Integrated Geophysical Studies of the Basement Structures, the Mississippi Chert, and the Arbuckle Group of Osage County Region, Oklahoma

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ABSTRACT

We use the integration of gravity, magnetic, and 3D seismic data to map sedimentary features and study the relationships between sedimentary and basement features in the Osage County area of northeast Oklahoma and adjacent Kansas. We employ volumetric seismic attributes such as coherence and curvature derived from 3D seismic data to better characterize subtle features such as collapse features, faulting and fracturing within the Mississippian and Ordovician carbonate deposits that are difficult to detect on conventional 3D seismic data displays. Blended seismic image of these reservoirs shows polygonal, highly coherent, and high amplitude lineaments with northwest and northeast strike. Lineaments density increases from base of the Pennsylvanian downward through the Mississippian to the top of the Arbuckle Group and decreases downward from the top of the Arbuckle Group toward the Reagan Sandstone. While a one-to-one correlation between the basement structures and the carbonate reservoirs cannot be established, basement structure lineaments are parallel in orientation to those seen within the Mississippian Chert and the Arbuckle Group. We interpret the northeast-striking lineaments to be correlated to the late-Paleozoic Nemaha tectonic and the northwest-striking lineaments to the Osage County basement fabric or the draping of the Mississippian over a cockpit-karsted terrain**.** Due to the prominent gravity and magnetic anomalies interpreted to be associated with the Mid-Continent Rift System (MCRS), we suggest that the MCRS extends into northern Oklahoma. However, geochronological data for basement rocks imply that such an extension would have to be limited to intrusive bodies that have little or no subcrop.

INTRODUCTION

Osage County is located in northeastern Oklahoma and is bounded by the Ozark uplift to the east, the Nemaha uplift to the west, the Kansas state boundary to the north, and the Arkansas River to the southwest (Figure 1). Paleozoic sediments were deposited in this area on part of a gently southward-sloping stable shelf that extends into the Anadarko and Arkoma basins (Thorman and Hibpshman, 1979). Currently, the regional dip is to the west-south-west (Guo and Carroll, 1999). The area has been a prolific oil producing area since the discovery of the giant Burbank field in 1920. Although oil and gas seeps within Osage County have been reported as early as the seventeenth century, production has been mostly from the Pennsylvanian sandstone deposits, namely the Red Fork and the Bartlesville sandstones (Sands, 1927). Significant production has also come from the Cambrian-Ordovician Arbuckle Group that lies unconformably on top of the irregular Precambrian basement surface as well as from Mississippian Chert reservoirs (Thorman and Hibpshman, 1979; Franseen et al., 2004).

The Osagean Mississippi Tripolitic Chert reservoir, informally called "Mississippi Chat" by drillers, is formed from exposed and diagenetically-altered cherty limestone (Rogers, 2001). The vast majority of oil production from Arbuckle reservoirs in Kansas and Oklahoma occurs on the Central Kansas and Nemaha structural highs respectively (Thorman and Hibpshman, 1979). The occurrence of these fracture-controlled reservoirs has been linked to Precambrian basement uplifts (Franseen et al., 2004) and differential compaction and post Arbuckle weathering (Thorman and Hibpshman, 1979). Less clearly established is the interaction between Precambrian basement structures and these fracture-controlled carbonate reservoirs. Even with more than 50 years of production from chert reservoirs, a myriad of misconceptions and enigmas still surround these reservoirs. For example, chert reservoirs are generally associated with carbonate rocks that contain secondary porosity, but Rogers and Longman (2001) have documented a deep-marine clastic chert type of reservoir in California that produces from a primary porosity. These Monterey Cherts have never been sub-aerially exposed and were diagenetically stable in the subsurface where they became an early hydrocarbon accumulation site.

Chert reservoirs are structurally, depositionally, and diagenetically complex. Such complexities are reflected in their heterogeneity, which can be caused by faulting and fracturing. Examples include the Thirty-one Chert reservoirs in the Three Bar field of the Permian Basin, Texas (Ruppel and Barnaby, 2001), and carbonate dissolution in Dickman field in Kansas (Nissen et al., 2006) resulting from transportation and deposition of siliceous sediments (Ruppel and Hovorka, 1995). Faulting and fracturing can act as hydrocarbon barriers creating compartmentalization when they are shale-filled or hydrothermally altered. In other situations, the faults and fractures that cause the heterogeneity can act as a fluid flow conduit (Davies and Smith, 2006). Thus, it becomes imperative to understand these features and map their distribution in the Osage County area. The understanding of porosity and heterogeneity often associated with chert reservoirs is important for the exploration and management of such complex reservoirs.

For the last decade, independent operators have used conventional interpretation methodologies for 3D seismic data to study Midcontinent carbonate reservoirs. Increasingly, volumetric seismic attributes such as coherence, curvature, and amplitude gradients calculated from the 3D seismic data are being incorporated into Mid-Continent exploration workflows to better characterize subtle carbonate features such as karsting, faulting and fracturing, and hydrothermal dissolution that are difficult to image from standard 3D seismic (e.g. Nissen et al., 2006). Seismic attributes that are sensitive to fractures and impedance have also been used to characterize porosity and field scale fractures that are associated with chert reservoirs (Fu et al., 2006). Studying chert reservoirs with the aid of seismic amplitude and attribute data can effectively help delineate fault and fracture distributions within chert reservoirs.

In this paper, we present the results of regional potential field data analysis integrated with and seismic data analysis from several 3D seismic surveys acquired in Osage County, Oklahoma (Figure 1). Our efforts are directed at the fractured-controlled Ordovician Arbuckle dolomite and Mississippian Chert reservoirs that have been faulted, fractured, and diagenetically altered through subaerial exposure and hydrothermal processes. Our objective is to understand the interaction between Precambrian structures and the fracture-controlled carbonate reservoirs. We attempt to establish an association between these structures and the karst reservoirs. In addition, we examine potential linkage between features identified within the Precambrian basement with corresponding features within the sedimentary section.

In addition to Paleozoic targets of current economic interest, we integrate seismic data, regional gravity, and regional aeromagnetic data to study the basement rocks. Our scientific objective is to investigate the extent of the 1100 Ma Mid-Continent rift system (MCRS) across southern Kansas and Oklahoma and the large gravity anomalies in Osage Country that may or may not have a relationship with the MCRS. Density variations (Cook, 1956), deeper crustal sources (Denison, 1981), thinned crust, and Moho-bumps or anti-root (Roark, 1962) have been suggested as the cause of the Osage County anomaly (Figure 2) because of its lack of correlation with known structural features.

GEOLOGIC BACKGROUND

The present configuration of the Osage County area basement rocks reflects subtle Paleozoic movements; according to Chenoweth (1968), the basement surface, which is an irregular erosional surface with series of domes, controls the overlying Paleozoic sedimentary distribution and thickness (Walters, 1946). The Precambrian basement of the region that has been penetrated by drilling consists of petrographically and chronologically-related intrusive and extrusive rocks and their metamorphic rock equivalents. These rocks occur as a relatively thin veneer of shallow intrusive and extrusive rocks that cover unknown older basement rocks (Denison, 1981). These rocks are part of the widespread 1400 – 1340 Ma intracratonic magmatism that formed the Western Granite-Rhyolite Province (WGRP) or its Southern Granite-Rhyolite (SGR) province equivalent (Bickford et al., 1986; Van Schmus et al., 1996) that overprints the earlier Proterozoic continental orogenic outer tectonic belt (Whitmeyer and Karlstrom, 2007) and extends from western Ohio to west Texas (Lidiak et al., 1966; Muehlberger et al., 1967).

Based on the work of Denison et al. (1966) and Denison (1981), the basement rocks of northeastern Oklahoma can be classified into four igneous units: the Washington Volcanic Group (WVG), the Spavinaw Granite Group (SGG), the Osage Microgranite (OM), and the Central Oklahoma Granite Group (COGG), whose distribution are shown in Figure 2. A detailed description of these units can be found in Denison (1981).

Broad domes in the basement are widespread within an approximately 320 square-mile area (829 km^2) that spatially correlates with the prominent Osage gravity anomaly (Figure 2). The western part of Osage County, which is less deformed than the eastern part, also contains fewer northeasterly and northwesterly striking domes, anticlines, and structural basins (Guo and Carroll, 1999).

Two sets of major Precambrian basement faults have been identified within Osage County. The northeast-southwest striking Labette fault that juxtaposes metarhyolitic rocks on the northwestern side (up-thrown) against rhyolitic rocks to the southeast (downthrown) extends northward from Payne County through Osage County and into southern Kansas. In addition, four other northwest-southeast striking faults cross the area (Denison, 1981; Guo and Carroll, 1999).

The intensely sheared and mylonitic Central Oklahoma granite group underlies the Nemaha uplift that bounds Osage County on the west. This uplift consists of a number of crustal blocks that are surrounded on the east and west by Middle Pennsylvanian faults (Luza et al., 1978) that are probably reactivated older features.

Common Paleozoic features that occur within the county include north-northeast and weakly defined northwest-trending broad open-folds and en-echelon normal faults (Bass, 1942). These structures developed sporadically throughout Paleozoic time, and the dip of their flanks increases with depth mostly within the Cambrian and Ordovician strata (Thorman and Hibpshman, 1979).

The Paleozoic sequences in northeast Oklahoma reflect four episodes of north-south marine transgression and regression, and each of these sequences is bounded above and below by a regional unconformity. Figure 3 shows a schematic lithologic column for

Osage County. A late Cambrian sea deposited granite wash or the Lamotte-Reagan Sandstone that probably represents reworked lag gravel deposits eroded from exposed basement unconformably on the Precambrian basement (Keroher and Kirby, 1948).

The Arbuckle Group either unconformably overlies the Lamotte-Reagan Sandstone or directly overlies the Precambrian basement and includes limestone, dolomite, and sandstone units. Where the Arbuckle Group directly overlies the Precambrian basement, the lower Arbuckle Group units onlap rugged Precambrian basement topography; the upper Arbuckle Group is bounded at the top by a major interregional unconformity representing a major sea regression and subaerial exposure of the North America craton (Sloss 1963). Due to post-Arbuckle erosion and weathering which enhances porosity and permeability, the upper Arbuckle Group contains a series of karst sinkholes, collapse structures, and fractures and joints similar to its Ellenberger equivalent in the Fort Worth basin in Texas. Cansler and Carr (2001) suggest that the distribution and alignment of these karst features in the Kansas Arbuckle Group are influenced by basement structures. Thus, the complexity of the Arbuckle structures increases in structurally high areas (Franseen et al., 2004).

During the middle Ordovician, the Simpson Sea transgressed and regressed across Osage County depositing the Simpson Group. A shallow sea covered most of Oklahoma during the Mississippian period depositing the Mississippian Limestone, which consists partly of limestone (chert) and dolomite that lies conformably on top of the Woodford Shale. Uplift and either surface/near surface erosion or in-situ weathering of the underlying Mississippian Limestone resulted in erosion and diagenetic alteration of the top of the this unit. The resulting irregular surface of this highly porous, hard, and tight

Mississippian Chert and the dissolution of calcite create secondary porosity that makes the Mississippi Chert a good hydrocarbon reservoir. In north-central Oklahoma and south-central Kansas, the Mississippian Chert present between the Pennsylvanian and Mississippian unconformity occurs as widespread, heterogeneous reservoirs that are generally not continuous (Rogers, 2001).

PREVIOUS GEOPHYSICAL STUDIES

In 1948, one of the first geophysical collaboration efforts between the United State Geological Survey and the United State Coastal and Geodetic Survey resulted in the collection of regional gravity data around northeast Oklahoma and southeast Kansas. Cook (1956) recognized that the Osage anomaly did not correlate with regional geology. Roark (1962) suggested the cause of this anomaly to be due to crustal thinning, a Moho-bumps, or anti-root.

Guo and Carroll (1999) conducted a lineament study that consisted of surface and subsurface fracture analysis by comparing satellite images and aerial photographs from Osage County. The results of this study showed a correlation between northeast-southwest and northwest-southeast surface lineaments with subsurface features.

Mid-Continent Rift System

The Middle Proterozoic Mid-Continent Rift System (MCRS) of North America is a 1100 Ma failed rift that extends for more than 1243 miles (2000 kilometers) (Hinze et al., 1997) from Lake Superior, through northwestern Wisconsin, southeastern Minnesota, southwestern Iowa, and southeastern Nebraska toward central Kansas. Robbins and Keller (1990) and Adams and Keller (1994) suggested that dikes related with the MCRS mafic intrusion extend into Oklahoma. Other authors that have shared similar thoughts include Yarger (1985) and Xia et al. (1996). However, (Berendsen, 1997) and Bickford (1988) failed to validate such an extension via drill holes. Repeated reactivation of Paleozoic structures (Berendsen, 1997) covering the MCRS by Phanerozoic cover as well as rift offset (Xia et al., 1996) are some of the explanations given as to why the MCRS cannot be seen directly in Oklahoma.

DATASETS

Potential field data

The association of the MCRS with prominent gravity and magnetic anomalies makes the potential field methods an effective tool to investigate the MCRS. The datasets used in this study include aeromagnetic data that is part of the North American Magnetic Map project grid (http://crustal.usgs.gov/namad), which is the result of a combined effort of the United State Geological Survey (USGS), Geological Survey of Canada (GSC) and Consejo de Recursors Minerales of Mexico (CRM). This dataset contains grids obtained from the Geological Society of America's (GSA) Decade of North American Geology (DNAG) program and is available for download at: (ftp://ftpext.usgs.gov/pub/cr/co/denver/musette/pub/open-file-reports/ofr-02-0414).

In addition to the aeromagnetic grid, gravity data points were downloaded from a community online gravity database that is maintained by the Pan American Center for Earth and Environmental Studies (PACES) at the University of Texas at El Paso (UTEP) (http://research.utep.edu/paces). In addition, in the summer of 2008, we collected an additional 200 gravity readings to better constrain the Osage anomaly. The gravity points were spaced at 200 m (656 ft) intervals and acquired along existing roads. We reduced the gravity data using the standard data reduction program of Holom and Oldow (2007), utilizing a standard Bouguer reduction density of 2670 kg/m^3. This spreadsheet uses the standards proposed by the North American Gravity Database Committee (Hildenbrand et al., 2002; Hinze et al., 2005). The resulting Bouguer anomaly values were gridded and upward continued to 1 km. Residual anomaly grid was produced by subtracting the upward continued grid from the original Bouguer anomaly grid thereby emphasizing relatively shallow features (Figure 2).

Potential field data enhancement and filtering techniques

Potential field anomalies contain a wide range of signals originating from various sources and depths; there are times when a local anomaly needs to be extracted from a regional anomaly. The techniques of enhancing an anomaly of interest from the Precambrian basement allows us to compare deeper, Precambrian basement structures with shallower, sedimentary structures identified on seismic amplitude and attribute data. All potential field enhancement and filtering are performed using modern magnetic and gravity processing and interpretation software.

