GIS AS AN IMPORTANT AID TO VISUALIZING AND MAPPING GEOLOGY AND ROCK PROPERTIES IN REGIONS OF SUBTLE TOPOGRAPHY: AN EXAMPLE FROM NORTH-CENTRAL OKLAHOMA

By

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CHAPTER 1

Introduction

Regional variation of earth surface topography can be attributed to a number of phenomena. Climatic factors such as annual rainfall, temperature, temperature fluctuations, and wind; the history of the region and the events that occurred such as flooding, glaciations, earthquakes, uplift or subsidence, and volcanic activity; and other surface shaping events such as erosion, sedimentation, vegetation, and more recently, humans, have worked for centuries to millions of years to give rise to the current topography that we now see.

Changes in landscapes are a natural process in the geomorphic evolution of any area. Human activity, however, has had and will continue to have serious and far-reaching impacts when it comes to change. Issues such as global warming, desertification, habitat destruction, and erosion have the potential to drastically change the living conditions to which we have become accustomed.

Fundamental earth surface information is needed to fully understand the potential consequences of our current trajectory. If global temperature is increasing, possibly resulting in increased instances of drought and loss of vegetation, it would be of great benefit to understand how different areas respond to rapidly changing erosional conditions.

Once the landcover is removed or dramatically altered, how will the underlying abiotic environment respond? By better documenting mechanisms that give form to our planet, including the manner in which the geological formations respond to those mechanisms, we better equip ourselves for making the most appropriate decisions and strengthen our ability to plan for the future.

As mentioned above, many factors work in unison to give shape to the surface of the earth. However, within small geographic areas, many important factors are relatively constant and exert an equal influence on all surface rock formations (such as the influence of climate). Consequently, only factors that differ significantly over short spatial distances need to be considered when attempting to document controls on the formation of erosional topography. For example, various sedimentary rock units (formations or lithofacies) juxtaposed by time may erode quite differently based on differences in lithologies, paleodepositional environments, and/or differences in the pressures and temperatures (diagenetic history) to which the units were subjected during burial.

Statement of Problem and Hypothesis

Within regions of low relief, systematic topographic change can be subtle and difficult to detect with traditional topographic tools. Topographic variations can also be difficult to quantify in these areas. In order to recognize and quantify subtle topographic change and variation, tools must be available that are accurate, reliable, economically feasible, and flexible in their capabilities. Geographic information systems (GIS), a digital elevation model (DEM), and digital and paper surface geology maps of a study area in north-central Oklahoma have been used in the present study to quantify topography. GIS contains both the visual and analytical tools that are necessary to make topographic observations and to quantify those observations on a regional scale. I propose that the combination of GIS, DEMs, and bedrock geology maps provide the tools necessary to efficiently quantify and evaluate the systematic differences in the topography of areas with subtle relief. I also hypothesize that topographic differences between geologic units in close spatial proximity to one another are due to variations in how different bedrock types respond to erosional forces.

Objectives

The objectives of this study are three fold: 1) to create maps of the north-central Oklahoma study area using GIS, DEMs, and bedrock geology maps in order to identify and quantify subtle and systematic changes in the topography, 2) determine the regional geologic controls on subtle differences in surface topography, and 3) and assess the feasibility and practicality of using GIS in such studies.

The Importance of GIS to the Study

GIS is critical to the current study for a number of reasons. First, in order to understand topography, properties of geologic formations must be analyzed over large geographic areas. In areas of low relief with subtle topographic differences within and between rock units, detection of differential patterns of erosion requires large sample sizes. GIS can accommodate these large data sets. Secondly, erosion, desertification, and other types of environmental change are large regional problems. In order to detect, visualize, and study these events, you must have a means of generating maps capable of showing the complete spatial extent of a study area and processing the large data sets necessary for the creation of such maps. Third, GIS contains many of the analytical tools that are needed to quantify much of the observed properties from regional studies and the means to manipulate maps in order to maximize the amount of information that can be visually extracted. Finally, GIS is a highly used, tested, and accepted method of studying regional scale environmental phenomena in the scientific community.

Study Area and Geologic Background

The area under investigation consists of a rectangular region of north-central Oklahoma (Fig. 1). The northern boundary coincides with the Kansas border with geographic coordinates of 37° 00" 00', the western edge at 98° 12" 45', the eastern edge at 96" 00' 00, and the southern boundary at 35" 25' 00.

The bedrock in the study area contains Permian and Pennsylvanian aged sedimentary rocks and Quaternary alluvium and terraces. The Pennsylvanian Period occurred about 286-325 mya. During this time, much of the world's coal was deposited. It was also during the Pennsylvanian Period that the Appalachians of North America began to rise as well as the ancestral Rockies. During the late Cretaceous and early Tertiary, further uplift of the Rockies resulted in the development of the regional elevation difference we see in Oklahoma today (elevation decreases as you travel east). Interestingly though, the dip of the bedrock in the study area is to the west.

The Permian Period followed the Pennsylvanian Period and occurred approximately from 245-286 mya. The end of the Permian also marked the end of the Paleozoic Era with a mysterious massive extinction of up to 90-99% of the earth's life forms. The Permian Period was also the time of the supercontinent Pangea when a warm, shallow sea covered much of western Oklahoma. The Permian rocks evaluated in this

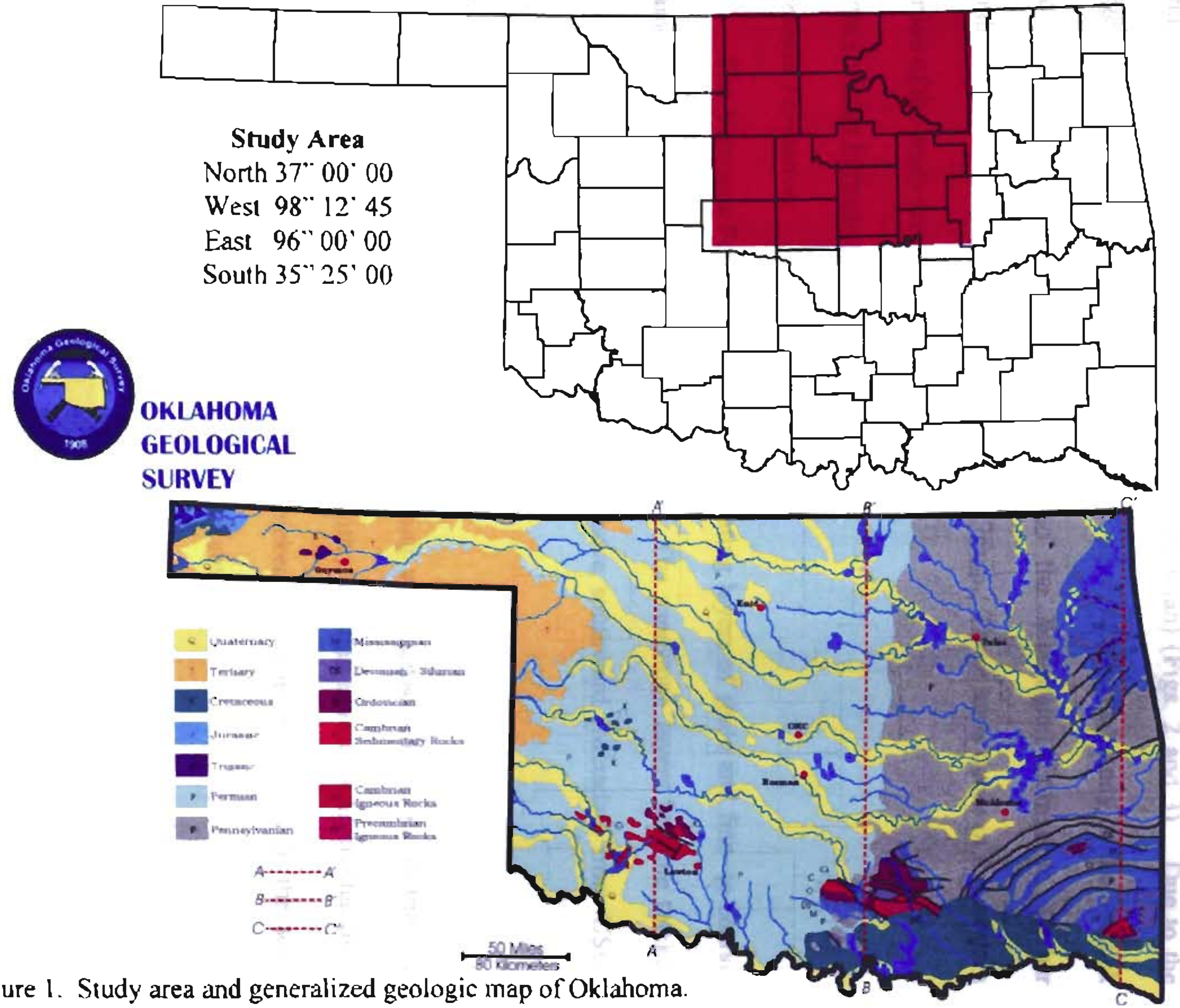


Figure 1. Study area and generalized geologic map of Oklahoma.

study are dominantly continental deposits with some evidence of marginal marine influence. The Pennsylvanian and Permian aged units within the study area consist of portions of the Vanoss, Ada, and Vamoosa Formations (Pennsylvanian), the Chase, Council Grove, and Admire Groups, Wellington Formation, Garber Sandstone, Hennessey Shale, and the White Horse Group (Permian) (Figs. 2 and 3). Due to the large spatial extent of the study area and time constraints, detailed study of the bedrock and topographic properties were restricted to the Wellington Formation, Garber Sandstone, Hennessey Shale, and White Horse Group. These units occur in the western portion of the study area.

Pennsylvanian Formations

Vamoosa Formation:

The Vamoosa Formation contains alternating layers of shale and fine- to coarse-grained sandstone, with some thin limestones. The sandstone layers become thicker, coarser grained, and more numerous as you move southward (Metadata from USGS Digital Surface Geology Maps).

Ada Formation:

The next formation encountered traveling west across Oklahoma is the Ada Formation which is mainly composed of shale with many thin limestone layers that pinch out southward. Fine-grained sandstones are thicker and more numerous in the south (Metadata from USGS Digital Surface Geology Maps).

Erathem	System	Unit		
Cenozoic	Quaternary	Alluvium		
		Terrace Deposits		
Paleozoic	Permian	Whitehorse Gp		Guadalupian Stage
		El Reno Gp	270 Ma	
		Hennessey Shale		Leonardian Stage
		Garber Sandstone		
		Wellington Fm		
			275 Ma	
		Chase Gp		
		Council Grove Gp		Wolfcampian Stage
		Admire Gp		
			290 Ma	
	Pennsylvanian	Vanoss / Ada Fms		Virgillian Stage

Pennsylvanian

Figure 2. Stratigraphy of the study area in north-central Oklahoma.

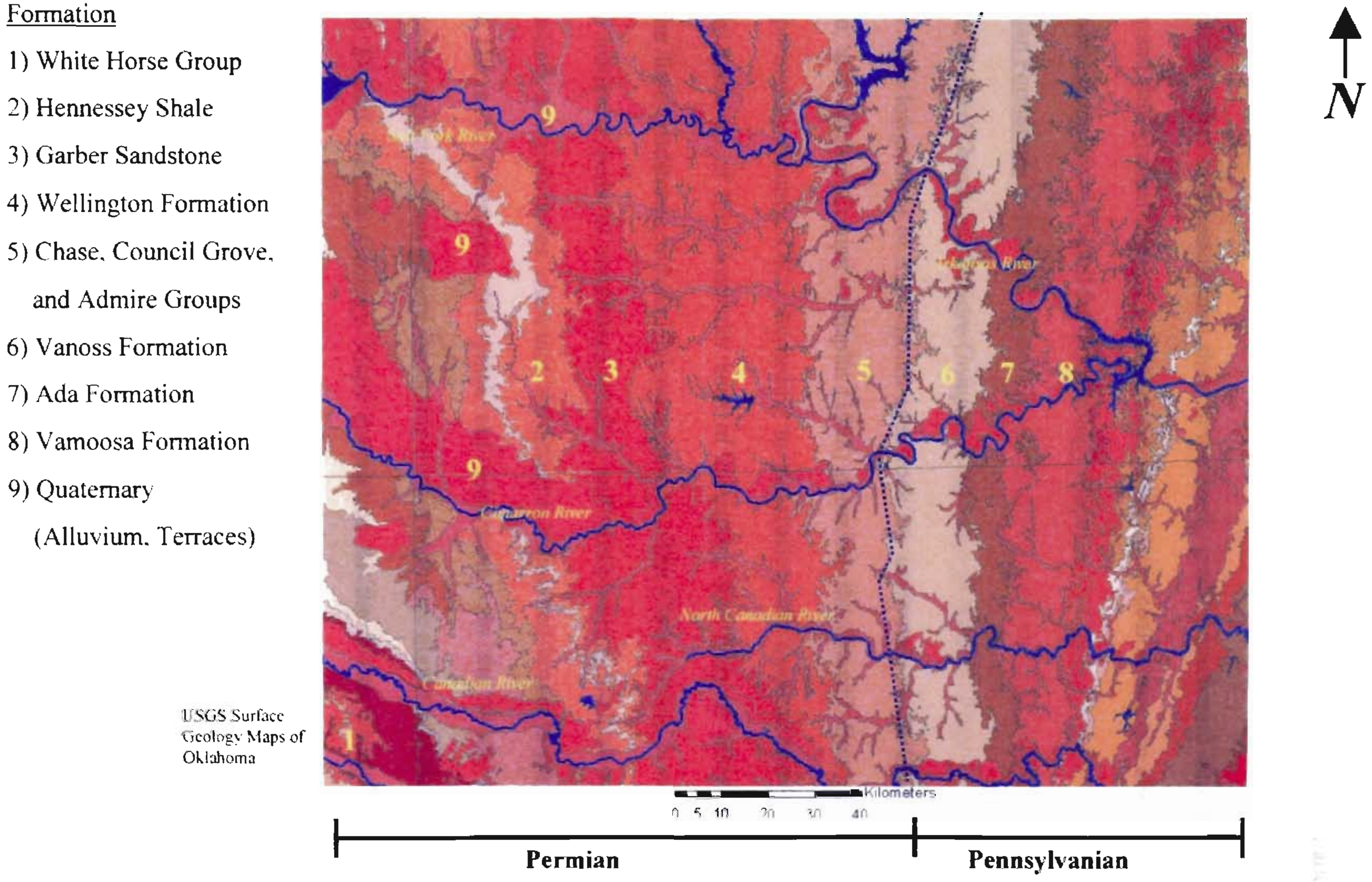


Figure 3. Geologic map of study area in north-central Oklahoma.

Vanoss Formation:

The Vanoss Formation is the last of the Pennsylvanian aged Formations encountered as one travels west across the state. The Vanoss Formation consists of alternating layers of limestone and shale to the north, grading southward into limestone, shale, and fine-grained feldspathic sandstone. Some local coal seams can also be found (Metadata from USGS Digital Surface Geology Maps).

Permian Formations

Chase, Council Grove, and Admire Groups:

The lower units of the Permian aged rock are composed of the Chase, Council Grove, and Admire Groups. Chaplin (1988) describes the Council Grove and Chase Groups in Kay County, OK. According to his studies, the Council Grove Group is mostly made up of thin, lenticular beds of sandstone, thin beds of shale, and algal, nodular lime mudstones and skeletal wackestones. The Chase Group is composed of thick, lenticular beds of sandstones, shales, and chert-bearing skeletal wackestones, packstones, and grainstones. As a unit, the Group is mainly red-brown to gray shale with many layers of limestones that pinch out southward. In the south, fine-grained feldspathic sandstones are present, becoming thicker and more numerous (Metadata from USGS Digital Surface Geology Maps description of the Oscar Formation [Oscar Formation is also called the Chase, Council Grove, and Admire Groups]).

Wellington Formation:

The Wellington Formation consists mostly of red-brown shale in the northern portion of the study area, grading into fine-grained sandstone and mudstone-clast conglomerate southward (Metadata from USGS Digital Surface Geology Maps).

Garber Sandstone:

This unit is also heavily stained with the reddish-brown mineral hematite and is made up of deltaic deposited lenticular beds of sandstone, siltstone, and shale, which can vary in thickness over very short distances. Mosier and Bullock (1988) describe the sandstones as fine to very fine grained and friable with a matrix primarily consisting of red mud. The Garber Formation has also been described as mostly orange-brown, fine- to medium-grained quartzose sandstone and conglomerate, interbedded with shales and mudstones in the southern portion of the study area (Metadata from USGS Digital Surface Geology Maps). As you go northward within the formations toward the Kansas border, you encounter different lithofacies where the sandstones interbedded with mudstone and shale grades into shales with the disappearance of sandstones.

Hennessey

The sedimentary material that gave rise to the Hennessey formation is believed to be deltaic in origin and was mostly derived from lands to the east. This occurred at a time of extended arid conditions and during the regression of the Permian Sea (Gould, 1911). It is largely composed of massive reddish-brown mudstone with lesser amounts of orange-brown to greenish gray siltstone and reddish-brown and fine-grained sandstone (Breit et al, 1990) The shales of the Hennessey are often more "blocky" than most Permian shales and have a conchoidal fracture (Aurin et al, 1926). Layers or small circular spots of whitish/green shale produced from the chemical reduction of hematite can also be found within the shale beds.

Quaternary Deposits

Terraces

The terraces are relics of older stream systems that dissected the underlying alluvium and bedrock. The terraces contain gravel, sand, silt, and clay.

Alluvium

The recent alluvium of the study area is composed of gravel, sands, silts, and clays. These sediments were deposited by fluvial systems, some of which were glacially fed to the west in the Rocky Mountains. Some of the deposits are wind blown loess due to the southerly prevailing winds.

CHAPTER 2

Literature Review

GIS can be described as a combination of hardware (monitor, mouse, CPU), software (tools), people, and data that can be used for the analysis, integration, and visualization of spatial data. It is much more than map making. The digital form of the data allows greater integration of various data types (land-use, land-cover, climatic, demographic, etc) and ease of handling large data sets. With the advent of the internet, retrieving and sharing data has become increasingly easy to do.

The use of GIS has exploded in the past decade. The software is becoming more affordable, user friendly, and increasingly familiar to its potential users. The different applications are limited only by the constraints of available resources (data, money, expertise, computing systems) and ones' imagination.

Digital elevation models (DEM's) are one of the most commonly used types of digital data in GIS. It is a two-dimensional raster representation of the topography of an area consisting of consistently spaced points (resolution, in meters) for which the x, y (geographic coordinates), and z (elevation) values are known and referenced to a datum. DEM's can be made using several methods and data sources. The sources for the creation of DEM's include topographic maps, aerial photographs, satellite imagery, and other (smaller resolution) DEM's. DEM accuracy depends on the quality and resolution of the source, horizontal spacing of the elevation matrix, collection and processing procedures, and digitizing systems (USGS, http://edcwww.cr.usgs.gov/glis/hyper/guide/usgs_dem).

GIS and the variety of potential digital data sets (such as geologic maps, land use/land cover, climatic data, demographics, highways, water bodies, etc.) have been put to numerous uses. The following are but a few of the many examples of GIS uses. Applications such as hydrologic modeling (Yin and Wang, 1999; Hellweger and Maidment, 1999; Eash, 1994; Jensen, 1991), calculations of slope length (Hickey, 1994), revised universal soil loss equation (RUSLE) (Wang et. al, 2001), measurements of slope movements (Iwahashi et al, 2001), the creation of slope class maps (Hammer et. Al, 1995), DEM generation (Fried et. al, 2000), automated landform classification (Ventura and Irvin, 2000), and numerous others have become increasingly more common. Moore, Grayson, and Ladson (1991) give an excellent review on possible applications for DEM's in hydrology, geomorphology, and biology.

