GIS as an aid to visualizing and mapping geology and rock properties in regions of subtle topography

Kevin Belt[†]
Environmental Science Graduate Program, 003 Life Science East, Oklahoma State University, Stillwater, Oklahoma 74078, USA

Stanley T. Paxton[‡]
School of Geology, 105 Noble Research Center, Oklahoma State University, Stillwater, Oklahoma 74078, USA

ABSTRACT

This study visualizes, quantifies, and evaluates relationships between bedrock geology and topography through the use of GIS. The study area contains weakly consolidated Permian-aged sandstone and shale of slightly differing ages that have been dissected by the regional drainage. The erosion of these rocks has produced a subtle but well-defined topography. Data for this work were obtained from a 30 m resolution digital elevation model (DEM) and the bedrock geology map of Oklahoma. Numeric values of local slope angle and relief were extracted from the DEM and associations with geologic formations were summarized and compared. The maps reveal that local topographic variations are dependent on the relative abundance of sand to shale in the underlying bedrock. This finding is significant because the topographic expression is so subtle that associations between topography and bedrock geology would not be easily recognized or quantified with conventional field techniques. To identify controls on topography, sandstone thicknesses were measured in outcrop and the bulk density of field samples was measured in the laboratory. We find that sandstone thickness is greater in areas of higher local relief and thinner in areas of lower relief. In contrast, bulk density, used as a proxy for susceptibility to erosion, is not significantly different between areas. These findings suggest that presence and thickness of sandstone, even if weakly consolidated, plays a role in determining topographic expression of bedrock. This GIS-based technique, when constrained by geology, can enhance the quality of multiuse mapping programs in the geosciences, agriculture, and civil engineering.

[†]E-mail: cecilbelt@hotmail.
[‡]Corresponding author e-mail: pstanle@okstate.edu.

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INTRODUCTION AND STATEMENT OF PROBLEM

With the prospect of global warming and increased instances of drought, much benefit could be derived from regional documentation of the geological controls on surface erosion and topography. Landscape change is a natural process in the geomorphic evolution of any region. Regional and local variations in surface topography can be attributed to numerous factors such as climate, geology (e.g., regional uplift, lithology), and people. Within small, geographically restricted areas, the extent to which some of these factors (such as climate) operate to sculpt surface topography is more or less constant. Consequently, differences in erosional topography across short spatial distances can be attributed primarily to the properties of the underlying bedrock. For example, juxtaposed sedimentary rock units (formations or lithofacies) will erode quite differently based on differences in lithology and/or differences in the lithification history (extent of compaction and cementation during burial), prior to uplift and erosion. Toward this end, we designed a study to quantify and evaluate some of the controls on erosional topography within a geographically restricted area of north-central Oklahoma. For this study, we hypothesize that topographic differences observed within and between geologic units result from the response of differing bedrock types to erosion. In essence, this study is using currently available digital tools and data sets to quantitatively evaluate G.K. Gilbert's Law of Structure (1877). The Law of Structure states, "…erosion is most rapid where resistance is least, and hence as the soft rocks are worn away the hard rocks are left prominent."

Quantitative evaluation of landscapes can be difficult with traditional topographic maps, particularly for large geographic areas with subtle relief where a large number of measurements would be required to quantify the fabric of the landscape. To quantify topography and test relationships to bedrock geology, a digital elevation model (DEM) with a 30 m resolution and a digital surface geology map of the study area were integrated through Geographic Information System (GIS) software. GIS provides most of the visual and analytical tools necessary to study topography and to quantify observations on a regional scale. Statistical analysis software was also used to summarize and evaluate some of the observations.

The objectives of the study were threefold: (1) create composite maps of the study area using a DEM and bedrock geology maps, (2) based on these maps, identify and quantify the subtle but systematic differences in the topography between and within geologic units, and (3) establish the geological reasons for the observed differences in topography.

The 30 m DEM used for this study was the highest resolution image publicly available at the time the work was performed. The DEM is a raster grid of regularly spaced elevation values that have been primarily derived from the U.S. Geological Survey 1:24,000 scale topographic map series. We are confident that a 30 m resolution DEM is adequate for our needs because visual comparisons of the DEM with standard 1:24,000 scale U.S. Geological Survey topographic maps of the study area show strong similarity at points of topographic inflection. In this study, our intent is not to find optimum grid spacing for uniquely defining the topography of north-central Oklahoma, but instead to test that each of the mapped geological units, by virtue of the rock properties, has a unique topographic expression that can be identified with 30 m spacing. Although a lower resolution DEM could have been used for this work (such as a DEM with a grid spacing of 60 m or 90 m rather than 30 m), we believed that lower resolution would fail to capture the topographic detail

needed to define some of the bedrock properties within and between formations.
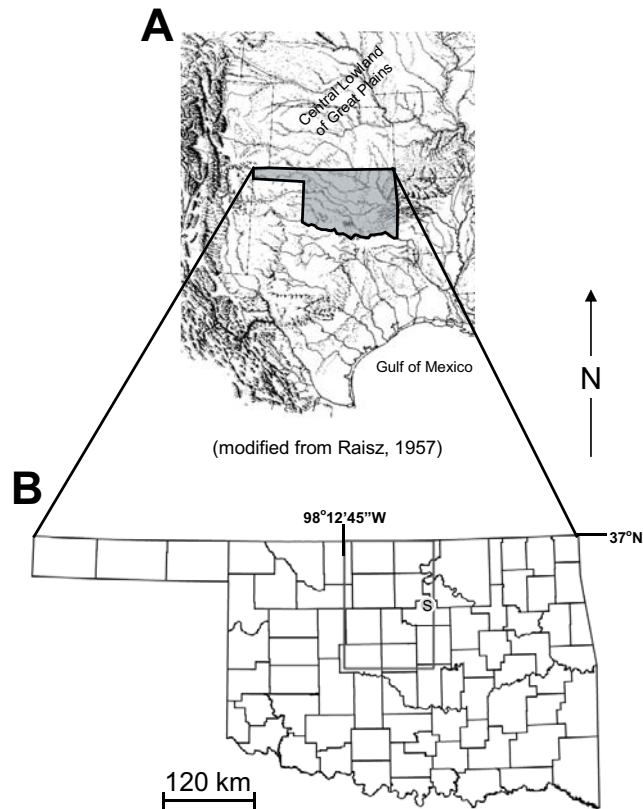
LOCATION AND GEOLOGIC BACKGROUND

The study area (Fig. 1), located within the Central Lowland physiographic region of the United States, is made up of weakly consolidated Permian sandstone and shale. The study area contains gently rolling hills in the southern portion while the northern portion is a relatively flat plain (Figs. 1, 2, and 3). The Arkansas and Cimarron Rivers dissect this portion of north-central Oklahoma, flowing from the Rocky Mountains in the west toward the east. Elevation of the study area ranges from 445 m in the west to 240 m in the east (205 m maximum relief). Topography in the hilly areas of the study exhibit gradual up/down relief changes of ~9–14 m/km (slope of ~0.5–0.8°). Most of the study area has relief that is much less than 9–14 m/km. The study area receives ~76 cm of rainfall in the west and 90 cm in the east. Average annual surface temperature ranges from 58° to 62° (north versus south). Seventy-five days per year have temperatures of 32° or lower in the south. In the north of the study area, 105 days per year are 32° or lower (Oklahoma Mesonet, 2003). The topography within the area is similar to other unglaciated portions of the Central Lowlands and Great Plains physiographic regions of North America.

The stratigraphic thickness of the Permian in the study area is estimated to be ~600 m (inferred from illustrations of Johnson et al., 1989). The Permian thickens into the adjacent basins, with ~2000 m of section present in the Anadarko Basin to the southwest. Regional dip of the Permian units is ~1/2° to the west (9.5 m/km or 50′/mile). From the base up, the Permian stratigraphic units sampled in the study include the Wellington Formation, Garber Sandstone, Hennessey Group, and the Whitehorse Group (Fig. 2A). The El Reno Group (including the Flower Pot Shale and Duncan Sandstone), which lies stratigraphically between the Hennessey and Whitehorse Groups, was not included in this study due to limited areal extent and surface exposure. The stratigraphic nomenclature used for this study is adapted from U.S. Geological Survey metadata files (U.S. Geological Survey, 1996a, 1996b, and 1996c).