The gravity and aeromagnetic data are gridded with a grid spacing of 5000 m (16404 ft) and 1000 m (3281 ft) respectively. The aeromagnetic data were reduced-to-the pole (RTP) in order to remove magnetic anomaly distortion caused by varying magnetization inclination and azimuth. This linear transformation transforms a total magnetic intensity field into a vertical component field such that the magnetic anomaly will lie directly over its causative source (Kis, 1990). To highlight the effect of anomalies within the Precambrian basement, we generate a residual Bouguer anomaly and a residual total magnetic intensity (TMI) map from the complete Bouguer anomaly and the RTP TMI grids, shown in Figure 4.

To highlight lateral or abrupt changes in magnetization, which can delineate faults or lateral changes in magnetic susceptibility, we compute the horizontal gradient magnitude (HGM), tilt derivative, horizontal derivative of the tilt derivative, and vertical derivative for both gravity and aeromagnetic datasets (Figures 5a-d). Although these edge-detecting derivatives enhance lateral discontinuities, it is the interpreter's responsibility to provide a geologically acceptable interpretation. The mathematical foundation gradient method interpretation workflows can be found in Grauch and Cordell (1987), Roest et al., 1992, Miller and Singh (1994); Blakely (1996), Verduzco et al. (2004), and Li (2006). For example, Grauch and Cordell (1987) cite an example of where the gradient from a sloping interface could leads to maxima with two edges. This observation can be misinterpreted as two separate interfaces separating three geological units.

We also apply directional filters to isolate linear anomalies associated with the MCRS. Figure 6 shows trends parallel to those of the MCRS indicating the MCRS may extend southward into Oklahoma.

Seismic data

Four different 3D seismic surveys provided by the Osage Nation and Spyglass Energy LLC (Figure 1) allow us to map and understand the interaction between sedimentary features and structures within the Precambrian basement. The seismic data provide spatially and vertically-limited structural details but at higher resolution than the potential field data. More importantly, the seismic data allow us to image the thin, non-magnetic chert reservoirs.

After generating the Arbuckle Group and the Mississippi Chert time-structure map, we generate horizon slices through attribute volumes to enhance fractures, faults, karst, and differential compaction that are not easily seen in the seismic amplitude data. The physical and geometrical features in the attributes use models of dip and azimuth, waveform similarity, amplitude, and frequency content from adjacent seismic samples, which can then be rendered on a computer for interpretation. Attributes that we found useful include coherence, most-negative and most-positive curvature, total energy, and energy-weighted coherent amplitude gradients; examples of their application and mathematical background are available in Chopra and Marfurt (2007).

PRECAMBRIAN SECTION DATA ANALYSIS AND INTERPRETATION

Potential field expression of Osage basement features

Osage County exhibits simple Bouguer gravity anomalies and complex magnetic anomalies (Figures 2). We note the broad gravity high “Osage anomaly” (OS1 on Figure 4a) (Cook, 1956; Denison, 1981) that underlies most of Osage County, the elongate north-northwest gravity high anomaly that occurs west of the Nemaha uplift (OS2 on Figure 4a), and the elongated north-northeast gravity high that abuts against the Wichita uplift (OS3 on Figure 4a). Robbins and Keller (1990) indentified gravity anomaly OS3 and through 2D gravity modeling concluded it to be a Keweenawan volcanic rock.

The broad high amplitude anomaly se on the residual gravity and magnetic maps (OS1) (~ 20 mGal, ~150 nT) measures approximately 99 km by 75 km (Figure 4) suggesting a deep, broad, high density, high magnetic susceptibility source. Gravity and magnetic derivative maps suggest a northwest-trending anomaly (Figures 5a, 5b, and 5d). However, the directional filtering map in Figures 6 indicates both a northwesterly- and northeasterly- trending anomalies. OS1 anomaly occurs within the Osage Microgranite and Washington Volcanic Group. At locations where the Spavinaw Granite Group is present, this kind of prominent high gravity response is lacking (Figure 4).

High gravity and magnetic values (~18 mGal, ~200 nT) dominate the 83 km by 48 km OS2 anomaly (Figures 4). Occurring south of the MCRS relics, gravity, a magnetic derivative map, and directional filter maps (Figures 5 and 6) suggest a northwest-trending anomaly. The short wavelength nature of this elongate anomaly suggests a shallow source.

The anomaly that abuts against the Wichita uplift (~10 mGal) measures 75 km by 33 km and trends northeast (OS3; Figures 4 and 5). The magnetization displayed by this elongated anomaly (-250 nT to the north +115 nT to the south) is complex but forms a distinct signature.

Based on the gravity data and its derivative maps alone, we interpret that the MCRS extends across Oklahoma, abutting against the Southern Oklahoma aulacogen (Figure 5).

Directional filters show that the OS1 anomaly has both northwestern- and northeastern-trending components. OS2 has a characteristic northwest and northeast anomaly trend while OS3 anomaly exhibits a trend that is consistent with the northeast trend displayed by the MCRS (Figures 6). Thus, we interpret the OS2 anomaly to be part of the MCRS; the same conclusion cannot be made about the OS1 anomaly.

Ages dating from Precambrian wells available from the work of Denison (1981) and Van Schmus et al. (1993) only provide one date as young as the MCRS. The Texaco Inc. Kohpay well (Table 1), which is the only well that penetrates the Osage Microgranite and lies close to OS1 gives a Rb/Sr age of 1183 ± 46 Ma (Figure 6). However, the wells to basement are sparse to the south and the anomalies can be from intrusions that do not subcrop. In a similar case, a massive 1.1 Ma mafic intrusions from the Central basin platform of west Texas, which has been missed by previous wells, was penetrated by the Nellie #1 well that that was drilled into about 5 km of basement rocks. The well was centered on a gravity anomaly maximum; and surprisingly, a well that is just 5 km north tested granitic and metamorphic basement rocks (Keller et al., 1989).

Seismic description of Osage basement reflectors

Basement rocks generally display incoherent signals on seismic data, which may be due to the lack of bedding, high dip and structurally complex, diagenetic homogenization, relatively small impedance contrast, and limited angles of illumination. Very seldom do we see coherent intra-basement reflection similar to that observed on seismic data from Osage County (Figure 7). The Osage intra-basement reflectors display a positive reflection coefficient (positive acoustic boundary) that is caused by an increase in acoustic impedance resulting in the red (trough) blue (peak) red (trough) pattern seen in the inset of Figure 7. The base of the intra-basement reflector displays a decrease in acoustic impedance marked by a change from peak to trough. The increase in acoustic impedance at the top intra-basement reflector (similar to what can be observed at a hard water bottom) also has a positive impedance change.

Beneath the base of the top of the basement and below the nearly horizontal Paleozoic section of Osage County, we identified many highly coherent dipping intra-basement reflectors. Between the bright intra-basement reflectors and the top of basement are reflecting sequences that we interpret to be meta-igneous or meta-sedimentary (Figure 8). McBride et al. (2003) identified similar broad "basinal" sequences bounded below by three highly coherent layers beneath the Paleozoic Illinois basin.

Generally, within the granite-rhyolite province, dipping intra-basement reflectors are associated with volcanics (Hinze et al., 1997; Richard et al., 1997). For example, Schaming and Rotstein (1990), and Schlich et al. (1993) interpreted dipping intra-basement reflectors on seismic data from the Kerguelen Plateau in south Indian Ocean, as basaltic flows that are associated with the volcanic margin. Hinze et al. (1997) and Richard et al. (1997) also interpreted dipping intra-basement reflectors seen in the southern margin of the MCRS of western Lake Superior as Keweenawan volcanic and Pre-Mount Simon basins of western Ohio as eastern granite-rhyolite rocks respectively.

To understand the nature and geometry of these bright coherent intra-basement reflectors, we mapped the intra-basement reflectors from the available 3D seismic data. The intra-basement reflectors exhibit a basinal geometry with the high end occupying the northeastern end of the survey (Figure 8a). This kind of geometry is also similar to the sill geometry described in Hansen et al. (2004). On Figure 8b, the geometry observed is similar to growth or detachment faults. However, the intra-basement reflectors crosscut each other in Figure 8c. This crosscutting relationship is generally seen in an igneous intrusion setting and according to the law of crosscutting relationship, a younger igneous intrusion always crosscuts an older igneous body.

Using the intra-basement reflector dip, we classify these reflectors into two groups (I and II). Reflectors in group I dip south-southwest and reflectors in group II dip east (Figure 8c). In addition to these geometries, other 3D data volumes show interactions of intra-basement features with younger sedimentary strata (Figure 9a-c). This suggests that both the intra-basement reflectors and the Paleozoic section have been affected by the same tectonic event.

Based on the crosscutting relationship of the intra-basement features shown in Figure 8c, reflector group II (blue line) crosscuts reflector group I, which implies that reflector group I, which strikes northwesterly, is oldest. The areas of the 3D seismic surveys are part of the granite-rhyolite province (Denison, 1981); thus, we interpret the basement reflectors as being from the lower portion of the eastern granite-rhyolite province units.

PALEOZOIC SECTION DATA ANALYSIS AND INTERPRETATION

Seismic attribute expression of chert reservoirs from Osage County

We evaluate Mississippi and Arbuckle Group reservoirs comparing structures and lineaments on both seismic amplitude and attribute data. Structural mapping of both reservoirs shows generally southeast-dipping, undulating horizons (Figures 10). The chert horizons display an irregular surface that is typical of a karsted carbonate region. Structural complexity increases from the shallow Mississippi Chert to the deeper Arbuckle Group. We also note an east-west feature in the southern portion of the seismic data (Figures 10).

Coherence, curvature, total energy, and inline gradient attributes computed from the seismic data facilitates mapping of karst features and associated fracture patterns. The coherence horizon-slice along the Mississippi Chert shows the presence of circular low-coherence features that we interpret as collapse features (red arrows on Figure 11a). At the Arbuckle Group level, these incoherent features are more dominant. We notice that some of these low coherence features are cut by very coherent linear features (Figures 12a).

Figures 11b-12b shows the most-negative curvature horizon slice that enhances valley- or bowl-shaped features. We note that most-negative curvature enhance the lineaments that we now interpret as fractures and faults. We identify an increase in the number of lineaments within the Arbuckle Group (Figures 12b). We manually map these coherent and most-negative curvature lineaments and plot them as a rose diagram. The rose diagram plots in Figures 12b inset indicate two sets of orthogonal lineaments (northeast-southwest and northwest-southeast). We note that the northeast striking lineaments are similar to the solution-enhanced faults and fractures reported by Nissen et al. (2006) in the Mississippian reservoir of Dickman field in Kansas. The long anomalous northeast-striking lineament (yellow lineament) on the rose diagram is the fault seen on the southeast corner of the most-negative curvature horizon slice (Figures 12b).

Based on our interpretation, the density of the northwest-striking lineaments increases upward towards the Arbuckle Group (Figures 11b-12b). However, lineaments densities decreases deeper towards the Reagan Sandstone that lies on the basement rocks. The blended images of the most-negative curvature, the total energy, and the coherence with the inline energy gradient attribute show these lineaments to be nearly polygonal in shape (Figure 13). The coherent, high energy, structural lows (Figures 14-15) suggesting diagenetically-altered fractures filled with high porosity cherts.

The lineaments over the Mississippi Chert and Arbuckle Group have a general northeasterly- and northwesterly-strike, consistent with the surface and subsurface remote sensing study of lineaments conducted by Guo and Carroll (1999). These authors also identified a northeast-southwest and northwest-southeast striking surface lineament, which correlated with subsurface lineaments interpreted from structure maps (Figures 16).

Precambrian Basement Lineaments

Rose diagrams from potential field derivative map delineate basement features that are parallel to the northwest and northeast strike direction of lineaments identified from the local seismic amplitude and attributes images (Figures 17). However, the northwest-striking anomalies on gravity and magnetic derivative maps shown in Figures 17, appear longer more often than the northeast-striking anomalies. Thus, we interpret the northwest-southeast Precambrian structures to reflect the broader structural fabric of northeastern Oklahoma.

Given the similarity in orientation of the lineaments seen within the Paleozoic section and Precambrian basement of Osage County, we hypothesize that the Precambrian basement controls the Mississippian Chert and Arbuckle Group reservoirs and some of the structures seen within the Paleozoic section are reactivated structures.

CONCLUSIONS

This paper describes an integrated geophysical analysis that utilizes seismic data and potential field data to study Precambrian basement controls on carbonate reservoirs in Osage County in northeast Oklahoma. Seismic attribute images of the Mississippi Chert and the Arbuckle Group of Osage County illuminate faults and fractures in these reservoirs. We propose that these fractures are diagenetically altered, thereby explaining their valley shape. These fractures are filled with low-impedance, high coherent fills, which could either be high porosity chert forming a reservoir conduit and sweet spot or overlying Simpson Group forming a baffle and reservoir compartmentalization.

Our fracture analysis study on the most-negative curvature and rose diagram revealed that lineaments within the study area strike northeast-southwest and northwest-southeast. These lineaments interpreted as fractures and their density increase from the Mississippi Chert downward toward the Arbuckle Group but decreases from the Arbuckle Group toward the Reagan Sandstone. These lineaments also appear as polygonal and are highly coherent with high amplitude on the most-negative curvature, coherence, and total energy attributes respectively.

Basement structure lineaments were found to be parallel in orientation with the trend of lineaments seen within the Mississippian and Arbuckle Group. We interpret northeast-striking lineaments to be related to the late-Paleozoic tectonism (such as the Nemaha reactivated structure) that affected both the Precambrian and Paleozoic section of Osage County. The northwest lineaments are interpreted to be related to the inherent structural fabric of the basement rock orthe draping of the Mississippian over a cockpit karsted terrain.

In summary, we propose the Precambrian basement controls the Mississippian Chert and Arbuckle Group reservoirs. Thus, for Mississippi Chert and Arbuckle group exploitation, structurally high areas that are fractured will be a primary exploration target.

In addition, highly coherent areas with high total energy may be a good indicator of a viable chert reservoir.

In our investigation of the possible extension of the Mid-Continent Rift System (MCRS) through Oklahoma and toward the Texas border, the potential field anomalies indicates that the Osage anomaly (OS1) centered within Osage County is not related to the MCRS. Based on the orientation of the OS2 and OS3 anomalies, which occur west of the Nemaha uplift and abut the Wichita uplift respectively, we hypothesize that both anomalies are related to MCRS extension through Oklahoma. However, we cannot substantiate this conclusion with a geochronological age dating data at this time.

