to within 20% of its “actual” yield.” (R. Bolich, personal communication, 2006). The most accurate method of determining well yield is a pumping test, or a step-drawdown test, but these types of tests are rarely conducted on private household wells due to their expense. The state of North Carolina requires 24-hour pumping tests prior to the approval of a CWS well.

Two previous studies have used reported well yield data to calculate the average yield for wells located within the Rolesville granite of Wake County. May and Thomas (1968) reported an average yield of 20 gpm for the wells in their study. Both private and CWS wells were included in this calculation. Wilson (1982) found the average yield of CWS wells within the Rolesville granite to be 27.5 gpm.

Materials and Resources

The materials and resources used in the field work portion of the study are: a Brunton® geological compass, a Garmin® hand-held GPS system, a Kodak® 3.1 megapixel digital camera, 100 and 50 meter measuring tapes, a meter stick, 7.5 minute quadrangle maps of the study area, a field notebook, and the book "An Inventory of Significant Natural Areas in Wake County, North Carolina" by Harry E. LeGrand Jr.

The materials and resources employed for the computer work section of the research are: the Wake County GIS Webpage (www.wakegov.com, http://lnweb02.co.wake.nc.us/gis/gismaps.nsf), NC DOT GIS Contour Maps of Wake County (http://ncdot.org/it/gis/DataDist/GISContourmaps.html), the USGS Ground-Water Site Inventory of North Carolina (http://waterdata.usgs.gov/nc/nwis/gwsi?county_cd=37183&format=station_list), a plotter, a ruler, and the computer programs ENVI® (Environment for Visualizing Images), ArcGIS®, Adobe® PhotoShop®, and Rick Allmendinger's StereoWin 1.2 Computer Program (http://www.geo.cornell.edu/geology/faculty/RWA/RWA.html).

Methods

The research portion of this study involved two distinct phases: fieldwork, followed by computer work. The purpose of the fieldwork was to identify and measure the orientation of fractures within pavement outcrops of the Rolesville batholith in Wake County. After the field data was collected to provide an idea of the primary fracture directions, the first step in the computer portion of the research was to test to see how well ENVI's directional filters were capable of identifying lineaments of geological

interest to the study. The second portion of the computer work involved the comparison of the fracture and lineament data with well data in the Rolesville batholith area of Wake County. The purpose was to determine if the same lineament directions could be found amongst those wells with greater than average yields.

Fieldwork Methods

The fieldwork consisted of three distinct parts; 1) Locating granitic pavement outcrops within the study area, 2) Obtaining permission from landowners to visit and study the rock outcrops located on their private property, and finally, 3) Visiting the rock outcrop and taking measurements.

Based on collected information (LeGrand Jr., 2003; E. Stoddard, personal communication, 2003), twelve payment outcrops were targeted for possible study. (Table 1)

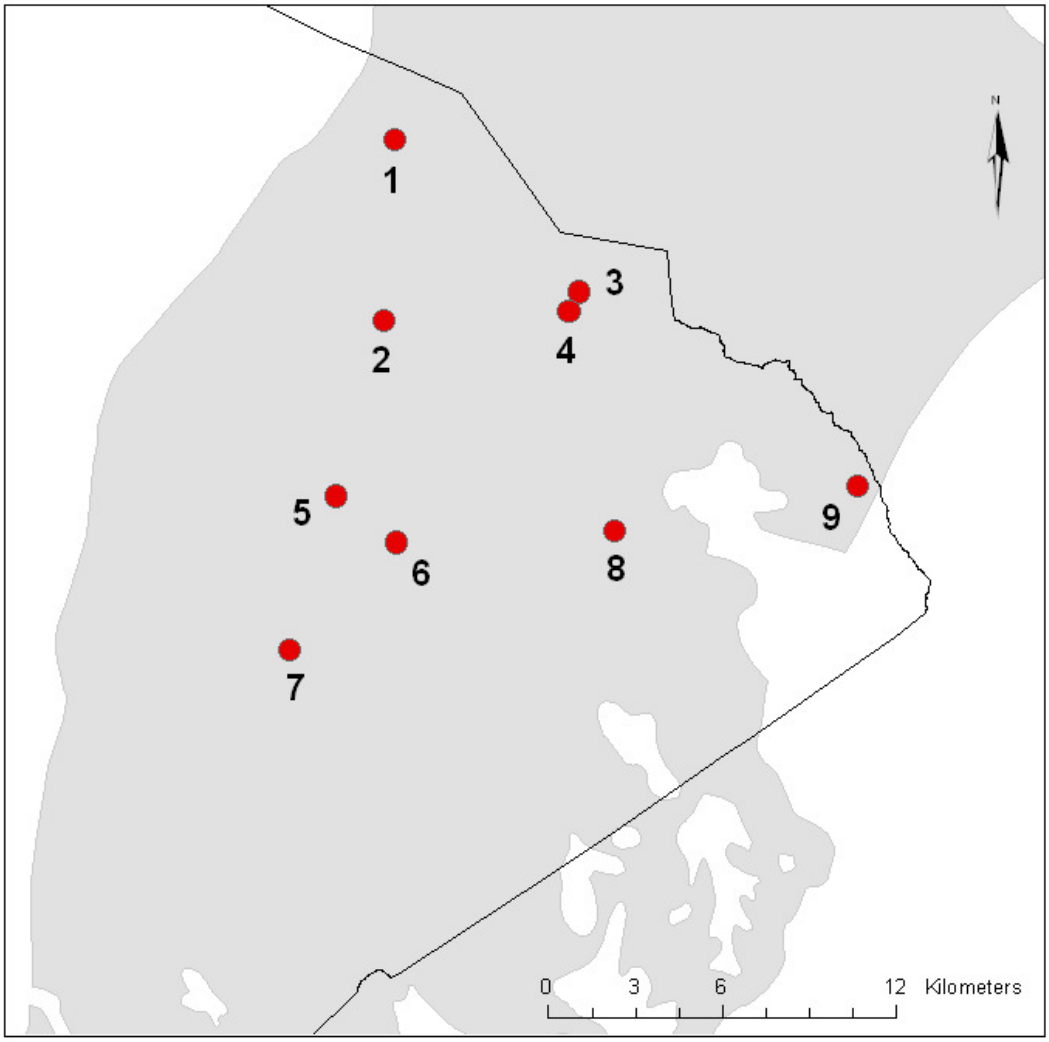
Table 1: Potential field study sites

Site Number	Site Name	Visited
1	Wildcat Hollow	Yes
2	Barham Granitic Flatrock	No
3	Mitchell Millpond State Park	Yes
4	Pulleytown Road Granitic Flatrock	Yes
5	Fowler's Mill Creek	No
6	Southwest Rolesville Granites	Yes
7	Lake Mirl Granitic Flatrock	Yes
8	Hodges Mill Creek Flatrock	No
9	Temple Flat Rock	Yes
10	Wake Stone Quarry (Knightdale)	Yes
11	The Rocks Preserve	Yes
12	Old 64 Granite	Yes

Once the potential study areas were identified, the Wake County tax information web page was used to obtain the names of the property owners for each outcrop. The landowner's phone number was then found using an online telephone directory of Wake County. Each owner was called to obtain permission for a site visit and to take measurements on their property. Most owners were gracious, and granted access to the outcrops on their land. Refusal by, or inability to contact owners prevented the visitation of the following properties: Barham Granitic Flatrocks, Fowlers Mill Creek Granites, and Hodges Mill Creek Granites. In the case of Barham Flatrocks, and the Fowlers Mill Creek Granites, the quality of the data should not be adversely affected due to the

extremely close proximity of two other field study sites: the Mitchell Millpond and Pulleytown Road granite outcrops.

The nine field sites for which permission was obtained to study are: Old US 64 Granitic Flatrock, Mitchell's Millpond State Park, Pulleytown Road Granitic Flatrocks, The Rocks Preserve, Wildcat Hollow, Southwest Rolesville Granitic Outcrops, Lake Mirl Granitic Flatrocks, Temple Flat Rock, and finally the Wake Stone Quarry in Knightdale. (Figure 9)



Legend

Wake County

Rolesville Batholith

Field Study Sites

1 - Wildcat Hollow
2 - Southwest Rolesville
3 - Mitchell Millpond
4 - Pulleytown Road
5 - Lake Mirl
6 - Temple Flat Rock
7 - Wake Stone Quarry (Knightdale)
8 - The Rocks Preserve
9 - Old 64 Granite

Figure 9. Field Sites Visited

Data obtained at each outcrop location include the orientation of the fracture, fracture length, GPS location of fracture, and the cross cutting relationships of the fractures. In the field, the dominant fracture orientations were determined by measuring the orientation of surface joints located in the bedrock (pavement) outcrops. Due to the nature of the pavement outcrops studied, dips were not recorded. However, it is our assumption that most dips trend near-vertical (E. Stoddard, personal communication, 2007). Also, a determination of the number of fractures that occur along a transect line was measured in order to provide an estimate of "fracture density." Our assumption in this fieldwork is that those fractures present at the surface are also present at depth (LeGrand, 1979).

The procedures followed for taking measurements in the field are as follows: 1) Locate the granite outcrop using a 7.5-minute quadrangle map and compass. 2) In a systematic manner, traverse the outcrop until a fracture is located. 3) Lay out the measuring tape along the length of the exposed fracture. 4) Use measuring tape and meter stick to help with the measurement of fracture orientation (In the case of slightly curved fractures an estimated orientation was recorded); record strike of the fracture 5) Record GPS waypoint for one end of the fracture. 6) Record length of fracture in meters 7) Record data on fracture width, fracture cross cutting relationships, and areas of fracture intensification zones (if present) 8) Take digital photograph(s) of fracture. Limited data was recorded for dikes and veins as they were found.

Computer Work Methods

The computer program ENVI® (The Environment for Visualizing Images) was used to filter aerial photographs in order to aid in the identification of land surface lineaments. ENVI is a commercially available image processing system designed to manipulate satellite and aircraft remote sensing data and provide data visualization and analysis for images of any size and any type. ENVI is written in Interactive Data Language (IDL®), a structured programming language that offers integrated image processing which is required to run ENVI (ENVI User's Guide, 2003).

For this project, ENVI was used to apply a directional filter to aerial photographs in order to help identify potential land surface lineaments. The directional filter used is a first derivative edge enhancement filter that selectively enhances image features having specific direction components (gradients). The sum of the directional filter kernel elements is zero. The result is that areas with uniform pixel values are zeroed in the output image, while those that are variable are presented as bright edges. This output representation allows for determination of surface longitudinal lineament features (ENVI User's Guide, 2003).

The aerial photographs used for analysis in this project were downloaded from Wake County's GIS webpage (http://lnweb02.co.wake.nc.us/gis/gismaps.nsf). Due to the time consuming nature of the process of filtering and marking lineaments, it was decided to limit the aerial photograph analysis to portions of the county that had known fracture data, i.e. those sites which were visited in this study and had field measurements taken.

The individual aerial images downloaded from the Wake County GIS web site covered a smaller area of land than was desired for this study, so it was necessary to combine multiple images into "mosaics" containing the desired land areas. For each field location a mosaic was made containing between 4-8 individual color aerial photographs. The resulting mosaic formed one large square or rectangular image containing the field study location as well as some surrounding land area. Due to their proximity, the Temple Flat Rock and Lake Mirl outcrops were both included in a single land area mosaic. The Mitchell Millpond and Pulleytown Road granites were also in close enough proximity to warrant their inclusion in a single mosaic. In all, a total of 6 land mosaics were constructed containing all field measurement locations with the exception of the Old 64 outcrop. The Old 64 outcrop was not included in the aerial photograph analysis due to the extremely limited and poor quality fracture information recorded at the outcrop.

The six mosaics that were created are: Mitchell Millpond and Pulleytown Rd Granites, Rocks Preserve, Southwest Rolesville Granites, Temple Flat Rock and Lake Mirl Granites, Wake Stone Quarry, and Wildcat Hollow.

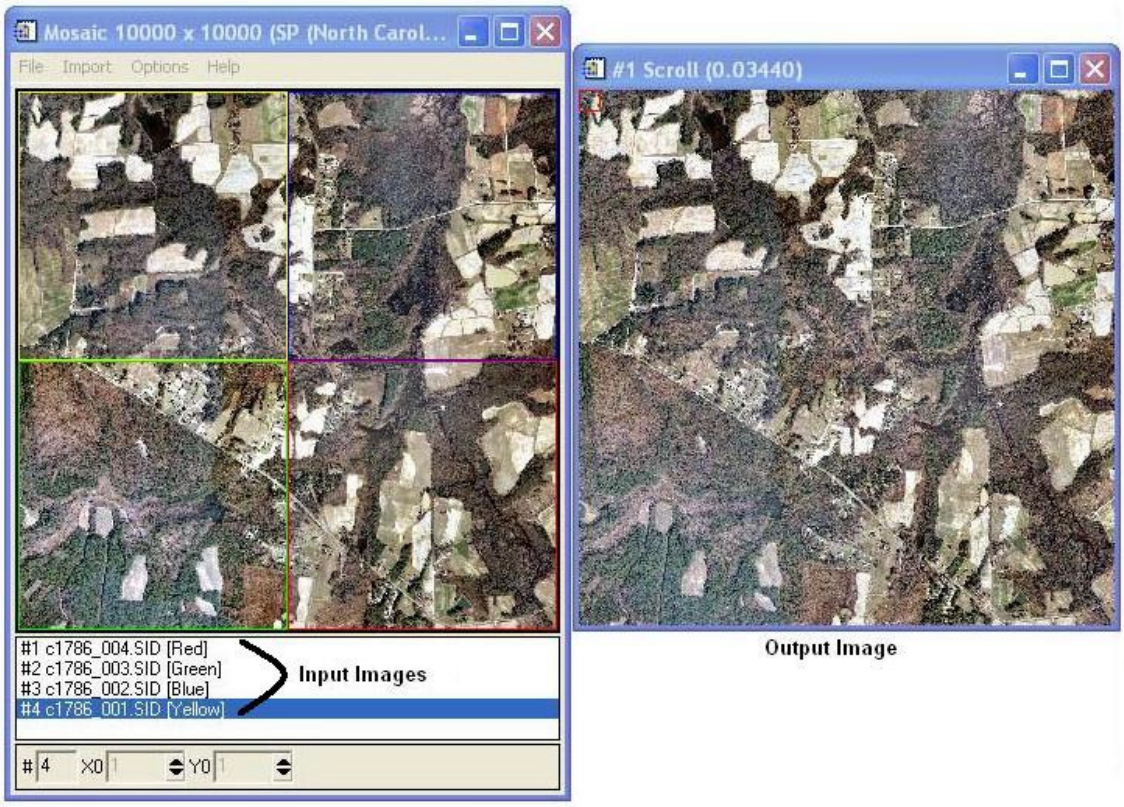
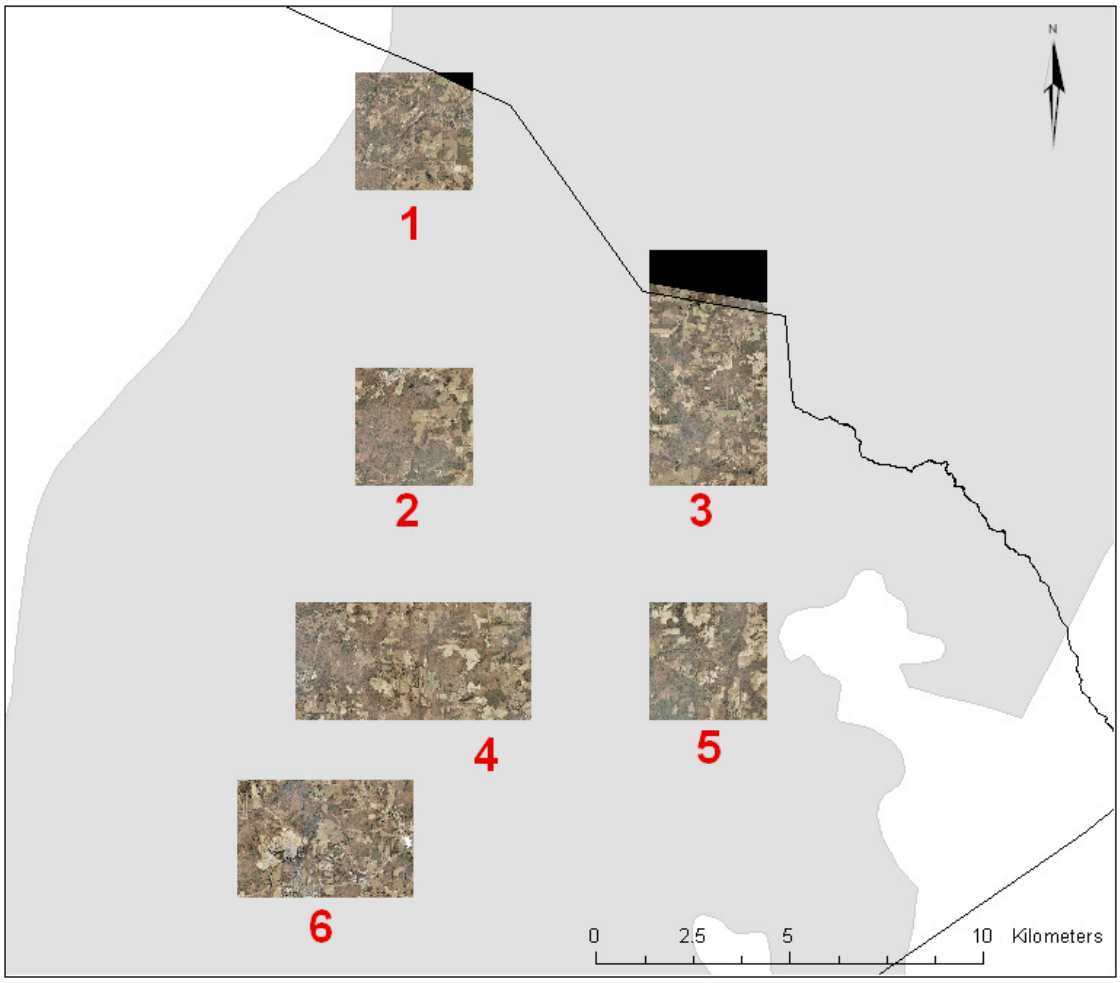


Figure 10. Image mosaicking in ENVI



Legend

Wake County

Rolesville Batholith

1 - Wildcat Hollow
2 - Southwest Rolesville
3 - Mitchell Millpond
4 - TFR & Lake Mirl
5 - Rocks Preserve
6 - Wake Stone Quarry

Figure 11. Land Areas Analyzed in ENVI

Each mosaicked image was then filtered for the following four azimuths: 0°, 45°, 90°, and 315°. These directions were chosen in order to insure that lineaments from all 360° would be found. The way that ENVI's directional filter works is that the closer in direction the lineament is to the inputted analysis value, the more the resulting lineament will stand out on the output file. So those linear features closest to the inputted value would appear the darkest on the filtered image. It was determined that all lineaments within 22.5° of the angle selected for enhancement would be enhanced enough to be visible, thus by filtering for 0°, 45°, 90°, and 315° all lineaments in any compass direction would be found. (Figure 12)

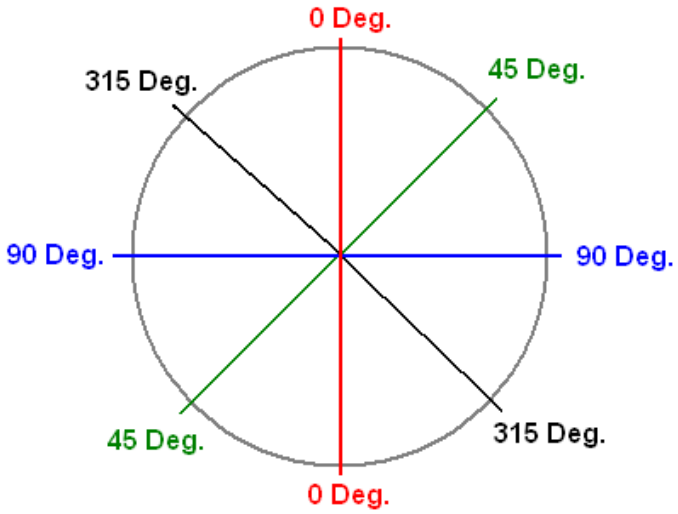


Figure 12. ENVI filtering directions.

After each mosaic was filtered for all four directions, the next step was to mark the geologically significant lineaments (i.e. those that were not man made). ENVI's directional filter finds all linear features on a photograph including roads, buildings, walls, power lines, etc. As a result, an additional step was required to eliminate as many

of the obvious man-made lineaments as possible. This step was necessary in order to give a more accurate representation of the true geological lineaments present on the land surface.

In order to compare both the land area mosaic and the filtered images side by side, the displays were linked together in ENVI, allowing both images to be viewed simultaneously and at the same scale. By comparing both images side by side, many man-made features that had been identified in the filtering process were eliminated. It is important to note that in some instances it was virtually impossible to determine what had caused the lineament (either man made or natural sources), and in these instances those features were marked as and were considered natural lineaments. (Figure 13)

The resulting lineaments that were found and considered to be from natural sources were marked onto an overlay of the original (non-filtered) air photo mosaic. The marking lines were drawn the same length and compass direction as the found lineaments, but were offset slightly in one direction. This was done so that on the final image one would be able to view both the actual lineament and the marking line, making it easier for the viewer to discern what features were being identified. The aerial images were zoomed in to provide as much detail in the land surface as possible when identifying and marking the lineaments. This process was done on a total of 24 filtered aerial images (six different land-area mosaics by four directions per mosaic). The identification and marking of each land-area was found to be rather time consuming, taking anywhere from 3 to 6 hours per image depending on the total surface area being covered. In order to eliminate the effects of fatigue from sitting in front of a computer

screen for extended periods of time, 30-minute breaks were taken for every 60-90 minutes of lineament identification and marking.

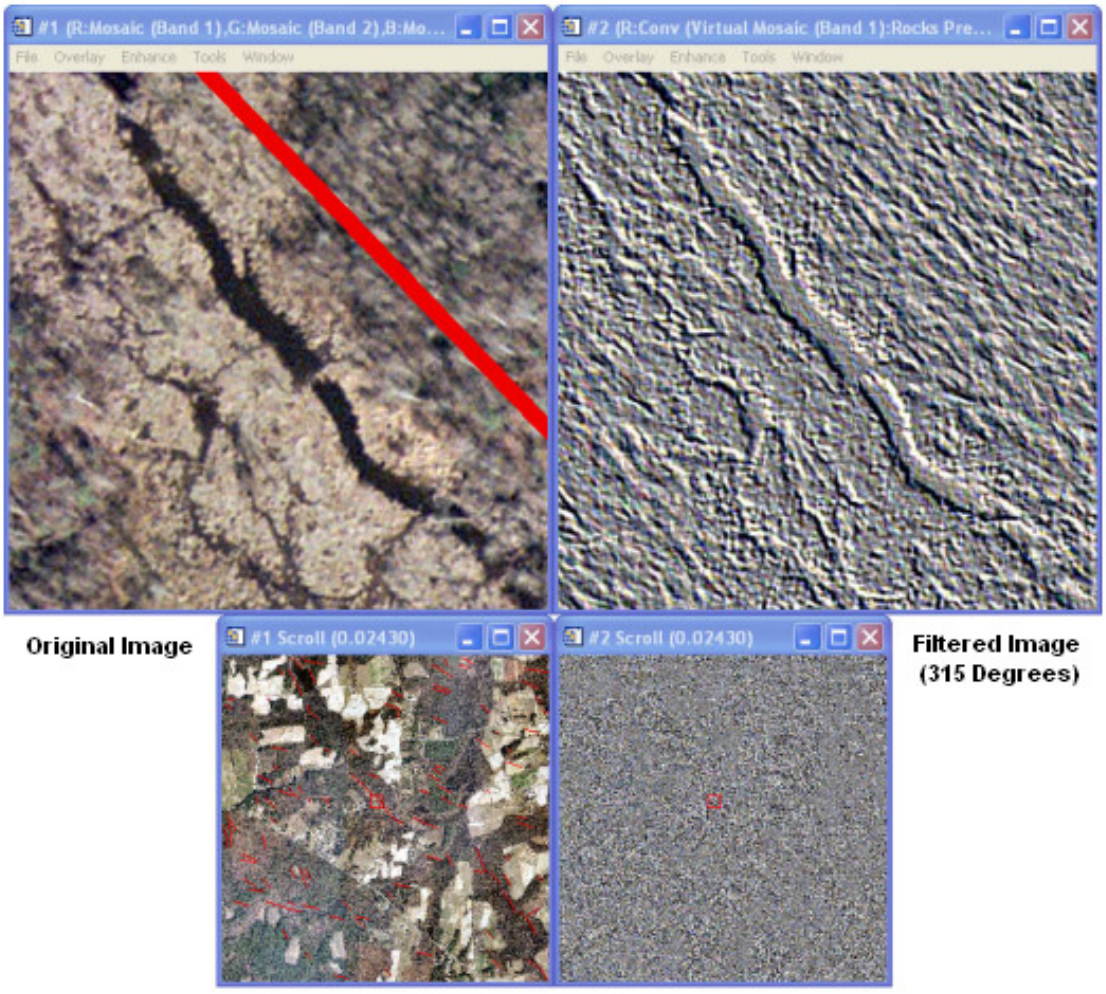


Figure 13 – Linked Displays in ENVI.

In this example both the original aerial photograph and the resulting filtered image (315°) are displayed. The top boxes represent the scale at which lineaments were identified and marked (with red lines), while the bottom boxes display one complete land area that was analyzed.

The resulting mosaics with directional overlay files were extremely large (0.5 – 1.0 GB in size), so the next step was to compress and scale down the images to an acceptable size for printing on an 8.5" x 11" sheet of paper. This was done in ENVI by saving the image as a TIFF file. This file was then opened up in Adobe Photoshop and was saved as medium size TIFF file using Photoshop's JPEG compression. The resulting files were much smaller (~100MB), while still retaining much of the original image detail. All 24 overlay images were then printed onto 8.5" x 11" sheets of paper using a high-quality color laser printer.

The next step in the computer portion involved measuring the orientation (azimuth) of all the lineaments that were identified via ENVI's directional filter. These compass orientations were measured directly from the color printouts. A procedure was developed to ensure that all lineaments were measured as accurately as possible. First, all lineaments were individually numbered by hand, and each color printout was given its own unique identification code. The lineament directions were then measured using a plotter (a navigational protractor) and ruler (as a straight edge). The values were recorded onto loose-leaf paper containing the identification code of the image. Upon the completion of a page, random lineaments were double-checked to ensure repeatability and accuracy of the measurements. In order to avoid eye fatigue, 15-minute breaks were taken after every hour of lineament direction measurement. The data were then entered into a Microsoft Excel spreadsheet containing the following information: site name, lineament ID, lineament number, and compass direction.