Few modern stratigraphic studies have been conducted on the Permian units outcropping in the study area. Past studies are listed in Table 1. Some U.S. Geological Survey research has been completed on equivalent Permian stratigraphic intervals that occur far to the south of the study area. The U.S. Geological Survey work has focused more on water quality than

Figure 1. (A) Portion of the Raisz (1957) physiographic map of the United States showing the location of Oklahoma in the central lowlands of the Great Plains. (B) The study area in north-central Oklahoma (outlined by rectangle) is 120 km west to east and 175 km north to south. "S" indicates location of Stillwater, Oklahoma.

on stratigraphic description (see Christenson and Havens, 1998, for a summary of the U.S. Geological Survey research on the Central Oklahoma Aquifer). Quaternary terraces and recent alluvium unconformably overlie the Permian units in the major river drainages of the study area. Terraces and recent alluvium were not included in the topographic analyses performed in this study.

In most cases, sandstone that occurs in any of these Permian units can be easily crushed with the hand. Reconstruction of burial history suggests the rocks have been buried no greater than 1.0 km (Schmoker, 1986). Locally, the sandstones contain minor carbonate and Fe-oxide cements, particularly in the more thinly bedded (<10 cm), fine grained intervals. The rocks contain no quartz cement, suggesting that the sandstones have not been subjected to burial temperatures >60–80°C. The sandstones are lithified because of a combination of mechanical compaction from overburden pressure and the presence of Fe-oxide-rich depositional matrix that loosely binds the grains together (Table 1).

PREVIOUS WORK

To our knowledge, this north-central Oklahoma study is the first attempt to quantify topography relative to bedrock geology in an area of subtle relief (vertical up/down changes of <9–14 m/km). Kühni and Pfiffner (2001) performed a similar study in the high-relief setting of the Swiss Alps using a 250 m resolution (rather than 30 m as in the present study) DEM. Through numerical analysis of the geomorphological characteristics and comparing the geomorphology with an erodibility map, they concluded an "intimate relationship existed between mountain-scale erodibility and topography." Though the geological settings are distinctly different, the Kühni and Pfiffner study is significant in that their conclusions suggest that the hypothesis of this north-central Oklahoma study is viable.

Haugerud et al. (2003) highlight the geological benefits of using lidar (light detection and ranging) at one-meter resolution for imaging part of the Seattle, Washington, fault zone.

A

Permian (Leonardian/Guadalupian)

Quaternary Alluvium and Terraces

Whitehorse Group

Hennessey Group

Garber Sandstone

Wellington Formation

(after USGS, 1996c)

B

36° 20' N Latitude

N

Slope Angle Classes (in degrees)

- 0.00 - <0.25
- 0.25 - <0.50
- 0.50 - <0.75
- 0.75 - <1.00
- 1.00 - <1.25
- 1.25 - <1.50
- 1.50 - <1.75
- 1.75 - <2.00
- 2.00 - <2.25
- 2.25 - <2.50
- 2.50 - <2.75
- 2.75 - <3.00
- 3.00 - <3.25
- 3.25 - <3.50
- 3.50 - <3.75
- 3.75 - <4.00
- 4.00 - <4.25
- 4.25 - < 4.50
- 4.50 - <5.00
- 5.00 - <8.00
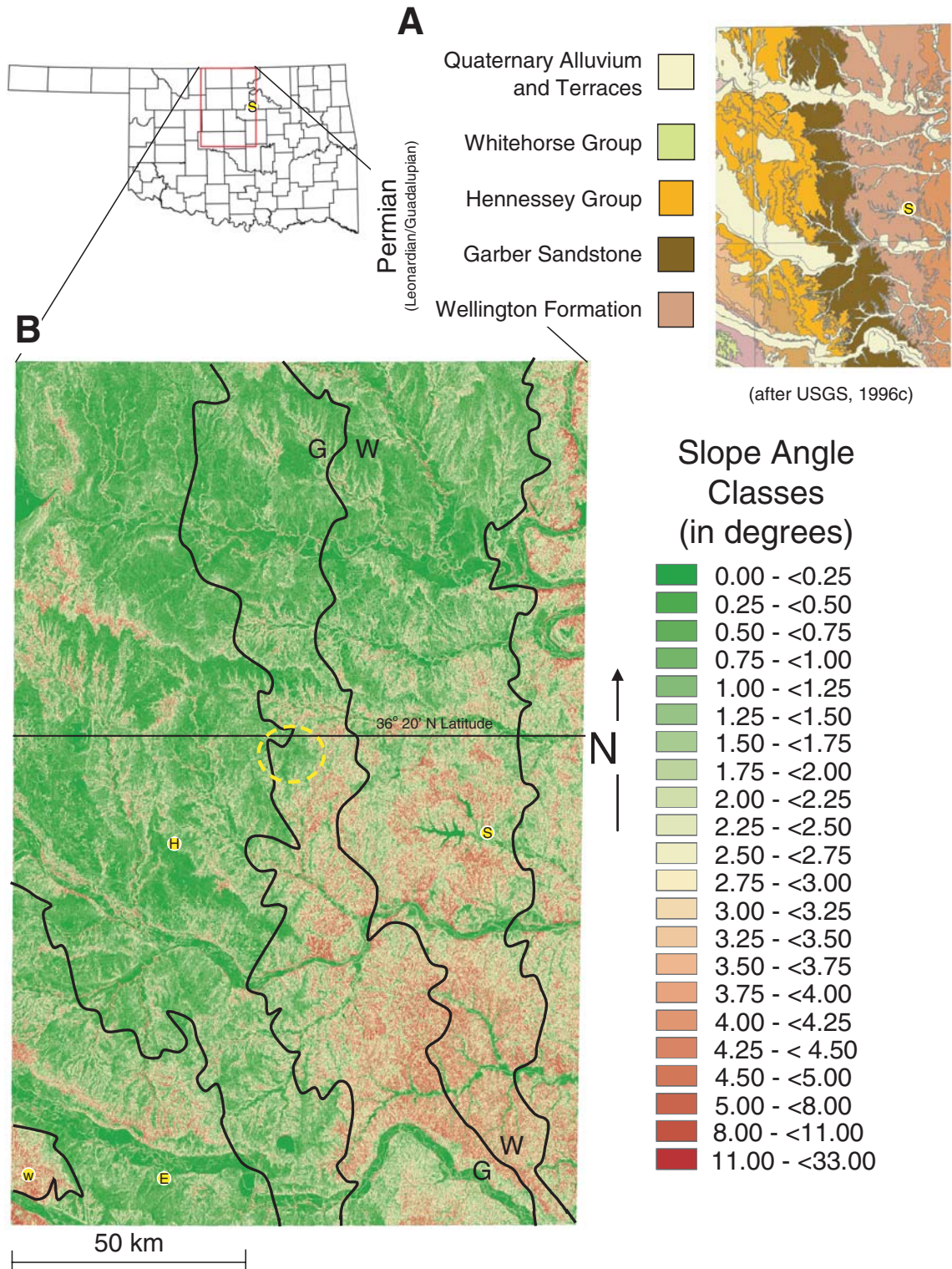- 8.00 - <11.00
- 11.00 - <33.00

50 km

Figure 2. (A) Permian bedrock map and stratigraphic column for section evaluated in this study. The Whitehorse Group (lime green) is present in the far southwest corner of the map. The map pattern on the far east side of (A) is Pennsylvanian-age rock that was not included in this study. Other map features are discussed in the text. (B) Slope angle map of north-central Oklahoma. The colors on the map correspond to a window or range of local slope angle as defined by the 3 × 3 pixel window. The bold lines on the slope angle map are the contacts between the major formations, identified in (A). Other map features are discussed in the text. "S" indicates location of Stillwater, Oklahoma, in (A) and (B). Small white circles containing H and W in (B) correspond to the locations of Hennessey Group and Whitehorse Group rock units, respectively. These areas are also identified by color code in (A). The small white circle containing an "E" is the approximate location of the town of El Reno, Oklahoma.

This high-resolution approach is revolutionizing investigations into modern geomorphic processes and events in the seismically active Puget Lowland. Though the present work in north-central Oklahoma does not use lidar, we propose that in cases where quantifying local geological detail is advantageous, use of readily available high resolution DEMs (30 m, 10 m) can yield comparable geological information at a fraction of the cost required to acquire, process, and analyze lidar data.