REFERENCES CITED

Adams, D. C., and G. R. Keller, 1994, Possible extension of the Midcontinent Rift in west Texas and eastern New Mexico: Canadian Journal of Earth Science, 31, p. 709-720.

Bass, N. W., 1942, Summary of subsurface geology with special reference to oil and gas - Part II: U.S. Geological Survey Bulletin, 900-K, p. 343-393.

Berendsen, P., 1997, Tectonic evolution of the Midcontinent Rift System in Kansa, *in* R. W. Ojakangas, A. B. Dickas, and J. C. Green, ed., Middle Proterozoic to Cambrian rifting, Central North America: Geological Society of America, Geological Society of America Special Paper 312, p. 235-241.

Bickford, M. E., W. R. Van Schmus, and I. Zietz, 1986, Proterozoic history of the midcontinent region of North America: Geology, 14, p. 492-496.

Bickford, M. E., 1988, The formation of continental crust: Part 1. A review of some principles: Part 2. An application to the Proterozoic evolution of southern North America: Geological Society of America Bulletin, 100, p. 1275-1391.

Blakely, R. J., 1996, Potential theory in gravity and magnetic applications: Cambridge, UK, Cambridge University Press, 461 p.

Cansler, J. R., and T. R. Carr, 2001, Paleogeomorphology of the sub-Pennsylvanian unconformity of the Arbuckle Group (Cambrian - Lower Ordovician): Kansas Geological Survey 2001-55.

Chenoweth, P. A., 1968, Early Paleozoic (Arbuckle) overlap, southern Mid-Continent, United States: AAPG Bulletin, 52, p. 1670-1688.

Chopra, S., and K. J. Marfurt, 2007, Seismic Attributes for Prospect Identification and Reservoir Characterization, *in* S. J. Hills, ed., Society of Exploration Geophysicists Geophysical Development Series No. 11, 464 p.

Cook, K. I., 1956, Regional gravity survey in northeastern Oklahoma and southeastern Kansas: Geophysics, 21, p. 88-106.

Davies, G. R., and L. B. Smith Jr., 2006, Structurally controlled hydrothermal dolomite reservoir facies: An overview: AAPG Bulletin, 90, p. 1641-1690.

Denison, R. E., E. A. Hetherington Jr., and G. S. Kenny, 1966, Isotopic-age dates from basement rocks in Oklahoma: Oklahoma Geology Notes, 26, p. 170-176.

Denison, R. E., 1981, Basement rocks in northeastern Oklahoma: Oklahoma Geological Survey Circular, 84, p. 1-84.

Franseen, E. K., A. P. Byrnes, J. R. Cansler, D. M. Steinhauff, and T. R. Carr, 2004, The geology of Kansas - Arbuckle Group: Kansas Geological Survey - Current Research in Earth Science, 250p.

Fu, D. T., E. C. Sullivan, and K. J. Marfurt, 2006, Rock-Property and seismic-attribute analysis of a chert reservoir in the Devonian Thirty-one Formation, West Texas, U.S.A.: Geophysics, 71, p. B151-B158.

Grauch, V. J. S., and L. Cordell, 1987, Limitation of determining density or magnetic boundaries from the horizontal gradient of gravity or pseudogravity data: Geophysics, 52, p. 118-121.

Guo, G., and H. B. Carroll, 1999, A new methodology for oil and gas exploration using remote sensing data and surface fracture analysis: Prepared for United States Department of Energy, Assistant Secretary for Fossil Energy, p. 1-83.

Hansen, D. M., J. A. Cartwright, and D. Thomas, 2004, 3D seismic analysis of the geometry of igneous sills and sill junction relationships, *in* R. J. Davies, J. A. Cartwright, S. A. Stewart, M. Lappin, and J. R. Underhill, ed., 3D Seismic Technology: Application to the Exploration of Sedimentary Basins: Geological Society, London, Memoir, 29, p. 199-208.

Hildenbrand, T. G., A. Briesacher, G. Flanagan, W. J. Hinze, A. M. Hittelman, G. R. Keller, R. P. Kucks, D. Plouff, W. Roest, J. Seeley, D. A. Smith, and M. Webring, 2002, Rational and operation plan to upgrade the U.S gravity database: U.S. Geological Survey Open-File Report 02-463.

Hinze, W. J., D. J. Allen, L. W. Braile, and J. Mariano, 1997, The Midcontinent Rift System: A major Proterozoic continental rift, *in* R. W. Ojakangas, A. B. Dickas, and J. C. Green, ed., Middle Proterozoic to Cambrian Rifting, Central North America, Geological Society of America Special Paper 312, p. 7-35.

Hinze, W. J., C. Aiken, J. Brozena, B. Coakley, D. Dater, G. Flanagan, R. Forsberg, T. Hildenbrand, G. R. Keller, J. Kellogg, R. Kucks, X. Li, A. Mainville, R. Morin, M. Pilkington, D. Plouff, D. Ravat, D. Roman, J. Urrutia-Fucugauchi, M. Véronneau, M. Webring, and D. Winester, 2005, New standards for reducing gravity database: The North American gravity database: Geophysics, 70, p. J25-J32.

Holom, D. I., and J. S. Oldow, 2007, Gravity reduction spreadsheet to calculate the Bouguer anomaly using standardized methods and constants: Geosphere, 3, p. 86-90.

Keller, G. R., J. M. Hills, M. R. Baker, and E. T. Wallin, 1989, Geophysical and geochronology constraints on the extent and age of mafic intrusions in the basement of west Texas and eastern New Mexico: Geology, 17, p. 1049-1052.

Keroher, R. P., J. J. Kirby, 1948, Upper Cambrian and Lower Ordovician rocks in Kansas: Kansas Geological Survey Bulletin, 72, 140 p.

Kis, K. I., 1990, Transfer properties of the reduction of magnetic anomalies to the pole and to the equator: Geophysics, 55, p. 1141-1147.

Li, X., 2006, Understanding 3D analytical signal amplitude: Geophysics, 71, p. L13-L16.

Lidiak, E. G., R. F. Marvin, H. H. Thomas, and M. N. Bass, 1966, Eastern area, pt. 4 of geochronology of the Mid-Continent region, United States: Journal of Geophysical Research, 71, p. 5427-5438.

Luza, K. V., R. L. Dubois, P. Foster, J. E. Lawson, and L. Koff, 1978, Seismicity and tectonic relationships of the Nemaha uplift in Oklahoma, *in* C. J. Mankin, ed., Oklahoma Geological Survey Document NIREG/CR-0050.

McBride, J. H., D. R. Kolata, and T. G. Hildenbrand, 2003, Geophysical constraints on understanding the origin of the Illinois basin and its underlying crust: Tectonophysics, 363, p. 45-78.

Miller, H. G., and V. Singh, 1994, Potential field tilt - a new concept for location of potential field sources: Journal of Applied Geophysics, 32, p. 213-217.

Muehlberger, W. R., R. E. Denison, and E. G. Lidiak, 1967, Basement rocks in continental interior of United States: AAPG Bulletin, 51, p. 2351-2380.

Nissen, S. E., T. R. Carr, and K. J. Marfurt, 2006, Using new 3-D seismic attributes to identify subtle fracture trends in Mid-Continent Mississippian Carbonate Reservoirs: Dickman Field, Kansas: Search and Discovery Article # 40189.

Northcutt, R. A., and Campbell, J. A., 1995, Geologic provinces of Oklahoma: Oklahoma Geological Survey Open-File Report 5-95.

Richard, B. H., P. J. Wolfe, and P. A. Potter, 1997, Pre-Mount Simon basins in western Ohio, *in* R. W. Ojakangas, A. B. Dickas, and J. C. Green, ed., Middle Proterozoic to Cambrian Rifting, Central North America: Geological Society of America Geological Society of America Special Paper 312, p. 243-252.

Roark, J. J., 1962, Earth crust measurements by seismograph in Oklahoma - An interim report Geophysical Society of Tulsa Proceedings, 1959-1961, *in* D. L. Ralph, ed., 30th Annual meeting of the Society of Exploration Geophysicists, Galveston, Texas, p. 34-39.

Robbins, S. L., and G. R. Keller, 1990, Complete Bouguer and isostatic residual gravity maps of the Anadarko Basin, Wichita Mountains, and surrounding areas, Oklahoma, Kansas, Texas, and Colorado: United State Geological Survey Bulletin, 1866-G, p. G1-G11.

Roest, W. R., J. Verhoef, and M. Pilkington, 1992, Magnetic interpretation using 3-D analytical signal: Geophysics, 57, p. 116-125.

Rogers, S. M., 2001, Deposition and diagenesis of Mississippian chat reservoir, north-central Oklahoma: AAPG Bulletin, 85, p. 115-129.

Rogers, J., and M. W. Longman, 2001, An introduction to chert reservoirs of North America: AAPG Bulletin, 85, p. 1-5.

Ruppel, S. C., and S. D. Hovorka, 1995, Controls on reservoir development in Devonian Chert: Permian Basin, Texas: AAPG Bulletin, 79, p. 1757-1785.

Ruppel, S. C., and R.J . Barnaby, 2001, Contrasting styles of reservoir development in proximal and distal chert facies: Devonian Thirty-one Formation, Texas: AAPG Bulletin, 85, p. 7-33.

Sands, J. M., 1927, Burbank Field, Osage County, Oklahoma: AAPG Bulletin, 11, p. 1045-1054.

Schaming, M., and Y. Rotstein, 1990, Basement reflectors in the Kerguelen Plateau, south Indian Ocean: Indications for the structure and early history of the plateau: Geological Society of America Bulletin, 102, p. 580-592.

Schlich, R., Y. Rotstein, and M. Schaming, 1993, Dipping basement reflectors along volcanic passive margins - new insight using data from Kerguelen Plateau: Terra Nova, 5, p. 157-163.

Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geological Society of America, Bulletin, 74, p. 93-114.

Thorman, C. H., and M. H. Hibpshman, 1979, Status of mineral resource information for the Osage Indian Reservation, Oklahoma: U.S. Geological Survey and Bureau of Mines, Administrative Report BIA-47.

Van Schmus, W. R., M. E. Bickford, and K. C. Condie, 1993, Early Proterozoic crustal evolution, *in* J. C. Reed, M. E. Bickford, R. S. Houston, P. K. Link, D. W. Rankin, P. K. Sims, and W. R. Van Schmus, ed., Precambrian conterminous U.S.: Boulder, Geological Society of America, The Geology of North America, C-2, p. 270-281.

Van Schmus, W. R., M. E. Bickford, and A. Turek, 1996, Proterozoic geology of the east-central mid-continent basement, *in* B. A. Van der Pluijm, and Catacosinos, P. A., ed., Basement and basin of eastern North America: Geological Society of America Special Paper 308, p. 7-32.

Verduzco, B., D. J. Fairhead. C. M. Green, and C. MacKenzie, 2004, The meter reader - New insight into magnetic derivatives for structural mapping: The Leading Edge, 23, p. 116-119.

Walters, R. F., 1946, Buried Precambrian hills in northeastern Barton County, central Kansas: AAPG Bulletin, 30, p. 660-710.

Whitmeyer, S. J., and K. E. Karlstrom, 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, 3, p. 220-259.

Xia, J., D. R. Sprowl, and D. W. Steeples, 1996, A model of Precambrian geology of Kansas derived from gravity and magnetic data: Computers & Geosciences, 22, p. 883-895.

Yarger, H. L., 1985, Kansas basement study using spectrally filtered aeromagnetic data, *in* W. J. Hinze, ed., The Utility of Regional Gravity and Magnetic Anomaly Maps: Society of Exploration Geophysicists, p. 213-232.

LIST OF CAPTIONS

Figure 1. Map shows the major geologic province in Oklahoma, geologic boundaries, structural boundaries, the study area (Osage County), and seismic data used for this study (colored boxes). Red lines are seismic sections that are shown in Figures 8 and 9.The blue rectangle box indicate the seismic survey used mainly for the chert reservoir studies in Figures 10 -15. (Map adapted from Northcutt and Campbell, 1995 Map).

Figure 2. Simple residual Bouguer anomaly map of the Midcontinent United States. White box indicate the location of Figures 4 -6. Black box is the location of the inset map. Inset map shows the basement rocks identified by wells in central Oklahoma overlain on residual Bouguer anomaly map. Dashed yellow line shows the outline of the Osage anomaly that lacks spatial correlation with regional structural geology. Pink-fault boundaries are downloaded from (http://www.ogs.ou.edu/geolmapping.php). (Map modified after Denison's (1981) map of basement rocks in central Oklahoma).

Figure 3. Schematic stratigraphic column for Osage County. Extracted from Zeller (1968), Thorman and Hibpshman (1979), and Franseen (2004).

Figure 4. (a) Residual Bouguer anomaly map (b) Total magnetic intensity (TMI) map showing the relic of the MRS, Osage anomaly, other anomalies investigated in this study, as well as the Precambrian basement geology of Osage County. Magnetic anomaly over the anomalies and the relics of the MCRS are complex and inconclusive when compared with the gravity anomaly in (a).

Figure 5. Derivative maps computed on the residual gravity grid. (a) First vertical derivative (b) Horizontal gradient magnitude. Corresponding derivative maps on TMI anomaly grid. (c) Horizontal gradient magnitude (d) Tilt derivative and. (See text for interpretation).

Figure 6. Directional filter of the 90 km high-pass filtered Bouguer anomaly map that enhances (a) northeast structures related to the MRS and (b) northwest structures. Age dating from Precambrian well (black dots) were from Van Schmus et al.'s (1993) and Denison's (1981) work. Inset map shows rose diagram showing anomaly trends (a) northwest and (b) northeast.

Figure 7. 3D Visualization of seismic data from Osage county showing the geometry of intra-basement reflectors beneath the nearly horizontal Paleozoic section. Inset shows the top of the intra-basement reflector and polarity of one of the seismic lines. Location of seismic is indicated by blue box in Figure 1.

Figure 8. Seismic section (a), (b), and (c) shows the intra-basement reflectors indicated by yellow arrows. Black line is the top basement. Between the intra-basement reflectors and the top basement are suggested meta- sedimentary section. (c) Seismic section shows crosscutting relationship of the intra-basement reflectors, which we classed into type I and II based on reflector dips. Inset map shows time shows time structure map over the basement reflectors from two seismic surveys.

Figure 9. Seismic section (a), (b), and (c) shows the intra-basement reflectors indicated by yellow arrows from Osage seismic survey. (d) Map showing the location of the seismic section. Processes that affect the intra-basement reflector also influence the sedimentary sections also.

Figure 10. Time structure map on (a) the Mississippi Chert and (b) top of Arbuckle Group from two Osage County surveys. Map shows a general southeast dipping undulating and irregular surface. Features marked with black arrows suggest residual hills associated with a karsted carbonate region. Red box is the part of the survey that will be shown subsequently in the next few figures.

