

## **Improving Geologic and Engineering Models of Midcontinent Fracture and Karst-Modified Reservoirs Using New 3-D Seismic Attributes**

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## **ABSTRACT**

Our project goal is to develop innovative seismic-based methodologies and workflows for the incremental recovery of oil from karst-modified reservoirs within the onshore continental United States. The karst-modified reservoirs that we selected for study (Ordovician Arbuckle, Mississippian Spergen-Warsaw, and Permian San Andres) are among the most productive karst reservoirs within the mid-continent, and represent a wide variety of karst types.

Our objectives for this reporting period were to: 1) gather 3-D seismic, petrophysical, and engineering data on all fields in the study, 2) generate multi-trace seismic attribute volumes for the Permian San Andres study area, and 3) start the process of reservoir characterization of the Permian San Andres reservoir. We have accomplished all of our objectives and are ahead of schedule in our studies of the Mississippian and Arbuckle datasets. Preliminary interpretation of multi-trace curvature attributes in all study areas reveals a variety of geomorphologic features related to karst. In particular, attribute analysis of the San Andres reservoir suggests that fractures imaged by curvature volumes (but not by conventional seismic) cut across anhydrite-cemented karst and correspond with localized high volumes of water production.

In addition to beginning the attribute-based interpretation of all reservoirs, we are exploring combining curvature attributes with acoustic impedance inversion as a method of imaging reservoir extent in low porosity, karst modified reservoirs.

All of our reports, publications, and publicly available digital data will be posted to our new project website (<http://www.kgs.ku.edu/SEISKARST>).

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## EXECUTIVE SUMMARY

Our project goal is to develop innovative seismic-based methodologies and workflows for the incremental recovery of technically recoverable oil from known and undiscovered karst-modified reservoirs within the onshore continental United States. Our objectives include the calibration of new multi-trace seismic attributes to advance imaging of small scale subsurface features in karst-modified reservoirs, and to develop attribute-based, cost-effective workflows to better identify, characterize, and quantify karst-modified carbonate reservoirs and fracture systems. We are studying Paleozoic karst-modified reservoirs in Texas, Colorado, and Kansas that represent a diversity of lithologies, karst processes, and porosity/permeability systems.

During this first reporting period, from October 1, 2004 through March 31, 2005, the project focused on three tasks: (1) gather 3-D seismic, petrophysical, and engineering data for four study areas (a Permian San Andres reservoir in Crane County, Texas, a Mississippian reservoir in Cheyenne County, Colorado, an Arbuckle reservoir in Rooks County, Kansas, and an Arbuckle reservoir in Russell County, Kansas); (2) generate multi-trace seismic attribute volumes for Waddell Field, Crane County, Texas; and (3) begin the process of seismic, geologic, petrophysical, and engineering characterization of the "High Volume" San Andres reservoir in Waddell Field. We have accomplished these objectives and, in addition, are ahead of schedule in our studies of the Mississippian and Arbuckle datasets.

We now have in house 3-D seismic data from the four study areas, along with well logs and production data. We have generated multi-trace seismic attribute volumes, including coherence, maximum positive curvature, and maximum negative curvature, for all of the surveys. We have created synthetic seismograms and have tied the logs to seismic in all study areas, and have begun generating acoustic impedance inversion volumes for the seismic surveys. We anticipate these acoustic impedance inversion volumes will help delineate reservoir extent. We have started the process of reservoir characterization in the Permian San Andres reservoir by seismically mapping the structural top and base of the reservoir and generating grids, as well as an isochore map. Fracture systems, indicated by lineaments in the San Andres curvature volumes, coincide with reservoir compartmentalization documented by well production and tracer studies. Based on examination of core data, these fracture systems appear to be related to late stage fracturing and dissolution of anhydrite-cemented karst.

For the Mississippian and Arbuckle reservoirs, we have made preliminary seismic interpretations of the Mississippian and Arbuckle unconformity surfaces and have begun to extract volumetric attributes for analysis. Lineaments on curvature slices are being mapped and their orientations are being analyzed. Preliminary interpretations of the volumetric curvature data have revealed preferred lineament directions that appear to be related to regional structure, as seen in aeromagnetic and gravity maps, as well as geomorphic features, such as polygonal karst. These features will be included in a catalog of karst features, which is to be compiled during the next reporting period.

Experimentation with combined attributes (such as shape index and integrated coherence/dip/azimuth) shows promise for improving imaging of certain small karst features, such as sinkholes, and we anticipate these combined attributes will be an important part of the karst catalog.

During the next six months, we will continue to use volumetric attributes to refine our seismic interpretations. Geomodel construction will begin for the Permian San Andres reservoir. We will generate fault plane maps as needed and convert our seismic time maps to depth and thickness grids, building a geologic framework. We will then populate this framework with petrophysical and engineering data.

A project website (<http://www.kgs.ku.edu/SEISKARST>) is being constructed for dissemination of information, including non-proprietary digital data, the catalog of karst features, and electronic versions of reports and publications.

## **DATA GATHERING**

3-D seismic, geologic, petrophysical, and engineering data have been acquired for the project study areas as detailed below. Non-proprietary digital data will be made available through the project website (<http://www.kgs.ku.edu/SEISKARST>).

### Permian San Andres Study Area

Schlumberger Oilfield Operating Company, on behalf of Burlington Resources, has provided us with digital LAS well logs and production data for 50 wells in the San Andres reservoir of Waddell Field, Crane County, Texas (Figures 1 and 2). Production data include oil, gas, and water production by month, and water injected per month. We have in house the 104 sq. km (65 sq. mi.) post-stack 3-D seismic survey covering the karsted San Andres “High Volume” field (Figure 3). Schlumberger has supplied us with 10 large-scale hardcopy modern log cross-sections, basemaps of producers and injectors, and the results of 15 radioactive tracer tests. The tracer studies are particularly important in showing actual inter-well connectivity and flow paths that we can compare to seismic attribute anomalies.

### Missippian Study Area

Over the past six months, we have acquired from Mull Drilling Company, Wichita, Kansas, two cores, LAS log files, formation tops, and 14.2 sq. km (5.5 sq. mi.) of 3-D seismic data for the Cheyenne Wells and Smoky Creek Fields, Cheyenne County, Colorado (Figures 1 and 4). In addition, approximately 360 raster images of well logs have been downloaded from the Colorado Oil and Gas Conservation Commission’s (COGCC) website (<http://www.oil-gas.state.co.us>). There are 64 wells within the 3-D seismic survey area, ten of them with sonic logs. The sonic logs, along with density logs where available, are used to create synthetic seismograms for tying to the seismic data. Raster images of the sonic and density logs within the 3-D seismic survey area have been digitized for use in generating the synthetic seismograms. Production data, including monthly oil, gas, and water production and days online per month, have been collected from Mull Drilling Company.

### Arbuckle Study Areas

There are currently two Arbuckle study areas (Figures 1 and 5). We will conduct seismic interpretation and attribute analysis for both of these areas, but only one study area will undergo detailed geomodel construction and reservoir simulation. The suitability of each area for the detailed study is being evaluated based on data availability and data quality.

Murfin Drilling Company, Wichita, Kansas, has provided three 3-D seismic surveys, with more than 90 sq. km (35 sq. mi.) of data coverage, for Arbuckle study area 1, Rooks County, Kansas. 342 wells within the 3-D survey bounds penetrate to the Arbuckle, and well information (including well location, completion date, well type, and formation tops) and lease production data have been downloaded from the Kansas Geological Survey’s

(KGS) website (<http://www.kgs.ku.edu/PRS/petroDB.html>). LAS log files for four wells have been provided by Murfin Drilling Company, and raster images of logs for five additional wells have been downloaded from the KGS website. Paper copies of wireline logs for more than 200 additional wells are stored in the KGS data library and selected logs will be scanned if this area is chosen for detailed study.

Arbuckle study area 2 is located in Russell County, Kansas. John O. Farmer, Inc., Russell, Kansas, has provided 25 sq. km (10 sq. mi) of 3-D seismic data and LAS log files for four wells in this study area. Well information has been downloaded from the KGS website for wells in the study area, including 176 wells within the bounds of the seismic survey that penetrate to the Arbuckle. Paper copies of wireline logs are available in the KGS data library for 96 of these wells, and these logs will be scanned, as needed. Lease production data has also been downloaded from the KGS website.

Both prospective study areas have a reasonable amount of seismic and well data available. However, one drawback to study area 1 is that it is located in a region where shallow salt thickness varies due to dissolution. This produces areas of poor seismic data quality and unreliable seismic time to depth conversions. Salt dissolution effects are not present in study area 2. Based on the lack of complications from overlying salt dissolution, study area 2 at this time appears to be the leading candidate for detailed study.

