

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

Type of Report: Semiannual Scientific/Technical

Reporting Period Start Date: April 1, 2005

Reporting Period End Date: September 30, 2005

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Date Report was Issued: November 2005

DOE Award Number: DE-FC26-04NT15504

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## ABSTRACT

In order to address our project goal of developing innovative seismic-based workflows for the incremental recovery of oil from karst-modified reservoirs, we are conducting an integrated study of three reservoirs: the Permian San Andres in west Texas, the Mississippian Spergen in Colorado, and the Ordovician Arbuckle in Kansas. Our objectives for this reporting period were to: (1) generate a preliminary seismic attribute catalog of karst features; (2) conduct reservoir characterization studies for the three study areas; (3) begin construction of an integrated 3D reservoir geomodel for the San Andres study area; and 4) provide technology transfer.

We have developed a preliminary catalog of karst features, available online at <http://www.kgs.ku.edu/SEISKARST/catalog.html>, using the results of 3-D seismic attribute analysis for the three study areas, augmented with examples from other areas. The catalog shows karst-related features such as solution-enhanced fractures, sinkholes and collapse features, and polygonal features. Reservoir characterization studies, incorporating seismic, geological, petrophysical, and engineering data, are well underway for the three study areas, and we have constructed the geological framework for a reservoir geomodel in the San Andres study area. Technology transfer activities include submittal of abstracts for presentations at regional and national conferences, as well as posting of technical reports on our project website (<http://www.kgs.ku.edu/SEISKARST>).

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## EXECUTIVE SUMMARY

Our project goal is to develop innovative seismic-based workflows for the incremental recovery of oil from karst-modified reservoirs within the onshore continental United States. The project objectives are to calibrate new multi-trace seismic attributes for improved imaging of reservoirs, develop attribute-based, cost-effective workflows to better characterize karst-modified carbonate reservoirs and fracture systems, and improve accuracy and predictiveness of resulting geomodels and reservoir simulations. In order to develop our workflows and validate our techniques, we are conducting an integrated study of three karst-modified reservoirs: the Permian San Andres in west Texas, the Mississippian Spergen in Colorado, and the Ordovician Arbuckle in Kansas.

During this second reporting period, from April 1, 2005, through September 30, 2005, the project focused on the following tasks: (1) generate a preliminary seismic attribute catalog of karst features; (2) conduct reservoir characterization studies for the three study areas; (3) begin construction of an integrated 3D reservoir geomodel for the San Andres study area; and 4) technology transfer.

We have developed a preliminary catalog of karst features using the results of 3-D seismic attribute analysis for the three study areas, augmented with examples from other areas. The catalog shows that volumetric curvature attributes can provide enhanced visibility of certain features compared to other seismic analysis methods. Karst-related features identified using volumetric curvature attributes include solution-enhanced fractures, sinkholes and collapse features, and polygonal features. The catalog can be accessed online at <http://www.kgs.ku.edu/SEISKARST/catalog.html>.

Reservoir characterization studies, incorporating seismic, geological, petrophysical, and engineering characterizations of the reservoir, are well underway for the three study areas.

Permian San Andres Study Area. Structural and isopach maps of the San Andres reservoir interval indicate that internal layers are fairly parallel over the immediate study area. The 30 m (100 ft) reservoir interval is within the Permian Guadalupian 8 and Guadalupian 9 fourth order High Frequency sequences, and is above the Guadalupian 4 regional unconformity. The Guadalupian 8 sequence boundary is a well developed unconformity, and is potentially a flow baffle. The San Andres field has more than 60 wells with recent vintage log data (1995-2004). Although we only have two cores within the field, they contain an abundance of relevant features, and additional core material is available in surrounding fields. In both cored wells, the Guad 9 sequence is characterized by grain-rich oolitic lithofacies, and the lower part of the reservoir, within the Guad 8 sequence, is characterized by burrowed fusulinid lithofacies, usually indicative of deeper, more seaward conditions. Both cores have an anhydrite cemented karst overprint, with evidence of later anhydrite dissolution along fractures. Core analyses indicate there is as much as 16% gypsum present. This gypsum can cause well log porosity to read erroneously high. Low temperature whole core porosities are as high as 18% and permeabilities in three samples are as high as 695 mD. These permeabilities are almost an order of magnitude greater than in the surrounding fields. Pressure data and data from

tracer injection (38 wells) in the study area indicate compartmentalization in the reservoir.

Mississippian Spergen Study Area. We have generated a model based acoustic impedance inversion of the seismic data, and find that acoustic impedance extracted at the top of the Spergen reservoir clearly shows spatial variation. Variation in acoustic impedance can be an indicator of porosity variation. Crossplots of acoustic impedance versus well log porosity at well locations will be used to determine whether such a relation exists for the study area. There are two cores available in the Mississippian study area. Core analysis reveals a complex history for the Spergen reservoir. Depositional environment is interpreted as a restricted lagoon with a migrating carbonate shoal. Lithofacies range from mudstone to packstone-grainstone; however, the entire section has been heavily dolomitized, obscuring primary depositional structures. Porosity is mostly intercrystalline, except where it is oomoldic in the productive zones. Fractures identified in the cores are mostly filled. Petrophysical parameters (including porosity, permeability, and water saturation) were obtained from a combination of core and log data.

Arbuckle Study Area. We have generated a model based acoustic impedance inversion of the seismic data to better define the Arbuckle horizon, which is difficult to interpret across the seismic survey using the original seismic amplitude data. We will run volumetric curvature attributes on the impedance volume to generate a more refined picture of curvature lineaments at the top of Arbuckle. This will be a novel use of the curvature attributes: we appear to be the first to try this approach. Basic rock properties have been measured in two cores from sections near the study area. Additional core analysis, petrophysical analysis, and engineering analysis will be conducted during the next reporting period.

Our first geocellular model for simulation is the Permian San Andres reservoir, and will incorporate the Kansas Geological Survey's collaborative web-based geologic and engineering reservoir modeling program GEMINI and web-based PFEFFER log analysis program. We are building a geomodel for a 13 square kilometer (5 square mile) area and will be performing simulation for a sub area of approximately 3 square kilometers (1 square mile). This simulation will test one reservoir compartment defined by integrated seismic, geologic and engineering data and will allow us to predict historic production from a second reservoir compartment.

Technology transfer of our in-progress work is being accomplished through Kansas Geological Survey and University of Houston web sites and through presentations at professional society meetings. We have submitted four abstracts for upcoming national meetings and have acknowledged DOE support in presentations given at five local and regional meetings.

## **INTRODUCTION**

Our project goal is to develop innovative seismic-based workflows for the incremental recovery of oil from karst-modified reservoirs within the onshore continental United States. The project objectives are to (1) calibrate new multi-trace seismic attributes for improved imaging of reservoirs, (2) develop attribute-based, cost-effective workflows to better characterize karst-modified carbonate reservoirs and fracture systems, and (3) improve accuracy and predictiveness of resulting geomodels and reservoir simulations.

In order to develop our workflows and validate our techniques, we are conducting an integrated study of three karst-modified reservoirs: the Permian San Andres in west Texas, the Mississippian Spergen in Colorado, and the Ordovician Arbuckle in Kansas (Figure 1).

In the first reporting period, from October 1, 2004, through March 31, 2005, we (1) gathered 3-D seismic, petrophysical, and engineering data for all of our study areas, (2) generated multi-trace seismic attribute volumes (including coherence and volumetric curvature attributes) for the 3-D seismic surveys in all of our study areas, (3) began interpreting key seismic horizons in all study areas, and (4) made preliminary interpretations of volumetric curvature attributes in all study areas.

During this second reporting period, from April 1, 2005, through September 30, 2005, the project focused on the following tasks: (1) generate a preliminary seismic attribute catalog of karst features; (2) conduct reservoir characterization studies for the three study areas; (3) begin construction of an integrated 3D reservoir geomodel for the San Andres study area; and (4) technology transfer (Figure 2). Accomplishments for each of these tasks are addressed below.

## **SEISMIC ATTRIBUTE CATALOG OF KARST FEATURES**

A preliminary catalog of karst features has been developed using the results of 3-D seismic attribute analysis for the three study areas, augmented with examples from other areas. The catalog shows that volumetric curvature attributes can reveal previously unknown features in the seismic data or can provide enhanced visibility of certain features compared to other seismic analysis methods (Figure 3). Karst-related features identified using volumetric curvature attributes include solution-enhanced fractures (Figure 3), sinkholes and collapse features (Figure 4), and polygonal features (Figure 5). Surface examples of these features are shown for comparison with the seismic examples. Reservoir implications related to the karst features are indicated, where known. The reservoir implications section of the catalog will become better developed as our study progresses.

The catalog is available online at <http://www.kgs.ku.edu/SEISKARST/catalog.html>.

## RESERVOIR CHARACTERIZATION STUDIES

Reservoir characterization studies are in progress for all three of the study areas. These studies consist of seismic characterization, geological characterization, petrophysical (log and core) characterization, and engineering characterization. Parameters obtained from these studies will be used to populate geomodels for reservoir simulation.

### Permian San Andres Study Area

The Permian San Andres study area covers approximately 13 square kilometers (5 square miles), within a larger, multi-operator Waddell field of some 130 square kilometers (50 square miles) (Figure 6, 7). The study area is known by the operator as the “High Volume Area” and is characterized by variable fluid production, with per well cumulative fluid production up to 18 million barrels and individual well cumulative oil production of over 900,000 barrels. Operator-interpreted tracer and pressure data indicate this field is a highly compartmentalized reservoir with an active water drive, and core from two wells contain definitive karst features. However, log and conventional seismic data do not allow definition of fracture or karst system patterns that coincide with production patterns. Therefore, the focus of the San Andres study is to integrate conventional and multi-trace attributes with geologic and engineering data to better map reservoir compartments and to develop new insights on controls of reservoir behavior.

#### *Seismic Characterization*

We used sonic logs to create synthetic seismograms for tying seismic reflectors to stratigraphic boundaries, and mapped the key seismic horizons of the Permian Grayburg and San Andres (Figure 8). In addition, we correlated a regional unconformity (the Guadalupian 4 High Frequency Sequence boundary of Kerans and Fitchen, 1995), mapped over the northern part of the field by Sullivan (1995), to logs and seismic within the study area (Figures 8, 9, 10, and 11). We have generated time-structure maps for the Grayburg, San Andres and the San Andres reservoir. We performed time-depth correlations from the sonic logs to create depth-structure and isopach maps, and generated multi-trace curvature and coherence volumes. We then used time slices and horizon extractions of several multi-trace attributes to interpret discontinuities and possible compartment boundaries. Although discontinuities are apparent in the data and form rough north-south patterns across the study area (Figure 7), none has strong visual correlation to the production. Qifeng Dou, a PhD student at the University of Houston supported by this project, is mapping the Guadalupian 4 unconformity in detail, in an attempt to determine breaks in the strong reflector that may be responsible for the observed large volumes of water to enter the reservoir from the underlying aquifer. Upcoming work this semester includes running impedance inversion and a new spectral decomposition algorithm on the reservoir interval. Modern shear wave sonic logs in a well logged in 2001 may be particularly useful in modeling reservoir heterogeneity.

### *Geological Characterization*

We have completed our structural and sequence stratigraphic framework within the immediate study area, and have developed conceptual lithofacies, depositional and diagenetic models for the San Andres reservoir interval. There is one core within the field (W.N. Waddell 1261, cored 2003) that has detailed core description available (see Figure 12). One other core cut in 1995 has a generalized written description that allows identification of the upper San Andres Guadalupian 8 High Frequency Sequence boundary (Guad 8) of Kerans, et al. (2000) within the cored interval. This is an important fourth order sequence boundary that potentially is a permeability baffle within the reservoir. Original depositional reservoir lithofacies above the Guad 8 are dominated by oolitic grainstones and packstones that grade upward into peloidal lithofacies and record a shallowing of water depth. Reservoir facies below the Guad 8 unconformity are dominated by burrowed fusulinid packstones. French and Kerans (2004) working in the Penwell Jordan San Andres Field a few miles to the north of the high volume area report that most of the production there is from oolitic grainstone shoal facies in the Guad 4 and Guad 3 high frequency sequences. They also report only a very mild karst overprint in all of the 12 cores they studied. In the next few weeks we will examine the existing cores and select samples for thin sections to establish pore systems.

During the remainder of the calendar year we will complete the initial geologic characterization by integrating core, log and seismic data to better define our lithofacies, depositional and diagenetic models, and build a geocellular model for reservoir simulation.