METHODOLOGY AND PROCEDURES

Surface geology maps were downloaded from the U.S. Geological Survey Water Resources of Oklahoma web page (U.S. Geological Survey, 1996a, 1996b, 1996c). 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 GIS. In addition to the digital geology map, a paper map of the state (Miser, 1954) was acquired from the Oklahoma Geological Survey (scale of 1:500,000). A composite 30 m resolution DEM was purchased through the U.S. Geological Survey National Elevation Data set (NED). The DEM for this study has a consistent datum, elevation unit, and projection. Edge matching, filling slivers of missing data, and other corrections to minimize artifacts were performed on the DEM prior to purchase. A DEM is a two-dimensional raster representation of topography that consists of uniformly spaced points (resolution in meters) for which the x, y (geographic coordinates), and z (elevation) values are known and referenced to a datum. A DEM can be made using several methods and data sources. Readers are referred to the U.S. Geological Survey Web site for details about the construction, resolution, and accuracy of

Figure 3. Two images of the north-central Oklahoma landscape. (A) View toward the south showing the rolling hills of the Wellington Formation, located in the southern portion of the study area near Stillwater ("S" on maps). Sandstone is exposed in the lower left corner of the photo (arrow). Sandstone is commonly exposed at or near the top of most hills. (B) View to the west showing the plains landscape developed on the Hennessey Group shale near Hennessey, Oklahoma ("H"). Photo locations are indicated on the map in Figure 2B.

DEMs (see U.S. Geological Survey, 2003). U.S. Geological Survey DEMs are used in research and represent one of the best digital topographic products available at a reasonable cost.

Slope, Hillshade, and Composite Maps

Using GIS, a raster-based slope angle map was created using the DEM of the study area. A slope angle map reflects the surface topography of an area by classifying slopes based on the angles (which are mapped as different colors using a color ramp). Therefore, as the slope angle changes from one location to another, 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

TABLE 1. DESCRIPTION OF GEOLOGICAL UNITS IN NORTH-CENTRAL OKLAHOMA

Formation/Group	Lithology	Lithification	Reported depositional setting	References
Wellington Formation	Red-brown shales in the north, grading into fine-grained red lenticular sandstone bodies and mudstone-clast conglomerate southward	Poor[†] to moderate[‡]	Deltaic/Tidal Flat	U.S. Geological Survey (1996a); Shelton (1979); Shelton et al. (1985); Ross (1972)
Garber Sandstone	Mostly orange-brown, fine- to medium-grained quartzose sandstone and conglomerate, interbedded with shales and mudstones in the southern portion of the study area. In northern portion of study area, shales dominate and sandstones are almost completely absent	Poor to moderate	Fluvial/Deltaic/Tidal Flat	U.S. Geological Survey (1996a); Shelton (1979)
Hennessey Group	Massive reddish-brown mudstone, orange-brown to greenish gray siltstone, and fine-grained sandstone. More "blocky" than most Permian shales and have a conchoidal fracture	Poor	[§]	Breit et al. (1990); Aurin et al. (1926); Gould (1911)
White Horse Group	Orange-brown, cross-bedded, fine-grained sandstone and siltstone with some dolomite and gypsum beds	Poor to moderate		U.S. Geological Survey (1996b)

[†]Poorly lithified: Sandstone can be crushed to yield individual sand grains between thumb and forefinger.
[‡]Moderately lithified: Sample can be broken into pieces with bare hands but fragments are difficult to crush into individual sand grains between thumb and forefinger.
[§]Previous authors have not addressed details of depositional settings.

in slope. In this case, GIS was used to create a slope angle map from the DEM by calculating a slope angle value from a 3 × 3 pixel window. A map of local slope angle values is calculated for the center pixel of the 3 × 3 window. A GIS algorithm then compares the elevation of the center pixel relative to the elevation of the surrounding pixels. A slope angle calculation is performed for each pixel on the DEM, and the output is used to construct the slope map. The number of pixels on the DEM and the resolution of the new raster-based slope map are identical to the original input map (i.e., 30 m). This approach yields slope angle values that are a function of local relief and *virtually independent* of regional changes in elevation across the study area. From a statistical analysis point of view, however, the technique does yield an output data set that contains spatial autocorrelation (Laurini and Thompson, 1992; Reynolds, 1997). Each of the output data points is to a degree mathematically related to neighboring points. This is because six of nine pixels used to calculate slope angle at each position on the map are in common with pixels used to calculate the immediately adjacent estimate of slope. Autocorrelation should not compromise the results and conclusions of the present study because we are not trying to establish bivariate or multivariate relationships between slope and any other DEM-derived attribute of topography.

A map of local relief for the study area was constructed next. This was accomplished in a manner similar to generation of the slope angle map (use of a 3 × 3 pixel window) except that the algorithm output is expressed in terms of the absolute value of relief (in meters) rather than slope in degrees.

The 30 m DEM was used to create a hillshade map of the study area. The hillshade map simulates illumination of the study area. The user sets the angle and direction of illumination to bring out the fabric of the landscape. The hillshade map greatly aids in visualization of the study area by providing a sense of how the terrain would look in 3-D. As an internal check on data quality, the hillshade map was compared with standard shaded-relief topographic maps to ensure that the hillshade map was providing an image that honors recognized topographic inflexions in the study area.

A composite map was constructed by sequentially overlaying the DEM, slope angle, relief, hillshade, and surface geology maps. County boundaries, towns, and roads were added to assist in locating areas of interest. The slope, relief, hillshade, and composite maps were visually inspected to identify locations of abrupt or anomalous topographic change. Areas of abrupt change were later evaluated in the field and with rock samples in the laboratory so as to test hypotheses regarding the associations between bedrock properties and variations in topography.

Quantifying Topography

For this portion of the study, numeric cell values were extracted from specific areas of the slope (or relief) map corresponding to the character of the bedrock geology (within and between formations). Polygons corresponding to the shape of each bedrock formation were used to "clip" the slope angle map so that the cell values could be analyzed with respect to a formation only. "Clipping" can be thought of as a cookie cutter that is cutting through cookie dough. In this case, the polygons are like cookie cutters while the slope map is the cookie dough. This approach enables one to statistically isolate the topography of areas with special geological interest, such as the topography associated with a specific formation, bedrock type, or to evaluate an abrupt change in topography within a formation. Based on inspection of the composite map and knowledge of the local geology, polygons were drawn and used to clip out portions of the Whitehorse Group, Hennessey Group, Garber Sandstone, and Wellington Formation within the geographic bounds of the study area. Quaternary alluvium and terraces that occur along the drainages within these bedrock units were not included in the analysis (were clipped out). The Garber Sandstone and Wellington Formation were also separated into northern and southern halves (divided at Perry, Oklahoma) to evaluate observed intraformational topographic differences. The subdivision of each of the two formations into northern and southern halves at Perry is supported by the work of Aurin et al. (1926) who noted (p. 793) that Wellington mudstones occur to the north of Perry while alternating beds of red shales and red sandstones persist to the south of Perry.

The clipped cell values were extracted from the maps and imported into a statistical analysis program in order to perform univariate analysis of the data (mean, mode, median, range, and minimum-maximum). The univariate analysis included systematic inspection of histogram shapes relative to bin-interval size for each of the geological populations. Histogram shapes were inspected to find unrecognized geological subpopulations that may be hidden in the data. In addition, sample means for within and between-formation polygon-defined areas were compared using pooled (equal variance) and Satterthwaite (unequal variance) t-tests to determine if slope angle (and relief) populations were significantly different from one another.

RESULTS AND DISCUSSION

Hillshade Map

Angular illumination of the DEM transformed the subtle topography of north-central Oklahoma into a region that appeared to have an erosional mountain belt located in the southern and eastern portions of the study area (Fig. 4). Trial and error revealed that the grain of the topography was most enhanced when illuminated from the north at 65°. In a totally unexpected finding, the hillshade map reveals that a large system of lineaments crosscuts the study area in NE-SW and NW-SE directions. 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. (1) the state of Oklahoma bedrock-geology map (Miser, 1954) shows the occurrence of faults in the southeastern portion of the study area and beyond; the faults run approximately parallel to both sets of lineaments in the hillshade map; (2) Shelton et al. (1985) showed that the bedrock of Payne County (which is in the center of the study area) is locally jointed in two directions and that the orientations of the joints are in close agreement with the lineaments of the hillshade map; (3) the streams on a hydrographic map of Payne County overlay the lineaments, suggesting a subtle but important structural control on the location of low order streams (in the sense of Strahler, 1952); and (4) numerous field observations (and a few measurements) of joint orientation made by the authors are aligned with the lineaments. This finding is unexpected in that the Permian rocks exposed at the surface have never been buried very deeply and are weakly consolidated. Intuitively, we suspected that the rocks, because of the relatively simple burial history, would not have acquired a regional tectonic overprint. Moreover, we suspected that the rocks were not coherent enough to maintain a regional system of joints upon exhumation by erosion. The true source of the jointing is unknown. As the lineaments penetrate all formations, any influence on the topographic analysis is assumed to be uniform throughout the study area.