The effect of DEM accuracy has been a heavily researched area. Holmes et al. (2000) studied the effect of 30m USGS DEM's on terrain analysis over a 27 km^2 area. They found that although global (average) error may be small, local error values can be large and spatially correlated. However, they do conclude that the USGS DEM is typically quite accurate. In another study, Kenward et al. (2000) examined the effect of vertical accuracy in a USGS 30m DEM on hydrologic predictions. They found that inaccuracies impact delineation of drainage network, elevation, slope, and contributing area. It must be remembered, however, that a DEM is a simplified model of the topography of a given area. Because of this, complete accuracy is not possible. USGS DEM's are heavily used in research and represent one of the best products reasonably available.

Spatial resolution is also an important factor for determining the accuracy of measurements derived from DEM's. Yin and Wang (1999) examined the effects of substituting USGS 1:24,000 (30m) DEM for a 1:250,000 DEM when estimating common drainage basin parameters. They found that although the courser resolution 1:250,000 DEM can provide accurate estimates for elevation-based and stream-length based basin parameters, it was not reliable for slope-based parameters relative to the finer resolution 1:24,000 DEM. In another study, Moglen and Hartman (2001) looked at various DEM resolutions and their impact on hydrologic modeling parameters. They found that relative error was a function of resolution, the parameter being measured, the presence of any bias, and the sample value of the parameter itself. They concluded that relative error increased with lower resolution DEM's. Thompson et al. looked at both horizontal resolution and vertical precision impacts on terrain attributes and soil-landscape models. They found that some landscape features were less discernable on the lower resolution DEM and tended to smooth out the topography in low relief areas. The lower resolution DEM also produced lower slope gradients on steeper slopes and steeper slope gradients on flatter slopes.

The use of GIS in geology has also been an area of fast growth. Cocker (1999) of the Georgia Geologic Survey used GIS and geochemical data of stream sediments and water to determine that bedrock geology and mineralization are the most important variables that influence the stream sediments and water geochemistry. GIS has also been used in geoenvironmental studies pertaining to cross-border areas (Satkunas and Graniczny, 1997) as well as in conjunction with airborne gamma ray spectrometer data for geological mapping and mineral exploration (Graham and Bonham-Carter, 1993).

GIS in land-use planning is also an area with many potential applications. Dai et al. (2001) used GIS to evaluate a geoenvironmental approach to land-use planning in Northwest China and GIS was also used for territorial planning with lands shared between Poland and Lithuania (Satkunas and Graniczny, 1997). Finnish and Norwegian scientists (Neeb, 1996) showed how geological data and GIS could be used in various ways in urban planning, providing an overview of the natural resources of a municipality, and in detecting land-use change (when combined with data from the local planning office). In Vicosa, Brazil, geological data was used with GIS in order to determine geological urban risks that could be used in urban planning

One of the most powerful features of GIS is its ability to integrate and analyze large data sets of various types (Walker et al.1996). Dale et al. (1998) demonstrate a means of assessing land-use impacts on natural resources on the Oak Ridge Reservation in East Tennessee. They applied the technique to identify potential limestone barrens habitat by overlaying digital maps of soils, geology, slope, and land-use/land-cover. Thomas et al. (1999) used GIS to study the relationship between streamwater pH and alkalinity at base flow with geology, soils and relief.

In closely related study, Swiss scientists used 250m DEM's to study the relief in the Swiss Alps and its relationship to lithology and structure. By conducting a numerical analysis of the large-scale geomorphological characteristics and comparing this with an erodibility map, they determined that there is an "intimate relationship between mountain-scale erodibility and topography" (Kuhni and Pfiffner, 2001). This study is significant in that the hypothesis of their study closely mirrors the intent of the present north-central Oklahoma study. However, their work focused on an area with extremely high relief, whereas in the current study I am attempting to quantify subtle topography.

CHAPTER 3

Methodology and Procedures

Surface geology maps were downloaded from the USGS Water Resources of Oklahoma web page (http://ok.water.usgs.gov/). These maps consist of the Enid quadrangle and portions of Oklahoma City, Woodward, and Clinton quadrangles. The maps show the major geologic formations in the study area at a scale of 1:250,000. The surface geology quadrangles were merged using ESRI® ArcMap™ GIS (Fig. 3 in Chapter 1).

In addition to the digital geology map, a paper map of the state published in 1954 was acquired from the Oklahoma Geological Survey with a scale of 1:500,000. This map also shows the major geologic formations within the state.

A 30m DEM was acquired through the USGS National Elevation Dataset (NED) (Fig. 4). The NED was assembled by the USGS in order to provide seamless a DEM for the conterminous United States, Hawaii, and Puerto Rico at a resolution of 30m. The DEM has a consistent datum, elevation unit, and projection. Edge matching, filling slivers of missing data, and other corrections to minimize artifacts were performed (USGS NED Homepage; http://edcnts12.cr.usgs.gov/ned/default.asp). The vertical accuracy of the DEM will depend upon the source DEM's used to construct the final DEM. However, this should be in the range of +/- 7 to 15m (Personal Communication with USGS).

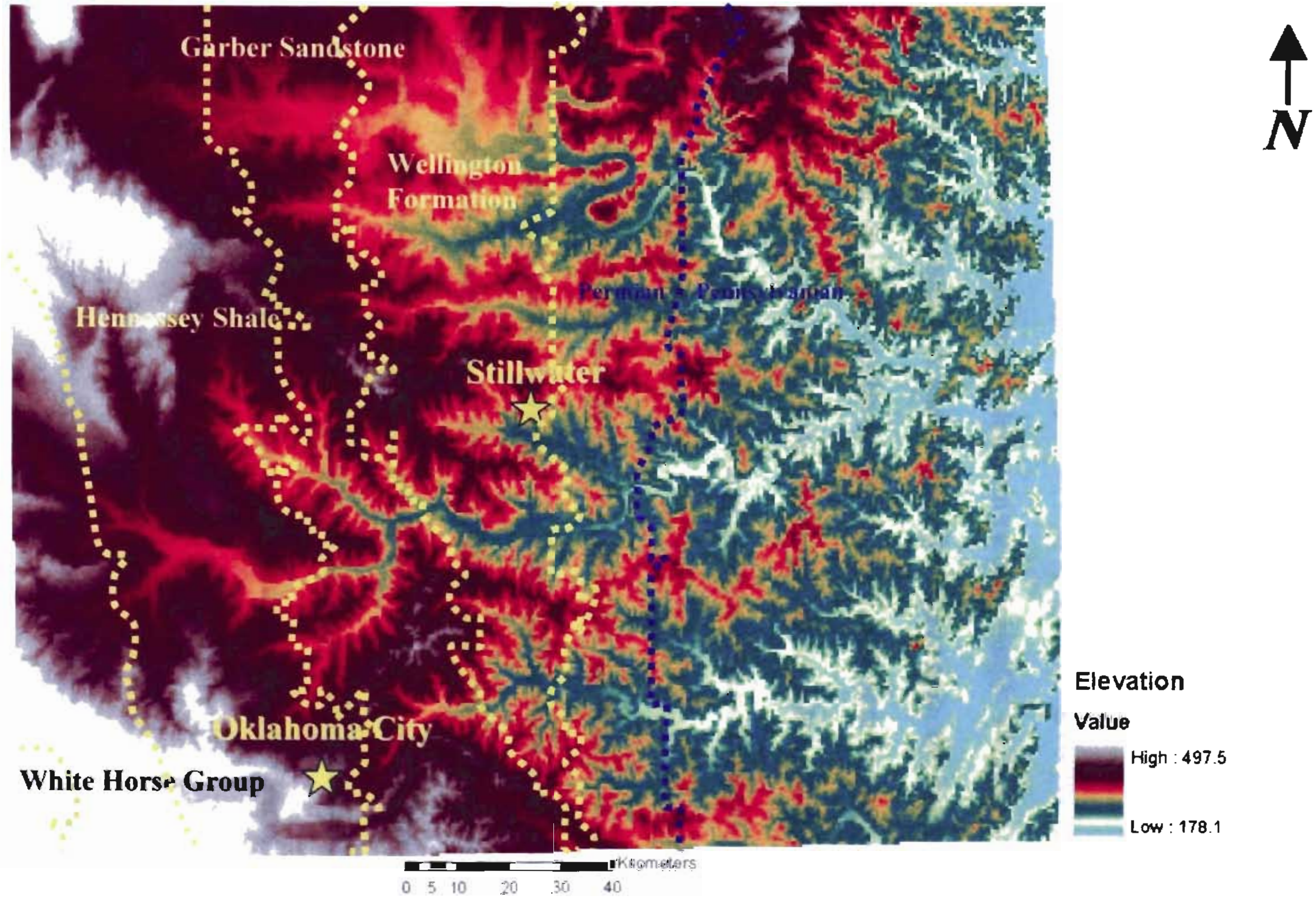


Figure 4. DEM of study area (elevation in meters).

Creation of Slope, Relief, and Hillshade Maps

Slope Map

Using ESRI® ArcMap™ GIS and the Spatial Analyst™ extension, a raster based slope map was created using the DEM of the study area (See Flowchart in Appendix). A slope map reflects the surface topography of an area by classifying slopes based on their angles (which are mapped as different colors using a color ramp). Therefore, as the slope angle changes from one location to another (at 30m increments, the resolution of the DEM), the change in slope angle can be recognized by a difference in the pixel color on the map. If the locations have similar slope angles, the colors will be different tones of the same color (or the same color if the slope angles fall into the same class). Similarities in color reflect similarities in slope.

Spatial Analyst™ creates a slope map by using an input map, in this case the USGS NED 30m DEM, and taking the value of a pixel and the values of the immediately surrounding pixels, and inserting them into an algorithm to calculate the slope angle (from the horizontal) for the corresponding pixel of the output map. The number of pixels and the resolution of the new raster based slope map is the same as the original input map (i.e. 30m DEM). With this approach, slope values are a function of *local* relief and independent of *regional* changes in elevation.

Relief Map

The next task was to construct a relief map of the study area. This was accomplished in Spatial Analyst™ by using a user-defined 3x3 pixel window and the 30m DEM. Using an algorithm, a value is calculated for the center pixel (kernel) of a 3x3 window based on its' elevation and the surrounding pixels in the window elevations.

The value for the center pixel is then used to construct an output map as done with the slope map. This map was created in order to visualize the relief aspect of topography. Relief is a function of *local* geologic characteristics and is independent of ***regional*** elevation differences.

Hillshade Map

In addition to the slope and relief map, Spatial Analyst™ used the 30m DEM to create a hillshade map of the study area. The hillshade map shows the hypothetical illumination of the study area. Spatial Analyst™ enables the user to set the angle and direction (i.e. north, east, south, west or anywhere in between) of illumination in order to bring out the fabric of the landscape. The hillshade map can greatly aid in visualization of the study area by providing a sense of how the terrain would look in 3-D.

The DEM, slope, relief, hillshade, and surface geology maps were overlain in ArcMap®. County boundaries, towns, and roads were added when needed to assist in locating areas of interests (Spatial and Environmental Information Clearinghouse, Digital Atlas of Oklahoma, http://www.ocgi.okstate.edu/indexold.html).

The composite map was visually inspected to identify occurrences of abrupt change in topography. These areas were first evaluated to test the hypothesis that variations in topography is strongly related to differences in how the bedrock responds to erosional forces. Upon completion of the visual analysis, several areas were selected for further field studies. The additional studies were designed to evaluate the geologic controls on the observed variations in topography.

GIS and SAS Analysis of the Slope and Relief Map

For this portion of the study, I extracted cell values from the portions of the slope and relief map's corresponding to areas under study. In order to accomplish this, polygons were created using the digital map of surface geology (so as to exclude Quaternary aged material) for examination of specific locations under investigation. The polygons were used to "clip" the slope and relief maps so I could examine the cell values (slope and relief) for the areas defined by the polygons. Clipping can be conceptualized as a cookie cutter that is cutting cookie dough. In this case, the polygons serve as the cookie cutter while the slope and relief map's are the cookie dough. This approach enabled me to look statistically at only the areas in which I was interested such as a specific bedrock type. This was done in ArcView GIS® (Fig. 5).

For the study area, polygons were drawn over the area of interest. This included separate portions of the White Horse Group, Hennessey Shale, Garber Sandstone, and Wellington Formation. Polygons were created for the Garber Sandstone and Wellington Formation in their entirety and the Garber Sandstone and Wellington Formation separated into northern and southern halves (divided at Perry, OK) in order to accommodate observed differences in the geology.

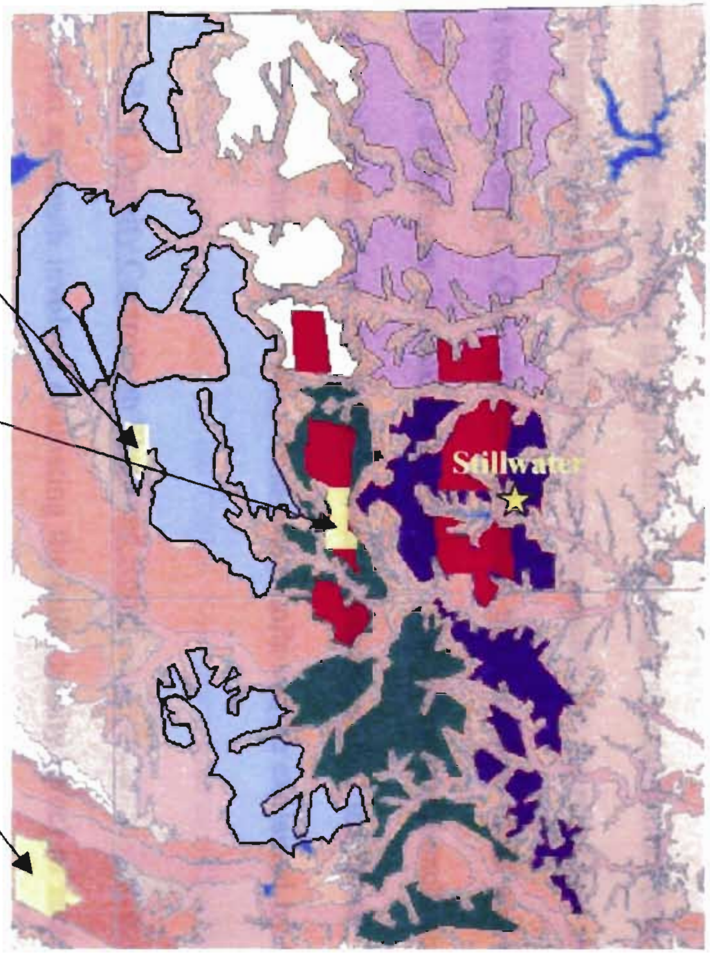
The cell values, once clipped, were extracted from the slope and relief maps (for the area defined by the polygons) and imported into Statistical Analysis System (SAS) software. This enabled me to perform univariate analysis by creating frequency histograms and examining the mean, median, mode, and range of the data. The bin-interval was carefully chosen in order to create a histogram that best represented the

Bulk Density Study Areas (Yellow)

Cedar Hills Sandstone
(Sample Site 2)

Garber Sandstone
(Sample Site 1)

White Horse Group
(Sample Site 3)



Wellington Formation and Garber Sandstone

Wellington Fm.
North (light purple)
South (purple)

Garber Sandstone
North (cream)
South (green)

Hennessey Shale (sky blue)

Transects for Sand bed Thickness Measurements (Red)

Wellington Formation
(Transect 2)

Garber Sandstone
(Transect 1)

Figure 5. Polygons used for clipping overlying geologic units of interest.

distribution of the cell values and to examine for subpopulations that may have been hidden in the data. In addition, the sample means were compared using a t-test to determine if the samples (cell values of slope and relief for the polygon defined area) were significantly different.

Field Work Designed to Test Controls on Slope Angle and Relief

Based on results obtained from the visual analysis of the slope and relief map, a series of field studies were designed to test our ideas on the controls of relief and slope in sand-prone units (See Flowchart in Appendix). Although several factors (e.g. land-use, climate, mineralology) are, to varying degrees, responsible for the relief and slope of an area, just two were tested. One approach addressed differences in relief and slope that may be due to differences in rock bulk density. The second approach was to test differences in relief and slope due to differences in sandstone bed thickness. I believe that most of the variation seen between sand-prone units can be explained by these two variables.

Approach 1: Bulk Density Controls on Slope and Relief

The first approach involved evaluating the bulk density (g/cc) of rock samples. This was done for units from geologically adjacent areas with differing topography, as identified on the slope and relief map, and within the same mapped geologic unit (Fig. 14 in Chapter 4). The idea behind this strategy was to use bulk density (grain volume + pore volume) as a surrogate measurement for the susceptibility of the sandstones to weathering. High bulk density sandstones have little pore space due to compaction and cementation of the sandstone. Low bulk density sandstones are more porous due to lack of cementation, therefore more susceptible to erosion. Areas composed of these low bulk density (more erodable) sandstones will be characterized by lower relief and slope relative to areas composed of higher bulk density (less erodable) sandstones.

Bulk Density Sample Area 1 is located in the western portion of Payne County and the eastern portion of Logan County, running in a north-south direction (Fig. 5). This sample area was selected based on the abrupt change in topography, as revealed on the slope map, and the agreement with existing geologic maps as being the approximate location of the Hennessey Shale and Garber Sandstone contact. The site is characterized as a relatively flat area, representing the Hennessey Shale, which rather abruptly transitions into an area to the east with a higher concentration of local relief change (and higher slope angles) in the Garber Sandstone (Fig. 14 in Chapter 4).

Numerous sandstone samples were collected in the area of the Garber Sandstone (Bulk Density Sample Site 1) adjacent to the location of change identified on the slope map. Care was taken to ensure these sandstones taken for analysis were representative of the variation found within this area of the Garber Sandstone (composition, grain size, bedding style). Samples were taken from outcrops located along various roads in the vicinity of Hwy. 51. Coordinates were recorded using a hand held global positioning system (GPS) receiver.

In Sample Site 1, no sandstones are found on Hennessey Shale side of the area of abrupt topographic change (identified on the slope map). Therefore, the Cedar Hills Sandstone member of the Hennessey Shale (Sample Site 2), located in Kingfisher and Garfield Counties between the towns of Hennessey and Enid, was surveyed for outcrops of sandstone with comparable composition, grain size, and bedding style to Garber Sandstone.

The White Horse, in the southwest corner of the study area in Canadian County between the North Canadian and Canadian River (Sample Site 3), was surveyed for sandstones samples (Fig. 16, Chapter 4). Samples were taken from roadside outcrops and the coordinates recorded via a hand held GPS receiver.