In order to provide a way to visually compare the field fractures with the ENVI lineament data, a series of rose diagrams was produced. For the field data, a rose diagram

was produced for each study area containing the strike of all fractures found. A rose diagram containing all of the fieldwork fractures into a single graph was also made. From the ENVI aerial photograph data analysis, a similar set of rose diagrams was produced. Data from each filtering direction (0°, 45°, 90°, and 315°) were plotted individually for each site, as well as a "master" rose diagram containing all four directions combined from each site. From this data, one is able to quickly compare and contrast the field measurements with the lineaments found through air-photo analysis.

The next step of the research was to compare the surface lineaments that were identified via air photos with current topographic data. The purpose of this was to compare lineaments against the topographic data that reflects the underlying geologic structure of the area. Areas of depressions such as draws or valleys suggest that the underlying rock has more openings (joints and fractures) through which groundwater can move (Le Grand and Mundorff, 1952). The topographical contour data used in this study were acquired from the NC DOT GIS web page: (http://ncdot.org/it/gis/DataDist/GISContourmaps.html). This data were generated in March 2005 using LIDAR Data, and at the time of this report is the most up to date elevation information available for Wake County. In order to display the ENVI lineament data in ArcGIS, the ENVI overlay layers were converted into DHX files using an ENVI convert feature. Once all of the required data was loaded into Arc View, an 8.5" x 11" layout was created for each of the six land areas that were analyzed. Each layout contained four quadrants, one for each of the compass directions for which lineaments were filtered (0°, 45°, 90°, and 315°). This lineament information was displayed over the elevation data so that all data sets could be quickly and easily compared. (Appendix A)

The final research portion involved acquiring well yield data for wells located within the study area. In order to be useful in this study, the acquired data must include both well location (latitude and longitude) and well yield. Well depth information was also desired for yield per foot of total well depth calculations. In all, five unique well yield databases were found:

Table 2: Well yield data used in the study

Well Yield Data (Rolesville Batholith)		
Data Source	**# of Wells (Yield >0)**	**# of Wells (Yield and Depth Data > 0)**
Wake Well Permit Database	437	437
Public Water Supply Wells	238	142
Aqua North Carolina CWS Wells	73	71
1968 Groundwater Bulletin # 15 Wells	58	58
NC DENR Study Wells	4	4
Total Number of Wells	**810**	**712**

This well yield data was acquired from five different sources. The Wake County Well Permit database was acquired from John Boyer at Camp, Dresser, and McKee (CDM). The shapefile containing the Wake County Public Water Supply Wells was obtained from David Hammerman at the Source Water Assessment Program at the North Carolina Department of Natural Resources (NC DENR). Jill Strickler provided the data on the Aqua North Carolina CWS wells. Rick Bolich at NC DENR supplied the

spreadsheet data titled "NC DENR Study Wells." The author of this report created the 1968 Groundwater Bulletin # 15 GIS shapefile by compiling data from two separate sources. The Groundwater Bulletin # 15 contained both a paper map of Wake County showing well locations, and a corresponding table that provided information about the wells including: well number, depth (ft), and yield (gpm). This data for the wells located within the Rolesville Batholith portion of Wake County was entered into an Excel spreadsheet. The well location data (latitude and longitude) for each well was acquired from the USGS Ground-Water Site Inventory of North Carolina webpage: (http://waterdata.usgs.gov/nc/nwis/gwsi?county_cd=37183&format=station_list). The USGS webpage is designed in such a way that well WK-085 corresponds to the location of well number 85 in the Groundwater Bulletin # 15, and so on. The location data for each of the wells was presented in degrees, minutes, and seconds. This latitude and longitude data for each well was copied from the web site and pasted into the spreadsheet containing the well record data. Next, these latitudes and longitudes were converted into decimal degrees so that the data could be plotted in ArcGIS. To confirm that the well location data was displayed properly, the paper location map from the 1968 GW Bulletin # 15 was scanned and the image file was then georeferenced in ArcGIS. All well yield data in this study is reported in gallons per minute (gpm).

The data was then displayed in ArcGIS. Prior to any analysis, the well data was filtered so that only those wells reporting yields (yield > 0gpm) were included in this study. A new column was also added to each data table in ArcGIS containing a calculation of yield per foot of total well depth calculation (gpm/feet) for those wells with both yield and depth data available. The data was then reviewed in an attempt to locate

any outliers or anomalous values. Ultimately, two wells were removed from the data sets due to much greater than average reported yields (545gpm at a depth of 545 ft., from PWS (05/05), and yield per foot of total well depth (1.7241gpm/ft, depth = 29 ft., yield = 50gpm, from the1968 GW Bulletin).

Four different maps were ultimately created using the acquired well data. First, a map was made of all 810 wells having yields greater than zero gallons per minute. The yields of the wells were grouped into 3 categories, those wells of "average" (25 gpm) yield or below were colored yellow, those wells ranging in yield from 26-50 gpm were marked in green, and all wells with yields 51 gpm or greater were colored red. The second image created was a plot of all 712 wells having both yield and depth data available. This data was displayed using yield per foot of well depth calculations (gpm/ft), this was done in order to identify those areas where well productivity is greatest per foot of depth. In theory, the highest yielding wells per foot of depth will be located in areas where the bedrock fracturing is the most intense. Finally, maps were made of the Aqua NC CWS well data both by yield in gpm, and by yield per foot of well depth in gpm/ft. This data was displayed on its own, because it was the only data set containing solely data on wells that had undergone a 24 hour pump test prior to the determination of yield. All well maps were displayed over a LIDAR elevation layer to provide visualization of the topography in the Rolesville Batholith at the location of each well.

The next step was to infer linear zones of higher than average well yields by drawing lines connecting above average yielding wells that are in close proximity. After all zones of higher than average well yields were identified and marked onto an Arc GIS image, the files were printed out, and the orientation of each zone was measured by hand

using the same procedure as the ENVI lineaments. Rose diagrams were then produced for each map to help visualize the primary directions associated with wells of higher than average yields.

Results

Field Research

In the field a total of 151 individual joints and fractures were identified and recorded. Six of the nine granite pavement outcrops visited were found to be moderately or sparsely fractured, with each containing 25 or more exposed fractures on the outcrop examined. The remaining three granite outcrops were found to contain limited surface fracture data. In the case of Wildcat Hollow, the granite exposure turned out to be comprised of large surface boulders and caves making it difficult to find relevant bedrock fracture information. Another field site that produced data of questionable value was the Old 64 granite outcrop. This outcrop appeared to be unevenly weathered, and the surface joints that were visible were extensively curved, giving the appearance that these were shallow surface fractures, most likely the result of weathering.

Table 3: Fracture and Lineament Frequency

Site Name	# of Field Fractures	# of Computer Lineaments	# of Lineaments 0 Degrees	# of Lineaments 45 Degrees	# of Lineaments 90 Degrees	# of Lineaments 315 Degrees
All Sites Combined	151	2362	486	667	633	576
Mitchell Millpond + Pulleytown Rd.	40	488	96	195	79	118
Rocks Preserve	35	499	102	143	136	118
Southwest Rolesville	35	232	52	69	61	50
Temple Flat Rock (TFR) + Lake Mirl	25	498	117	120	150	111
Wake Stone Quarry (Knightdale)	5	363	67	57	127	112
Wildcat Hollow	6	282	52	83	80	67
Old 64 Granite	5	n/a	n/a	n/a	n/a	n/a

Computer Research

In the computer portion of the research ENVI was used to identify a total of 2362 lineaments. All of this data originated from the 6 aerial photograph mosaics that were

analyzed. Combining the data from all six sites allows one to get an idea of the prominent lineament directions throughout the Rolesville batholith portion of Wake County. Lineaments identified with a 0° filter applied in ENVI accounted for 20.6% of all lineaments. Those lineaments identified after filtering for 45° were found to be the most numerous, comprising 28.2% of the total. Filtering for 90° found the second most common direction with 26.8% of all lineaments. Finally, 24.4% of all lineaments identified were found as a result of filtering for 315°. (Table 3)

Images Produced

The data acquired in the research phase of this thesis allowed for the production of many graphics that help to visualize the lineaments and fractures that were identified. For each of the six land-areas analyzed in ENVI, multiple graphical representations of the lineaments were produced. Lineaments found in each land area were displayed in five separate graphics. One graphic was produced for each of the four filter directions: 0°, 45°, 90°, and 315°. These pictures show all of the lineaments identified for each direction displayed on top of an aerial photograph of the land area. The final image produced for each land area contains all of the identified lineaments (all four filter directions: 0°, 45°, 90°, and 315°) displayed over the aerial photograph of the land area. (Figures 14-43)

Figure 14. Mitchell Millpond and Pulleytown Rd. lineaments filtered for 0°.

Figure 15. Mitchell Millpond and Pulleytown Rd. lineaments filtered for 45°.

Figure 16. Mitchell Millpond and Pulleytown Rd. lineaments filtered for 90°.

Figure 17. Mitchell Millpond and Pulleytown Rd. lineaments filtered for 315°.

Figure 18. Mitchell Millpond and Pulleytown Rd. all lineaments.

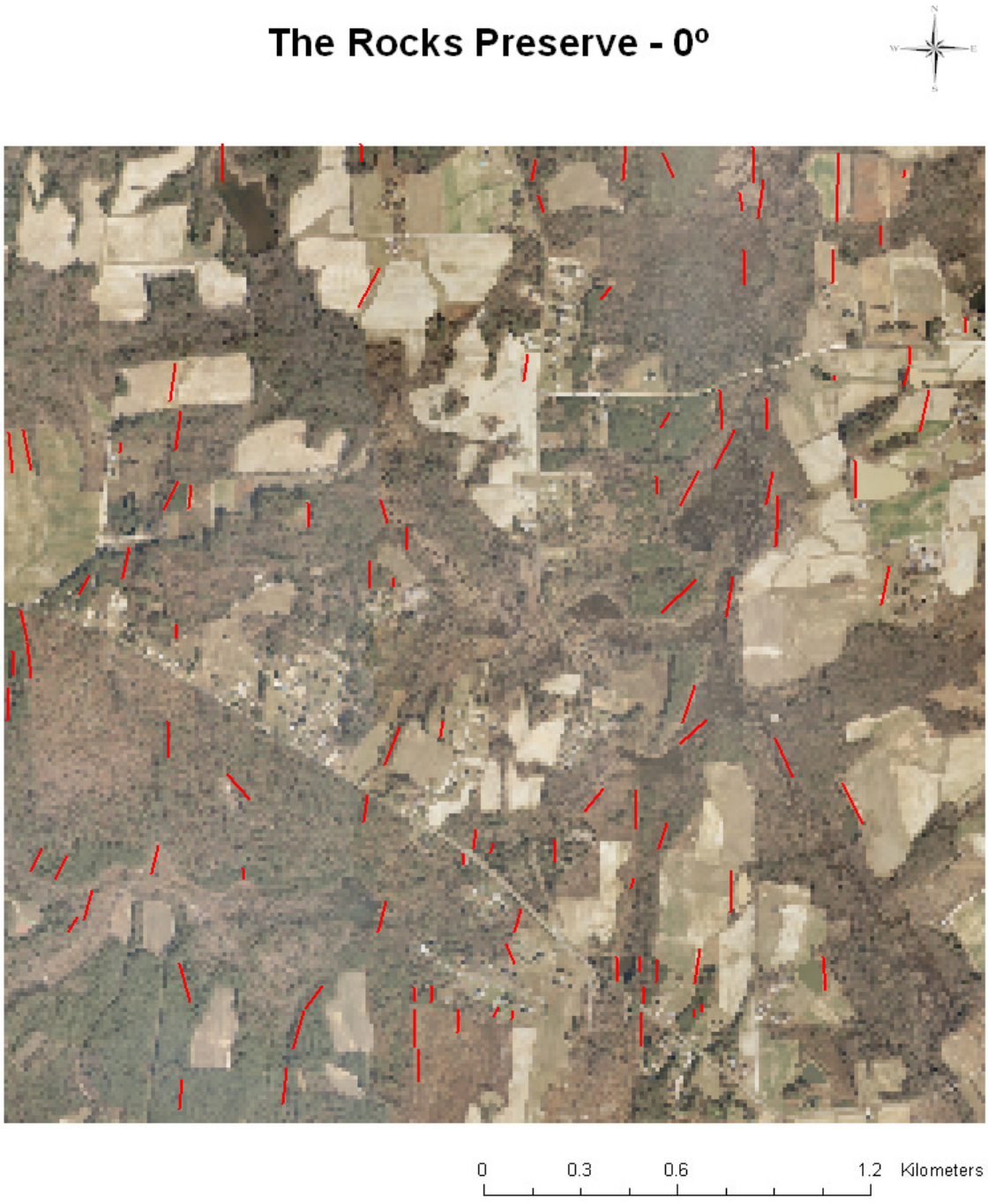


Figure 19. The Rocks Preserve lineaments filtered for 0°.

Figure 20. The Rocks Preserve lineaments filtered for 45°.

Figure 21. The Rocks Preserve lineaments filtered for 90°.

Figure 22. The Rocks Preserve lineaments filtered for 315°.

Figure 23. The Rocks Preserve all lineaments.

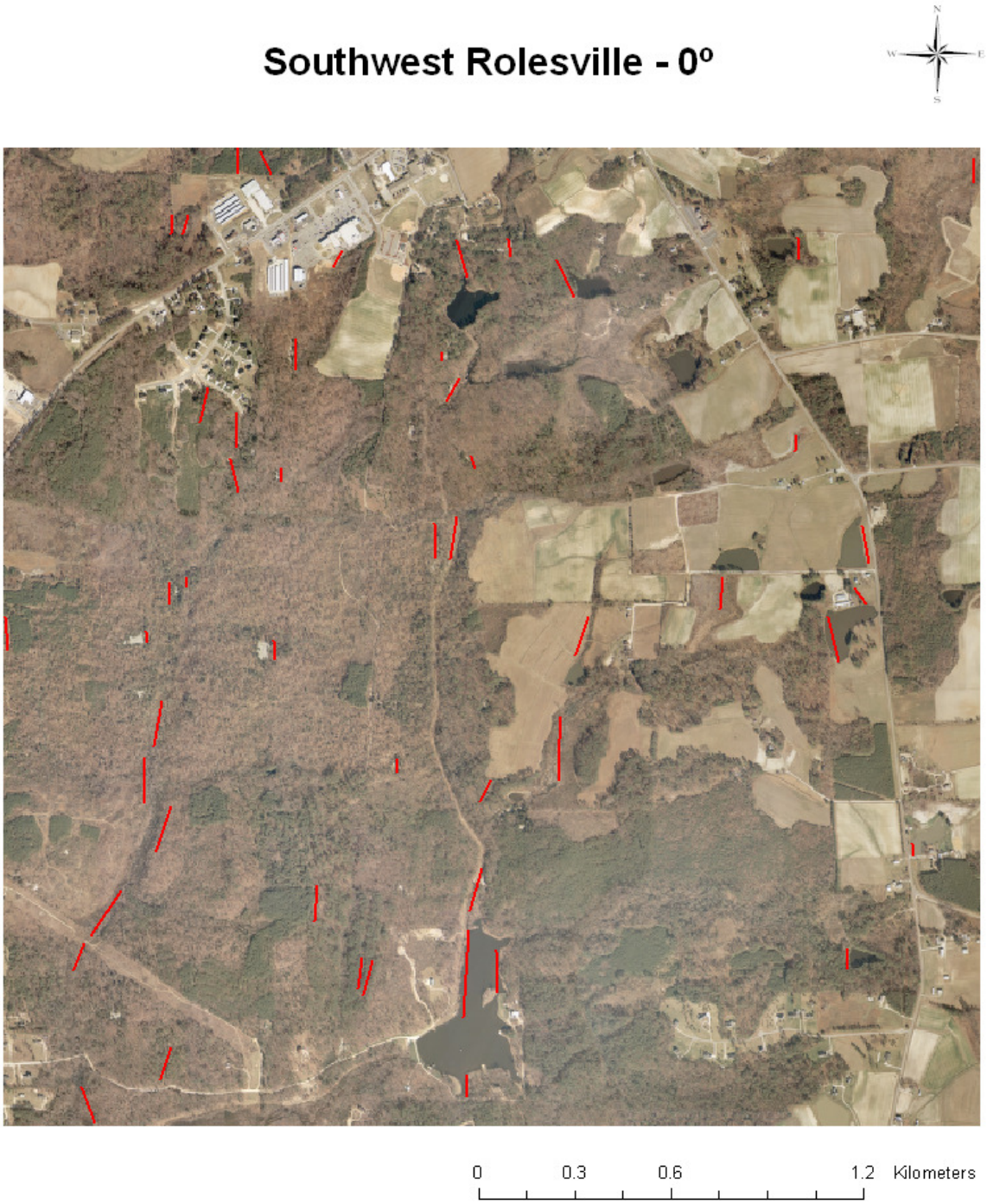


Figure 24. Southwest Rolesville lineaments filtered for 0°.

Figure 25. Southwest Rolesville lineaments filtered for 45°.

Figure 26. Southwest Rolesville lineaments filtered for 90°.

Figure 27. Southwest Rolesville lineaments filtered for 315°.

Figure 28. Southwest Rolesville all lineaments.

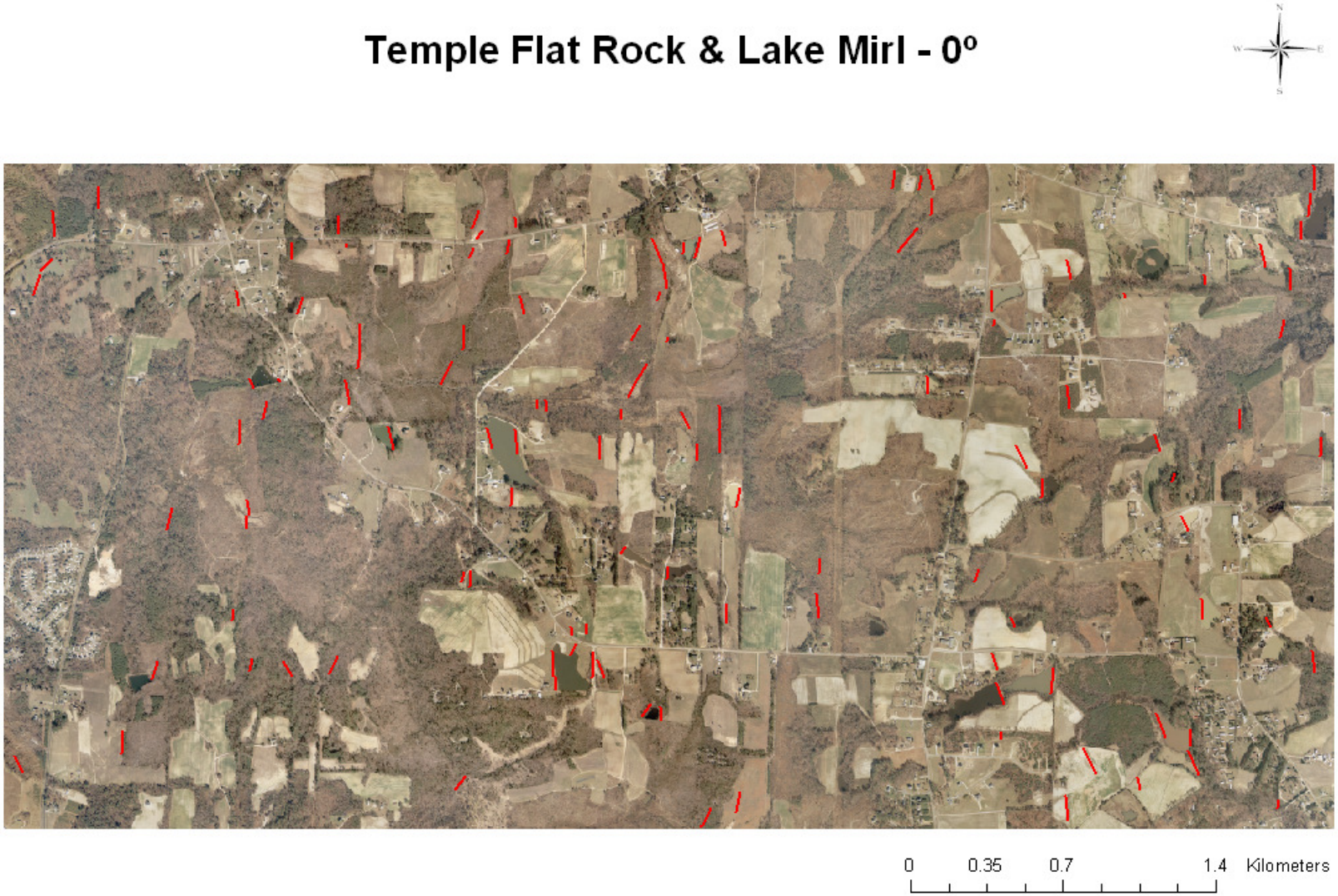


Figure 29. Temple Flat Rock and Lake Mirl lineaments filtered for 0°.

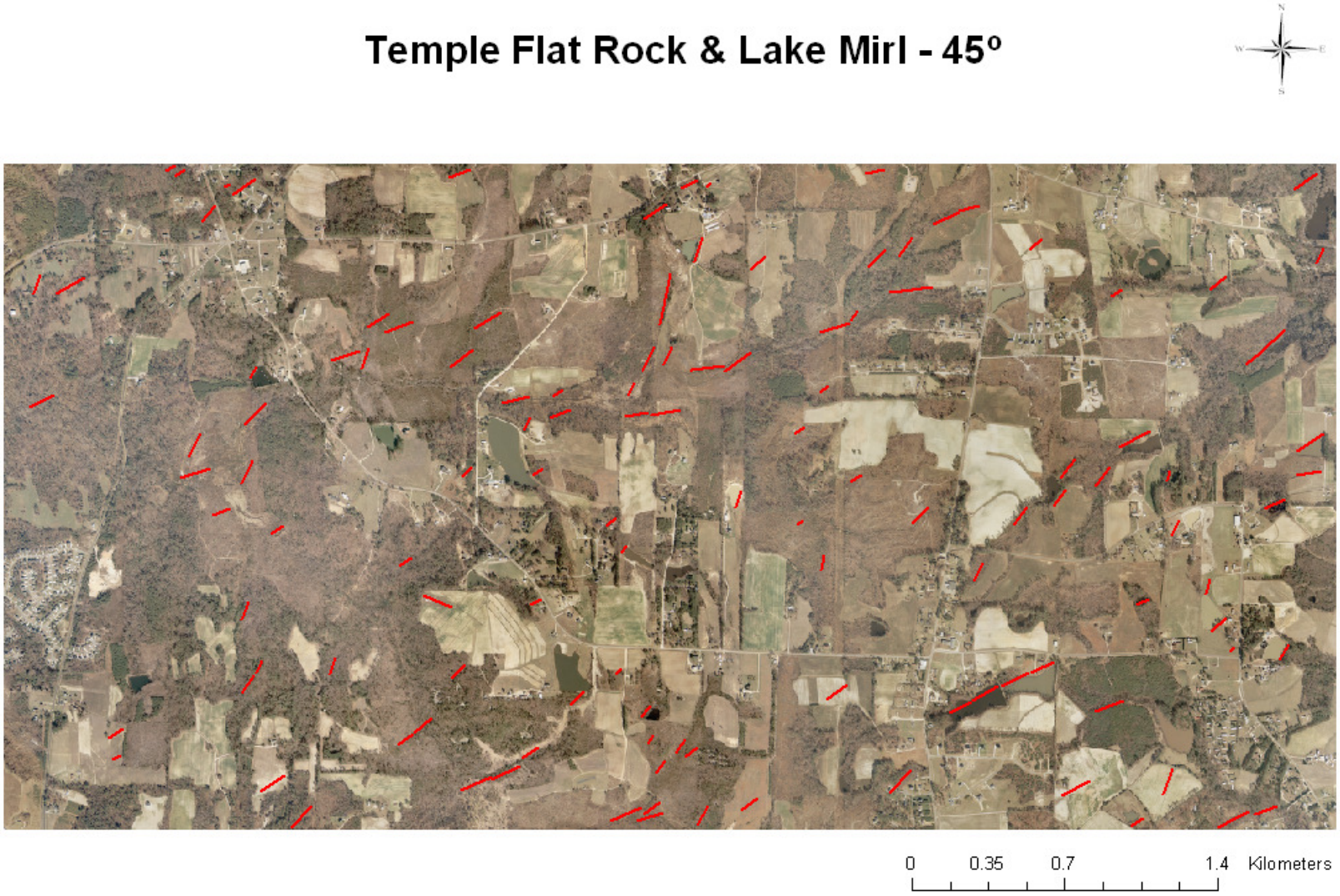


Figure 30. Temple Flat Rock and Lake Mirl lineaments filtered for 45°.

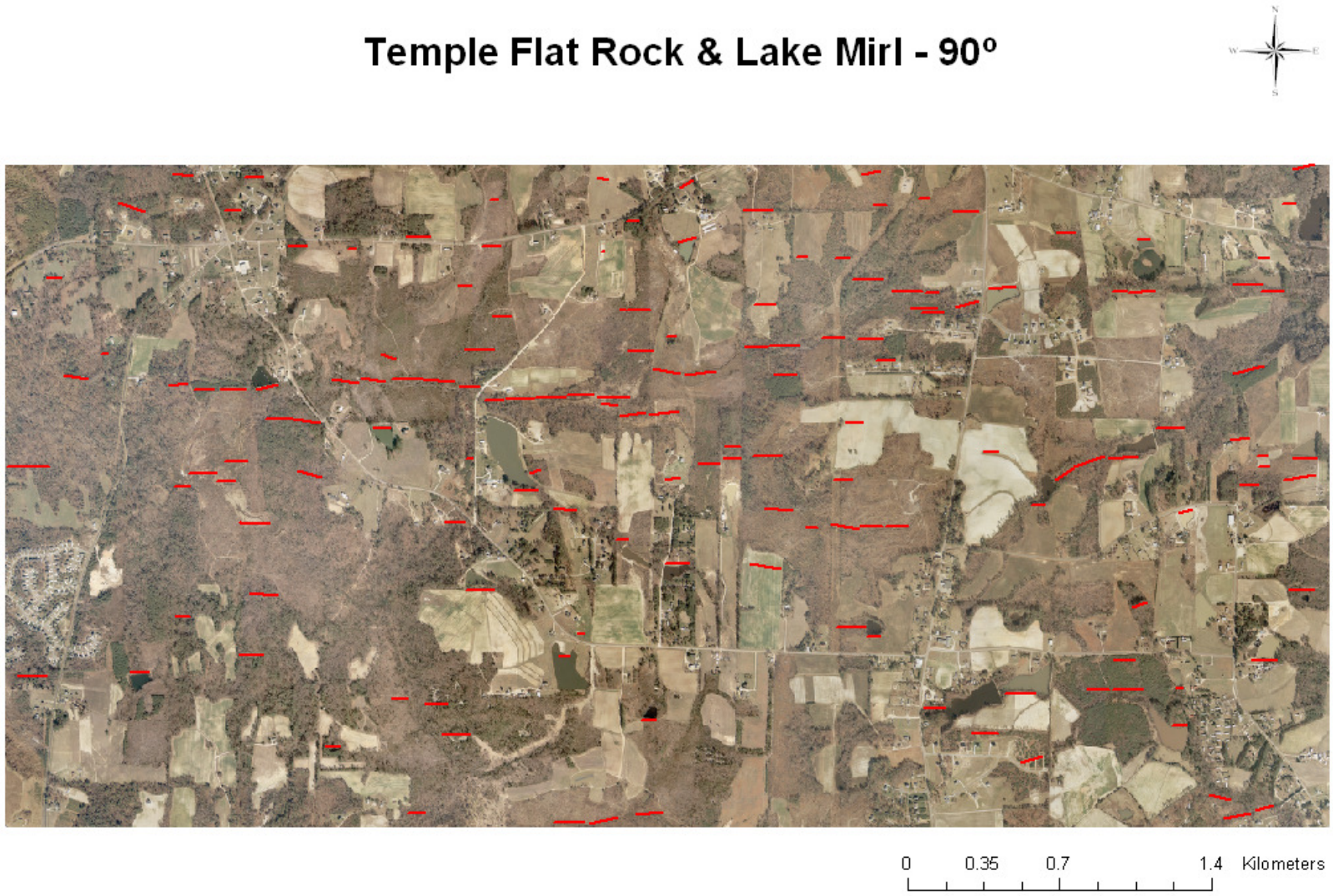


Figure 31. Temple Flat Rock and Lake Mirl lineaments filtered for 90°.