### *Petrophysical Characterization*

Well log data are extremely high quality, with 61 wells drilled and logged between 1995 and 2003. Many, but not all, of these new wells are replacements for older wells drilled, largely in the 1940's and 50's. Log suites include modern porosity logs and photoelectric cross section curves (particularly helpful for identifying changes in lithology and mineralogy). Core data exist for two wells within the field, and for a number of wells in the nearby San Andres fields, but outside the immediate High Volume study area. Petrophysical measurements available for these cores include porosity, Kmax and K90 permeability, grain density, water saturation, oil saturation, fluorescence, and calculated percent gypsum. Core from the 1204 well was analyzed by standard core plug analysis. The 1261 core taken within the study area was analyzed (by the operator) by plug samples, and by low temperature whole core analysis, which in heterogeneous carbonates, gives more reliable results than does core plug analysis. Whole core porosity and permeability measurements were made using a low temperature drying process and compared with results from core plugs treated with a standard high temperature core drying process to determine the presence and effects of gypsum. In general, gypsum buried below a depth of about 1067 m (3500 ft) will have lost all associated water and will be converted to anhydrite. Anhydrite bearing carbonates exposed to late stage meteoric waters or to burial fluids with relatively low chlorides and sulfate saturations may partially dissolve and may partially convert back to gypsum. In core analyses that use high temperature drying, this gypsum will dehydrate, and will yield erroneously high

porosity and permeability measurements. In the 1261 well, gypsum volumes were calculated from core analysis to be as high as 15.9%. Gypsum volumes greater than 5% are regarded as an indicator that only core analyses made with low temperature processes should be regarded as a reliable indicator of porosity and permeability. Porosities in the low temperature analyses of the 1261 core yield porosities as high as 18%, and Kmax permeabilities of up to 695 mD. High permeabilities were confined to only about three whole core samples, but are about an order of magnitude higher than generally observed in San Andres rocks (Figure 13). We are comparing core data directly to well logs to define facies and diagenetic signatures on well logs.

The recent well logs are currently loaded on GeoFrame. We are in the process of loading them into Petra and PFEFFER (<http://www.kgs.ku.edu/PRS/software/pfeffer1.html>), which is an Excel add-in log analysis program partially supported by DOE in 1996, and incorporated as a Java-based web-application in the Kansas Geological Survey's GEMINI program for quantifying reservoir pay, graphically evaluating key reservoir properties, and defining stratigraphic layering for volumetric analysis and reservoir simulation.

### *Engineering Characterization*

Available engineering data include production and tracer study results. Operator-provided, individual well production data is displayed in Figures 6 and 7 as bubble maps. Pressure data and data from tracer injection (38 wells) both indicate compartmentalization. Tracer breakthrough from injector to nearby producers ranged from 3 days to 56 days.

### **Mississippian Study Area**

The Cheyenne Wells and Smoky Creek Fields, Cheyenne County, Colorado, have produced in excess of 8 MM bbls of oil; however, well performance in these fields is extremely variable. Some wells have performed better than expected while others have underperformed, based on calculations from matrix porosities alone. Karst and fracturing are believed to contribute to the variable productivity. The focus of this reservoir study is to understand porosity type and distribution in the Mississippian Spengen (Figure 14) reservoir, identify relationships between porosity and permeability, and determine whether fractures and karst features that impact reservoir performance can be imaged using seismic attributes.

### *Seismic Characterization*

Synthetic seismograms have been created from the 10 sonic logs available within the 3-D seismic survey. These synthetics have been used to tie formation tops to seismic reflections (Figure 15) and to guide a model-based acoustic impedance inversion of the seismic data. The model based inversion was generated using the Hampson Russell STRATA software.

The sonic logs show that the Mississippian (St. Louis) unconformity surface and the Spergen reservoir interval do not correspond to significant acoustic impedance contrasts (Figure 16). The closest surface containing a strong impedance contrast is the Base Morrow Shale/ Top Keyes Sandstone (BMS/KYS) surface, approximately 38 m (125 ft) or 15 ms above the top of Spergen. This surface can be readily interpreted on the acoustic impedance volume (Figure 17). Seismic attributes for the Spergen reservoir interval (Figures 18 and 19) are extracted parallel to this horizon.

Acoustic impedance (Figure 18) at the top of the Spergen clearly shows spatial variation. Variation in acoustic impedance can be an indicator of porosity variation. In order to test whether there is a relationship between acoustic impedance and porosity in the Spergen reservoir, acoustic impedance will be extracted at well locations and crossplotted against porosities obtained from well logs.

Most negative curvature (Figure 19) extracted at the top of the Spergen shows numerous high curvature lineaments. These lineaments will be interpreted and their relationship to reservoir production will be evaluated during the October 2005 to March 2006 reporting period.

### *Geological Characterization*

#### Structure and Isopach Maps

Formation tops for the wells in the study area have been obtained from the Colorado Oil and Gas Conservation Commission's (COGCC) website (<http://www.oil-gas.state.co.us/>) and from the operator. These tops have been used to generate structure and isopach maps for the top Mississippian (St. Louis Limestone), Spergen Limestone (Figures 20 and 21), and Warsaw Limestone.

#### Core Description

There are two cores available in the study area (Figure 20). These cores have been described using a digital format created by KGS research staff. This digital description includes rock type, Dunham/Folk classification, amount of argillaceous material, initial grain size, main pore type, subsidiary pore types, crystal size, bedding, fauna, color, presence of glauconite, pyrite, anhydrite nodules, and oil staining, whether dolomite is sucrosic or not, and if fractures present are cement filled. Core analysis reveals a complex history for the reservoir. Depositional environment is interpreted as a restricted lagoon with a migrating shoal. Lithofacies range from mudstone to packstone-grainstone; however, the entire section has been heavily dolomitized, obscuring primary depositional structures. Porosity is mostly intercrystalline, except where it is oomoldic in the productive zones. Fractures identified in the cores are mostly filled. 196 thin sections have been prepared from samples from the two cores. The thin sections will allow a better understanding of the pore systems in the reservoir. Thin section description will take place during the October 2005-March 2006 reporting period.

## *Petrophysical Characterization*

### Core and Log Porosity Comparison

For the two wells with core, well log depths were calibrated to core depths. Porosities from neutron and density logs were averaged to remove lithology effects, and well log porosities were then compared to core helium porosities. The two data sets display similar trends (Figure 22).

### Log Analysis

Water saturation ( $S_w$ ) was calculated from the Archie equation,

$$S_w = \left[ \frac{a}{\Phi^m} * \frac{R_w}{R_t} \right]^{1/n}, \text{ where}$$

$\Phi$  = porosity

$R_w$  = formation water resistivity

$R_t$  = formation resistivity

$a$  = a constant

$m$  = cementation exponent

$n$  = saturation exponent, generally equal to 2

$\Phi$  was obtained from neutron-density logs.  $R_t$  was obtained from induction logs. The reconnaissance water resistivity technique ( $R_{wa} = R_t \Phi^m / a$ ) was used to estimate  $R_w$  ( $R_{wa} = R_w$  when  $S_w = 1$ ). An  $R_w$  of 0.06 was obtained, assuming an  $m$  of 2 and an  $a$  of 1. For intercrystalline carbonates,  $m$  is typically 2. However, in low porosity carbonates,  $m$  decreases rapidly toward 1 with decreasing porosity. We used a Phi cutoff of 5 % in our  $R_{wa}$  calculations to alleviate this problem. The irregular  $S_w$  values seen at low porosities in Figure 23 are also a result of the variation in  $m$ .

A graph of  $S_w$  and Phi versus depth (Figure 24) shows us that there is a good correlation between low  $S_w$  values and higher Phi values in the perforated intervals of the Champlin Aldrich #3 and Klepper #4.

### Core Permeability vs. Porosity

Crossplots have been made of core analysis permeability (K) vs. porosity (Phi) for Champlin Aldrich #3 and Klepper #4. Lithofacies from core descriptions have been highlighted on this plot, since a dependence on lithofacies is expected in the permeability-porosity relationship. The crossplots show a discrepancy between data from the two wells. This is potentially due to the fact that the data sets from the two wells are based on different methods of analysis. Champlin Aldrich #3 has whole core analysis, whereas Klepper #4 has plug analysis. We will take core plug samples from the Champlin Aldrich #3 and run K and Phi analyses on them, and then compare the two data sets.

### *Engineering Characterization*

Production data from PI Dwigths have been imported into Petra. Monthly production is available by well from January 1, 1999 to present. Prior to 1999, production was reported on a lease basis. Where leases contain multiple wells, a method is being developed to estimate the amount of pre-1999 production to be allocated to each well within the lease.

### **Arbuckle Study Area**

Two candidate areas with Arbuckle production were evaluated for study (Figure 1). Based on seismic data quality, Arbuckle study area 2, in Russell County, Kansas, has been selected for detailed reservoir analysis. In this study area, the Arbuckle reservoir sits at or near a pre-Pennsylvanian unconformity surface (Figure 25). Reservoir quality is variable, and reservoir characterization focuses on distinguishing tight Arbuckle from porous Arbuckle.

### *Seismic Characterization*

Three wells within the Arbuckle seismic survey have sonic logs for use in creating synthetic seismograms. The synthetic seismograms indicate that the Arbuckle horizon corresponds approximately to a negative to positive zero crossing in the seismic data (Figure 26). This horizon is difficult to interpret across the entire survey using the original seismic amplitude data, so a peak approximately 10 ms above the Arbuckle (corresponding approximately to the base of the Kansas City Group (BKC)) was tracked for use in initial attribute analysis (e.g., volumetric curvature extraction shown in Figure 5).

A model based inversion of the seismic data has been generated using the Hampson Russell STRATA software in order to better define the Arbuckle horizon. A vertical section through the model based inversion impedance volume is shown in Figure 27. As is seen in Figure 27, the Arbuckle horizon can be clearly interpreted on the impedance volume. Figure 28 shows the time structure map of the Arbuckle horizon interpreted from the impedance volume. During the October 2005 to March 2006 reporting period, this horizon time map will be converted to depth to provide a more detailed picture of present-day Arbuckle structure than is available with well control alone (Figure 29). Also, volumetric curvature attributes will be run on the impedance volume to generate a more refined picture of volumetric curvature lineaments at the top of Arbuckle.

### *Geological Characterization*

Ben Brocke, a graduate student at the University of Kansas, is working on a Master's project focusing on the Arbuckle in Russell County, Kansas. Over the past two months, he has created a base map of Russell County and downloaded log data and formation tops from the KGS well database (<http://www.kgs.ku.edu/PRS/petroDB.html>). He has defined an area where a regional cross section would best demonstrate trends in the Arbuckle surface. This cross section trends NE-SW, and traverses the 3D seismic study area (Figure 29). Within the cross section area and the 3-D seismic study area, he has gathered

additional data from Scout Cards and has scanned well logs to be used in stratigraphic analysis.

### *Petrophysical Characterization*

Scanned well logs will be digitized to augment existing digital well logs in the study area. Petrophysical characterization will be conducted using these well logs and data from 5 cores in sections near the study area. Basic rock properties have been previously measured in two of the cores. The remaining three cores will be plugged and porosity and permeability will be measured, along with Archie cementation exponent and capillary pressure on selected samples. Porosity, permeability, and lithofacies relationships will be determined from the core data.

### *Reservoir Characterization*

Lease production has been downloaded from the KGS database. Because production in the study area is from multiple intervals, it will be necessary to identify which wells produce from the Arbuckle. Lease production will also need to be assigned to individual wells. These tasks will be conducted during the October 2005 to March 2006 reporting period.

## **GEOMODEL CONSTRUCTION**

Our first geocellular model for simulation is the Permian San Andres reservoir in west Texas. The objective of the simulation is to integrate the compartmentalization defined by engineering, geology and seismic attributes and to test one compartment against historic production. The second objective is to predict historic production from a second reservoir compartment. We are building a geomodel for a 13 square kilometer (5 square mile) area and will be performing simulation for a sub area of approximately 3 square kilometers (1 square mile).

Within the geomodel area, depositional layering of the San Andres is relatively flat, but overprinted by karst. The 30 m (100 ft) reservoir interval is subdivided into two units, separated by an unconformity. Each main layer appears to be dominated by aggradational to increasingly progradational carbonate lithofacies, now thoroughly dolomitized. We are in the process of tying core facies to log signatures and assigning petrophysical properties to log derived facies. Our study area is adjacent to an area of detailed core-based reservoir characterization work by French and Kerans (2004). Their work provides considerable regional control for our study.

## **TECHNOLOGY TRANSFER**

A catalog of karst features has been developed and can be accessed from our project website (<http://www.kgs.ku.edu/SEISKARST/catalog.html>).

The following abstracts have been accepted for presentation at the 26th Annual GCSSEPM Foundation Bob F. Perkins Research Conference, December 3-6, 2006:

Application of Volumetric 3-D Seismic Attributes to Reservoir Characterization of Karst-Modified Reservoirs, by C. Sullivan, S. Nissen, and K. Marfurt

An Integrated Study Delineating Karst and Fracture Features Affecting Reservoir Performance in a Mississippian Reservoir, Cheyenne County, Colorado, by N. B. Givens and S. Nissen

The following abstracts have been submitted for presentation at the AAPG Annual Convention, April 9-12, 2006:

Application of New Seismic Attributes to Identify Karst and Fracture Related Compartmentalization: Permian San Andres Formation, Central Basin Platform, West Texas (USA), by E. C. Sullivan, S. Nissen, K. J. Marfurt, and C. H. Blumentritt

Karst and Fracture Features Affecting Reservoir Performance in a Mississippian Reservoir, Cheyenne County, Colorado, by N. B. Givens and S. Nissen

In addition, technical reports are posted to our project web site:  
<http://www.kgs.ku.edu/SEISKARST>.

Also, recent presentations on new seismic attribute development by Allied Geophysical Laboratories personnel acknowledged DOE funding of the San Andres karst project. These presentations took place at the Society for Independent Petroleum Explorationists (August 12 and September 13, 2005), Eastern AAPG, Morgantown West Virginia (September 20, 2005), PTTC Conference, Michigan Basin (October 20, 2005), and the West Texas Geological Society (October 25, 2005).

## CONCLUSIONS

### General

- The preliminary catalog of karst features illustrates that volumetric curvature attributes can reveal previously unknown features in the seismic data or can provide enhanced visibility of karst features.

