OKLAHOMA GEOLOGY notes

Oklahoma Geological Survey

Vol. 62, No. 4 Winter 2002

Featuring:

- *Diversifying Oklahoma's energy resources with wind power*
- *Oklahoma natural gas: past, present, and future*
- *Birth of the seismic reflection method*

on the cover

Blue Canyon Wind Farm, Southwestern Oklahoma

The cover picture shows a computer-generated illustration of Oklahoma's first wind farm, dubbed "Blue Canyon," which will be located north of Lawton in the Slick Hills area. This wind farm, to be installed by late 2003, will include 39 1.65-megawatt (MW) wind turbines, for a total output of 64 MW, and will generate enough electricity on average for more than 20,000 houses. The developer of this project is Zilkha Renewable Energy, LLC, of Houston, Texas. Western Farmers Electric Cooperative, provider of electricity to 19 of Oklahoma's rural electric cooperatives, will purchase the electricity.

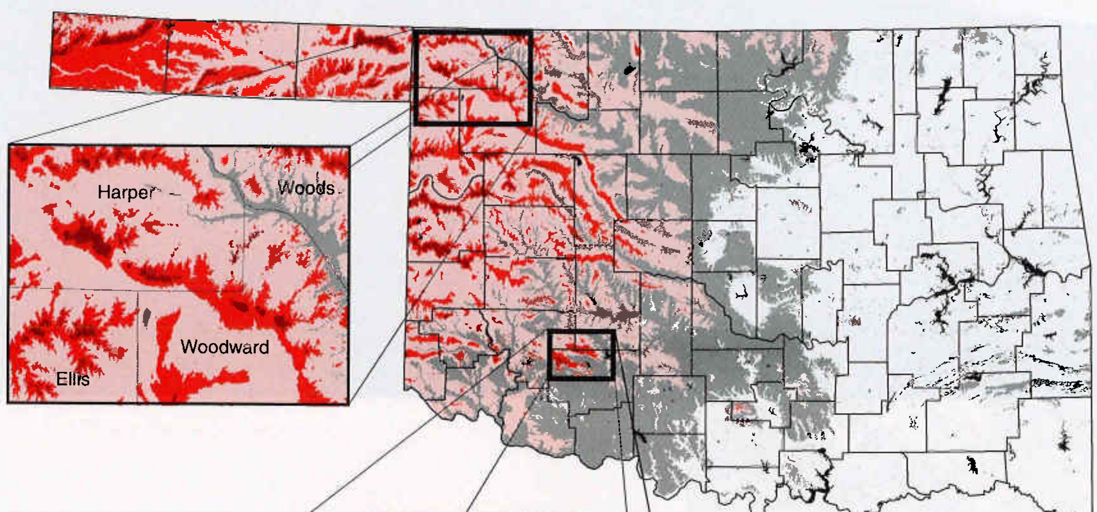
The figure below shows one wind-resource map produced by the Oklahoma Wind Power Initiative (OWPI). The development of the model used to produce this map is described in further detail in the article beginning on page 132 of this issue. The lower inset shows a zoom to the Slick Hills area, with the approximate location of the Blue Canyon Wind Farm indicated. While phase I calls for 64 MW, Zilkha expects that the complete project will someday produce as much as 300 MW of affordable pollution-free electricity when all phases of construction are complete. In addition to power generation, the project will bring new jobs and tax revenues to surrounding counties. Furthermore, a Zilkha company official estimates that well over 500 MW could be developed in the Slick Hills area alone, with appropriate upgrades to transmission capacity (Wayne Walker, Director of Project Development, Zilkha Renewable Energy, LLC, personal communication, February 2003).

For those interested in diversifying their companies' and Oklahoma's energy-production portfolio, the value of OWPI's wind-resource mapping is illustrated here. One need only look at this relatively small, albeit incredibly wind-rich, area and compare it to the class 4 and 5 ("good" to "excellent") regions found throughout western Oklahoma to get a sense of the State's tremendous potential for wind-power development. One economic study performed by OWPI, explained in the feature article, predicts that Oklahoma could develop about 14,000 MW of capacity, a figure comparable to our total generating capacity from coal and natural gas. Prolific development of wind energy can free Oklahoma's natural gas for other burgeoning markets in the United States.