Once the sandstone samples from the sites were collected, their bulk density was determined. This was done by first determining the weight (grams) of an uncoated sandstone sample. Next, the sample was coated with paraffin and reweighed. Finally, the paraffin coated specimen was weighed in water. The values obtained from these measurements were then used to calculate the bulk density (bulk specific gravity) of the sandstone sample according to the following formula:

$$\text{Bulk Density} = A/D\text{-}E\ (D\text{-}A/F)$$

where:

A = mass of the dry specimen in air (g)

D = mass of the dry specimen plus paraffin coating in air (g)

E = mass of the dry specimen plus paraffin in water (g)

F = specific gravity of the paraffin (0.89)

Approach 2: Sand Bed Measurements for Comparison of Unit Thickness

In the second approach to understanding controls on topography, I tested the idea that the thickness of the sandstone units in the Garber Sandstone and Wellington

Formation are responsible for observed topographic differences in the area. As sand beds become exposed to the surface (or immediate subsurface), I believe they well erode at differing rates as a function of the sand bed thickness, with the thicker sand beds eroding more slowly than the thinner sand beds. I evaluated the role of sandstone thickness by completing two linear transects (one in the Garber and one in the Wellington). Both transects were oriented north-south and ran parallel to the strike. A Jacobs Staff was used to approximate the average thickness of the sandstone bodies at each outcrop. Every outcrop encountered was inspected and measurements made (if a reasonable amount of sand bed was exposed). In locations where more than one measurement was made, the thickness of the sandbeds was added together and the mean calculated. The locations of measurements were recorded using a hand-held GPS receiver.

The survey of the Garber Sandstone (Transect 1) began about 3 miles west of Crescent on Hwy. 74C in Logan County. The rural dirt road surveyed begins on approximately the same latitude as southern Payne County. The road was traveled northward through the Midway and Hayward area. The transect ends at a point just past Hwy 412 in Garfield County (Fig. 6).

In the Wellington Formation (transect 2), outcrops on Coyle and Hackleman Roads (west of Stillwater) were surveyed from the southern border of Payne County to the southern portion of Lake Carl Blackwell at Hwy. 51. The measurements continued at the intersection of Hwy. 51 and 86, west of Lake Carl Blackwell, and continued north until reaching the town of Perry, at which point Hwy. 77 was followed to the north. The road was surveyed for outcrops until just north of Hwy 412 in Noble County. From just north of Hwy. 412, another route was selected just east of Hwy. 77 on parallel rural section roads. The roads were traveled to the south until reaching the northern portion of Lake Carl Blackwell.

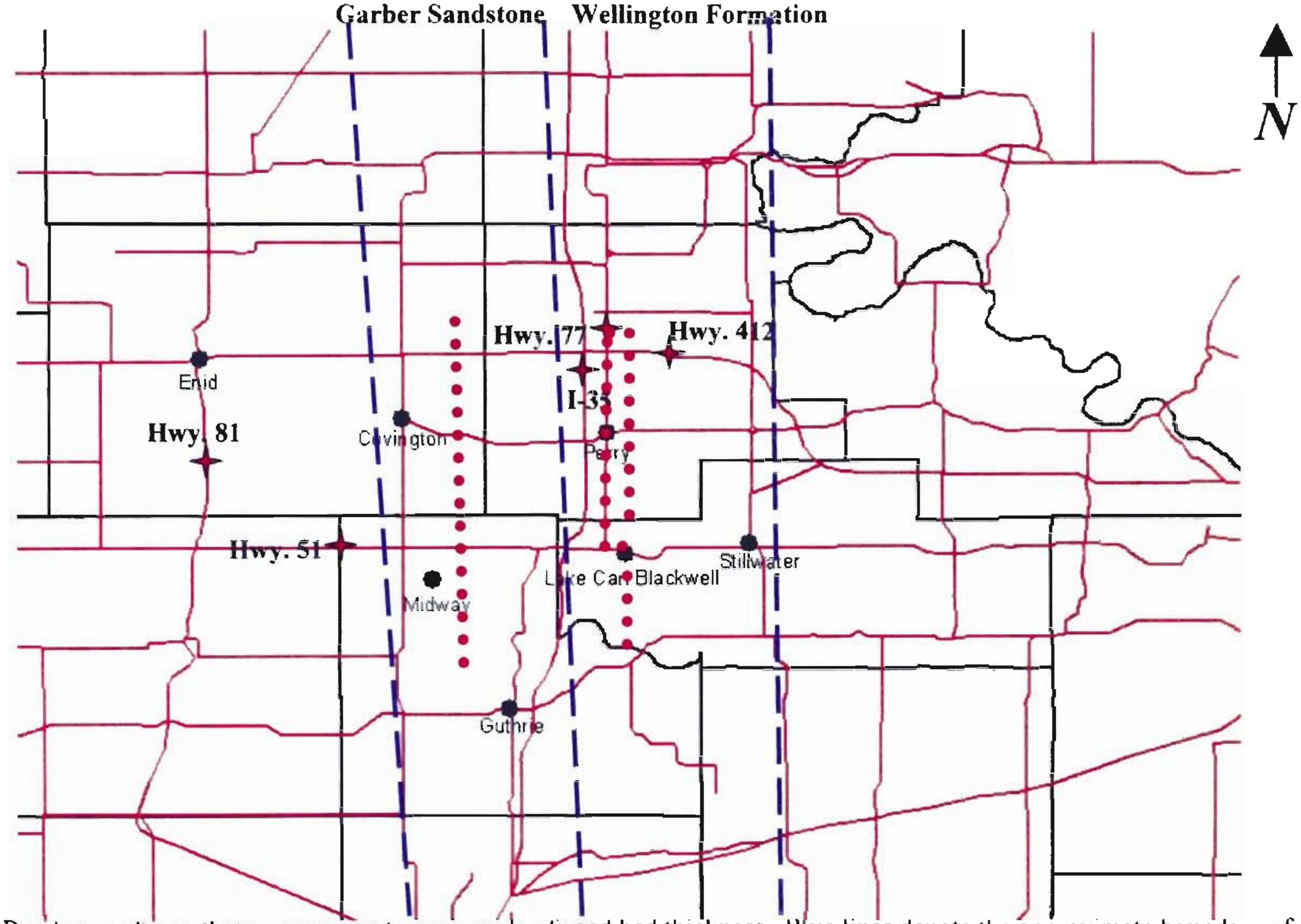


Figure 6. Road map of area that measurements were made of sand bed thickness. Blue lines denote the approximate boundary of the Garber Sandstone (Transect 1) and Wellington Formation (Transect 2). Red dotted lines show approximate path traveled.

CHAPTER 4

Results and Discussion

Recall, the objectives of this study are three fold: 1) to create maps of the north-central Oklahoma study area using GIS, DEMs, and bedrock geology maps in order to identify and quantify subtle and systematic changes in the topography, 2) determine the regional geologic controls on subtle differences in surface topography, and 3) assess the feasibility and practicality of using GIS in such studies.

Results of the Slope, Relief, and Hillshade Maps

The mapped region under study is characterized by low relief and slope. Topographic differences from one geologic unit to the next are very subtle or virtually non-existent. Classifying the slope and relief maps required a bit of trial and error. In order to recognize systematic changes in topography, slope angle and relief classes had to be designed to reflect the minor variations in terrain. I found that as I increased the number of classes, more and more detail could be seen (which also varied depending upon the choice of color ramp). It was therefore necessary to group the slope angles and relief into 22 classes. This decision was, however, somewhat subjective, but aided by my knowledge of the geology.

Because a goal of this work is to establish associations between geology and topography, I selected a class interval that maximized the contrast in slope between the visibly different geologic units. The ability to "tune" the slope and relief classes relative to the geology is a major strength of the GIS approach. The slope map indicates stark contrast between some of the different geological units, though these differences would probably not have been noticed in the field. The sharp contrast on the maps between units is therefore a result of the classification choice. Had I selected fewer classes, the contract between units would not have been recognized.

Slope Map

Recall that slopes are represented by pixels with a 30m resolution and are derived from the USGS NED 30m DEM. The summary statistics obtained from ArcMap® shows that slope angles for the entire study area vary between 0° and 36.8° and has a mean angle of 2.1°. The standard deviation is about 2.2° and the distribution is strongly positively skewed. The 22 class intervals (0.25°) are kept equal at the lower slope values (0-4°) due their high occurrence (large number of observations). However, class or bin intervals are larger with increased slope angle due to the low frequency of occurrence of high slope angles. There are a total of 38.8 million (3.88×10^7) observations of slope angles (Figs. 7, 8, and 9).

Relief Map

Relief provides another means of visualizing and quantifying the topographic differences between areas under study. The differences in relief between areas of differing topography strongly agree with what is seen in the slope map and as would be expected, both maps appear quite similar. The maps were created using the same 30m DEM.

The relief map of the entire study area has a mean relief of 3.1m, a range of 0 to 59.9m, and a standard deviation of 2.9m. As with the slope map, the frequency histogram is positively skewed. I again used small class or bin intervals for the lower relief values (large number of observations) and larger class intervals for the tail of the

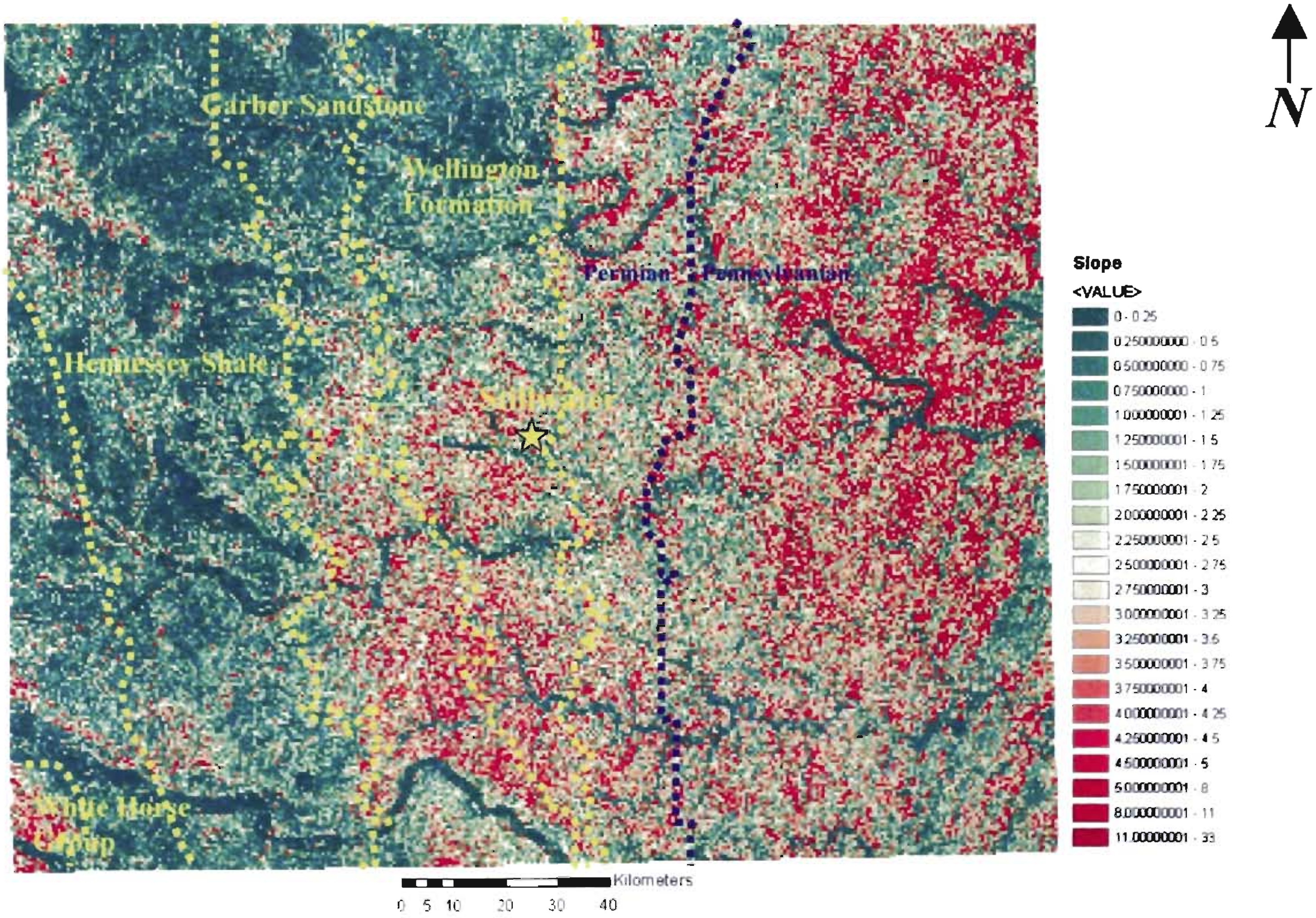


Figure 7. Slope map of the study area (slope in degrees).

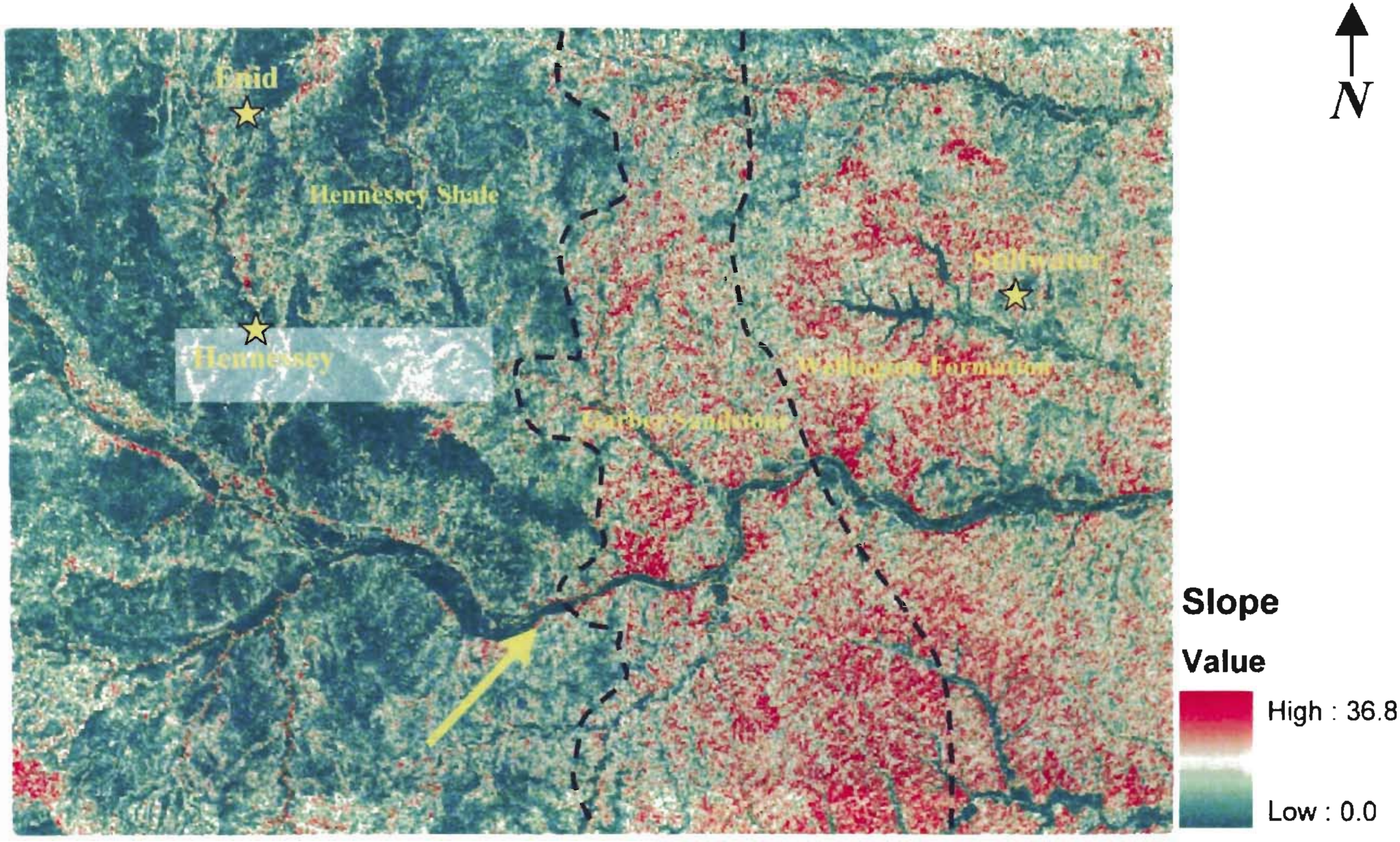


Figure 8. Slope map (in degrees) location where the Hennessey Shale borders the Garber Sandstone. Notice how the Cimarron River's flood plain "pinches" (arrow) in as it passes into the Garber Formation from the Hennessey. This is due to the river encountering the more erosion resistant sandstones of the Garber.

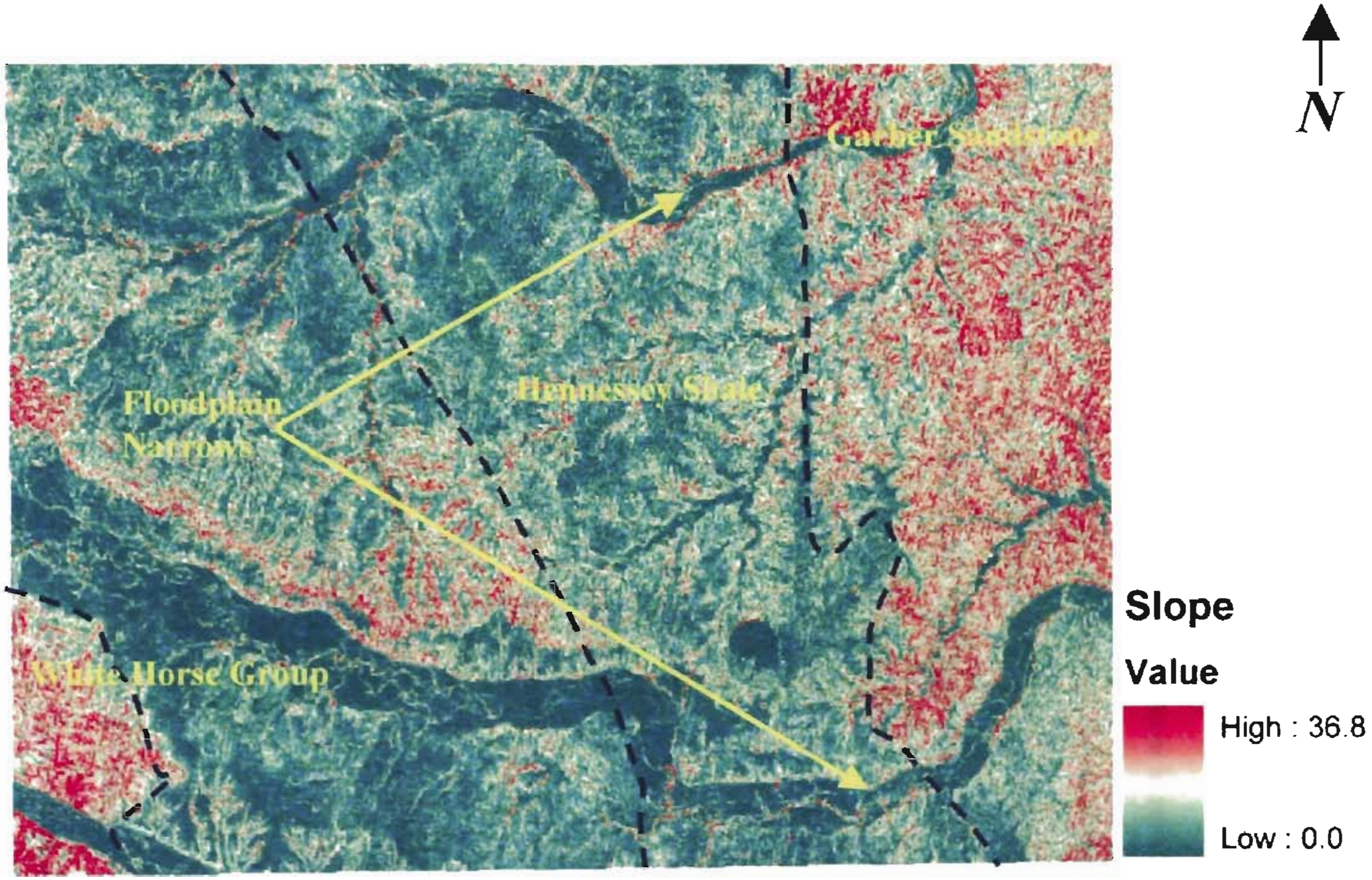


Figure 9. Garber Sandstone and Hennessey Shale contact and White Horse Group in south-west corner of study area. Note the similarities on the slope map between the White Horse Group and the Garber Formation. Also, notice the squeezing of the Canadian and the North Canadian River's floodplain as they pass into the Garber Formation (arrows).

distribution (Fig. 10). The positively skewed tail of the distribution represents the high relief values (fewer number of observations relative to the frequency of low relief values).

