Integrated geophysical studies of the basement structures, the Mississippi chert, and the Arbuckle Group of Osage County region, Oklahoma

Olubunmi O. Elebiju, Shane Matson, G. Randy Keller, and Kurt J. Marfurt

ABSTRACT

We use the integration of gravity, magnetic, and 3-dimensional (3-D) seismic data to map sedimentary features and study the relationships between sedimentary and basement features in the Osage County area of northeast Oklahoma. The prominent gravity and magnetic anomaly studied within this region are related to the mid-continent rift system. However, we cannot substantiate this conclusion with geochronological age–dating data at this time. Prominent dipping Precambrian reflectors seen on seismic section suggest that extension occurred before emplacement of shallow basement. A regional episode of extension possibly occurred early in the development of the 1400 to 1340 Ma magmatic province. Thus, we interpret the structure we see to be a basin that might have formed during this interval. We use volumetric seismic attributes such as coherence and curvature derived from seismic data to better characterize subtle features such as collapse features and faulting and fracturing within the Mississippian and Ordovician carbonate deposits that are difficult to detect on conventional 3-D seismic data displays. Blended seismic images of these carbonate reservoirs reveal polygonal, highly coherent, and high-amplitude lineaments, which trend northeast and northwest. The northeast-striking lineaments are related to the late Paleozoic Nemaha tectonics, whereas the northwest lineaments are interpreted to be related to the inherent basement fabric or the draping of

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the Mississippian over a cockpit karst terrain. Although 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.

INTRODUCTION

Osage County is located in northeastern Oklahoma and is bounded by the Ozark uplift to the east and the southern Nemaha uplift to the west (Figure 1). Within this county, Paleozoic sediments were deposited on part of a gently southward-sloping stable shelf that extends into the Anadarko and Arkoma basins (Thorman and Hibpshman, 1979). The current regional dip of the Paleozoic strata is to the west-southwest (Guo and Carroll, 1999).

Osage County has been a prolific oil-producing area since the discovery of the giant Burbank field in 1920, and as early as the 17th century, oil and gas seeps have been reported within this area. Oil and gas production has been mainly from the Pennsylvanian sandstone deposits, namely the Red Fork and the Bartlesville sandstones (Sands, 1927). There has also been significant production from the Cambrian–Ordovician Arbuckle Group that lies unconformably on top of the irregular Precambrian basement surface as well as from Mississippian tripolitic chert reservoirs (Thorman and Hibpshman, 1979; Franseen et al., 2004). Most of the 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.

The Osagean Mississippian tripolitic chert reservoir, informally called “Mississippi chat” by drillers, is formed from exposed and diagenetically altered cherty limestone (Rogers, 2001). Even with more than 50 yr of production from chert reservoirs, many 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 primary porosity. These Monterey cherts have

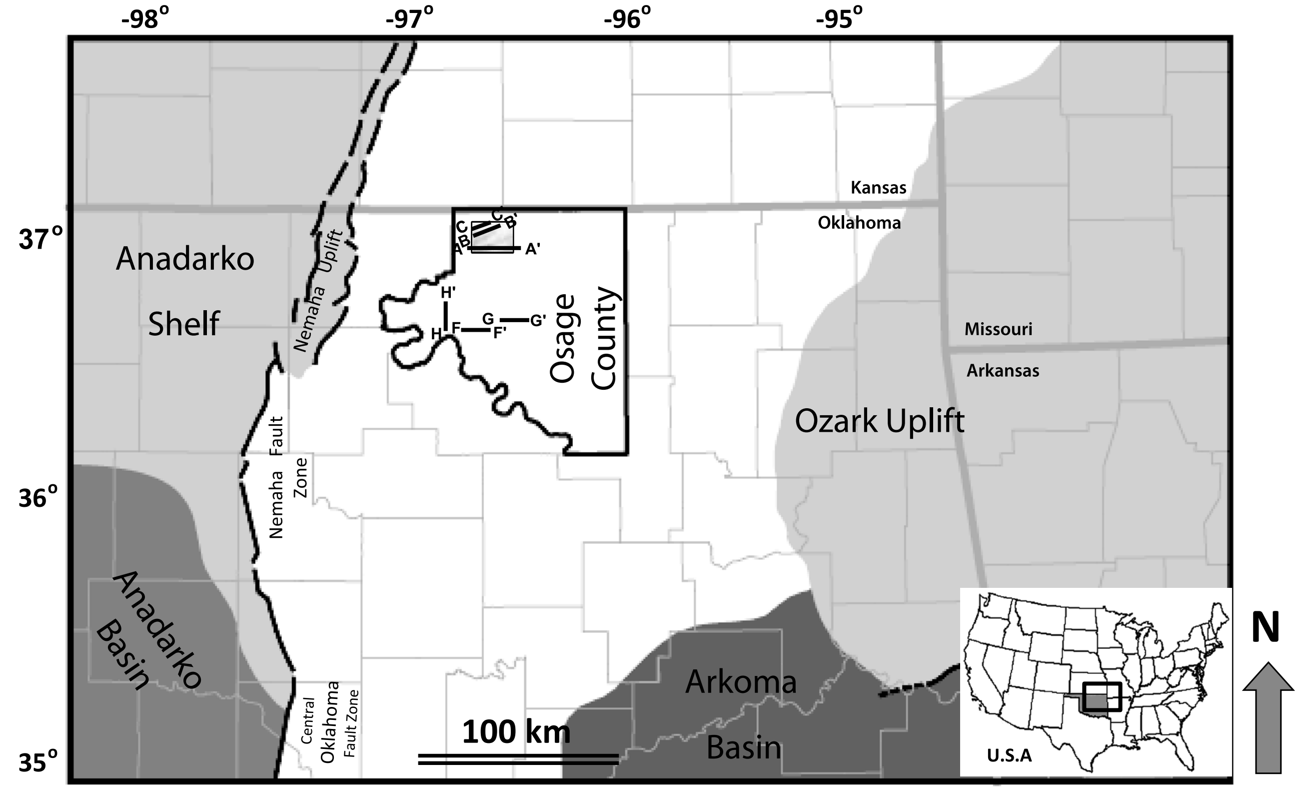


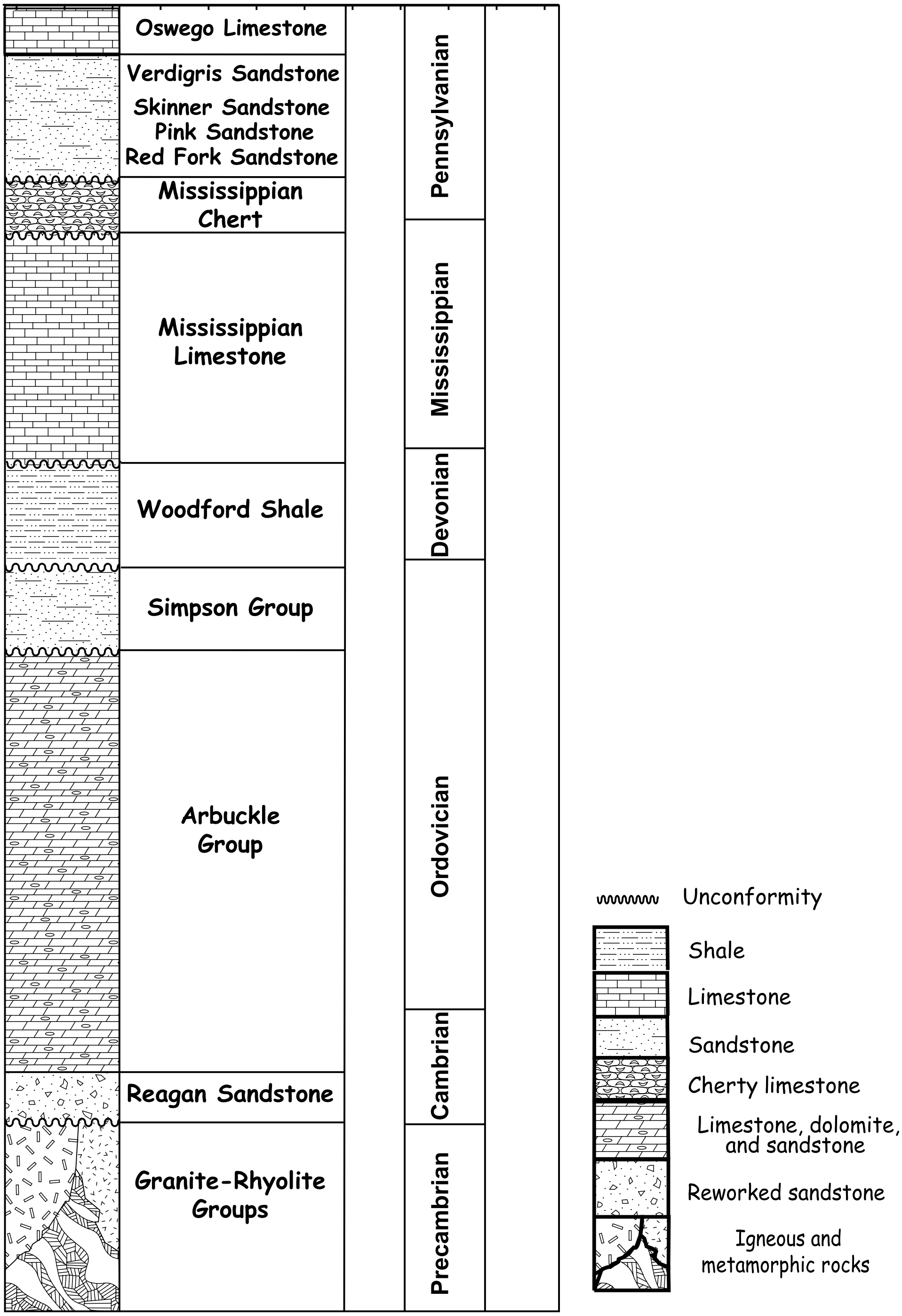
Figure 1. Map showing the major geologic province in Oklahoma, faults (dashed black lines), the study area (Osage County), and the location of the seismic data available for this study (shaded rectangular box). Lettered lines indicate seismic sections that are shown in Figures 7, 8. The shaded rectangular box indicates the seismic survey used for the chert reservoir discussed in Figures 9–14. Modified from Northcutt and Campbell (1995).

never been subaerially 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 expressed in their heterogeneity, which can be caused by faulting and fracturing (e.g., 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), and 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 commonly 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 from three-dimensional (3-D) seismic data to study mid-continent carbonate reservoirs. Increasingly, volumetric seismic attributes such as coherence, curvature, and amplitude gradients calculated from the 3-D seismic data are being incorporated into mid-continent exploration workflow to better characterize subtle carbonate features such as karsting, faulting and fracturing, and hydrothermal dissolution that are difficult to image from standard 3-D seismic (Nissen et al., 2006) data. 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

Figure 2. Stratigraphic column for Osage County. Extracted from Zeller (1968), Thorman and Hibpshman (1979), and Franseen et al., 2004.



with the aid of seismic amplitude and attribute data can effectively help delineate fault and fracture distributions within chert reservoirs.