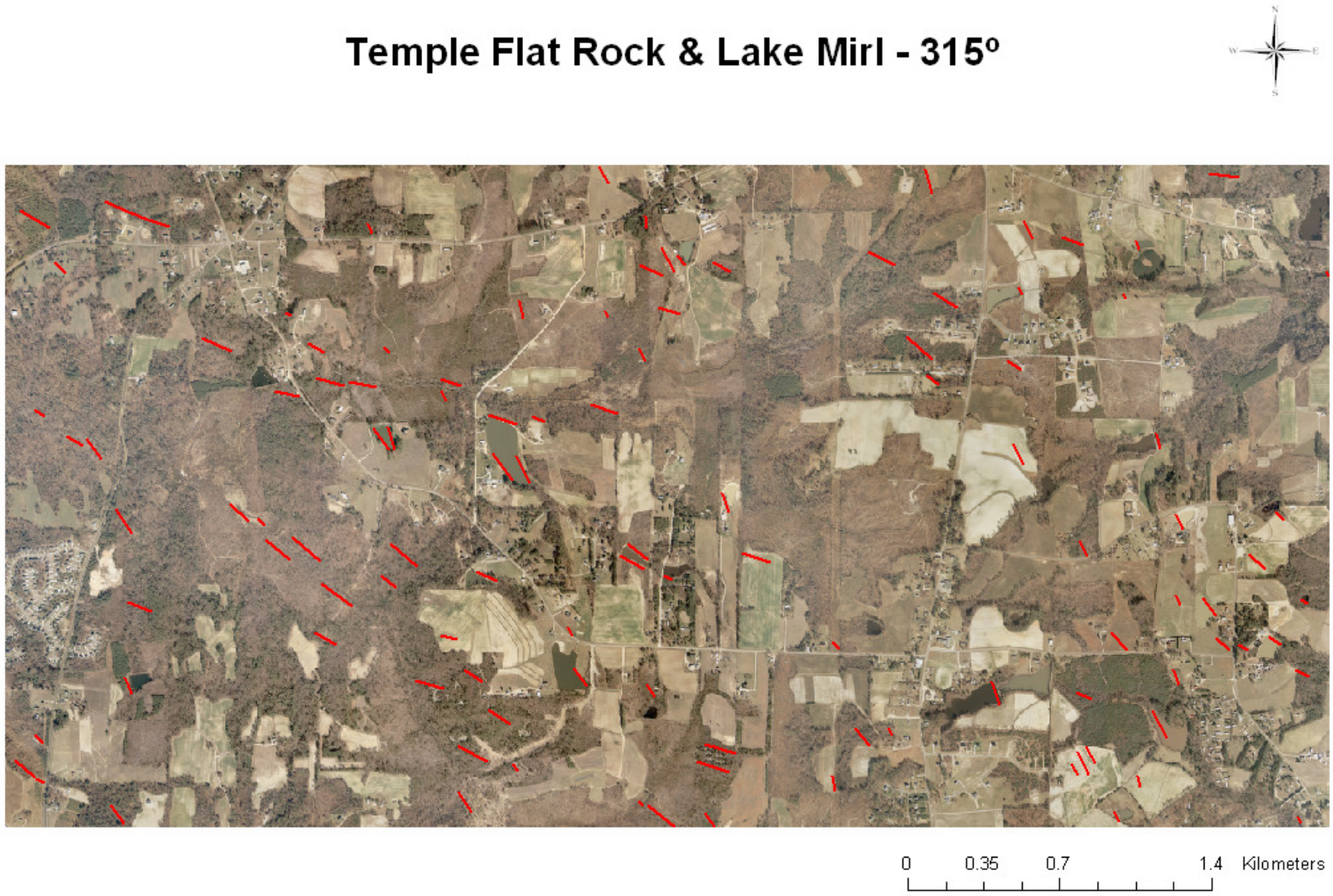


Figure 32. Temple Flat Rock and Lake Mirl lineaments filtered for 315°.

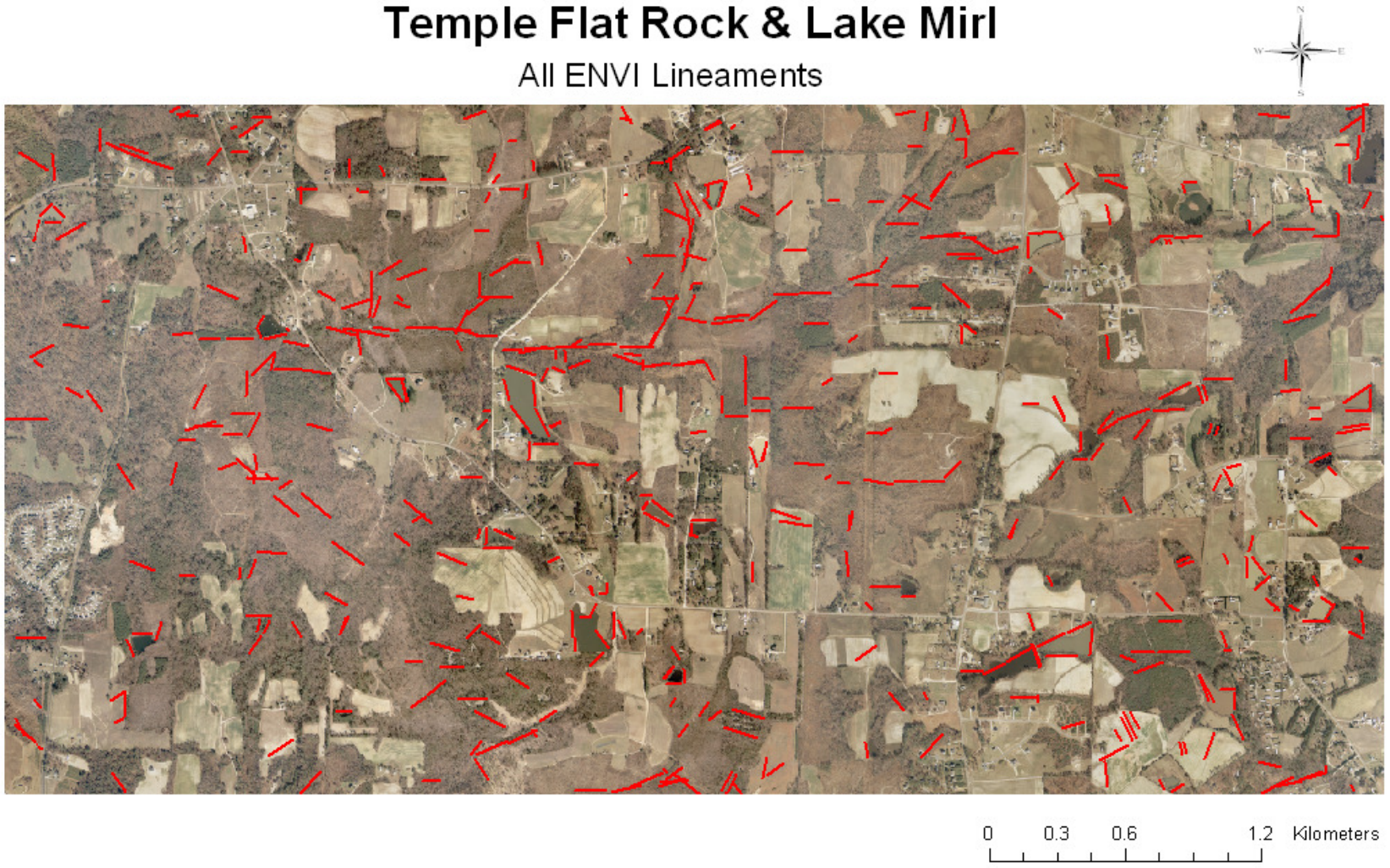


Figure 33. Temple Flat Rock and Lake Mirl all lineaments.

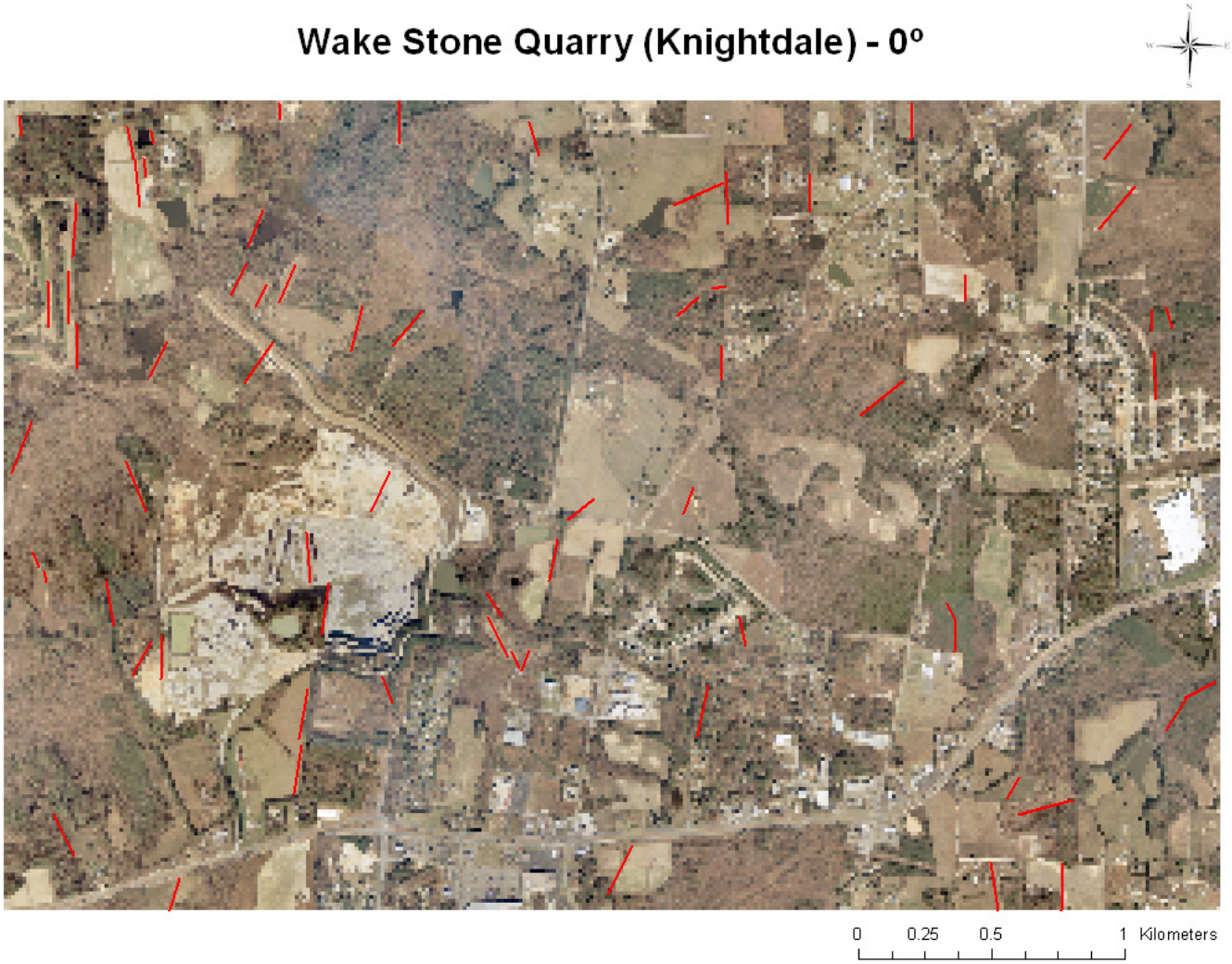


Figure 34. Wake Stone Quarry (Knightdale) filtered for 0°.

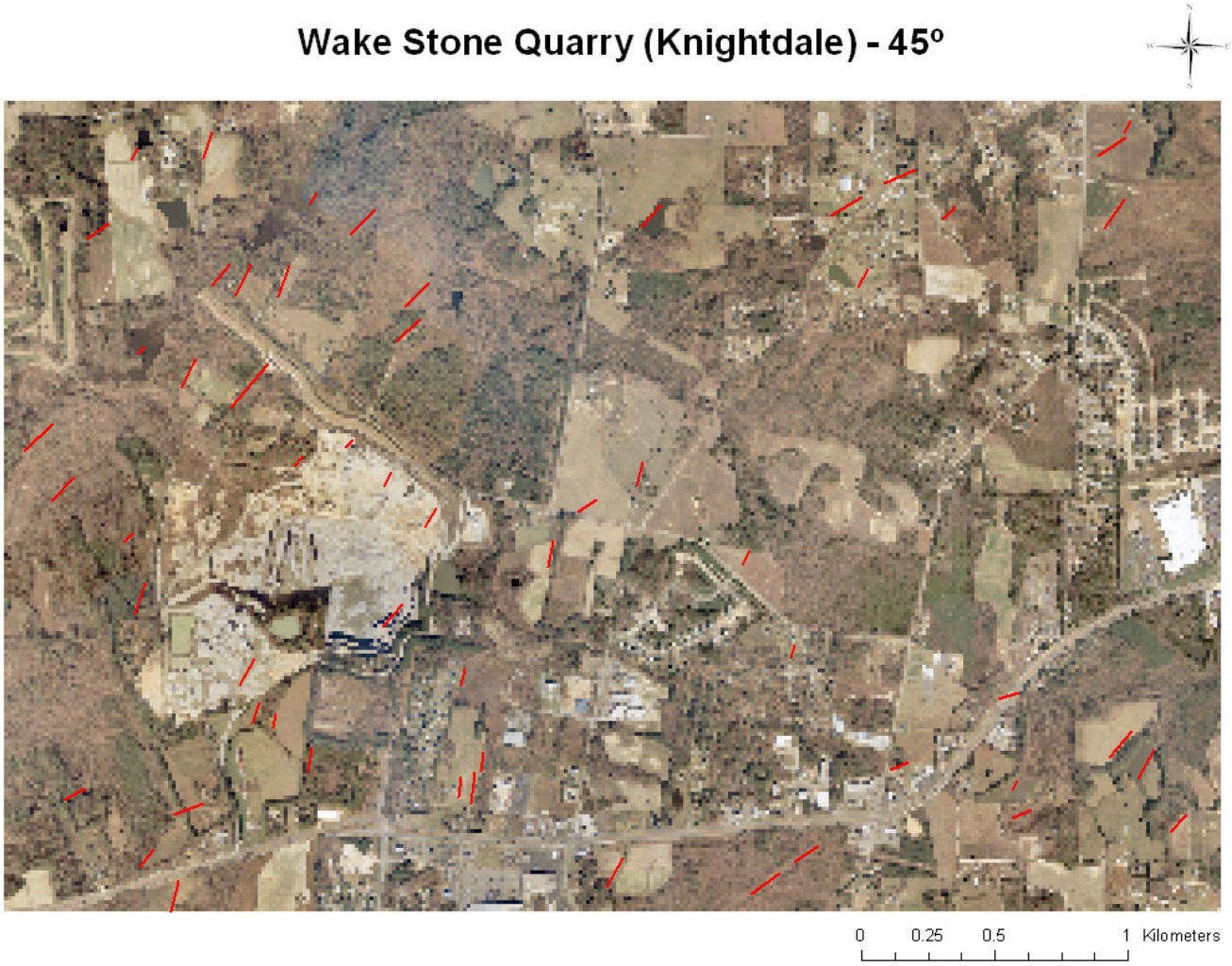


Figure 35. Wake Stone Quarry (Knightdale) filtered for 45°.

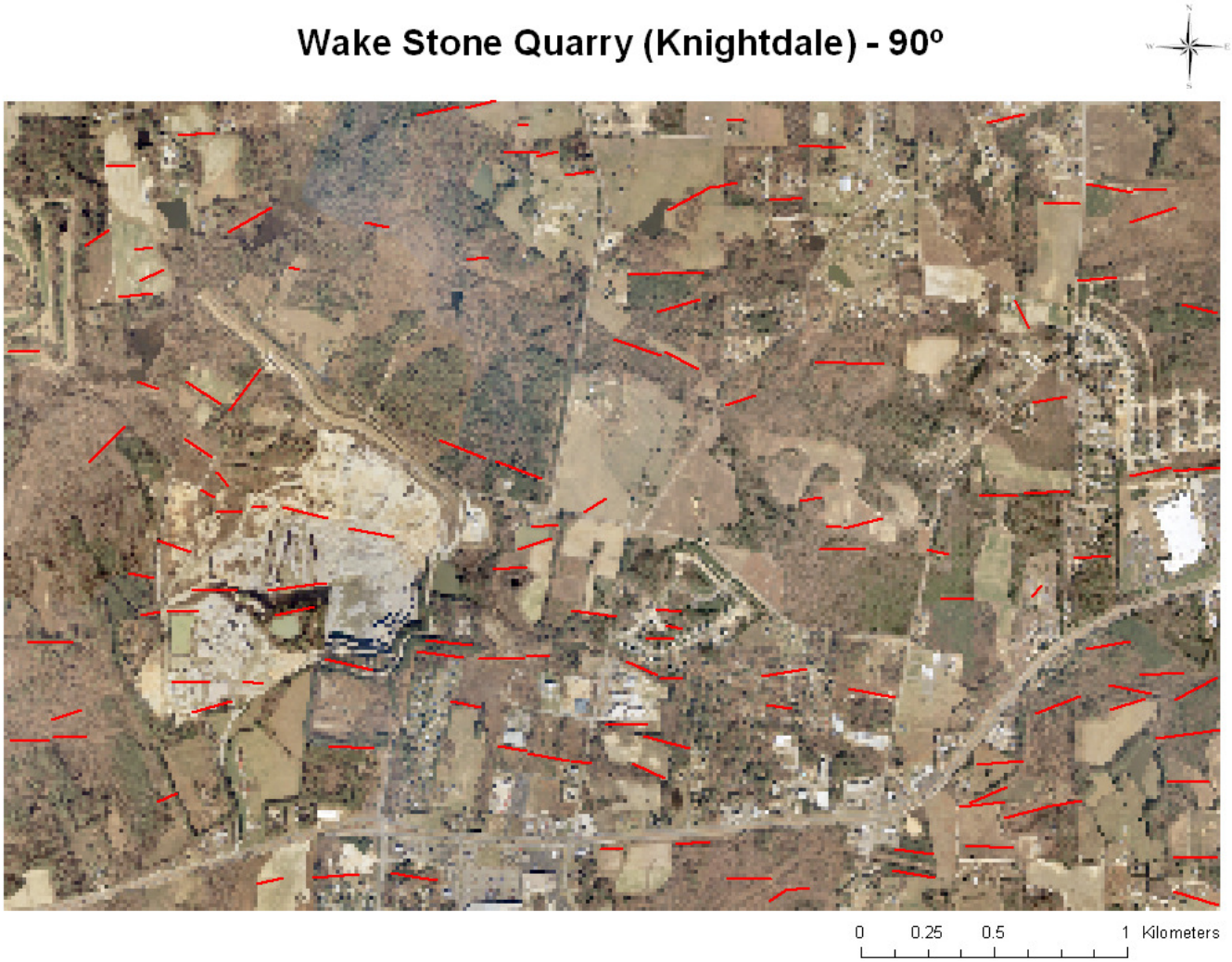


Figure 36. Wake Stone Quarry (Knightdale) filtered for 90°.

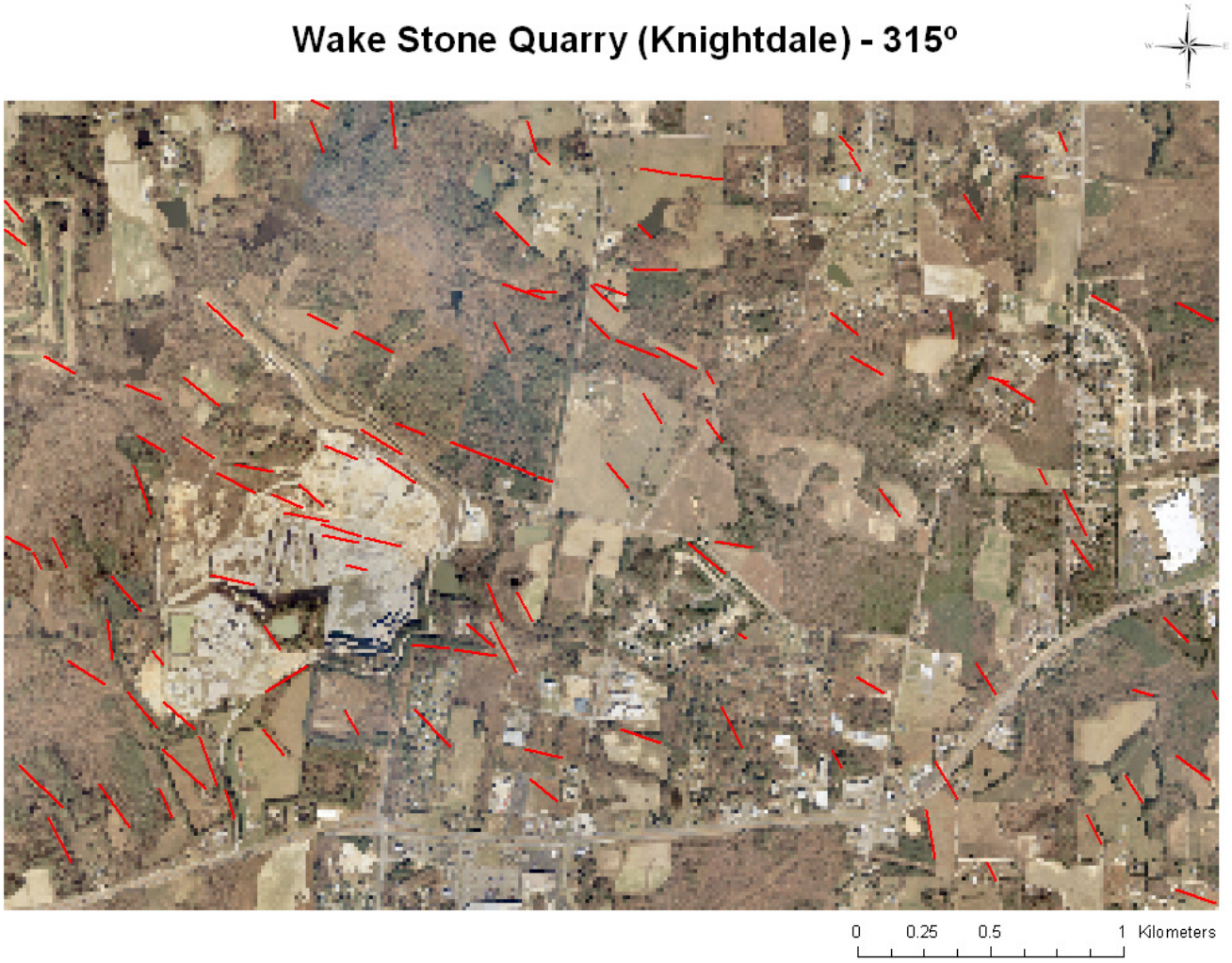


Figure 37. Wake Stone Quarry (Knightdale) filtered for 315°.

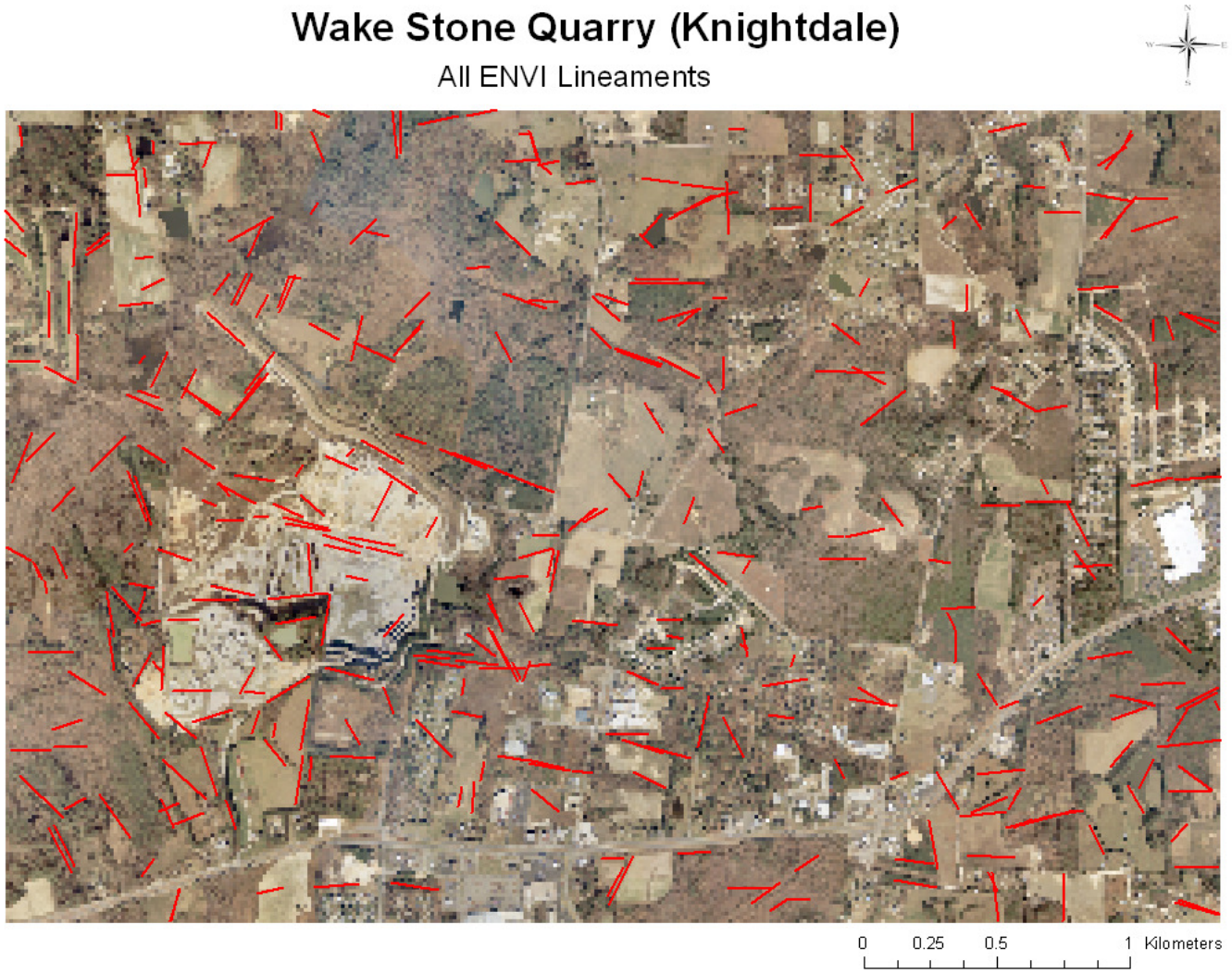


Figure 38. Wake Stone Quarry (Knightdale) all lineaments.