As with the slope map, abrupt and systematic differences in relief can be seen on the relief map. These differences correspond to areas that differ in resistance to erosion due to differences in bedrock lithology and the manner in which that lithology responds to erosional forces. Areas that look similar on the relief map are due to their similarities and bedrock lithology. Areas that are more sand-prone give rise to topography with greater relief while areas consisting primarily (or entirely) of shales have less relief.

Hillshade Map

The hillshade map provides an opportunity to view the landscape in a very unique way. Several illumination directions and angles were attempted. It was found that when illuminated from the north at 65°, a large system of lineaments appears to cross the study area in a NE-SW and NW-SE direction (Fig. 11). Four separate sources of data suggest that these lineaments are real and not artifacts of the DEM or algorithm used to create the hillshade map. Lines of evidence include the following: 1) some field observations made of the directionality of jointing in outcrops supported the existence of this large network of lineaments; 2) the paper map of the state surface bedrock geology has faults in the southeastern portion of the study area and beyond that run approximately parallel to the lineaments in the hillshade maps; 3) Shelton et al. (1985) showed that the bedrock of Payne County (which is in the center of the study area) is locally highly jointed in two general directions and in close agreement with the lineaments of the hillshade map, and

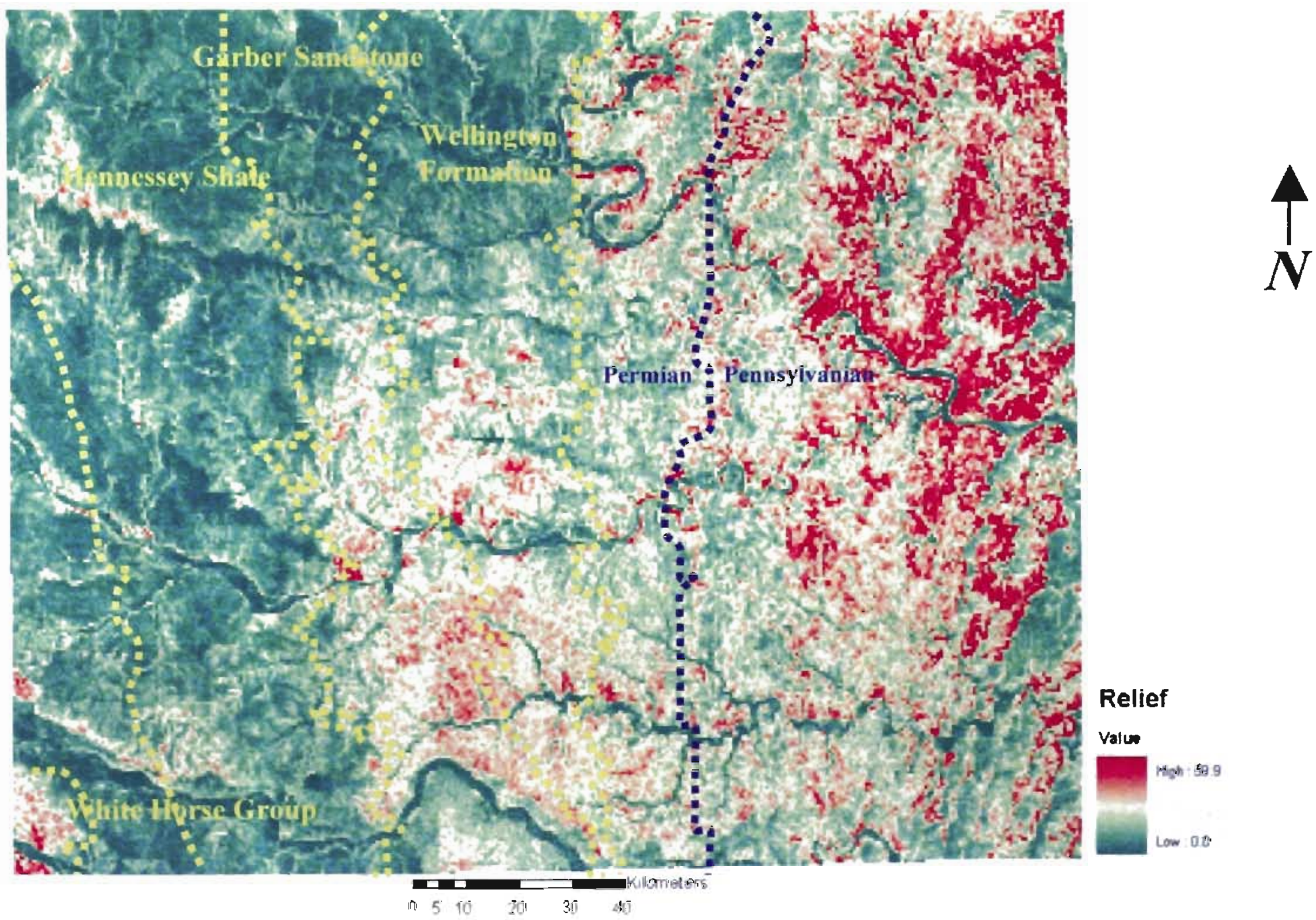
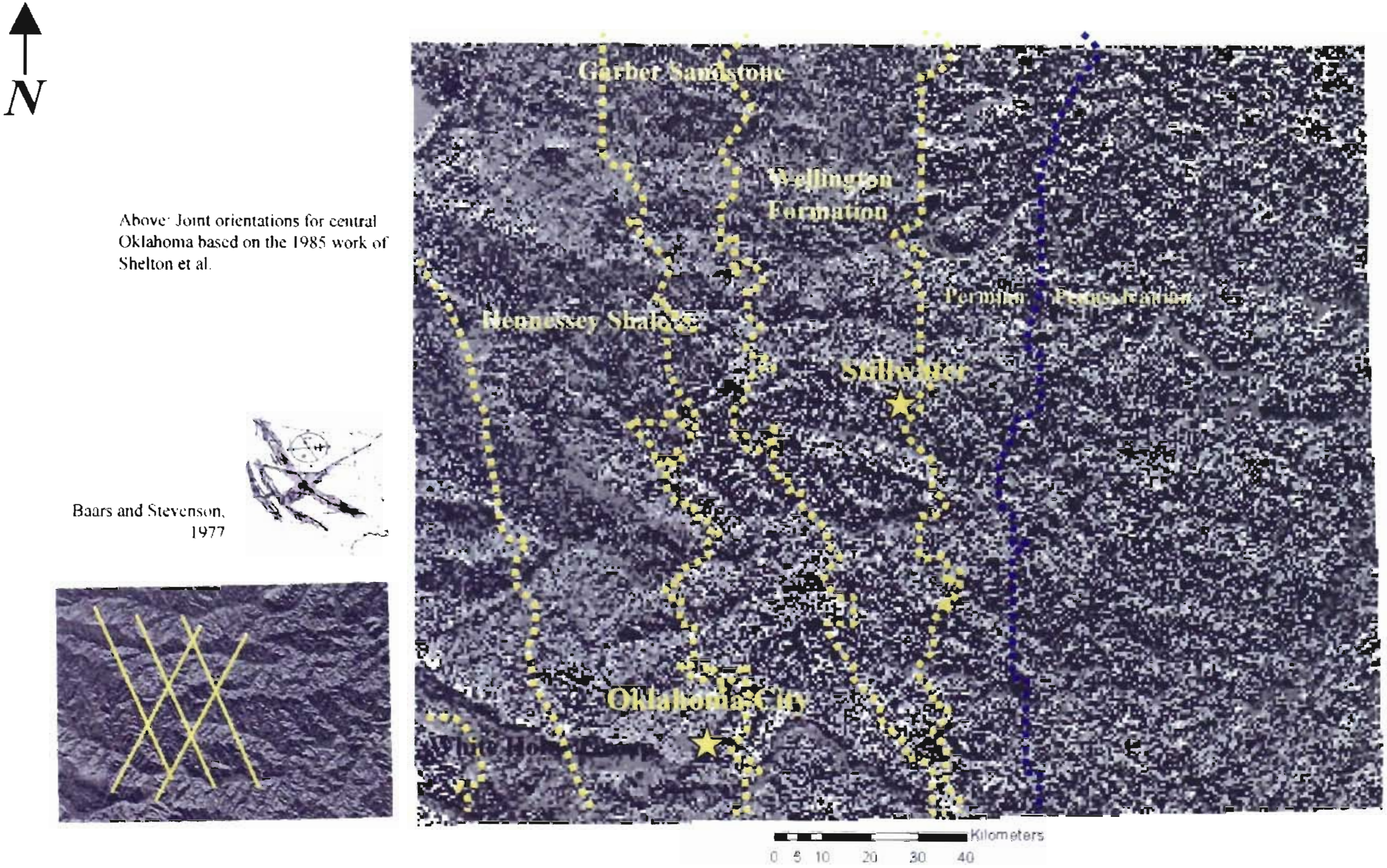


Figure 10. Although the relief map (in meters) appears very similar to the slope map, it provides another means of visualizing the topography.



Above: Joint orientations for central Oklahoma based on the 1985 work of Shelton et al.

Baars and Stevenson, 1977

Figure 11. Hillshade map of study area. Note joint and fracture patterns in the hillshade map above (illuminated from the north). Orientation of joints are in agreement with field observations and the work of Shelton et al. (1985).

4) the streams on a hydrographic map of Payne County overlay the lineaments (suggesting a structural control of secondary regional drainage) (Fig. 12).

The discovery of the regional joint pattern was a totally unexpected finding of this study. The source of these joints is unknown. One option is that the joints are due to release (through denudation) of residual tectonic stresses inherited from a phase of structural compression during folding of the Ouachita Mountains (conjugate vertical-shear fractures). Another option is that the fractures are extensional in nature and related to the Arbuckle-Wichita Mountains Structural trend (regional orthogonal system).

The implications of the lineaments for the topography in the study area are yet to be fully realized and needs further investigation. The data suggest that much of the secondary drainage of the region is structurally controlled. Chorley et al. (1984) state that "the direction of jointing and bedding does exercise some control over the orientation of the *smallest fingertip tributaries* (italics added)...", however, I believe there is the possibility the jointing exerts greater control on the drainages (and topography) of the north-central Oklahoma study area.

GIS and SAS Analysis of the Slope and Relief Map

The summary statistics and frequency histograms (from SAS) of slope and relief for the Hennessey Shale, Garber Sandstone, and Wellington Formation appear quite similar but differ considerably from the White Horse Group (Table 1 and 2 and Fig 13). The Hennessey, Garber, and Wellington are positively skewed while the White Horse distribution is broader and more normally distributed. Although the topography of the Hennessey Shale (as observed in the field and slope and relief maps) is relatively flat and

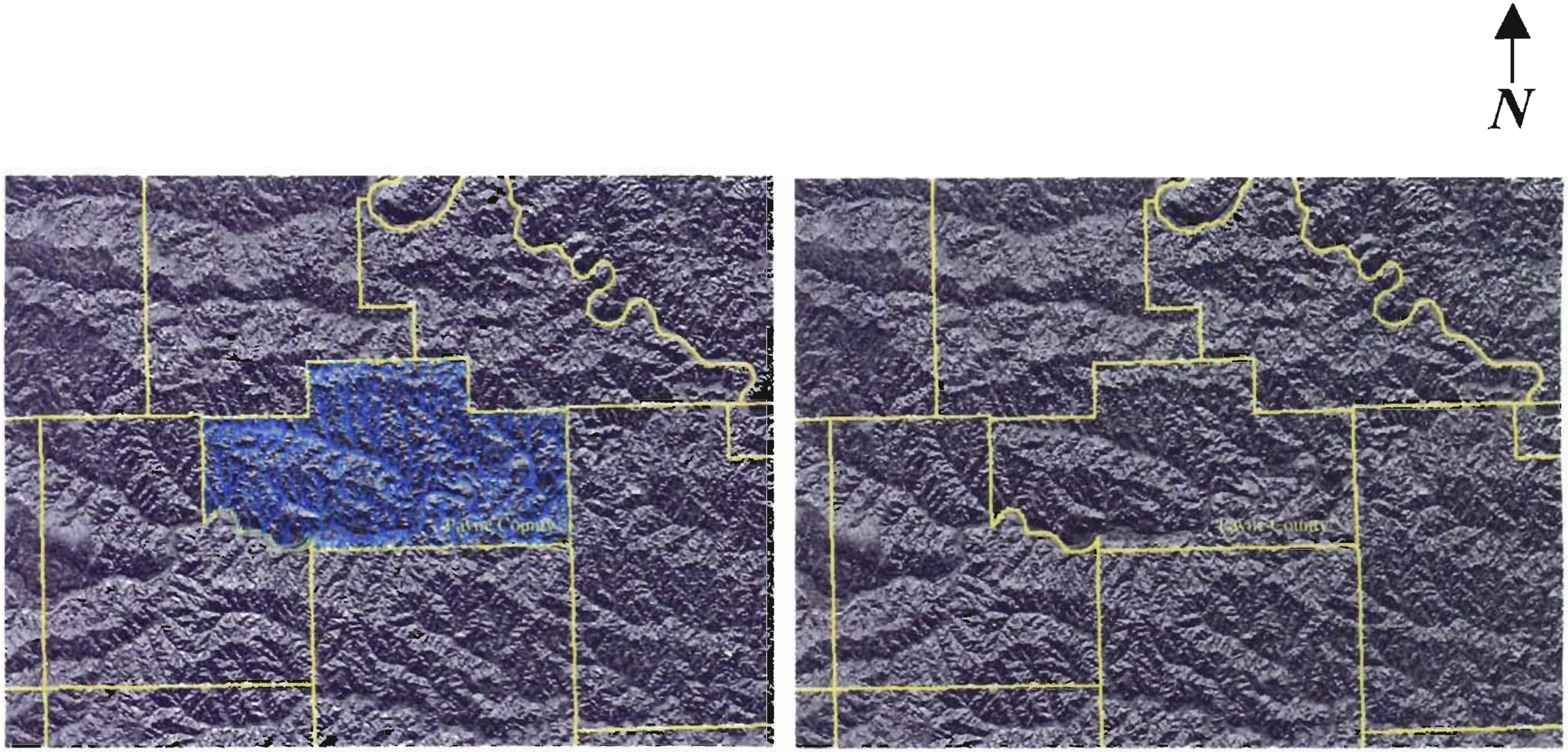


Figure 12. Hydrography of Payne County overlaying a portion of the hillshade map. Notice how the drainage of Payne County overlies the "lines" visible on the Hillshade Map.

Relief (m)

Formation or Group	n	mean	SD	min	max
Whitehorse Gp	123,759	4.7	2.4	0.0	21.0
Hennessey Shale	2,807,676	1.7	1.5	0.0	23.0
Garber Sandstone (All)	2,439,484	2.6	2.2	0.0	23.9
Garber Ss (North)	969,638	1.2	1.0	0.0	15.2
Garber Ss (South)	1,460,097	3.6	2.3	0.0	23.9
Wellington Fm	2,865,411	2.6	2.1	0.0	23.4
Wellington (North)	1,654,263	1.5	1.2	0.0	16.7
Wellington (South)	1,209,395	4.0	2.2	0.0	23.4

Slope (degrees)

Formation or Group	n	mean	SD	min	max
Whitehorse Gp	123,759	3.3	1.9	0.0	17.7
Hennessey Shale	2,807,676	1.2	1.1	0.0	19.8
Garber Sandstone (All)	2,439,484	1.9	1.6	0.0	17.5
Garber Ss (North)	969,638	0.8	0.8	0.0	13.3
Garber Ss (South)	1,459,724	2.6	1.7	0.0	17.1
Wellington Fm	2,865,411	1.8	1.6	0.0	19.6
Wellington (North)	1,654,263	1.1	0.9	0.0	14.3
Wellington (South)	1,209,395	2.8	1.7	0.0	19.6

Table 1. Summary statistics for relief and slope in the White Horse Group, Hennessey Shale, Garber Sandstone, and Wellington Formation.