In this article, we present the results of an integrated geophysical study that used regional potential field data and seismic data from several 3-D seismic surveys acquired in Osage County, Oklahoma (Figure 1). Our efforts are directed at the fracture-controlled Ordovician Arbuckle dolomite and Mississippian chert reservoirs that have been faulted, fractured, and diagenetically altered through subaerial exposure and hydrothermal processes. Primarily, our objective is to understand the interaction between Precambrian structures and the fracture-controlled carbonate reservoirs. We hypothesize that a relationship exists between these

Precambrian structures and the karst reservoirs. In an effort to understand this relationship, we examine potential linkage between features identified within the Precambrian basement and corresponding features within the sedimentary section.

Furthermore, we integrate seismic, gravity, aeromagnetic, and drilling data to study the basement structure in the region. In our study area, the basement lies at a depth of approximately 1000 m (~3281 ft) (Denison, 1981; Van Schmus et al., 1996). In this study, our scientific objective was to understand the origin of the large gravity anomalies present in Osage County and their relationship with the 1100 Ma Mid-Continent rift system (MCRS). Density variations (Cook, 1956), deeper crustal sources (Denison, 1981), thinned crust, and Moho-bumps or an antiroot (Roark, 1962) have been suggested as the cause of the Osage County anomaly because of its lack of correlation with known structural features.

GEOLOGIC BACKGROUND

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 2 shows a schematic lithologic column for Osage County. A Late Cambrian sea deposited granite wash (a localized basal unit) or the 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 rests on the 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 American craton (Sloss, 1963). Because of erosion and weathering that enhance 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. 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. The Woodford Shale deposited by the Middle Devonian sea overlies the Simpson Group. A shallow sea covered most of Oklahoma during the Mississippian (Kinderhookian–Osagean) period, depositing the Mississippian limestone, interbedded carbonate and chert beds that locally lie unconformably on top of the Woodford Shale and the Arbuckle Group (Thorman and Hibpshman, 1979). Uplift and either surface and/or near-surface erosion or in-situ weathering of the Mississippian limestone resulted in diagenetic alteration of the top of the unit, occasionally resulting in a Mississippian tripolitic chert facies that exhibits very high porosities, low permeabilities, and when encountered in the subsurface can be a good hydrocarbon reservoir. In north-central Oklahoma and south-central Kansas, the Mississippian tripolitic cherts are widespread heterogeneous reservoirs that are generally not continuous (Rogers, 2001).

Marine advancement in the Pennsylvanian and successive deposition of shale, limestone, and sandstone constituted the last phase of deposition in this area.

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 a series of domes, controls the overlying Paleozoic sedimentary distribution and thickness. 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. Several drill holes from this region indicated that thin 1- to 3-m (3281–9843 ft) veneers of high-silica volcanic fields with associated epizonal granite

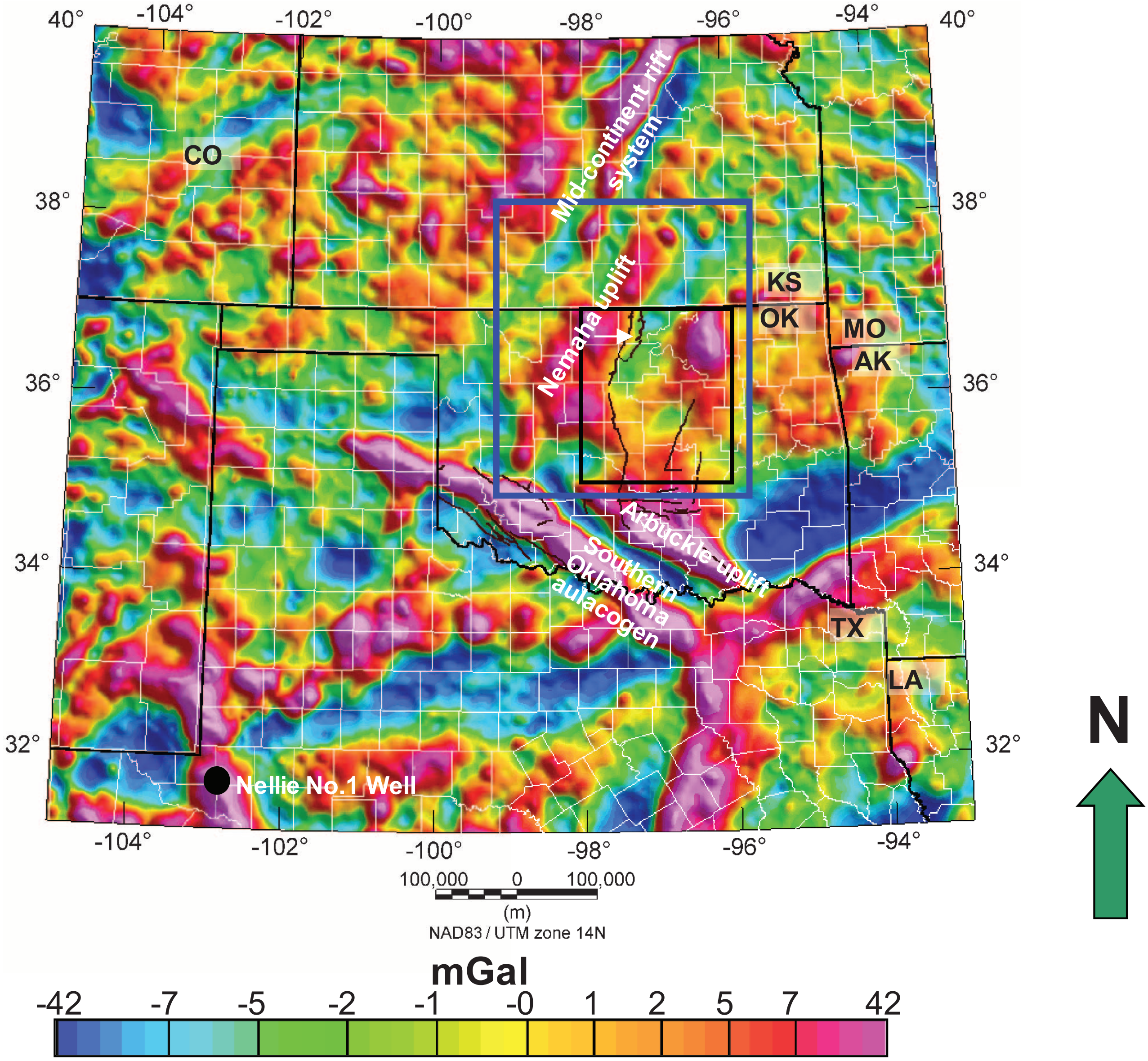


Figure 3. Simple residual Bouguer anomaly map of the mid-continent region. Blue box indicates the location of Figures 4, 5. Prominent gravity anomalies are associated with features such as the Mid-Continent rift system, Arbuckle uplift, southern Oklahoma aulacogen, Nemaha uplift, and Osage County, Oklahoma.

pluton overlie the older basement rocks (Renee Rohs and Van Schmus, 2007). These rocks are part of the widespread 1400- to 1340-Ma intracratonic magmatism that formed the western granite-rhyolite province or its southern granite-rhyolite province equivalent (Bickford et al., 1986; Van Schmus et al., 1996) that overprints the previous 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).

Broad domes with approximately 396 m (~1300 ft) of relief are identified from wells drilled to Precambrian basement (Thorman and Hibpshman, 1979) and are widespread within an approximately 829-km^2 (~320-mi^2) area that spatially correlates with the prominent Osage gravity anomaly (Figure 3). 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).

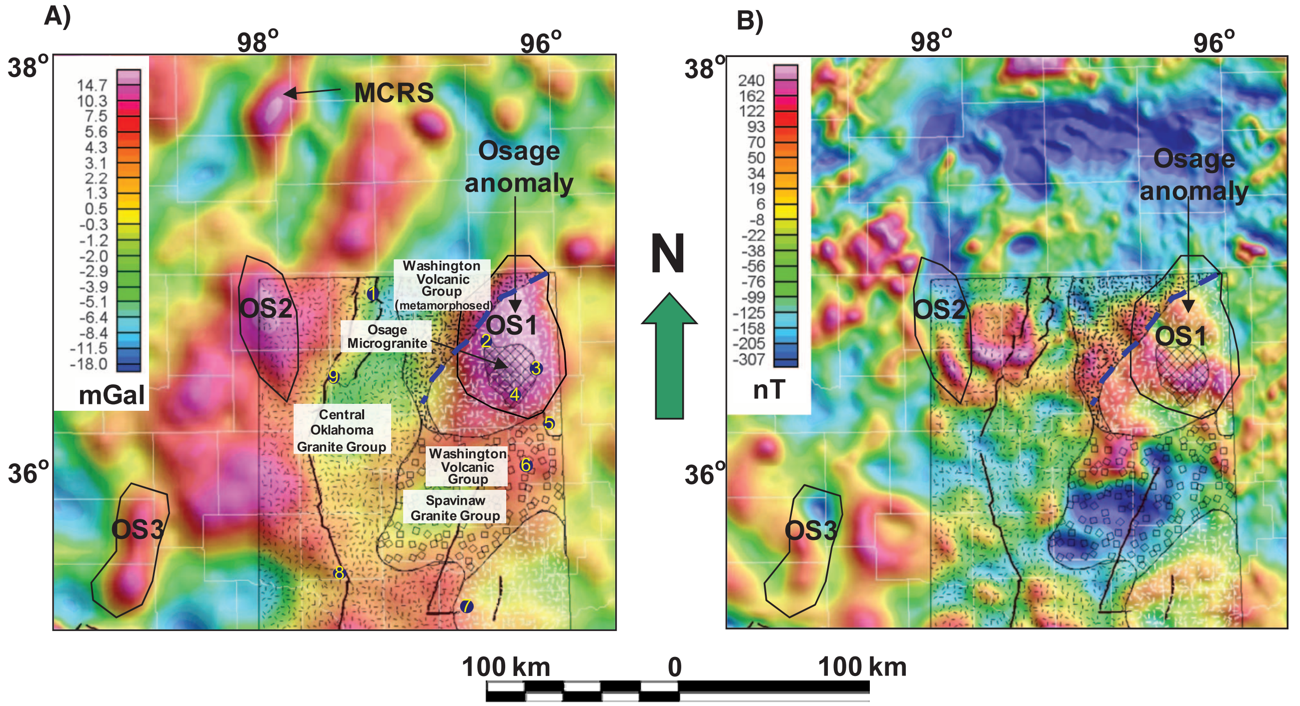


Figure 4. (A) Residual Bouguer anomaly map and (B) total magnetic intensity map showing a possible southern Mid-Continent rift system (MCRS) anomaly, the Osage gravity anomaly, and other features investigated in this study, as well as the Precambrian basement geology of Osage County. Magnetic anomalies over the region are more complicated than the gravity anomalies, suggesting a magnetically heterogeneous basement. Wells encountered in the Precambrian basement rock are shown with the numbers. Detailed information on these wells is available in Table 1. Faults and geologic boundaries are as in Figure 1 and were downloaded from the Oklahoma Geological Survey Web site (2009). Precambrian units are patterned and labeled and were modified from Denison (1981).