Figure 11. (a) Coherence and (b) most-negative curvature horizon slice along Mississippi Chert from two Osage county surveys with overlain time-structure contours. Red-arrows indicate the location of collapse features, magenta-arrows indicate networks of fracture lineaments enhanced by curvature attributes. Circular features dominate curvature along the Mississippi Chert and no preferred order of lineament is identified.

Figure 12. (a) Coherence and (b) most-negative curvature horizon slice at the top of Arbuckle Group from two Osage county surveys with overlain time-structure contour. Magenta-arrows indicate networks of fracture lineaments enhanced by curvature attributes, and yellow arrows indicate low coherence feature that spatially correlate with structurally high area. We manually mapped these

lineaments to generate the inset rose diagram shown in Figure 12b. Inset rose diagram show lineaments orientation and density, which increases toward the top of the Arbuckle group and decrease downward toward the Reagan sandstone. Anomalous northeast trending lineament (yellow petal) on the rose diagram correspond to the northeast trending lineament that we interpreted as fault located on the southeast corner of the lower survey.

Figure 13 Co-rendering most-negative attributes with inline gradient. This attribute combination better enhances the lineaments shape with added benefit of a shaded relief display.

Figure 14. Co-rendering total gradient attributes with inline gradient. This attribute combination better enhances the lineaments amplitude with added benefit of a shaded relief display.

Figure 15. Co-rendering coherence attributes with inline gradient. This attribute combination better enhances the lineaments coherent nature with added benefit of a shaded relief display.

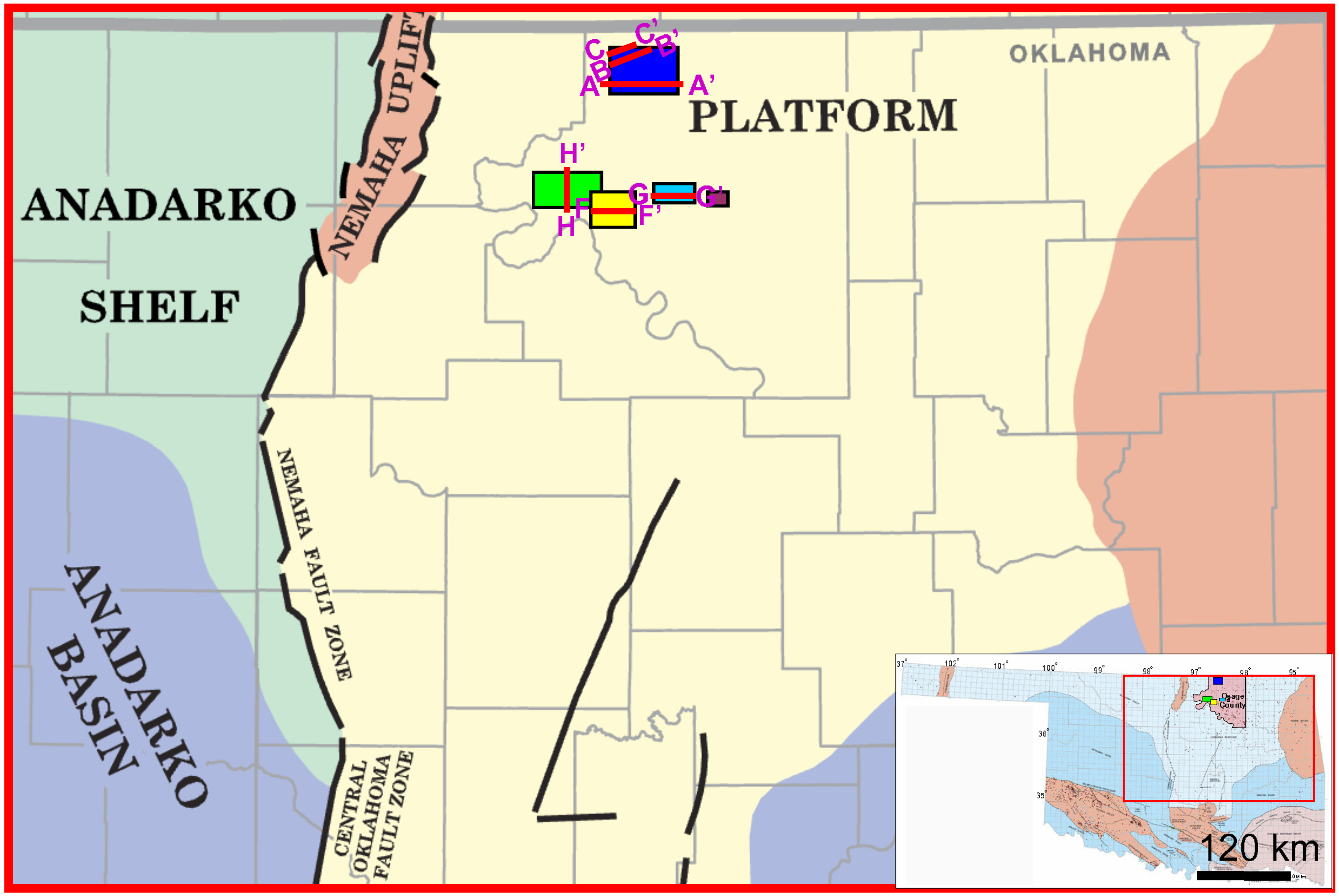
Figure 16. Rose diagrams showing the lineaments trend computed from aerial photograph and satellite images of (a) surface and (b) subsurface structures within the Osage County. (c) Schematic diagram shows the trend of structures within the Precambrian basement. (d) Major lineament trend within the Osage County trends northeast-southwest and northeast-southeast (Adapted from Guo and Carroll, 1999).

Figure 17. (a) Horizontal gradient magnitude and (b) horizontal derivative of the tilt derivative map with corresponding rose diagrams showing Precambrian structural trends.

LIST OF TABLES

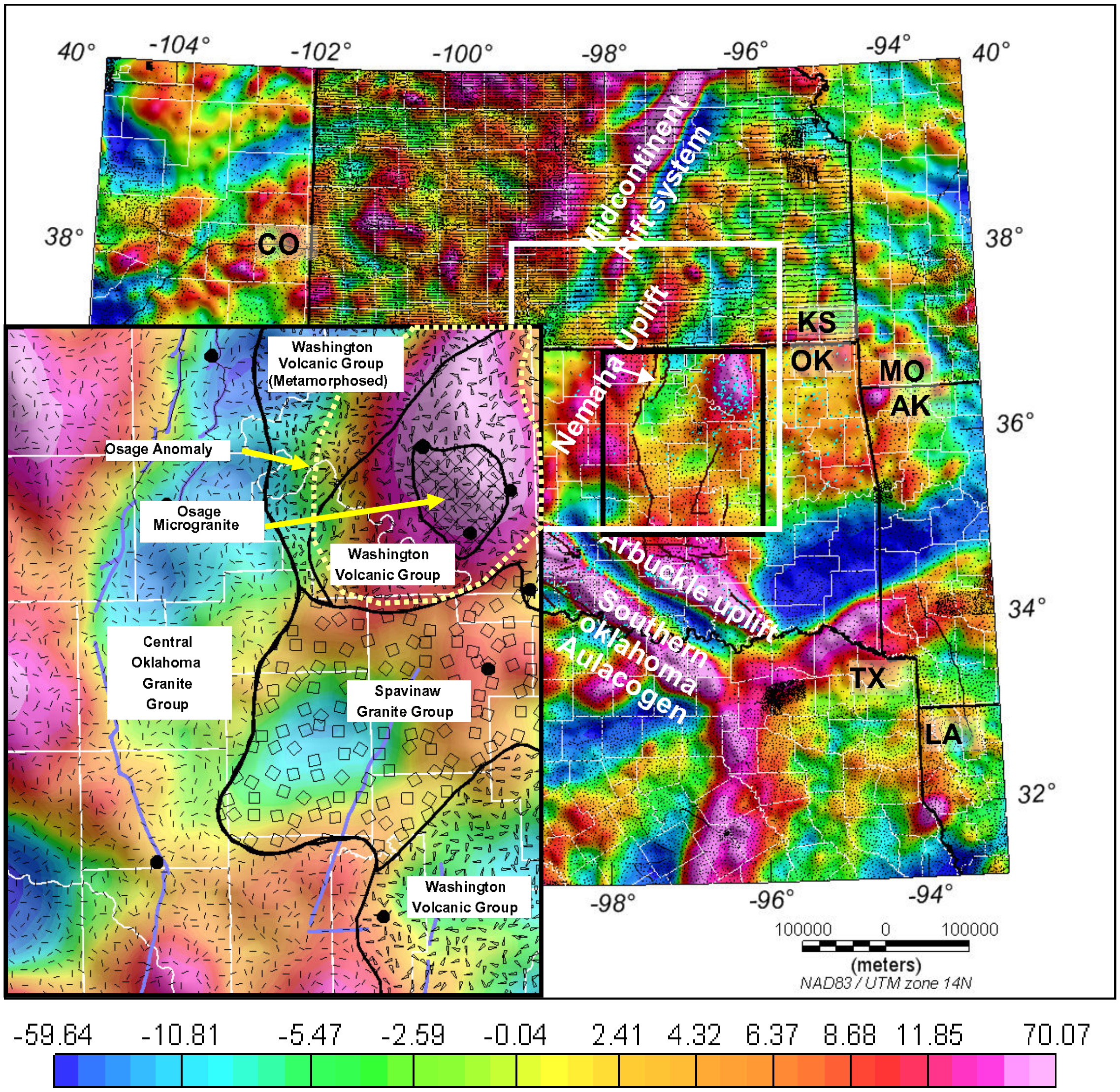
Table 1. Wells in north-central Oklahoma that penetrates Precambrian basement. The depth to the top of basement is listed under column title “BASEMENT TOP (ft)”. Column title “BASEMET (ft)” is the subsea depth, which is the basement depth relative to mean-sea-level (MSL). Isotope ages were compiled from Denison (1981) and Van Schmus et al. (1996).

API	OPERATOR	LEASE	WELL #	SECTION TOWNSHIP RANGE	YEAR DRLLED	TOTAL DEPTH (FT)	SURFACE ELEVATION (ft)	BASEMENT TOP (ft)	BASEMENT THICKNESS (ft)	BASEMENT SUBSEA DEPTH (ft)	LATITUDE	LONGITUDE	ROK AGE	REFERENCE SOURCE	ISOTOPE AGE
13320229	PAWNEE PETROLEUM CO.	RENTIE	1	23 9N 6E	1968	7261	886	7224	37	-6338	35.24469	-96.64333	1242 ± 21 Ma	Denison, (1981	Rb/Sr
03715553	CENTRAL COMMERCIAL	JOHNSON HAY	3	10 17N 10E	1930 or 1937	4282	793	4278	4	-3485	35.96382	-96.24289	1212 ± 48 Ma	Denison, (1981	Rb/Sr
11330447	TEXACO INC.	OSAGE C	1A	24 20N 11E	1965	3634	1002	3634	56	-2632	36.19272	-96.08434	1286 ± 24 Ma	Denison, (1981	Rb/Sr
11303718	NORBLA OIL	LYMAN	2	24 22N 9E	1963	2972	860	2933	39	-2073	36.36426	-96.29443	1281 ± 48 Ma	Denison, (1981	Rb/Sr
11315912	CITIES SERVICE OIL CO.	OSAGE LOT	1-SWD	8 23N 11E	1953	3032	762	3007	25	-2245	36.48741	-96.14216	1233 ± 50 Ma	Denison, (1981	Rb/Sr
11306916	TEXACO INC.	L KOHPAY	16WS	29 25N 8E	1963	2848	1088	2813	35	-1725	36.62072	-96.45967	1183 ± 46 Ma	Denison, (1981	Rb/Sr
07101424	ANDERSON-PRICHARD OIL CORP.	J WELSH	20	17 28N 1E	1918 or 1956	4408	1138	4406	2	-3268	36.90384	-97.22348	1228 ± 56 Ma	Denison, (1981	Rb/Sr
Unknown	EAGLE PICHER MINING CO.	BEAVER	43-C	19 29N 23E	unknown	1650	833	1610	40	-777	36.98608	-94.85449	1383 ± 8 Ma	Van Schmus et al., (1996)	Zircon
10937486	CITIES SERVICE CO.	FARLEY	5	19 11N 2W	1947	8344	1249	8272	72	-7023	35.41797	-97.45326	1220 ± 73 Ma	Denison, (1981	Rb/Sr
10300893	OKLAHOMA NATURAL GAS CO.	HARDROW	1	15 23N 2W	1964	5508	959	5464	44	-4505	36.46829	-97.39674	1381 ± 29 Ma	Denison, (1981	Rb/Sr
00321255	CHAMPLIN PETROLEUM CO.	RAY N SMITH	1	1 27N 10W	1985	7300	1161	7239	61	-6078	36.84963	-98.22701	1380 ± 24 Ma	Van Schmus et al., (1996)	Zircon
Unknown	AMAX	DAC	2	6 20N 23E	unknown	1723	1165	1674	49	-509	36.24235	-94.88778	1270 ± 32 Ma	Denison, (1981	Rb/Sr
11701034	SINCLAIR OIL & GAS CO.	LOUISA M. JONES	46	20 21N 8E	1962 or 1988	2945	961	2929	16	-1968	36.27682	-96.47240	1224 ± 51 Ma	Denison, (1981	Rb/Sr
14502643	HENDERSON OIL CO.	KELLEY	1	18 17N 17E	1965	2505	553	1828	667	-1275	35.95263	-95.54615	1299 ± 26 Ma	Denison, (1981	Rb/Sr



OKLAHOMA
PLATFORM
ANADARKO
SHELF
NEMAHA UPLIFT
NEMAHA FAULT ZONE
ANADARKO BASIN
CENTRAL OKLAHOMA FAULT ZONE
A
A'
B
B'
C
C'
F
F'
G
G'
H
H'
120 km
Osage County

Figure 1



40°
-104°
-102°
-100°
-98°
-96°
-94°
40°
38°
CO
38°
Midcontinent
Rift system
Nemaha Uplift
KS
OK
MO
AK
36°
34°
Arbuckle uplift
Southern
oklahoma
Aulacogen
TX
LA
32°
-98°
-96°
-94°
100000
0
100000
(meters)
NAD83 / UTM zone 14N
Washington Volcanic Group (Metamorphosed)
Osage Anomaly
Osage Microgranite
Washington Volcanic Group
Central Oklahoma Granite Group
Spavinaw Granite Group
Washington Volcanic Group
-59.64
-10.81
-5.47
-2.59
-0.04
2.41
4.32
6.37
8.68
11.85
70.07