The growth of wind power in Oklahoma is already evident. Two projects of similar size are expected in the next 18 months. The Oklahoma Municipal Power Authority is expected to purchase electricity from a 50-MW wind farm to be built north of Woodward (area shown in the upper inset zoom) by the end of 2003, and Oklahoma Gas and Electric Company will purchase electricity from a 50-MW wind farm, expected to be installed by mid to late 2004.

Timothy W. Hughes, Director
Oklahoma Wind Power Initiative

Cover picture courtesy of Zilkha Renewable Energy, LLC



Northwest Oklahoma is a prime region for utility-scale wind farms. Oklahoma Municipal Power Authority has plans to buy electricity from a wind farm to be developed north of Woodward by the end of 2003.

The Slick Hills area in southwestern Oklahoma (north of the Wichita Mountains Wildlife Refuge) has excellent wind resources. Good access to transmission lines (shown in white) makes this area a leading contender for wind-power development. The Blue Canyon Wind Farm will be installed in the circled area by late 2003. The cover photo is a simulation of what Oklahoma's first wind farm will look like from the intersection of Highways 58 and 19, looking south–southeast.

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EDITORIAL MATTER: Short articles on aspects of Oklahoma geology are welcome from contributors; please direct questions or requests for general guidelines to the *NOTES* editor at the address above.

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OKLAHOMA GEOLOGY notes

Vol. 62, No. 4 **Winter 2002**

Developing Oklahoma Wind-Resource Models and Products: Opportunities for Energy Diversification by the Oklahoma Oil and Gas Industry

Timothy W. Hughes[1], *Mark Meo*[2], *Troy Simonsen*[1], *Steven J. Stadler*[3], *and Jeremy Traurig*[1]

ABSTRACT.—As the fastest growing energy resource in the world, wind power has become an attractive option for energy consumers and for energy-development companies concerned about providing power that is clean, inexpensive, and sustainable. Oklahoma's wind resource holds promise for developers and landowners who want to benefit from the nation's growing desire to secure reliable energy supplies from domestic resources. Other Great Plains states, such as Iowa, Minnesota, and Texas, have already seen much development in wind power. Oklahoma will soon follow with its first wind farm, which will go on the ground in 2003 (see cover-photo description, p. 130).

The Oklahoma Wind Power Initiative (OWPI) began in July 2000 with a mission to provide wind-resource information and educational outreach to stimulate wind-power development in our State. OWPI is a collaborative project between the University of Oklahoma and Oklahoma State University. One of OWPI's goals has been to develop and improve high-resolution (1 km or better) wind-power maps for Oklahoma at heights of 50 m above ground level, which correspond to hub heights of many modern wind turbines.

To provide these wind-power maps, OWPI investigated the use of models that could be run on personal computers. The two models selected were the mass-consistent model and the neural-network model. Data from the Oklahoma Mesonetwork (Mesonet), a network consisting of 114 environmental monitoring stations, were then entered into the model programs.

The results of the model programs show that significant parts of western Oklahoma and the Panhandle have wind resources that make the development of large, utility-scale wind farms economically feasible. These wind farms could potentially bring billions of dollars to Oklahoma in economic development. Wind-farm developers are now typically out-of-State concerns. OWPI hopes that its research and outreach efforts will spur Oklahoma's oil and gas industry to recognize wind power as an opportunity to diversify energy portfolios through investments to extract this inexhaustible resource. Investments by these and other in-State concerns will keep more economic benefit inside Oklahoma.

INTRODUCTION

A growing number of multinational energy corporations have been focusing their investment dollars on generating energy from a natural resource that has long been abundant in Oklahoma. BP–Amoco, ChevronTexaco, ConocoPhillips, and Shell are all involved in developing wind-power facilities at attractive sites around the world as well as within the United States. For example, Shell has recently purchased an additional 41 megawatts (MW) of wind-generation capacity in the Cabazon Pass wind farm, 25 mi west of Palm Springs, California. The purchase brings Shell WindEnergy's total U.S. capacity to >230 MW. In July 2002, Shell, as part of the NoordzeeWind consortium, signed an agreement with the government of the Netherlands for development of the 100-MW Near Shore wind farm at Egmond-aan-Zee. Overall, >3,000 MW of wind-energy projects are currently being developed or evaluated by Shell in the United States and Europe (see July 23, 2002, press release at www2.shell.com).