Based on the work of Denison and Kenny (1966) and Denison (1981), the basement rocks of northeastern Oklahoma can be classified into four igneous units: the Washington volcanic group, the Spavinaw Granite group, the Osage microgranite, and the central Oklahoma granite group, the distribution of which are shown in Figure 4. A detailed description of these units can be found in Denison (1981).

One major Precambrian basement fault has been identified within Osage County. The northeast-southwest–striking Labette fault that juxtaposes metarhyolitic rocks on the northwestern side (upthrown) against rhyolitic rocks to the southeast (downthrown) extends northward through Osage County and into southern Kansas (Figure 4). 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 several 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).

PREVIOUS GEOPHYSICAL STUDIES

In 1948, one of the first geophysical collaboration efforts between the U.S. Geological Survey and the U.S. 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 crustal thinning, a Moho-bump, or an antiroot.

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 MCRS of North America is a 1100-Ma failed rift that extends for more than 2000 km (1243 mi) (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 to the MCRS mafic intrusion extend into Oklahoma. Other authors who 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 and rift offset (Xia et al., 1996) are some of the explanations given as to why the MCRS cannot be seen directly in Oklahoma.

DATA SETS

Seismic Data

Four different 3-D 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. These 2-s record-length seismic data are poststack migrated data sampled at every 2 ms. 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 nonmagnetic chert reservoirs.

After generating the Arbuckle Group and the Mississippian chert time-structure map, we generate horizon slices over these horizons 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 curvatures, total energy, and energy-weighted coherent amplitude gradients. Examples of their application and mathematical background are available in Chopra and Marfurt (2007).

Potential Field Data

The association of the MCRS with prominent gravity and magnetic anomalies makes the potential field method an effective tool to investigate the MCRS. The data sets used in this study include aeromagnetic data that are part of the North American Magnetic Map project grid which is the result of a combined effort of the U.S. Geological Survey, Geological Survey of Canada, and Consejo de Recursors Minerales of Mexico. This data set is available for download at the U.S. Geological Survey Web site (2008).

In addition to the aeromagnetic grid, gravity data points were downloaded from The University of Texas El Paso online gravity database (2008) that is maintained by the Pan American Center for Earth and Environmental Studies at the University of Texas at El Paso.

The resulting Bouguer anomaly values were gridded and upward continued to 20 km (12.4 mi). The residual anomaly grid was produced by subtracting the upward continued grid from the original Bouguer anomaly grid, thereby emphasizing relatively shallow features (Figure 3).

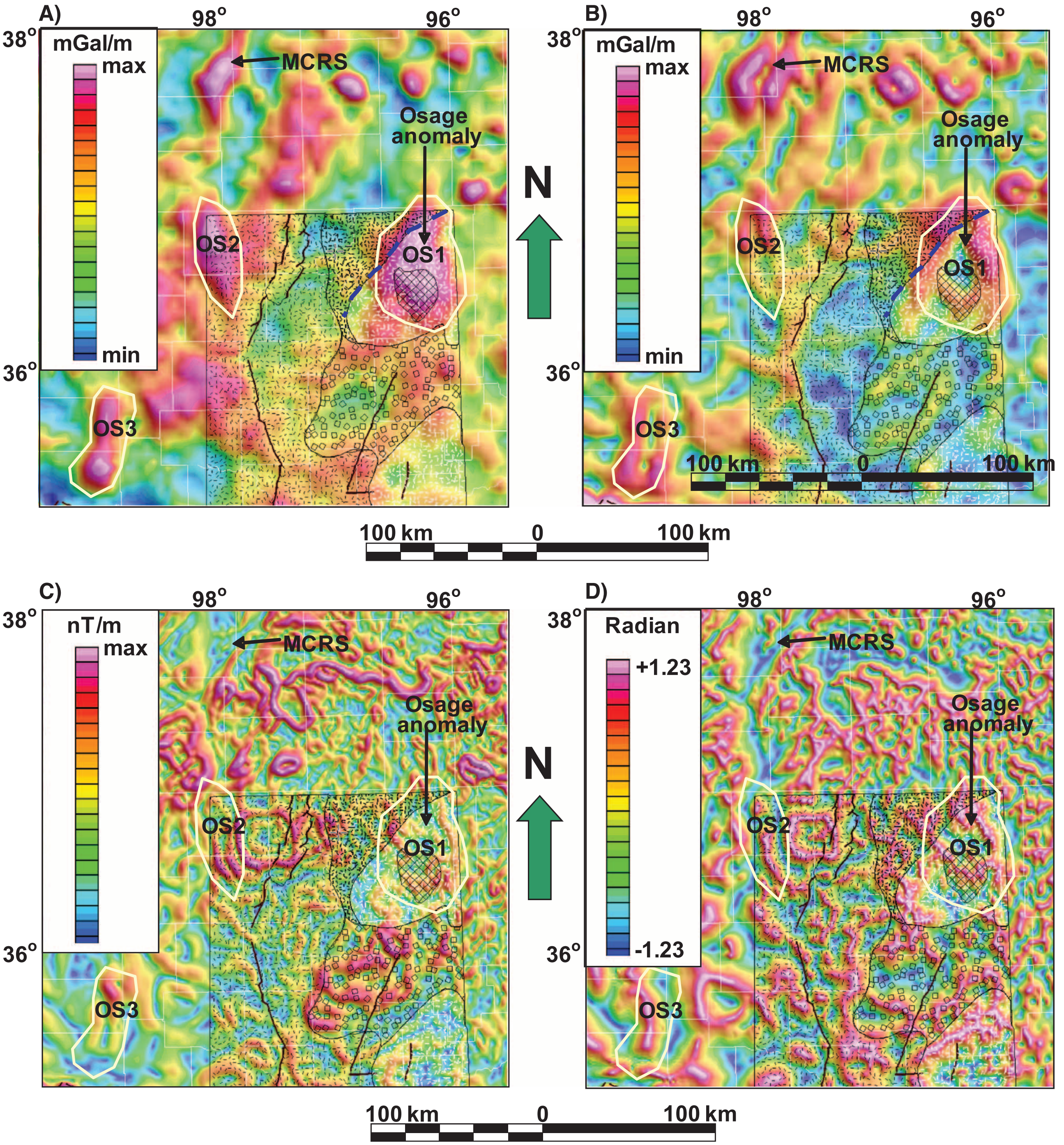


Figure 5. (A) First vertical derivative and (B) horizontal gradient magnitude map computed from the residual gravity grid shown in Figure 4A. (C) Horizontal gradient magnitude and (D) tilt derivative maps computed from the total magnetic intensity grid shown in Figure 4B (see text for interpretation). MCRS = Mid-Continent rift system.

Potential Field Data Enhancement and Filtering Techniques

Potential field anomalies contain a wide range of signals originating from various sources and depths; at times a local anomaly needs to be extracted from a regional anomaly. The techniques of enhancing an anomaly of interest from the Precambrian basement allow one 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 were gridded with a grid spacing of 5000 m (16,404 ft) and 1000 m (3281 ft), respectively. The aeromagnetic data were reduced to the pole 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 generated a residual Bouguer anomaly and a residual total magnetic intensity map from the complete Bouguer anomaly and the reduced to the pole total magnetic intensity grids, shown in Figure 4.

To highlight lateral or abrupt changes in magnetization, which can delineate faults or lateral changes in magnetic susceptibility, we computed the horizontal gradient magnitude, tilt derivative, horizontal derivative of the tilt derivative, and vertical derivative for both gravity and aeromagnetic data sets (Figure 5). Although these edge-detecting derivatives enhance lateral discontinuities, it is the interpreter's responsibility to provide a geologically acceptable interpretation. The mathematical foundation of the gradient method interpretation work flows 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) cited an example of where the gradient from a sloping interface could lead to maxima with two edges. This observation can be misinterpreted as two separate interfaces separating three geologic units.

PRECAMBRIAN BASEMENT DATA ANALYSIS AND INTERPRETATION

Potential Field Expression of Osage Basement Features

The Osage County exhibits simple Bouguer gravity anomalies and complex magnetic anomalies (Figure 3). On the Bouguer gravity and magnetic anomaly map, we observed the broad gravity high Osage anomaly (labeled as 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 (labeled OS2 on Figure 4A), and the elongated north-northeast gravity high that abuts against the Wichita uplift (labeled OS3 on Figure 4A). The broad high-amplitude anomaly seen on the residual gravity and magnetic maps (OS1) (~20 mGal, ~150 nT) measures approximately 99 × 75 km (62 × 47 mi) (Figure 4), suggesting a deep, broad, high-density, high magnetic susceptibility source. Gravity and magnetic derivative maps suggest a northwest-trending anomaly (Figure 5A, B, D). However, Figures 4, 5 indicate both northwesterly and northeasterly trending anomalies. The 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 × 48 km (51 × 30 mi) OS2 anomaly (Figure 4). The suite of maps shown in Figure 4 shows that the OS2 anomaly trends north-northwest and cuts across the region north-northeast trend. This anomaly occurs south of the MCRS and has a northwest-trending direction (Figures 5, 6). The short wavelength nature of this elongate anomaly suggests a shallow crustal source.