Figure 2

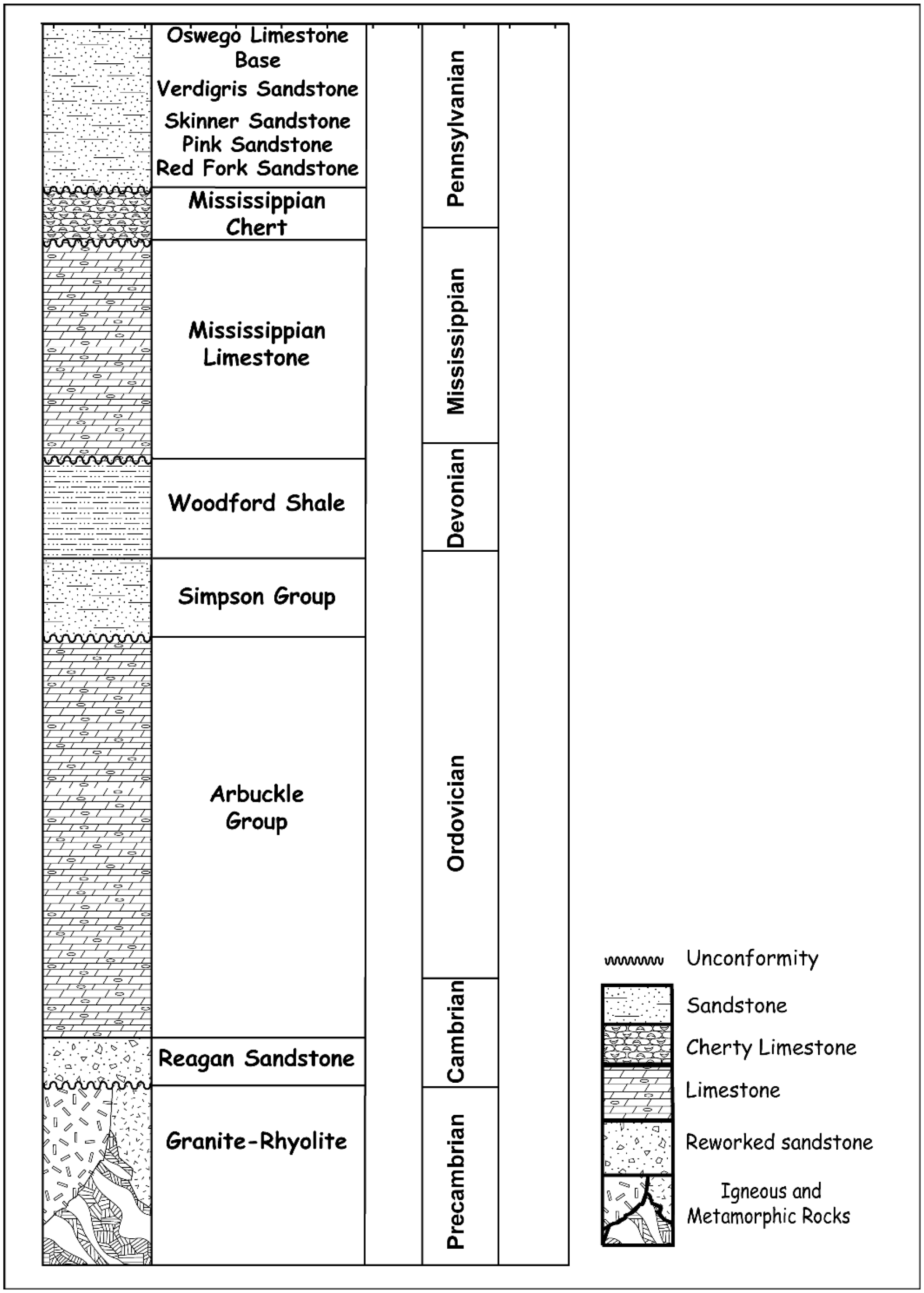

Oswego Limestone Base
Verdigris Sandstone
Skinner Sandstone
Pink Sandstone
Red Fork Sandstone
Mississippian Chert
Mississippian Limestone
Woodford Shale
Simpson Group
Arbuckle Group
Reagan Sandstone
Granite-Rhyolite
Pennsylvanian
Mississippian
Devonian
Ordovician
Cambrian
Precambrian
Unconformity
Sandstone
Cherty Limestone
Limestone
Reworked sandstone
Igneous and Metamorphic Rocks

Figure 3

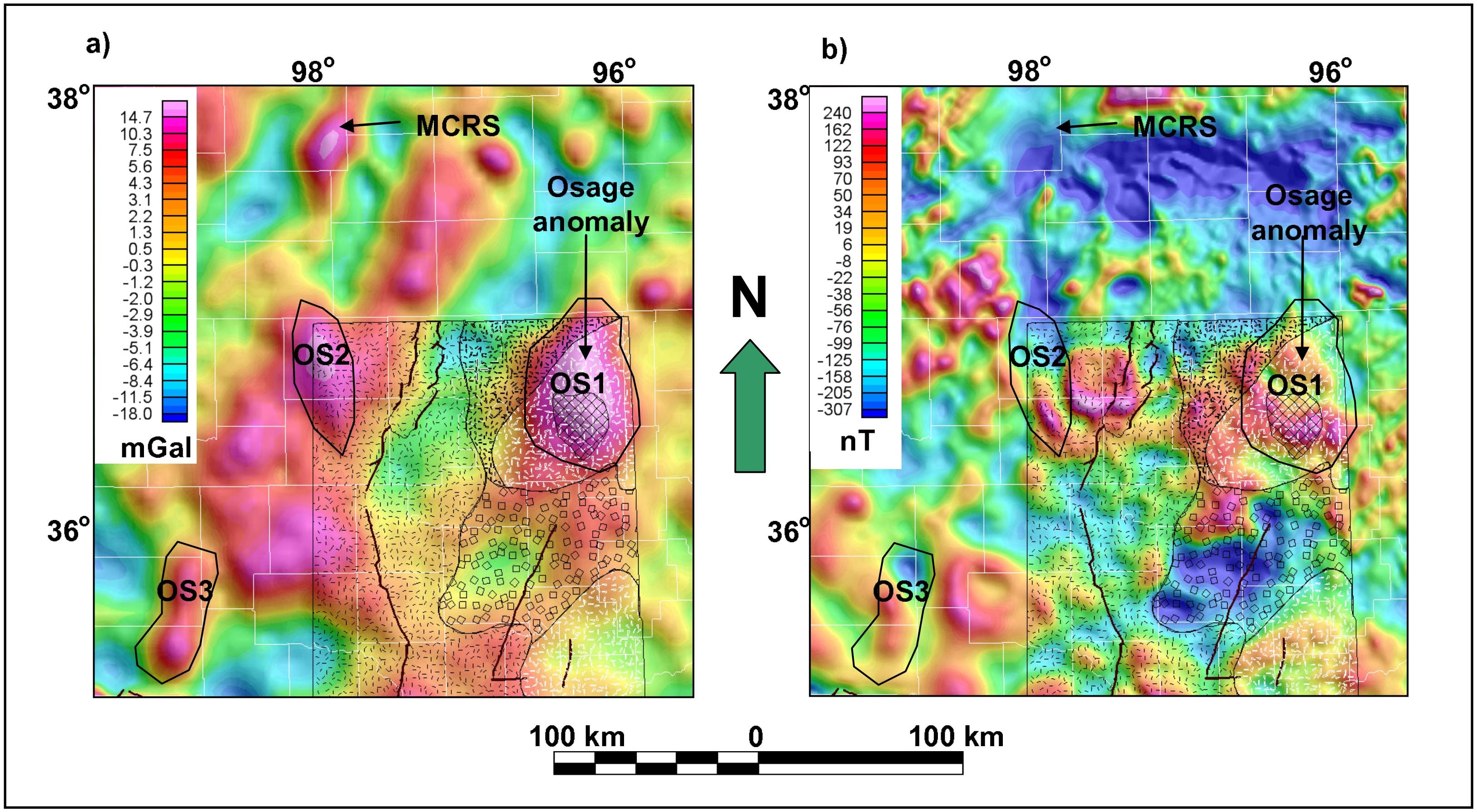

a)
98°
96°
38°
36°
14.7
10.3
7.5
5.6
4.3
3.1
2.2
1.3
0.5
-0.3
-1.2
-2.0
-2.9
-3.9
-5.1
-6.4
-8.4
-11.5
-18.0
mGal
MCRS
Osage anomaly
OS1
OS2
OS3
b)
240
162
122
93
70
50
34
19
6
-8
-22
-38
-56
-76
-99
-125
-158
-205
-307
nT
N
100 km
0
100 km