Fm/Location	Variable	Method	Variances	DF	t Value	Pr > |t|
Wellington North vs Wellington South	**Slope**	Pooled	Equal	$29x10^5$	-1136.7	<0.0001*
		Satterthwaite	Unequal	$17x10^5$	-1043.8	<0.0001*
Garber North vs Wellington North	**Slope**	Pooled	Equal	$26x10^5$	-210.72	<0.0001*
		Satterthwaite	Unequal	$23x10^5$	-218.94	<0.0001*
Garber North vs Hennessey	**Slope**	Pooled	Equal	$38x10^5$	-265.77	<0.0001*
		Satterthwaite	Unequal	$24x10^5$	-311.71	<0.0001*

***evidence to reject null hypothesis in favor of alternative**

Hypothesis

H_o: $\mu_1 = \mu_2$ (means of the two groups are equal)

H_a: μ_1 ne μ_2 (means of the two groups are not equal)

Table 2. Testing for differences in topography (slope and relief) by formation, north-central Oklahoma

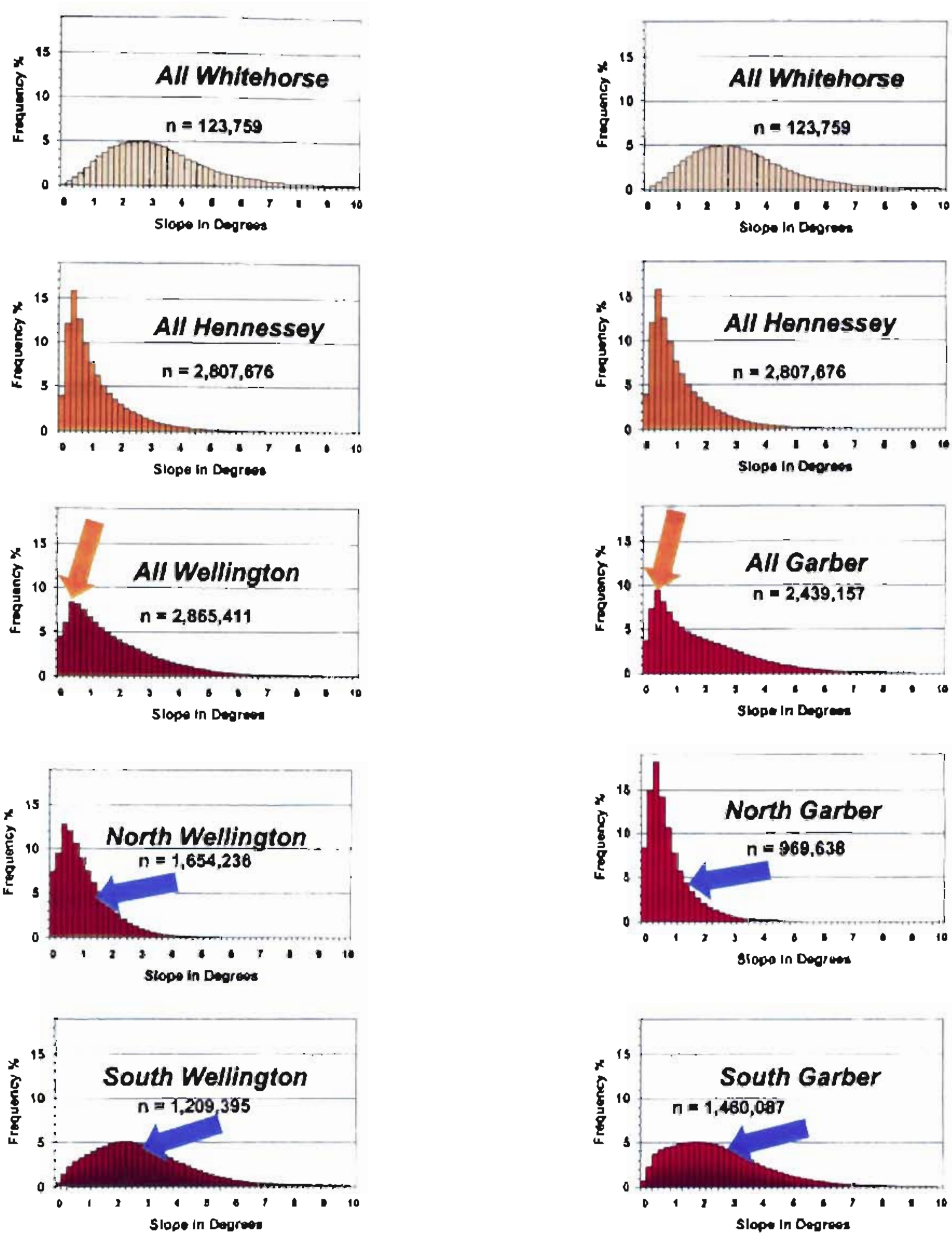


Figure 13. Slope angle frequency histograms of the White Horse Group, Hennessey Shale, Garber Sandstone, and Wellington Formation. Note both Wellington and Garber populations (orange arrows) on the left above can be resolved into two distinct slope populations (blue arrows) based on field observations and map interpretation.

homogeneous, that of the Garber Sandstone and Wellington Formation is not homogeneous. Therefore, based on my knowledge of the geology and inspection of the slope and relief maps, I divided both the Garber Sandstone and Wellington Formation into northern and southern halves at Perry, OK, for further analysis.

When separated into northern and southern halves at Perry, OK, it becomes apparent that both the Garber Sandstone and Wellington Formation (within the study area) contain two separate slope and relief populations (Fig. 14). These populations can be seen in the histograms shown in Figure 13 (arrows) and represent lithofacies changes within the formations. The northern area of the two units, characterized by lower slope angles (as can be seen on the slope map), has a mean slope angle value of 0.8° (Garber) and 1.1° (Wellington), while the southern portions has a mean slope angle of 2.6° (Garber) and 2.8° (Wellington). The means of the northern halves are more similar to the Hennessey Shale (1.2°) while the southern halves are more similar to the White Horse Group (3.3°) (Fig. 15). In addition to similar means, each of these shale-prone units displays a frequency distribution (histogram) of slope and relief values that are strikingly similar in form or shape. However, when the means were compared via a t-test, all are found to be significantly different. All similarities and differences discussed above can be observed on the relief map as well (Table 1 and Fig. 10).

The purposes of statistics in this study are to describe the sample populations and to test for differences between populations. Due the nature of this study, I was working with remarkably large sample sizes. According to the Central Limit Theorem, as sample size for a population increases, the sample mean ($\bar{x}$) converges on that of the true population mean (μ). Because of this, each of our sample populations is highly

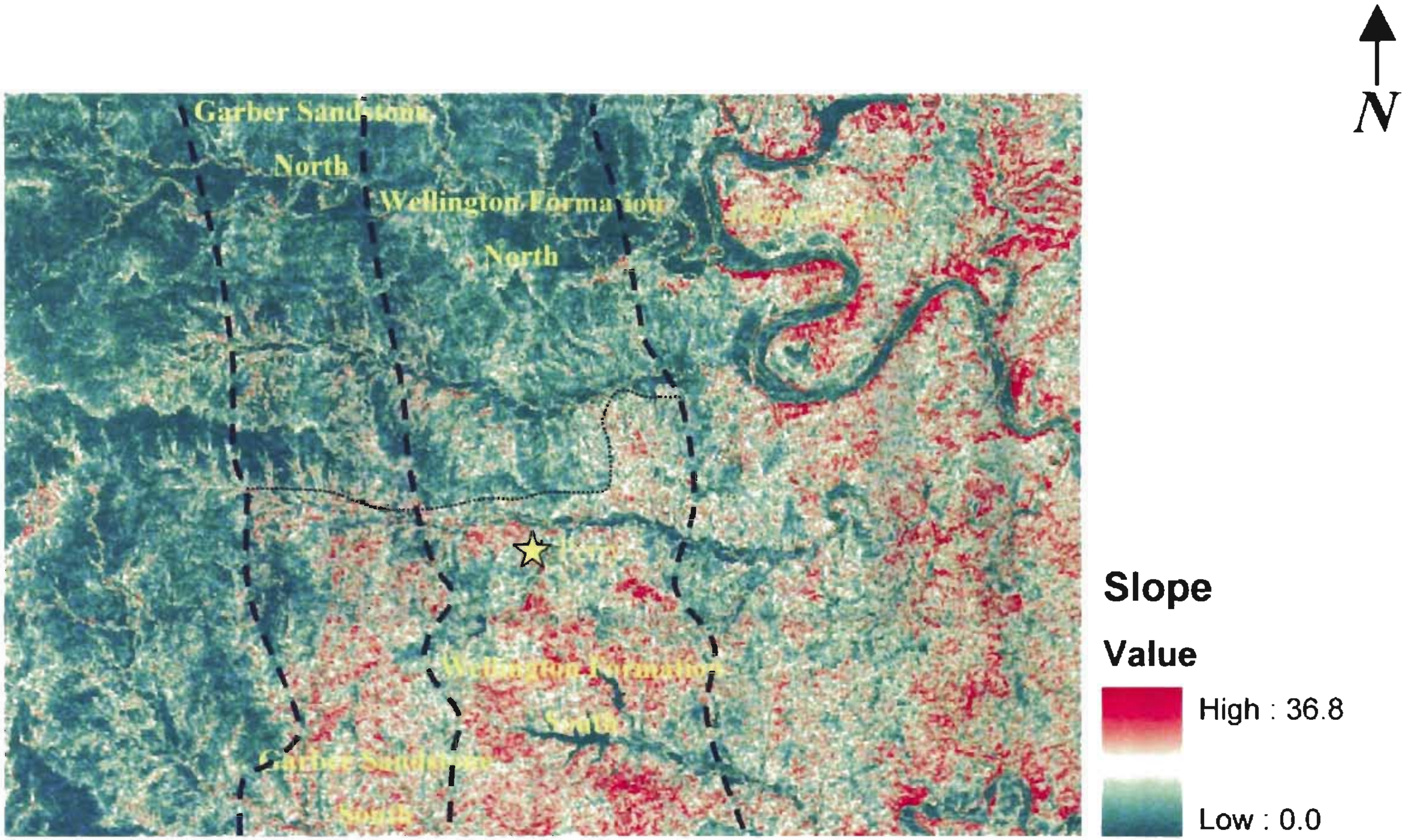


Figure 14.Lithofacies change (dotted line) in the Garber Sandstone and Wellington Formation at Perry, OK.

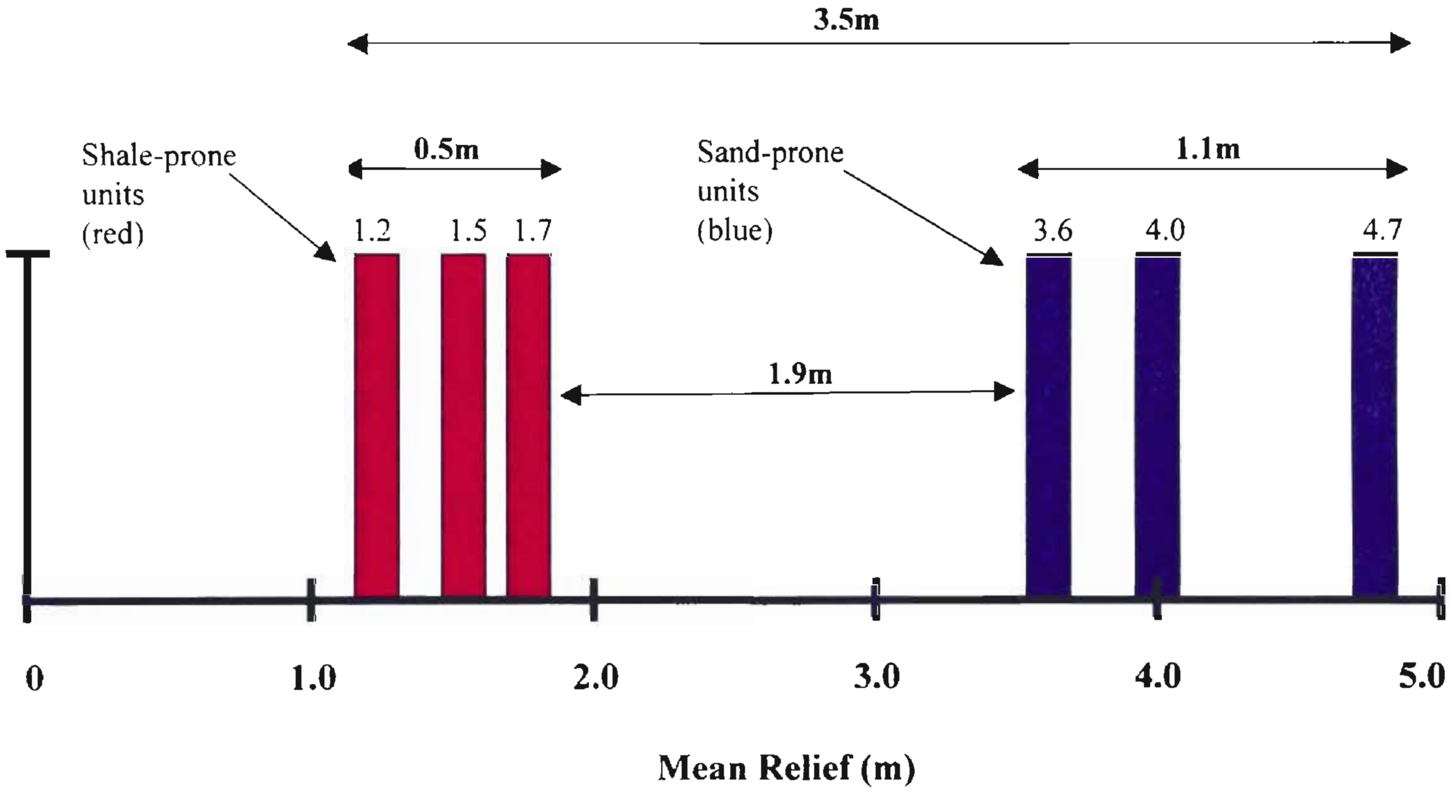


Figure 15. Bar graph showing the natural grouping of the geologic units when comparing mean relief. (Hennessey Shale: 1.2m; shale-prone Garber Sandstone North: 1.5m: shale-prone Wellington Formation North: 1.7m: Garber Sandstone South: 3.6m; sandstone-prone Wellington Formation South: 4.0m: White Horse Group: 4.7m). Note variation *within* sand and shale-prone units is less than variation *between* sand-prone and shale-prone units.

representative of the available population for that formation. This resulted in the means for the geological populations of the study area to be significantly different in all cases.

Although the hilly, high relief and sand-prone southern Garber, southern Wellington, and White Horse are found to be statistically significantly different (Table 2), I still consider these units to be very much alike in terms of slope and relief relative to the shale-prone Hennessey and northern Wellington and northern Garber (based on their histogram shape, mean slope angle, appearance on the slope map, and visual inspection of topography in the field).

On the basis of multiple lines of evidence (histogram shape, slope/relief maps, and field observations), I conclude that the *major* (although not exclusive) control on topography in the study area (White Horse Group, Hennessey Shale, Garber Sandstone, and Wellington Formation) is the lithology of the bedrock (sandstone vs. shale), or more simply, the presence/absence of sandstone.

Results of Field Work

In order to conduct further tests to determine the controls of topography, I initiated a series of field studies. The first of the two approaches addressed whether or not differences in relief and slope in the sand-prone units are due to differences in rock bulk density. The second tested to see if differences in relief and slope in the sand-prone units are due to differences in sandstone bed thickness.

Approach 1: Bulk Density Controls on Slope and Relief

Sandstones of similar composition within and between formations that have undergone similar burial history, for all practical purposes, should have been compacted and cemented to similar degrees. As the bulk density is a direct measure of the sandstone porosity, it also provides a measure of the extent to which the rocks have been compacted and cemented. Regional differences in the extent to which the sand-prone Permian rocks have been lithified may be reflected in resistance to weathering. This resistance to weathering is commonly observed in many areas of the world where a ridge forming geologic formation is a hard, durable quartzite (metamorphic variety of quartz sandstone). Therefore, I have tested the idea that changes in topography within or between sand-prone units are due to differences in the extent to which the sandstone has been lithified. Bulk density of sandstones is being used here as a measure of rock hardness and erodibility. The differences (in part) will be reflected in the bulk density of the rocks, with the harder and less erodable rocks (those in areas with greater slope/relief) having greater bulk density. For testing this idea, sandstones were collected from the Garber Sandstone and White Horse Group. No sandstones of appropriate grain size and composition were found in the Cedar Hills Sandstone Member of the Hennessey Shale.

Sandstone outcrops were found in great abundance in the Garber Sandstone (Sample Site 1) (Fig. 16 and Fig. 5 in Chapter 3). Numerous samples were taken of fine-grained quartz-rich sandstones that range in color from a deep orange-red to a light orange-red color. The samples taken from massive beds appeared to be much more friable than those sampled from thin beds that are interbedded and in close proximity to shales. This is due to the precipitation of carbonate cement (probably derived from the adjacent shales and mudstones) in the sandstones and a higher proportion of clay in the thinner sandstones.

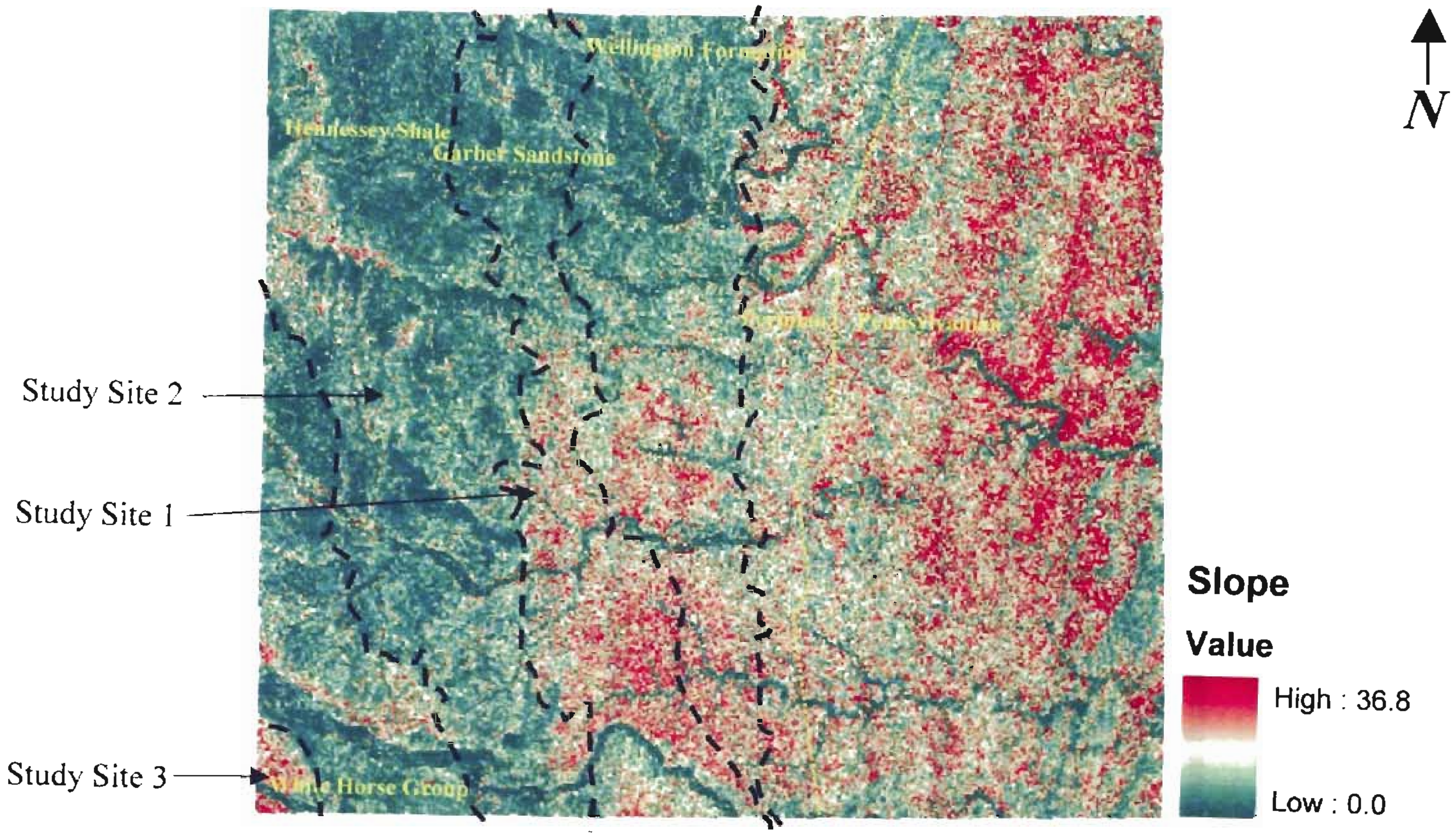


Figure 16. Bulk density study sites.

Over 161 km was traveled between the towns of Hennessey and Enid in the area shown on the state geologic map to contain Cedar Hills Sandstone (Sample Site 2) (Fig. 16 and Fig. 5 in Chapter 3). The terrain is relatively flat with great distances between ridges (relative to the Garber Sandstone study site). The site was surveyed on two excursions with very limited success in finding outcrops containing strata of sandstones. Only four outcrops were located. These sites yielded a few samples. The samples are very fine-grained and silty, moderately consolidated, and appeared to be very clay rich. Half are reddish-brown and the other whitish-gray in color. Since the area in the Hennessey Shale (Cedar Hills) that was surveyed is devoid of sandstones (or sandstones appropriate for comparison with the Garber sandstone), it was necessary to select another location for sandstone collection in order to perform the bulk-density comparison.

The terrain of the White Horse Group (Sample Site 3) (Fig. 16 and Fig. 5 in Chapter 3), although somewhat steeper (recall the White Horse has a mean slope angle of 3.3° and the southern Garber 2.6°), resembles that of the Garber Sandstone on the slope and relief maps and in the field. Several sandstone outcrops were located and sampled. The sandstones are moderately to well consolidated, very fine-grained and appeared to be very iron-rich.