The OS3 anomaly that abuts against the Wichita uplift (~10 mGal) measures 75 × 33 km (47 × 21 mi) and trends north-northeast (Figures 4, 5). The magnetization displayed by this elongated anomaly (−250 nT to the north +115 nT to the south) is complex and distinctive. This anomaly has been interpreted to be related to the MCRS by Robbins and Keller (1990) and Adams and Keller (1994). The anomaly is associated with the Keweenawan volcanic rock via gravity modeling.

Evidence of MCRS rock within Osage County is available from age dates from Precambrian wells in the work of Denison (1981) and Van Schmus et al. (1993). Only one well recovered samples with an age that is nearly as young as the MCRS (1100 Ma),

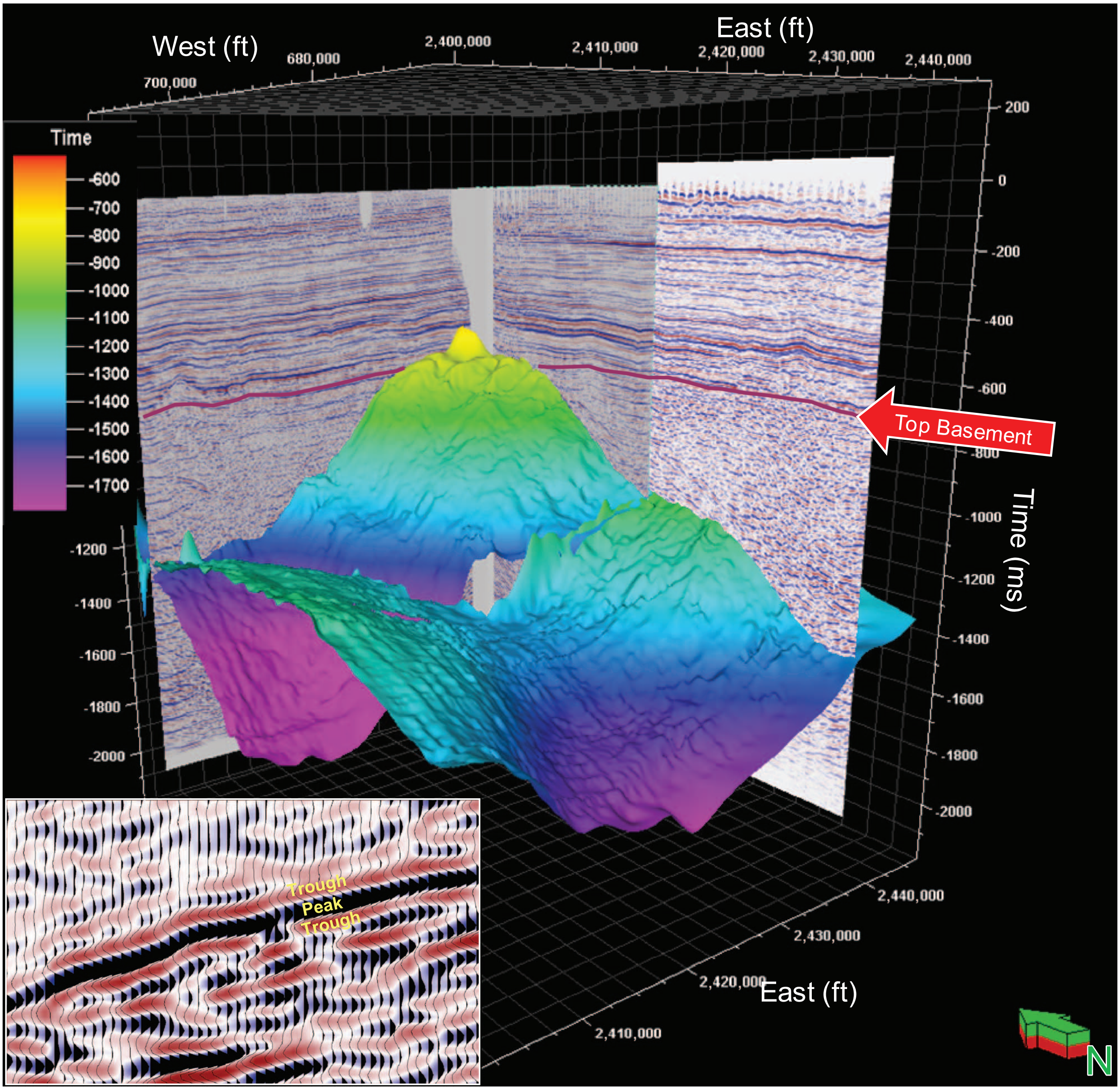


Figure 6. Three-dimensional visualization of seismic data from Osage County showing the geometry of intrabasement reflectors beneath the nearly horizontal Paleozoic section. Inset shows the top of the intrabasement reflector and reflector polarity for one of the seismic lines. Location of the seismic survey is indicated by the shaded rectangular box in Figure 1.

the Texaco Inc. Kohpay well (Figure 4, location 2; Table 1). This well lies close to the OS1 anomaly and is the only well that penetrates the Osage microgranite and provides an Rb/Sr age of 1183 ± 46 Ma (Figure 4). However, wells that penetrate the basement to the west and south are sparse, and the anomalies could be caused by MCRS-related intrusions that do not subcrop. In a similar case, a massive 1100-Ma mafic intrusion from the Central Basin platform of west Texas was penetrated by the North American Royalties 1 Nellie well that drilled into about 5 km (3 mi) of mafic basement rocks. The well was centered on a gravity anomaly maximum, and the anomaly is associated with a mafic intrusion whose subcrop area of this intrusion is small (Keller et al., 1989).

Table 1. Precambrian Basement Wells in Northeast Oklahoma*

Well Location**	API	Operator	Lease	Well No.	Quarter	Section Township Range	Year	Total Depth (ft)
7	13320229	Pawnee Petroleum Co.	Rentie	1	W2 NW NE	23 9N 6E	1968	7261
6	03715553	Central Commercial	Johnson Hay	3	SW NW SW	10 17N 10E	1930 or 1937	4282
5	11330447	Texaco Inc.	Osage C	1A	C NE SW	24 20N 11E	1965	3690
4	11303718	Norbla Oil	Lyman	2	NW SE SW	24 22N 9E	1963	2972
3	11315912	Cities Service Oil Co.	Osage Lot	1-SWD	NW SE NE	8 23N 11E	1953	3032
2	11306916	Texaco Inc.	L. Kohpay	16WS	C NE NE N	29 25N 8E	1963	2848
1	07101424	Anderson-Prichard Oil Corp.	J. Welsh	28	NW NE SW	17 28N 1E	1918;1956	4408
Not shown	Unknown	Eagle Picher Mining Co.	Beaver	43-C	NE NW NE	19 29N 23E	unknown	1650
8	10937486	Cities Service Co.	Farley	5	SW NE NW	19 11N 2W	1947	8344
9	10300893	Oklahoma Natural Gas Co.	Hardrow	1	NW SE	15 23N 2W	1964	5508
Not shown	00321255	Champlin Petroleum Co.	Ray N. Smith	1	E2 SE NW	1 27N 10W	1985	7300
Not shown	Unknown	AMAX	DAC	2	SE SE NE	6 20N 23E		1723
Not shown	11701034	Sinclair Oil and Gas Co.	Louisa M. Jones	46	W2 SE SW	20 21N 8E	1962 or 1988	2945
Not shown	14502643	Henderson Oil Co.	Kelley	1	SW SW NW	18 17N 17E	1965	2505

*The depth to the top of the basement is listed under the column title Basement Top (ft). Column title Basement (ft) is the subsea depth, which is the basement depth relative to mean sea level. Isotope ages were compiled from Denison (1981) and Van Schmus et al. (1996).
**Wells encountered in the Precambrian basement as shown on Figure 4.

Seismic Description of Osage Basement Reflectors

Basement rocks generally display incoherent signals on seismic data, which may be caused by the lack of bedding, high dip, structural complexity, diagenetic homogenization, relatively small impedance contrast, and limited angles of illumination. Very seldom does one see coherent intrabasement reflections similar to those observed on seismic data from Osage County (Figure 6). The Osage intrabasement reflectivity displays 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 6. The base of the intrabasement reflector displays a decrease in acoustic impedance marked by a change from peak to trough. The increase in acoustic impedance at the top intrabasement 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 intrabasement reflectors. Between the bright intrabasement reflectors and the top of basement are reflecting sequences that we interpret to be metaigneous or metasedimentary (Figure 7). McBride et al. (2003) identified similar broad basinal sequences bounded below by three highly coherent layers in the basement beneath the Paleozoic Illinois Basin.

Generally, within the granite-rhyolite province, dipping intrabasement 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 intrabasement reflectors on seismic data from the Kerguelen Plateau in the south Indian Ocean as being caused by basaltic flows. Hinze et al. (1997) and Richard

Surface Elevation (ft)	Basement Top (ft)	Basement Thickness (ft)	Basement Subsea Depth (ft)	Latitude	Longitude	Rock Age	Reference Source	Isotope Age
886	7224	37	−6338	35.24469	−96.64333	1242 ± 21 Ma	Denison (1981)	Rb/Sr
793	4278	4	−3485	35.96382	−96.24289	1212 ± 48 Ma	Denison (1981)	Rb/Sr
1002	3634	56	−2632	36.19272	−96.08434	1286 ± 24 Ma	Denison (1981)	Rb/Sr
860	2933	39	−2073	36.36426	−96.29443	1281 ± 48 Ma	Denison (1981)	Rb/Sr
762	3007	25	−2245	36.48741	−96.14216	1233 ± 50 Ma	Denison (1981)	Rb/Sr
1088	2813	35	−1725	36.62072	−96.45967	1183 ± 46 Ma	Denison (1981)	Rb/Sr
1138	4406	2	−3268	36.90384	−97.22348	1228 ± 56 Ma	Denison (1981)	Rb/Sr
833	1610	40	−777	36.98608	−94.85449	1383 ± 8 Ma	Van Schmus et al. (1996)	Zircon
1249	8272	72	−7023	35.41797	−97.45326	1220 ± 73 Ma	Denison (1981)	Rb/Sr
959	5464	44	−4505	36.46829	−97.39674	1381 ± 29 Ma	Denison (1981)	Rb/Sr
1161	7239	61	−6078	36.84963	−98.22701	1380 ± 24 Ma	Van Schmus et al. (1996)	Zircon
1165	1674	49	−509	36.24235	−94.88778	1270 ± 32 Ma	Denison (1981)	Rb/Sr
961	2929	16	−1968	36.27682	−96.47240	1224 ± 51 Ma	Denison (1981)	Rb/Sr
553	1828	677	−1275	35.95263	−95.54615	1299 ± 26 Ma	Denison (1981)	Rb/Sr

et al. (1997) also interpreted dipping intrabasement 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 intrabasement reflectors, we mapped them using the available 3-D seismic data. The intrabasement reflectors exhibit a basinal geometry with the high end occupying the northeastern end of the survey (Figure 7A). This geometry is also similar to the sill geometry described in Hansen et al. (2004). On Figure 7B, the geometry observed is similar to that of growth or detachment faults. However, the intrabasement reflectors crosscut each other in Figure 7C. This crosscutting relationship is generally seen in settings where tabular igneous intrusions are present, and according to the law of crosscutting relationships, a younger igneous intrusion always crosscuts an older igneous body.