As the fastest growing renewable energy resource in the world, wind power has become an attractive energy option for turbine manufacturers, such as GE Wind Energy, as well as for energy-development companies concerned about providing power that is clean, inexpensive, and sustainable. In the Great Plains region, Oklahoma's wind resource holds promise for developers and landowners who wish to benefit from the nation's growing desire to secure reliable energy supplies from domestic resources. One Oklahoma energy company, Chermac Energy Corporation, has made significant inroads toward wind-farm development in northwestern Oklahoma. Some Oklahoma oil and gas landmen have even added work with "wind rights" to their repertory, having become active in negotiating land leases for wind-farm developers.

Many facets of wind-farm development—permitting, land leasing, and construction, to name a few—involve

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aspects that oil and gas industry professionals are well equipped to handle. However, wind-resource evaluation is quite different from typical oil and gas exploration. Hence, a need was perceived for developing products and services for locating and evaluating wind resources to aid those who are interested in diversifying their energy sources but who lack experience in wind-resource assessment. Furthermore, because an in-State ownership scenario returns economic benefits to Oklahoma that are many times the economic returns from ownership by out-of-State concerns, these products and services are thought to be an important stepping-stone toward promoting economic development in our State.

The Oklahoma Wind Power Initiative (OWPI) began in July 2000 with a mission to provide wind-resource information and outreach to stimulate wind-power development in our State. OWPI's principal products include long-term wind-energy climate products and statewide wind-resource maps (see www.seic.okstate.edu/owpi). This paper describes development of the wind-resource maps and the use of such maps for estimating economic-development potential. It also touches on the future prospects for development of wind-to-hydrogen production facilities and their production of hydrogen gas as a feedstock, along with natural gas, for fuel cells.

DEVELOPING OKLAHOMA'S WIND-RESOURCE PRODUCTS

Background

Oklahoma Wind Power Initiative (OWPI)

OWPI is a collaborative project between the University of Oklahoma and Oklahoma State University. OWPI provides resource and economic information to policy makers, landowners, potential wind-energy investors, and citizens of Oklahoma, and it helps wind-power stakeholders to network through outreach activities.

One of OWPI's many goals is to develop and improve high-resolution (1 km or better) wind-power maps for Oklahoma at heights of 50 m and more, corresponding to hub-heights of many modern wind turbines. Prior to this study, the best resource map available for Oklahoma was developed by the U.S. Department of Energy and Pacific Northwest National Laboratory in 1987 (Fig. 1) as part of their nationwide assessment. The model grid from which this map was generated had a resolution of one-third degree longitude by one-fourth degree latitude, or approximately 25 to 30 km in each dimension (Elliott and others, 1987). At the time of its development, the primary source of wind data was from National Weather Service and military weather stations (Fig. 2), which are spaced relatively far apart. The creation of a wind-resource map for the entire country was ambitious and offered very good information for the time, but the resolution was too coarse to permit discernment of localized favorable terrain and vegetative features. Hence, this map is not practical to use for highly localized wind-farm prospecting or for development of State-scale economic models.

Selecting Appropriate Modeling Schemes

To provide maps with improved resolution and accuracy, OWPI investigated the use of simple models that could be run on personal computers. OWPI planned to use these models with input data from the Oklahoma Mesonetwork (Mesonet), a network consisting of 114 environmental monitoring stations (Fig. 2). These stations measure parameters from the soil and atmosphere; the data collected include readings of wind speed and direction at a height of 10 m.

Currently, two categories of simple analytical models exist for use in wind-resource assessment: mass consistent and