When inspecting the frequency histograms of the bulk density measurements for the Garber Sandstone and White Horse Group, there appears to possibly be at least two populations of density within each formation (Table 3 and Fig. 17). One of the populations within each corresponds to poorly consolidated quartz sandstones and the other population corresponds to the carbonate cemented and mud-silt rich sandstones. These subpopulations were not separated out for the statistical analysis. The Garber

	Variable	Method	Variances	DF	t Value	Pr > |t|
Fm/Location						
Garber South vs Whitehorse	**Density**	Pooled	Equal	75	-1.47	0.1467*
		Satterthwaite	Unequal	52	-1.45	0.1524*

***no evidence to reject null hypothesis in favor of alternative hypothesis**

Hypothesis

H_o: $\mu_1 = \mu_2$ (means of the two groups are equal)

H_a: μ_1 ne μ_2 (means of the two groups are not equal)

Table 3. Testing for differences in sandstone density (gm/cc) by formation, north-central Oklahoma

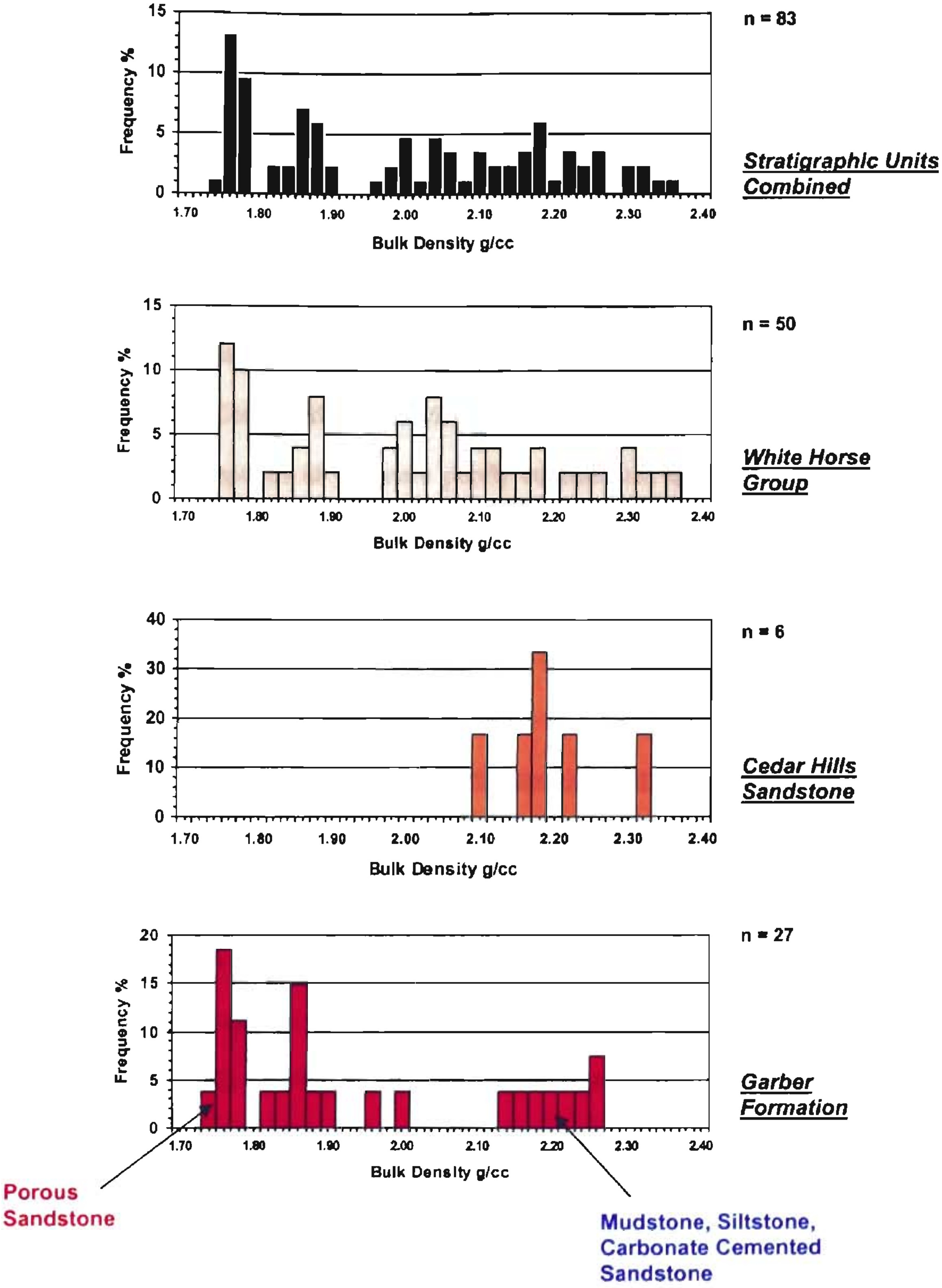


Figure 17. Frequency histograms of bulk density measurements.

Sandstone has a mean bulk density of 1.9 gm/cc and a standard deviation of 0.19, while the White Horse Group has a mean of 2.0 gm/cc and a standard deviation of 0.18. Based on a t-test, the means of bulk density for the two units are not significantly different (Table 3).

In the Cedar Hills Sandstone, the bulk density frequency histogram resembles the carbonate cemented, clay-silt rich sandstone portion of the Garber Sandstone and White Horse Group bulk density frequency histograms. As expected, based on inspection of the hand samples, the Cedar Hills Sandstone frequency histogram lacks a grain size population that corresponds to the more poorly consolidated quartz sandstones of the Garber Sandstone and White Horse Group frequency histograms. On the basis of this test, I conclude that one *cannot* argue that the slope and relief differences between the Whitehorse and Garber are due to differences in degrees of consolidation of the sandstones.

Approach 2: Sand Bed Measurements for Comparison of Unit Thickness

The Garber Sandstone and Wellington Formation are interesting in that the comparative topographic differences observed do not occur between the two formations but rather within each of the formations (Fig. 14). Another interesting point is that the topographic changes appear to occur at about the same geographic latitude in both formations (Perry, OK). The topographic change corresponds to the location on the slope and relief maps where there appears to be an abrupt transition of terrain with a relatively homogeneous area of green (representing lower slope angles/lower relief) to the north and a relatively homogenous area of red (representing higher slope angles/higher relief) to the south. These color changes correspond to an area in the southern portions of the study area where the Garber Sandstone and Wellington Formation contain a well-developed sandstone lithofacies. These massive and cross-bedded sandstones decrease in abundance and thickness to the north in the study area. Others have noted the tendency for sandstone beds to occur with a decreasing frequency, eventually ceasing to occur all together within the Garber Sandstone and Wellington Formation in the northern portion of the study area (Oklahoma Geological Survey Bulletin, 1917).

A total of 49 outcrops were located in the two transects from which sandstone strata were measured; 24 in the Garber Sandstone and 25 in the Wellington Formation. Thicker beds (1.5-3.0m) are found to occur in outcrops in the southern half of each formation than is observed in the northern halve (no beds > 1.5 m) of each formation when the formations are divided at Perry, OK (Fig. 18 and 19). Therefore, the Garber and Wellington were divided into northern and southern halves (at Perry) for comparison of sand bed thickness. Within both units, I also observe that the ratio of sandstone to shale (net-to-gross) decreases in outcrop and sandstone outcroppings become increasingly difficult to find as you approach and pass through the region of topographic change at Perry.

Comparisons of mean sand bed thickness (Table 4) were made (using a t-test) between the: 1) northern Garber/Wellington and southern Garber/Wellington, 2) sand bed thickness of the entire Garber vs. the entire Wellington (north and south portions combined for each unit), and 3) southern Garber and southern Wellington. It was found that the southern Garber and the southern Wellington do not statistically differ with respect to bed thickness. This was also found to be true when comparing the entire Garber to the Wellington (combined northern and southern units). However, when

Fm/Location	Variable	Method	Variances	DF	t Value	Pr > |t|
Garber / Wellington North vs Garber / Wellington South	**Thickness**	Pooled	Equal	58	-3.14	0.0026*
		Satterthwaite	Unequal	56.5	-3.61	0.0007*

***evidence to reject null hypothesis in favor of alternative**

Hypothesis
H_o: $\mu_1 = \mu_2$ (means of the two groups are equal)
H_a: μ_1 ne μ_2 (means of the two groups are not equal)

Garber Sandstone Vs Wellington Fm	**Thickness**	Pooled	Equal	58	0.32	0.7521*
		Satterthwaite	Unequal	57.3	0.33	0.7398*

***no evidence to reject null hypothesis in favor of alternative**

Hypothesis
H_o: $\mu_1 = \mu_2$ (means of the two groups are equal)
H_a: μ_1 ne μ_2 (means of the two groups are not equal)

Table 4. Testing for differences in bed thickness (m) by formation, north-central Oklahoma

Fm/Location	Variable	Method	Variances	DF	t Value	Pr > |t|
Garber South / vs Wellington South	**Thickness**	Pooled	Equal	35	-0.41	0.6820*
		Satterthwaite	Unequal	33.9	-0.42	0.6735*

***no evidence to reject null hypothesis in favor of alternative**

Hypothesis

H_o: $\mu_1 = \mu_2$ **(means of the two groups are equal)**

H_a: μ_1 **ne** μ_2 **(means of the two groups are not equal)**

Table 4 cont. Testing for differences in bed thickness (m) by formation, north-central Oklahoma

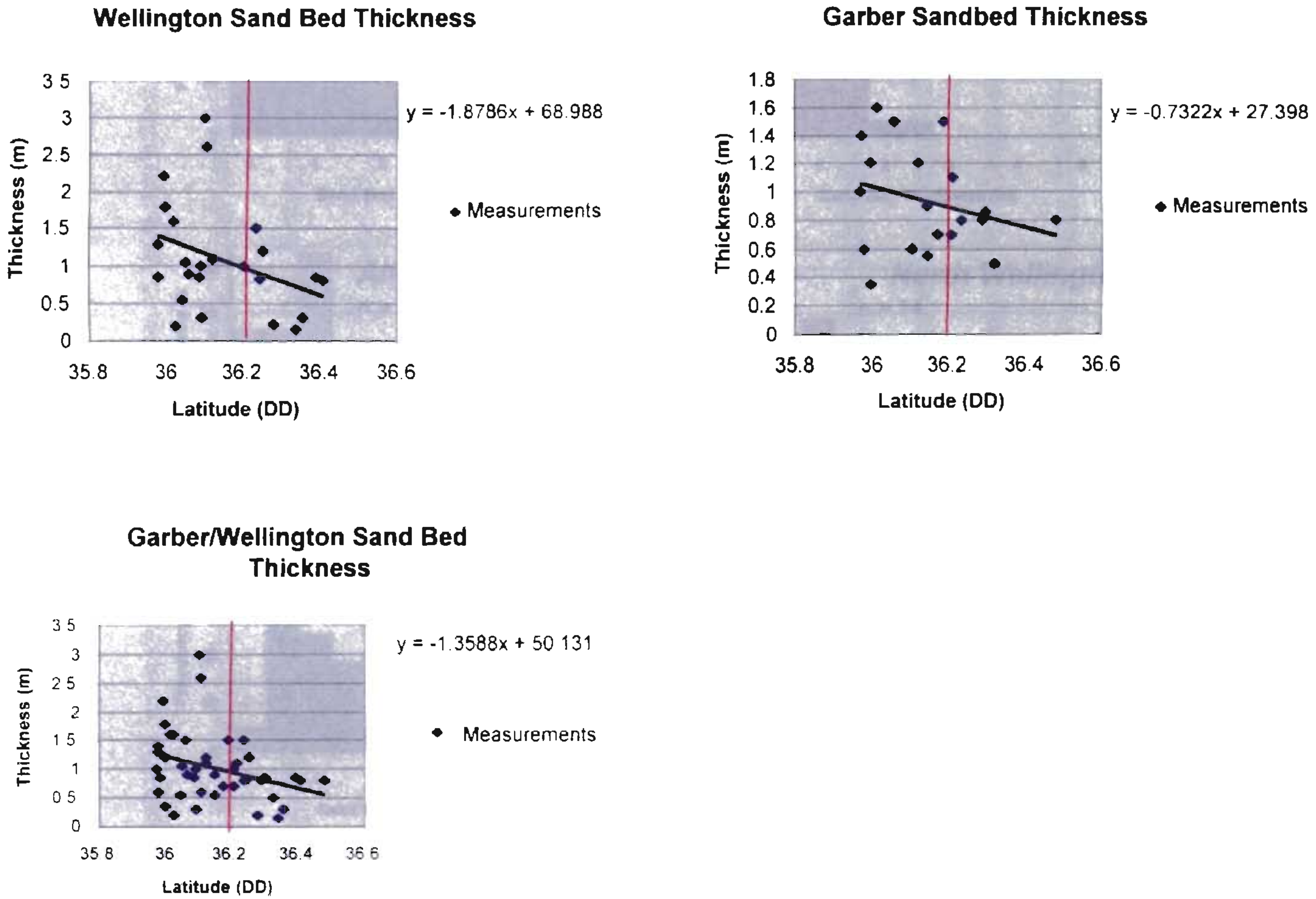


Figure 18. Frequency histograms of sandbed thickness for the Garber Sandstone, Wellington Formation, and the Garber/Wellington combined. Notice the variation in sand bed thickness decreases at about the same latitude in both the Garber and Wellington. It is interesting that this is also the location of the facies change identified on the slope map and the location of Perry, OK (red line).

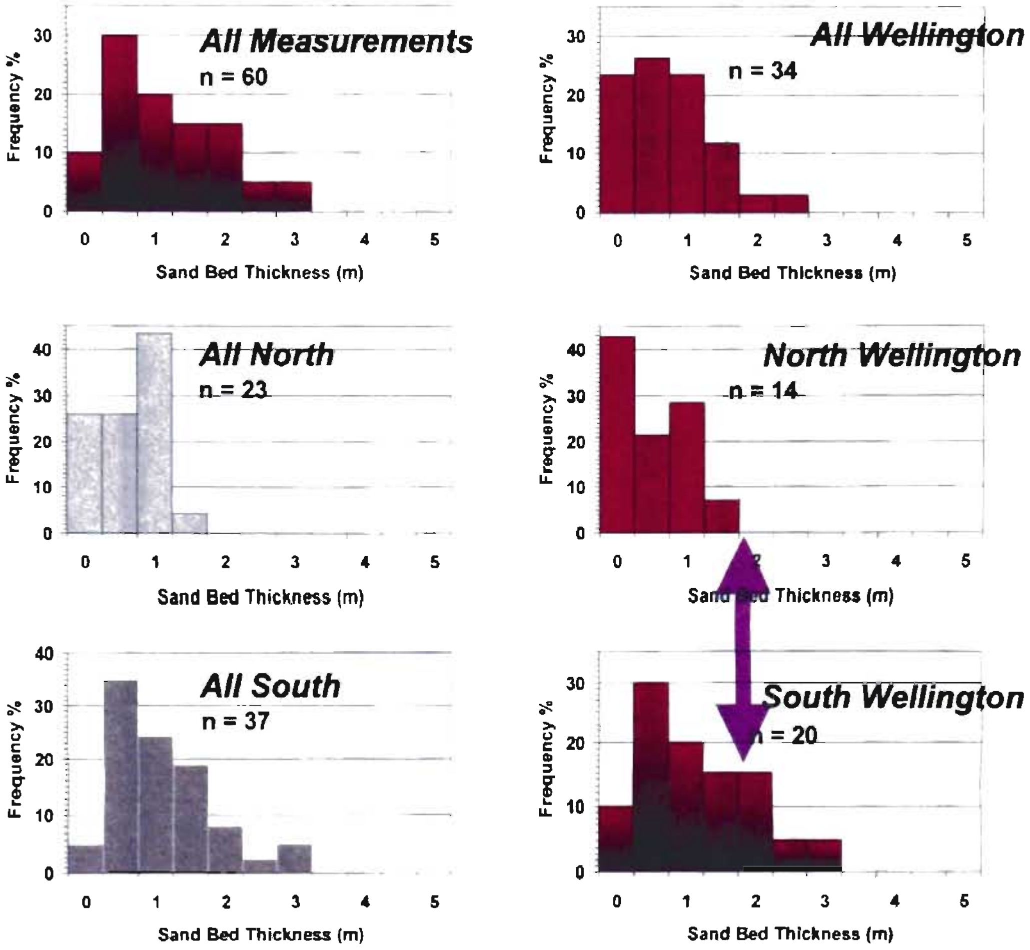


Figure 19. Frequency histograms of sand bed thickness in portions of the Wellington Formations. Note the shift in sand bed thickness in the southern portion of the Wellington Formation relative to the northern Wellington Formation (arrow).

comparing the sand bed thickness of the southern Garber and Wellington combined to their northern units combined, I found a statistically significant difference in means (Table 4 and Fig. 19).

Examination of Figure 18 and the above statistics indicates that indeed the sand bed thickness decreases as you progress north within the formations. Because of this relationship, the relative amount of sandstone vs. shale in the stratigraphic section decreases to the north. Absence of thicker sandstone beds (or the complete absence of sandstone) differentiates the northern and southern halves of these formations. I propose that the lithologic differences (sandstone presence/absence and sand bed thickness) result in the observed and quantifiable differences in topography (i.e. the southern halves have greater slope angles and relief than their northern counterparts).

The thinning of the sand beds to the north is possibly because the units are deltaic-like in origin. The Permian fluvial system(s) transporting the sediment to the north west underwent a loss of depositional energy, resulting in the sand dominated fluvial-deposited southern portion of the unit transitioning into a lower energy mud flat environment to the north.

Value of Using GIS and DEMs in Areas of Subtle Topography

The slope and relief maps provided invaluable information concerning the variation in topography within the study area. In addition to providing an effective means of visualization, they also served as a rich source of quantitative data. The creation of slope maps is not new in studies of topography. However, the spatial extent and resolution of the current study would have proved prohibitive prior to the availability of GIS, DEM's, and powerful desktop computers. Without the combination of these three tools the current study would have not been possible. The documented topographic differences between geologic units are often so subtle that detection is not possible with the unaided eye.

Production of the study maps was also relatively rapid using GIS. A person with limited GIS skills can produce these maps in a reasonably short time. The software is becoming more and more user friendly, inexpensive or accessible, and many people in a variety of fields are using it proficiently. GIS is a well known, valid, and acceptable tool for doing topographic analysis on a regional scale.

In order to fully appreciate the potential of GIS, you must consider its applications in conjunction with previously existing tools. I am not arguing that GIS should replace the tools that are already being put to use by researchers. Rather I argue that one should consider how it can be used to enhance their work by adding another tool to their repertoire of existing tools.

In addition to qualitative values in research, GIS also provides many quantitative tools. This is the point, however, where I encountered limits with the use of ESRI® ArcGIS®. In order to perform the statistical analysis I desired, it was necessary (as described in the methods) to clip the areas of the slope and relief map and export the data to a statistical software package (SAS). SAS is a more nimble package for performing the univariate analysis with large sample sizes.

Chapter 5

Summary and Conclusions

Summary of Approach, Findings, and Discussion

I began this study by obtaining a 30m DEM of the study area. From the DEM, slope, relief and hillshade maps were generated. Based on the analysis of the maps and comparisons with bedrock geology, I identified several areas of interest or significance, speculated on the geologic controls on topography within these areas, and devised a series of methods for testing the ideas.