Figure 39. Wildcat Hollow lineaments filtered for 0°.

Figure 40. Wildcat Hollow lineaments filtered for 45°.

Figure 41. Wildcat Hollow lineaments filtered for 90°.

Figure 42. Wildcat Hollow lineaments filtered for 315°.

Figure 43. Wildcat Hollow all lineaments.

In order to visualize the lineaments and their relative frequency, the next images produced were rose diagrams. For this part of the study a total of 40 individual rose diagrams were created. A rose diagram was created for all of the fractures and joints identified in the field. A similar diagram was produced containing all lineaments identified through ENVI. This was done in order to compare the results from both research phases. Next, similar rose diagrams were created comparing the field and computer results for each individual study site. Four additional rose diagrams were made for each site, one for each of the four filtering directions (0°, 45°, 90°, and 315°). This was done so that differences between individual study sites could be compared at a glance. A rose diagram was also produced for the pegmatite dikes found in the field, and one was also produced for the quartz veins identified during the field research. (Figures 44-57)

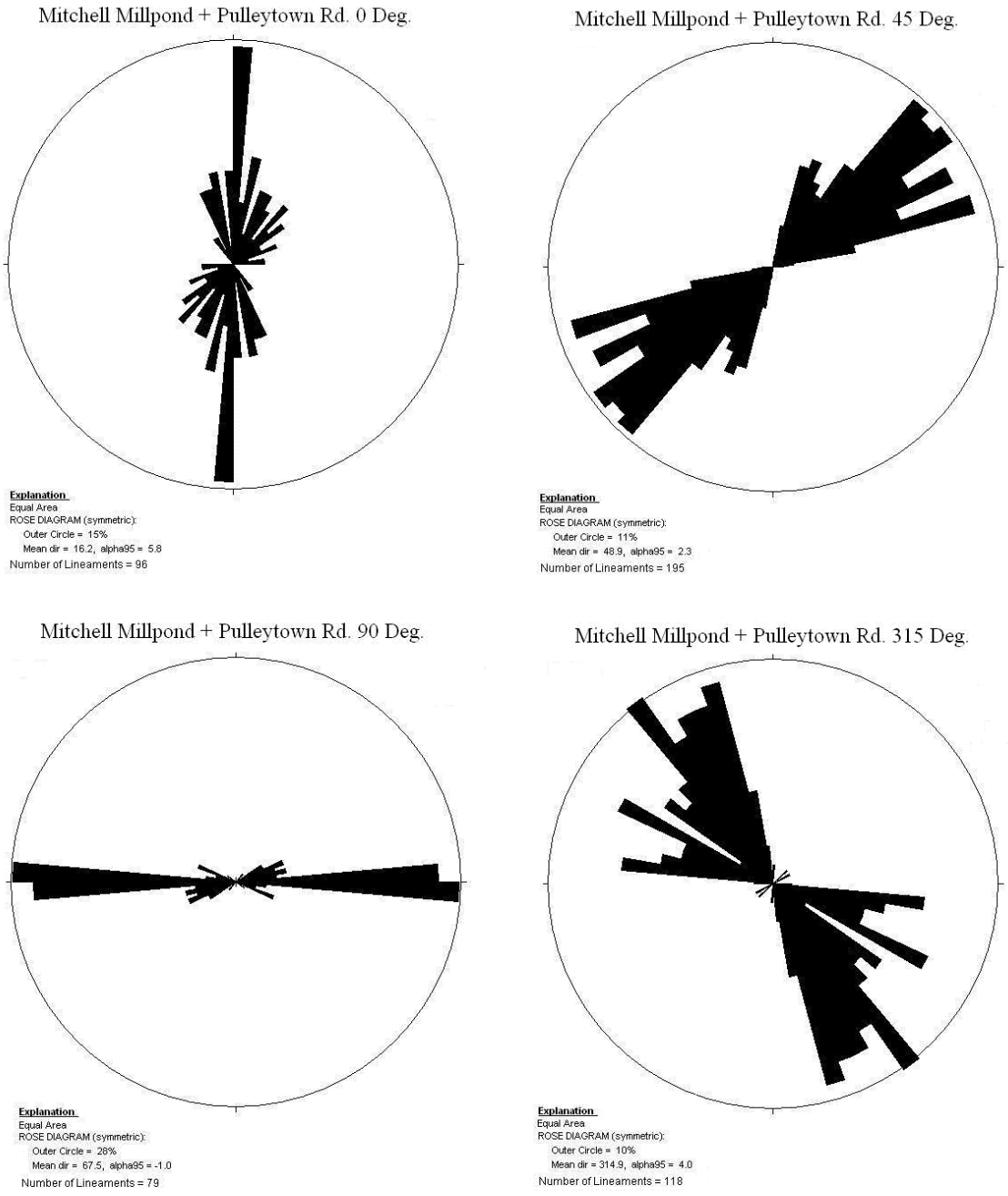


Figure 44. Rose diagrams of ENVI lineaments for the Mitchell Millpond and Pulleytown Rd. land area.

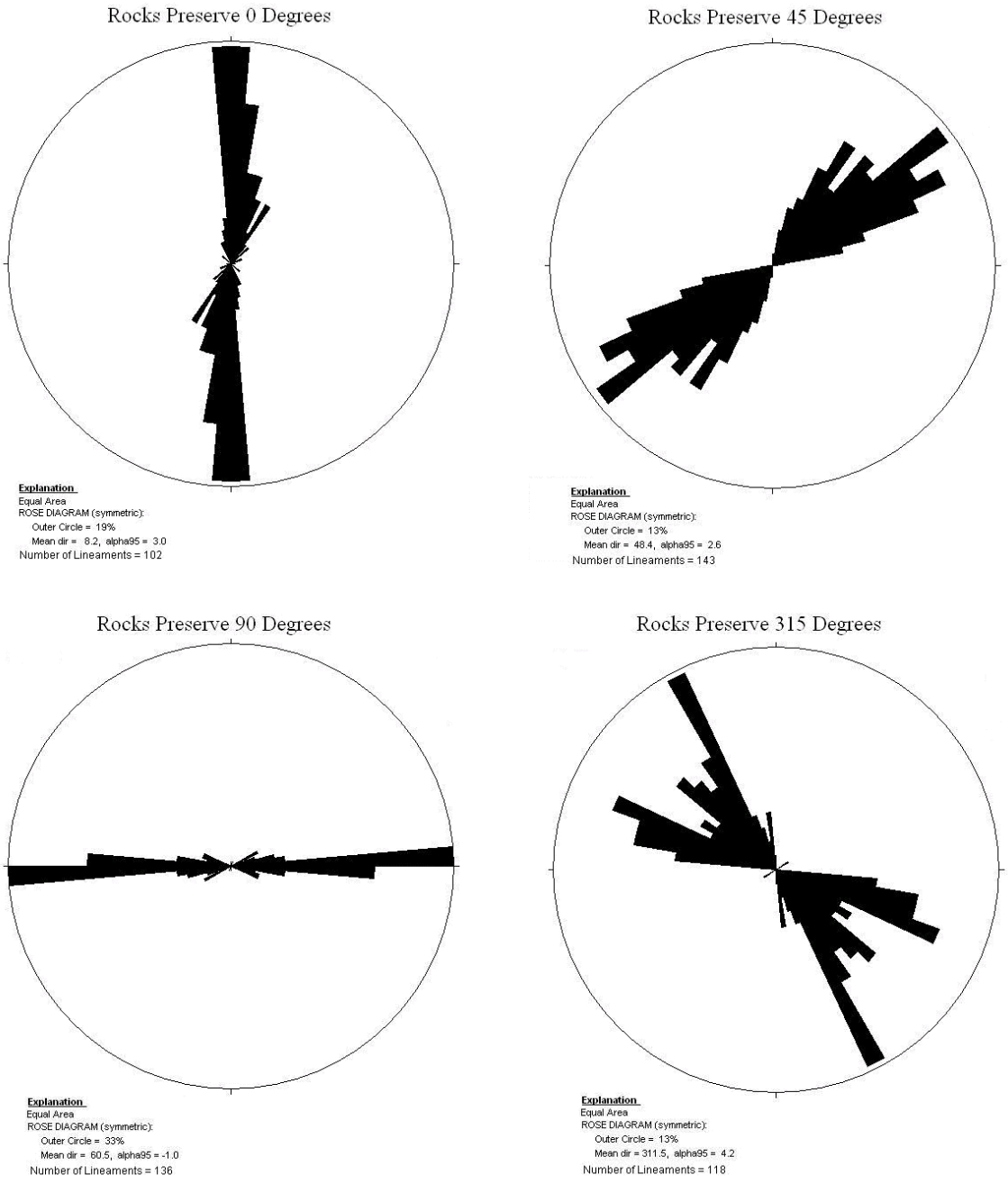


Figure 45. Rose diagrams of ENVI lineaments for the Rocks Preserve land area.

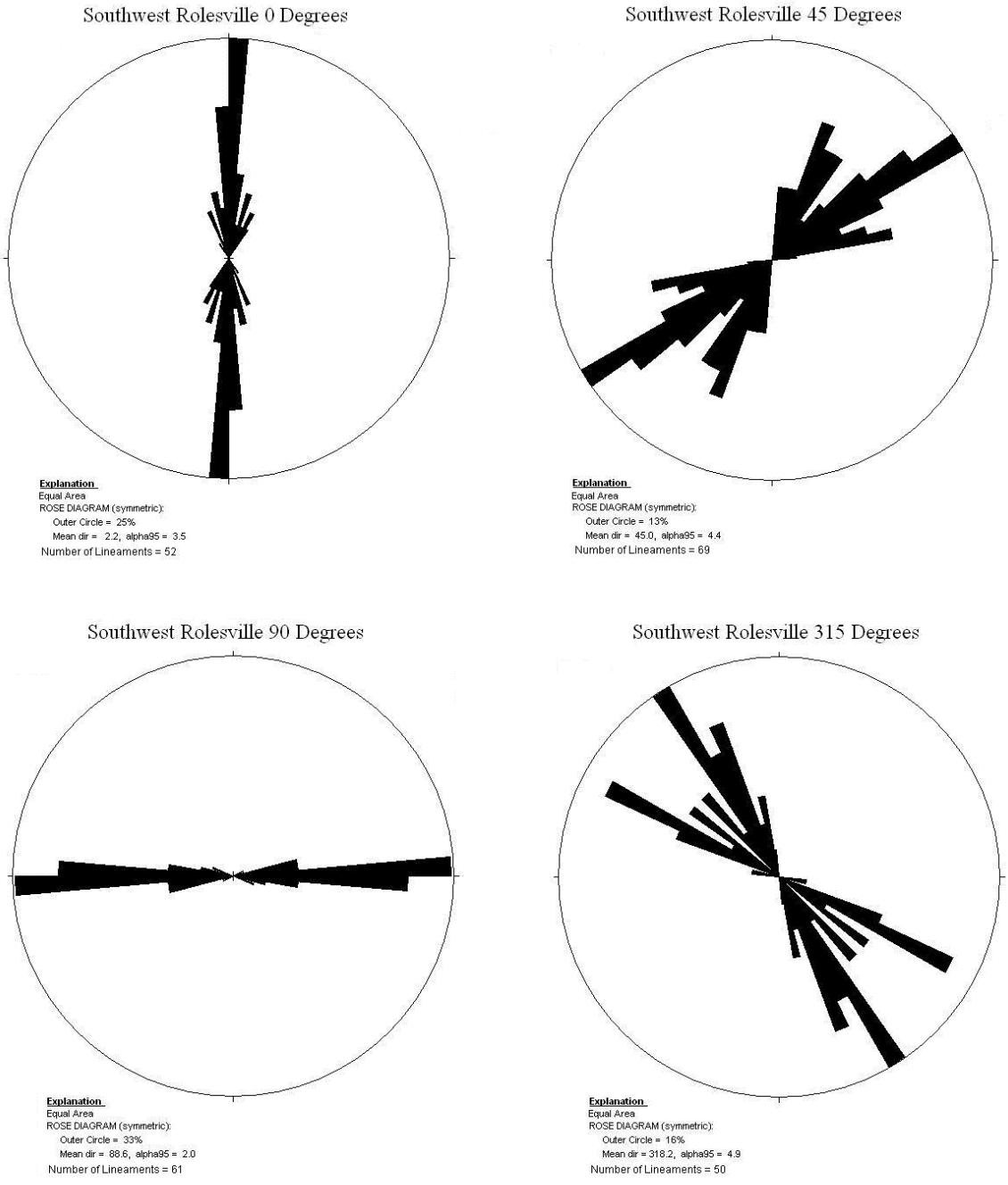


Figure 46. Rose diagrams of ENVI lineaments for the Southwest Rolesville land area.

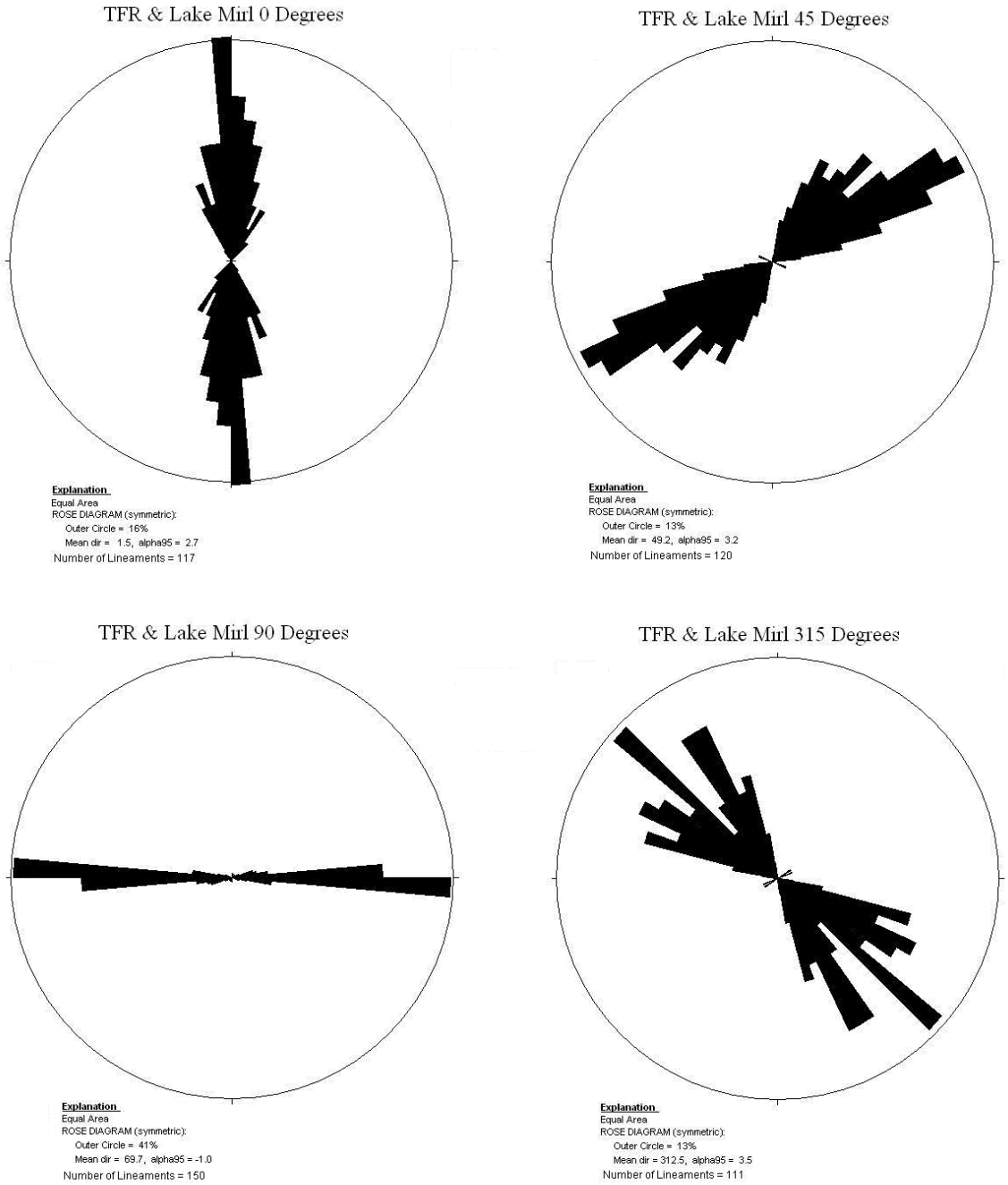


Figure 47. Rose diagrams of ENVI lineaments for the Temple Flat Rock and Lake Mirl land area.

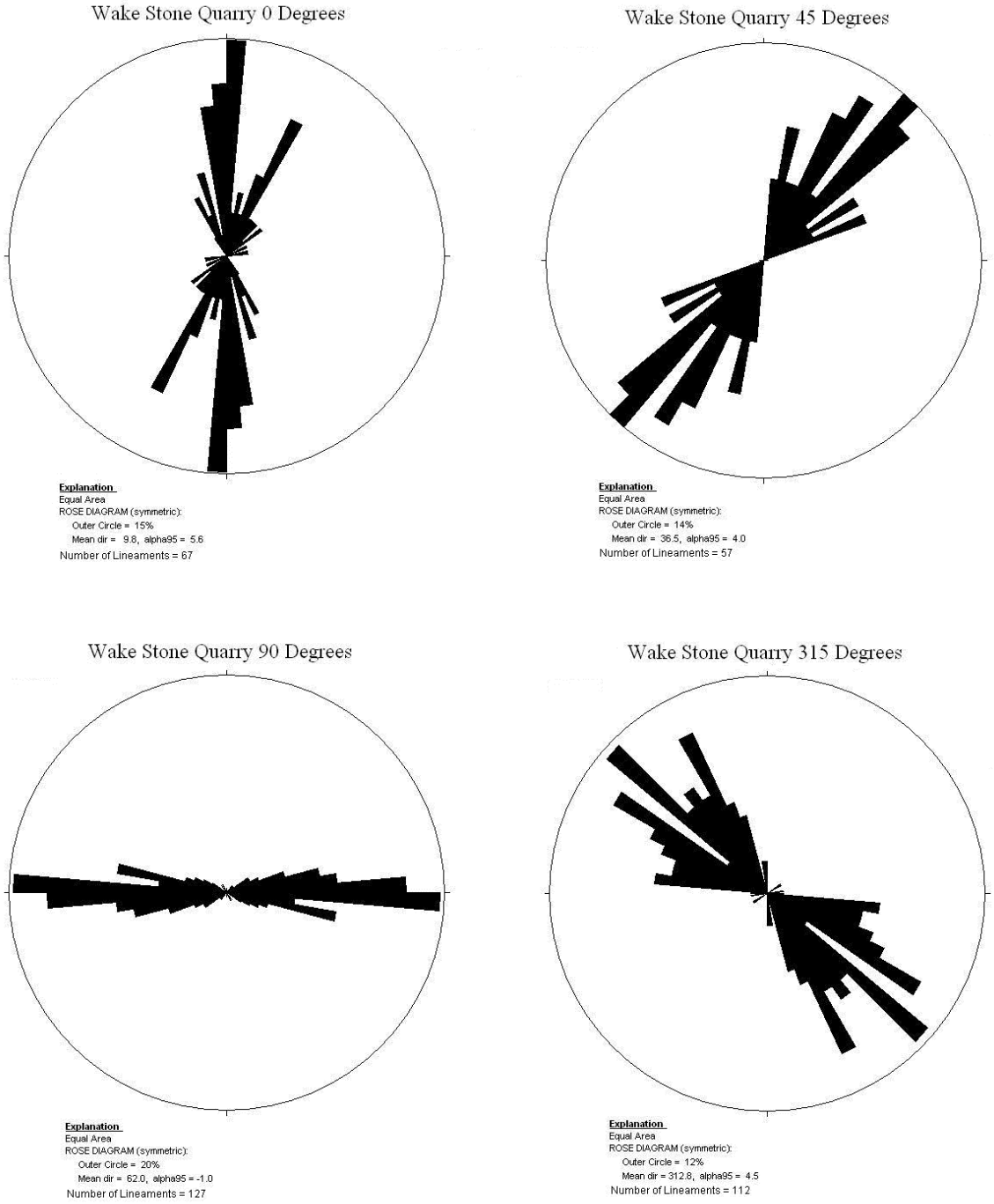


Figure 48. Rose diagrams of ENVI lineaments for the Wake Stone Quarry (Knightdale) land area.

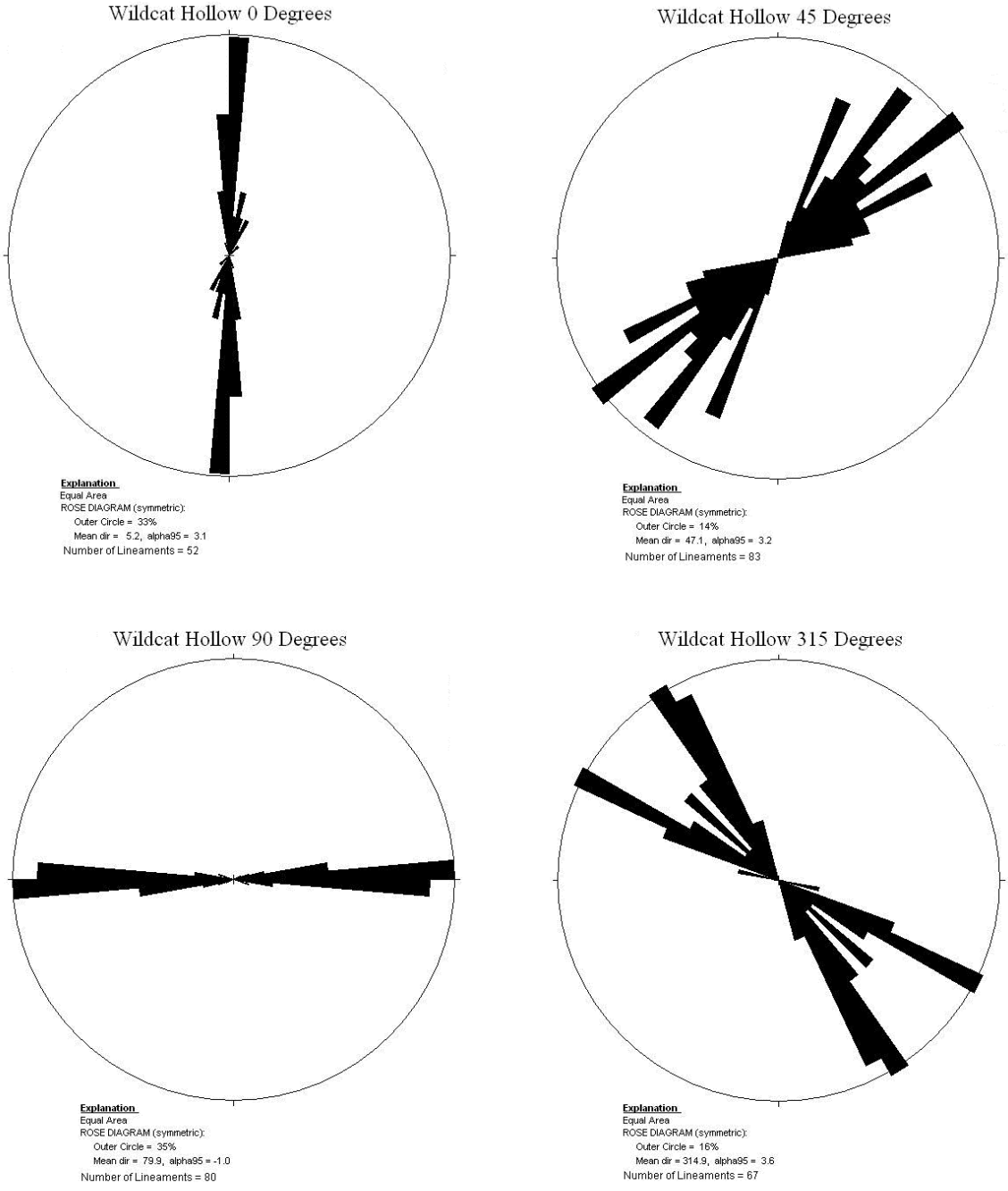


Figure 49. Rose diagrams of ENVI lineaments for the Wildcat Hollow land area.