## **DATA ANALYSIS AND RESULTS**

One of the best-accepted geologic models for determining deformation is the relation between reflector curvature (Figure 6) and the presence of open and closed cracks. Reflector curvature is fractal in nature, with karst detail versus regional compaction features illuminated by short wavelength and long wavelength scales, respectively. Until now, such curvature estimates have been limited to the analysis of picked horizons. In contrast, the spectral estimates of reflector curvature used in this study allow us to examine broken reflectors within the entire seismic volume. We find that the maximum positive and maximum negative curvatures (Figures 3, 9, 13, and 14) are particularly useful in mapping lineations, including faults, folds, and flexures (Sullivan et al., 2005). Long spectral wavelength curvature estimates (Figure 3) are of particular value in extracting subtle, broad features such as fault blocks and compaction over karst landscape.

Multi-trace seismic attribute volumes, including maximum positive curvature and maximum negative curvature at both long and short spectral wavelengths, have been generated for all of the 3-D seismic surveys in our study areas.

### Permian San Andres Study Area

Charles (Chuck) Blumentritt, a PhD candidate at the University of Houston, has mapped top and base of the reservoir (Figure 7), and generated a complete suite of attribute volumes for the 3-D seismic survey. In addition, Chuck has been applying some of his

recent experiments in combining curvature attributes (Blumentritt et al., 2004) to enhance resolution of small scale irregular karst features, such as collapse features or sinkholes, in the San Andres. Our results, to date, based on preliminary integration of core, tracer, and production data with our volumetric attribute results, suggest that early San Andres subaerial karst was plugged by anhydrite cement. The high volume production of fluids in our study area appears to be the result of late field-scale fractures and localized dissolution of anhydrite cement that compartmentalizes the reservoir and connects the productive reservoir zone with the underlying aquifer.

Preliminary work has begun for constructing a reservoir geomodel. We have completed seismic mapping of the structural top and base of the reservoir and generated grids, as well as an isochore map. We will next refine our fault picks, using the volumetric attributes, and generate fault plane maps as needed. We will then be able to constrain our grids with well logs and convert our seismic time maps to depth and thickness grids. We will use these grids to build a geomodel framework, which we will populate with petrophysical and engineering data.

Jeff Jankoski, a Masters candidate at the University of Houston, has just started a petroleum systems study of the Central Basin Platform area. He will be analyzing oils and source rocks from the platform and from the Midland Basin. His data and preliminary basin modeling will provide useful parameters for the reservoir simulation of part of the San Andres field.

Several of our graduate students have been using the Waddell Ranch data to experiment with improving spectral decomposition and acoustic impedance technologies. Spectral decomposition and acoustic impedance inversion may permit us to see subtle but important changes in low porosity Ordovician and Mississippian carbonates. We plan on running volumetric curvature attributes on impedance volumes. To our knowledge, this is the first time anyone has run volumetric curvature on an impedance volume. We anticipate that this technique may highlight subtle diagenetic karst overprints.

### Mississippian Study Area

Natalie Givens, a graduate student at the University of Kansas, has begun a Master's project focusing on the Mississippian study area. She has completed an initial inspection of the two cores in the study area, in which she described half-foot sections of the cores using basic lithological characteristics. These basic lithological characteristics are: rock type, rock classification, amount of clay, sucrosic texture, if fractures were present or not and if they are filled with calcite or not, initial grain size, crystal size, main pore type, subsidiary pore type, bedding structures, fauna and color. Samples have been taken from intervals of the core and sent out for thin section processing.

An initial set of synthetic seismograms has been produced and tied to the 3-D seismic volume, allowing formation tops to be correlated with seismic horizons (Figure 8). The Mississippian unconformity surface occurs at a time of approximately 1.0 second. A horizontal slice through the maximum negative curvature attribute at this time shows sets

of large-scale lineaments trending approximately N30W and N65E (Figure 9). These features may be related to regional structural trends that are seen on aeromagnetic and gravity maps of Colorado (Figure 10), and may reflect fracture orientations that controlled karst development on the Mississippian surface. Curvature lineaments paralleling regional structural trends have already been identified on the Mississippian unconformity surface in 3-D seismic data from Kansas (Nissen et al., 2004), and these lineaments have been related to both open and closed fracture systems in the Mississippian reservoir.

### Arbuckle Study Areas

Synthetic seismograms have been created and tied to the 3-D seismic volumes in both study areas (Figures 11 and 12), and a preliminary interpretation of the Arbuckle surface has been made on the seismic data. A map of maximum negative curvature extracted along the interpreted Arbuckle horizon in study area 2 (Figure 13) shows two dominant lineament directions, approximately N35W and N45E, similar to regional structural trends seen on gravity and magnetics maps of Russell County, KS (Figure 14). A network of polygonal features, with average diameters of approximately 230 m (750 ft), is superimposed on the regional lineament trend. The polygonal features are reminiscent of polygonal (or cockpit) karst, as described by Williams (1972). Polygonal karst has been identified on the Arbuckle erosional surface at other locations in Kansas using well data (Cansler and Carr, 2001). In Arbuckle study area 1, a maximum negative curvature time slice at the approximate level of the Arbuckle unconformity surface (Figure 15) also appears to show polygonal features, although these features are less regular in size and shape than the features in study area 2, and range from 150 to 450 m (500 to 1500 ft) in diameter.

## **CONCLUSIONS**

Preliminary interpretation of volumetric curvature attributes in the study areas has revealed a number of characteristic karst features, which will provide the building blocks for us to develop a useful seismic attribute catalog of karst features during the next reporting period. In particular, maximum negative and positive curvature volumes image geomorphologies that appear to be related to mature, cockpit landscapes in the Arbuckle data, and collapse features in the San Andres data. These curvature images also illuminate lineaments that appear to be related to joint and fracture systems in all surveys.

Synthesis of attribute analysis with core, production, and tracer data in the Permian San Andres field indicates that the lineaments we observe in the curvature volumes are related to fractures and dissolution of anhydrite observed in core, and coincide with compartmentalization and localization of high produced-water volumes documented by engineering data.

We have begun to generate acoustic impedance volumes that will help us better define reservoir porosity distribution. Reservoir delineation in low porosity karst modified reservoirs has always been a difficult task, and we feel the combination of curvature and impedance inversion may improve our ability to define reservoir boundaries.

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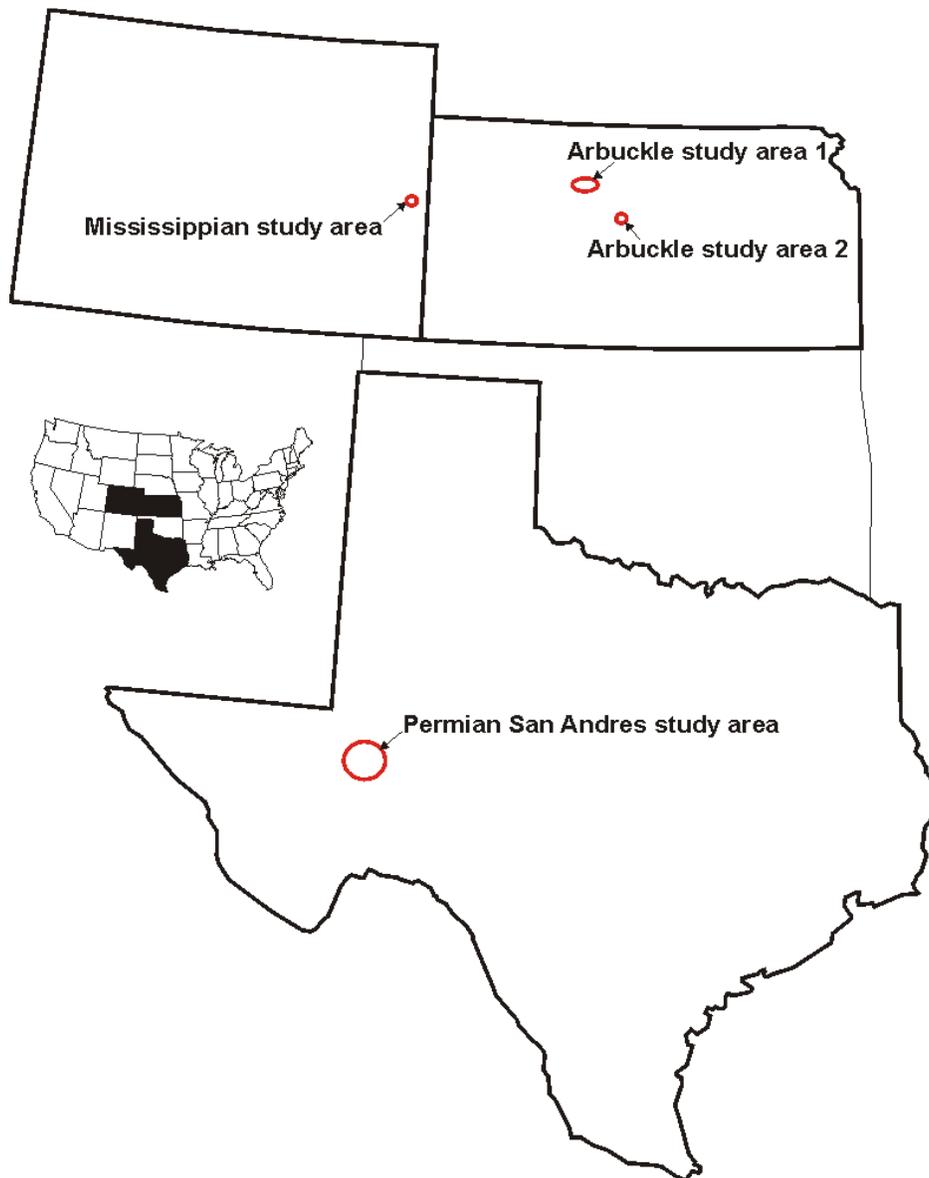