### San Andres study area:

- The 30 m (100 ft) dolostone reservoir is very well constrained stratigraphically within the upper two high frequency sequences of the San Andres Formation.
- Detailed work on 12 San Andres cores from a nearby field allows us to place our limited core-based depositional and diagenetic data into a better constrained shallow carbonate platform/shoal setting.
- Although only minimal karst overprint has been reported in time equivalent units in an San Andres field, anhydrite filled karst, overprinted by open fractures and anhydrite dissolution is conspicuous in our cores.

- Whole core, low temperature processed, core analyses indicate locally very high matrix permeabilities (695 mD), suggesting that the San Andres reservoir may have a locally well developed dual porosity system.

#### Mississippian study area

- Core analysis reveals a complex history for the Mississippian reservoir. Depositional environment is interpreted as a restricted lagoon with a migrating shoal. Lithofacies range from mudstone to packstone-grainstone; however, the entire section has been heavily dolomitized, obscuring many primary depositional structures. Porosity is mostly intercrystalline, but is dominantly oomoldic in the productive zones.
- Our petrophysical work indicates that are discrepancies between whole core and plug analyses; therefore, we need to resample and reanalyze petrophysical properties in fresh plugs cut from the whole core.
- Core and log petrophysical data can be correlated.

#### Arbuckle study area

- Acoustic impedance inversion aids the identification of seismic horizons related to the reservoir in the Arbuckle study area.

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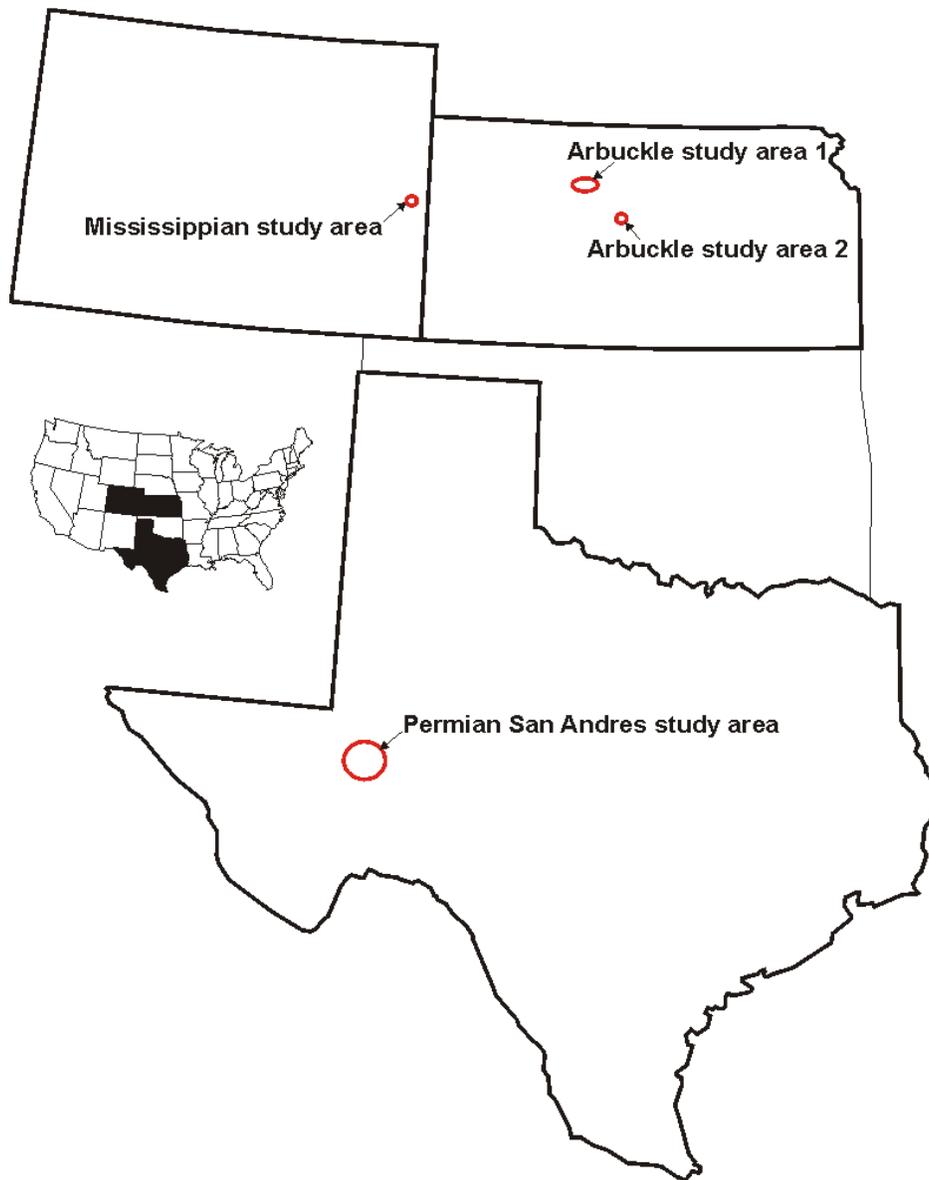


Figure 1. Index map showing locations of study areas.

Task Description	FY05				FY06				FY07			
	Oct 04	Jan 05	Apr 05	Jul 05	Oct 05	Jan 06	Apr 06	Jul 06	Oct 06	Jan 07	Apr 07	Jul 07
Task 1.0 Obtain 3-D seismic, geologic, petrophysical, and engineering data	█											
Task 2.0 Generate volumetric attributes												
Task 2.1 Generate attributes for Permian San Andres data		█										
Task 2.2 Generate attributes for Mississippian data			█									
Task 2.3 Generate attributes for Arbuckle data				█								
Task 3.0 Generate preliminary seismic attribute catalog of karst features												
Task 4.0 Perform reservoir characterization studies												
Task 4.1 Seismic characterization		█										
Task 4.2 Geologic characterization			█									
Task 4.3 Petrophysical (log and core) characterization				█								
Task 4.4 Engineering characterization					█							
Task 5.0 Construct integrated 3D reservoir geomodels												
Task 6.0 Conduct reservoir simulations												
Task 7.0 Synthesize best practices workflow												
Task 8.0 Model new well paths												
Task 9.0 Drill, log and core new wells												
Task 10.0 Calibrate attributes and reservoir models with new well data; review and refine attribute-based workflows												
Task 11.0 Rerun reservoir simulations with adjusted parameters												
Task 12.0 Finalize seismic attribute catalog and best practices workflows												
Task 13.0 Technology transfer												

Figure 2. Project schedule. Black boxes show project status as of September 30, 2005.

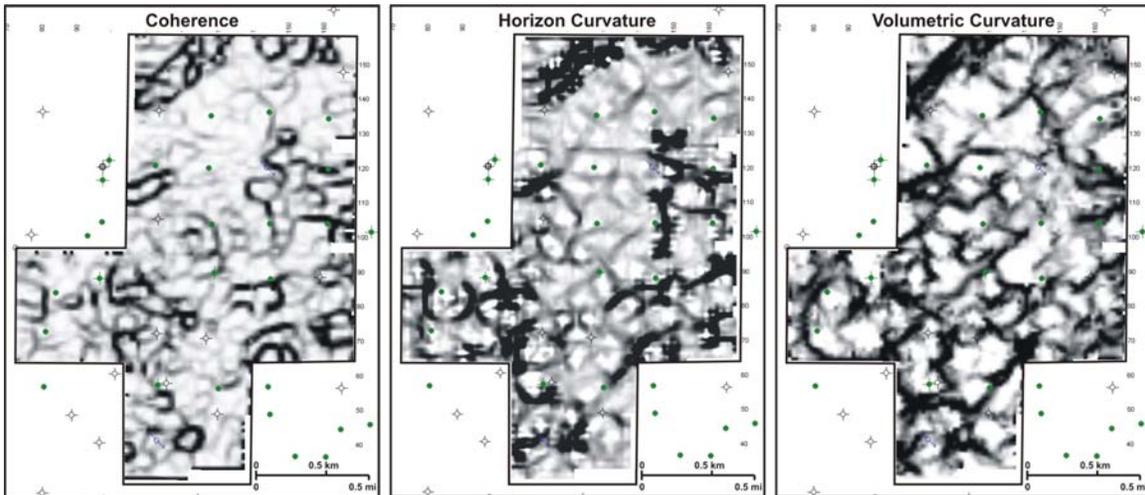


Figure 3. Comparison of coherence (left), most negative curvature from gridded, interpreted horizon (middle), and extracted volumetric most negative curvature (right) for a Mississippian reservoir in Kansas. Note that oriented lineaments, which cannot be seen on the coherence map, are visible on the two curvature maps. Also note that the lineaments are better defined on the volumetric curvature map than on the horizon curvature map. These lineaments are interpreted to relate to solution-enhanced fractures that affect reservoir performance. Images from <http://www.kgs.ku.edu/SEISKARST/cat-frac01.html>.

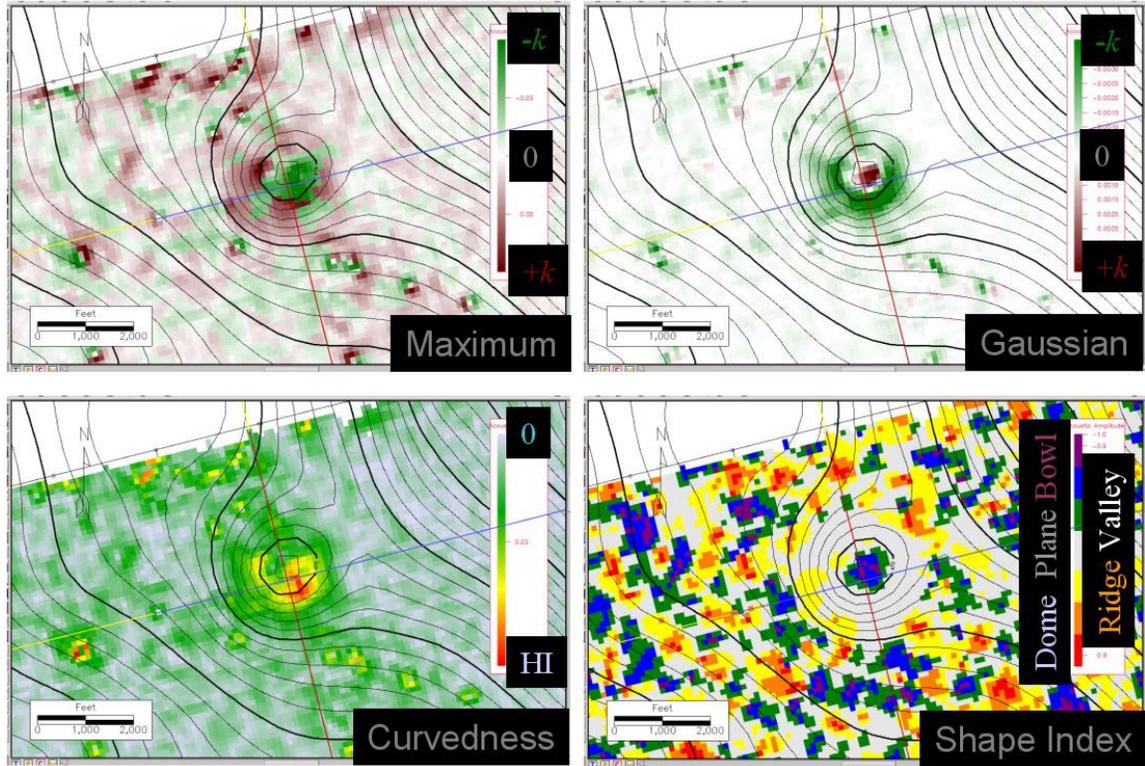


Figure 4. Time slices through various curvature volumes showing a Permian karst sinkhole in West Texas. Images from <http://www.kgs.ku.edu/SEISKARST/cat-sinkhole01.html>.