Slope Angle and Relief Maps

Classifying the data intervals or bins on the slope angle and relief maps required some trial and error. To recognize systematic changes in topography, slope angle and relief classes had to be very small to capture the minor variations in the landscape. Because the goal of this work is to determine if associations exist between geology and topography, a class interval was

selected that maximized the contrast in slope angle between the mapped geologic units established by the U.S. Geological Survey. The ability to "tune" the slope angle classes using geologic insight is a major strength of our GIS approach. The resulting slope map shows stark contrast between some of the different geological units, though these slope angle differences would probably not have been noticed in the field. The sharp contrast on our slope angle map between geologic units is, therefore, a result of our classification choice. Had fewer classes been selected, the contrast between geologic units on the maps might not have been recognized. Summary statistics for the slope and relief maps are summarized in Table 2.

Topographic differences on both maps appear to correspond to areas that differ in resistance to erosion (because of differences in bedrock lithology). Areas that are more sand prone appear to give rise to topography with greater slope angle than areas consisting primarily (or entirely) of shales, regardless of formation. The shale-prone areas in all the formations (shown in green on the slope map, Fig. 2B) have very low slopes relative to the sand-prone intervals. Most of the shale-prone areas have negligible slope.

Analysis of Slope Angle and Relief by Formation

The summary statistics and frequency histograms of slope angle for the formations and formation subpopulations are shown in Figure 5. On the basis of our analysis, slope data, which is a continuous random variable, yields histograms with a Gaussian character. All the histograms are positively skewed because of the occurrence of high slope angles on the margins of the drainages. The tails of the histograms in areas with low mean relief appear to be truncated at low slope angles. This is because, by definition, slope values cannot go below zero degrees. In an attempt to generate more symmetrically shaped distributions, a logarithmic transformation was applied to each of the data sets. This transformation did not improve the symmetry of the distributions but instead yielded distributions that were negatively skewed and truncated at higher slope angles. Histograms for the Wellington Formation, Garber Sandstone, and Hennessey Group shales (each in their entirety) appear quite similar but differ considerably from the shape of the Whitehorse Group histogram (Fig. 5). The Hennessey, Garber, and Wellington frequency distributions are strongly positively skewed (Figs. 5B, 5C, 5D) whereas the Whitehorse distribution is broader and more normally distributed (Fig. 5A).
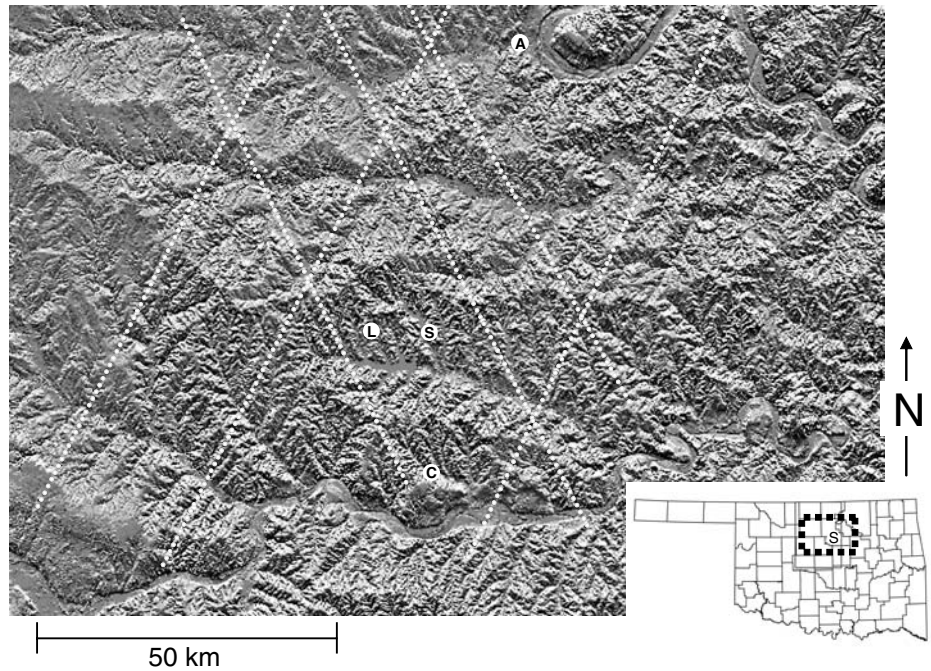
Figure 4. Hillshade map illuminated from the north at an angle of 65°. Note the NE-SW– and NW-SE–trending lineations in the landscape. Dotted lines have been added to the image to enhance the illustration. According to the hydrography map (not included), the lineations appear to control the location of minor tributaries to the major west-to-east drainages. The area covered by this field of view extends a distance to the east of the study area proper (see inset). The orientations of these two sets of linear features are roughly aligned with recognized faults mapped in eastern Oklahoma and appearing on the geologic map of Oklahoma (Miser, 1954). The faults are not indicated on the hillshade map above. The dashed lines on the image have been added to help in the visualization of the lineaments. "S" indicates location of Stillwater, Oklahoma. Lake Carl Blackwell ("L") is the flat area to the west of Stillwater. The Cimarron ("C") and Arkansas ("A") Rivers are also indicated.

TABLE 2. SUMMARY STATISTICS FOR ALL DATA FROM SLOPE AND RELIEF MAPS

Map	n	Mean	Standard deviation	Mode	Minimum	Maximum
Slope	3.88×10^7	2.1°	2.2°	0.29°	0	36.8°
Relief	3.88×10^7	3.1 m	2.9 m	0.35 m	0	59.9 m

Although the topography of the Hennessey Group (seen in the field and as observed on the slope angle map) is relatively flat and homogeneous throughout its extent, the topography of the Garber Sandstone and Wellington Formation is not homogeneous. Therefore, based on knowledge of the geology and inspection of the slope map, the north-south trending Garber Sandstone and Wellington Formation polygons were split into northern and southern halves near Perry, Oklahoma, for further analysis (36° 20′ N latitude). The reason for dividing the polygons at this latitude was based on observable rapid changes in topography. The change in topography at Perry was first noted by Aurin et al. (1926) and marks the transition from mudstones to the north and shales and sandstones to the south. Ross (1972), Shelton (1979), and Shelton et al. (1985) also note the change in bedrock lithology in this part of Oklahoma (including Noble and Payne Counties). In essence, based on their outcrop descriptions and narratives, the ratio of sand to shale is low north of Perry and higher to the south of Perry.