Figure 1. Index map showing locations of study areas.

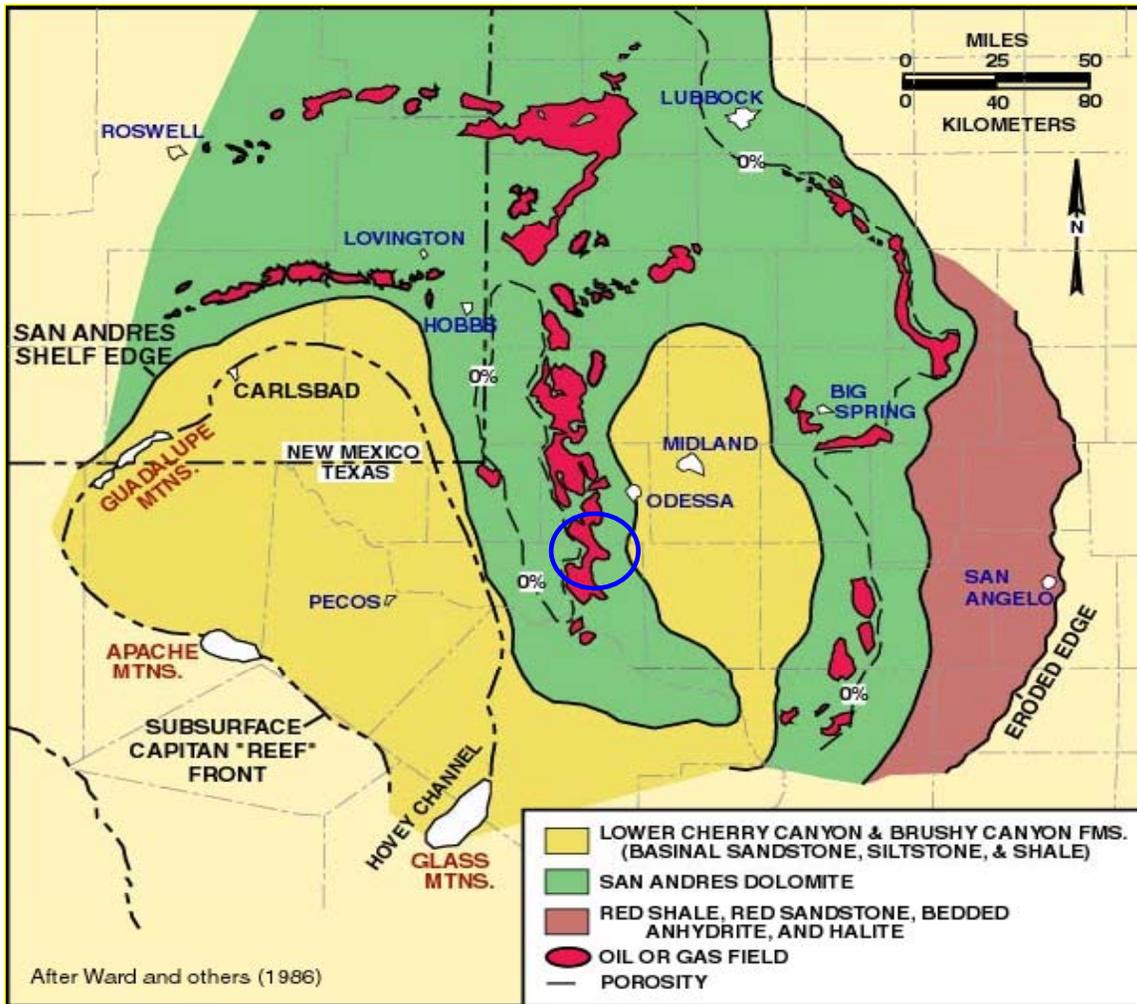
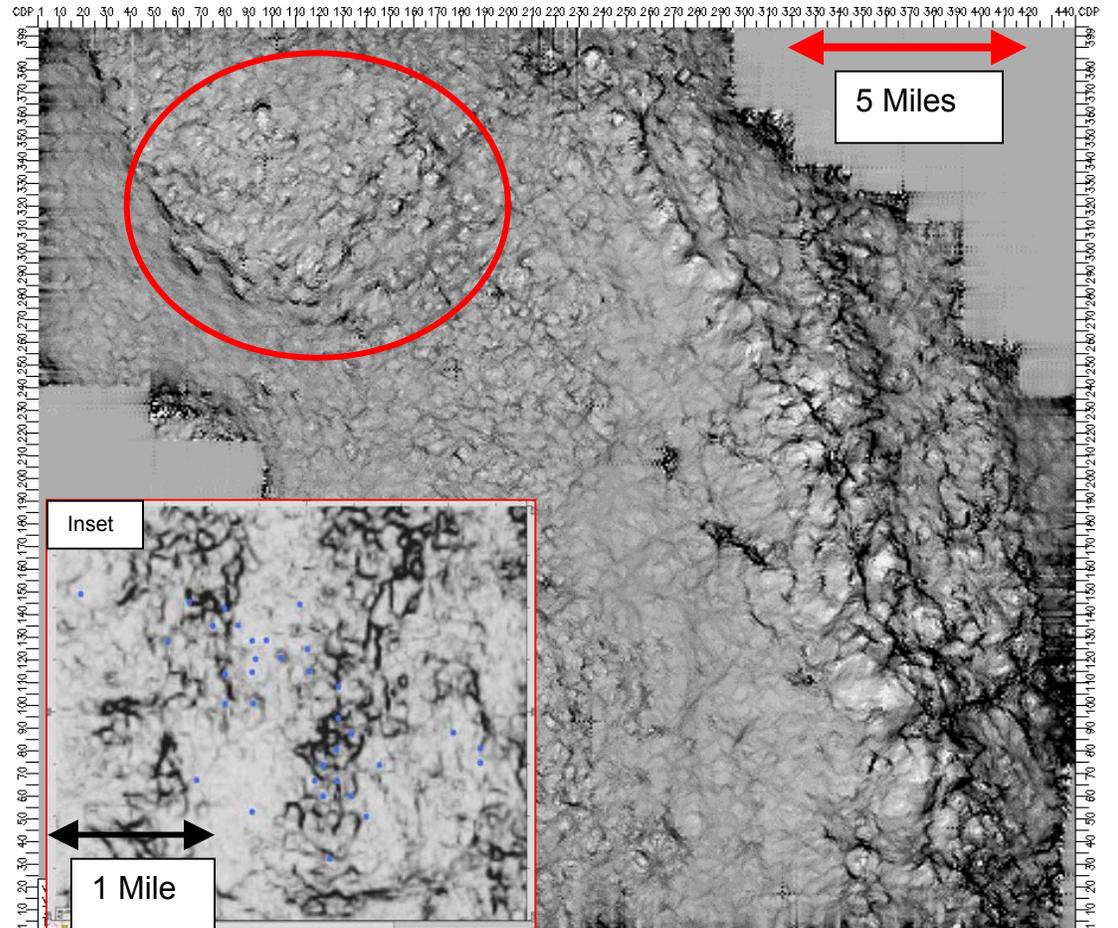


Figure 2. Location of major San Andres fields in the Permian Basin. The karsted reservoir in our study (blue circle) is in the “High volume” area of the Waddell Field in northern Crane County. Our work to date indicates that the production in this area, which is an order of magnitude greater than in the surrounding San Andres field, is the result of fractures and dissolution that irregularly cut across anhydrite-plugged, karsted, shallow water carbonates. (Map modified from Scholle, <http://geoinfo.nmt.edu/staff/scholle/guadalupe.html> .)