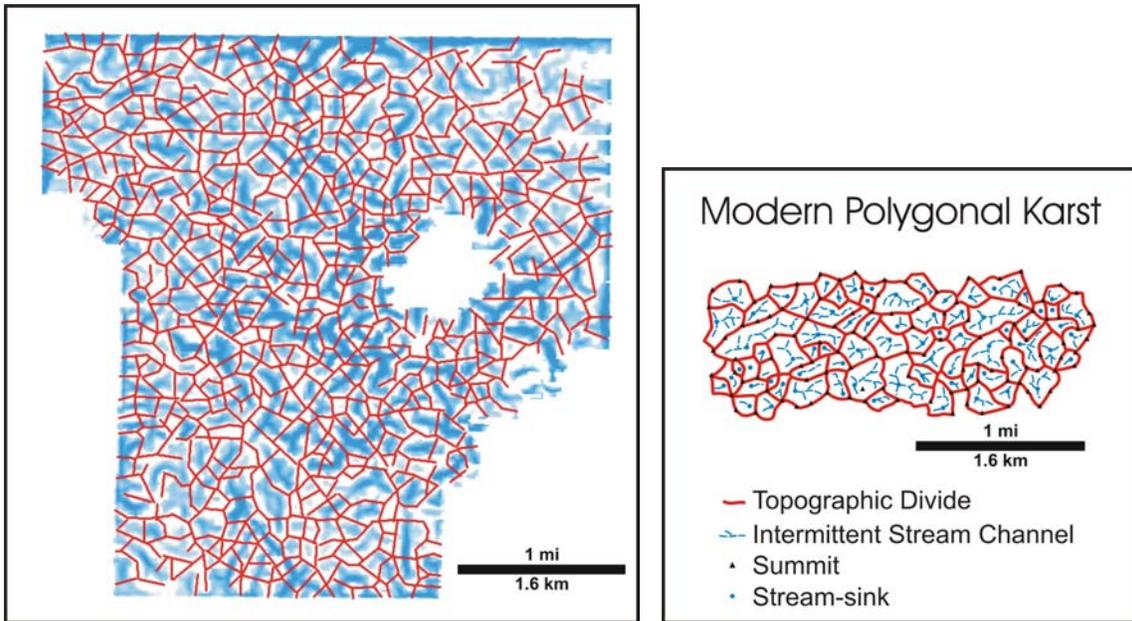
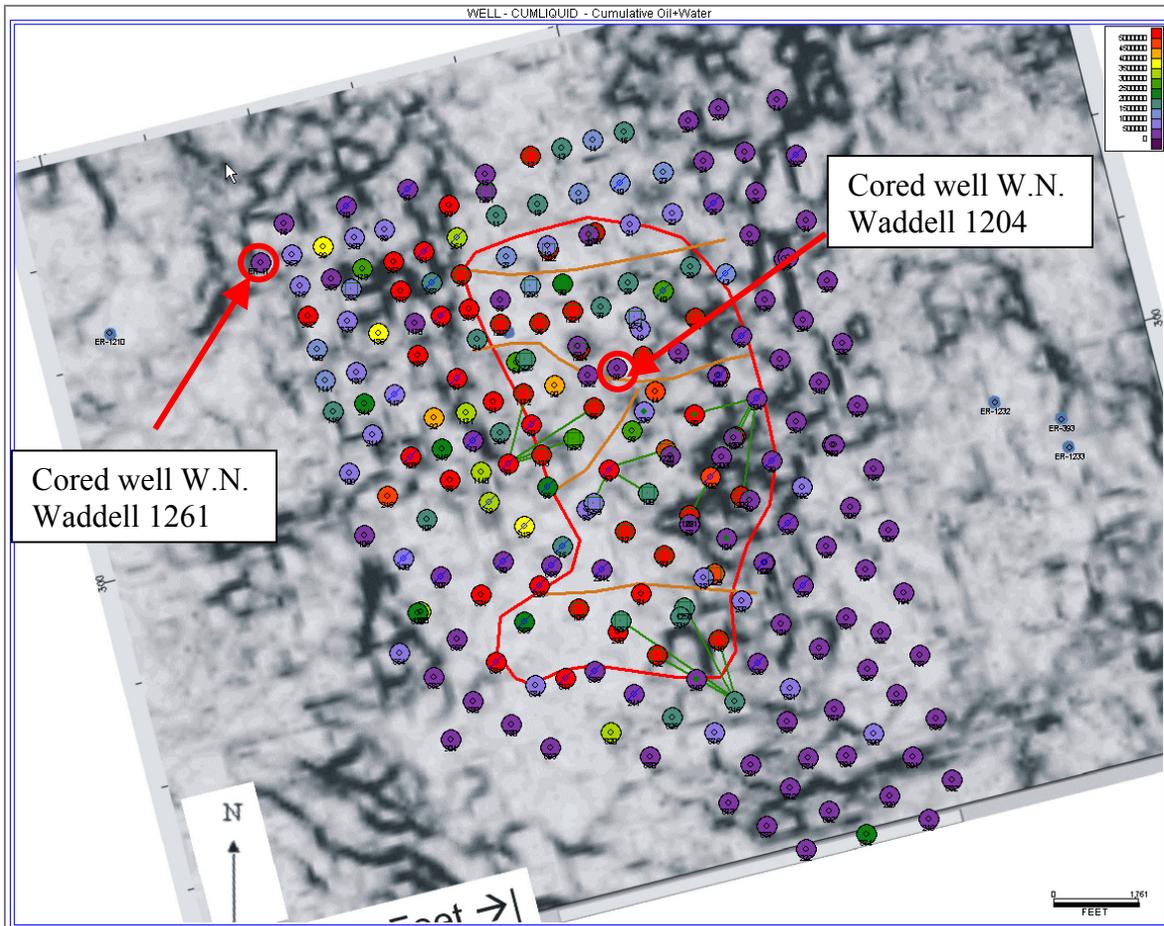
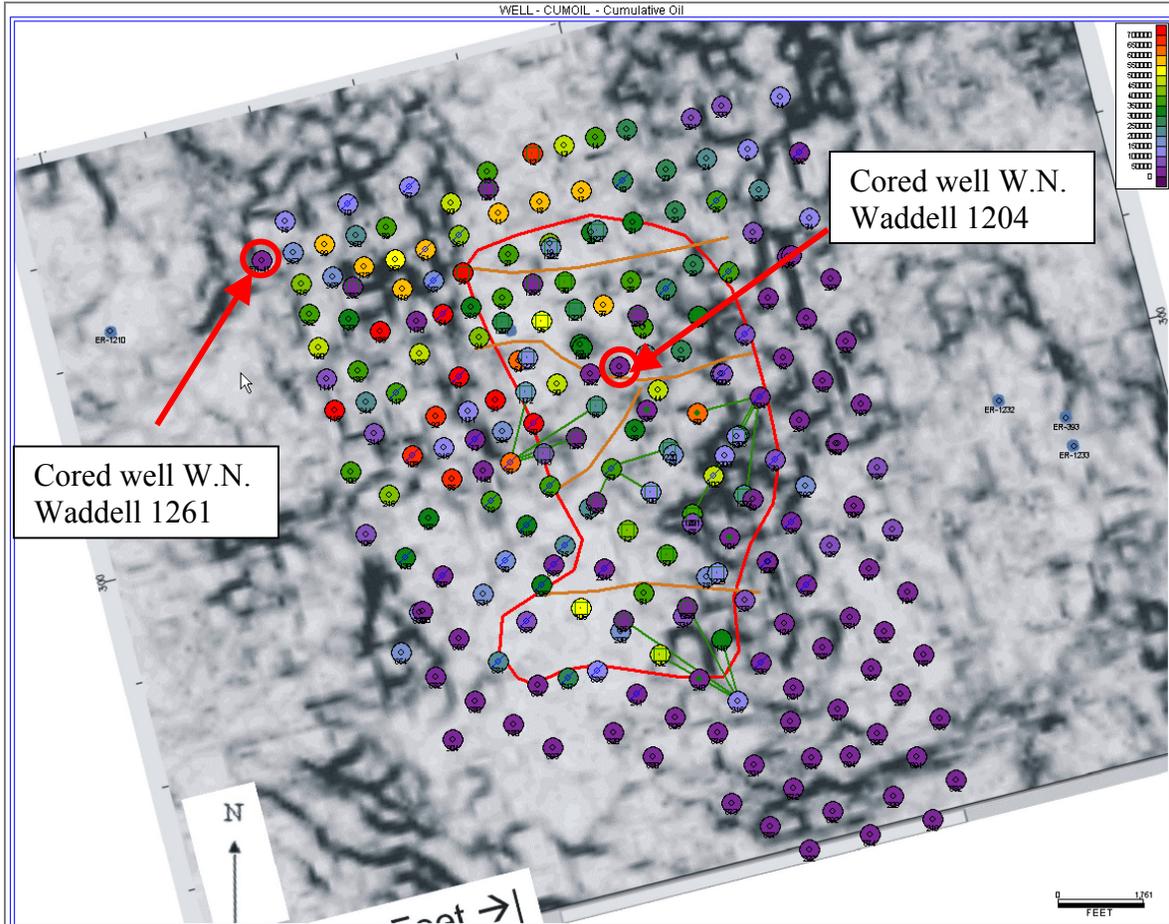


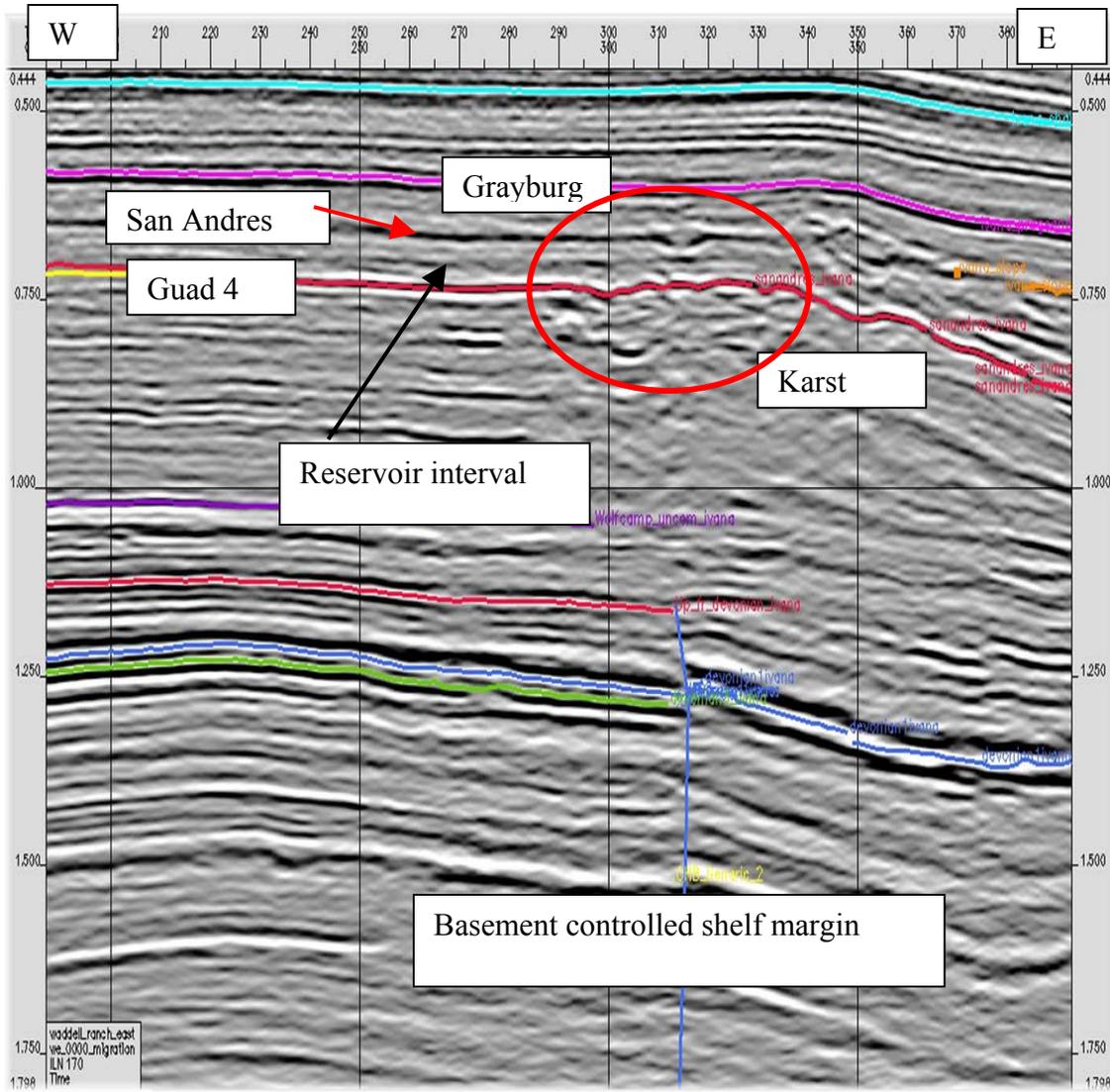
Figure 5. Left: Horizon extraction from the maximum curvature volume, Arbuckle study area, Russell County, Kansas, scaled to show only negative maximum curvatures (valleys or bowls). Darker blue indicates tighter curvature. Interpreted lineaments from the corresponding most positive curvature extraction are overlain in red. Right: Morphological map of karst area in New Guinea (modified from Williams, 1972). Images from <http://www.kgs.ku.edu/SEISKARST/cat-poly01.html>.