Figure 4

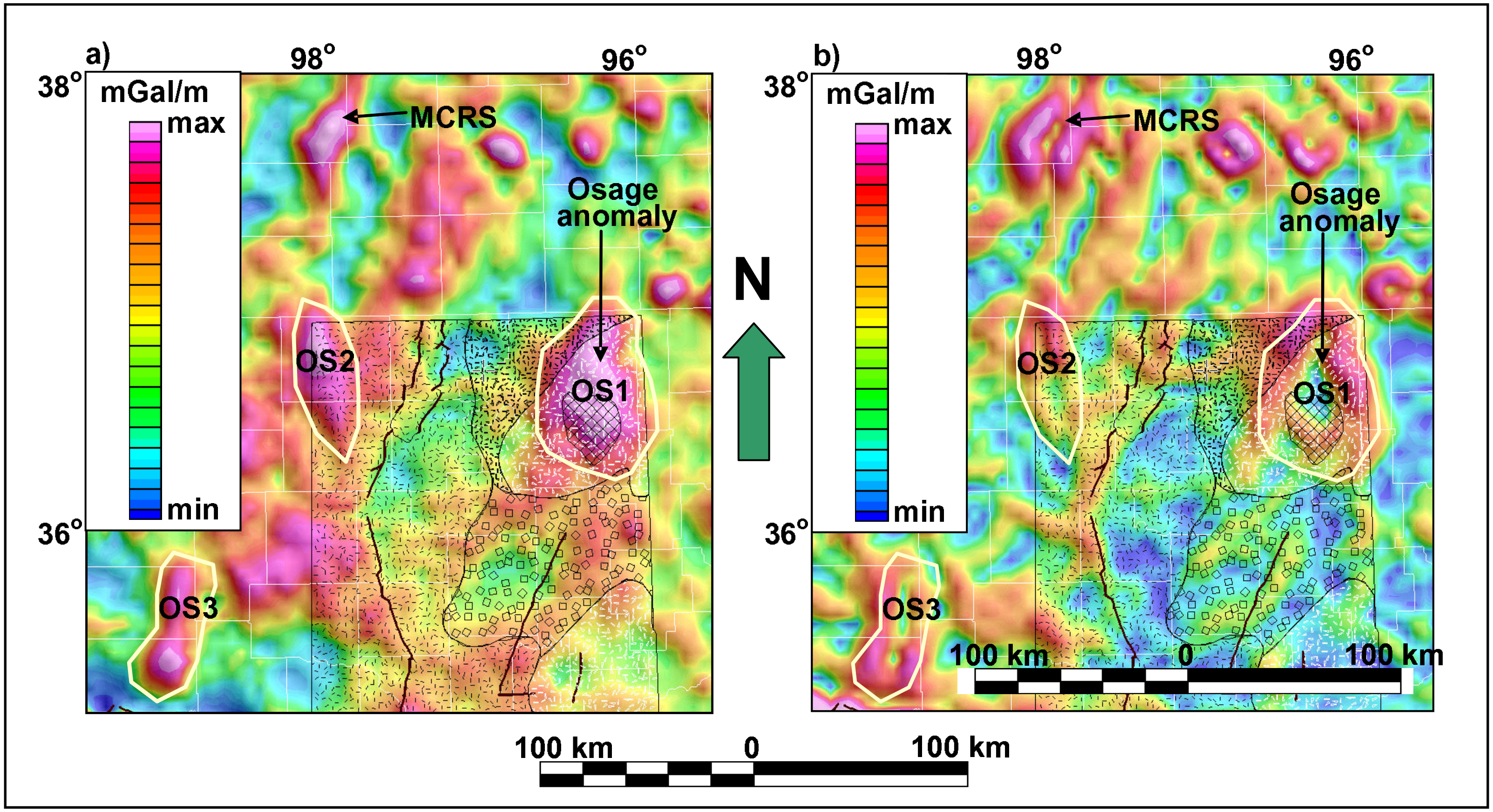


Figure 5a and 5b

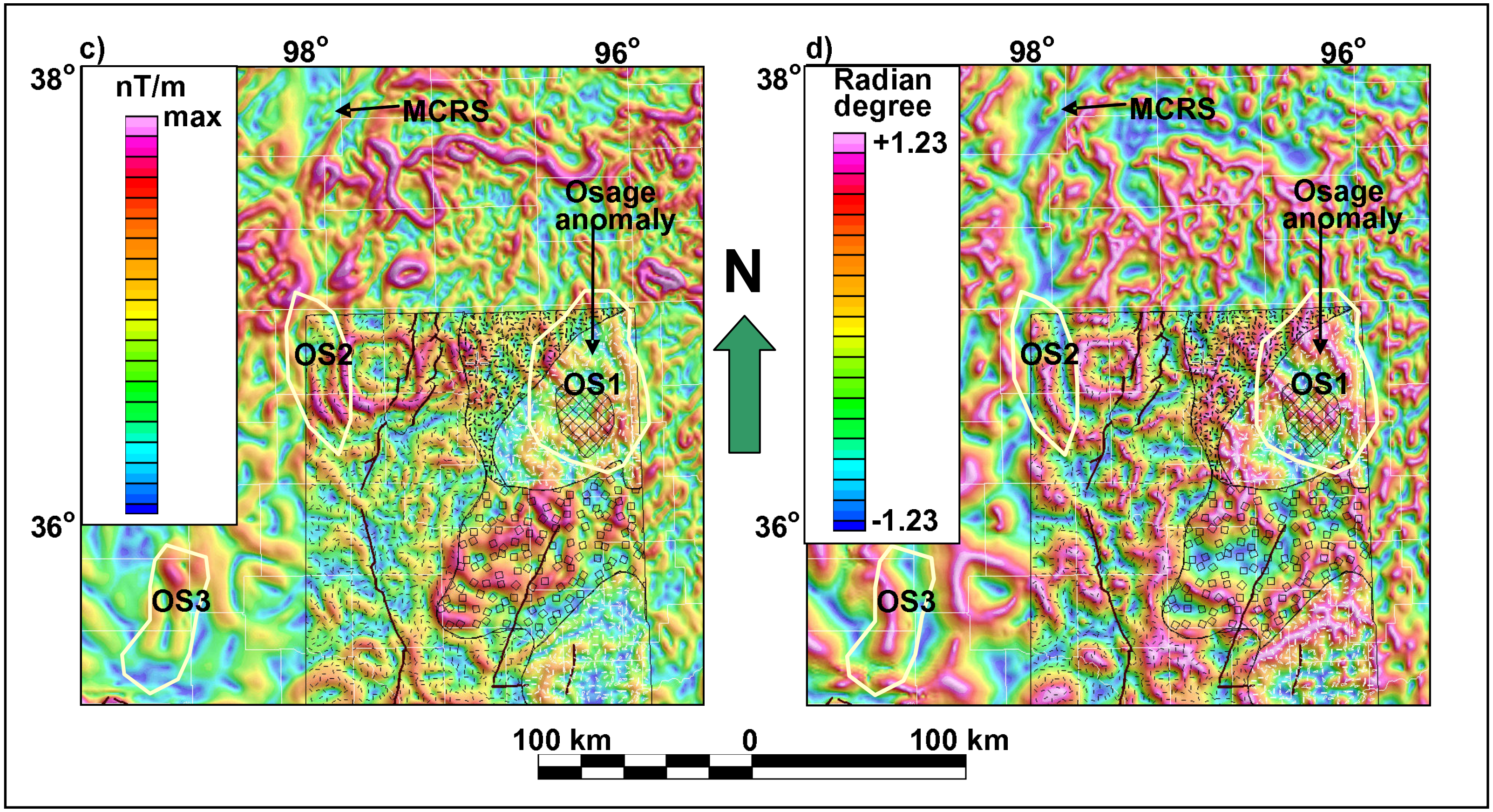
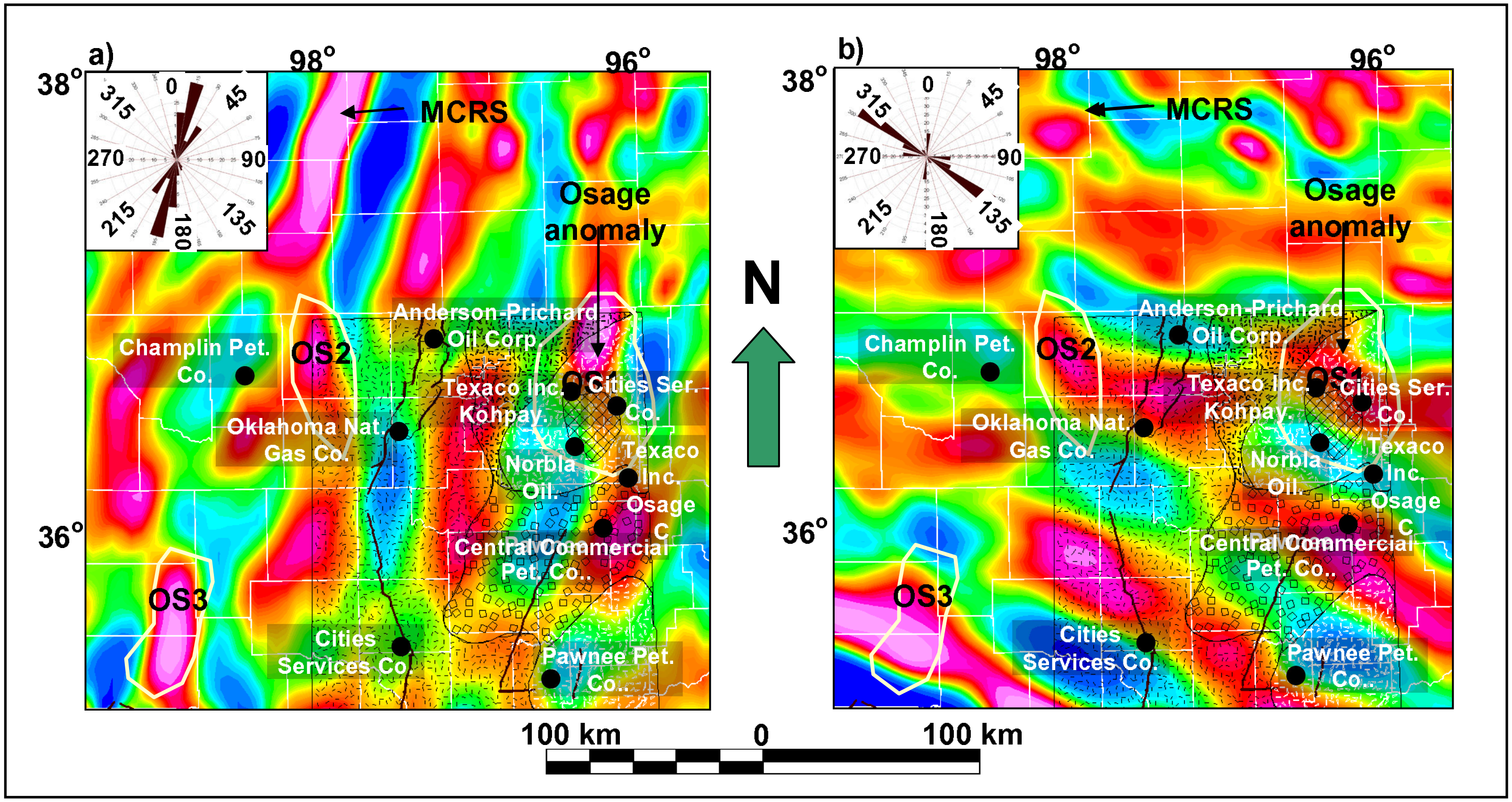
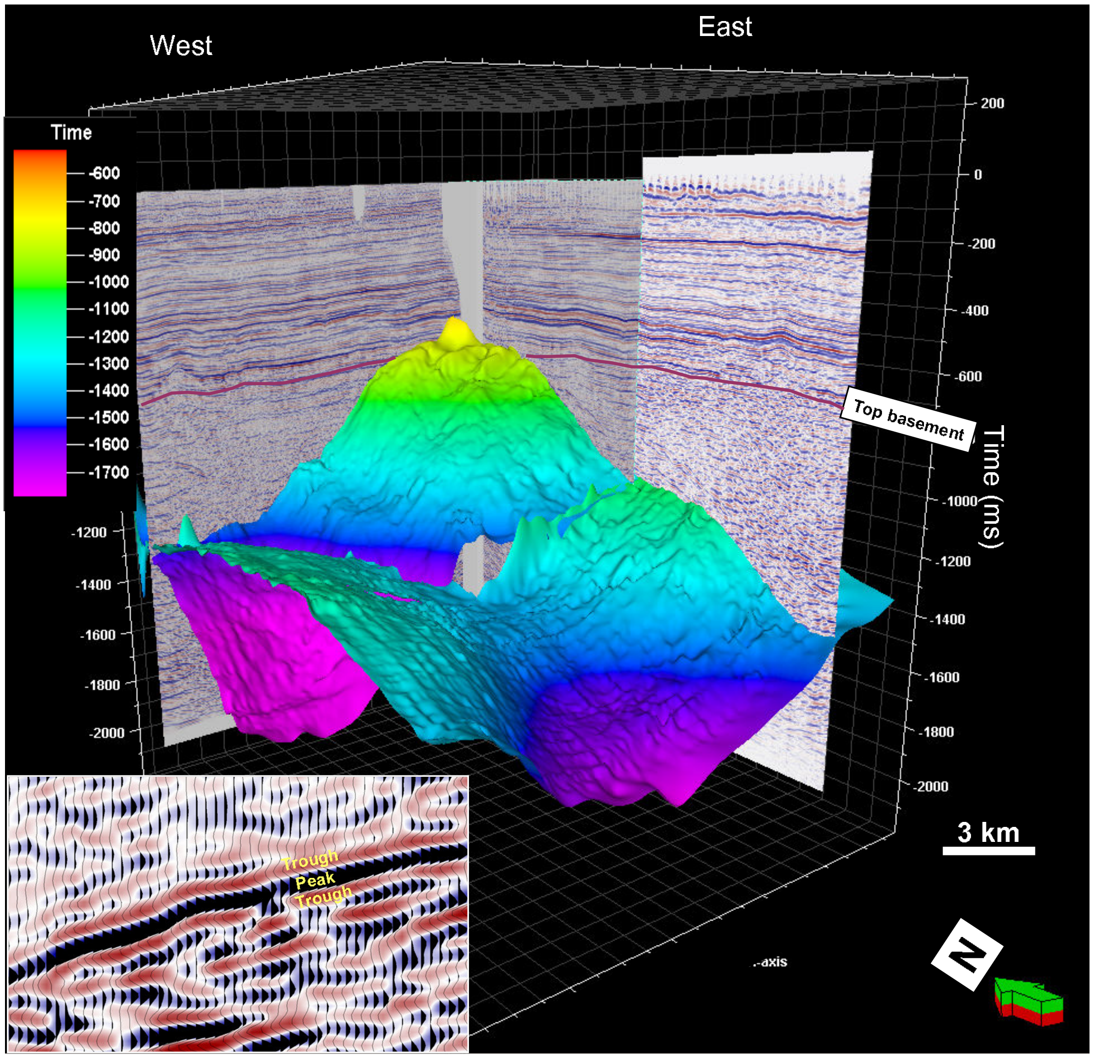


Figure 5c and 5d



a)
b)
38°
36°
98°
96°
MCRS
Osage anomaly
N
Anderson-Prichard Oil Corp
Champlin Pet. Co.
OS2
OS3
Oklahoma Nat. Gas Co.
Texaco Inc. Kohpay.
Cities Ser. Co.
Norbla Oil.
Texaco Inc.
Osage C
Central Commercial Pet. Co..
Cities Services Co.
Pawnee Pet. Co..
100 km
0
100 km

Figure 6



West
East
Time
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
-1500
-1600
-1700
Top basement
Time (ms)
200
0
-200
-400
-600
-1000
-1200
-1400
-1600
-1800
-2000
Trough
Peak
Trough
3 km
N

Figure 7

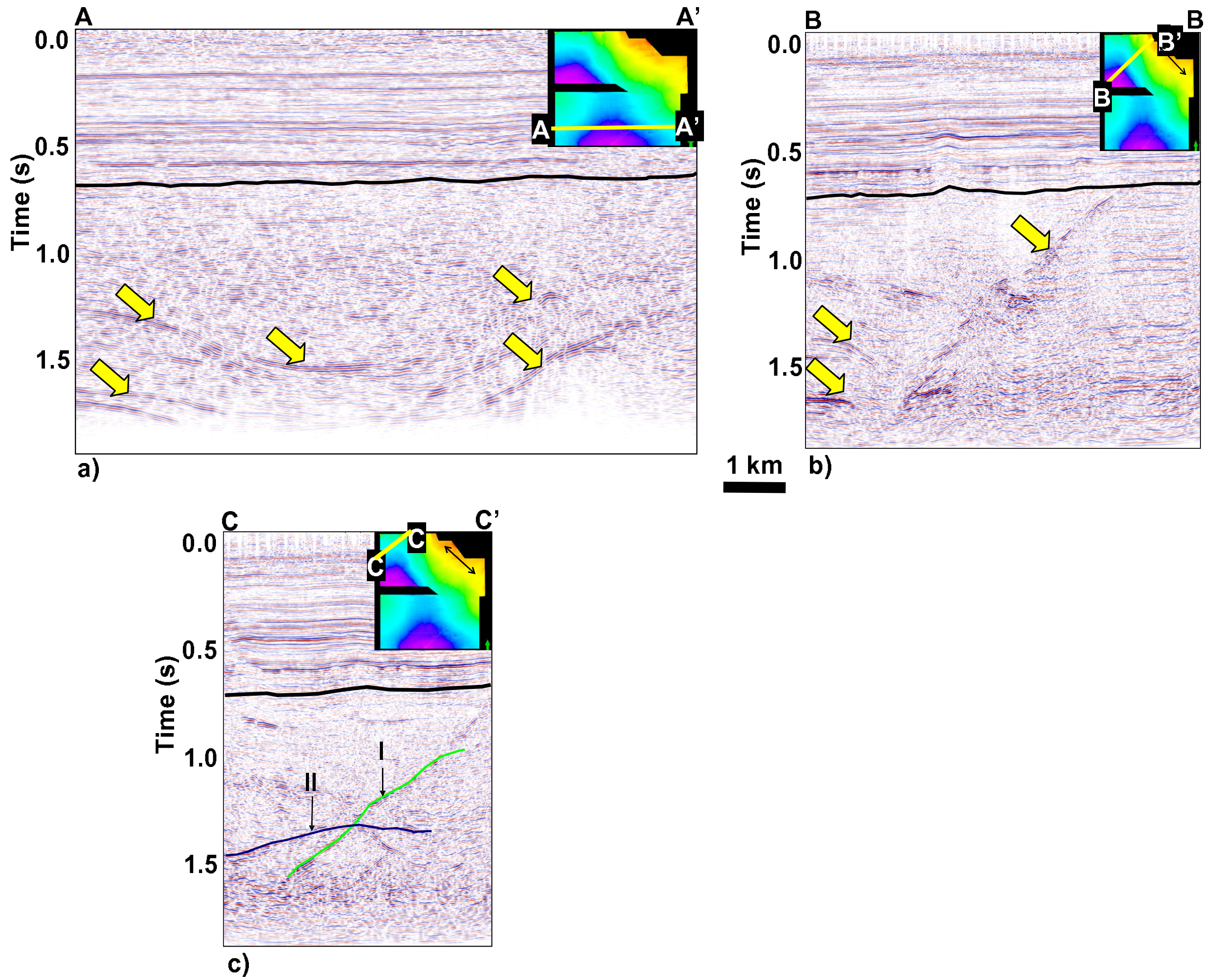
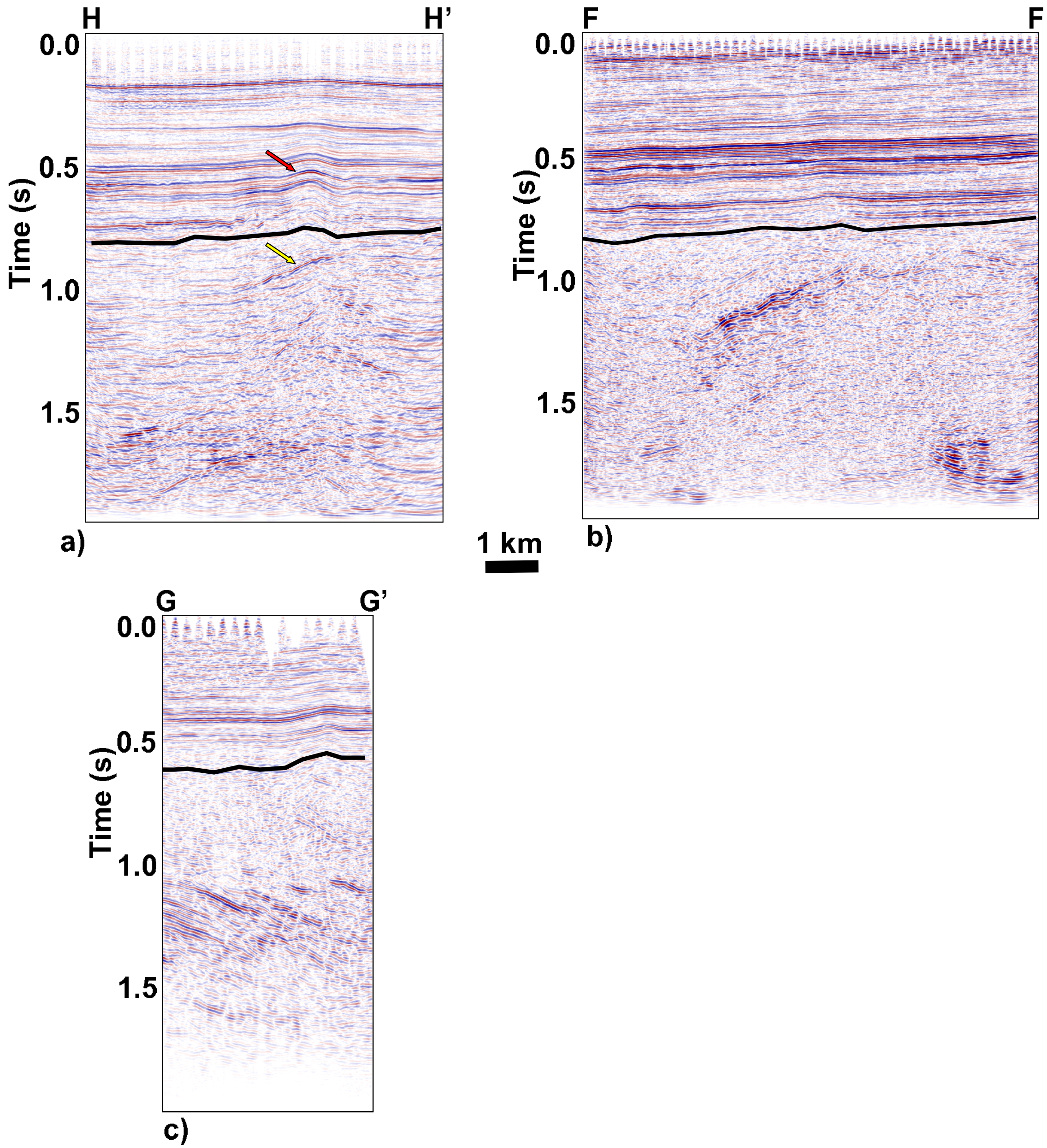