**Figure 3.** Time-slice from the maximum positive curvature attribute volume generated from the large, 3-D seismic survey that covers the Waddell San Andres Field in west Texas. The San Andres reservoirs produce across most of the survey area, but individual wells within the study area (red oval) have produced high volumes of fluid (up to 16 million BBLS of water and 2 million BBLS of oil). Dark lineaments in the map are areas of anticlinal curvature. White areas are areas of low positive curvature. Curvature lineaments have been shown in other data sets to be related to open and closed fracture systems and to small offset faults (Nissen et al., 2004). Inset is a coherence horizon extraction at the top of the reservoir interval within the “High Volume” area. Less coherent areas (dark broken areas) indicate disrupted seismic events, related to karsted and fractured reservoir rock. Producing wells are shown in blue in the inset; injectors are not shown in this display.

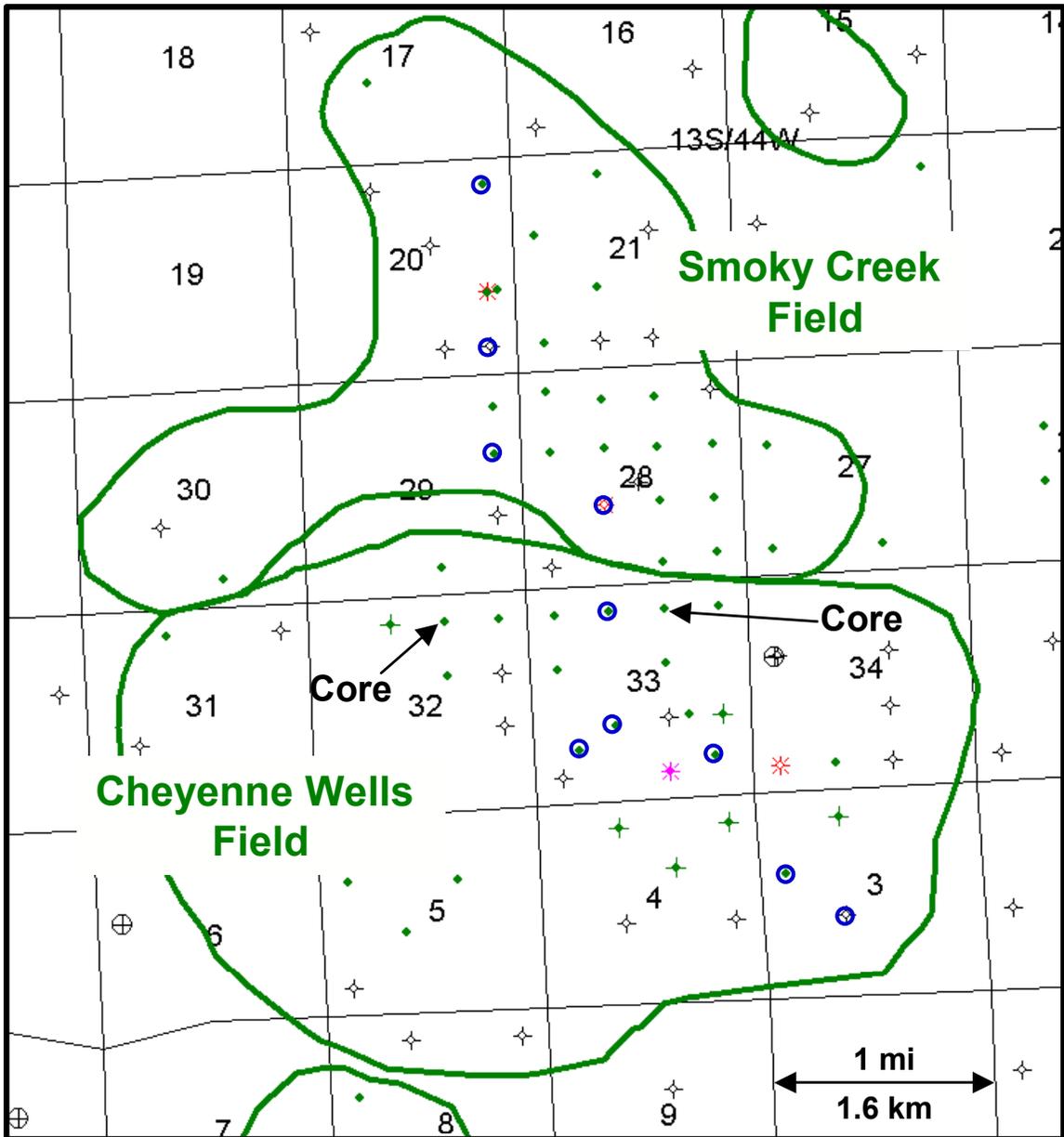
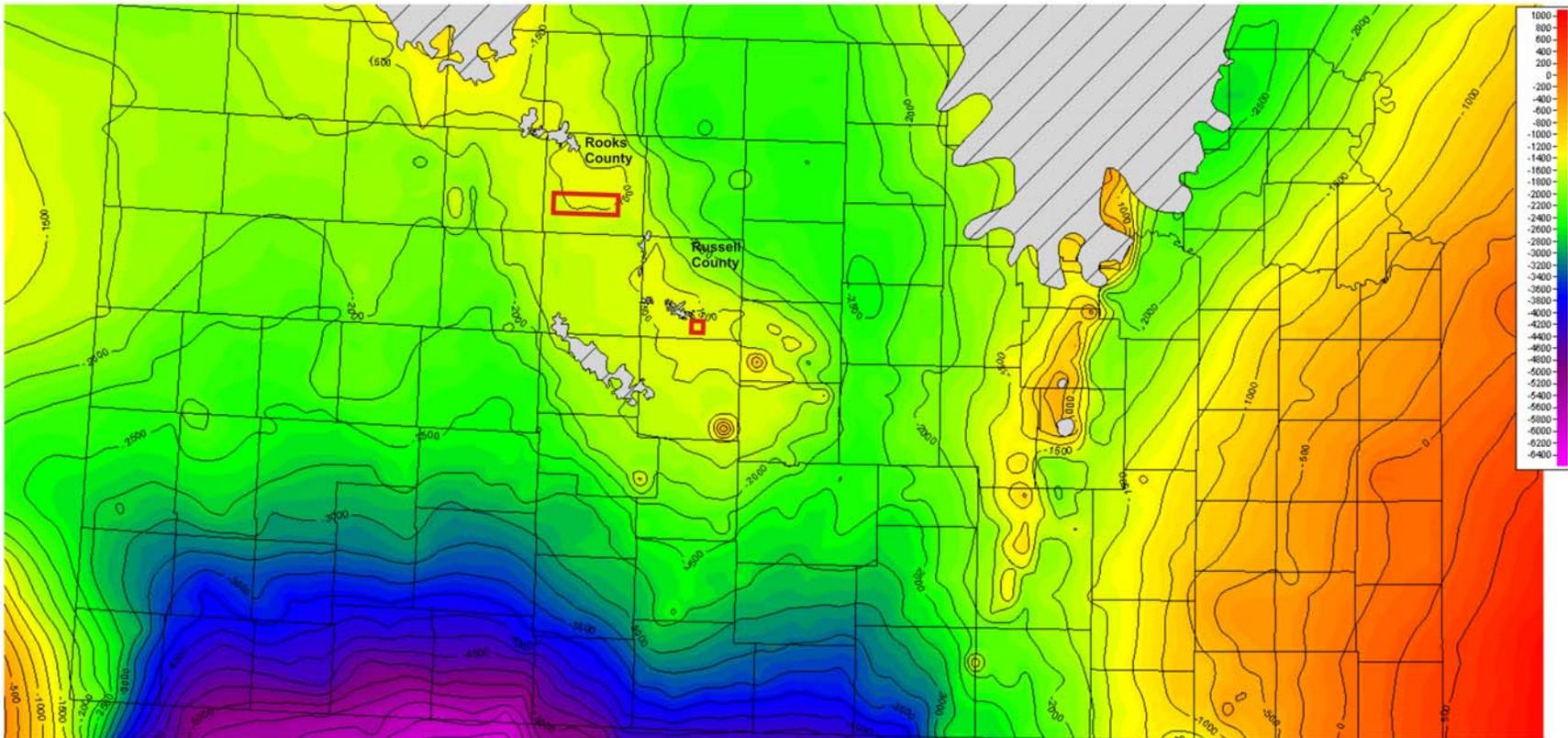


Figure 4. Map of Mississippian study area in Cheyenne County, Colorado. Cheyenne Wells and Smoky Creek Fields are outlined in green. Wells with sonic logs are highlighted with blue circles. Wells with core are annotated.