Using the intrabasement reflector dip, we classify these reflectors into two types (I and II). Type I reflectors dip south-southwest, and type II reflectors dip east (Figure 7C). In addition to these geometries, other 3-D data volumes show interactions of intrabasement features with younger sedimentary strata (Figure 8A–C).

In the crosscutting relationships of the intrabasement present in Figure 7C, a type II reflector (blue line) crosscuts a type I reflector, which implies that the type I event, which strikes northwesterly, is older. The areas of the 3-D seismic surveys are part of the granite-rhyolite province (Denison, 1981); thus, we interpret the basement reflectors as being from the lower part of the eastern granite-rhyolite province units. The upper part of the eastern and western granite-rhyolite province has been documented to contain Precambrian sedimentary rocks that yield metamorphic ages of between 1300 and 1100 Ma (Denison et al., 1984).

The prominent dipping Precambrian basement reflector sequence suggests that extension occurred before the emplacement of shallow basement encountered during drilling. A regional episode of

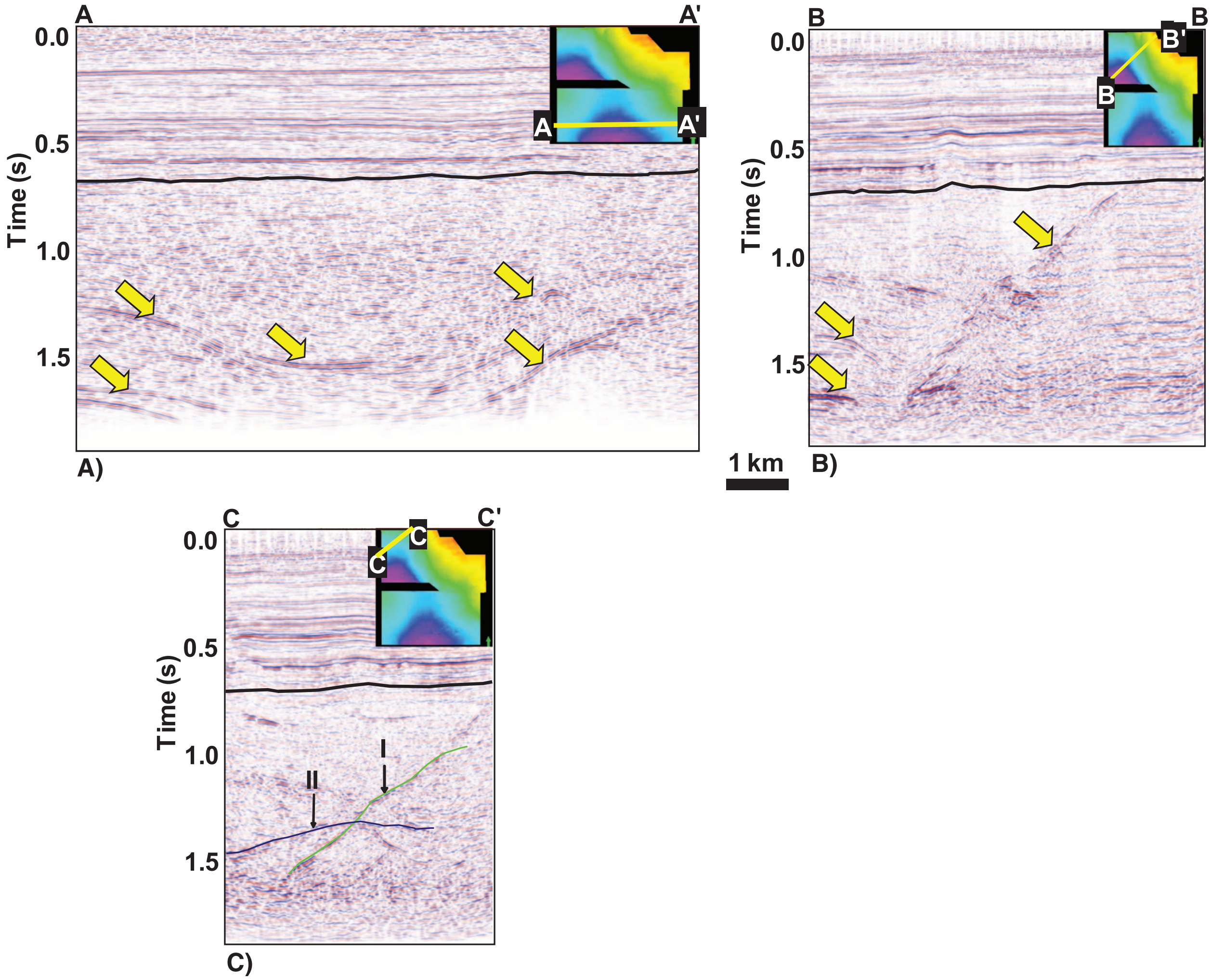


Figure 7. Seismic section (A) AA′, (B) BB′, and (C) CC′ showing the intrabasement reflectors indicated by yellow arrows. Black line indicates the top of the basement. We interpret the reflection events between the intrabasement reflectors and the basement to be part of a suggested metasedimentary section. Location of lines shown in Figure 1. Seismic section CC′ exhibits a crosscutting relationship of the intrabasement reflectors, which we classified as types I and II based on reflector dips. Insert index map is a time-structure map of the top of the basement.

extension possibly occurred early in the development of the 1400- to 1340-Ma magmatic province (Lidiak, 1996). Thus, we interpret the structure we see (Figures 6–8) to be a basin that might have formed during this interval.

PALEOZOIC SECTION DATA ANALYSIS AND INTERPRETATION

Seismic Attribute Expression of Chert Reservoirs from Osage County

We evaluate Mississippian and Arbuckle Group reservoirs by comparing structures and lineaments on both seismic amplitude and attribute data. Structural mapping of both reservoirs shows generally southwest-dipping undulating horizons (Figure 9). The chert horizons display an irregular surface that is typical of a karsted carbonate region. Sinkholes, cockpit karsts, frying-pan valleys, and collapse systems are some of the features that are generally associated with karsted carbonate regions. Most of these features exhibit polygonal valley shapes that may result from subaerial karst processes, cavern collapse, hydrothermal alteration and dissolution, fault tectonism, or a combination of these processes (Cansler and Carr, 2001; Sullivan et al., 2006). Structural complexity increases from the shallow Mississippian chert to the deeper Arbuckle Group.

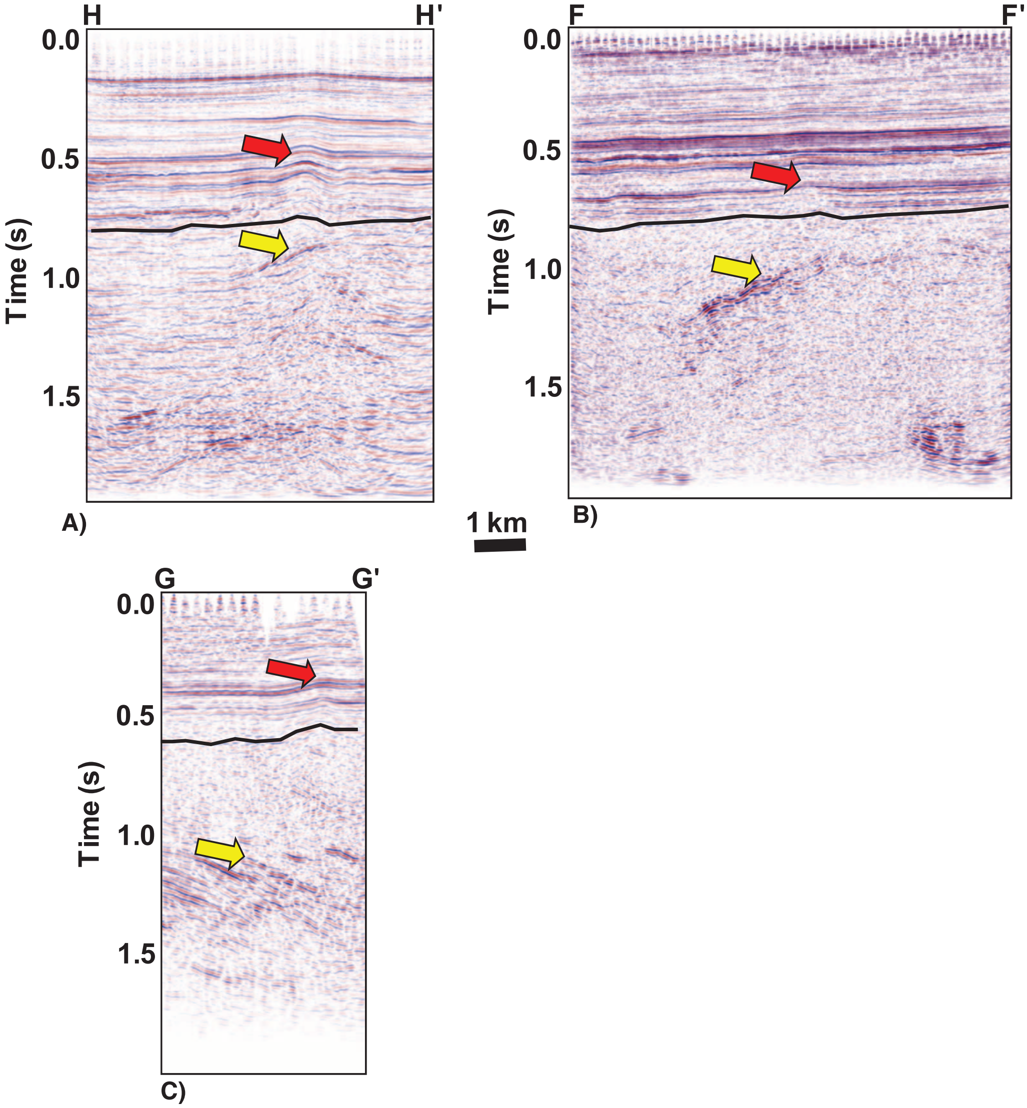


Figure 8. Representative vertical slices through three Osage County surveys (A) HH′, (B) FF′, and (C) GG′ showing the intrabasement reflectors indicated by yellow arrows. Location of lines shown in Figure 1.