The Garber Sandstone and Wellington Formation (within the study area) contain two separate slope angle subpopulations (Figs. 5C, 5D) that represent lithofacies changes within
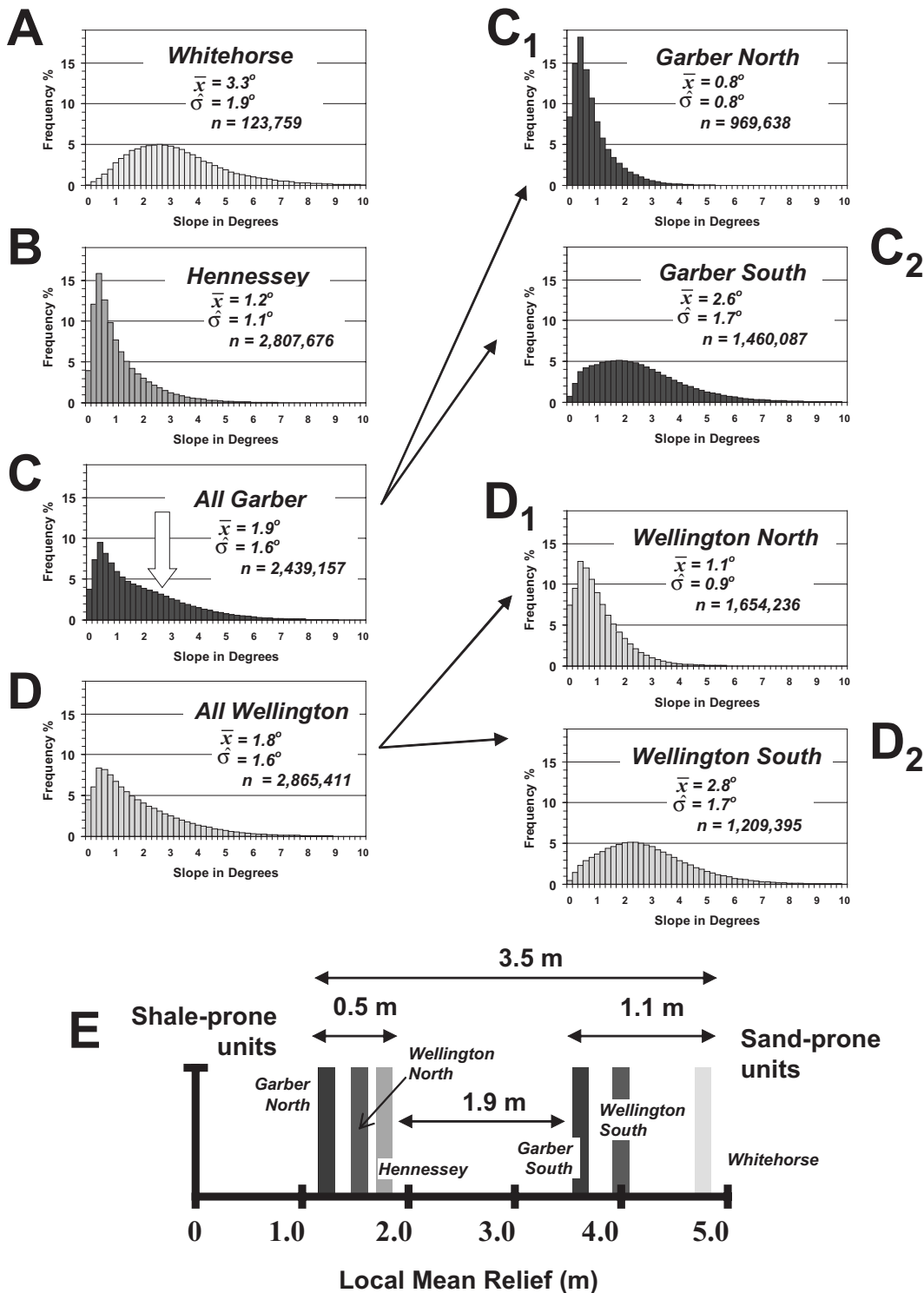
Figure 5. Slope angle frequency distributions for the White Horse Group, Hennessey Group, Garber Sandstone, and Wellington Formation. The arrow in the "All Garber" population (C) is pointing to the mean slope angle value that corresponds to the sand-prone portion of the Garber Sandstone (C_2), occurring in the southern portion of the study area. The shapes of the frequency distributions for the sand-prone portions of the Garber (C_2) and Wellington (D_2) are very similar in appearance to the bell-shaped curve of the sand-prone Whitehorse Group. (E) Bar graph showing the natural groupings of the geologic units on the basis of mean relief. The difference in mean relief (or slope angle) within populations of sand-prone (or shale-prone) units is less than the difference in relief between the sand- and shale-prone units. This suggests the relief (or slope angle) differences between the sand- and shale-prone units are probably dependent (in part) upon the relative proportions of sandstone and shale in the stratigraphic section.

the formations. The shale-prone northern area of the two units, characterized by lower slope angles (see slope map, Fig. 2B), has a mean slope angle of 0.8° (Garber in the northern part of the study area, Fig. 5C₁) and 1.1° (Wellington in the north, Fig. 5D₁), whereas the sand-prone southern portions of each formation has a mean slope angle of 2.6° and 2.8° respectively (Figs. 5C₂ and 5D₂). The means of the northern halves of these two formations (shale prone) are more similar to the Hennessey Group (1.2° and shale prone, Fig. 5B), whereas the means of the sand-prone southern halves of the Wellington and Garber are more similar to the Whitehorse Group (3.3° and sand prone, Fig. 5A). In addition to similarity in population means for the shale-prone units, each of the shale-prone units has a frequency distribution (histogram) of slope values that is strikingly similar in shape (Fig. 5B, C₁, D₁). The univariate statistics for relief are summarized in Table 3.

Statistics are used in this study to 1) describe the sample populations, and 2) test for differences among population means. The use of a high-resolution DEM helped to ensure that each bedrock sample population is an unbiased and representative subset of the entire available population that could possibly be sampled (at the surface and within the study area). Moreover, because of the nature of quantitative GIS-based studies, the data sample populations are inherently large. According to the Central Limit Theorem, as sample size of a population grows large, the sample mean converges on the true population mean. Consequently, each of the formations or subsets of formations (based on lithofacies differences) are significantly different from one another even though absolute differences between some of the populations are small. Some of the comparisons are highlighted in Table 4. Bedrock geology (formation or location within a formation) is the independent variable and mean slope angle is the dependent variable. In each case, the null hypothesis is rejected in favor of the alternative hypothesis (means of the two groups compared are significantly different from one another). Table 4 indicates that the difference between the means is too great to be a chance event (likelihoods of <1 in 10,000). The hilly, high relief (in a relative sense, of course) and sand-prone southern Garber, southern Wellington, and Whitehorse are all found to be statistically significantly different from one another. Likewise, all the shale-prone units (Hennessey, northern Garber, and northern Wellington) are statistically different from one another. Based on inspection of the frequency histograms, however, these sand-prone units are very much alike in terms of slope angle and relief relative to the shale-prone Hennessey, northern Wellington, and northern Garber units (Fig. 5E). Therefore, on the basis of multiple lines of evidence (histogram shape, mean slope angle/relief, appearance on the slope/relief maps, and field observations), we conclude that a major control on topography in the study area is the lithology of the bedrock (sandstone versus shale), or more simply, the presence/absence of sandstone regardless of age or formation. Though not explicitly documented in the geological literature, the rate at which shale weathers in outcrop must be so rapid that even the presence of weakly consolidated sandstone has a measurable influence on topographic relief.

Pennsylvanian-age bedrock occurs as a north-south swath on the far east side of the slope map (Fig. 2B). Note that the Pennsylvanian bedrock has high local slope angles (red) at all locations up and down the east side of the map and up to the western contact with the overlying Permian units. Though the Pennsyl-

vanian section was not evaluated in this study, the high slope angle suggests that fundamental differences in rock properties exist between the Pennsylvanian and Permian units in this portion of north-central Oklahoma.

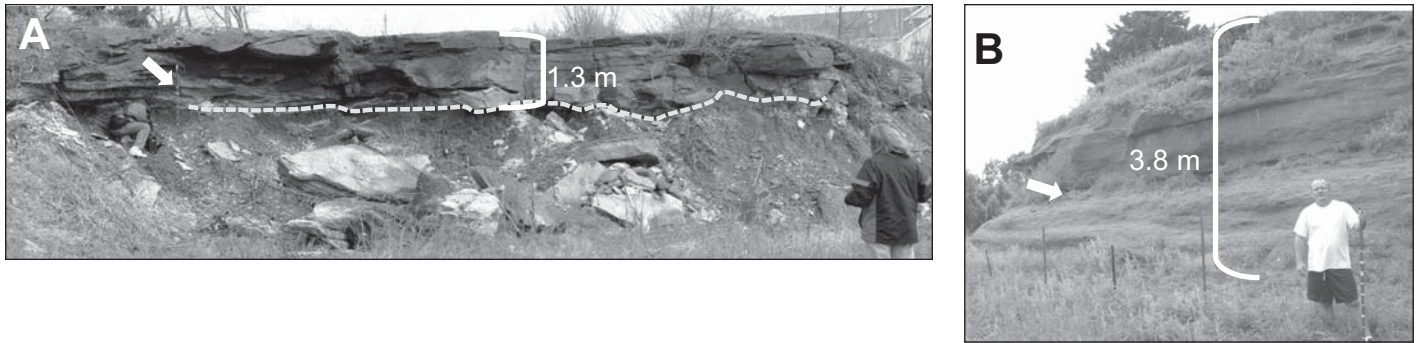## Field-Based Testing of Geological Controls on Topography

Two abbreviated field studies were conducted to more directly evaluate controls on slope angle/relief in the sand-prone Permian units. One approach tested the hypothesis that differences in slope angle result from differences in sandstone thickness (single bed, composite beds, or a high proportion of sand relative to shale). The second approach was to test to see if differences in slope angle result from differences in the integrity or hardness of the sandstone (a consequence of cementation and/or compaction during past burial and prior to uplift/erosion). Though other factors may play a role in controlling local differences in slope, some factors can be eliminated through inspection. Differences in climate should not play a role because of the limited geographic extent of

the study area. Land use can also be discounted because most of the land is mixed-use agricultural. Finally, proximity to major drainages can be dismissed because inspection of the slope angle map clearly shows that some of the lowest relief area (the shale-prone portion of the Wellington Formation) is located immediately adjacent to the Arkansas River, one of the major drainages of the southern Great Plains.