**Figure 5. Top of Arbuckle structure map for Kansas with locations of Arbuckle study area 1, in Rooks County, and Arbuckle study area 2, in Russell County, outlined in red. Contour interval = 250 ft (76 m). Arbuckle is absent in gray areas.**

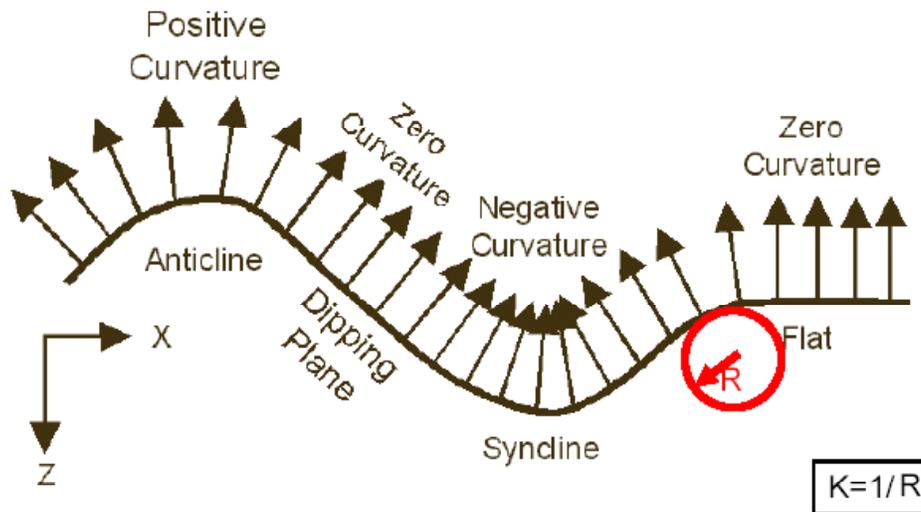
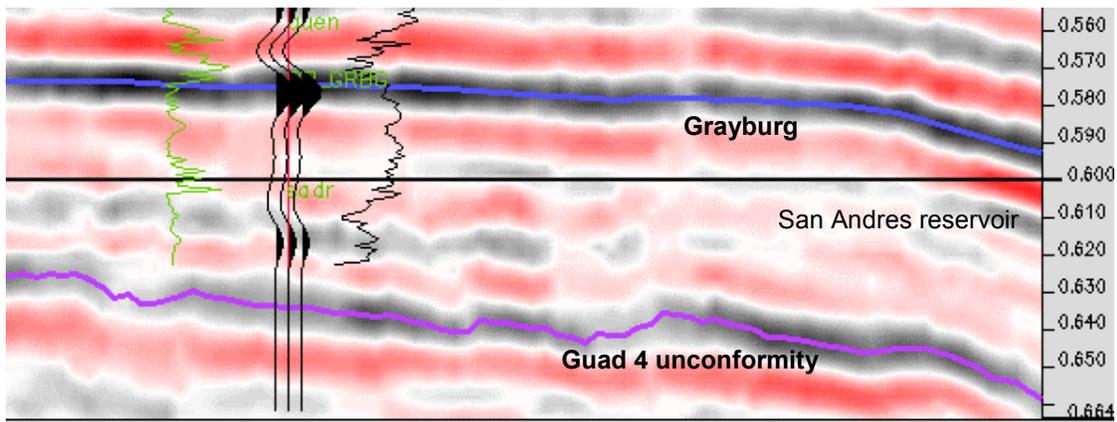


Figure 6. Curvature in two dimensions. Curvature (K) is defined as the inverse of the radius of a circle that is tangent to the surface at any point; positive curvature is concave downward and negative curvature is concave upwards. The curvature algorithms used in this study operate on the entire 3-D seismic volume, and do not require pre-interpretation of horizons. This is particularly helpful in karst areas with irregular surfaces. (After Roberts, 2001.)



Field of view: approx. 1 mile

Blumentritt et al., 2004

Figure 7. Segment of a West-East vertical seismic section in the “High Volume” area of the Waddell San Andres Field, west Texas. The Grayburg horizon and the Gaudalupian 4 (Guad4) regional unconformity are used to map the top and base of the karst-overprinted San Andres reservoir. Note the broken, irregular reflectors within the reservoir interval. For scale, at this depth, 10 ms two-way time is about 80 feet.