We also note an east-west feature in the southern part of the seismic data (indicated by the white arrow seen in Figure 9).

Coherence, curvature, total energy, and inline amplitude gradient attributes computed from the seismic data facilitate mapping of karst features and associated fracture patterns. The coherence horizon slice along the Mississippian chert shows the presence of circular low-coherence features that we interpret as collapse features (red arrows on Figure 10A). At the Arbuckle Group level, these incoherent features are more dominant. We notice that very coherent linear features cut some of these low-coherence features (Figure 11A).

Figures 10B and 11B show the most negative curvature horizon slice along the Arbuckle Group that delineates valley- or bowl-shaped features, which we interpret to be fractures and faults. We identify an increase in the number of lineaments within the Arbuckle Group relative to the Mississippian (Figure 11B). We manually map the azimuth of these coherent and most negative curvature lineaments and plot them as a rose diagram. The rose diagram plots in the Figure 11B 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

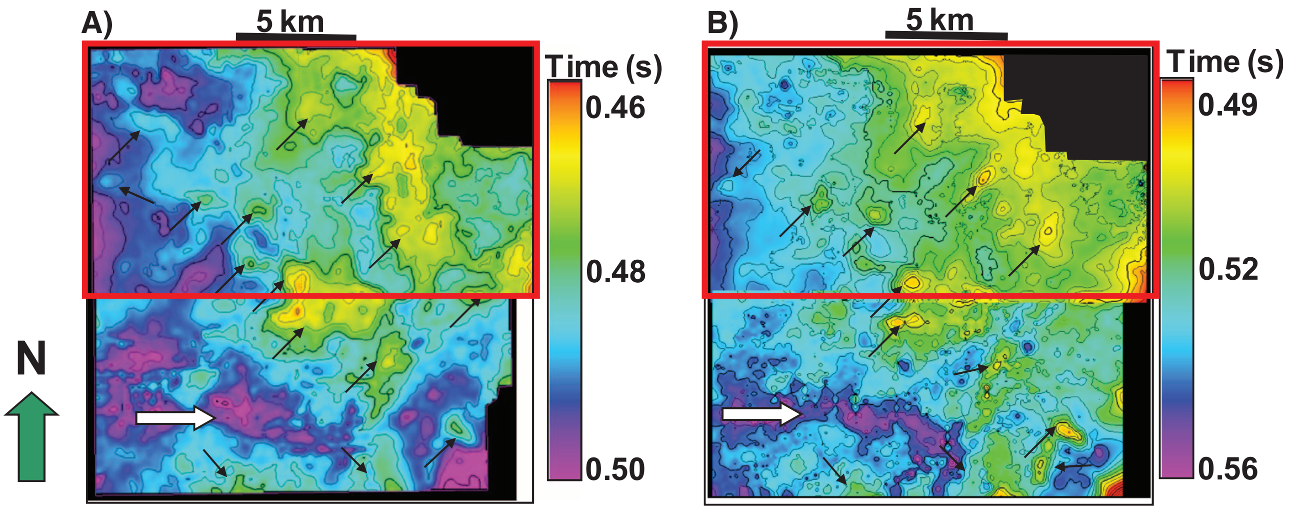


Figure 9. Time-structure map on (A) the Mississippian chert and (B) the top of the Arbuckle Group from two Osage County surveys showing a general southwest-dipping, undulating, and in places, highly irregular surface. Features marked by black arrows suggest residual hills associated with a karsted carbonate region. The red rectangular box indicates the part of the survey that will be shown subsequently in Figures 11–15.

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 (Figure 11B).

Based on our interpretation, the density of the northwest-striking lineaments increases from the Mississippian chert toward the Arbuckle Group and decreases from the Arbuckle Group toward the Reagan Sandstone that lies on the basement (Figures 10B, 11B). 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 12). The coherent and high total-energy nature of these lineaments and their occurrence in structural low areas (Figures 13, 14) suggest that the lineaments are diagenetically altered fractures filled with high-porosity cherts forming a reservoir conduit and sweet spot or the overlying Simpson Group forming a baffle and reservoir compartmentalization.

The lineaments over the Mississippian chert and Arbuckle Group have a general northeasterly and northwesterly strike, consistent with the

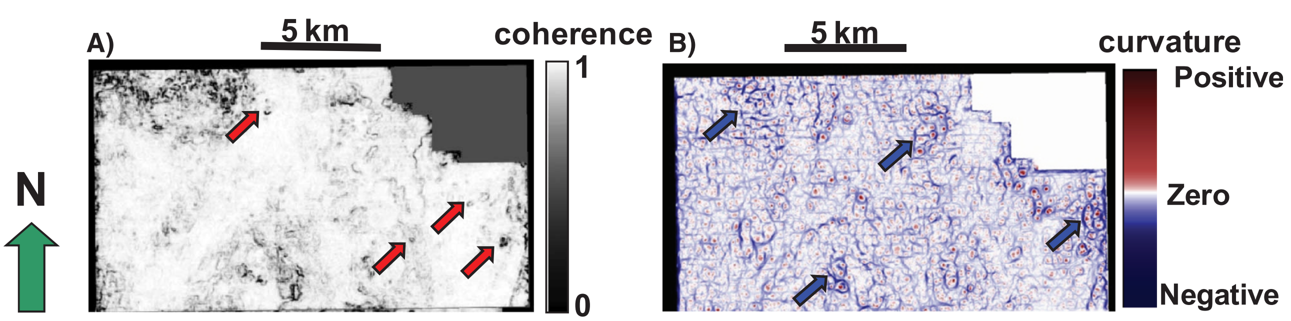


Figure 10. (A) Coherence and (B) most negative curvature horizon slices along the Mississippian chert from the Osage County surveys. Red arrows indicate the location of collapse features; blue arrows indicate networks of fracture lineaments enhanced by curvature attributes. Circular features dominate curvature along the Mississippi chert and no preferred order on lineament is identified.

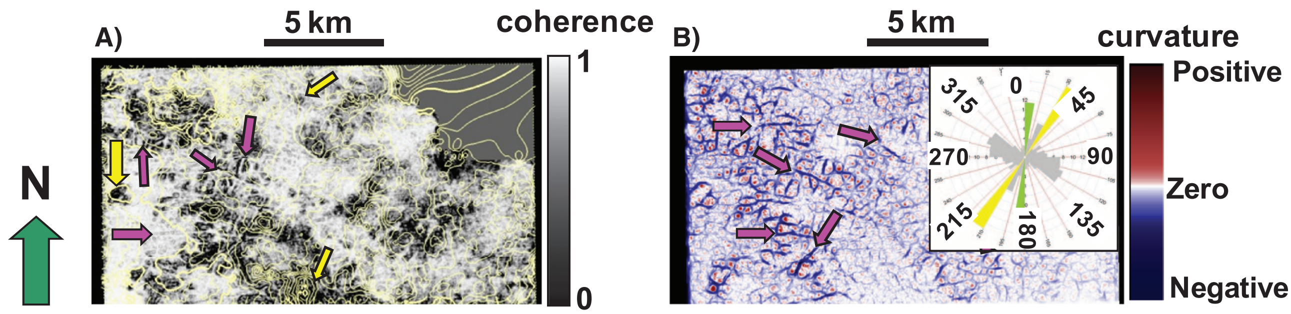


Figure 11. (A) Coherence and (B) most negative curvature horizon slices at the top of Arbuckle Group from two Osage County surveys with time-structure contour overlain (yellow). Magenta arrows indicate networks of some fracture lineaments enhanced by curvature attributes, and yellow arrows indicate low-coherence features that spatially correlate with structurally high areas. The inset rose diagram in panel B shows the distribution of the lineaments mapped manually. The rose diagram shows lineament orientation and density that increases from the Mississippi chert toward the top of the Arbuckle Group and decreases downward toward the Reagan sandstone. Anomalous northeast-trending lineament (yellow petals) on the rose diagram corresponds to a northeast-trending lineament that we interpreted as a fault.