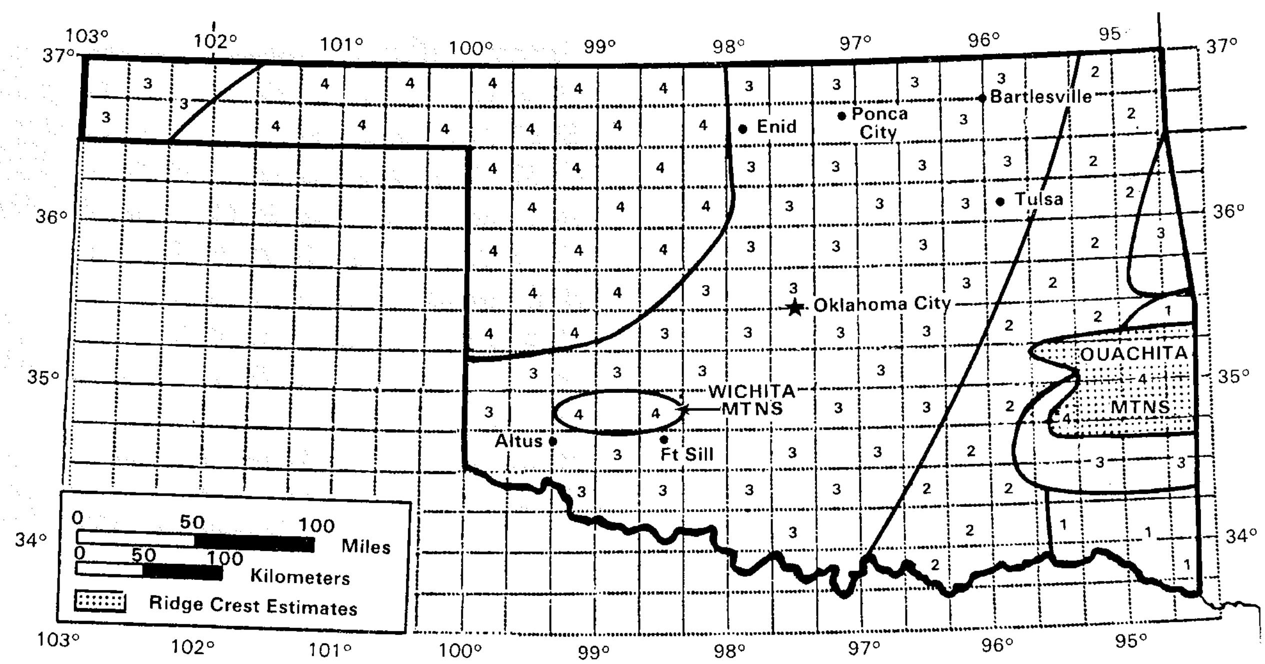

Figure 1. Map showing early estimation of wind resource in Oklahoma, from U.S. Department of Energy and Pacific Northwest Laboratory, 1987. Scale: 1 = poor; 2 = marginal; 3 = fair; 4 = good.

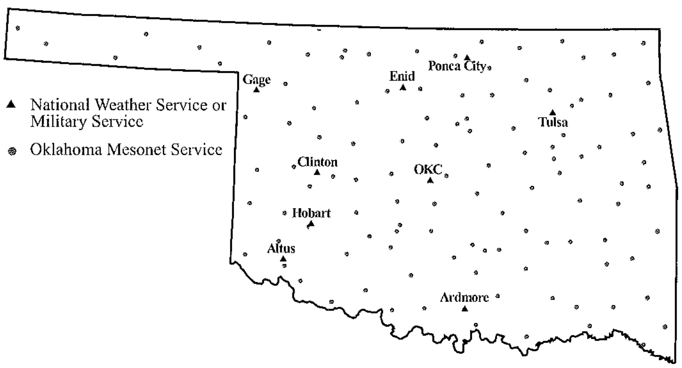

Figure 2. Map showing locations of Oklahoma Mesonet stations and National Weather Service and military stations.

Jackson-Hunt (Rohatgi and Nelson, 1994). Mass-consistent models conserve mass, whereas Jackson-Hunt models conserve mass and attempt to conserve momentum. In general, mass-consistent models have been used for surveying large areas (on the order of 100–1,000 km on a side). Jackson-Hunt models have been used more extensively for "micrositing," or locating microscale (tens to hundreds of meters) features that offer the best potential for wind energy.

The decision was made to use the simpler mass-consistent model for one of our statewide assessments because of OWPI's computational considerations, the size of Oklahoma, and the desired grid resolution of our model output.

Because of the large number of input data points made available by the Mesonet's dense spatial coverage, a modeling technique employing *neural networks* was also considered a credible tool for wind assessment. Neural nets are empirical models often used for statistical analysis and data modeling. They provide an alternative to conventional analytical techniques for solving nonlinear problems. To the authors' knowledge, neural networks have never been used for the purpose of wind assessment. Nonetheless, the technique has shown great promise in many other fields.