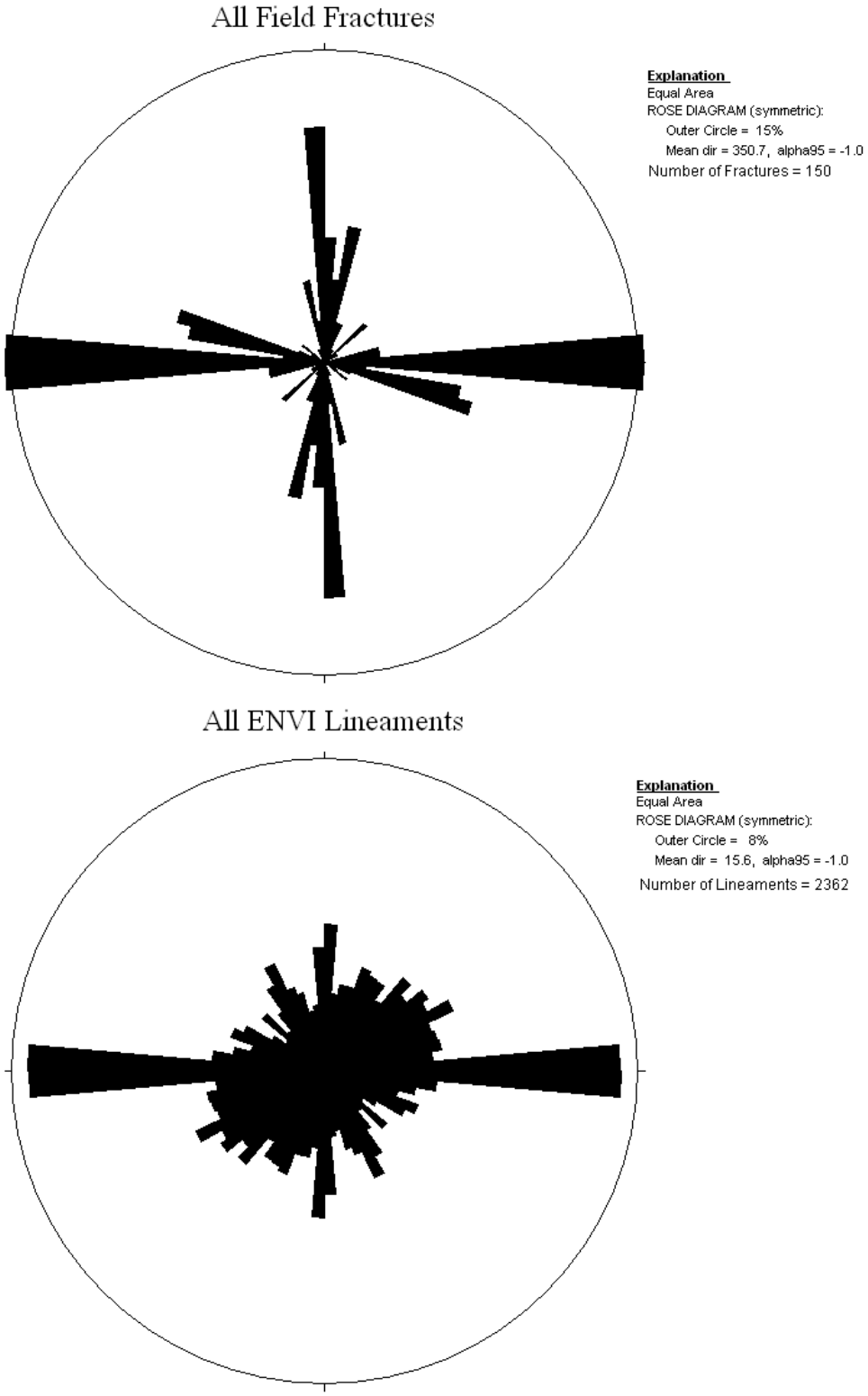


Figure 50. Comparison of fracture orientations to lineament orientations in the Rolesville batholith.

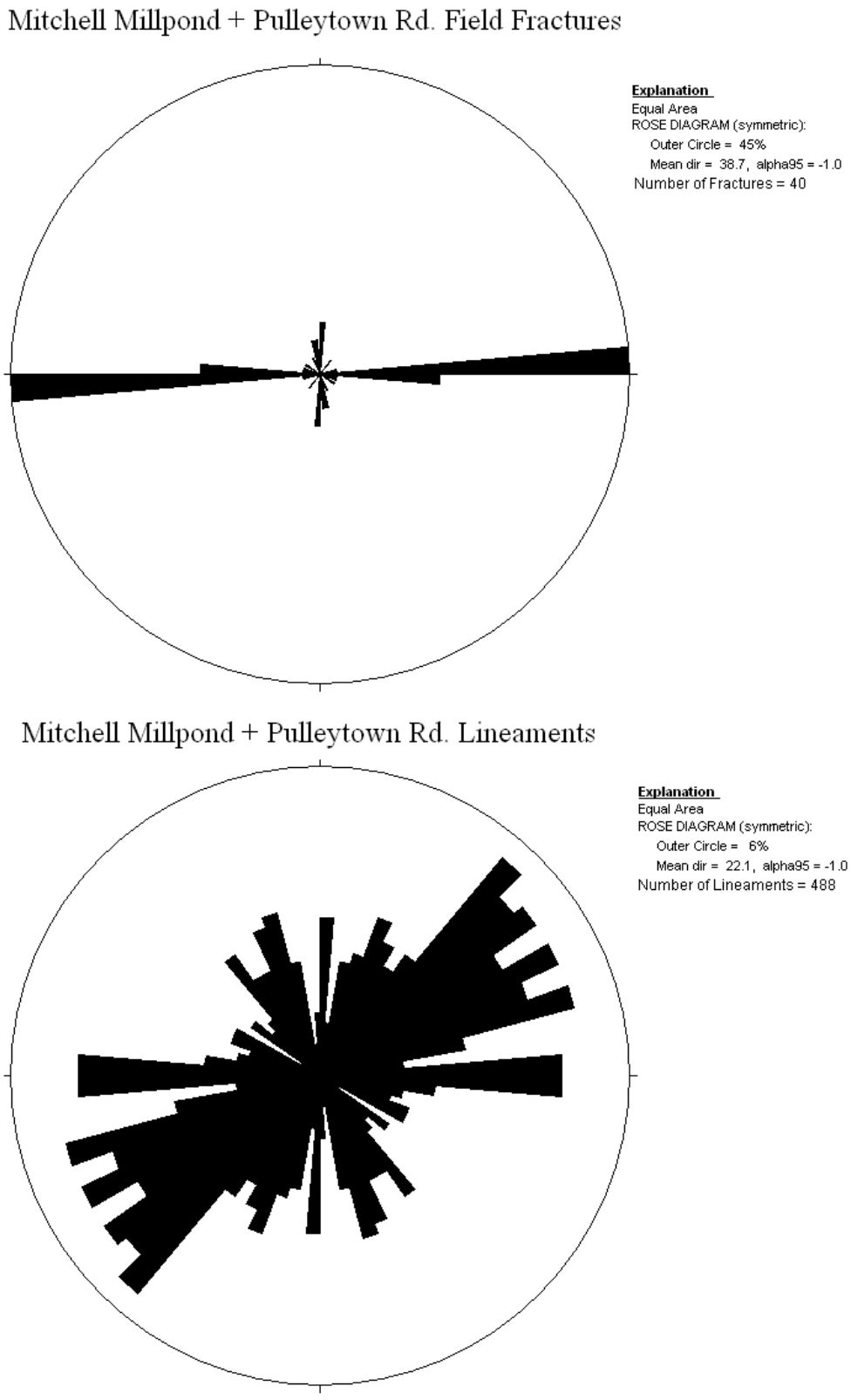


Figure 51. Comparison of field fracture orientations to ENVI lineament orientations for Mitchell Millpond and Pulleytown Rd. study areas.

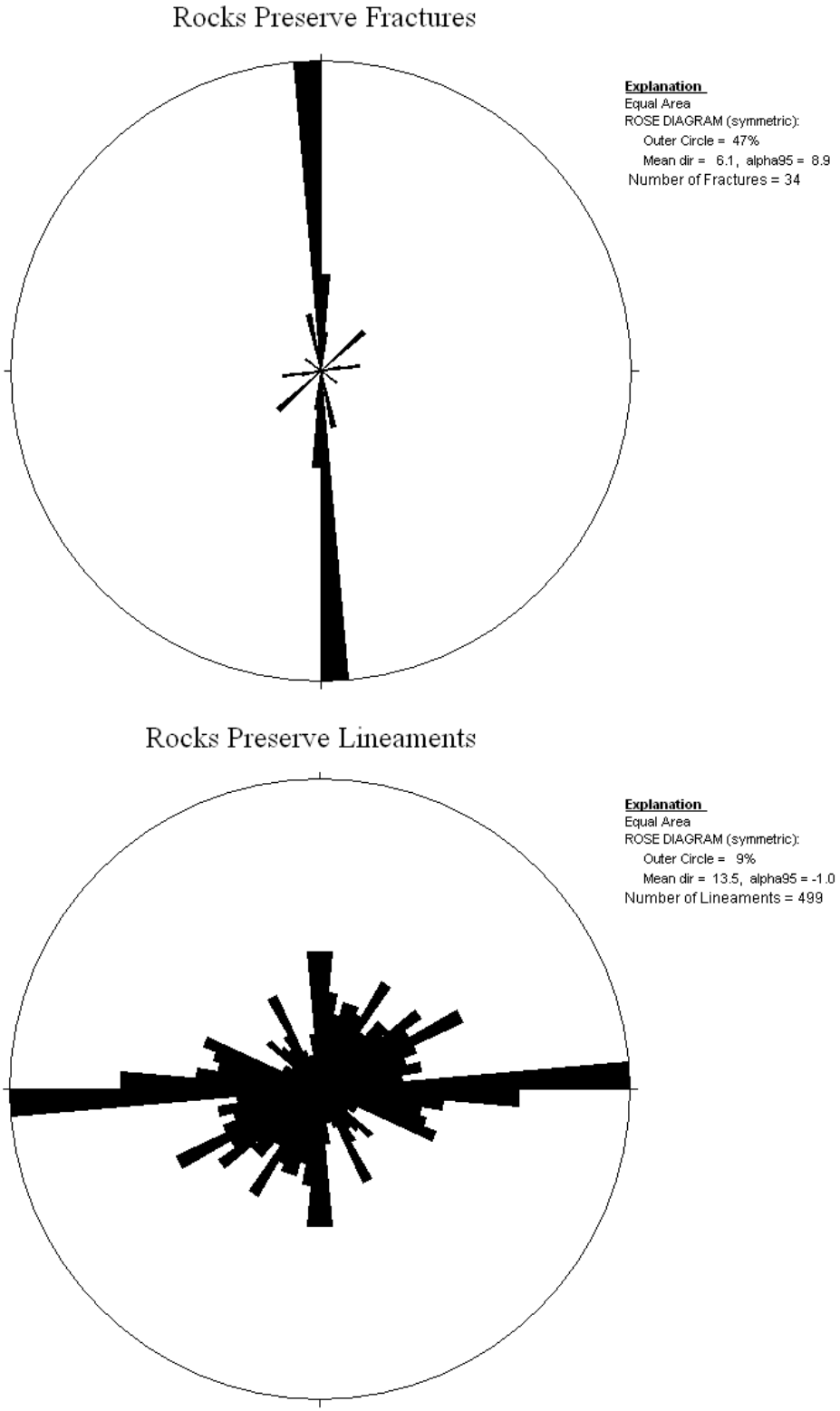


Figure 52. Comparison of field fracture orientations to ENVI lineament orientations for the Rocks Preserve study area.

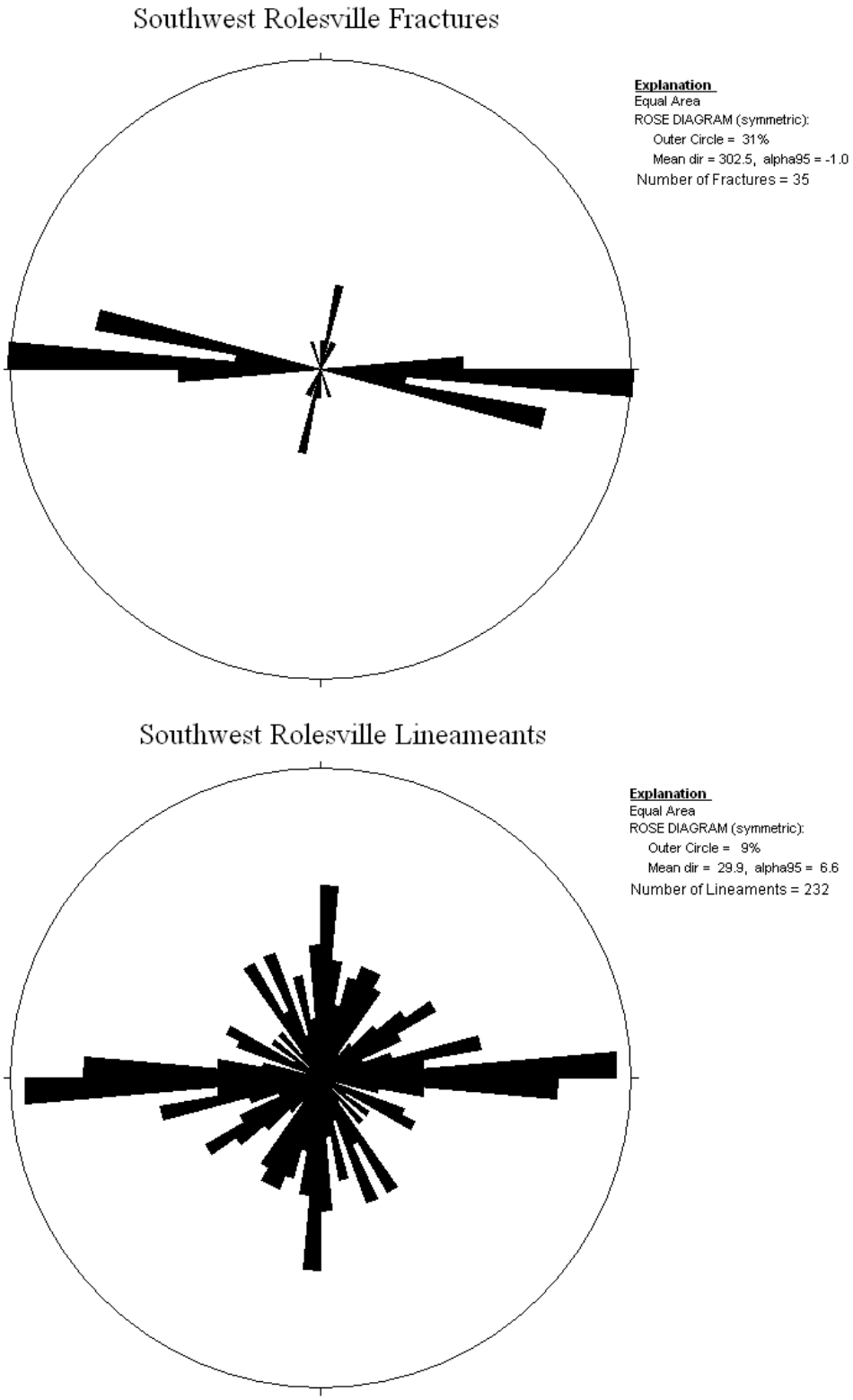


Figure 53. Comparison of field fracture orientations to ENVI lineament orientations for the Southwest Rolesville study area.

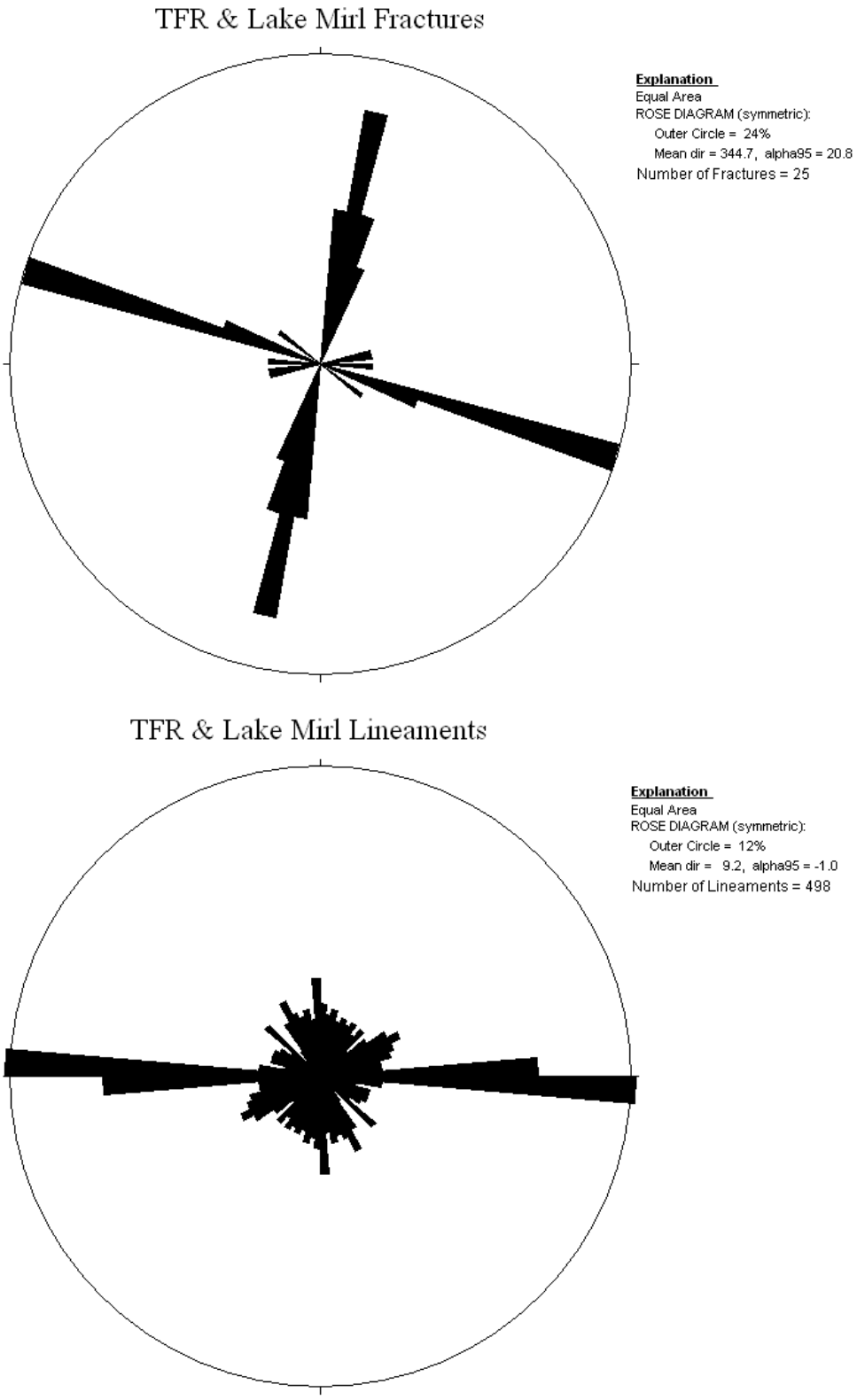


Figure 54. Comparison of field fracture orientations to ENVI lineament orientations for the Temple Flat Rock and Lake Mirl study areas.

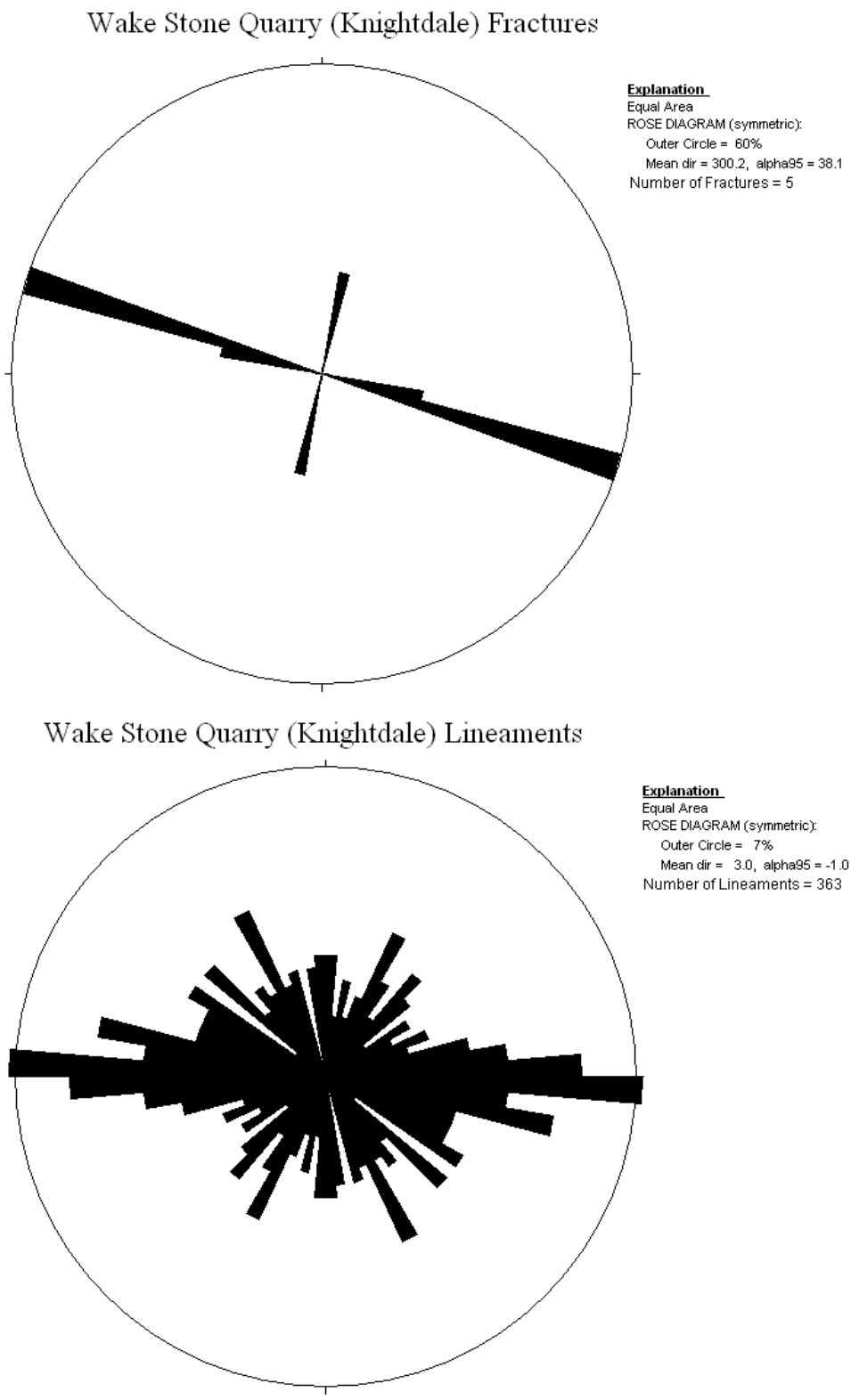


Figure 55. Comparison of field fracture orientations to ENVI lineament orientations for the Wake Stone Quarry (Knightdale) study area.

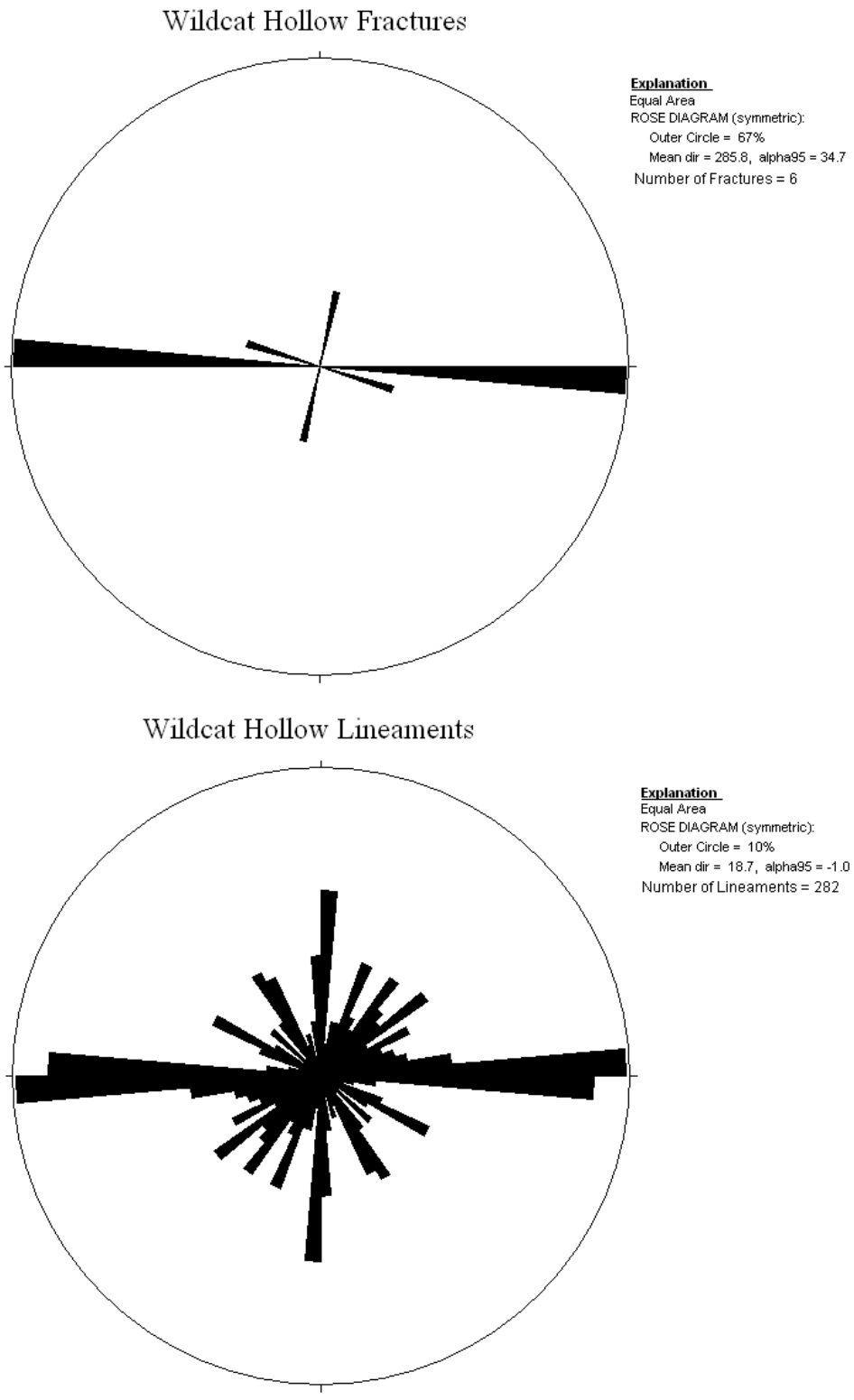


Figure 56. Comparison of field fracture orientations to ENVI lineament orientations for the Wildcat Hollow study area.