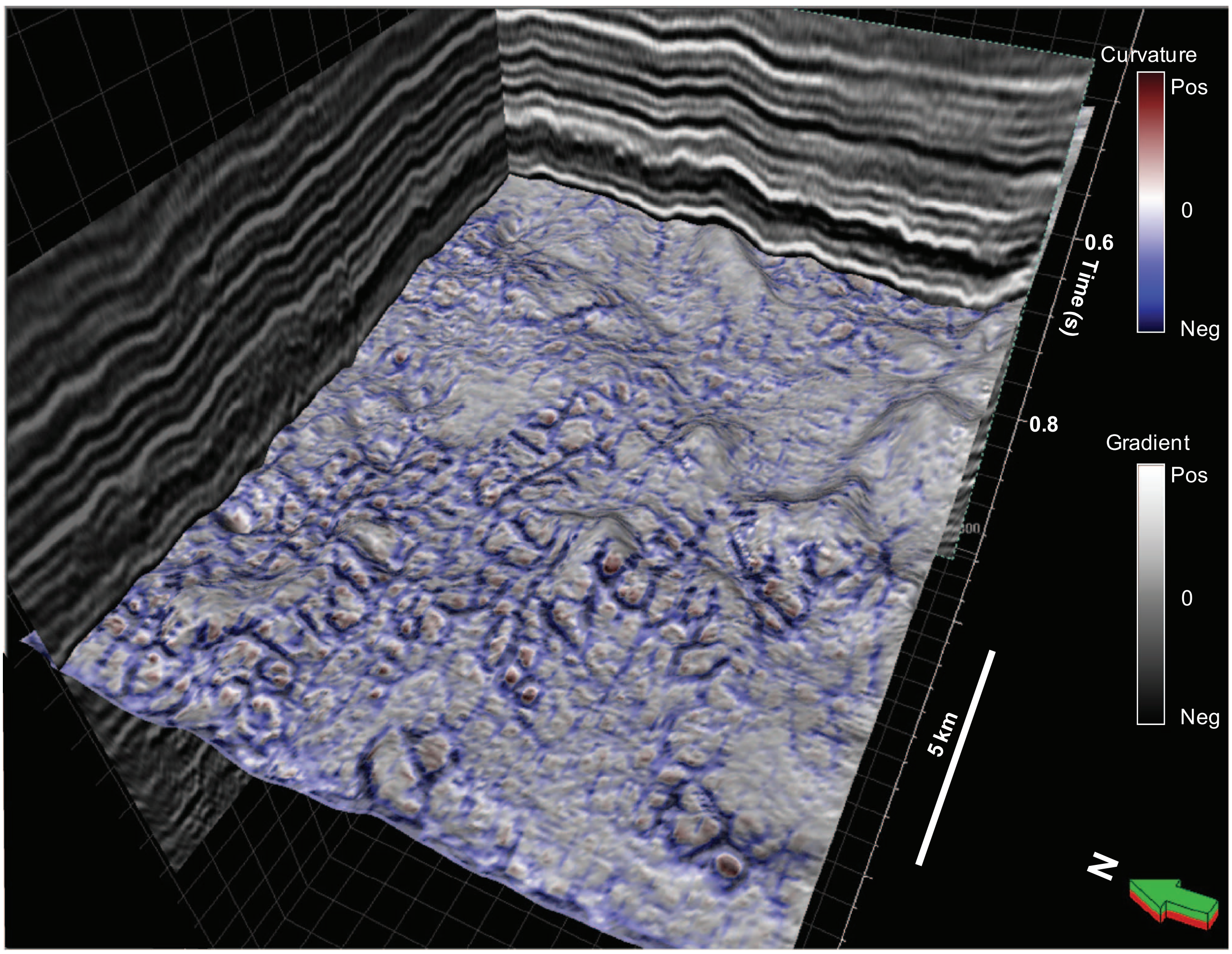


Figure 12. Horizon slice along the top of the Arbuckle Group of corendered most negative curvature (red-white-blue color bar) with inline amplitude gradient attribute (black-gray-white color bar) displayed as a shaded relief map. This image shows the correlation of the higher resolution most negative curvature lineaments to a more conventional lower resolution shaded relief time-structure map.

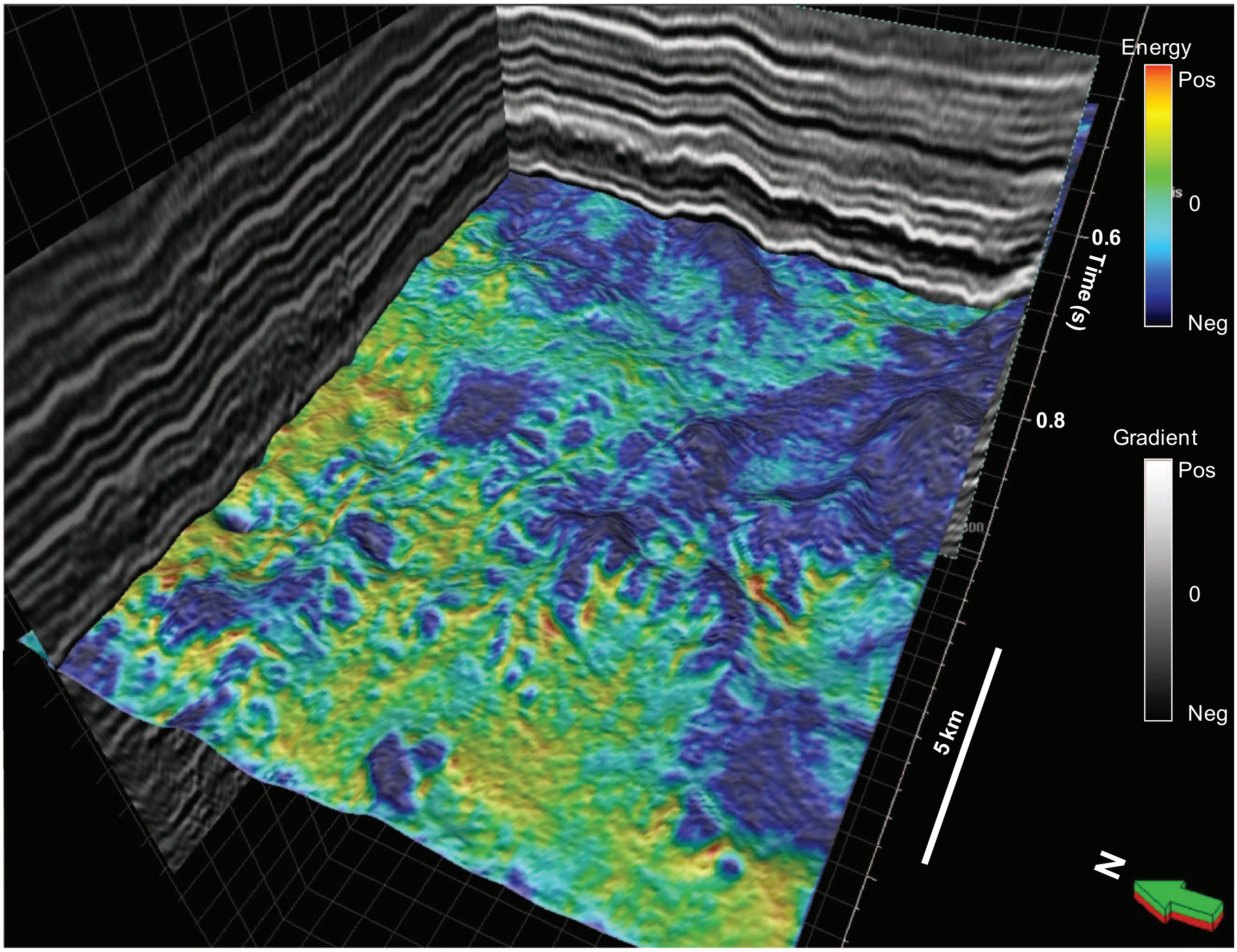


Figure 13. Horizon slice along the top of the Arbuckle Group of corendered total energy (thermal color bar) and inline amplitude gradient (black-gray-white color bar) attribute volumes. This image highlights high (low-impedance) lineaments.

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 (Figure 15).

The northwest-southwest–striking polygonal lineaments seen on the top of the Arbuckle seismic attribute are interpreted as related to the structural basement fabric that has been enhanced by extensive subaerial exposure. The northeast-southwest–striking polygonal lineaments observed on the top of the Mississippian offset the northwest-southeast–striking features and are likely caused by overlaying of Mississippian sediments on a highly karsted topography of the Arbuckle (dominated by the northwest-southeast strike). These northeast-southwest lineaments are related to the Nemaha tectonic event, and these influences are also seen within the Pennsylvanian section.

Precambrian Basement Lineaments

Rose diagrams from the 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 attribute images (Figure 16). However, the northwest-striking anomalies on the horizontal derivative of the tilt derivative maps shown in Figure 16 appear longer than the northeast-striking anomalies. Thus, we interpret the northwest-southeast

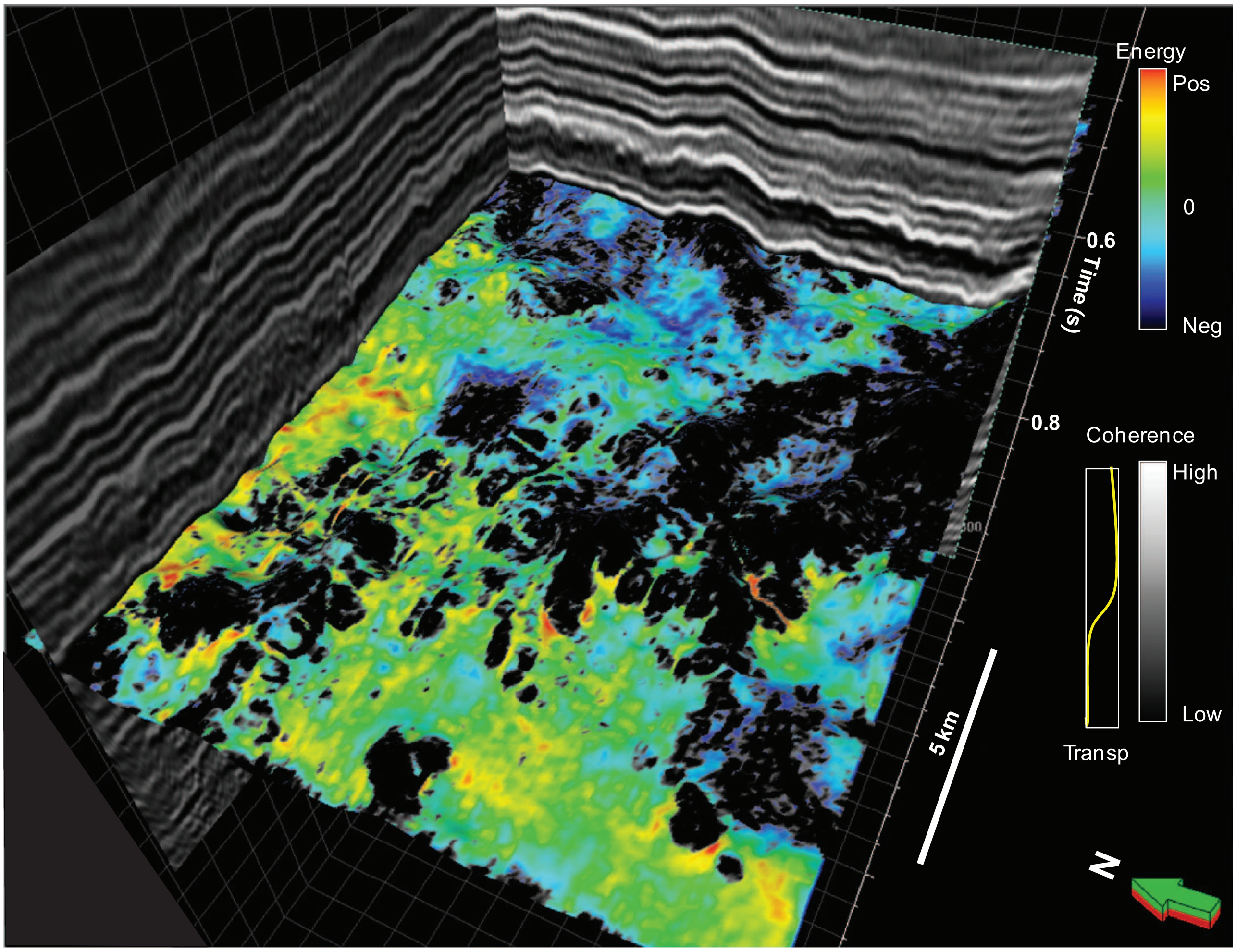


Figure 14. Horizon slice along the top of the Arbuckle Group of coherent energy masked by coherence, with low-coherence areas being displayed as black and high coherence areas rendered transparent. In this manner, we interpret the valley-shaped lineaments seen in Figures 12, 13 as being filled with high-amplitude, low-impedance, coherent material. In most seismic surveys, faults and fractures appear as low-coherence anomalies. The high-coherence anomalies seen in these images are consistent with wide diagenetically altered fracture zones that have been infilled with a coherent material—either chert as encountered in many wells or by overlying sandstones.