Using polygons drawn to exclude Quaternary aged material, the Permian White Horse Group, Hennessey Shale, Garber Sandstone, and Wellington Formation were clipped from the slope and relief maps. These bedrock units were clipped as a means to quantitatively look at the entire geographic distribution of each mapped bedrock unit. The pixel values were exported and univariate analysis was performed for each unit in SAS.

Based on the analysis of the frequency histograms of the Garber Sandstone and the Wellington Formation, each unit was further subdivided into northern and southern halves. The subdivision of these formations is based on the occurrence of a lithofacies change that occurs in both of the formations near Perry, OK. The slope and relief maps show the topography of the northern two units to smooth out, relative to the southern portions of the two units, at this location. Also, field observations support what is seen on the slope and relief maps (absence of sandstone or thinner sand beds to the north). The slope and relief difference in these areas (northern and southern halves of the

Garber/Wellington) is due to differences in bedrock composition and how that bedrock differs in response to erosional forces.

Although statistically different, the shape of the frequency histograms of the northern shale-prone Garber Sandstone and northern Wellington Formation are strikingly similar. The two units are also very similar in bedrock composition (mostly shale). This similarity (both the histogram and bedrock) can also be observed when comparing the northern Garber/Wellington (both shale-prone) and the Hennessey Shale. In addition to having similarities in bedrock, these units are geographically close, have equal or similar annual rainfall, and were buried to similar depths and lengths of time in the geologic past. For all practical purposes, the geologic history of the areas is indistinguishable. These three areas of low slope/relief are composed of argillaceous material that is jointed, very brittle, fissile, and/or easily breaks into small pieces when crushed in the hand. The high degree of fracturing and jointing in the Hennessey Shale and northern Garber/Wellington facilitates the movement of water, burrowing organisms, and the growth of roots. This enhances the degree of mechanical (freezing and thawing of water), chemical (dissolution and transport of bedrock), and biological (worms, insects, and plants) weathering of these units relative to sand-prone intervals.

The internally thick beds of sandstone in the White Horse Group, southern Garber Sandstone, and southern Wellington Formation are interbedded with mudstones and shales. However, it is the presence (high sand net-to-gross) of the sandstones that creates the higher slope and relief characteristics of the area (relative to the Hennessey Shale and northern Garber/Wellington [lower sand net-to-gross]). In addition, the bulk density of the sandstones in the Garber and White Horse do not significantly differ (the Wellington, although not measured, is very likely to not differ significantly in terms of bulk density). Because of these shared characteristics and close spatial proximity, these units are topographically very much alike. The massive and cross-bedded sandstone units of the White Horse, southern Garber, and southern Wellington, although somewhat easily broken, are not as jointed, brittle, or soft as the shales, mudstones, and siltstones of the northern Garber, northern Wellington, and Hennessey.

In addition to the presence or absence of sandstone, I demonstrated that the thickness of sand beds appears to contribute to differences in topography. North-south trending transects were created in both the Garber Sandstone and Wellington Formation. Measurements of sand bed thickness demonstrated that there is a significant difference between the sand bed thickness of the southern Garber/Wellington and northern Garber/Wellington while there was not a statistically significant difference between the southern Garber and southern Wellington. The thicker sand beds of the southern portion of the units require greater time and/or are more resistant to erosion than the thinner sand beds located to the north.

Conclusions

Topography

Based on visual inspection of frequency distributions and univariate summary statistics, the rank order of decreasing slope and relief are as follows:

White Horse (3.3°)>Wellington South (2.8°)>
Garber South (2.6°)>Hennessey Shale (1.2°)>
Wellington North (1.1°)>Garber North (0.8°)

I argue that the order in which the units occur is a function of the presence or the absence (or low occurrence) of sandstone. Therefore the units or portions of units with the highest slope and relief (Whitehorse, southern Wellington, and southern Garber) contain a larger percentage of sandstone (higher sand net-to-gross), and the units or portions of units with the lowest slope and relief contain few (if any) well developed sandstone units (lower sand net-to-gross).

The reason for the differences in topography between the shale-prone units (northern Garber, northern Wellington, and Hennessey) was not directly determined. Nor was the reason directly determined for topographic differences among the sand-prone units (southern Garber, southern Wellington, and White Horse). However, the differences in the sand-prone units could simply be due to subtle differences in bed thickness, subtle differences in bulk density, and subtle differences in mineralogy and bedding. Of these, sand bed thickness stands out as a likely candidate for controlling the variation in slope and relief in sand-prone areas. As I have shown, the sand-bed thickness does significantly differ between the northern Garber/Wellington and the southern Garber/Wellington. Therefore it could reasonably be argued that differences in sand bed thickness could account (at least partially) for differences in slope and relief in sand-prone units. In order to demonstrate the role of sand bed thickness in the sand-prone areas, however, larger sample sizes would be required than were collected for this study (southern Garber and southern Wellington sand bed thicknesses were not significantly different based on a limited sample size).

Regional Joint Pattern

I observe a NW-SE and NE-SW linearity in the low-order drainage systems. This linearity is probably part of a regional joint system. It is not entirely clear how the joints or fracture systems relate to the regional geological setting. One option is that the joints are due to release (through denudation) of residual tectonic stresses inherited from a phase of structural compression during development of the Ouachita Mountains (conjugate vertical-shear fractures). Another option is that the fractures are extensional in nature and related to the Arbuckle-Wichita Mountains trend (regional orthogonal system).

GIS

GIS was found to be a critical and effective tool for our study. However, I found the software to be limited in its ability to perform statistical analysis and was forced to export the data to other statistical software (SAS).

Future Studies

Primary limitations found in this study were due to the lack of detailed geologic information available for the bedrock units under study. In order to better validate the findings of this research, further work needs to be performed that describes the properties of the rocks (e.g. mineralogy and texture), and the regional stratigraphy of the units. In addition, regional structural effects and forces need to be further investigated (e.g. origins of the joints identified).

The causes of the observed differences in topography between the sand-prone White Horse and southern Wellington and Garber should be clarified with a more detailed study of bulk density and sand bed thickness in the units.

As better resolution DEM's (10m) become available, more accurate and detailed studies can be conducted. The present study is the first of its kind. Going into the study, I was unsure about what findings might emerge. This resulted in many challenges in the experimental design. Replication of this work with more complete measurements would assist in further validating my findings. In addition, these studies could involve the use of soil maps, land-cover, land-use, and hydrography for a more complete understanding of regional variation in topography. Further studies on the origin and topographic consequences of the regional jointing could be integrated with this study and has the potential for fascinating findings.

Studies can also be conducted that attempt to determine the social and economic consequences resulting from human modification of landscapes. This is a particularly important area of potential research with the threat of global warming. Oklahoma is undergoing erosion and denundation. It is therefore very susceptible to adverse effects due to the removal of vegetation, increased overland flow, and removal of topsoil. How bedrock (thus topography) responds to increased instances and durations of drought is of great economic and social importance.

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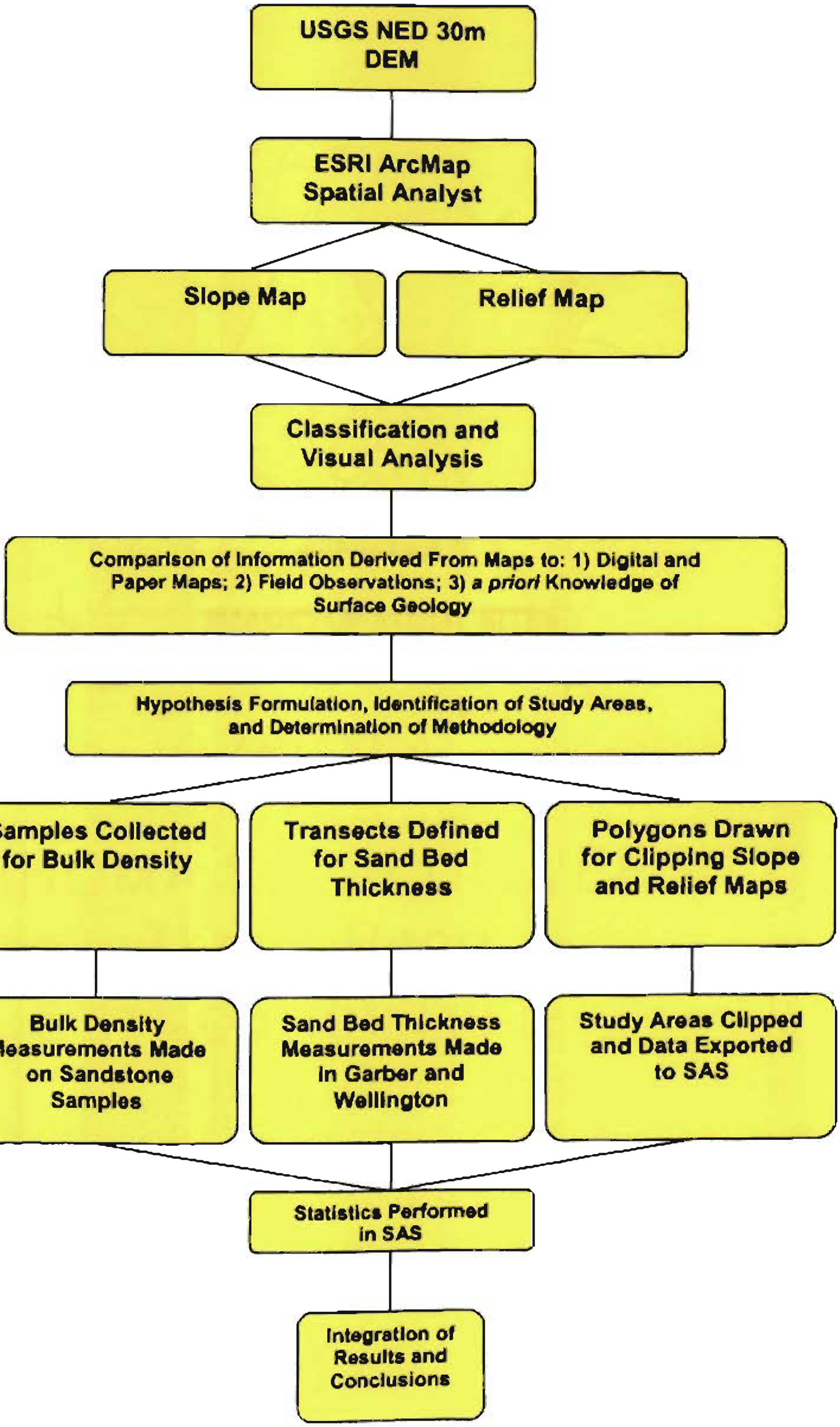
APPENDICES

APPENDIX A

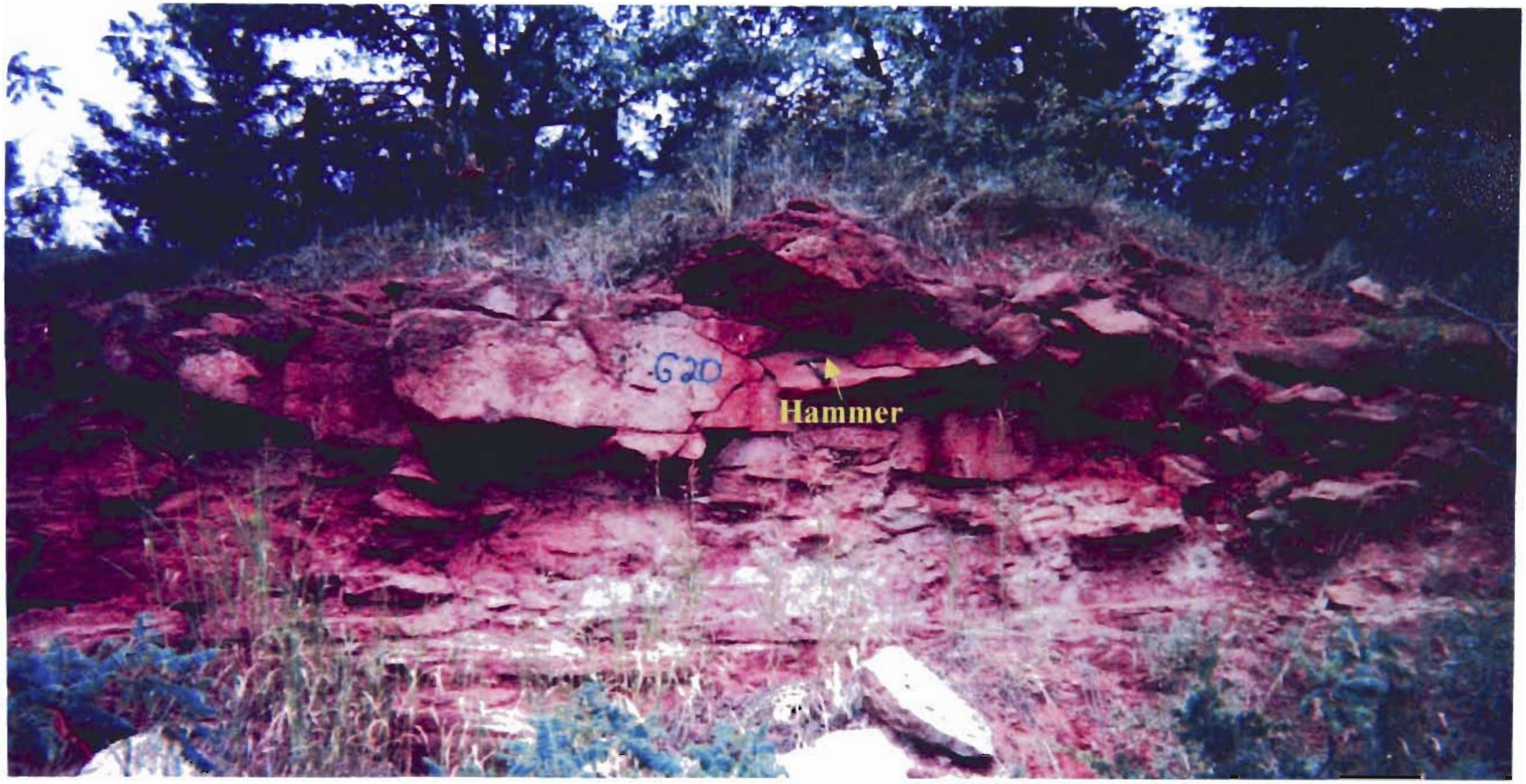
FLOWCHART OF APPROACH

Flowchart of Approach



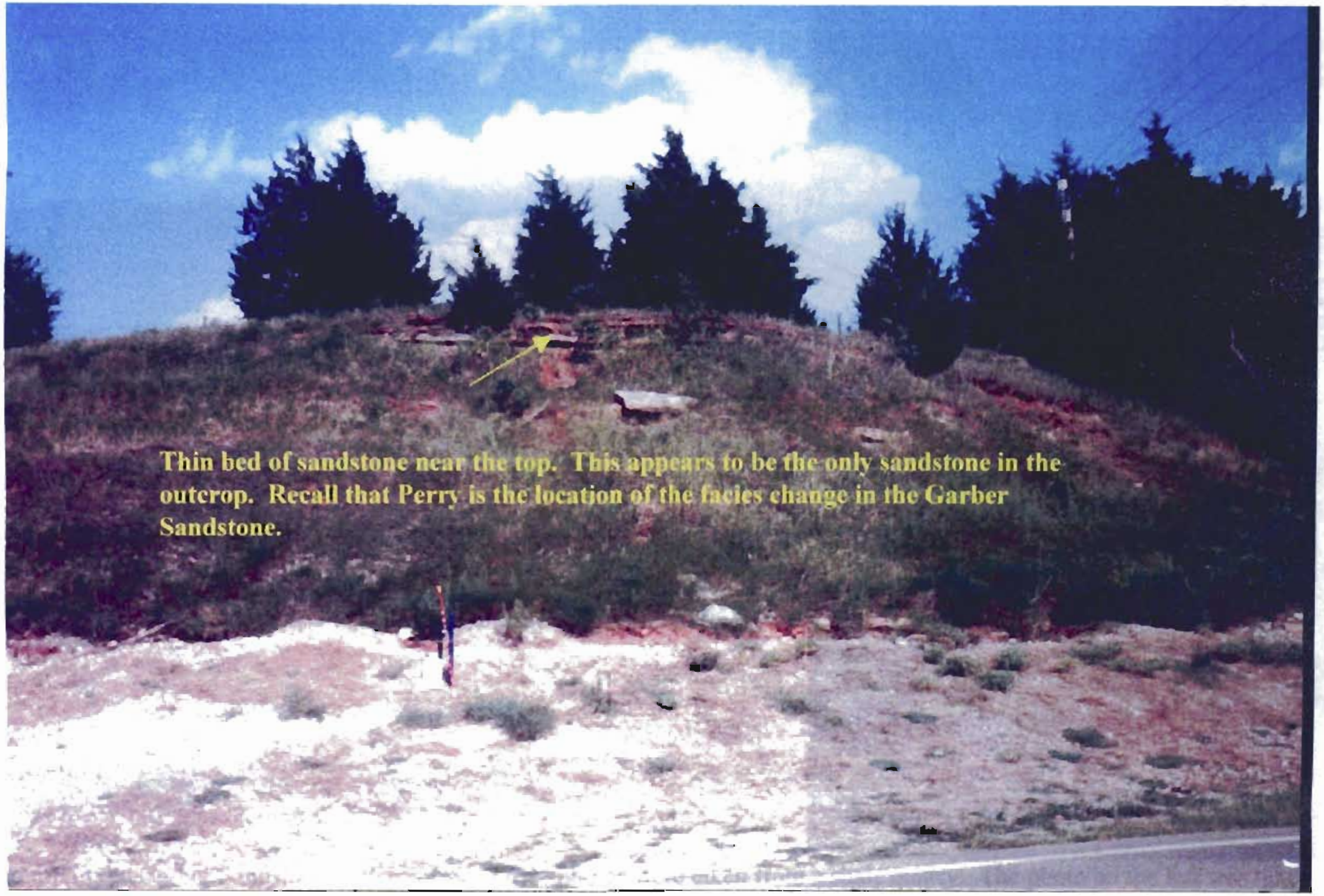
APPENDIX B

IMAGES OF STUDY SITES



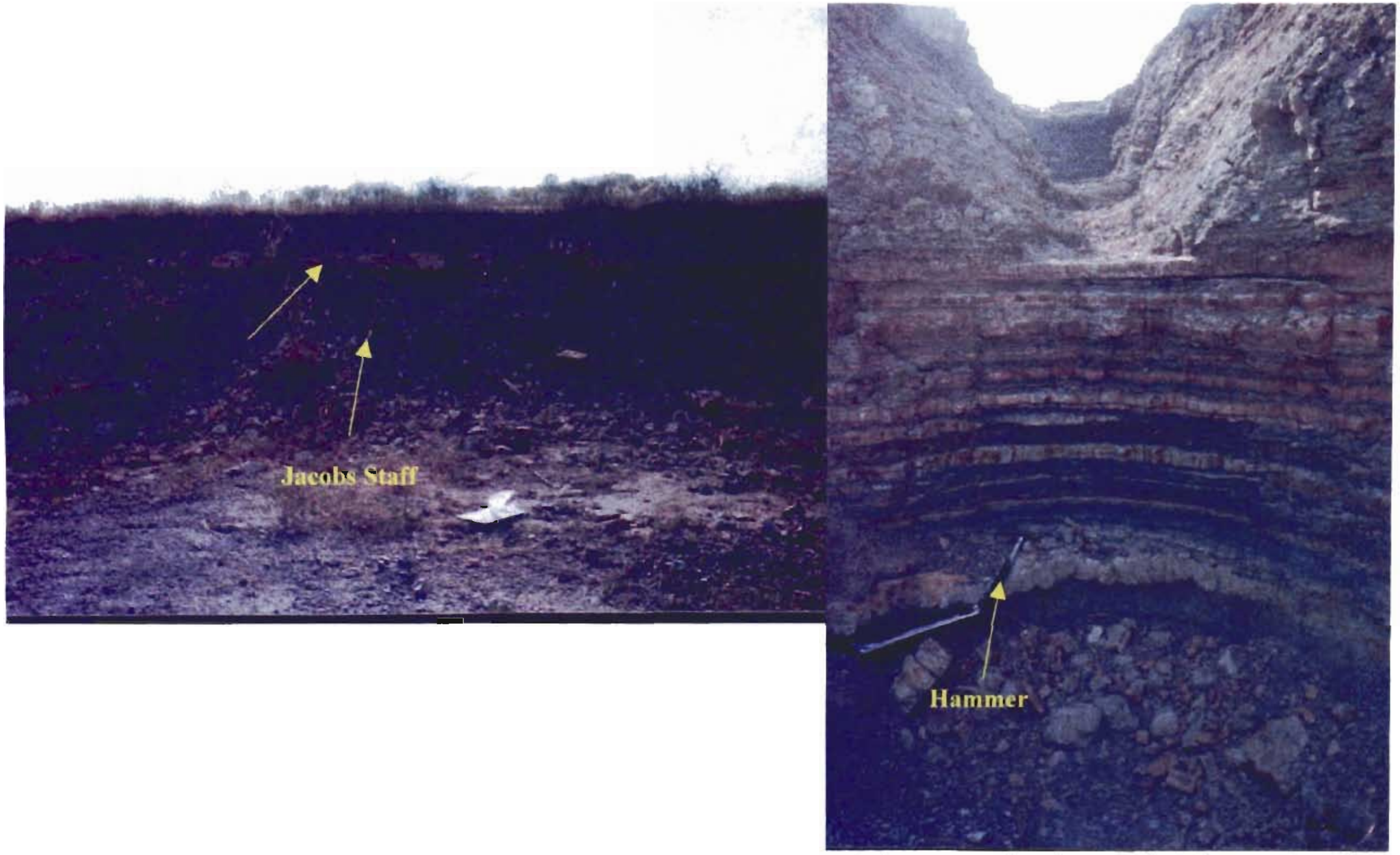
Outcrop of Garber Sandstone (southern half).