Surface Weather Data

Since 1993, Oklahoma has been home to one of the premier surface-weather networks in the world, the Oklahoma Mesonet (Brock and others, 1995). With 114 stations and 5-minute averaging intervals for surface-weather data, this network offers an opportunity to create detailed wind-power-density (WPD) maps to help determine optimal areas for placement of wind turbines.

Selecting Mesonet Stations for Wind-Assessment Models

Mesonet stations were sited to present the best overall estimate of local weather conditions and their variability across Oklahoma, but not all stations were optimally located to monitor the wind resource. Stations with poor exposure to the wind must be excluded from the assessment, because data from these sites would likely bias the wind-resource estimate. The following information was used to evaluate the wind exposure (i.e., fetch conditions) for each Mesonet station: (1) panoramic photos from the Oklahoma Mesonet web site (okmesonet.ocs.ou.edu), (2) 1-m-resolution digital orthophotos (Fig. 3), and (3) a 200-m resolution Land Use/Land Cover (LULC) grid.

Sites were rated "poor," "fair," "good," and "excellent" on the basis of subjective criteria. For example, stations with short, consistent vegetative cover and no obstructions in the immediate vicinity of the site were rated as having excellent or good fetch conditions. Stations with tall, inconsistent vegetative cover or anomalous vegetative cover too close to the site (e.g., a windbreak of trees) in prevailing wind directions were rated as having fair to poor fetch conditions, on the basis of the perceived degree of impact. Of the 114 Mesonet stations, 79 were classified as having good or excellent fetch conditions.

Mass-Consistent Modeling Using WindMap™

Input Wind Data

Mean wind speeds for 16 compass directions and a Weibull shape factor (a parameter that describes the shape of the wind-speed frequency-distribution curve) were entered for each Mesonet station incorporated into the model. Variables were calculated by using 7 years' worth of 5-minute, scalar-average 10-m wind speeds (5-minute average of 100 counts taken at 3-s intervals). Of the 79 Mesonet stations with good to excellent fetch conditions, wind data for 76 of these stations were included in the model (three were excluded as a result of site relocation at some time during the 7-year study). In addition to the 76 stations, 13 Mesonet stations with a fetch rating of fair were included in the model. These stations are in the eastern part of the State in areas that lack stations with good or excellent fetch conditions. No sites with a poor rating were used. Hence, data from 89 Mesonet stations were used in developing the WindMap model.

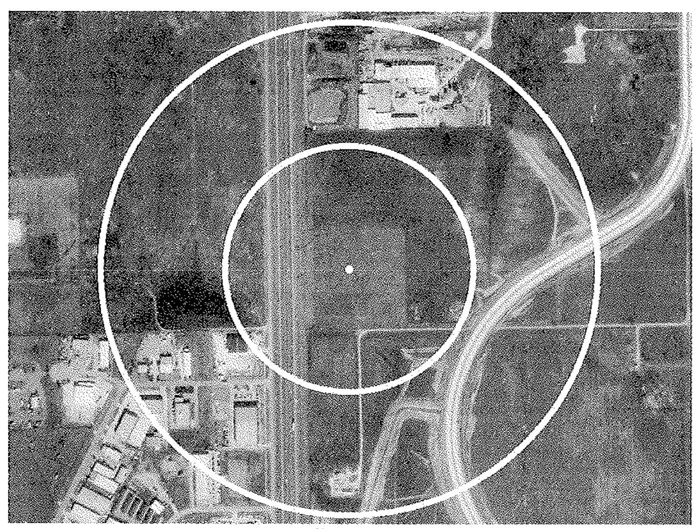

Figure 3. Aerial photo of the area around the Mesonet station at Norman; north is at the top. The inner circle represents a distance of 250 m, and the outer circle, 500 m. Although buildings obstruct some winds from the north and southwest, the wind exposure at this site was rated good because the prevailing wind direction at this site is from the south and southeast. Hence, the data were deemed acceptable for model input.