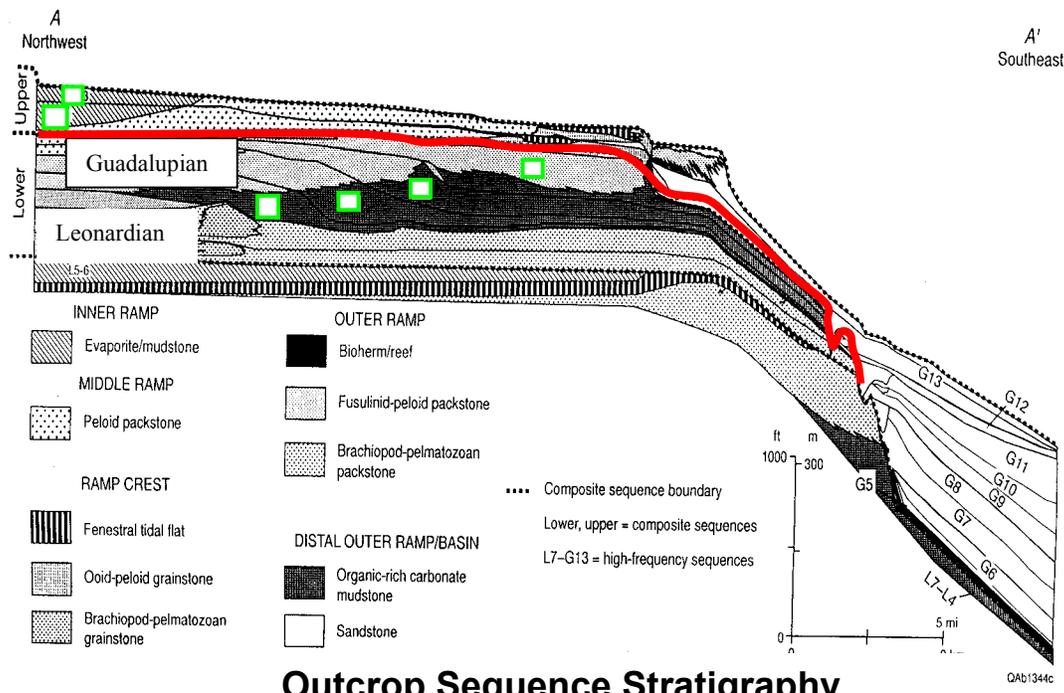
**Figure 6. Total liquid production (oil plus water) of wells in the Permian San Andres High Volume Area (HVA), over seismic coherency extracted along the top of the San Andres reservoir. Highest cumulative production (red circles) is from wells with a maximum of 18 million barrels. Straight green lines connect wells linked by tracer studies; orange lines are engineering based hypothetical reservoir compartments.**



**Figure 7. Total oil production of wells in the Permian San Andres High Volume Area (HVA) over seismic coherency extracted along the top of the San Andres reservoir. Highest cumulative production (red circles) is from wells with a maximum of more than 900,000 barrels. Straight green lines connect wells linked by tracer studies; orange lines are engineering based hypothetical reservoir compartments.**

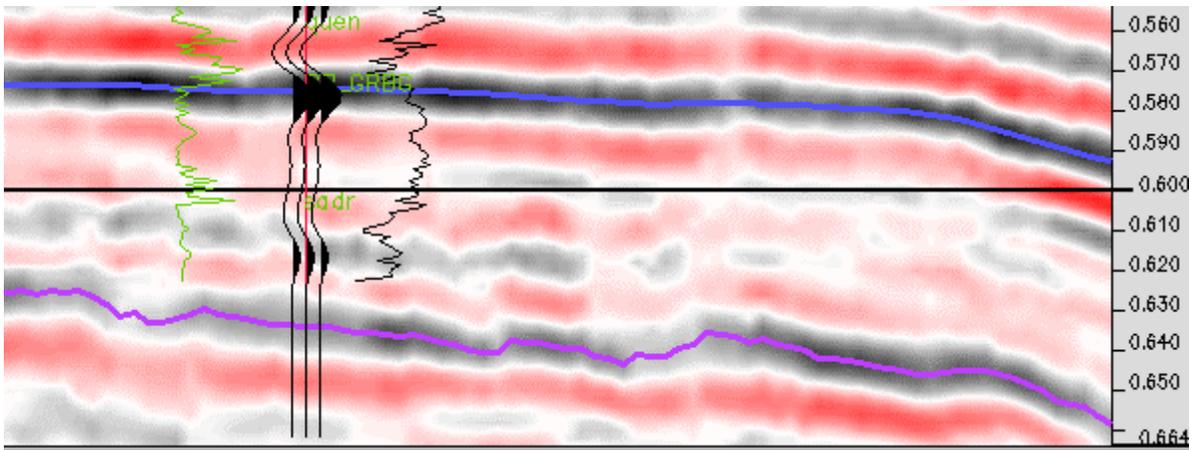


**Figure 8. West-East seismic line from the west Texas survey showing San Andres stratigraphy and seismic character of karst overprint along the San Andres Guad 4 shelf margin. As seen in Figure 10, the top of the San Andres becomes a poorer reflector in the High Volume area, north and west of this line.**



### Outcrop Sequence Stratigraphy

**Figure 9. Outcrop based sequence stratigraphy of the San Andres Formation. Leonardian fourth order High Frequency sequences (HFS) of the lower San Andres were deposited in broad ramp settings. The four Guadalupian HFS's of the upper San Andres, below the regional Guad 4 unconformity (red) were deposited in aggradational to progradational ramp to platform settings. The two fourth order HFS's above the unconformity on top of the Guad 4 HFS are relatively thin, reflecting decreasing accommodation space. The San Andres reservoirs of the High Volume area of this study occur in these two uppermost HFS's. The top of the San Andres, as well as the top of the Guad 4 and Guad 3 HFS's are marked by regional karst events. Outcrop stratigraphy after Kerans and Fitchen (1995).**



**Figure 10. Detail of log tie to seismic within the High Volume area. The blue horizon is the top of the Permian Grayburg Formation; the purple horizon is the unconformity at the top of the Guad 4 fourth order High Frequency sequence. The top of the San Andres is a reflector that is irregular and broken in the study area. At the depths shown above, 10 ms in time is equivalent to about 24 m (80 ft).**

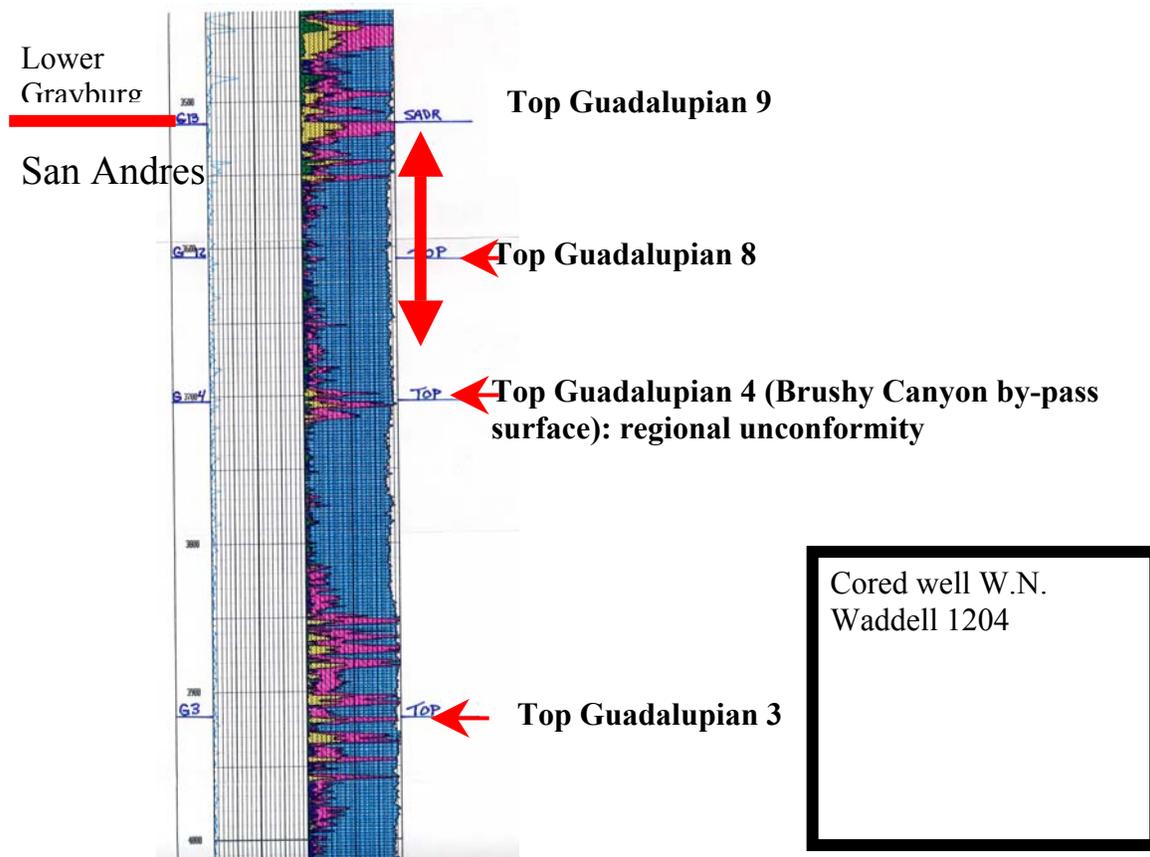
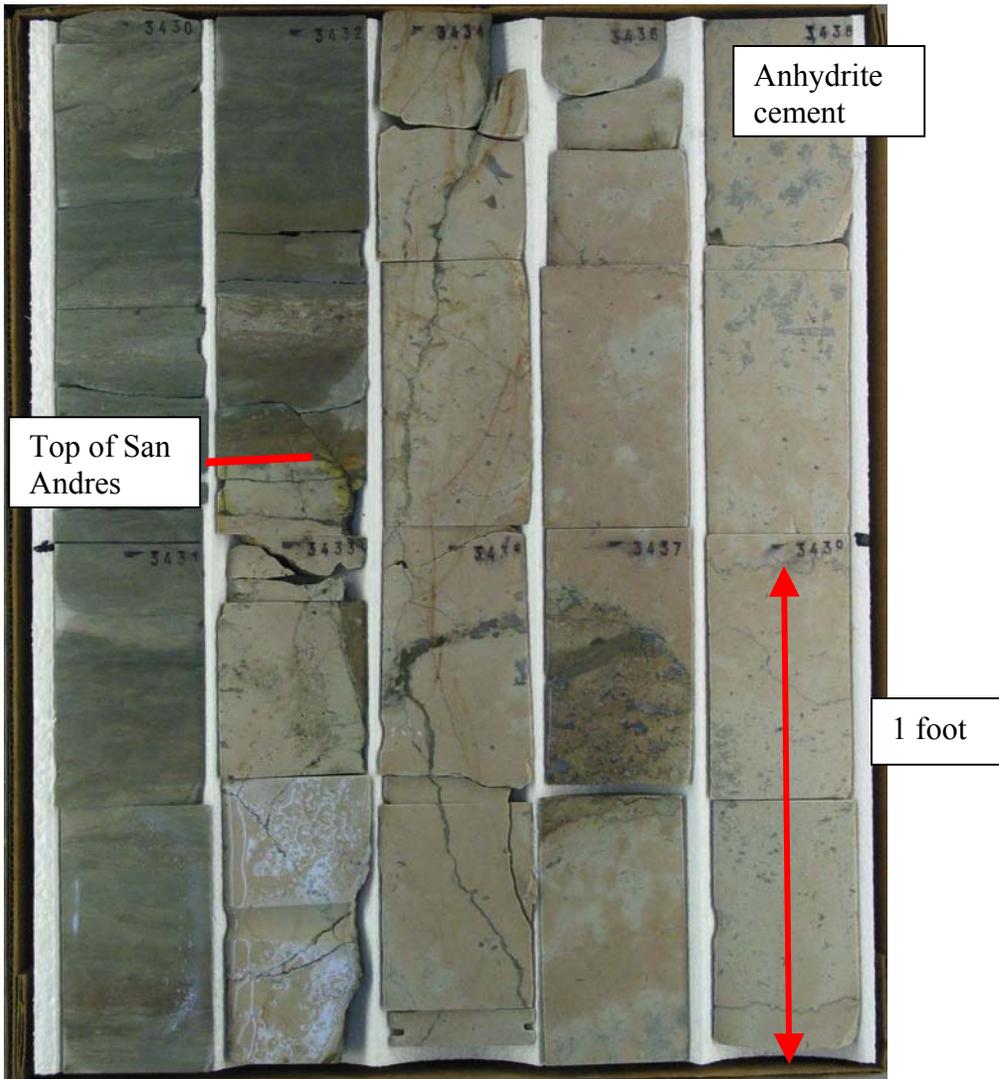
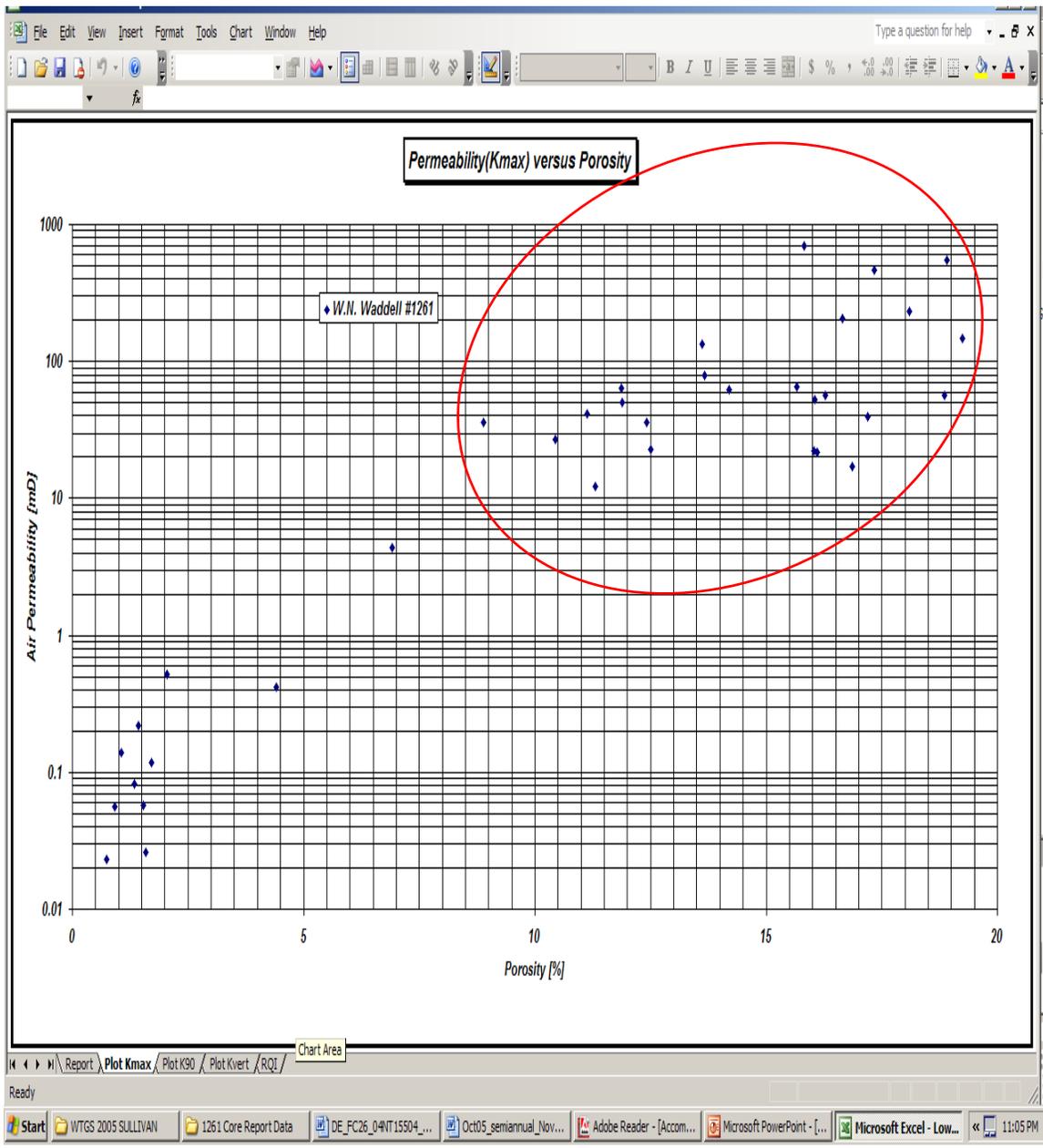