Figure 8.



H
H'
0.0
0.5
1.0
1.5
Time (s)
a)
F
F'
0.0
0.5
1.0
1.5
Time (s)
b)
1 km
G
G'
0.0
0.5
1.0
1.5
Time (s)
c)

Figure 9

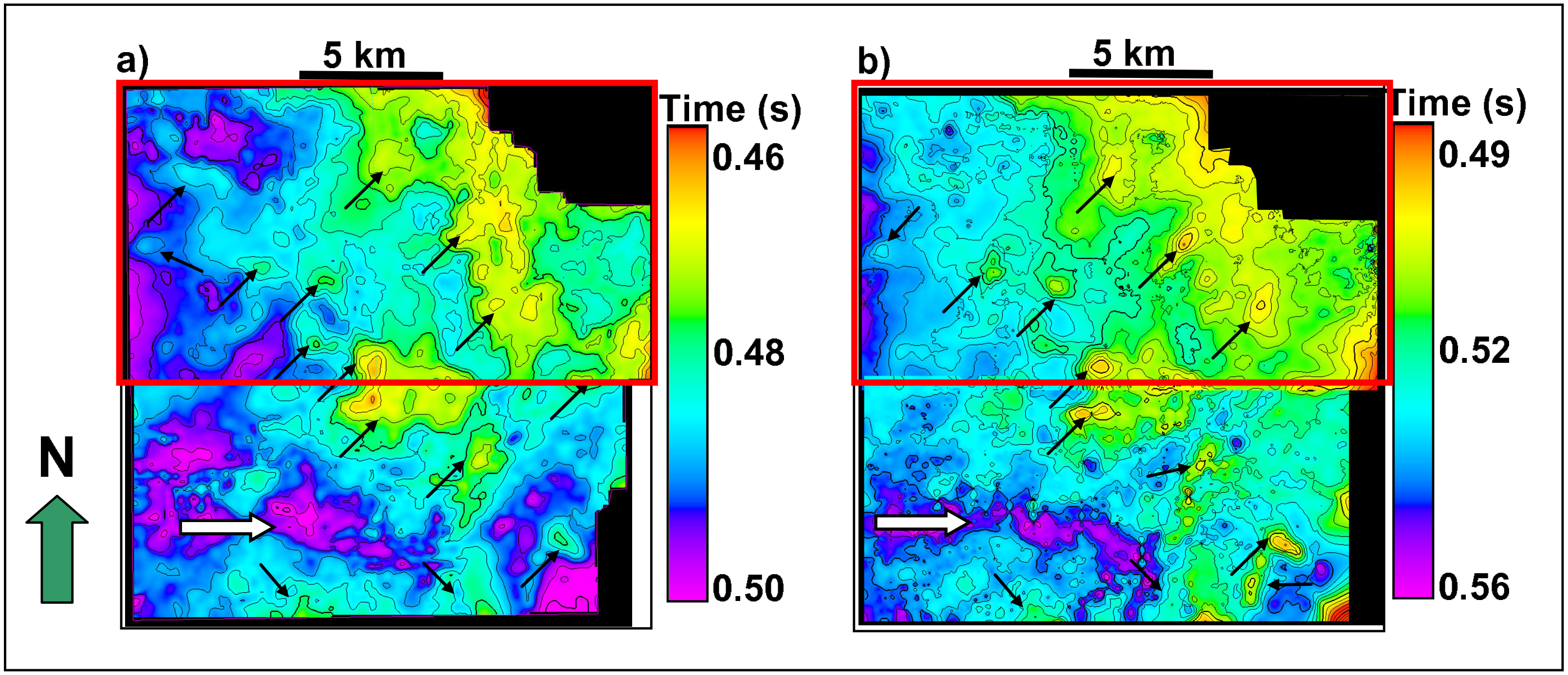


Figure 10

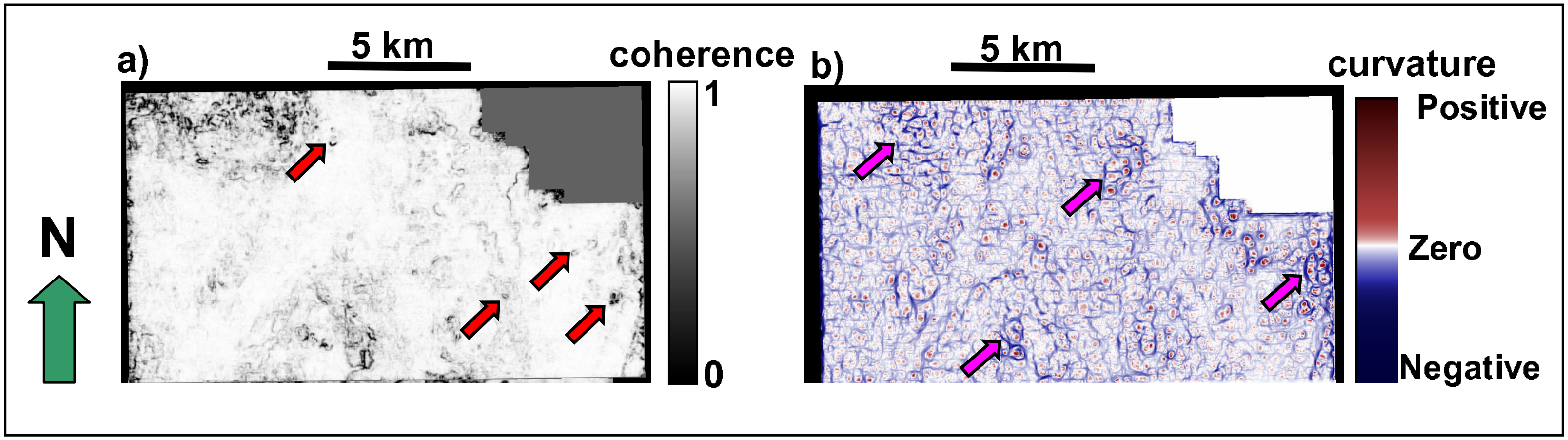
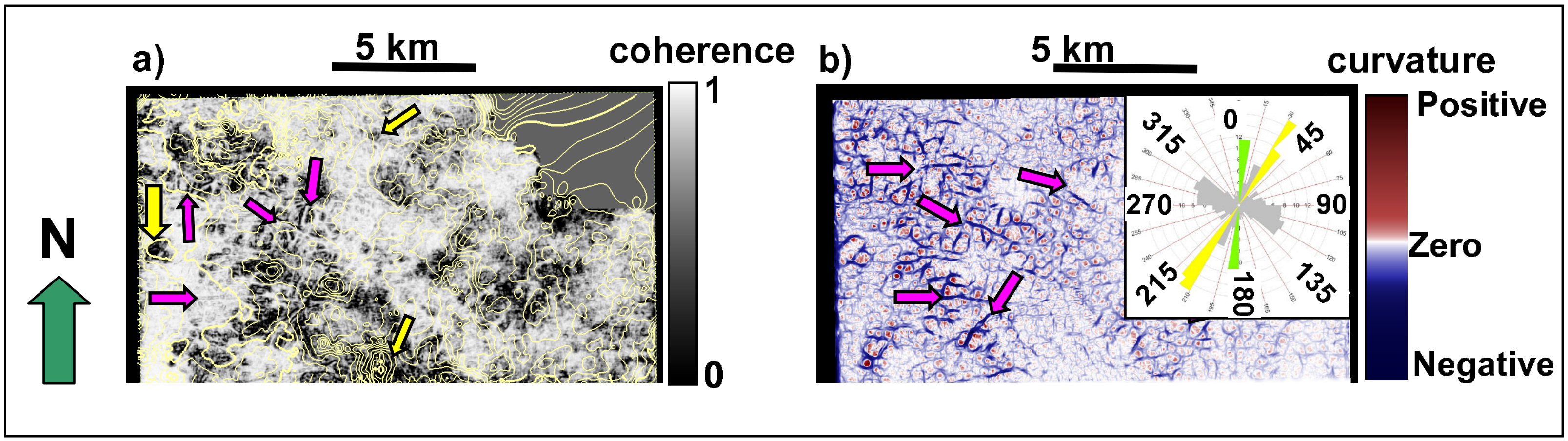


Figure 11



a)
5 km
coherence
1
0
N
b)
5 km
curvature
Positive
Zero
Negative
0
45
90
135
180
215
270
315

Figure 12

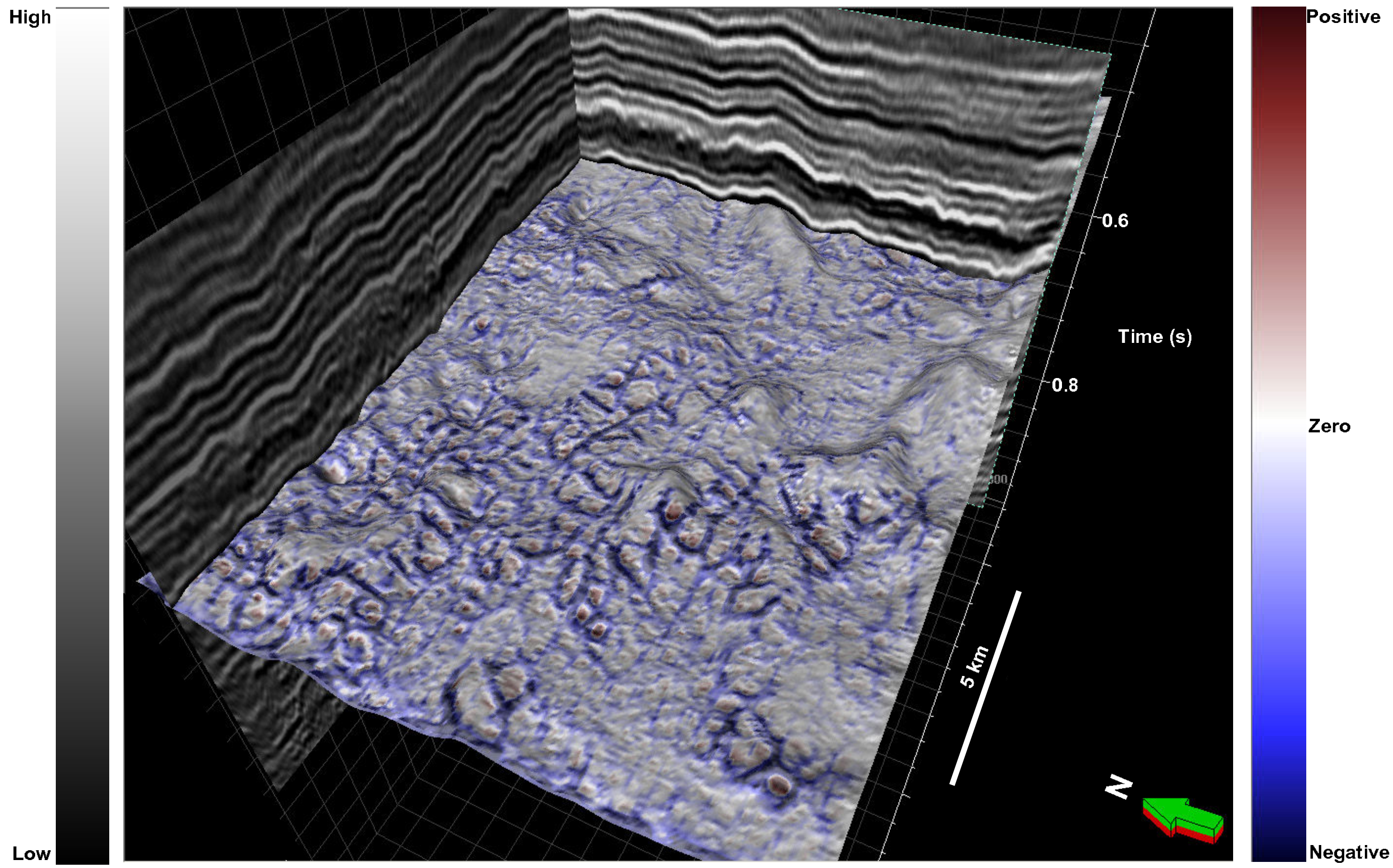


Figure 13.