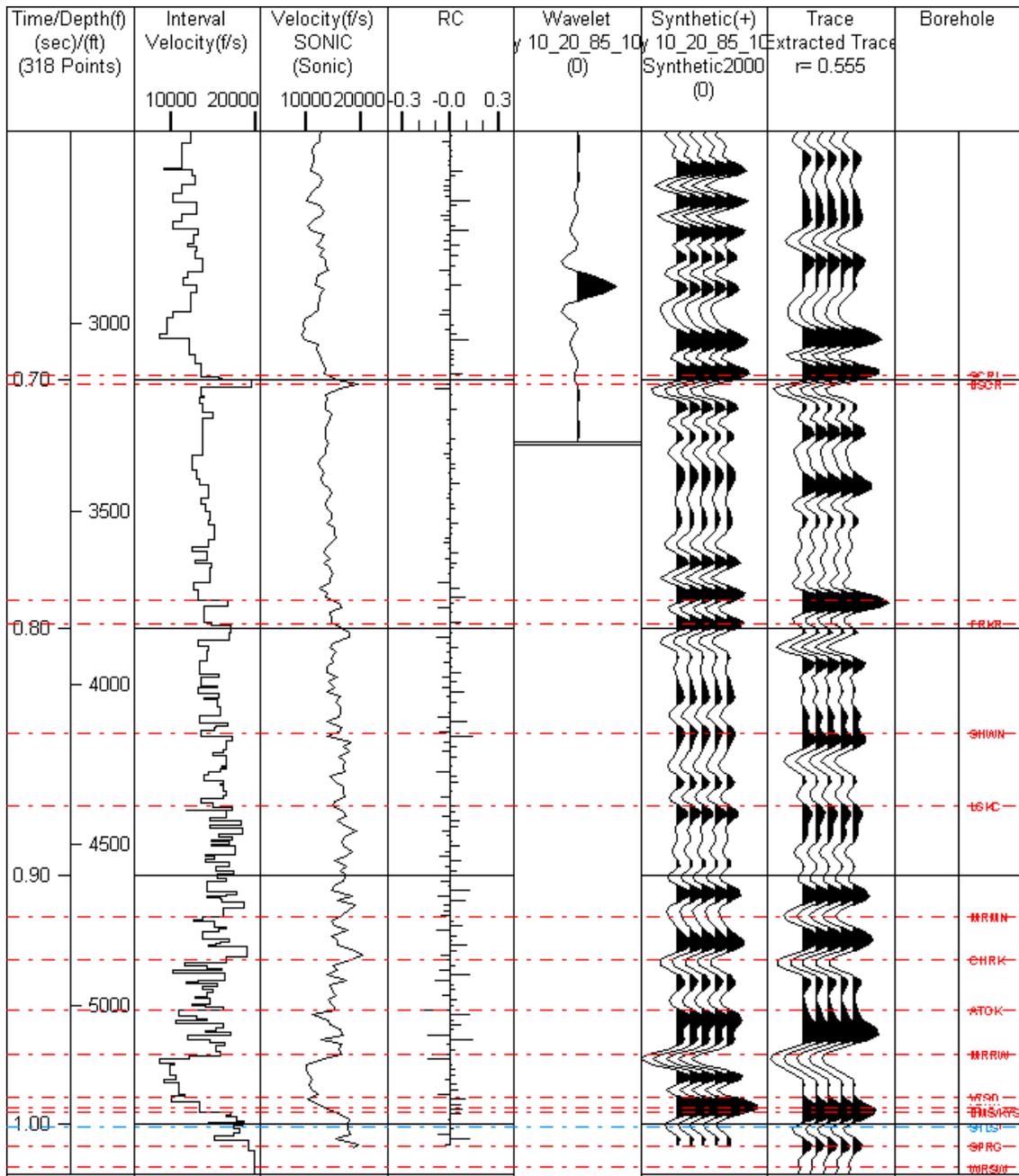
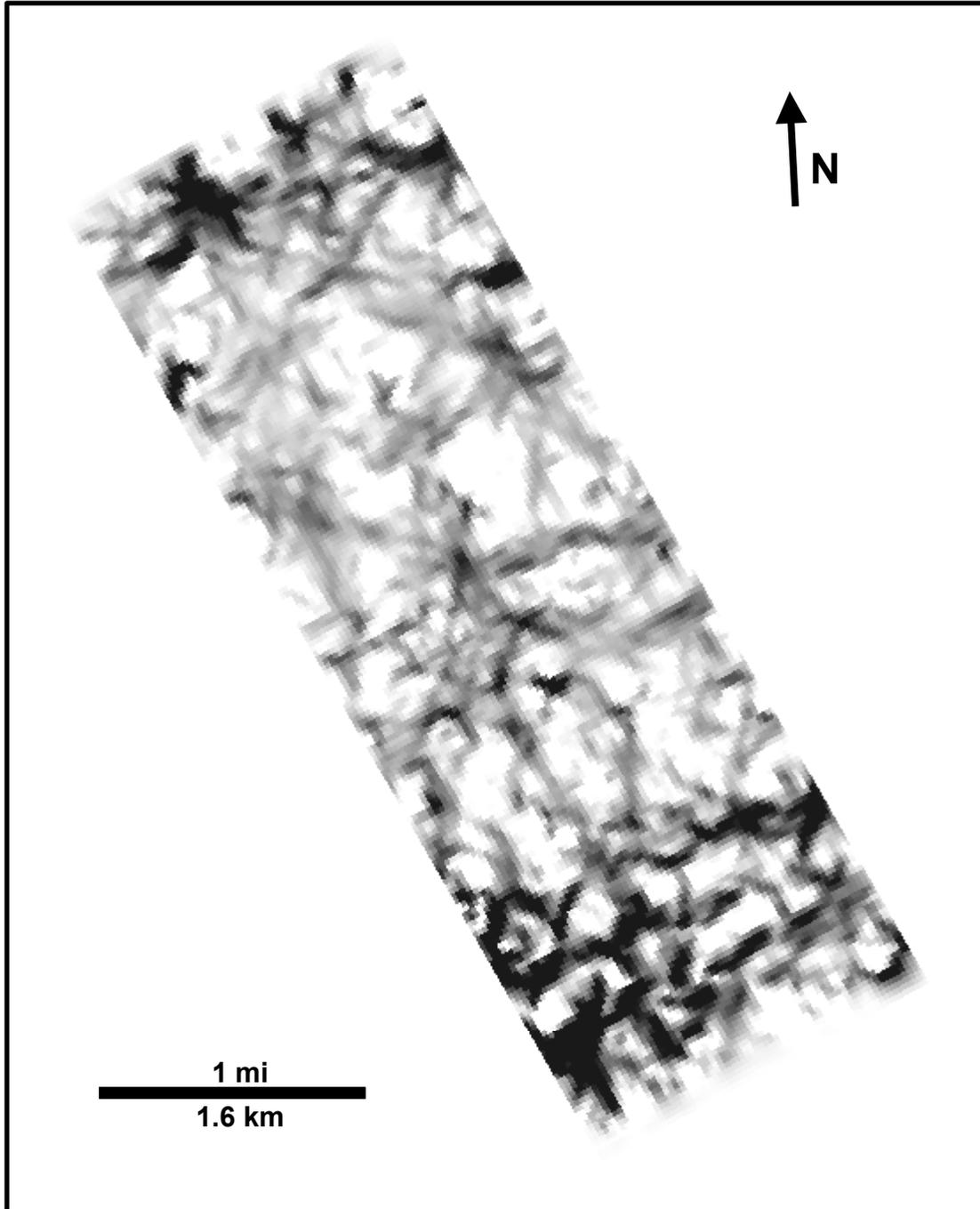
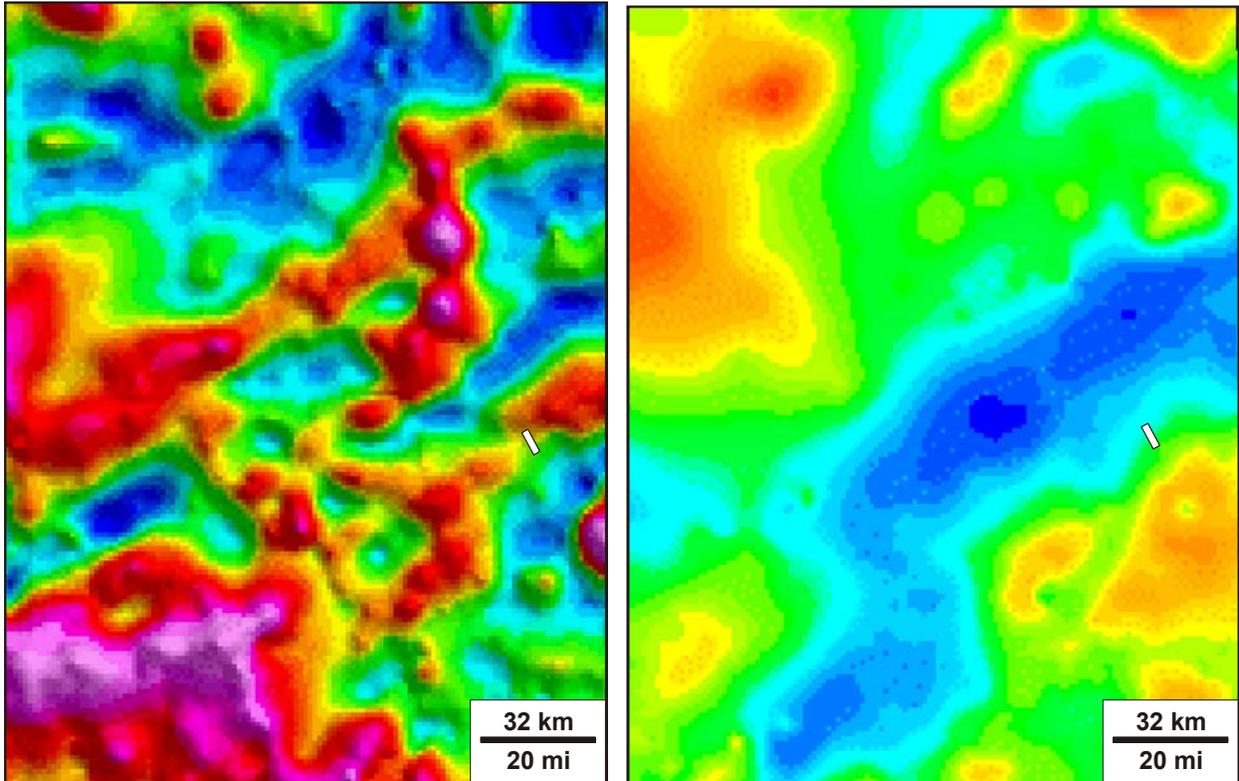


Figure 8. Synthetic seismogram from a well in the Smoky Creek Field, compared to trace extracted from the 3-D seismic survey. The top of Mississippian (blue line) is at approximately 1.0 seconds.



**Figure 9. Maximum negative curvature time slice at 1.0 second, the approximate level of the Mississippian karst surface, from the Cheyenne Wells/Smoky Creek seismic survey. Dark areas indicate high negative curvature and white areas indicate zero or positive curvature.**



**Figure 10. Aeromagnetic (left) and isostatic gravity (right) maps of central eastern Colorado. On both maps, dark blue represents lowest values and red to magenta represents highest values. The outline of the seismic survey in Figure 9 is shown by the small white box. Maps are modified from Oshetski and Kucks (2000).**