Outcrop of the Wellington Formation in Stillwater. OK.

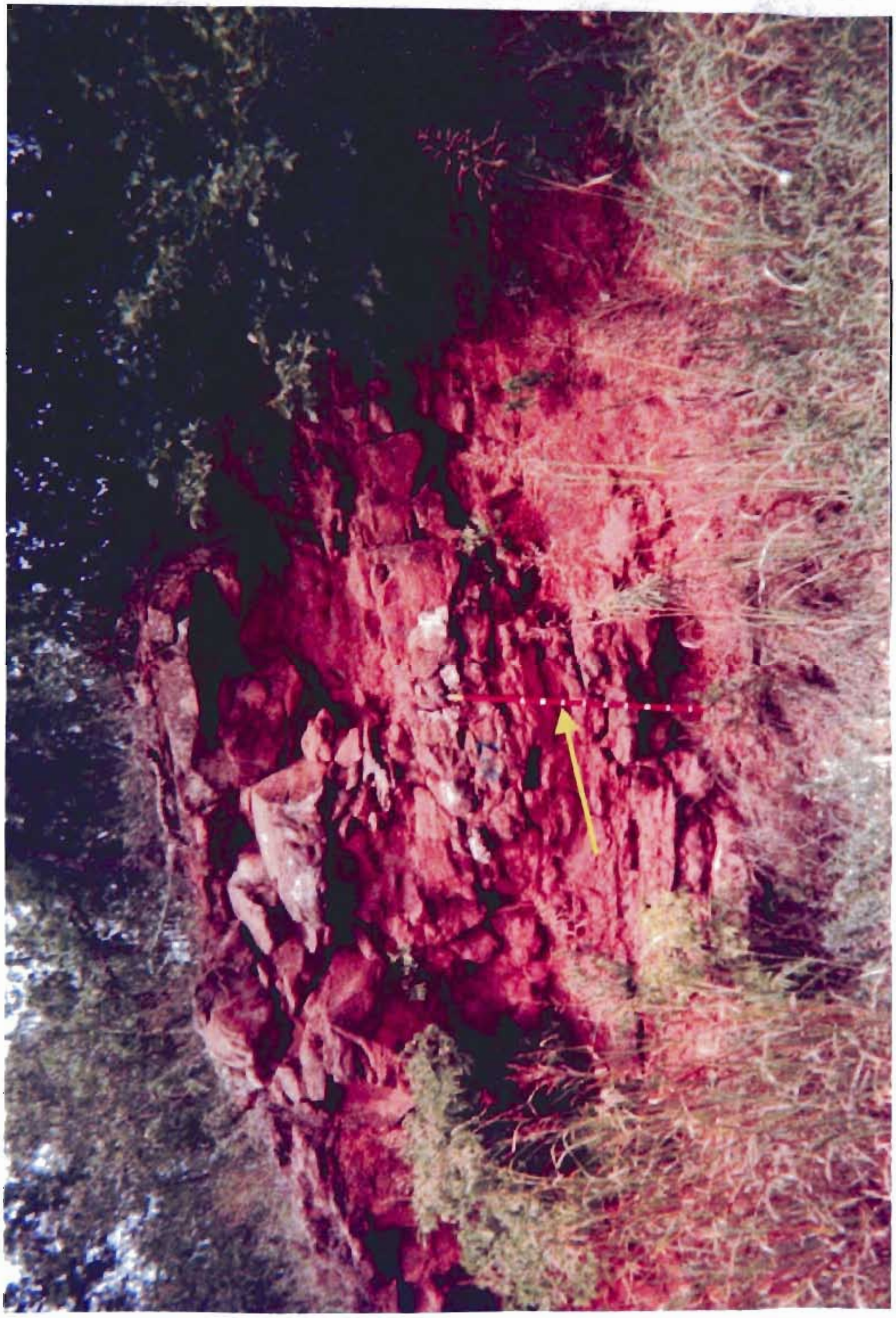


Thin bed of sandstone near the top. This appears to be the only sandstone in the outcrop. Recall that Perry is the location of the facies change in the Garber Sandstone.

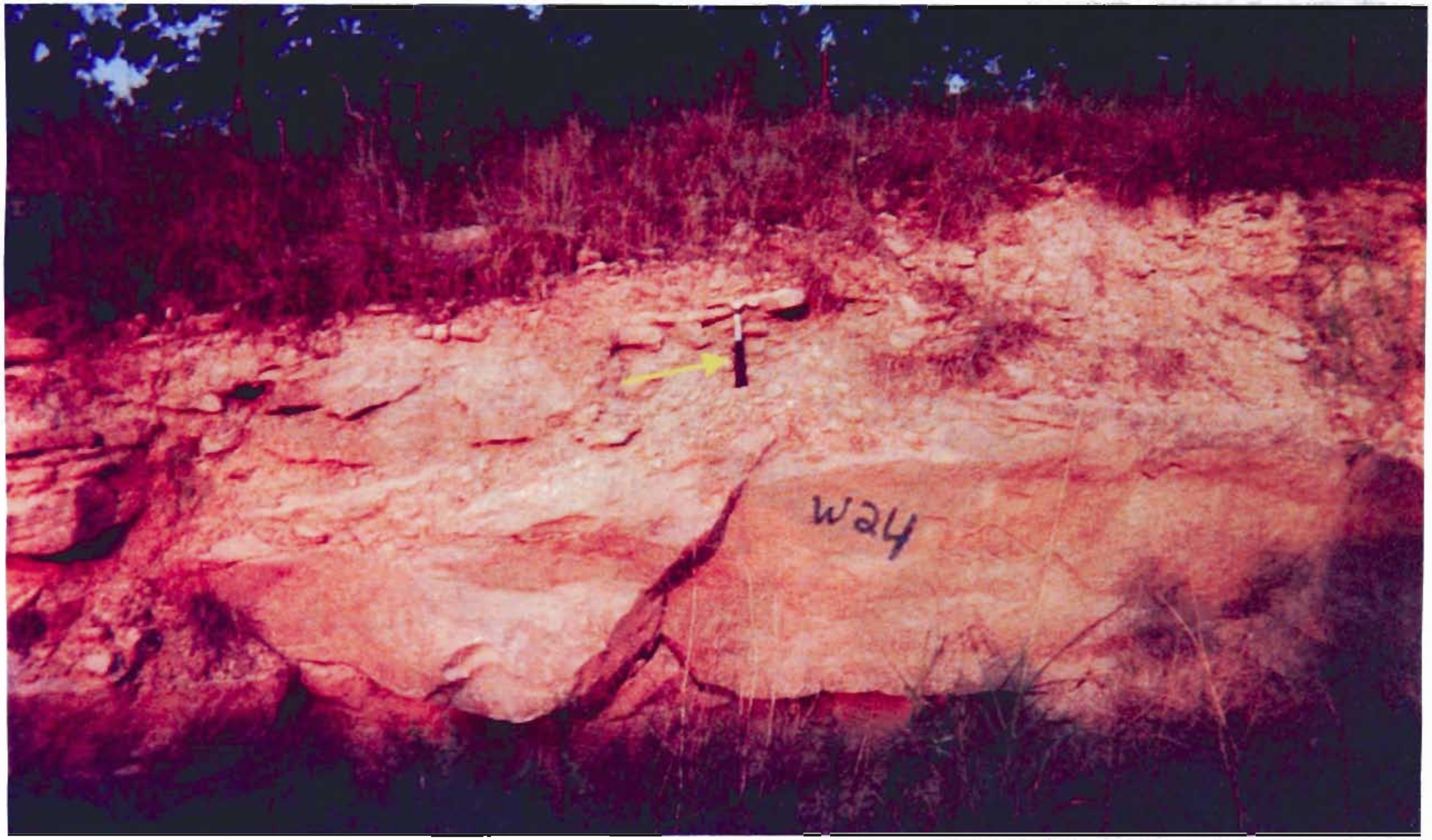
Outcrop of Garber Sandstone in Perry, OK.



Outcrop in the Garber Sandstone in Perry, OK. These photos were taken from a shale quarry. The photo on the left was taken of strata that would have been a few meters above the picture on the right. Notice the thin bed of sandstone at the top of the picture on the left.

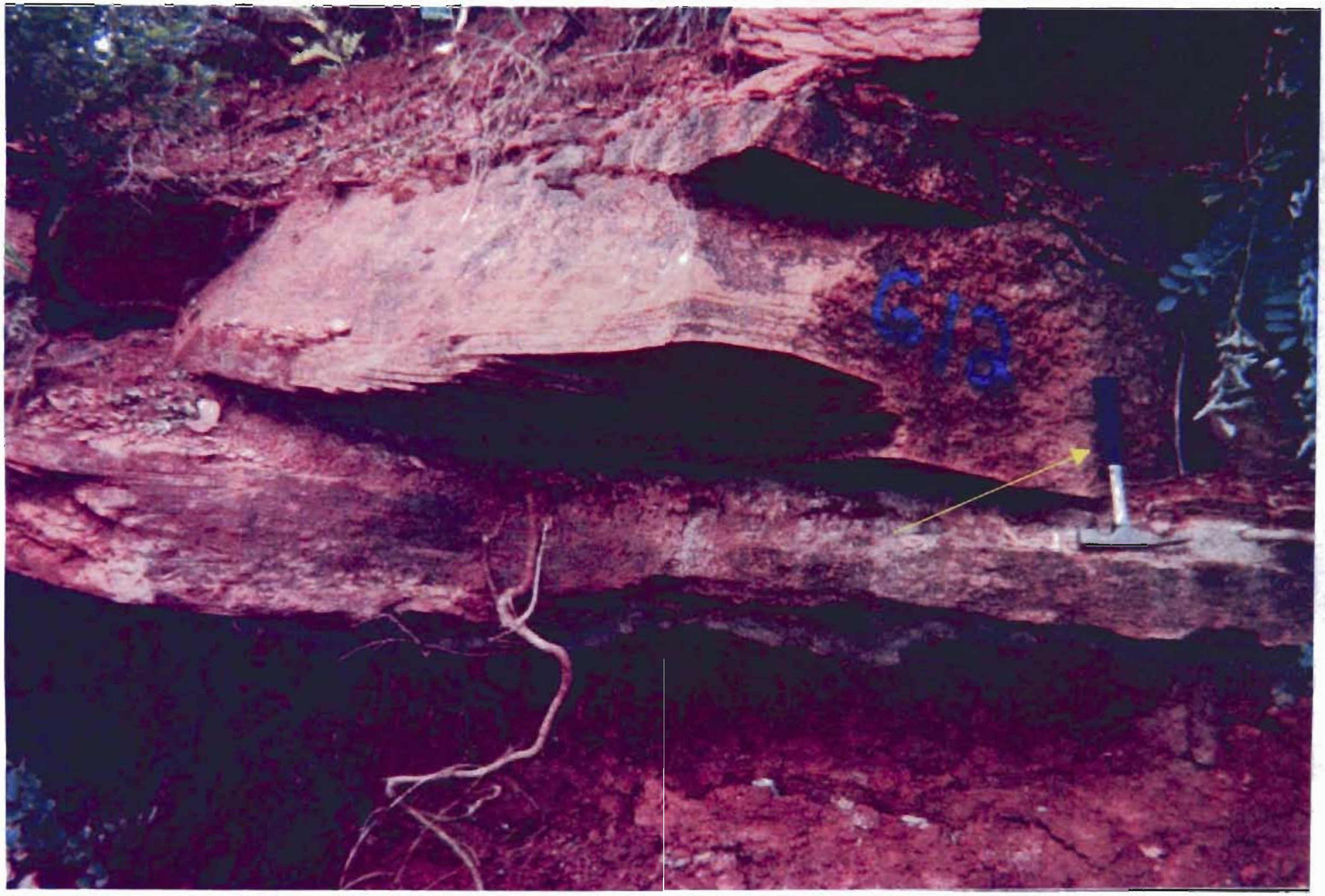


Outcrop in the Garber Sandstone (southern half of study area).

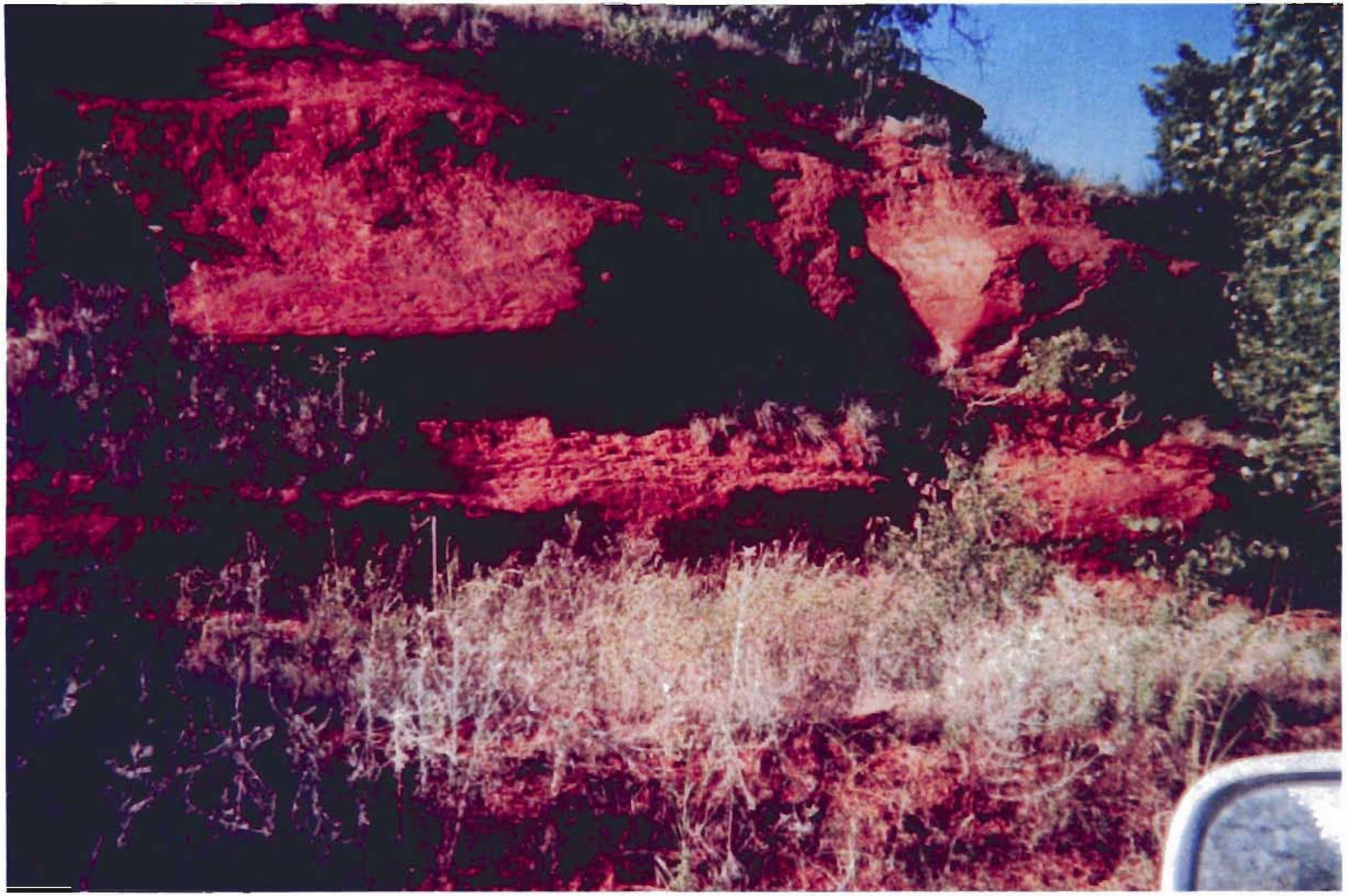


Outcrop of sandstone in the Wellington Formation a few kilometers north of Lake Carl Blackwell on a rural dirt road (southern half of study area).

Outcrop of silty-sandstone in the Wellington Formation less than a kilometer north of Hwy. 412 (northern half of study area).



Outcrop of Garber Sandstone (southern half of study area).



Outcrop of the White Horse Group (southwestern corner of study area).

Outcrop of the White Horse Group (southwestern corner of the study area).

Hand samples of sandstone from the White Horse Group. The sample on the right is coated with paraffin (Scale = 10cm between white bands).

Hand sample of Garber Sandstone.

Hand sample of mudstone in Garber Sandstone.

Hand sample of Cedar Hills Sandstone (clay- and silt-rich).

Hand samples of Cedar Hills Sandstone (clay- and silt-rich).

VITA #1

Cecil Kevin Belt

Candidate for the Degree of

Master of Science

Thesis: GIS AS AN IMPORTANT AID TO VISUALIZING AND MAPPING GEOLOGY AND ROCK PROPERTIES IN REGIONS OF SUBTLE TOPOGRAPHY: ANEXAMPLE FROM NORTH-CENTRAL OKLAHOMA

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