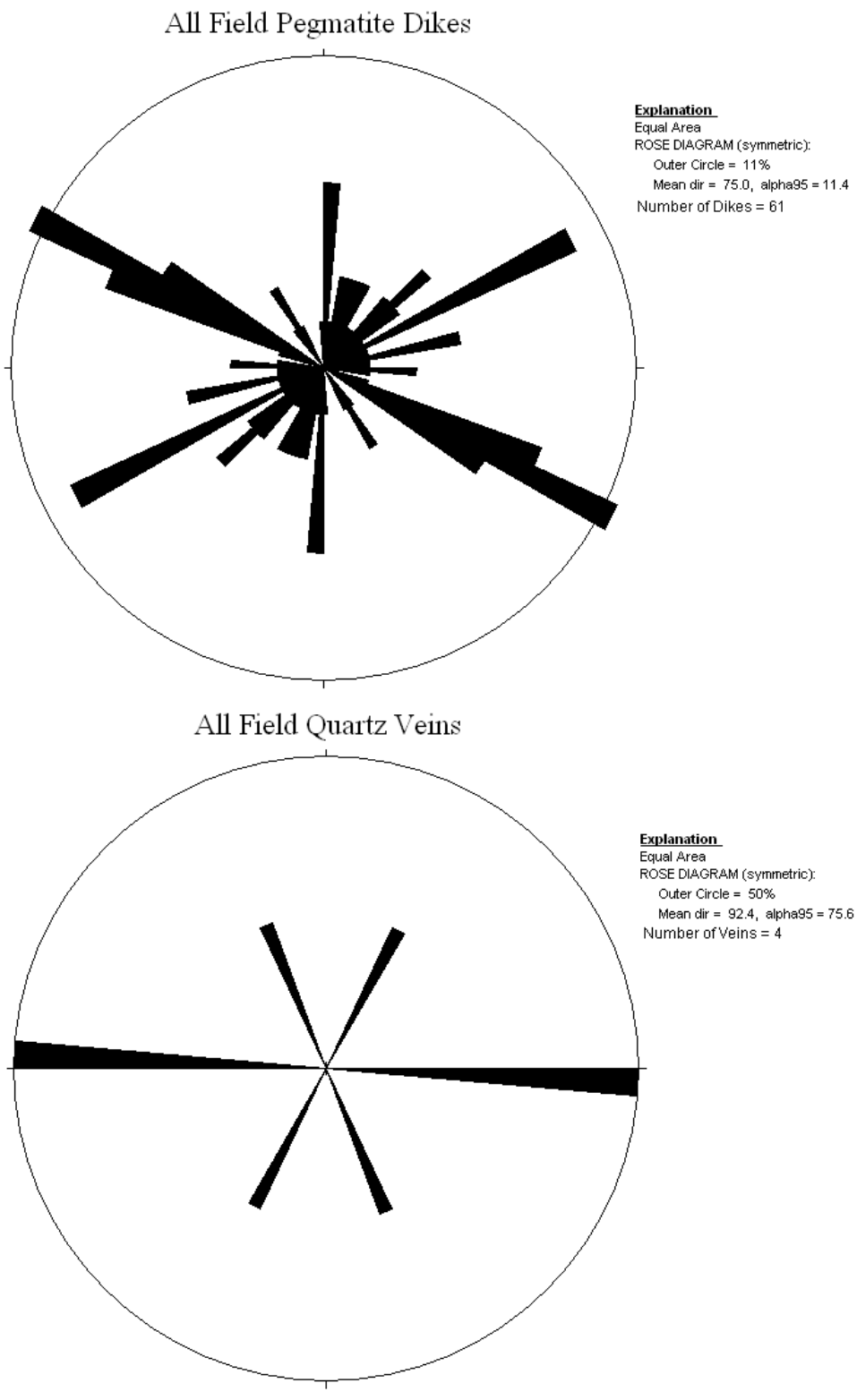


Figure 57. Rose diagrams of pegmatite dikes and quartz veins found in the field.

The final set of images created were ArcGIS plots created from the acquired well yield data. Table 4 shows the average well yield, depth, and yield/depth values for each individual data set, as well as the averages of all data sets combined. Table 5 displays the overall average yield, depth, and yield/depth values, as well as the maximum and minimum values for each category along with the number of wells included in each calculation.

The first image created shows the distribution of all 810 wells with yields greater than 0 gpm. A similar layout was produced of all 712 wells with yields per foot of total well depth larger than 0 gpm/ft. Images were also produced displaying only the Aqua NC CWS well data, as it is the only data set on which a 24 hour drawdown pump test was performed on each well. All wells were displayed over a LIDAR elevation layer in order to provide visualization of the topographic contours of the area. (Figures 58-67)

Table 4: Average well yield, yield/depth, and depth values for each well yield data set

Well Yield Data Source	Average Yield (gpm)	Average Yield/Depth (gpm/ft)	Depth (ft)
Wake Well Permit Database	13	0.0702	280
Public Water Supply Wells	46	0.1981	294
Aqua NC CWS Wells	45	0.1865	324
1968 Groundwater Bulletin #15	20	0.2016	122
NC DENR Study Wells	29	0.1292	239
All Well Data	26	0.1184	274

Table 5: Average well yield, yield/depth, and depth values for all well data used

Parameter	Average	Max. Value	Min. Value	# of Wells
Well Yield (gpm)	26	175	1	810
Total Well Depth (ft)	274	845	28	712
Well Yield/Total Well Depth (gpm/ft)	0.1184	1.384	0.0012	712

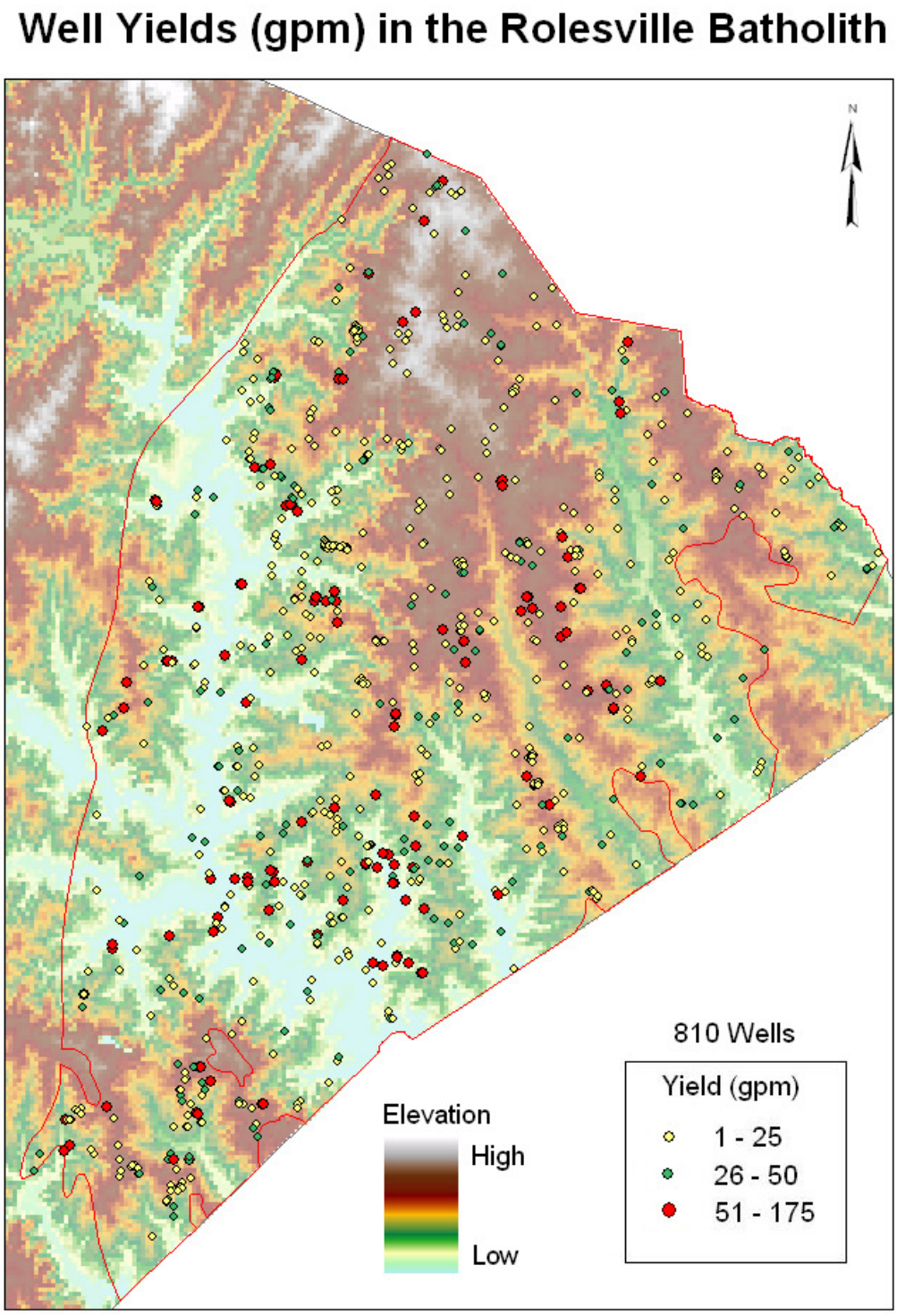


Figure 58. Location of all wells used in the study.

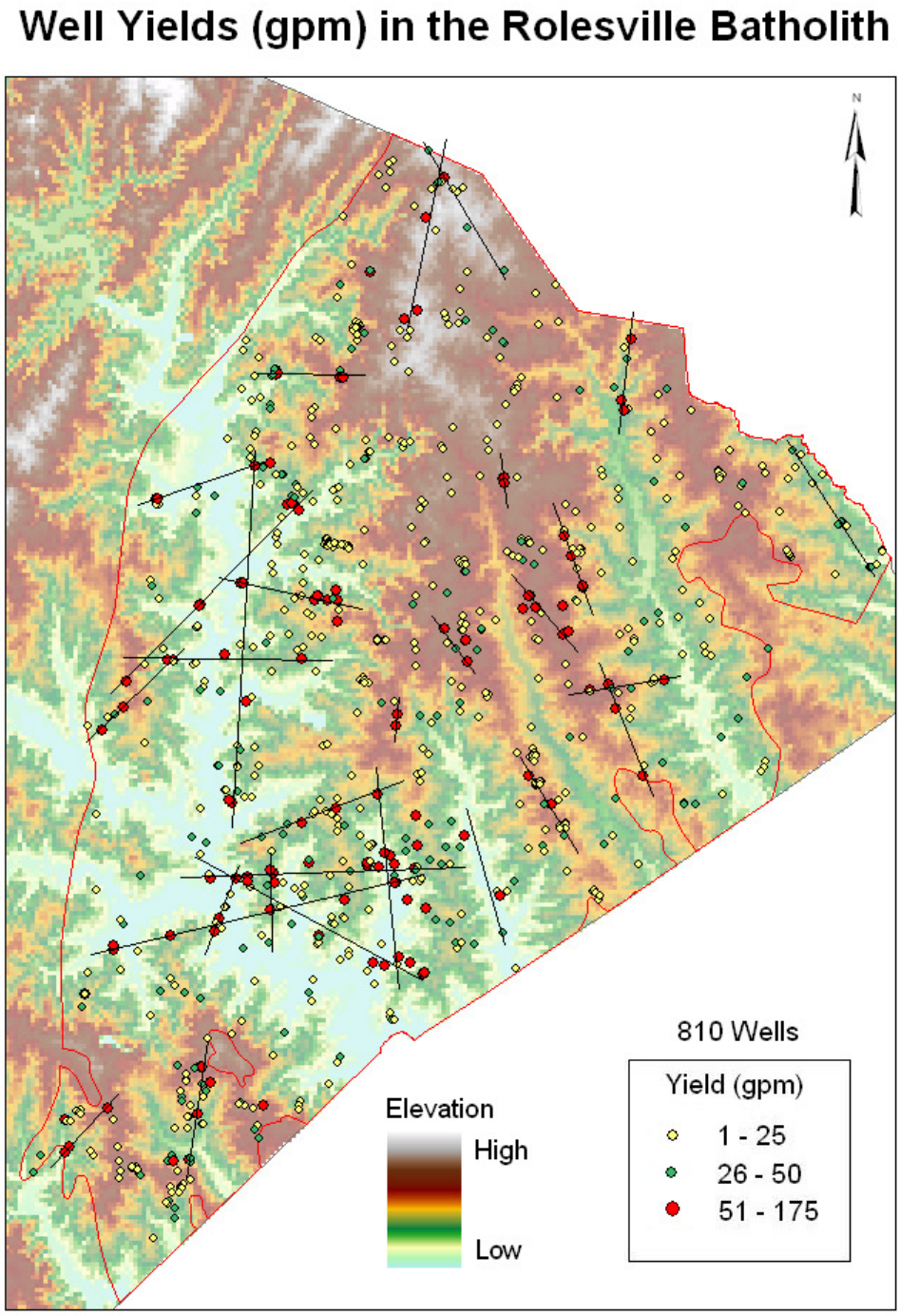


Figure 59. Location of all wells used in the study with inferred "zones of high yielding wells" marked with black lines.

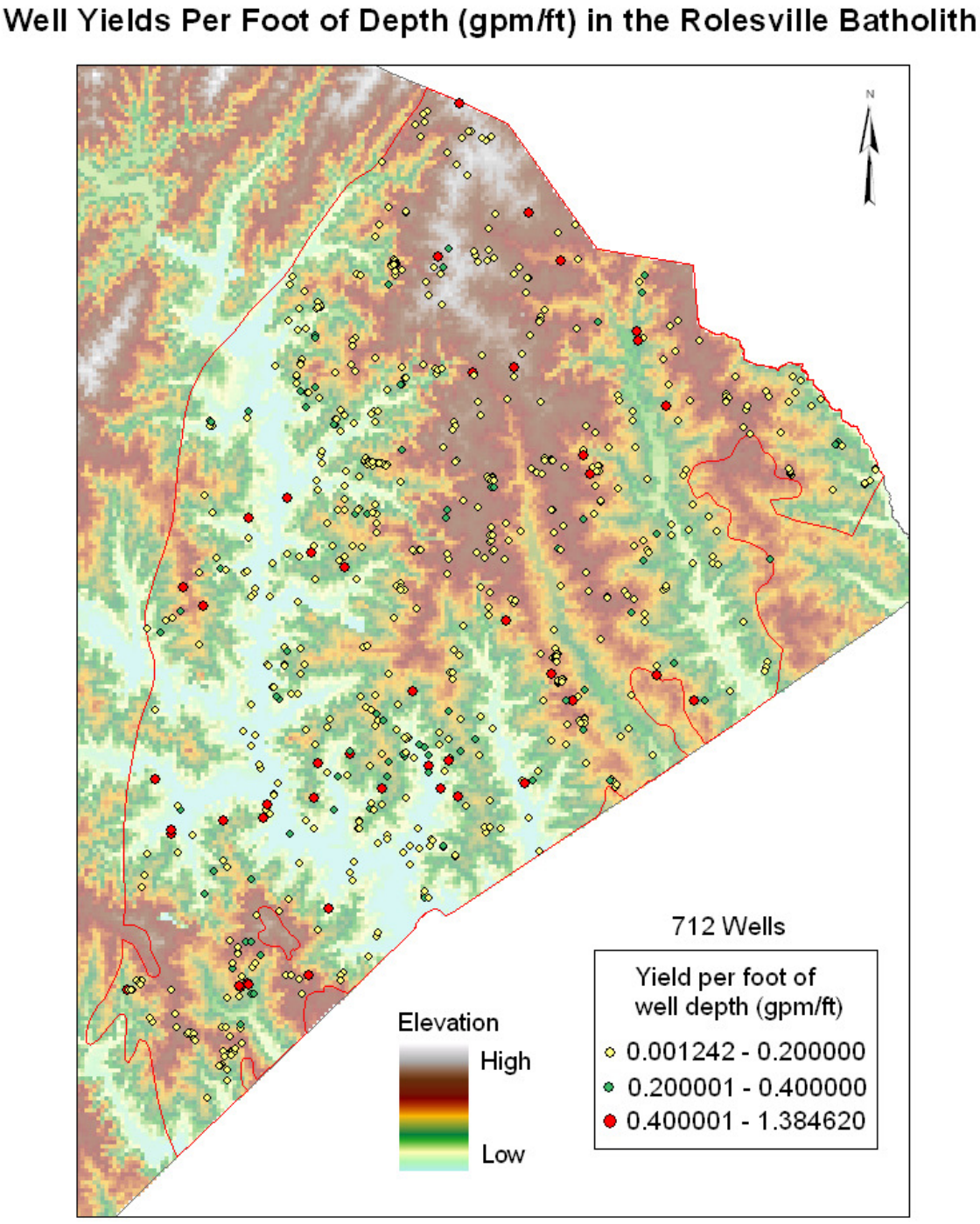


Figure 60. Location of all wells with yield and depth data that were used in the study.

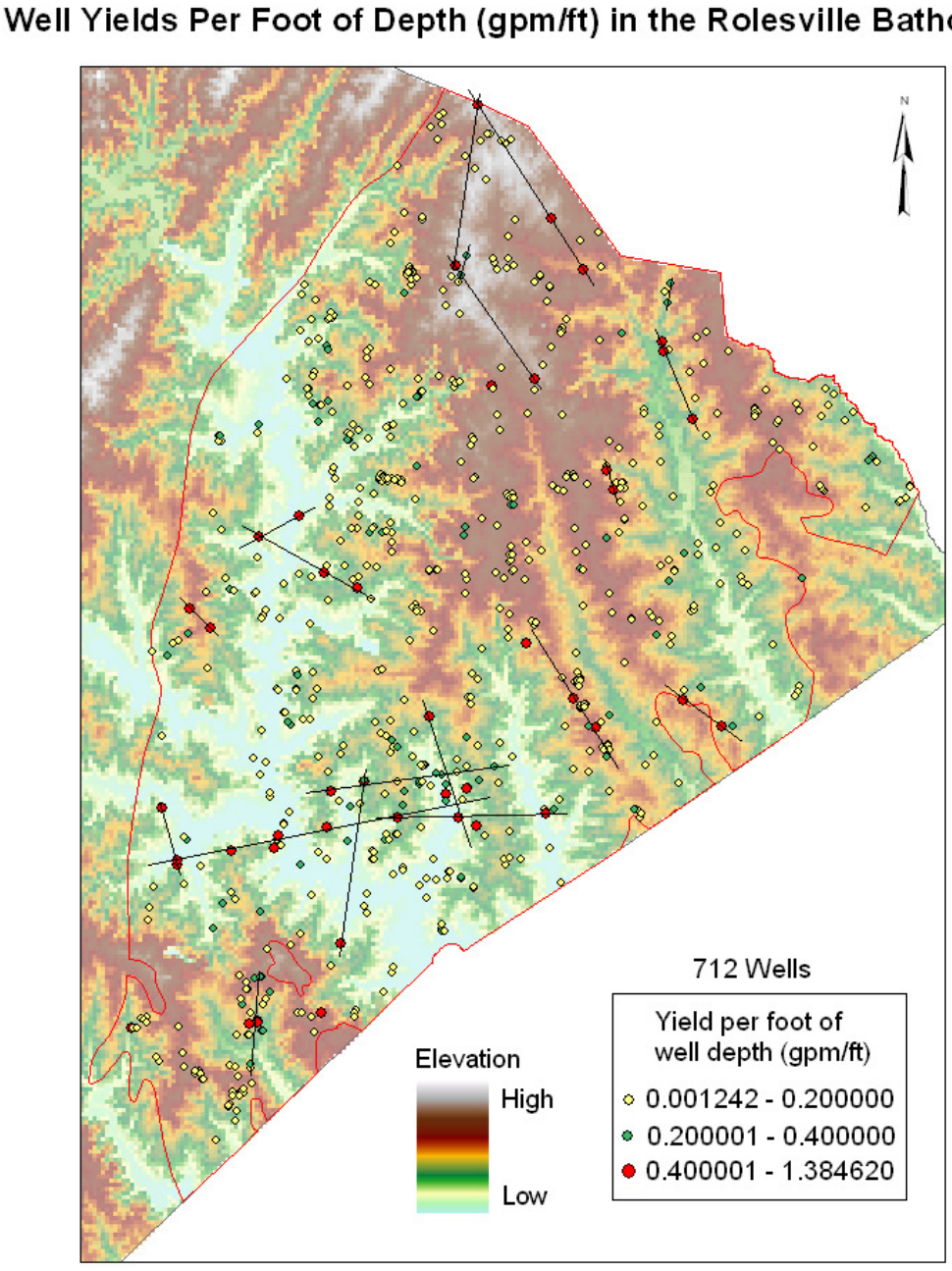


Figure 61. Location of all wells with yield and depth data with inferred "zones of high yielding wells" marked with black lines.

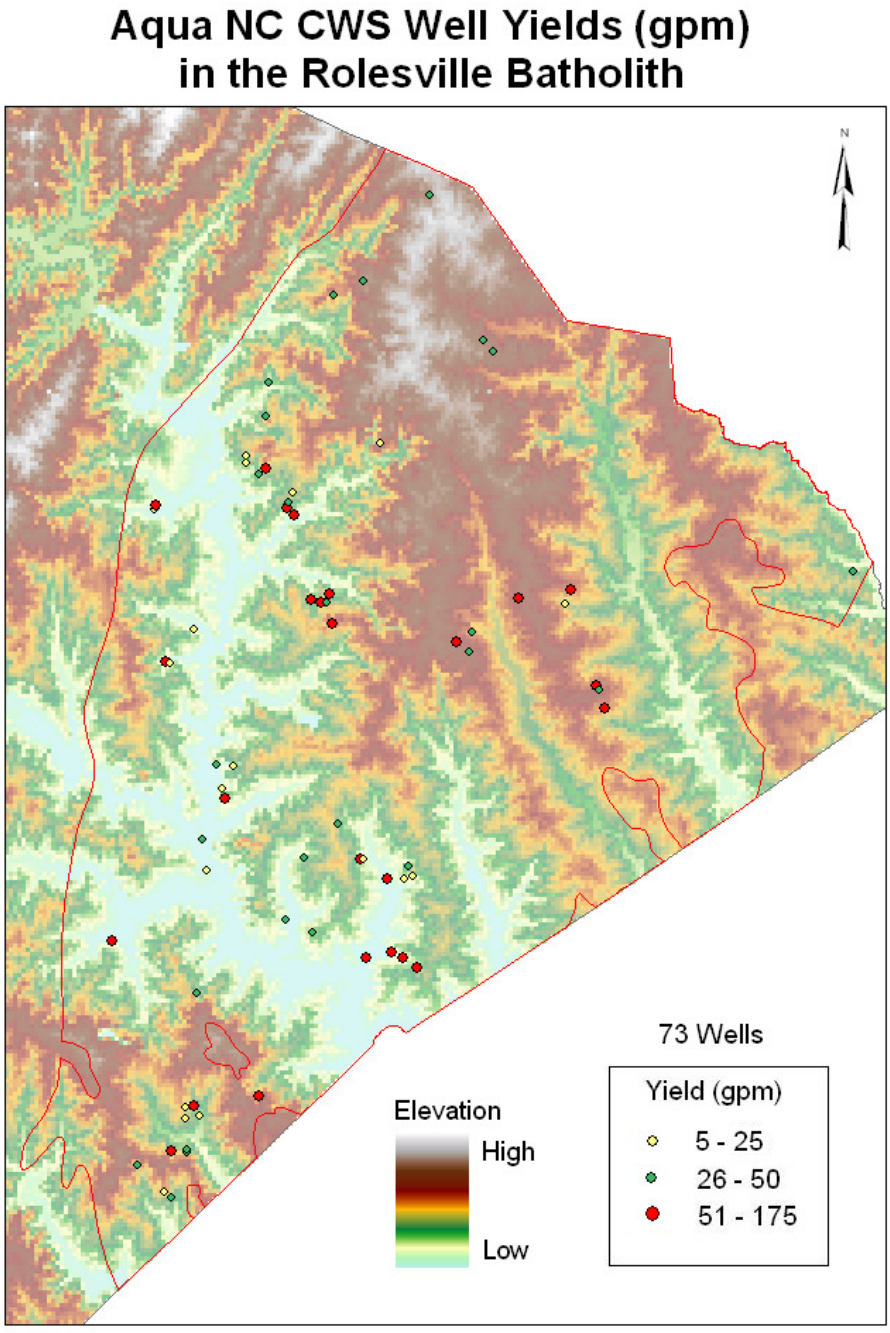


Figure 62. Location of all Aqua NC CWS wells with yield data.

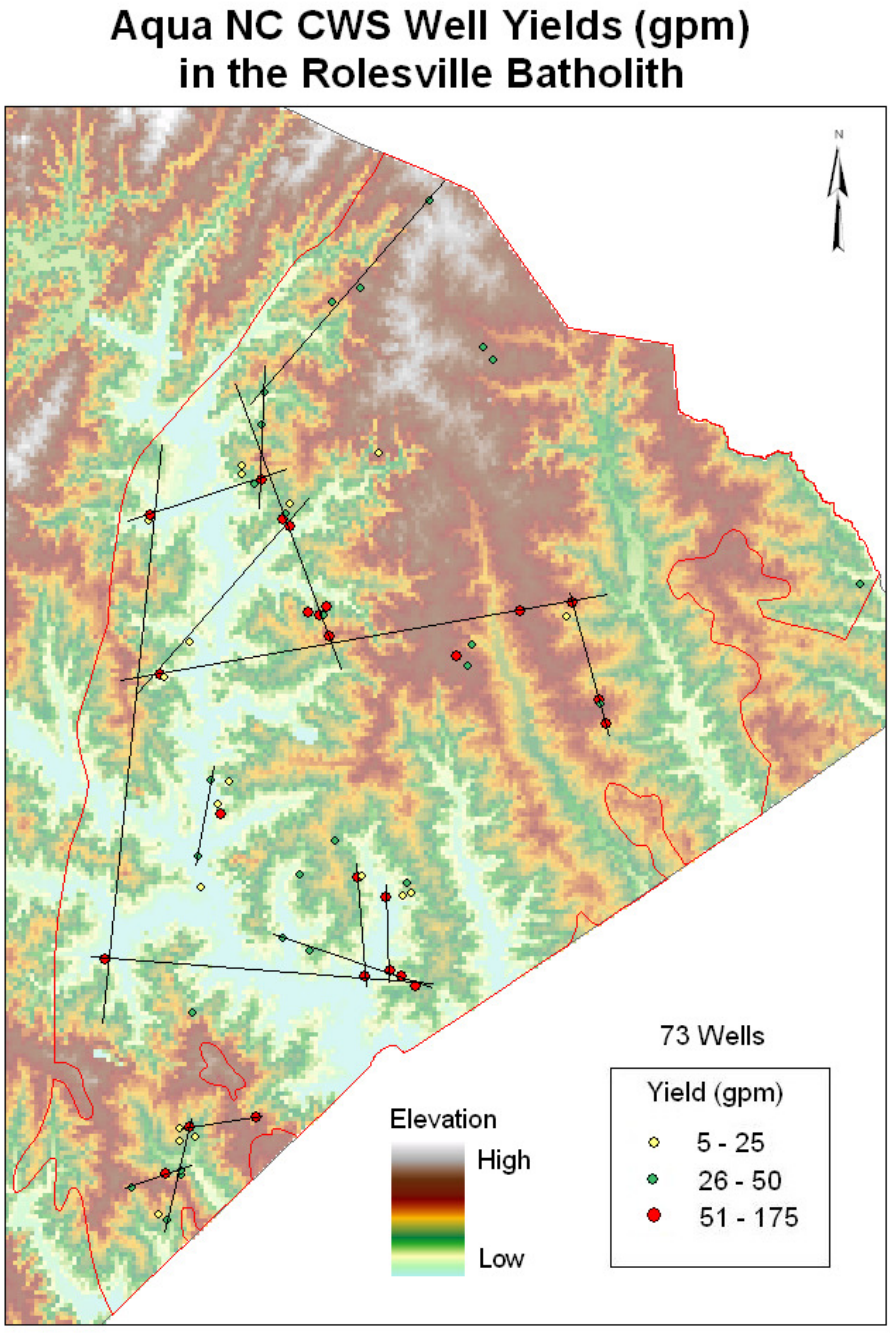


Figure 63. Location of all Aqua NC CWS wells with yield data with inferred "zones of high yielding wells" marked with black lines.