Figure 11. Electrofacies log of down-dip well east of the High Volume Area (HVA) showing fourth order High Frequency sequence (HFS) stratigraphic packages. Note abundance of anhydrite in cycles near many of the High Frequency sequence boundaries. The Guadalupian (Guad) 8 and Guad 9 together form the third order Composite Sequence 10 as identified by French and Kerans (2004) in the Penwell Jordan field about 3 km (2 miles) north of the HVA field. The Guad 8 and Guad 9 HFS's thin updip (west), reflecting decreased accommodation space on the basement controlled platform topography. (After Sullivan, 1995)



**Figure 12. Core from the W. N. Waddell 1261 well. The red line marks the unconformable top of San Andres Formation, coincident with the top of the Guad 9 HFS. Note presence of anhydrite filled fractures and scattered anhydrite cement.**



**Figure 13. Plot of W.N. Waddell 1261 whole-core derived Kmax permeability versus core porosity. Core with porosities above 9.5% have variable, but strikingly higher permeabilities, reflecting greater pore connectivity. Permeabilities in this core are as high as 695 mD.**

Era	System	Series	Stratigraphic Unit
Paleozoic	Pennsylvanian	Virgilian	Wabunsee Group
			Shawnee Group
			Douglas Group
		Missourian	Lansing Group
			Kansas City Group
			Pleasanton Group
		Desmoinesian	Marmaton Group
			Cherokee Group
	Atokan		
	Morrowan	Keyes Sandstone	
	Mississippian	Meramecian	St. Louis Ls.
			Salem (Spergen) Ls.
			Warsaw Ls.
		Osagian	
Kinderhookian			

Figure 14. Stratigraphic Column for Mississippian study area, Cheyenne County, Colorado. Spergen reservoir interval is highlighted in gray.

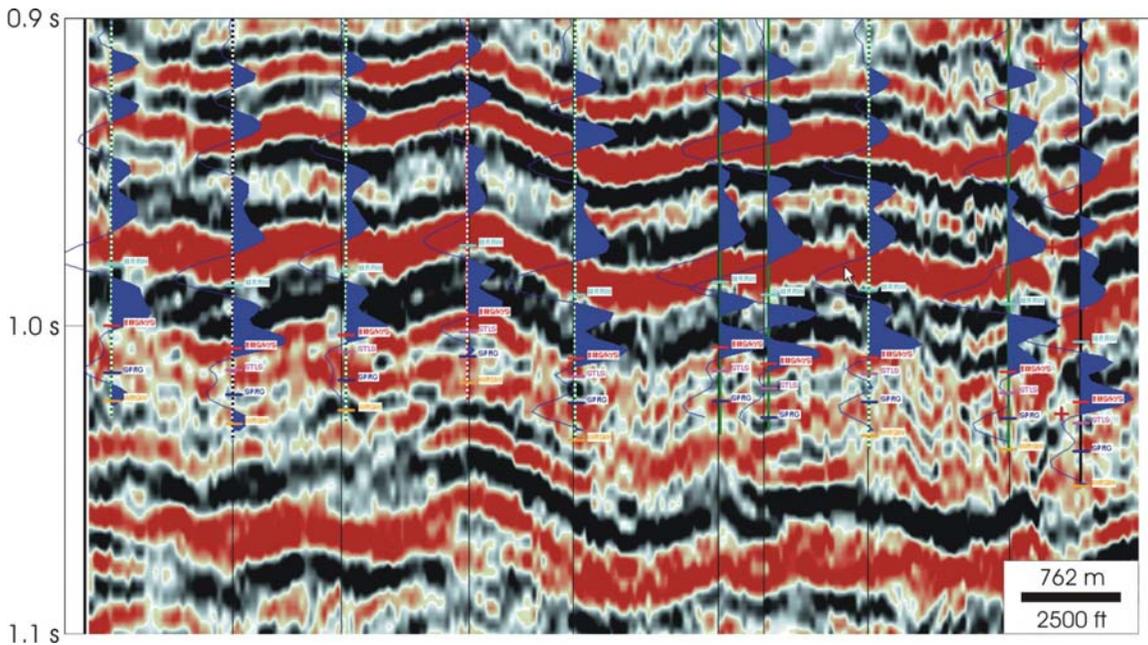


Figure 15. Vertical seismic section through wells with sonic logs in the Mississippian study area. Peaks are black and troughs are red. Synthetic seismograms generated from the sonic logs are superimposed in blue. The following formation tops are displayed: Morrow (cyan), BMS/KYS (red), Top Mississippian/St. Louis (violet); Spergen (dark blue); Warsaw (gold).

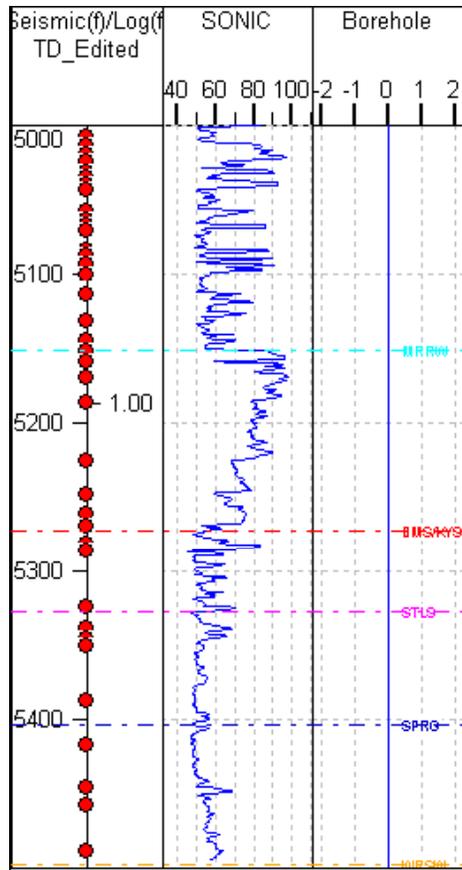


Figure 16. Sonic log for a well in the Mississippian study area showing that the top Mississippian (STLS) and top Spergen (SPRG) do not correspond to significant acoustic impedance contrasts.

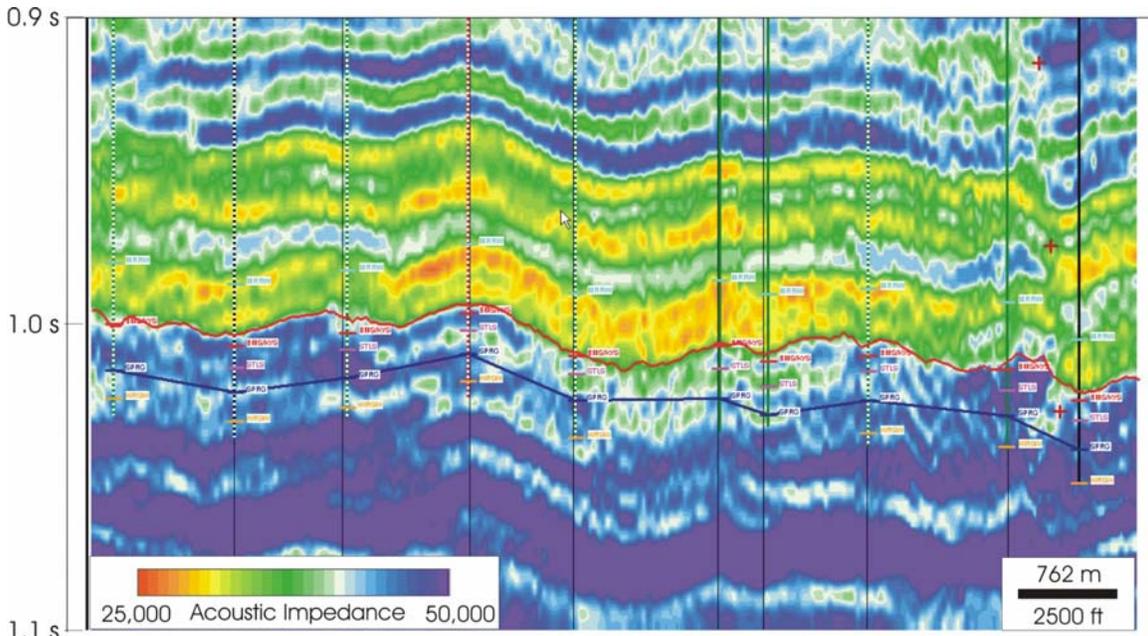
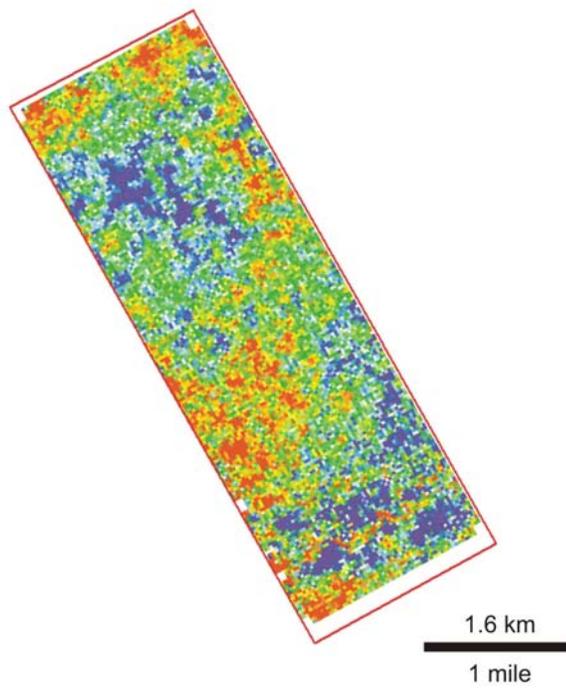
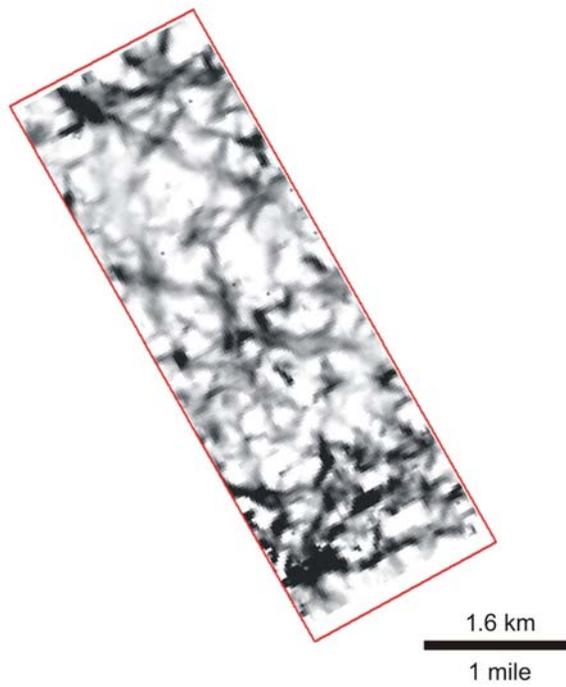


Figure 17. Section through model based inversion volume corresponding to seismic section in Figure 15. The interpreted BMS/KYS horizon is shown in red. Formation tops as in Figure 15.