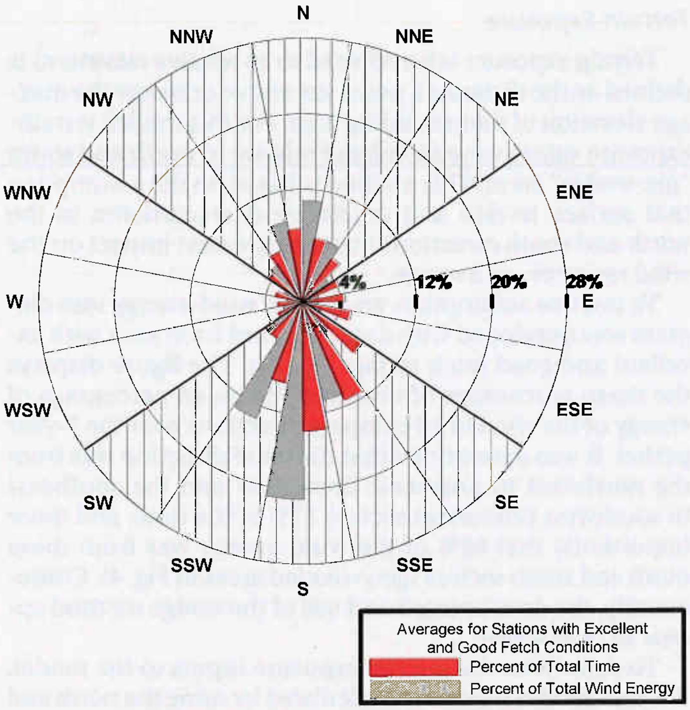

Figure 4. This wind-energy rose diagram depicts the average wind-energy conditions, by direction, for 78 Mesonet sites that were deemed to have good or excellent fetch conditions.

The use of WindMap requires a reference station to be chosen from one of the 89 stations. A reference station defines the directional frequencies of the wind. An average-wind rose diagram was computed for Mesonet stations with good to excellent fetch conditions (Fig. 4). Of these Mesonet stations, ARNE (near Arnett, Oklahoma) was determined to have a wind rose pattern most comparable to the average.

Topographic Data

Topographic information for the entire State was obtained from the *Digital Atlas of Oklahoma,* produced by the U.S. Geological Survey. The digital atlas provides a 60-m-resolution Digital Elevation Model (DEM) derived from 1:100,000-scale digital topographic maps of Oklahoma.

Surface-Roughness Data

Surface roughness is measured in terms of roughness length. In general terms, roughness length represents a height below which friction from obstacles (e.g., vegetation and buildings) effectively stifles air currents. Roughness lengths were obtained from a LULC grid model put together by the U.S. Geological Survey's National Gap Analysis Program, or GAP (Fig. 5). GAP's LULC grid describes specific land-use practices and natural vegetative covers for the State at a resolution of 30 m. The Oklahoma GAP land-cover analysis was performed by the Oklahoma Cooperative Fish and Wildlife Research Unit at Oklahoma State University. A land-cover-classification analysis was derived by computer classification of Landsat images covering the State. Forty-seven land-cover classes were derived, and the OWPI group converted these classes into estimates of surface roughness by interpolating between roughness values found for similar classes in the literature. For example, urban areas were assigned roughness values of 1.0 m, whereas regions with natural grasses and crops were assigned values from 0.025 to 0.05 m.

Modeling Process

The use of WindMap is limited to the size of the data grids that can be ingested into the computer model. As a result, the State was divided into 23 sections. For each section, the resolution of both the input and output grid models was 372 m. Although each section of the State does not fully utilize the resolution available from input data (i.e., 60 × 60 m for DEM, 30 × 30 m for LULC), the sizes of the grid models provide a sufficiently rigorous scale of examination in order to detect important landscape differences in topography and surface roughness while maintaining a reasonable computation time.

WindMap calculates horizontal wind fields for up to 25 vertical levels, thereby simulating a three-dimensional wind field. Like other mass-consistent models, WindMap is programmed to identify a divergence-free wind-velocity field that departs by the smallest possible amount from the initial wind field. The initial wind field was derived from the Mesonet 10-m wind data. Although the State was divided

Legend	Land Use/Land Cover Classification	Roughness Values (m)
	Barren	0.001 to 0.002
	Water	0.002 to 0.003
	Sandy Areas	0.01
	Short Grasses	0.025 to 0.035
	Mid-Grasses, Crops	0.035 to 0.050
	Tall Grasses, Shrubs	0.05 to 0.25
	Woodlands	0.40 to 0.60
	Forests	0.85 to 1.20
	Urban/Industrial	1.0