Sandstone Unit Thickness

We tested the hypothesis that relief differences in the study area result from differences in the thickness of the sandstone units. When traveling the roads of north-central Oklahoma, one is struck by the common observation that sandstone outcroppings tend to occur at or near the crest of most hills (Figs. 3A and 6). Because of the occurrence of sandstone at the ridge crests, one can safely assume that sandstone is more resistant to erosion than shale. Further, assuming that all the thick sand-prone units exposed at the surface are equally susceptible to weathering, a thicker sand bed (a single thick unit or amalgamation of thinner units to produce a thick unit) should yield more local relief.

TABLE 3. SUMMARY STATISTICS FOR LOCAL TOPOGRAPHIC RELIEF BY FORMATION AND LOCATION

Formation/group, location	n	Mean (m)	Standard deviation	Minimum	Maximum
Whitehorse Group	123,759	4.7	2.4	0.0	21.0
Hennessey Group	2,807,676	1.7	1.5	0.0	23.0
Garber Sandstone	2,439,484	2.6	2.2	0.0	23.9
Garber north	969,638	1.2	1.0	0.0	15.2
Garber 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

TABLE 4. TESTING FOR SLOPE ANGLE DIFFERENCES BETWEEN SOME OF THE FORMATIONS AND LOCATIONS

Formation/group, location	Variable (°)	Method	Variances	df	t value	pr > |t|
Wellington north versus						
Wellington south	Slope	Pooled	Equal	29×10^5	−1136.7	<0.0001[†]
(shale versus sand)		Satterthwaite	Unequal	17×10^5	−1043.8	<0.0001[†]
Garber north versus						
Wellington north	Slope	Pooled	Equal	26×10^5	−210.72	<0.0001[†]
(shale versus shale)		Satterthwaite	Unequal	23×10^5	−218.94	<0.0001[†]
Garber north versus						
Hennessey Group	Slope	Pooled	Equal	38×10^5	−265.77	<0.0001[†]
(shale versus shale)		Satterthwaite	Unequal	24×10^5	−311.71	<0.0001[†]

Note: df—degrees of freedom, t—t statistic, |t|—absolute value of t, pr—level of significance.
[†]Evidence to reject null hypothesis in favor of alternative.
Hypotheses: 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).

Figure 6. Photographs of outcroppings of the (A) Wellington Formation in Stillwater, Oklahoma and the (B) Whitehorse Group (Rush Springs Sandstone) that occur southwest of El Reno, Oklahoma. (A) The staff (arrow) in the upper photo is ~1.5 m in length. Erosional contact of this sandy lithosome with the underlying shale is indicated by the position of the dashed line. (B) This Whitehorse Group outcrop is ~3.8 m in thickness, though greater thickness may be present beneath the surface of the roadcut. The outcrop has an interval of shale near the middle of the exposure (~30 cm in thickness, arrow), though the thickness of the entire sandy interval is measured for comparison to topographic slope and relief measured from the DEM. Photo locations are indicated in Figure 2B where "W"—Whitehorse, "E"—town of El Reno, and "S"—Stillwater.

TABLE 5. SUMMARY STATISTICS FOR SANDSTONE THICKNESS
BY FORMATION AND LOCATION

Formation/group, location	n	Mean (m)	Standard deviation	Minimum	Maximum
Whitehorse Group	10	2.9	2.0	0.7	7.2
Hennessey Group	(no sandstone found in outcrops)				
Garber Sandstone	35	1.8	1.4	0.4	6.0
Garber north	10	1.2	0.7	0.7	3.0
Garber south	25	2.0	1.6	0.4	6.0
Wellington Fm.	30	1.0	0.8	0.1	3.0
Wellington north	15	0.5	0.4	0.1	1.5
Wellington south	15	1.5	0.9	0.2	3.0
Combined Garber and Wellington					
North	25	0.8	0.7	0.1	3.0
South	40	1.8	1.4	0.2	6.0

The role of sandstone thickness was evaluated by collecting measurements from Whitehorse Group, Garber Sandstone, and the Wellington Formation outcroppings along the E-W and N-S section roads in the study area (Fig. 6). The importance of sandstone thickness in controlling slope angle or relief was also evaluated internal to the Garber Sandstone and Wellington Formation. In these two formations, distinct differences in topographic relief occur within the formations rather than between formations. An abrupt change in topography is visible on the slope map at ~36° 20' N latitude (near Perry, Oklahoma, see Fig. 2B). This topographic change corresponds to an area in the southern portion of the study area where the Garber Sandstone and Wellington Formation are characterized by a thicker, cross-bedded sandstone lithofacies. This sandstone lithofacies decreases in thickness and abundance from south to north in the study area as the paleodepositional environment transitions from a more proximal alluvial setting in the south and east to a more distal marginal marine or mud-flat setting in the north and west.

Sandstone thicknesses were estimated with a Jacob's staff. A tape measure was suspended down from the top of the outcrop for exceptionally thick intervals. Measurements were made at ~70 locations (Table 5). Multiple measurements were made at a few locations. For the purposes of this analysis, outcrops dominated by amalgamated and stacked sandstones were considered one layer (>70% sand and with shale layers <40 cm in thickness) (Fig. 6). Details of the geometry and continuity of the Permian units have not been studied by previous workers. The sandstone layers in the Garber and Wellington are commonly lenticular, discontinuous, and have a channelized character. The Whitehorse

sand units, some of which have an aeolian character, are the thickest (~2.9 m on average, based on 10 measurements), whereas the shale-prone Garber Sandstone and Wellington Formation units that crop out in the northern portion of the study area are the thinnest (~0.8 m on average, based on 65 measurements, Table 5). T-tests were conducted to evaluate differences between mean sandstone thickness (dependent variable) and the bedrock geology (formation or location within a formation, the independent variable). The t-tests (Table 6) indicate that the combined Garber/Wellington shale-prone intervals located in the north of the study area are statistically different (thinner) from the combined sand-prone Garber / Wellington locations to the south (which contain thicker intervals of sand). The observed differences in the means would occur by chance in only about one in a thousand cases or less. In the southern portion of the study areas, the thickness of the Wellington Formation sandstones is not significantly different from sandstones that occur in the Garber Sandstone (observed differences in the means is likely to occur by chance in thirty to forty cases out of 100 trials). The mean Whitehorse Group sandstone thickness is statistically different (thicker) from the mean of the Garber / Wellington sandstones (thinner) located in the southern portion of the study area, though the level of confidence is not extremely high (the observed difference in means would be expected to occur by chance in five to thirteen cases out of 100 trials, Table 6).

In conclusion, these measurements show that the Permian bedrock in north-central Oklahoma has characteristic topographic expression that can be attributed to differences in sandstone thicknesses between and within formations. A

cross-plot showing the relationship of mean sandstone thickness to mean slope angle and relief (from the DEM summary statistics, Table 2 and Fig. 6) is provided in Figure 7. At the scale of our study, the data indicate that slope and relief vary positively with the thickness of the sandstones as measured in outcrop.

Bulk Density

Bulk density (g/cc) of sandstone from the southern Garber Formation and the Whitehorse Group were measured via a standard technique (see AASHTO, 1996) in the Civil Engineering Laboratory at OSU. Bulk density of sandstone is being used here as a measure of sandstone cementation. In this case, we hypothesize that sandstone from the higher relief Whitehorse Group will be more dense (contain more pore-filling cement) than the sandstone from the lower relief southern Garber Formation. In turn, the higher bulk density will render the White-horse sandstone more resistant to weathering. Sandstone with greater resistance to weathering has the potential to produce a landscape with greater local relief relative to sandstone that is relatively unconsolidated.

In outcrop, the Garber Sandstone and the Whitehorse Group appear to be very similar in terms of composition and texture. The White-horse Group sandstones, as discussed above, however, are more thickly bedded than the Gar-ber sandstones. In both units, sandstones sampled from thicker beds (>0.5 m) are more friable than sandstone samples taken from thinner beds (interbedded and in close proximity to shales). The thinner sand beds, at any given sample site, appear to be more cemented because of local carbonate or iron cement and the presence of a higher proportion of clay matrix. These field observations alone suggest that the slope angle differences, quantified from the DEM between these two sandstone populations, probably do not result from differences in cementation, as origi-nally hypothesized. As a rule of thumb, hilltops are capped with thick sandstones (which turn out to be friable) and not thin sandstones (some of which have a tendency to be cemented).