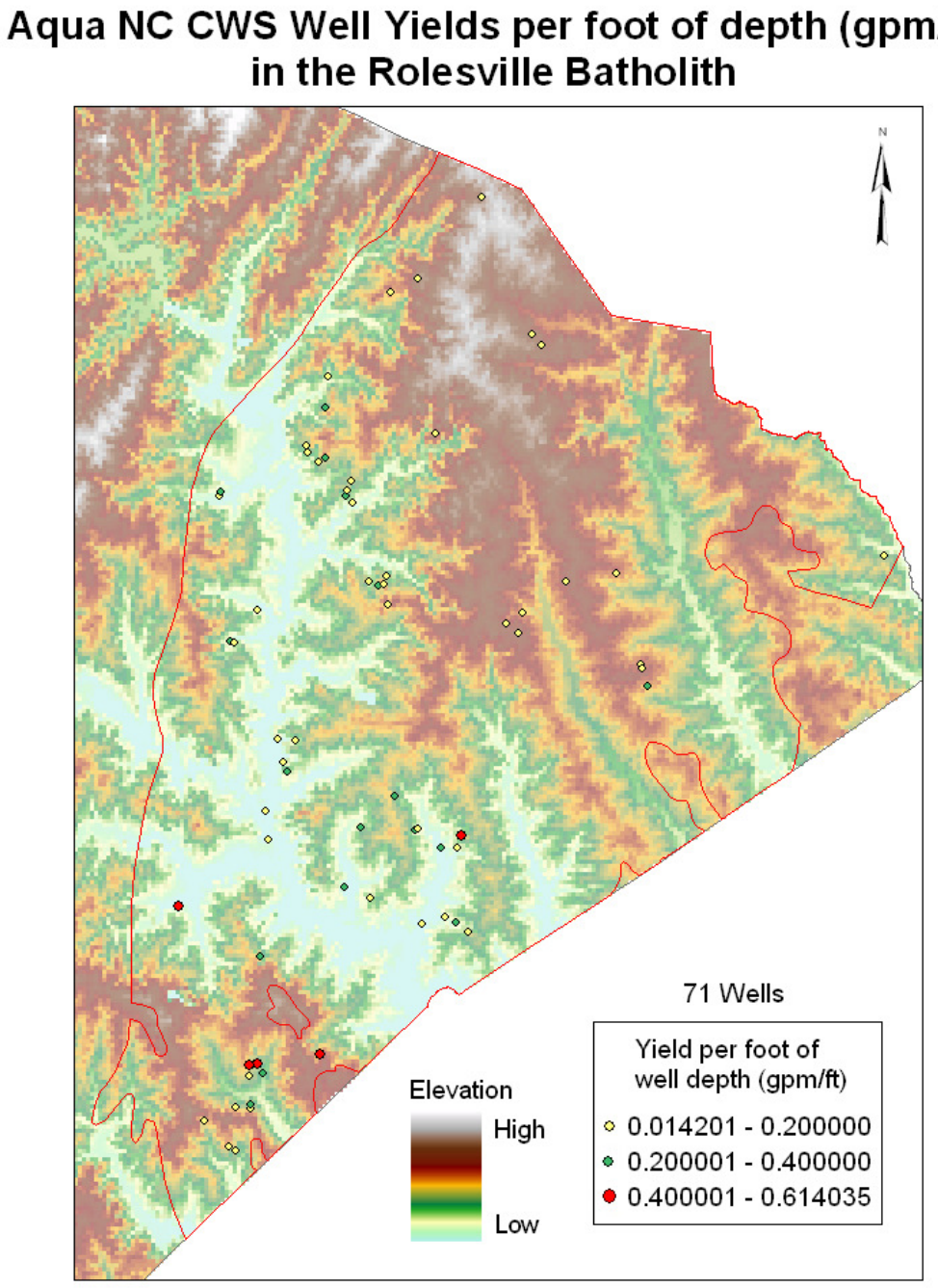


Figure 64. Location of all Aqua NC CWS wells with yield and depth data.

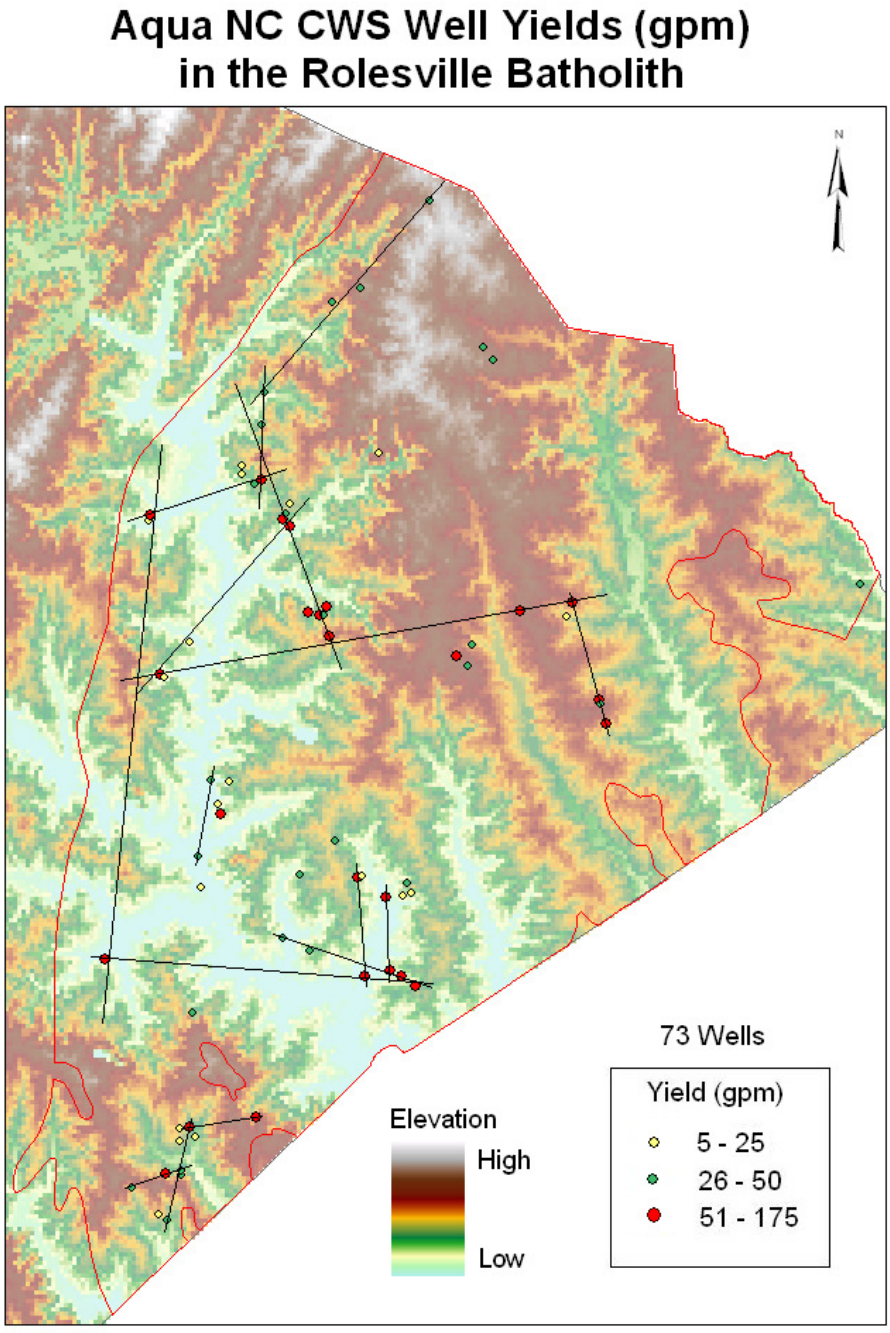


Figure 65. Location of all Aqua NC CWS wells with yield and depth data with inferred "zones of high yielding wells" marked with black lines.

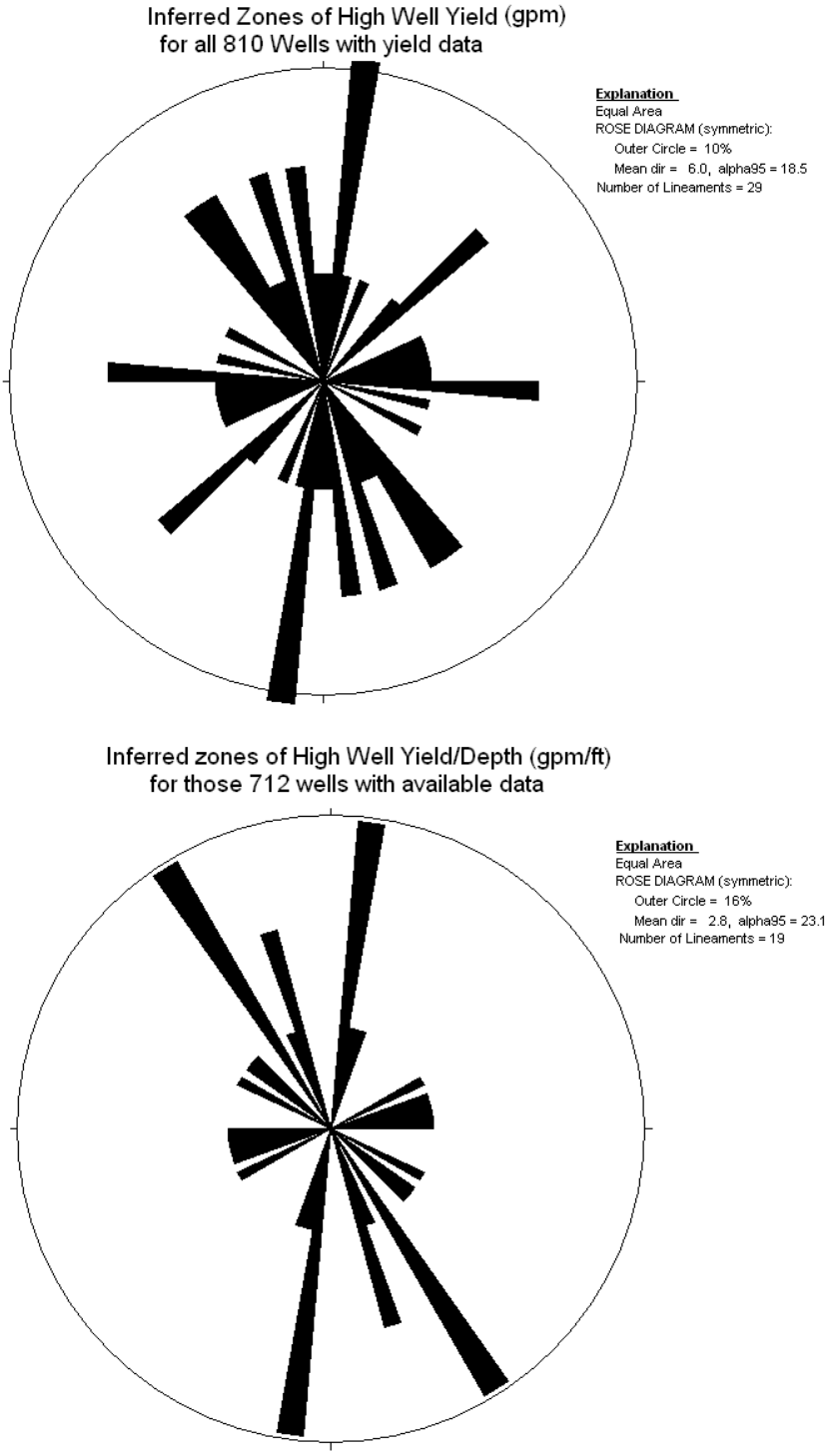


Figure 66. Inferred zones of high well yields for all yield and yield/depth data.

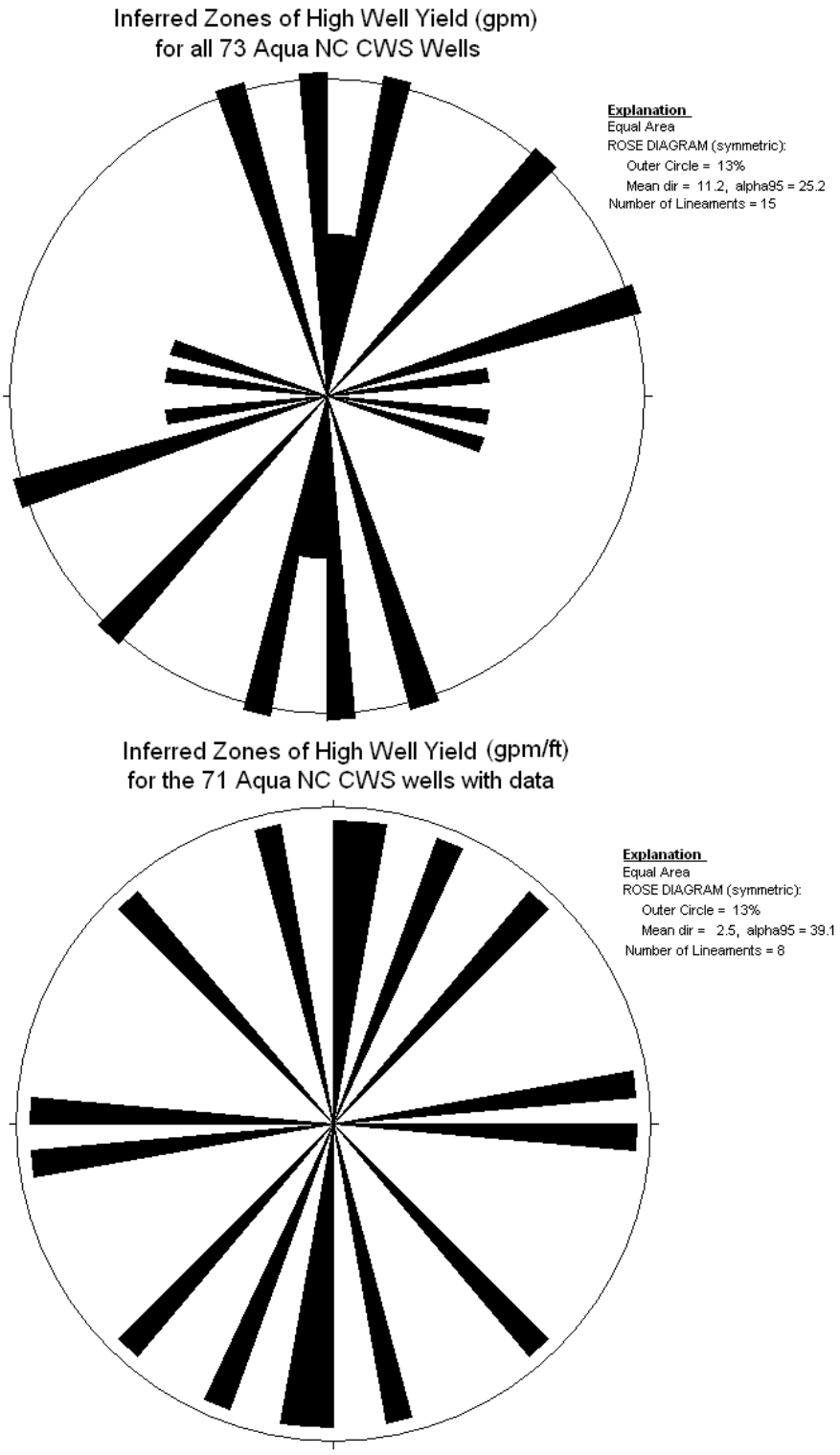


Figure 67. Inferred zones of high well yields for Aqua NC CWS wells with available yield and yield/depth data.

Discussion of Results

The three goals of this study were 1) to determine via field study the primary surface fracture directions present at pavement outcrops within the Rolesville granite area of Wake County, 2) to perform a larger scale land-surface lineament analysis using aerial photographs and remote sensing data to compare with the field data results and the results of previous geologic studies, and 3) to correlate available well yield data with the observed primary surface fracture directions in order to identify possible areas within the Rolesville granite of Wake County where these subsurface fractures should allow for the construction of wells with higher than average yields.

Comparison of Field and Computer Rose Diagram Data

Comparison of Field Fractures to Computer Lineaments *(Figure 50)*

Figure 50 shows the primary field fracture direction to be 90° ± 5°, with 30.67 % of all measured fractures falling in this range. The secondary fracture direction in the field is approximately 0° ± 5° (18 % of all fractures). The third most common fracture direction is roughly 280°-290° (14 %), and the fourth most common direction is 10°-15° (8.67 %).

The rose diagram of all the 2,362 land-surface lineaments found using ENVI, also exhibits the E-W trend (90° ± 5°) found in the fracture data. Lineaments in this range account for 15.66 % of those found. The second most common direction amongst the computer lineaments is 0° ± 5°. This number of fractures in this direction is roughly half that of the 90° trend, accounting for 7.28 % of all lineaments found. The remainder of the

lineament data seem to be more uniformly distributed, with slight preferences towards 332°, and ~ 62° respectively.

Mitchell Millpond and Pulleytown Rd. Fractures and Lineaments *(Figure 51)*

In Figure 51, the rose diagram of the 40 fractures found in the field shows a very strong fracture preference of 90° ± 5° at this site (62.5 % of all fractures found). The remaining fractures favors a N-S trend, representing 10 % of the fractures found.

The rose diagram containing all 488 lineaments found during the analysis of aerial photographs shows a different trend than the field data for this site. The most common lineament directions are those found between 40° and 80° (37.09 % of all lineaments). The second strongest trend is for the E-W (90° ± 5°) lineaments that account for 10.04 % of the lineaments found. Lineaments trending N-S (0° ± 5°) comprise only 4.30 % of the lineaments found. The lineaments ranging from 320° - 350° account for 16.1 % of all lineaments found.

Rocks Preserve Fractures and Lineaments *(Figure 52)*

The field data for the Rocks Preserve site contains a total of 34 fractures. These fractures strongly favor strike directions between 0° ± 5°, or those trending roughly N-S. Fractures found within this range account for 61.76 % of the fractures found in the outcrop. Few fractures were found trending E-W at this site.

The ENVI data (499 lineaments) acquired for the Rocks Preserve site shows that the E-W (90° ± 5°) direction is strongly favored for lineaments (15.03 %), followed by

lineaments trending N-S (0° ± 5°) with 8.62 %. The lineaments that were found by filtering for 45° and 315° exhibit a much wider range of orientations.

Southwest Rolesville Fractures and Lineaments *(Figure 53)*

The fracture data (35 fractures total) for the Southwest Rolesville field site shows the dominant direction of fracturing to be roughly E-W, ranging from 90° ± 5°. In fact these fractures account for 45.71 % of all fractures found at this site. The second most common direction for fractures at this site was 101°, representing 22.86 % of the fractures found. 8.57 % of the fractures found trend northeasterly with a strike of 10°.

The lineament data (232 total) also show the dominant directions for this site to be within 5° of E-W, with 16.38 %. The second most common direction among the marked lineaments is approximately N-S (0° ± 5°) with 10.34 %. The lineaments filtered for 45° and 315° also show a much wider range of directions, and do not show a strong singular directional trend.

Temple Flat Rock (TFR) and Lake Mirl Fractures and Lineaments *(Figure 54)*

The field data for this site reports that a total of 25 fractures were found. The Rose data shows two major directions of surface fracturing. The most dominant field fracture direction (32 %) was found to be between 285° - 295°, and the second band of fracturing (52 % of all fractures found) lies between 5° and 22°, with the most fractures in this range trending 10°.

The lineament analysis for this site found 498 lineaments in the land area studied. These results differ from the fracture data in that the 90° ± 5° trending lineaments were

the most dominant directions with 21.01 % of all lineaments within this range. The remaining lineaments appear to be more or less evenly distributed, with a very slight preference to N-S trending lineaments (7.23 % of total lineaments).

Wake Stone Quarry (Knightdale) Fractures and Lineaments *(Figure 55)*

The field fracture data for this site is limited with only a total of 5 fractures recorded. These fractures were measured at the bottom of the quarry pit in order to give an idea of fracture azimuth at depth within the Rolesville batholith. The data were limited due to a number of inaccessible areas due to active quarrying at the time of visit, and limited access time to the area. Because of the small number of fractures recorded there is no way to determine if they accurately reflect the subsurface fractures in this area.

The ENVI lineament analysis for this site recorded a total of 363 lineaments. The most frequent direction was found to be 90° ± 5° with 13.5 % of all lineaments found within this range. The remaining lineaments are more widely dispersed, with a slight preference towards those trending 335° ± 5° (7.16 %). The lineaments trending N-S (0° ± 5°) only account for 5.51 % of the lineaments found at this site.

Wildcat Hollow Fractures and Lineaments *(Figure 56)*

The fracture data for this site are limited to 6 fractures. This site consists of granite caves and boulders, and as a result it is difficult to discern if these rocks are in the same position as when they were emplaced. Therefore, it is difficult to determine the validity of these measurements. The dominant direction of fracturing (2/3 of the

fractures) in this area was found to trend E-W (91°). The other two fractures were found to trend 12° and 287°, respectively.

The ENVI data for this site showed a total of 282 lineaments within the land area analyzed. The dominant directional frequency was again found to be 90° ± 5° accounting for 19.15 % of the lineaments at this site. The second most frequent lineament direction was N-S with the 9.93 % of lineaments falling within 0° ± 5°. The remaining marked lineaments are fairly well distributed around the circular graph.

Well Yield Data in the Rolesville Batholith

Well Yields *(Figures 58 and 59)*

The raw well yield data (810 wells) shows fairly uniform distribution of wells throughout the area underlain by the Rolesville Batholith in Wake County. However, there does not appear to be much of a linear pattern to the locations of the wells, instead the highest yielding wells are often located within river or stream basins, implying a direction of preferential erosion due to fracturing. The greatest density of high yielding wells can be found in the southern portion of the batholith near the Knightdale and Wendell areas of the county, near the Neuse River. Amongst the wells with yields greater than or equal to 75 gpm, there exists a grouping of wells in this area trending roughly East-West (85°).

It appears that wells of low to average yields (1-25 gpm) are more common in the northern part of the Rolesville batholith within Wake County. Conversely, a greater concentration of high yielding wells is present in the southern half of the batholith.

Well Yields per Foot of Well Depth *(Figures 60 and 61)*

The yield per foot of well depth data (712 wells) also exhibits a fairly uniform coverage of wells located throughout the study area. As with the raw well yield data the southern portion of the study area exhibits a greater density of the high-yielding wells per foot of depth. In an attempt to identify the most productive wells per foot of depth a map including the yield per foot of total well depth data was created for all wells (712 wells). This plot shows that the most productive wells per foot are located in the southern portion of the Rolesville Batholith. The highest yielding of these wells (.390001 – 1.3846 gpm/ft) also exhibits a linear trend of roughly East-West (N85°E). This area is located at a topographically low elevation in a roughly east-west trending section of the Neuse River Basin. This portion of the river basin appears to be bedrock controlled, as the general trend of the Neuse is to flow roughly southeast through this part of the state.

Discussion of Limits to Well Data

Unfortunately, there are a number of limits to the reliability of the well data used in this study. First is the accuracy of the well yield values. Most yields reported in this study are based on often-unreliable estimates provided by the well driller. These estimates are generally not based on long-term aquifer pump tests. Proper estimation of well yield would involve measuring the static water level before pumping and periodic

measurements of both yield and water level throughout the test. Accurate well yield estimation usually requires a minimum 24-hour aquifer test.

Another factor affecting well yields is the presence of subsurface horizontal fractures. The vertical fractures studied in this thesis only represent two dimensions of the three dimensional aquifer system. Horizontal fracturing in the Rolesville batholith has the potential to greatly influence the flow of water throughout the aquifer, but these fractures are extremely difficult to measure directly at this time.

One more factor that could potentially affect the reliability of the well data is the lack of information about the diameter of each well. As was discussed by Daniel (1987), well yield increases dramatically as the well diameter increases. For wells of the same depth, increases in well diameter are directly proportional to increases in yield per foot of depth in a well. This is due to the increased storage in the well bore that a larger diameter well will allow. This additional storage should only provide a temporary increase in well yield until the stored water in the well bore is pumped dry, then the yield would be controlled by the transmissivity of the fractured granite aquifer through which the well was constructed. The methods employed for well yield estimation would ultimately affect the reliability of the yields reported for these larger diameter wells.

Finally, the well yield data set "Wake Well Permit Database" used an estimation method in the location of their wells. The data set used land parcel centroids, instead of actual well locations for the placement of private domestic wells. This resulted in well locations that were estimates rather than absolutes for this particular data set.

Discussion

In Figure 50, the strike direction for both field fracture data and ENVI lineament data clearly show that features trending 90° ± 5° are found the most frequently in the areas studied within the Rolesville batholith (30.67 % and 18 %, respectively). The second most frequent strike direction among both fracture and lineament measurements is found to be 0° ± 5°. The field fracture data clearly show that N-S (0° ± 5°) trending fractures are the secondary fracture direction, accounting for 18 % of all fractures found. The lineament data also show that lineaments trending 0° ± 5° occur second most frequently, accounting for 7.28 % of all lineaments.

Table 6: Percentage of total lineaments found for each ENVI filter direction

Lineament Filter Direction	Percentage of Total Lineaments Found
0°	20.60 %
45°	28.20 %
90°	26.80 %
315°	24.40 %

As reported earlier, the absolute numbers of ENVI lineaments found for each filtering direction may suggest that lineaments are of equal importance for all directions. However, when the rose diagrams showing the breakdown of each filtering direction are analyzed, an interesting trend becomes evident. At every study site the lineaments filtered for 90° show the least variability in orientation of the lineaments. Nearly all rose diagram

lineaments filtered for this direction occur within a single east-west trending band. This suggests that there is some underlying geologic feature that is strongly influencing the lineaments in this direction. Not surprisingly, the lineaments filtered for 0° show the second least variation among the lineament values. The widest distribution of lineament values was found in the 45° and 315° filter directions, suggesting there is no single strong geological influence in these directions.