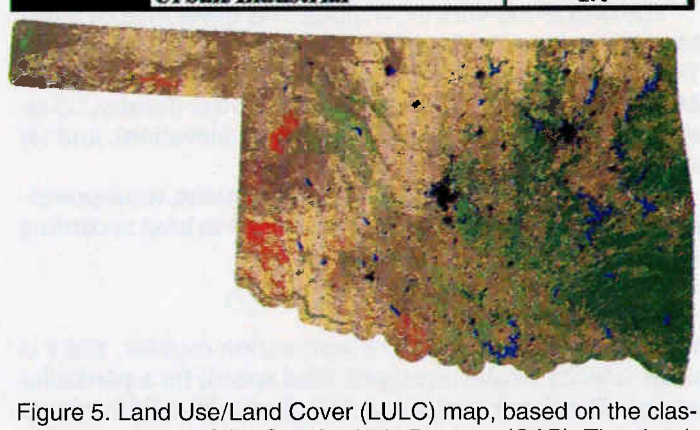

Figure 5. Land Use/Land Cover (LULC) map, based on the classification system of the Gap Analysis Program (GAP). The classification scheme consists of 47 categories, but for illustration purposes the categories are combined. Vegetative-roughness values are assigned to each category to provide input into models. It can be seen in this figure that the LULC grid was extended somewhat beyond Oklahoma's borders to allow for the models' use of data from outside the region being analyzed (notice Red River in southwestern part of image).

into 23 sections, the model utilizes surface data from outside each section. The influence of each Mesonet station is proportional to the reciprocal of the distance to each station squared ($1/r^2$).

Two key factors have a large effect on WindMap's predictions. One of these is the initial wind field. This field is created from observations, so the data must be accurate and representative of conditions throughout the region. Fortunately, Oklahoma Mesonet stations provide a dense statewide coverage.

A second key factor is the relative weights given to the vertical and horizontal adjustments to the wind field. These weights are based on the stability ratio, a parameter that provides a measure of the thermal stability of the atmosphere.

A lack of information about the stability ratio and how it varies across Oklahoma made the selection of a value difficult. Analyses from several model runs, using different stability values and advice from other users of WindMap, indicate that the best configuration is comparable to a wind-resource assessment of western and central Massachusetts (Potts and others, 2001). For this configuration, a stability length of 250 m was used instead of a stability ratio; however, a similar effect results by using a stability ratio of 0.25. Stability ratios <1 correspond to stable atmospheres (i.e., values near zero represent very stable atmospheres, whereas values close to 1 represent slightly stable conditions).

Empirical Modeling with Neural Networks

Neural networks represent a relatively new method for using computers to solve problems. Specifically, a neural network, or neural net, is a linked assembly of processors or processing elements whose interconnections are similar to those between neurons in a brain. By a process of adaptation, the computer is able to "learn" from a set of training patterns. Thus, neural networks are often viewed as a type of artificial intelligence.

Input Data

The neural-network (NN) model was developed by using Mesonet stations with good and excellent fetch conditions. The model incorporated the following information about the Mesonet stations: (1) calculated wind-power density, (2) elevation, (3) terrain exposure (or relative elevation), and (4) roughness length (vegetative influence).

Using 7 years of data from Mesonet stations, wind-power-density values were calculated for the 10-m level according to the equation below:

$$WPD = \frac{1}{2 \cdot n} \cdot \sum_{i=1}^{n} (\rho_i \cdot v_i^{\,3})$$

where ρ is air density, i is the summation counter, and v is wind velocity (scalar-averaged wind speed) for a particular station. The above equation was applied to all valid 5-minute data (n) for the time period. For each station, n was approximately 735,000. Air density was explicitly calculated, using air temperature and pressure data.

Elevation

Elevation data were obtained from Mesonet station metadata.

Terrain Exposure

Terrain exposure (also referred to as relative elevation) is defined as the distance a point sits above or below the average elevation of a surrounding area. For this model, terrain-exposure values were calculated relative to north and south "pie-wedge" areas. This method is based on the assumption that surface terrain and vegetative characteristics in the north and south directions have the greatest impact on the wind resource, on average.