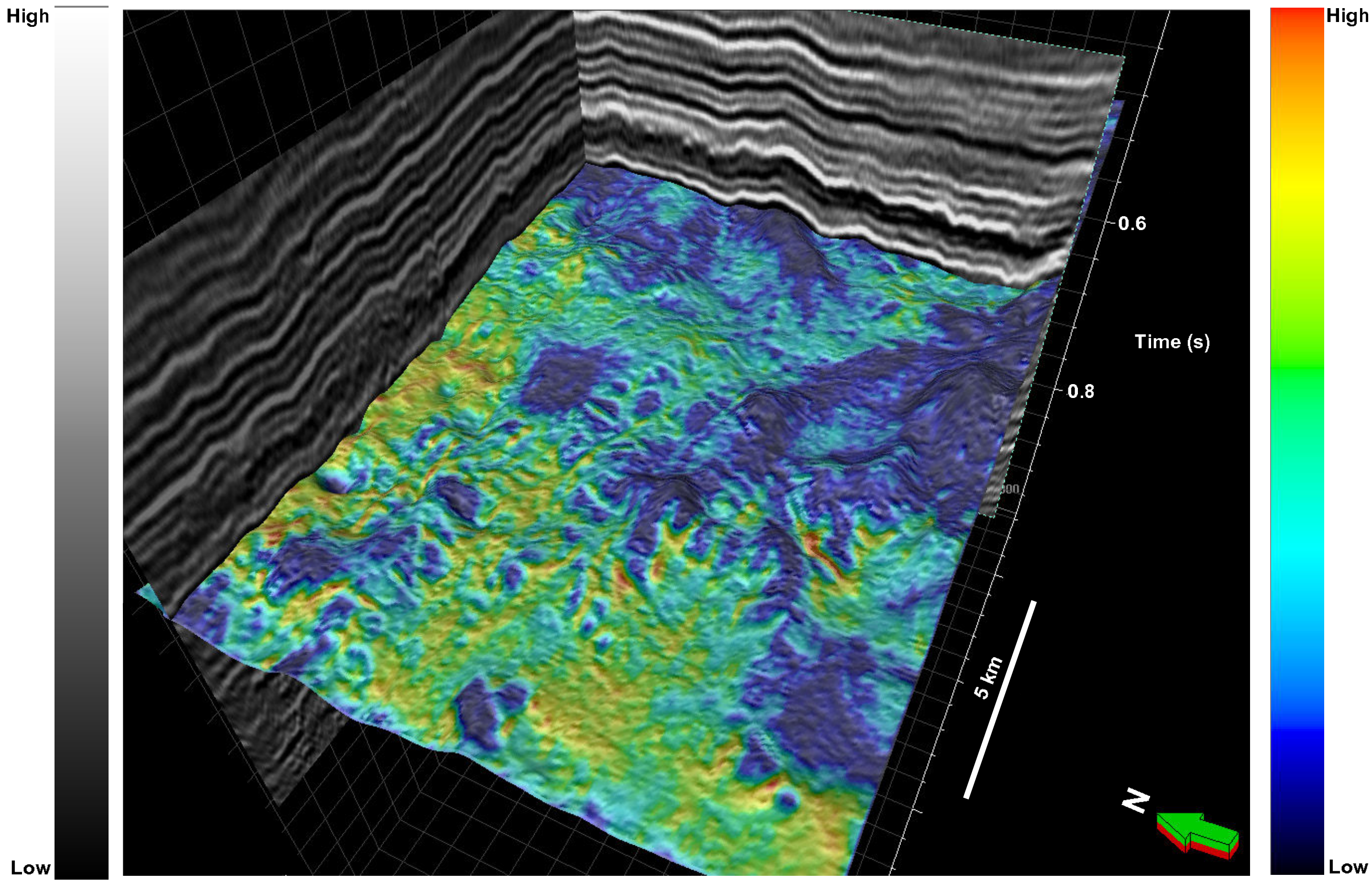


Figure 14.

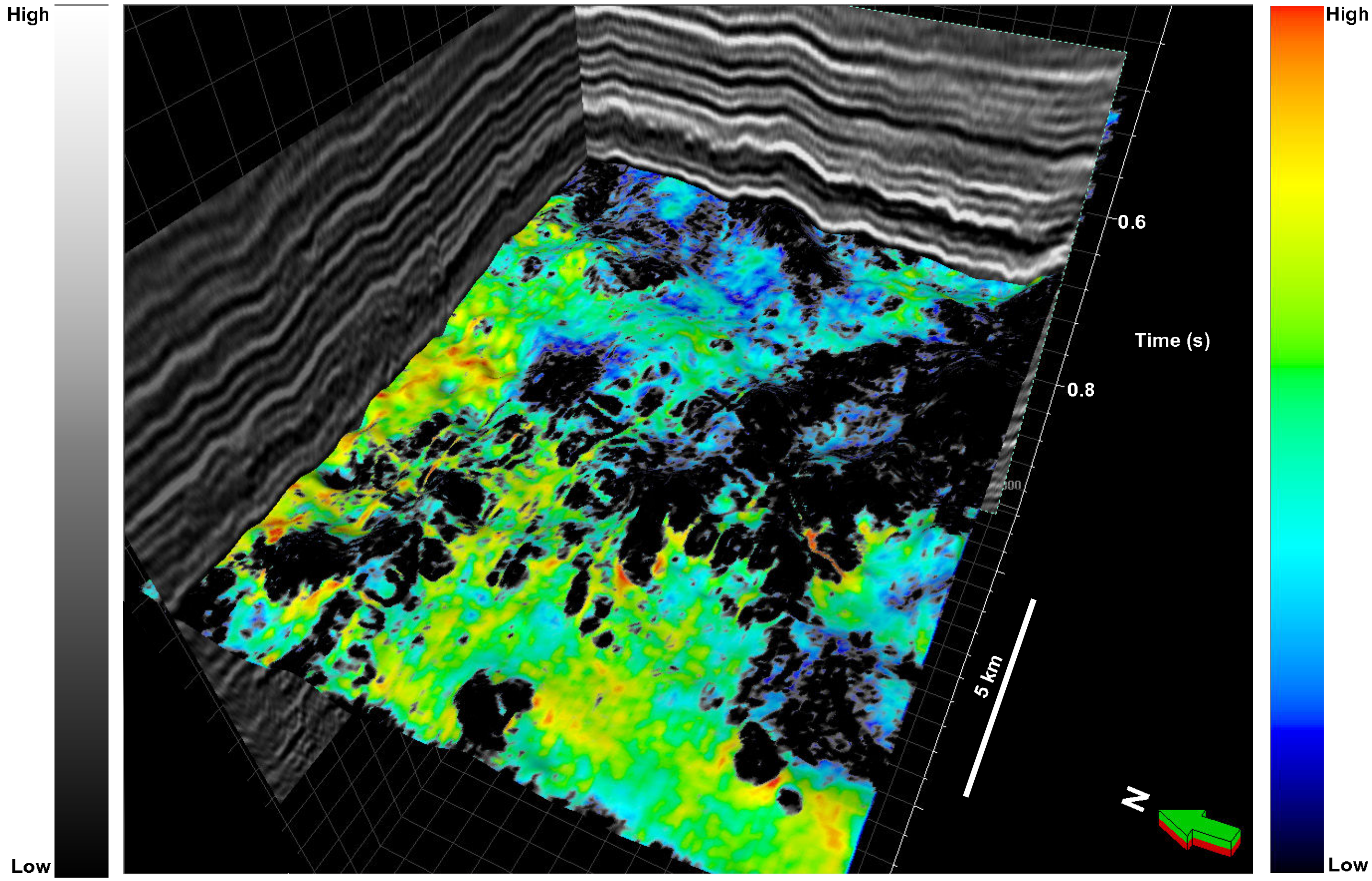


Figure 15

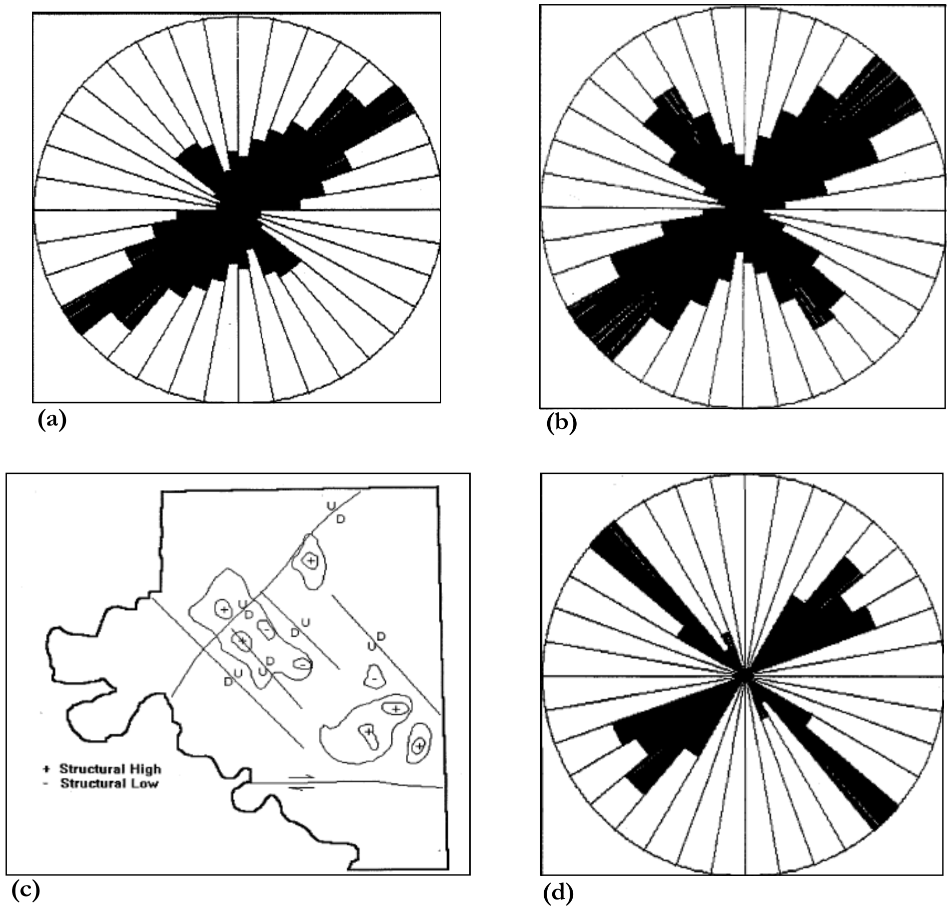


Figure 16

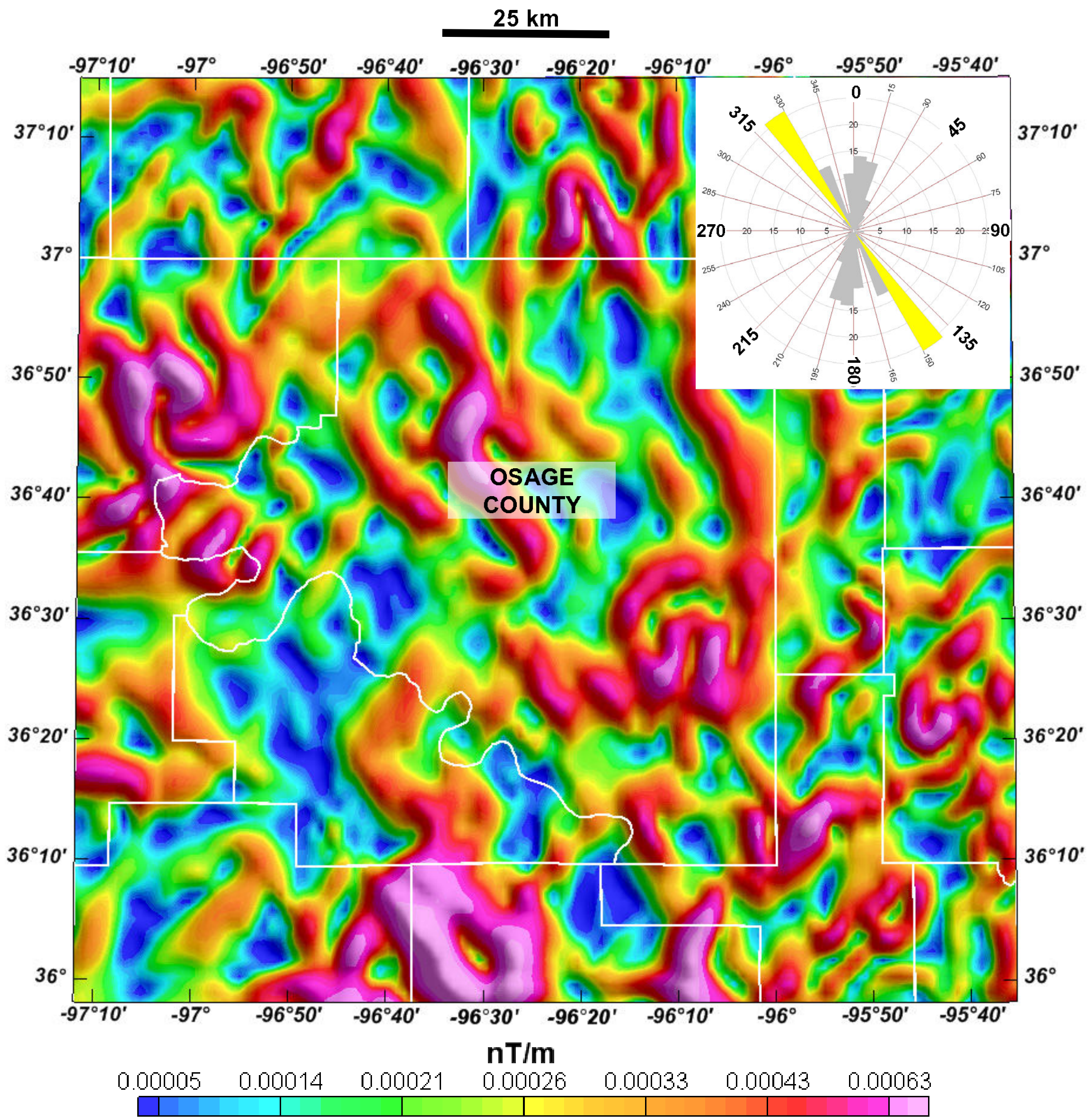

25 km
-97°10'
-97°
-96°50'
-96°40'
-96°30'
-96°20'
-96°10'
-96°
-95°50'
-95°40'
37°10'
37°
36°50'
36°40'
36°30'
36°20'
36°10'
36°
OSAGE
COUNTY
0
45
90
135
180
215
270
315
nT/m
0.00005
0.00014
0.00021
0.00026
0.00033
0.00043
0.00063

Figure 17.