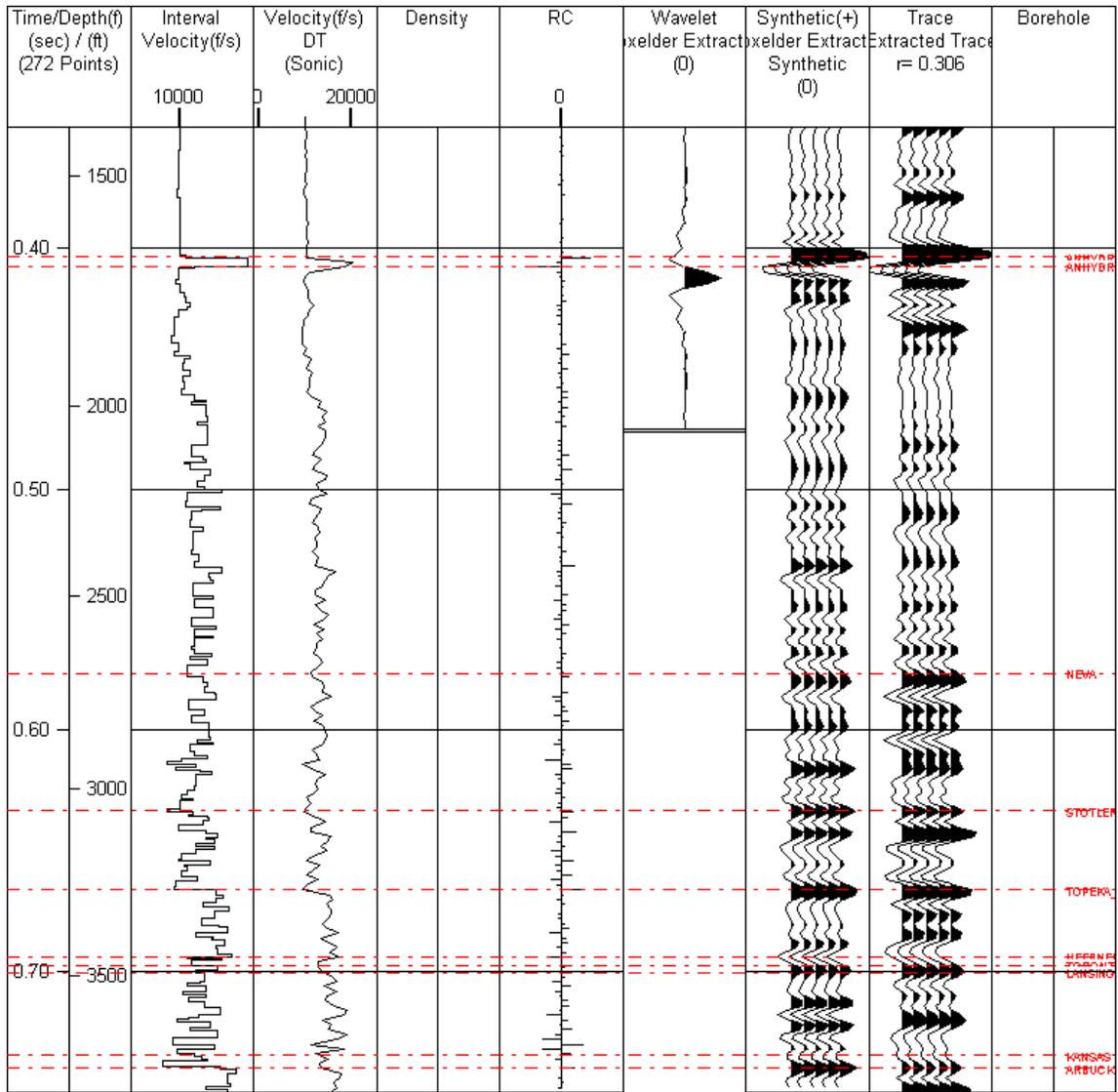


Figure 11. Synthetic seismogram from a well in Arbuckle study area 1, compared to trace extracted from the 3-D seismic survey.

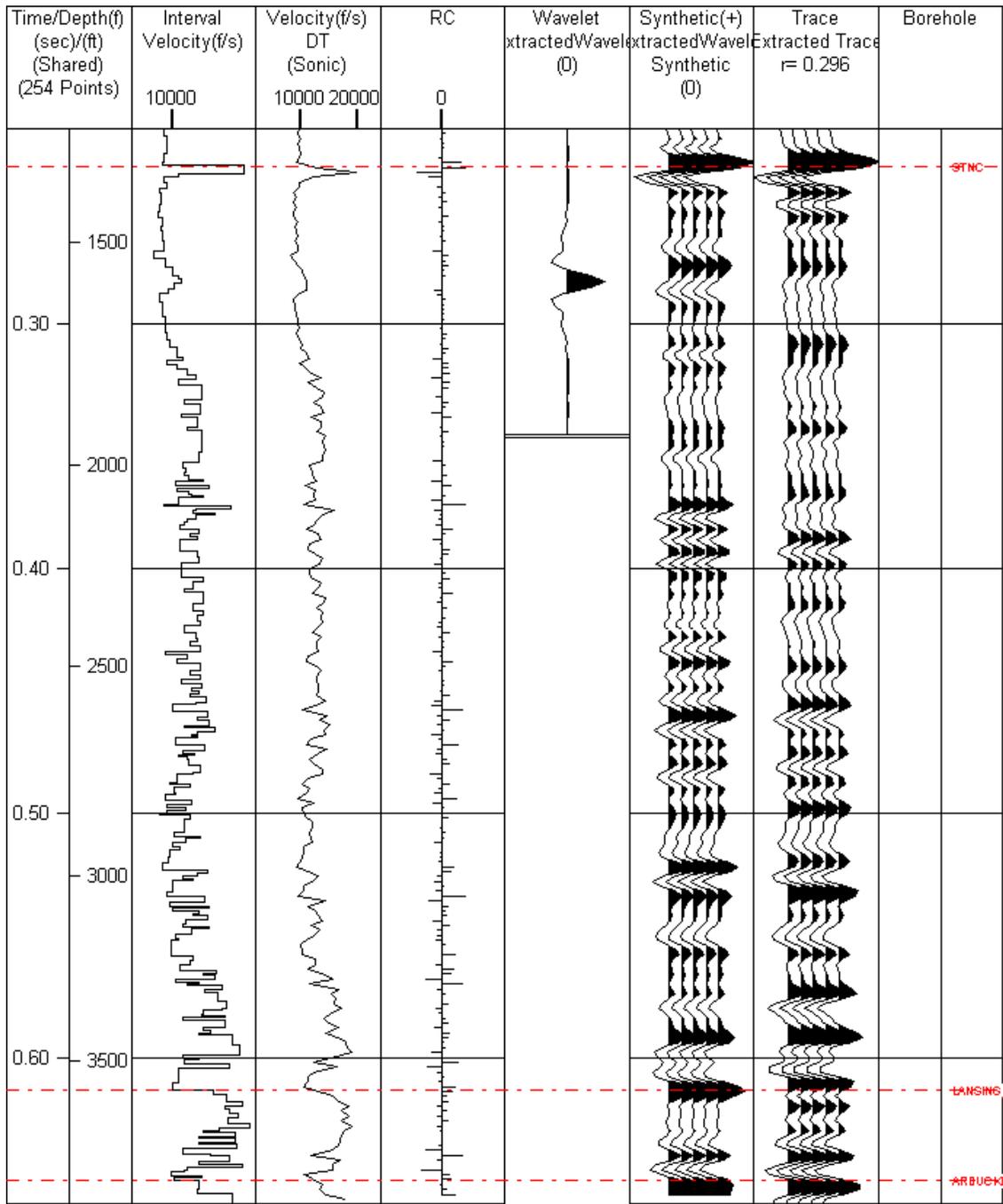
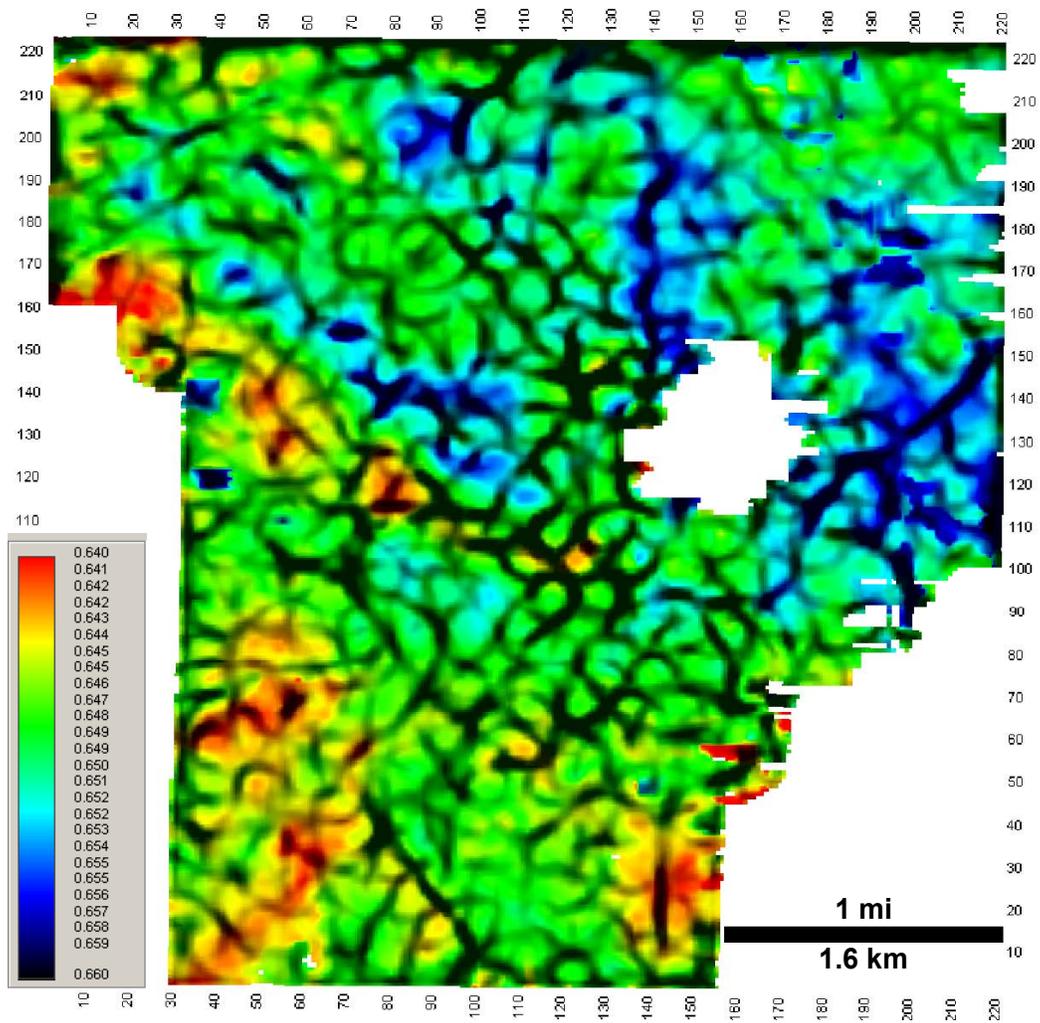