The Garber Sandstone has a mean bulk density of 1.93 g/cc and the Whitehorse Group, 1.99 g/cc. Inspection of a frequency histogram of bulk density measurements for the Garber Sandstone and Whitehorse Group, however, reveals the presence of at least two subpopulations of den-sity within each formation/group and mentioned above (a reflection of thicker vs thinner beds) (see arrow in Fig. 8). The population to the left of the arrow in Figure 8 is the low-density population, common to sandstones that occur on the hill-tops. This population, ranging from 1.74 g/cc to 1.98 g/cc, equates to a porosity range of 25–34%

TABLE 6. TESTING FOR DIFFERENCES IN SANDSTONE THICKNESS OBSERVED IN OUTCROP BETWEEN FORMATIONS AND LOCATIONS

Formation/group, location	Variable (m)	Method	Variances	df	t value	pr > |t|
Garber/Wellington north versus						
Garber/	Thickness	Pooled	Equal	63.0	−3.44	0.0011†
Wellington south		Satterthwaite	Unequal	59.7	−3.98	0.0002†
(shale versus sand for formations combined)						
Garber south versus						
Wellington Fm. south	Thickness	Pooled	Equal	38.0	1.01	0.3210‡
		Satterthwaite	Unequal	37.8	1.16	0.2550‡
(sand versus sand in the southern portion of the two formations)						
Garber/Wellington south versus						
Whitehorse Group	Thickness	Pooled	Equal	48.00	2.03	0.0479†
		Satterthwaite	Unequal	11.20	1.62	0.1322‡
(sand versus sand in different formations/groups)						

Note: df—degrees of freedom, t—t statistic, |t|—absolute value of t, pr—level of significance.
†Evidence to reject null hypothesis in favor of alternative.
‡No evidence to reject null hypothesis in favor of alternative.
Hypotheses: 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).

$$y = 1.9146Ln(x) + 2.3672$$
$$r^2 = 0.6571$$
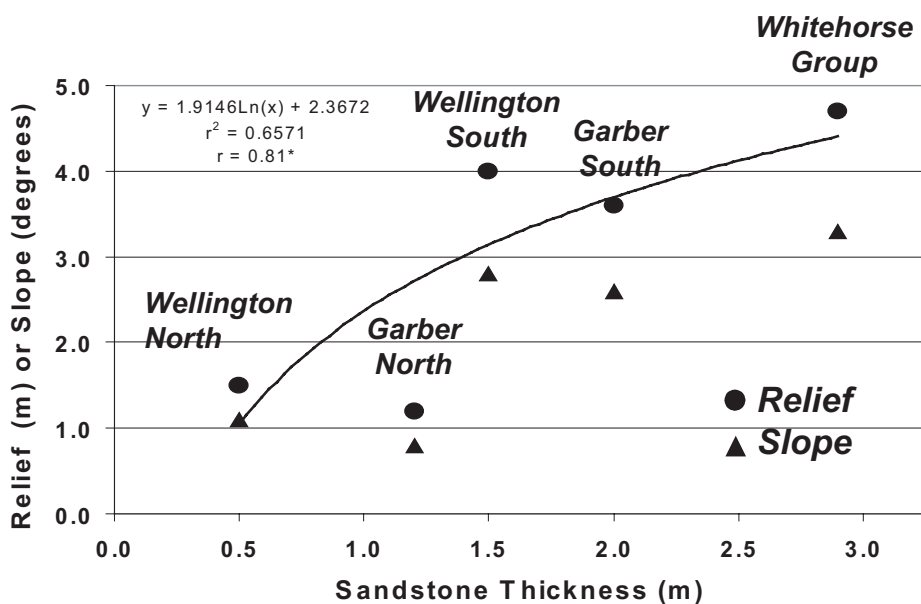$$r = 0.81*$$

*significant at p = 0.10, df=3

Figure 7. Illustration showing that as mean sandstone thickness increases, landscape slope angle and relief increase. The sandstone thicknesses were measured in the field while the relief and slope data were summarized from a 30 m resolution DEM. The logarithmic line of best fit for relief is significant at p = 0.10. The plot contains five mean values for both slope and relief. Each mean value is based on between 10 and 25 measurements. y—slope, the independent variable; r—sample correlation coefficient; r^2—proportion of the vari-ance of slope that can be attributed to regression on bed thickness; p—level of significance; df—degrees of freedom.
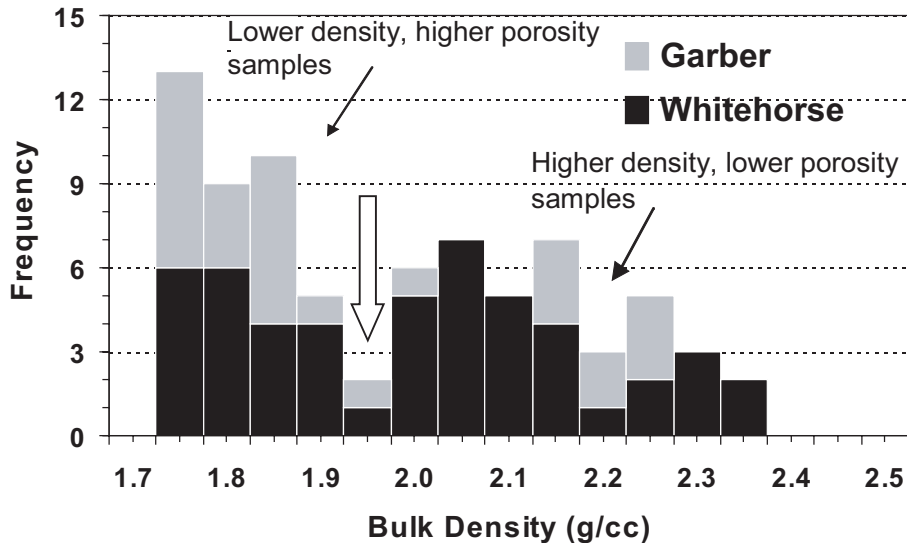
Figure 8. Stacked bar graph of bulk density measurements obtained for the Garber Sandstone and Whitehorse Group (Rush Springs Sandstone). Each formation contains at least two populations; a denser, less porous set of sandstones that occur in more thinly bedded intervals, and a less dense, more porous population of sandstones that occur in thicker sandstone intervals. Sandstones that cap the hilltops are most commonly thick, friable, and porous. The arrow indicates a natural break between the populations.

TABLE 7. SUMMARY STATISTICS OF SANDSTONE BULK DENSITY BY FORMATION FOR THE LOW DENSITY POPULATIONS HIGHLIGHTED IN FIGURE 8

Formation/group	n	Mean (g/cc)	Standard deviation	Minimum	Maximum
Whitehorse Group	22	1.830	0.070	1.750	1.975
Hennessey Group		(no sandstone found in outcrops)			
Garber Sandstone	18	1.810	0.060	1.740	1.960
Wellington Fm.		(not sampled)			

TABLE 8. TESTING FOR DIFFERENCES IN BULK DENSITY FOR GARBER AND WHITEHORSE SANDSTONES SAMPLED FROM OUTCROP

Formation/group	Variable (g/cc)	Method	Variances	df	t value	pr > ltl
Garber Sandstone versus						
Whitehorse Group	Bulk density	Pooled	Equal	38.0	-0.62	0.5422[†]
		Satterthwaite	Unequal	37.6	-0.62	0.5381[†]

Note: df—degrees of freedom, t—t statistic, ltl—absolute value of t, Pr—level of significance.
[†]No evidence to reject null hypothesis in favor of alternative.
Hypotheses: 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).

(assuming a grain density of 2.65 g/cc). This range in porosity is expected for sandstones that have been buried to ~1 km maximum burial depth prior to exhumation (comparison to chart in Paxton et al., 2002). The mean bulk density of the Garber and Whitehorse samples, contained within this low-density population is 1.81 g/cc and 1.83 g/cc, respectively (Table 7). Based on a t-test, the means of bulk density for these two units contained within the low-density population are not significantly different (Table 8). On the basis of this test, we conclude that one *cannot* argue that the slope angle differences between the Whitehorse and Garber result from differences in

degrees of consolidation of the sandstones. As mentioned, field observations suggest that the more highly cemented, thinner sandstone layers, the layers that would be expected to more resistant to weathering, occur rarely at the hilltops. Moreover, thin, cemented sandstone beds occur not only in the higher relief areas of the Garber Sandstone and Whitehorse Group, but also in the lower relief, shale-prone portions of the Garber north and Wellington north units. Therefore, based on multiple lines of evidence, we conclude that the observed differences in slope angle or relief, as measured with the DEM, do not appear to vary systematically with the degree of sandstone lithification. The data suggest that variations in the degree of Permian sandstone lithification and topography are independent of one another in north-central Oklahoma.