**Figure 18. Acoustic impedance from model based inversion volume extracted 15 ms below BMS/KYS horizon. Purple corresponds to highest impedance and red corresponds to lowest impedance.**



**Figure 19. Most negative volumetric curvature extracted 15 ms below the BMS/KYS horizon. High values of negative curvature are shown in black. Low values of negative curvature and all positive curvatures are shown in white.**

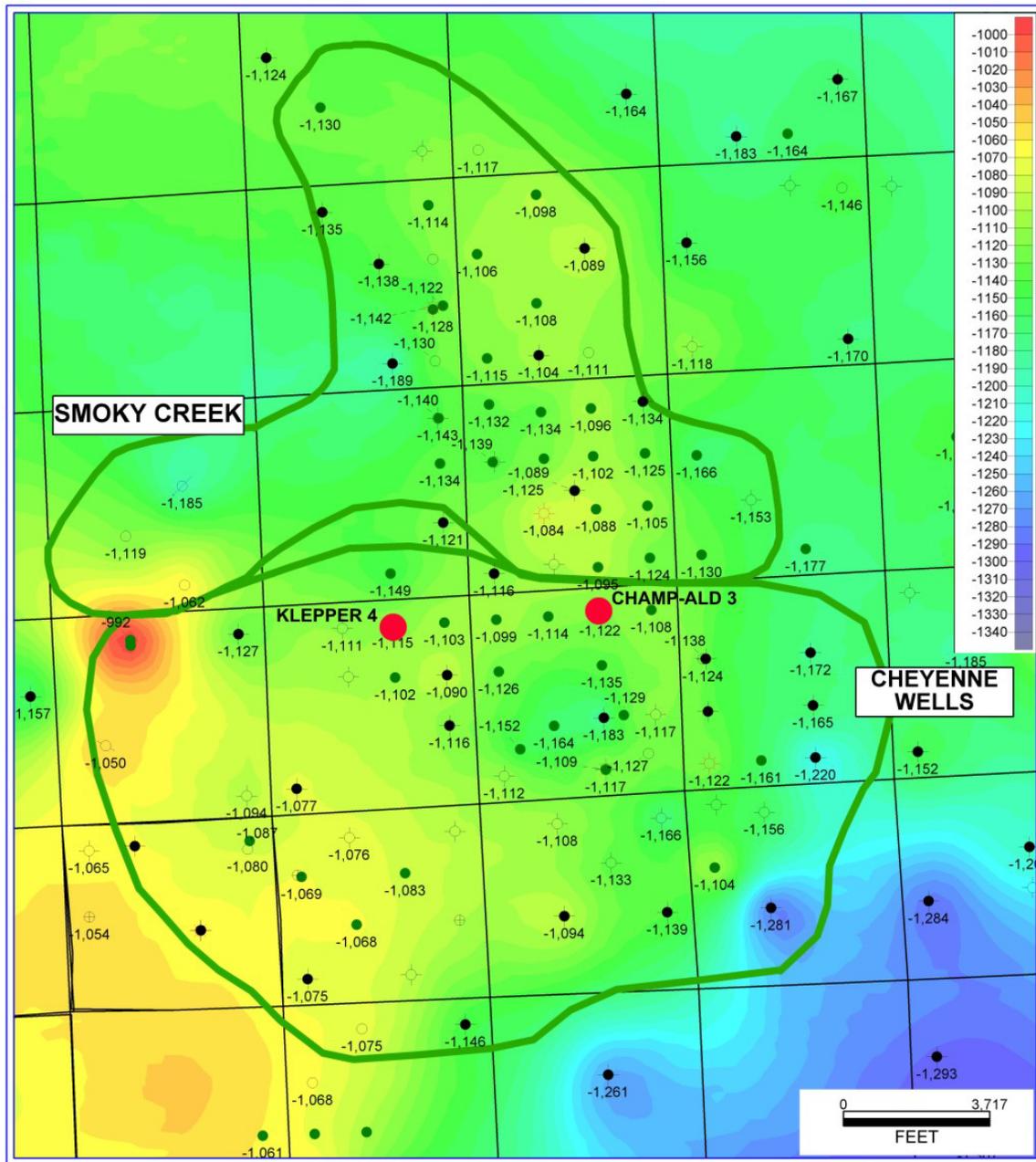


Figure 20. Structure of the top of the Spergen Limestone from well tops. Subsea depths (in feet) are labeled at the well locations. Field outlines are shown in green. Locations of cored wells are shown in red.

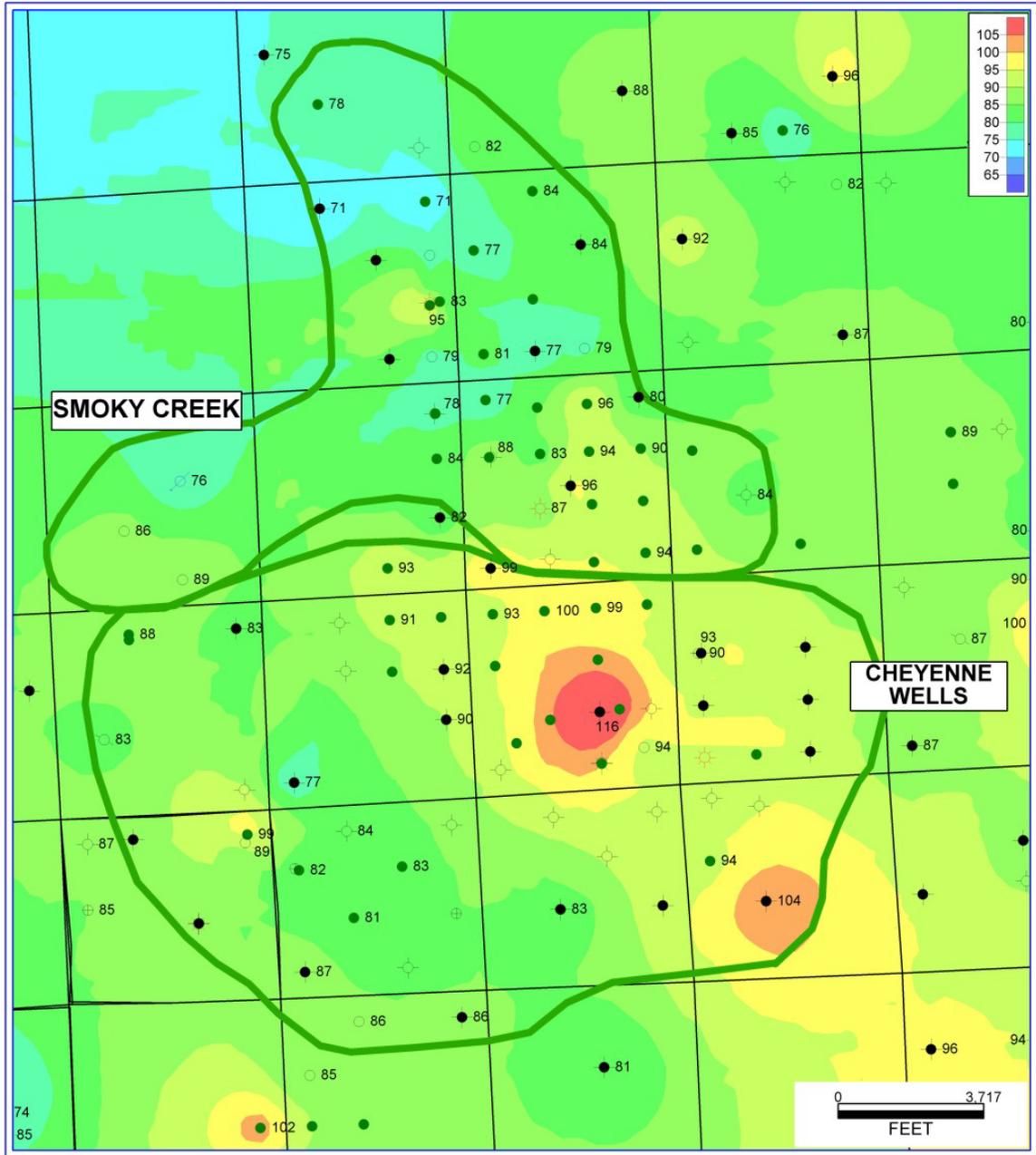


Figure 21. Isopach of the Spergen Limestone. Isopach values (in feet) are labeled at the well locations. Field outlines are shown in green.

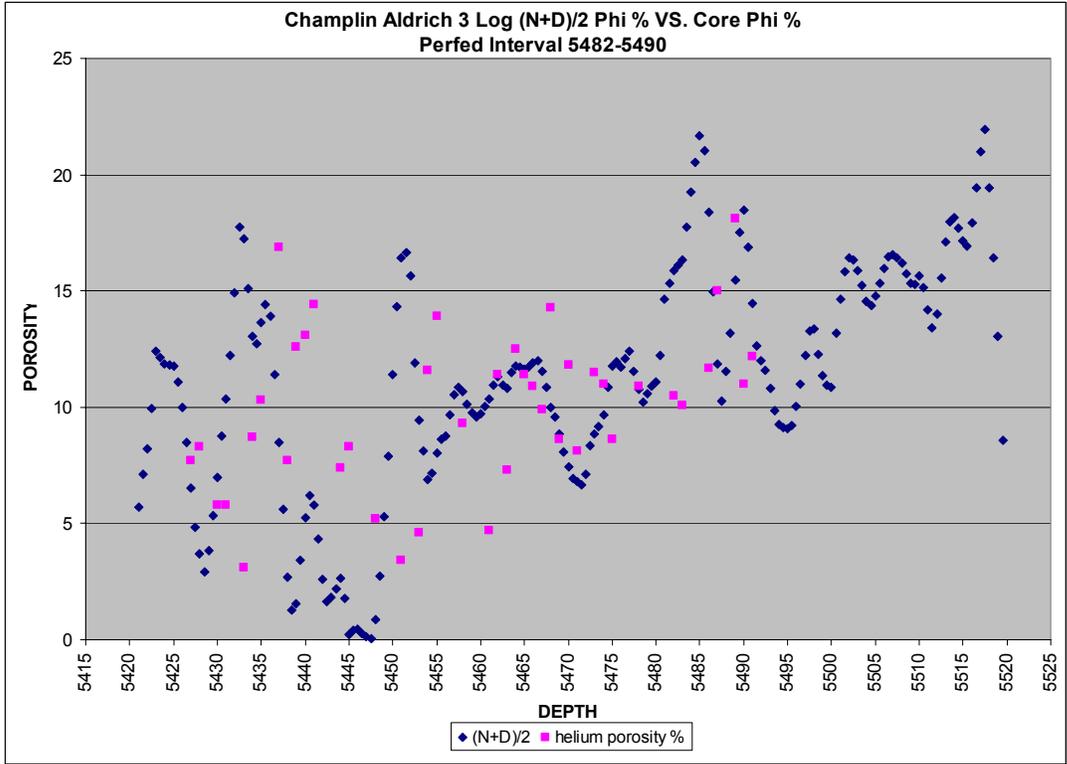


Figure 22. Graph of average neutron-density porosity (log) and helium porosity (core) versus depth in Champlin Aldrich 3.

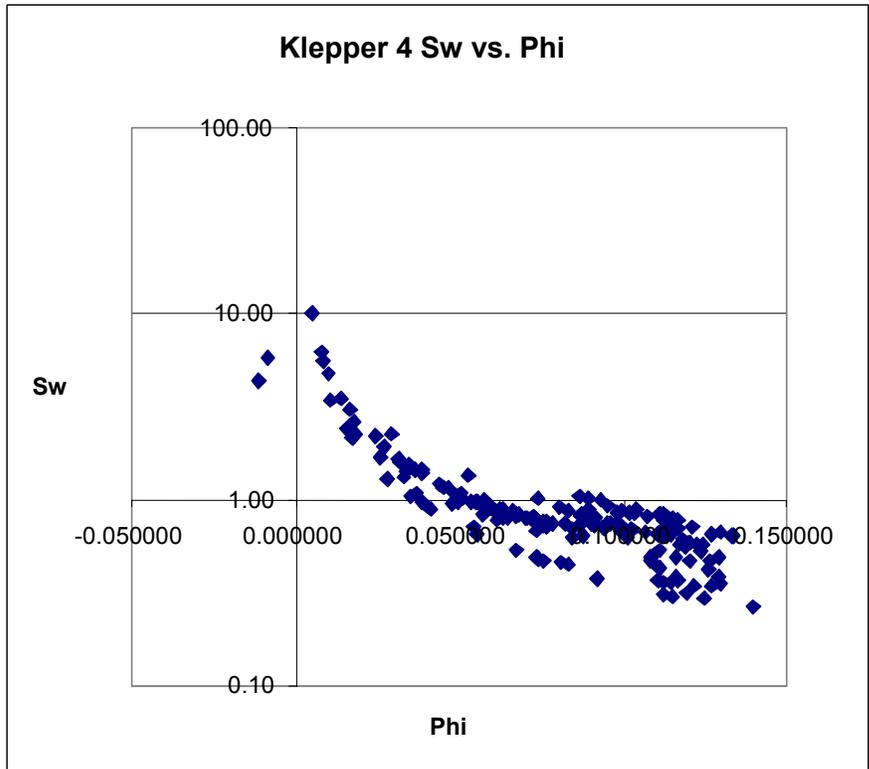


Figure 23. Graph of water saturation vs. porosity for Klepper 4.