Figure 12. Synthetic seismogram from a well in Arbuckle study area 2, compared to trace extracted from the 3-D seismic survey.



**Figure 13.** Arbuckle time structure map for Arbuckle study area 2 in Russell County, Kansas, with extracted maximum negative curvature superimposed. Color bar at left indicates time structure in seconds two-way travel time. Maximum negative curvature is scaled so that dark areas indicate high curvature.

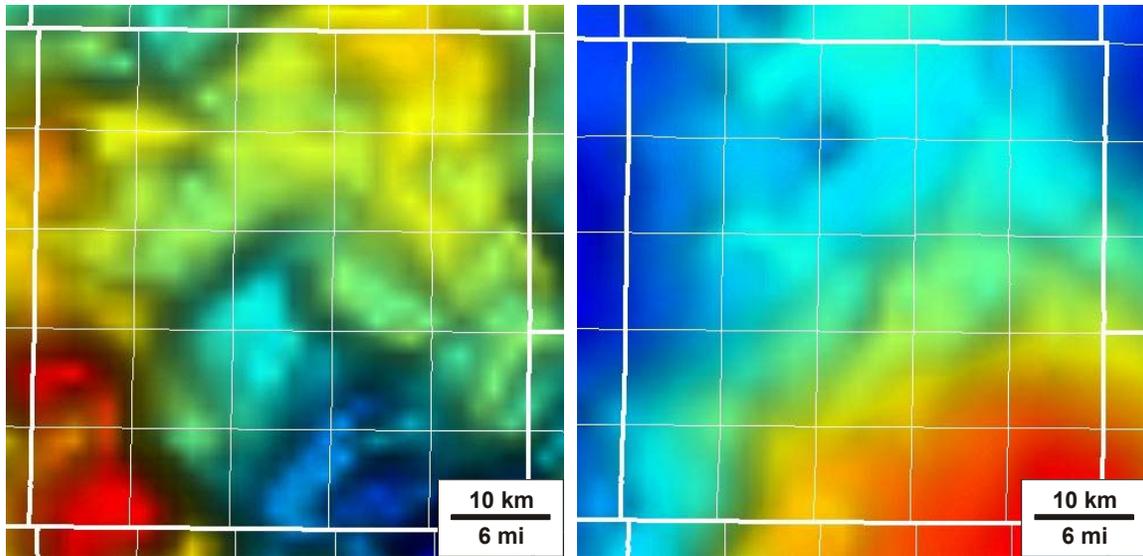
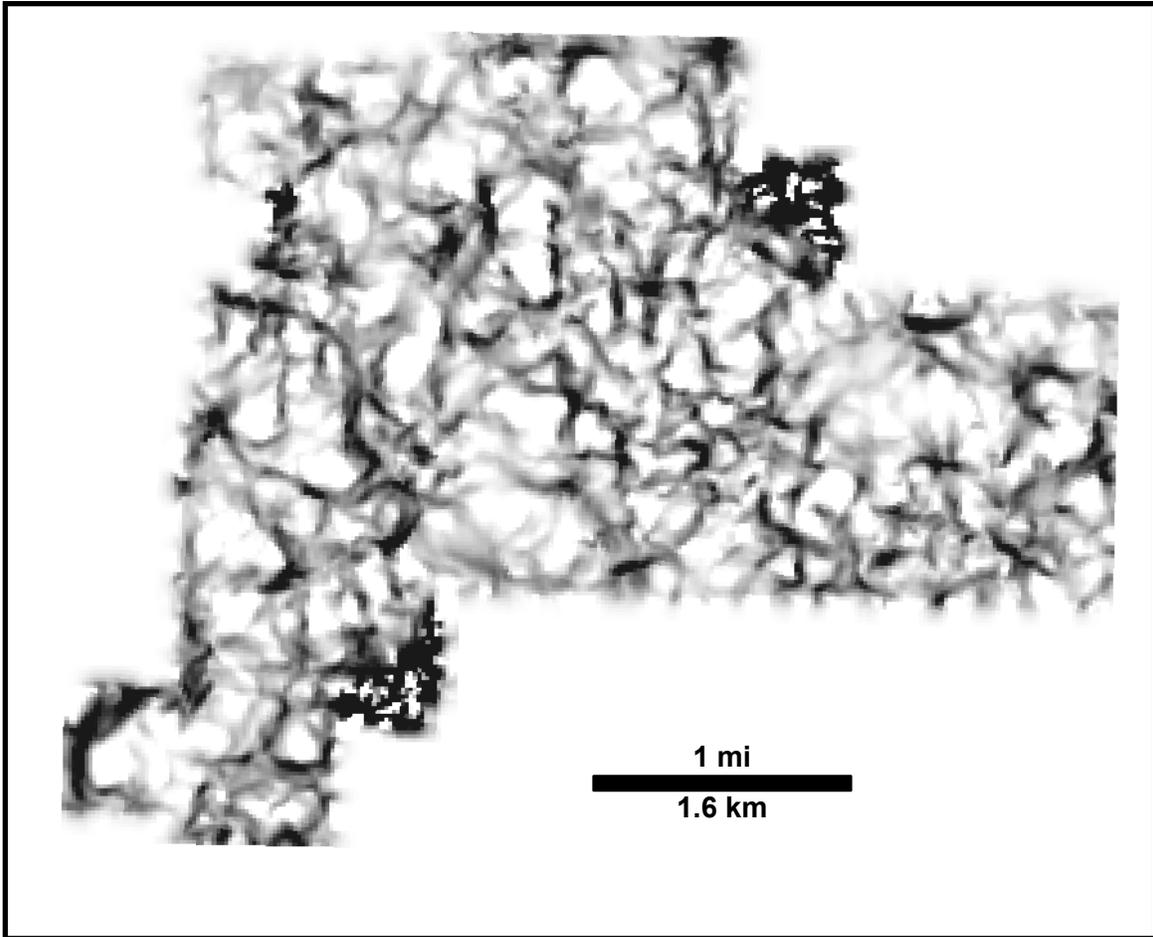


Figure 14. Aeromagnetic (left) and residual Bouguer gravity (right) maps of Russell County, KS. On both maps, dark blue represents lowest values and red represents highest values. Magnetic map is from <http://www.kgs.ku.edu/PRS/PotenFld/County/rs/russellMagCnty.html>, and gravity map is from <http://www.kgs.ku.edu/PRS/PotenFld/County/rs/russellGravCnty.html>.



**Figure 15. Maximum negative curvature time slice at 0.75 seconds, the approximate level of the Arbuckle karst surface, from Arbuckle study area 1 in Rooks County, Kansas. Color scale as in Figure 9.**