As stated in the "Discussion of Limits to Well Data" section above, there are limits to the accuracy of the well data used in this study. However, some conclusions can still be drawn from the data. The average yield for all of the wells in this study was 26 gpm. The average depth for a well in the Rolesville Batholith portion of Wake County was found to be 274 feet. The average yield per foot of total well depth in the study area was found to be 0.1184 gpm/ft. The southern half of the study area appears to have a greater concentration of higher-than-average yielding wells, than the northern part of the study area. In the southern part of the study area there is a roughly East-West trending band of wells of much higher than average yield (> 75 gpm), and yield per foot of well (> 0.39 gpm/ft). This is the area of the Rolesville Batholith in Wake County that appears to have the greatest potential for the construction of new high yielding wells.

Conclusions

1) The Rolesville batholith was found to be sparsely fractured throughout the study area, with no evidence of extensive fracturing found in any of the outcrops visited in the field. The major fracture directions found in the Rolesville batholith are 90° ± 5° (30.67%), and 0° ± 5° (18 %). These trends are also reflected in the lineaments found throughout the study area. The major lineament directions were found to be 90° ± 5° (18%), and 0° ± 5° (7.28 %) as well.

2) The consistency between the results of the computer and field data confirm the validity of using the computer program ENVI for the identification of lineaments within the Rolesville batholith portion of Wake County. The directional filter of the ENVI program appears to be the most effective on lineament analyses of large land areas (study area of kilometers), as the resolution of the aerial photos appears to limit the effectiveness of the identification of smaller lineaments (meters in extent). This suggests that ENVI may be a useful tool to help locate optimal sites for new high yielding wells situated within major lineaments.

3) Due to the nature of the well data used in this study, it is difficult to draw concrete conclusions on well yields. However, the area where well yields appear to be the greatest is in the southern portion of the study area within the Neuse River Basin. In this area there is a roughly E-W (N80°E) trending band of wells with yields greater than 50 gpm. It is possible that this band of wells correlates with a brittle

fault zone that has been studied and mapped immediately to the west of the Rolesville Batholith.

4) Several high yielding well trends appear to be aligned with river valleys and ridges. Rivers can be structurally controlled by the bedrock, and thus may indicate zones of more concentrated fractures. In particular the N-S trending river and stream valleys throughout the study area appear to exhibit preferential erosion, and thus are likely to be structurally controlled. The E-W trending lineations likely represent streams or tributaries that formed at right angles to the preferentially eroded river valleys. This seems to indicate that the N-S trending river and stream lineations may be used to help locate sites for new high productivity wells.

5) The well yield data used in this study reflects an average yield of 26 gpm, and an average well depth of 274 feet for wells in the study area. The Aqua NC CWS data, which is a better estimation of true actual maximum yields throughout the study area, had an average well yield of 45 gpm and an average well depth of 324 feet.

6) The reported yields of CWS wells are currently the best data on actual maximum groundwater yields for this study area. This is due to the fact that the state of North Carolina requires 24-hour pump drawdown tests to be performed on each CWS well after construction. This high quality well yield data is currently limited

to those areas of the county served by CWS, and as a result are more likely to be irregularly spaced and appear in clusters. However, our knowledge on well yields throughout this study area is constantly increasing. New CWS wells are constructed weekly, and detailed records are being maintained on the productivity of these wells.

7) Only vertical fractures were studied in this research. There is not enough evidence to confirm whether these vertical fractures control the fluid flow throughout the fractured rock aquifer system. Horizontal fractures may prove to have a greater influence on fluid flow within the Rolesville granite. Future research is required to determine the properties of the flow system present within the Rolesville batholith.

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APPENDIX

APPENDIX A – LINEAMENTS AND CONTOUR DATA

This set of images (Figures 68-73) displays the ENVI lineaments overlaid on top of a 5 ft. topographic contour data layer. This was done in order to compare the found lineaments with the underlying geologic structure of the area. Those lineaments that are located within underlying geologic structures are much more likely to be geologically and hydraulically significant, than those without.

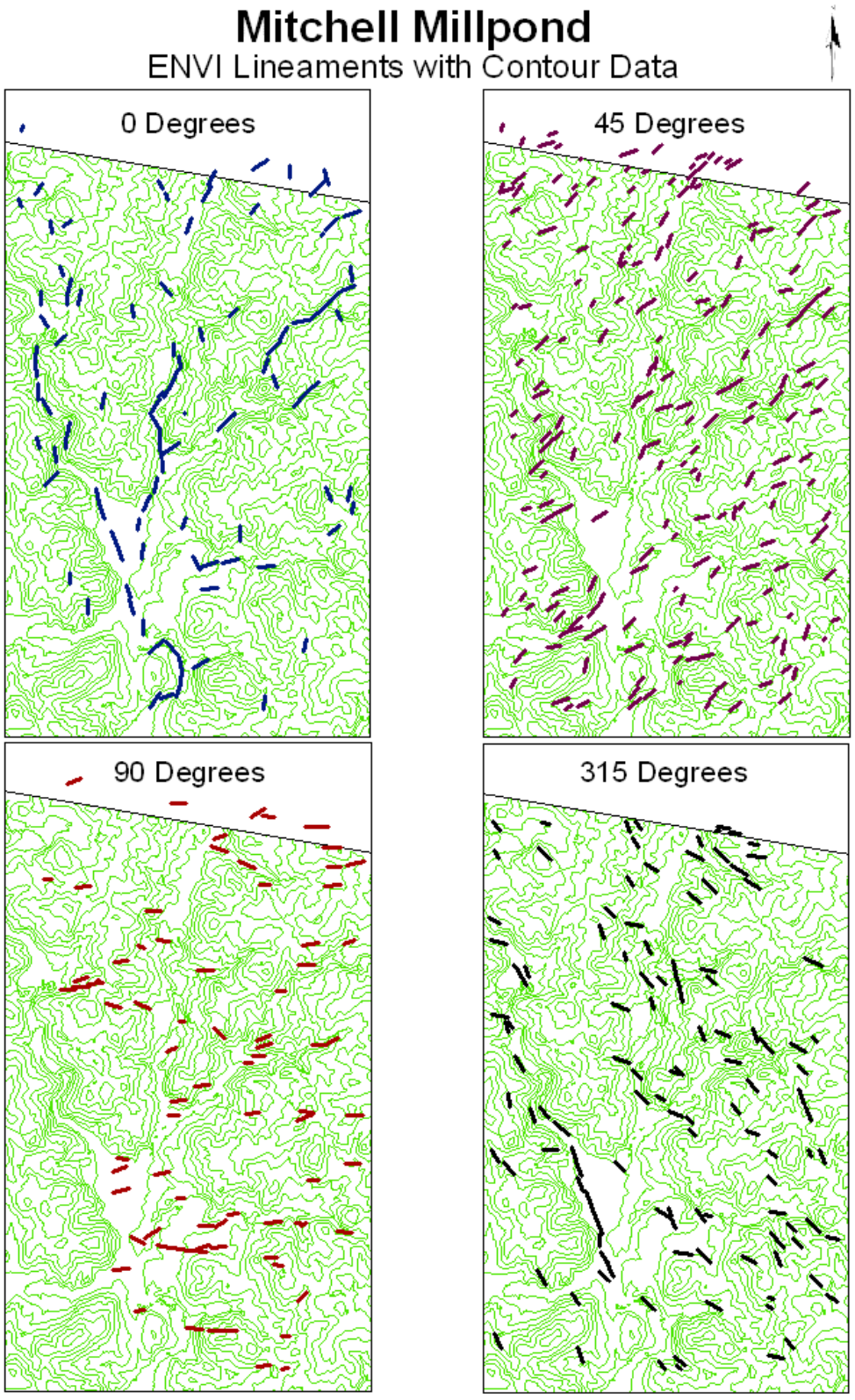

Figure 68. ENVI lineaments and 5 ft. topographic contours for the Mitchell Millpond and Pulleytown Rd. study area.

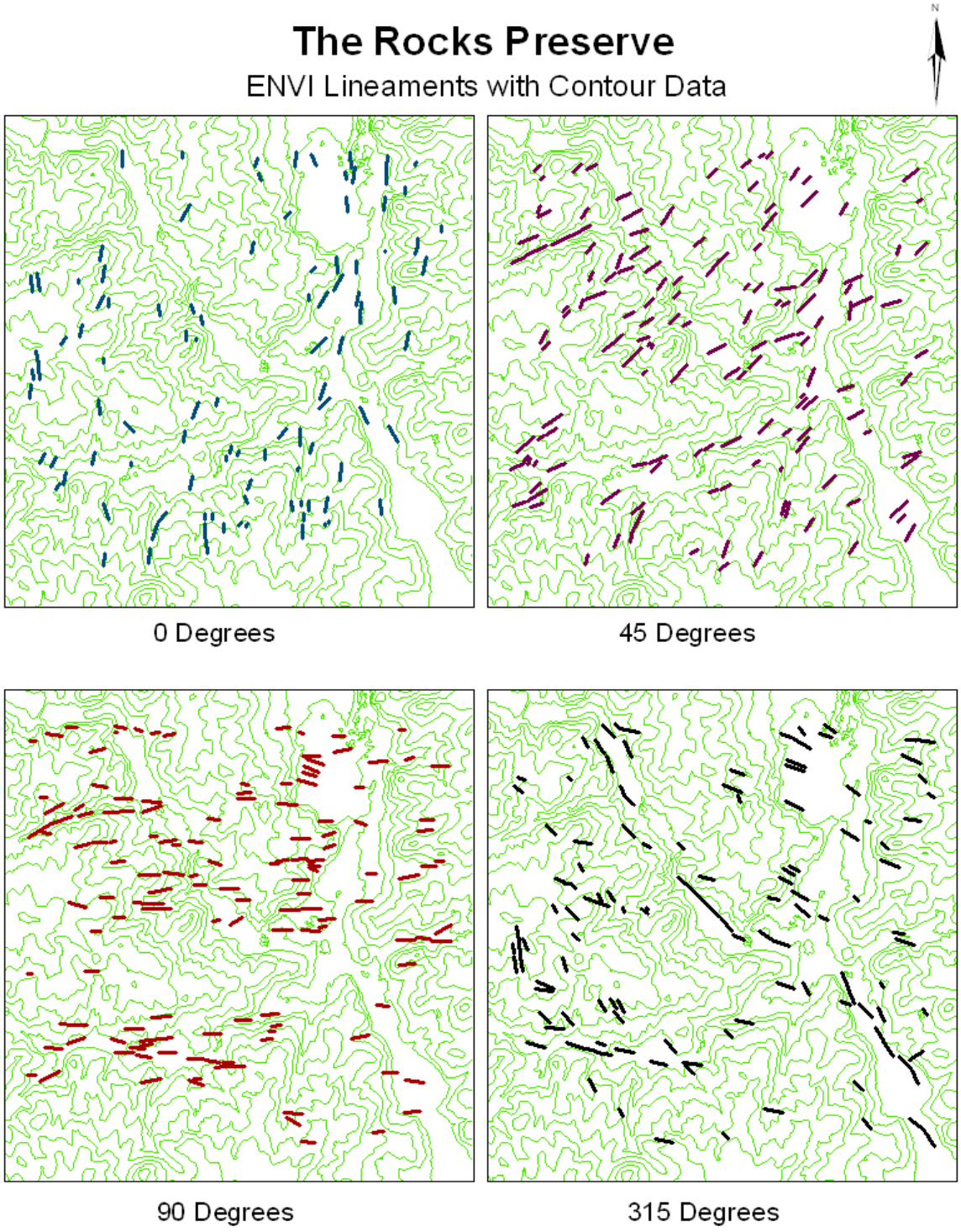

Figure 69. ENVI lineaments and 5 ft. topographic contours for the Rocks Preserve study area.

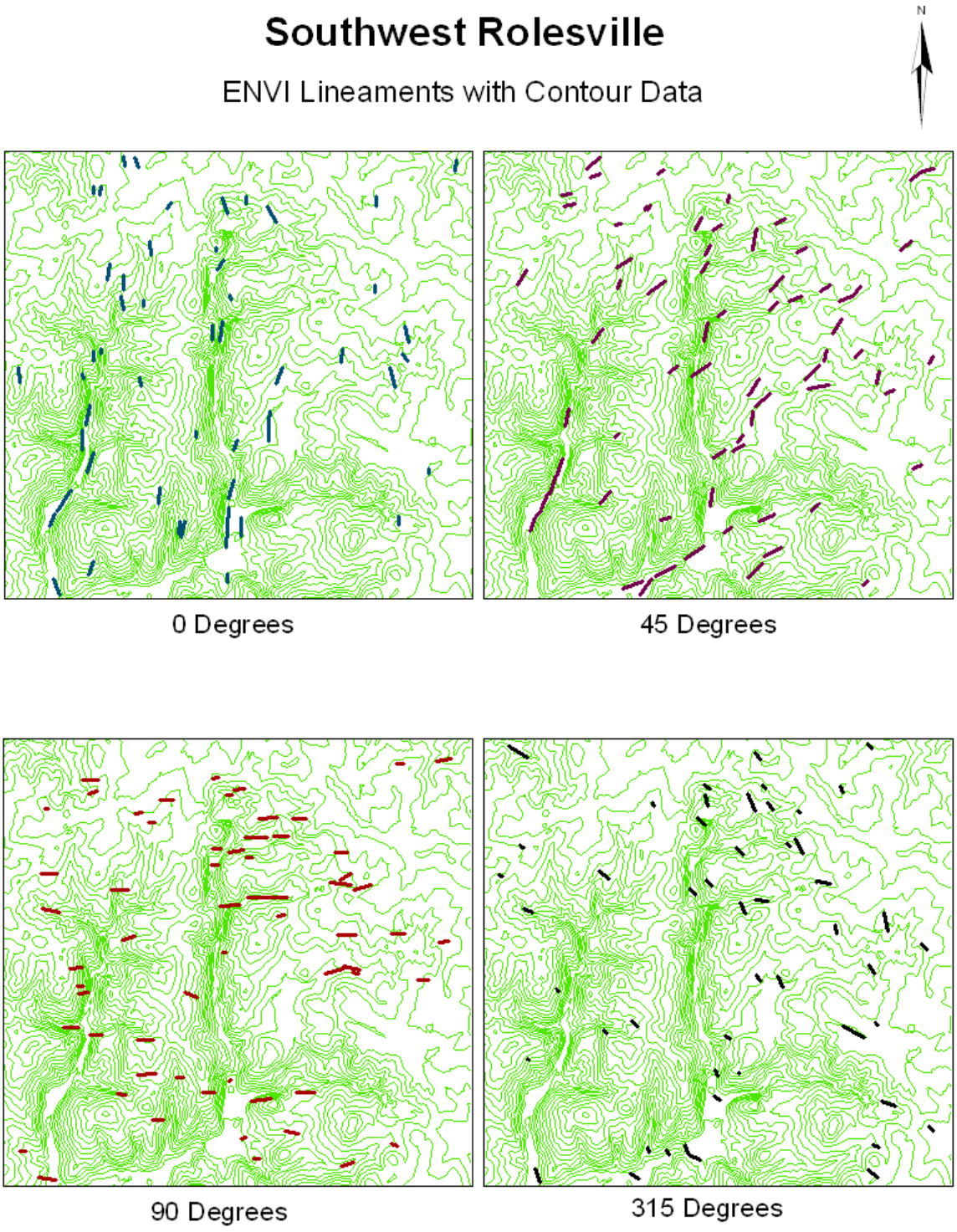

Figure 70. ENVI lineaments and 5 ft. topographic contours for the Southwest Rolesville study area.

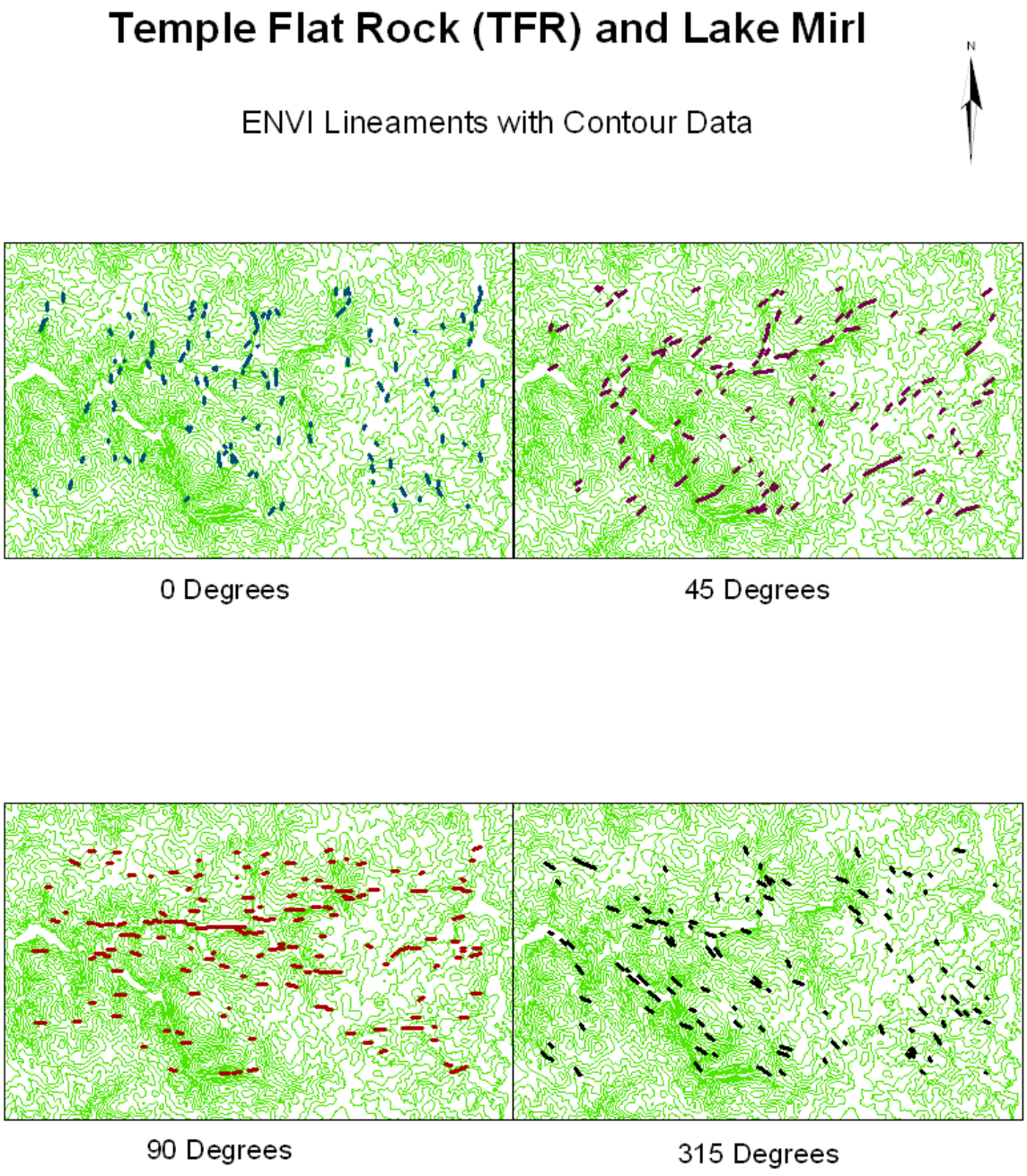

Figure 71. ENVI lineaments and 5 ft. topographic contours for the Temple Flat Rock and Lake Mirl study areas.

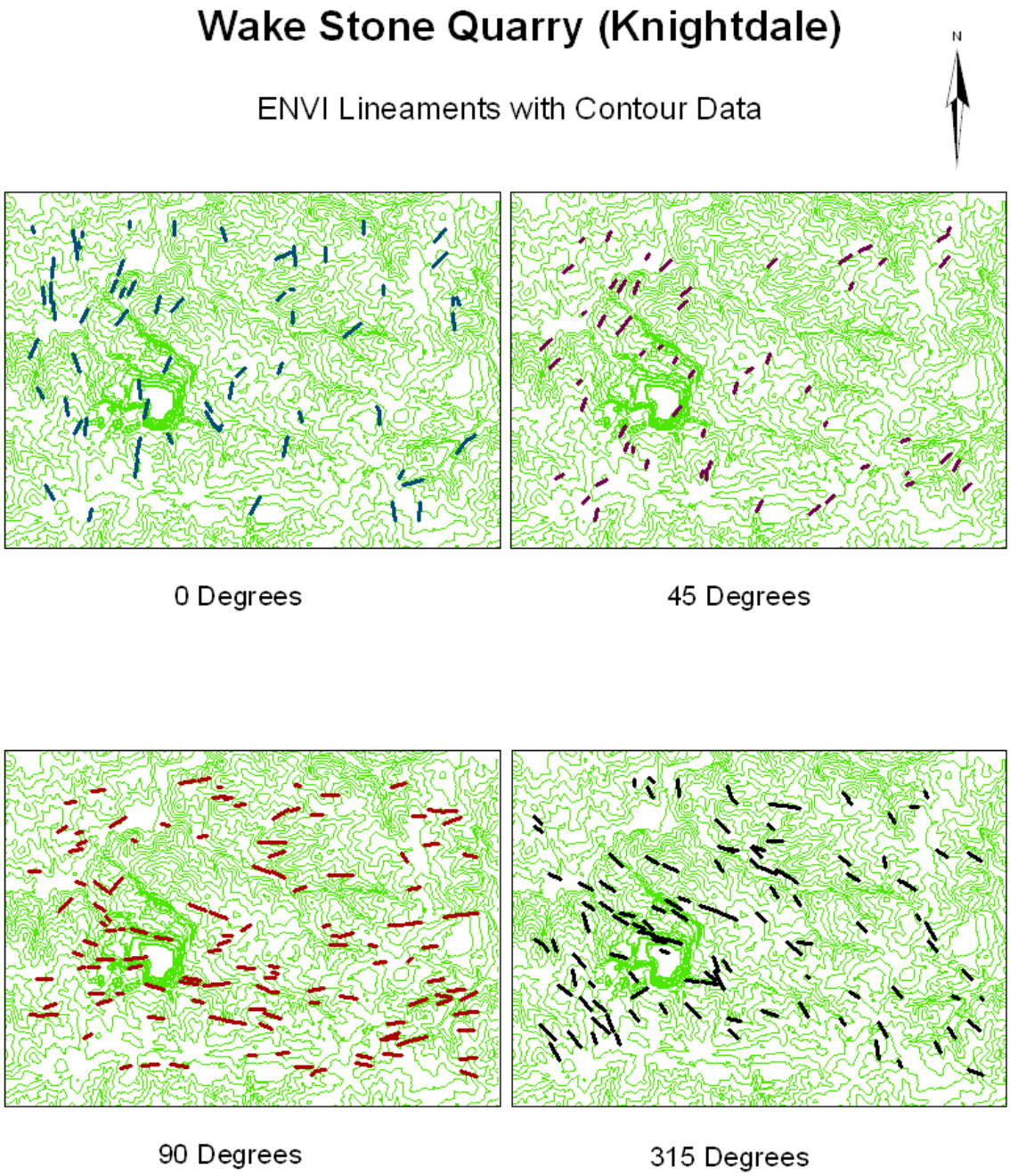

Figure 72. ENVI lineaments and 5 ft. topographic contours for the Wake Stone Quarry (Knightdale) study area.

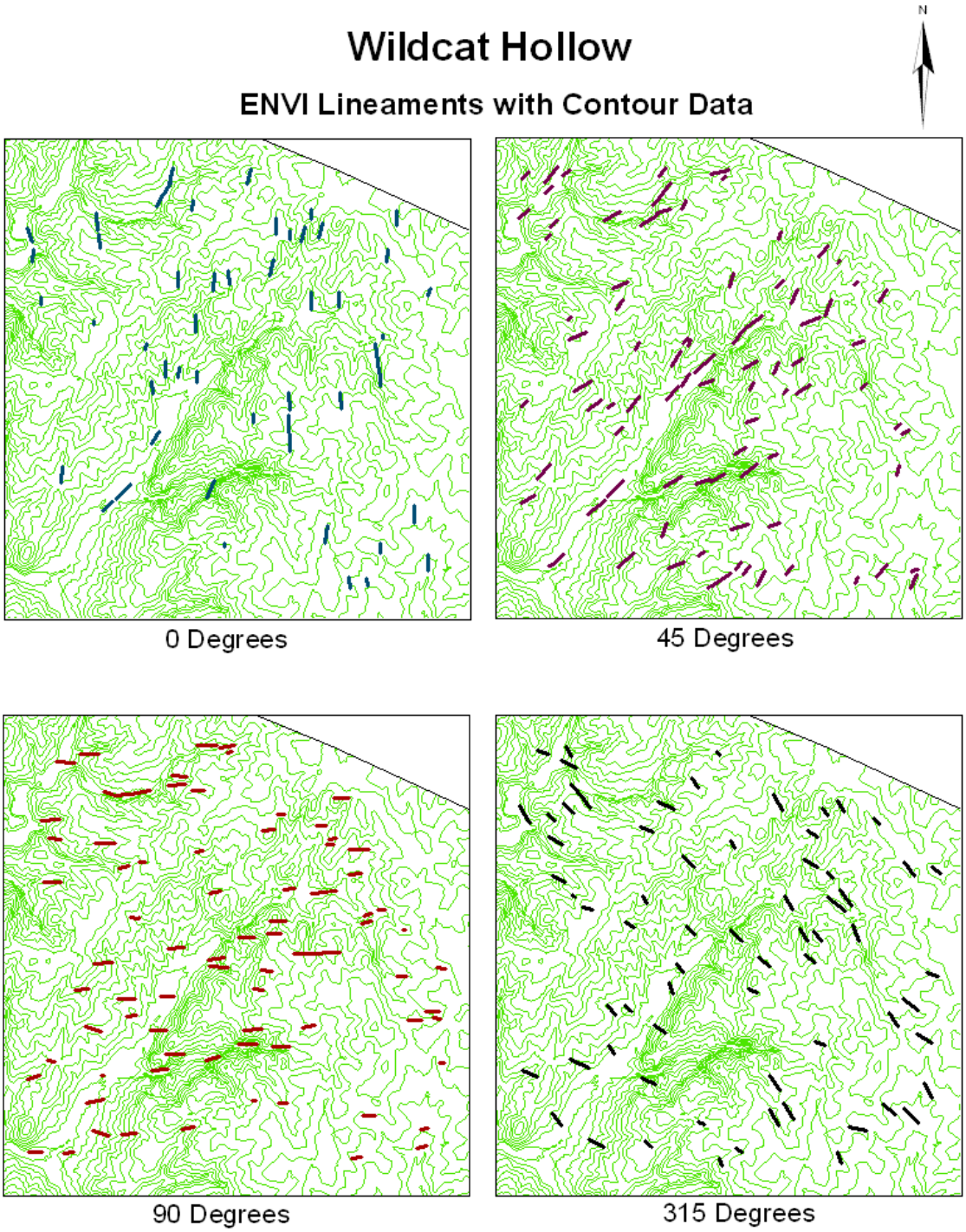

Figure 73. ENVI lineaments and 5 ft. topographic contours for the Mitchell Millpond and Pulleytown Rd. study area.