Other Comments

The hillshade, slope, relief, and other GIS-based maps are useful complements to conventional tools for mapping bedrock geology. Whether the objective is to produce generalized regional maps for structural analysis and stratigraphy or very detailed maps for agriculture and land-use planning, the GIS maps commonly reveal structural grain and lithologic features in the landscape that might not be detected otherwise. Detection of lineaments on the hillshade map (Fig. 4) is a case in point. Aside from structural analysis, the slope angle map (Fig. 2B) can be used to identify locations where established formation contacts between units may be called into question. For instance, the oval-shaped area drawn near the central part of the map, Figure 2B, has been mapped as Garber Sandstone. On the basis of the relief map, however, the topographic character of the bedrock at that site is more similar to Hennessey Group than to Garber Sandstone. Another recognized mapping issue in Oklahoma is the location of the contact between the Garber Sandstone and Wellington Formation (N-S contact on the map in Figure 2B is indicated by G-W). Historically, discriminating the contact between these two formations has been based on the relative proportion of sand-to-shale as noted in outcrop (fossils are rare in these continental deposits). The difference in sand-to-shale is not visually apparent on the slope map, suggesting that perhaps the location (or even the existence) of the contact between the two units should be reevaluated.

SUMMARY, CONCLUSIONS, AND FUTURE STUDIES

1. Based on visual inspection of frequency distributions and univariate summary statistics,

the rank order of decreasing slope angle (and relief) are as follows: Whitehorse (3.3°) > Wellington in the southern portion of the study area (2.8°) > Garber in the south (2.6°) > Hennessey Group shale (1.2°) > Wellington in the north (1.1°) > Garber in the north (0.8°). T-tests demonstrate that all these populations are statistically different from one another.

2. Based on field observations and the slope angle map, the sandstone-prone units (Whitehorse, Wellington in the southern portion of the study area, and Garber in the south) have higher slope relative to the shale-prone units (Hennessey Group shale, Wellington in the north, and Garber in the north). This observation suggests that the presence of sandstone, even if weakly consolidated, has a bearing on the occurrence of topography. Lithology is a more important determinant of relief than is formation designation.

3. Measurements of sandstone thickness conducted in the field suggest that the slope angle of the sand-prone formations vary with the thickness of the sandstone units (sandstones with higher proportion of sandstone have higher relief). This relationship appears to be valid both within and between formations. Therefore, the rank order of slope angle for the units cited above (in #1) may possibly be a direct function of the thickness or abundance of sandstone (proportion of sand relative to shale) at any given location. Bulk density of field samples evaluated in the laboratory and coupled with observations in outcrops suggests that the difference in slope between the sandstone-prone units does not result from differences in degree of lithification.

4. A hillshade map produced from the DEM reveals that the study area contains a series of NW-SE and NE-SW lineaments. These lineaments appear to have influenced the location of the headwaters and other low-order streams in the regional drainage system. The lineaments are parallel to sets of joints that have been locally documented by other researchers, suggesting that the joint sets and lineaments are genetically related.

5. Future studies could incorporate soil maps, land cover, land use, and additional hydrography to develop a more complete description of the regional variation in topography. Quantitative topographic studies in areas of subtle relief such as in the Great Plains have the potential to provide important data for the description of landscapes. Improved description of the landscape is important for the establishment of better land-use practices.

6. GIS and other similar digital tools provide an opportunity to quantify the landscape and see geological features that have not been previously recognized. This is an important advancement for many fundamental, map-based geoscience disciplines (geomorphology, sedimentology, stratigraphy, structural geology, petroleum geology, hydrogeology, and engineering geology).

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REFERENCES CITED

AASHTO, 1996, Bulk specific gravity of compacted bituminous mixtures using paraffin-coated specimens (T 275-91), *in* Standard Specifications for Transportation Materials and Methods of Sampling and Testing: Washington, D.C., American Association of State Highway and Transportation Officials, 1999 (Interim Edition), p. 600–601.

Aurin, F.L., Officer, H.G., and Gould, C.N., 1926, The sub-divisions of the Enid Formation: American Association of Petroleum Geologists Bulletin, v. 10, no. 8, p. 786–799.

Breit, G.N., Rice, C., Esposito, K., and Schlottmann, J.L., 1990, Mineralogy and petrography of Permian rocks in the Central Oklahoma aquifer: U.S. Geological Survey Open-File Report 90-678, 50 p.

Christenson, S., and Havens, J.S., (eds.), 1998, Ground-water-quality assessment of the central Oklahoma Aquifer, Oklahoma: Results of Investigations: Oklahoma City, Oklahoma, U.S. Geological Survey Water Supply Paper 2357-A, 179 p.

Gilbert, G.K., 1877, Report on the Geology of the Henry Mountains: U.S. Geographical and Geological Survey of the Rocky Mountain Region: Washington, D.C., U.S. Government Printing Office, 160 p.

Gould, C.N., 1911, Geological history of Oklahoma, Chapter III, Preliminary report on the structural materials of Oklahoma: Oklahoma Geological Survey Bulletin 5, 182 p.

Haugerud, R., Harding, D.J., Johnson, S.Y., Harless, J.L., Weaver, C.S., and Sherrod, B.L., 2003, High-resolution lidar topography of the Puget Lowland, Washington—A bonanza for earth science: GSA Today, v. 13, p. 4–10 doi: 10.1130/1052-5173(2003)132.0.CO;2.

Johnson, K.S., Amsden, T.W., Denison, R.E., Dutton, S.P., Goldstein, A.G., Rascoe, B., Sutherland, P.K., and Thompson, D.M., 1989, Geology of the Southern Midcontinent: Oklahoma Geological Survey Special Publication 89-2, 53 p.

Kühni, A., and Pfiffner, O.A., 2001, The relief of the Swiss Alps and adjacent areas and its relation to lithology and structure: topographic analysis from a 250 m DEM: Geomorphology, v. 41, p. 285–307 doi: 10.1016/S0169-555X(01)00060-5.

Miser, H.D., 1954, Geologic Map of Oklahoma: Reston, Virginia, U.S. Geological Survey, and Norman, Oklahoma, Oklahoma Geological Survey, Reprinted 1991, scale 1:500,000.

Laurini, R., and Thompson, D., 1992, Fundamentals of Spatial Information Systems: London, A.P.I.C. Series in Data Processing, No. 37, Academic Press, 680 p.

Oklahoma Mesonet, 2003, Data retrievable from http://www.mesonet.ou.edu/public/.

Paxton, S.T., Szabo, J.O., Ajdukiewicz, J.M., and Klimentidis, R.E., 2002, Construction of an intergranular volume compaction curve for evaluating and predicting compaction and porosity loss in rigid-grain sandstone reservoirs: American Association of Petroleum Geologists Bulletin, v. 86, no. 12, p. 2,047–2,067.

Raisz, E.J., 1957, Landform outline map of the United States with adjacent parts of Canada and Mexico: Brookline, Massachusetts, Raisz Landform Map Company, scale 1:4,500,000.

Reynolds, H., 1997, An introduction to geographical information systems (GIS): Retrieved May 18, 2003 from http://www.badpets.net/IntroGIS/.

Ross, J.S., 1972, Geology of central Payne County, Oklahoma [M.S. thesis]: Stillwater, Oklahoma State University, 87 p.

Schmoker, J.W., 1986, Oil generation in the Anadarko Basin, Oklahoma and Texas: Modeling using Lopatin's Method: Oklahoma Geological Survey, Special Publication 86-3, p. 7–9.

Shelton, J.W., 1979, Geology and mineral resources of Noble County, Oklahoma: Oklahoma Geological Survey Bulletin 128, 66 p.

Shelton, J.W., Ross, J.S., Garden, A.J., and Franks, J.L., 1985, Geology and mineral resources of Payne County, Oklahoma: Oklahoma Geological Survey Bulletin 137, 92 p.

Strahler, A.N., 1952, Dynamic basis of geomorphology: Geological Society of America Bulletin, v. 63, p. 923–938.

U.S. Geological Survey, 1996a, Compliant metadata for digitized geology of Enid quadrangle, north-central Oklahoma: Retrieved April, 2003 from http://ok.water.usgs.gov/gis/geology/index.html.

U.S. Geological Survey, 1996b, Compliant metadata for digitized geology of Clinton quadrangle, west-central Oklahoma: Retrieved April, 2003 from http://ok.water.usgs.gov/gis/geology/index.html.

U.S. Geological Survey, 1996c, Digital Surface Geology Maps of Oklahoma, U.S. Geological Survey Open File Reports 96-373 (Clinton), 96-374 (Enid), 96-378 (Oklahoma City), 96-381 (Woodward): Retrieved April, 2003 from http://ok.water.usgs.gov/gis/geology/index.html.

U.S. Geological Survey, 2003, Digital Elevation Models (DEMs): Descriptions found at http://edcwww.cr.usgs.gov/glis/hyper/guide/usgs_dem.