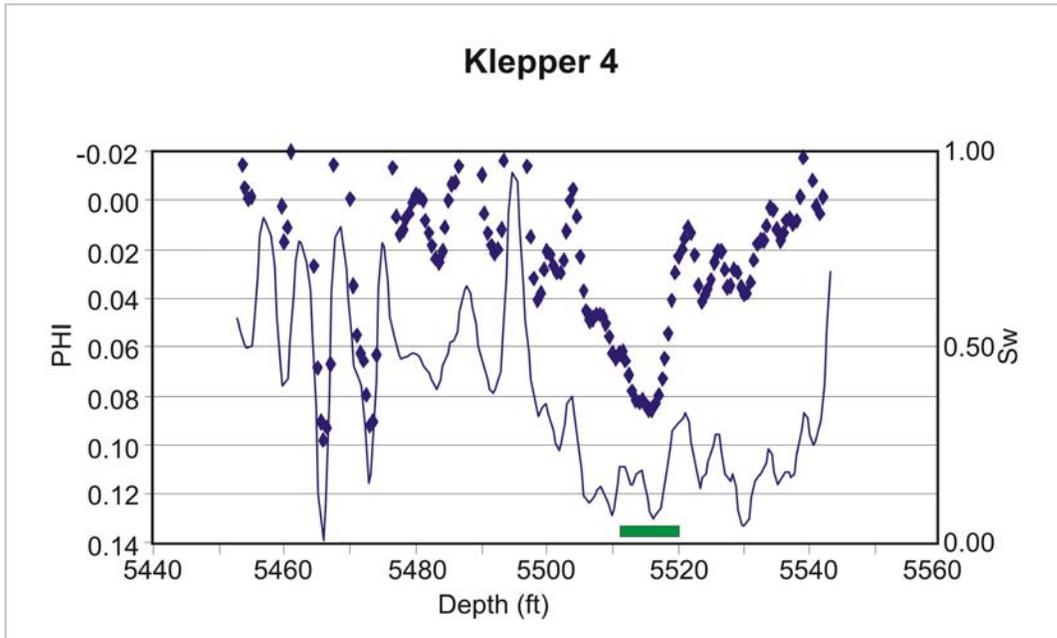


Figure 24. Graph of water saturation (diamonds) and average neutron-density porosity (line) versus depth in Klepper 4. The perforated interval is indicated by the green line.

Era	System	Series	Stratigraphic Unit	
Pennsylvanian	Virgilian		Wabunsee Group	
			Shawnee Group	
			Douglas Group	
	Missourian		Lansing Group	
			Kansas City Group	
			Pleasanton Group	
	Desmoinesian		Marmaton Group	
			Cherokee Group	
	Ordovician	Lower		Arbuckle Group
	Cambrian	Upper		Reagan Sandstone
			Granite, Schist	
Precambrian				

Figure 25. Stratigraphic Column for Arbuckle study area, Russell County, Kansas.

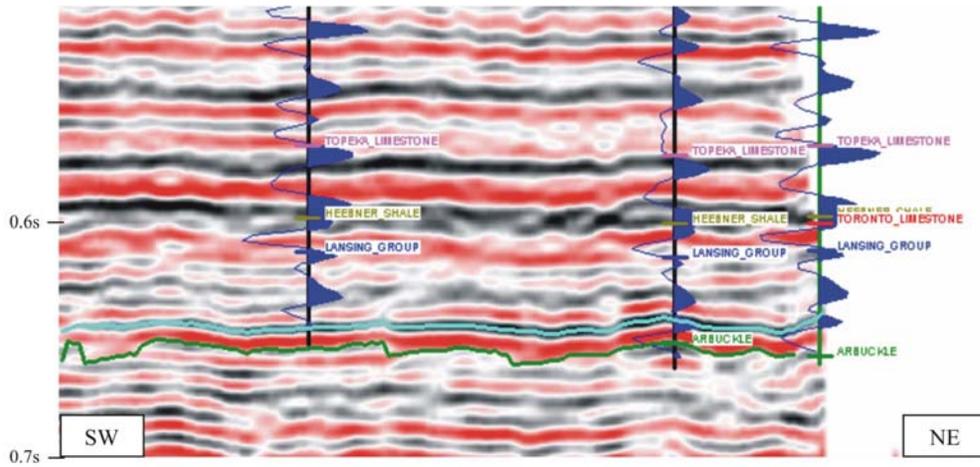


Figure 26. Vertical seismic section through wells with sonic logs in the Arbuckle study area. Peaks are black and troughs are red. Synthetic seismograms generated from the sonic logs are superimposed in blue. The Arbuckle horizon is shown in green. The Base Kansas City (BKC) horizon, which has been autotracked across the seismic survey, is shown in light blue.

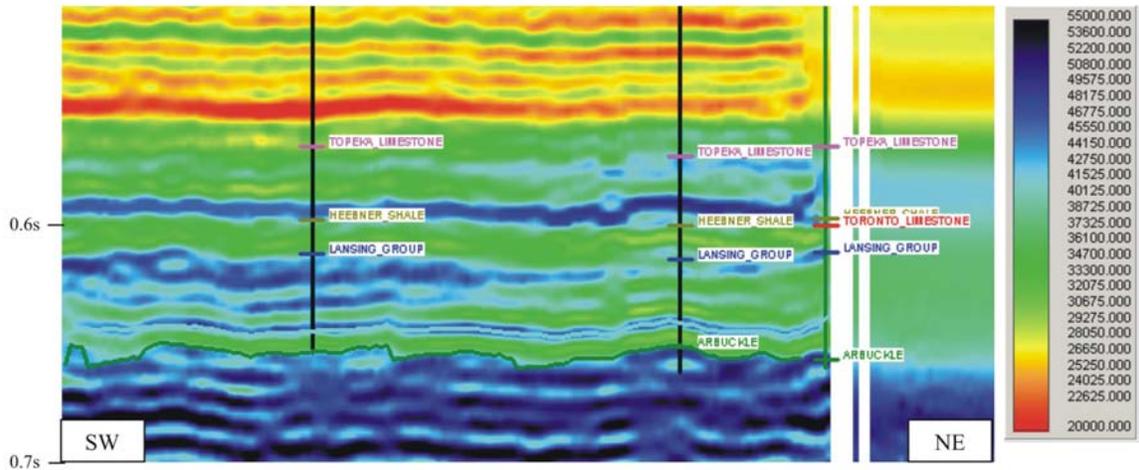


Figure 27. Vertical section through model based inversion volume for the Arbuckle study area. Horizons as in Figure 26.

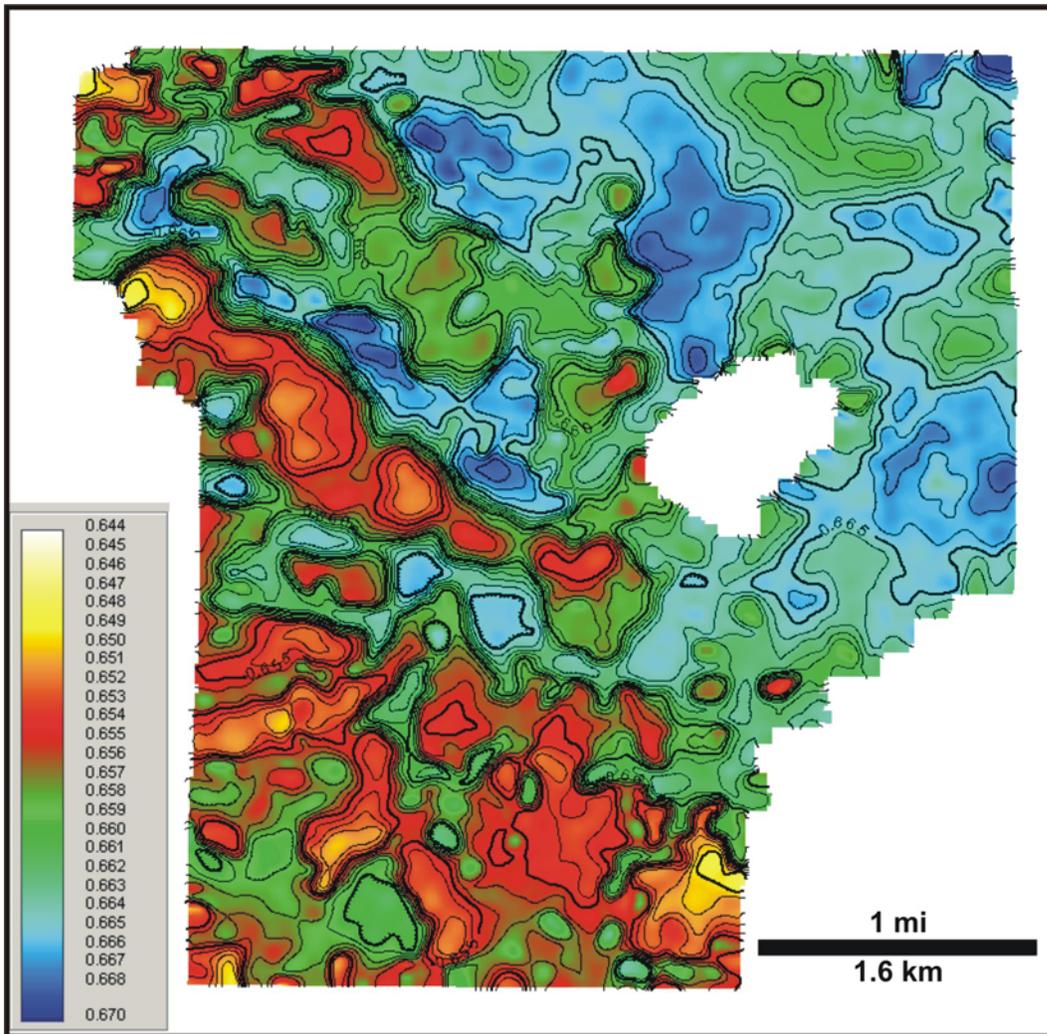
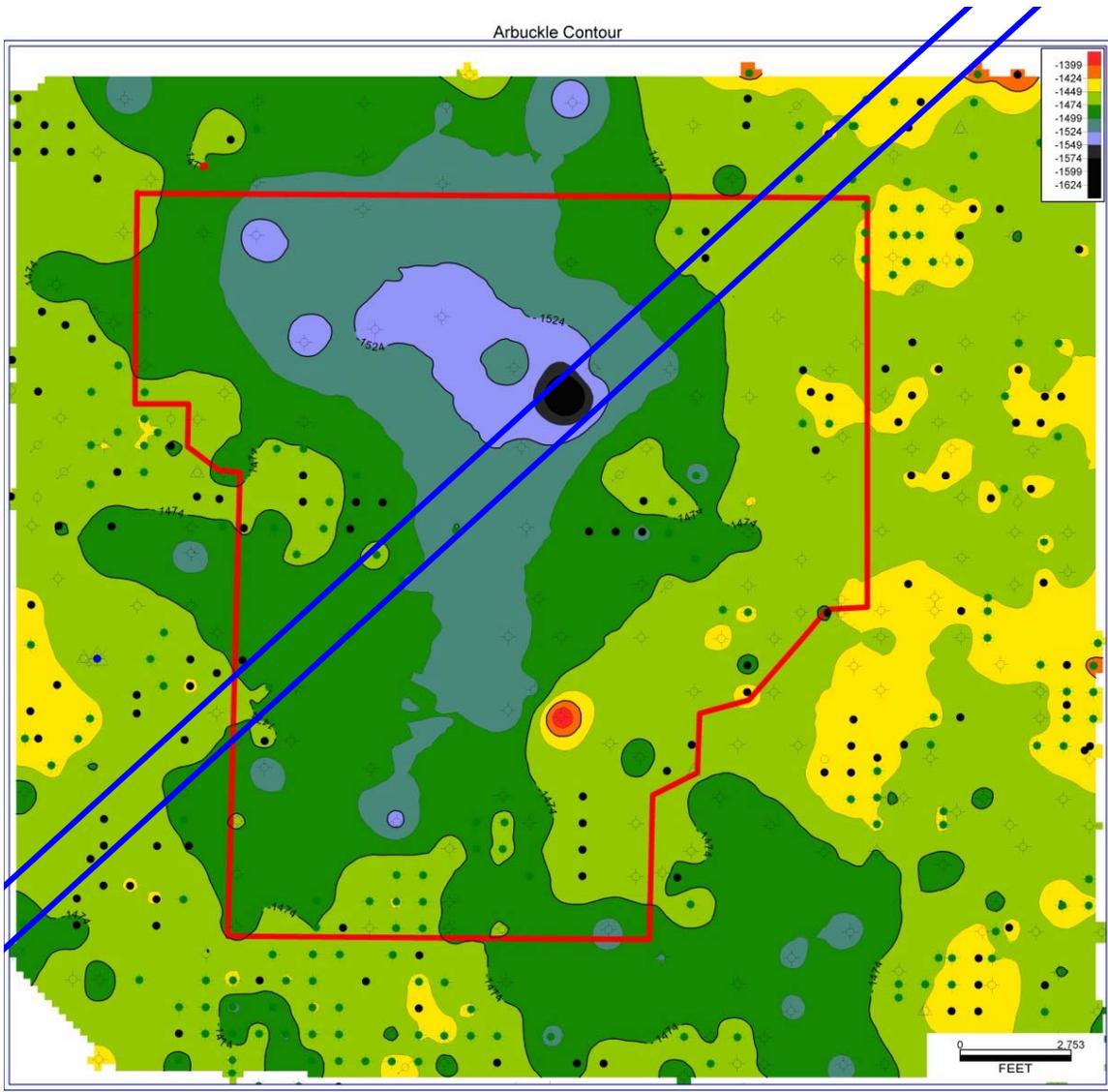


Figure 28. Arbuckle time structure map interpreted from the model based inversion volume. Color bar at left indicates time structure in seconds two-way travel time. Red areas are structurally high; blue areas are structurally low.



**Figure 29. Top of Arbuckle subsea structure from well tops for a portion of Russell County, Kansas. Red outline defines area of 3D seismic survey. Blue lines indicate general location of cross section. Contour Interval = 8 m (25 ft).**