Precambrian structures to reflect the broader structural fabric of northeastern Oklahoma.

The evaluation and comparison of the aeromagnetic anomaly trend seen on Figure 15 with the lineament trend from seismic and seismic attribute data (Figures 10–15) reveal similarities in the azimuths of the lineaments on these maps. 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 later deposition and fracturing of the Mississippian chert and Arbuckle Group reservoirs, and some of the structures seen within the Paleozoic section are reactivated structures.

CONCLUSIONS

A section of this article describes an integrated geophysical analysis that investigated the basement structure of Osage County in northeast Oklahoma. Our aim was to understand the relationship of the large gravity and magnetic anomaly in Osage County with the MCRS. The potential field anomalies indicate that the Osage anomaly (OS1) centered within the 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 the MCRS.

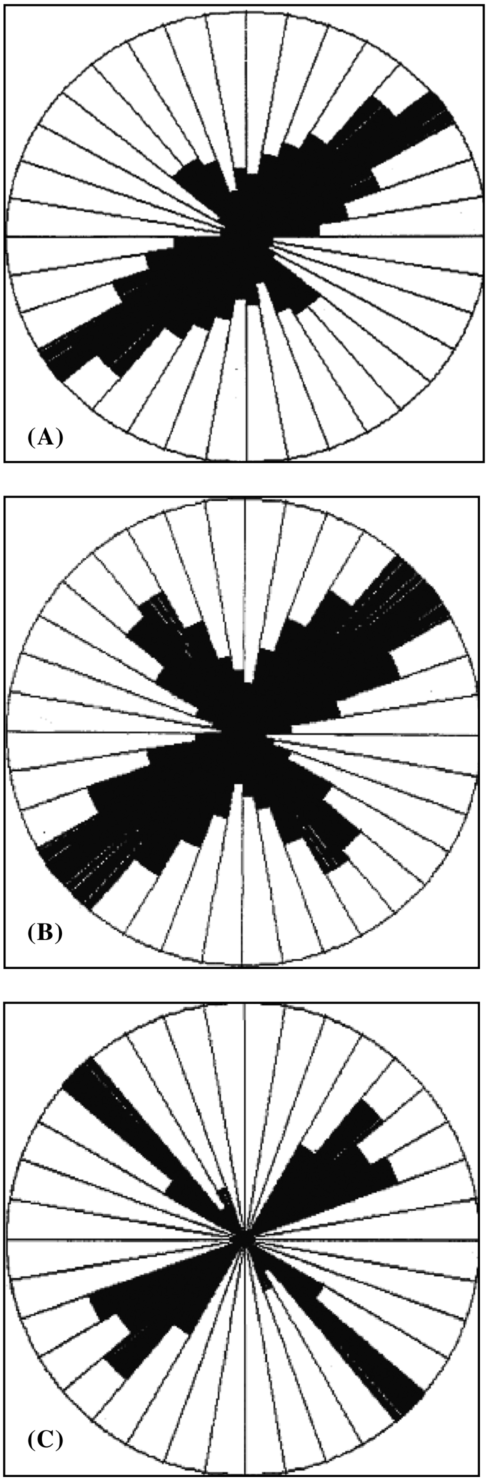


Figure 15. Rose diagrams showing lineament trends digitized from subsurface data, aerial photographs, and satellite images: (A) subsurface structures, (B) surface fracture traces, and (C) major surface lineaments from Osage County, Oklahoma (modified from Guo and Carroll, 1999).

However, we cannot substantiate this conclusion with geochronological age–dating data at this time.

In another section of our study that investigated the control of Precambrian basement on carbonate reservoirs in the Osage County in northeast Oklahoma, seismic attribute images of the Mississippian chert and the Arbuckle Group of Osage County illuminate faults and fractures in these reservoirs. The fractures interpreted on the most negative seismic attribute exhibit polygonal valley shapes that may result from subaerial karst processes, cavern collapse, hydrothermal alteration and dissolution, fault tectonism, or a combination of these processes. These fractures are diagenetically altered and are filled with highly coherent, high-amplitude, and low-impedance fill, which could either be in the Mississippian deposit high-porosity chert forming a reservoir conduit and sweet spot or, in the case of the Arbuckle filled with the preserved overlying Simpson Group, forming a baffle and reservoir compartmentalization.

Our fracture analysis study on the most negative curvature and rose diagram reveals that lineaments within the study area strike northeast-southwest and northwest-southeast. These lineaments interpreted as fractures show fracture density that increases from the Mississippian chert downward toward the Arbuckle Group but decreases from the Arbuckle Group toward the Reagan Sandstone. Basement structure lineaments are parallel in orientation to 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 sections of Osage County. The northwest lineaments are interpreted to be related to the inherent structural fabric of the basement rock or the draping of the Mississippian over a cockpit karst terrain.

In summary, we propose that the Precambrian basement controls the Mississippian chert and Arbuckle Group reservoirs. Although a one-to-one correlation between the basement structures and the carbonate reservoirs cannot be established, highly coherent areas with a high total energy may be a good indicator of a viable chert reservoir.

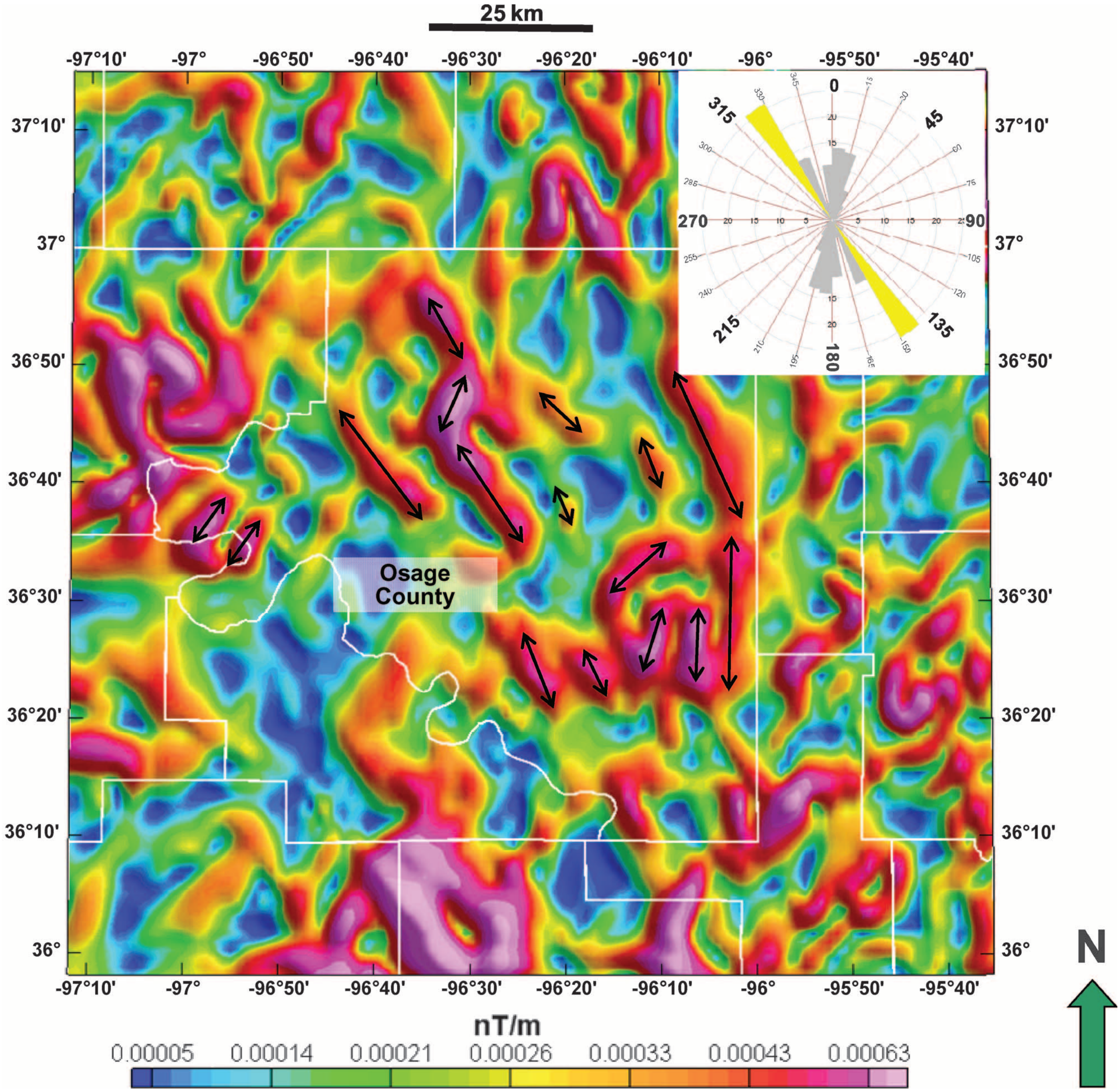


Figure 16. (A) Horizontal gradient magnitude of the tilt derivative map of the magnetic data with corresponding rose diagrams showing Precambrian structural trends. Arrows show the lineaments mapped on the rose diagram.

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