To test this assumption, an average wind-energy rose diagram was developed with data collected from sites with excellent and good fetch ratings (Fig. 4). The figure displays the mean percentage of time and the mean percentage of energy of the wind in 16 compass directions over the 7-year period. It was determined that the wind direction was from the northwest to northeast (inclusive) and the southeast to southwest (inclusive) sectors 77% of the time, and more importantly that 89% of the wind energy was from these north and south sectors (gray-shaded areas in Fig. 4). Consequently, the development and use of the wedge method appear to be justified.

To determine the terrain-exposure inputs to the model, the average elevations were calculated by using the north and south pie wedges with 10-km radials. The north wedge subtends the northeast to northwest (Cartesian coordinates 34°–146°), and the south wedge subtends the southwest to southeast (Cartesian coordinates 214°–326°). Cartesian-coordinate degrees were used instead of compass degrees because of software requirements. ArcView Geographical Information Systems (GIS) software spatial-analysis tools, from ESRI, were used to calculate the average elevations in these pie wedges. North and south terrain-exposure values were then determined for each Mesonet station used in the model by subtracting the average elevation from the actual elevation at a site. A positive number represents a site that sits above an adjacent wedge area on average; a negative number represents a site that sits below an adjacent wedge area on average.

Modeling Process

The neural-network model was "trained" by using the first 50 of the 76 selected Mesonet stations, arranged alphabetically by station name. The remaining 26 stations were set aside as the validation group. In essence, the neural-net model related 10-m WPD values to elevation, terrain exposures (north and south), and roughness-length averages (north and south) for the 50 stations.

Figures 6, 7, and 8 show the relationship between the 10-m calculated WPD and three of the five primary inputs. From these graphs, an obvious trend exists between WPD and elevation as well as surface roughness. On the basis of these relationships, the model created several possible nonlinear formulas.

Each formula was then used to predict values of WPD for the remaining 26 Mesonet stations. The root-mean-square (RMS) error was computed between the model-output and calculated WPDs for the validation group. The formula that minimized the RMS error was selected as the final equation.

The resulting formula was then applied to the following grids: elevation (based on DEM data), terrain exposures

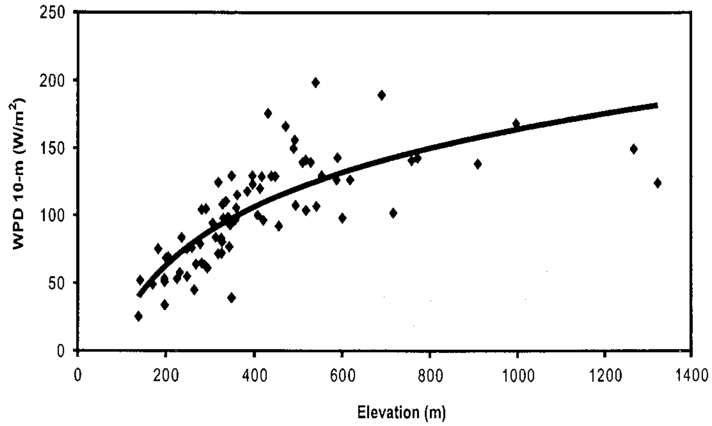

Figure 6. Correlation between elevation and calculated 10-m WPD at Mesonet stations with good to excellent fetch conditions.

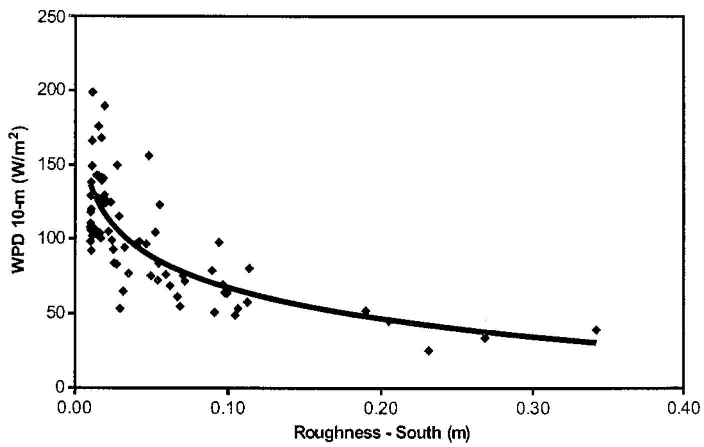

Figure 7. Correlation between average vegetative roughness to the south and calculated 10-m WPD at Mesonet stations with good to excellent wind exposure.

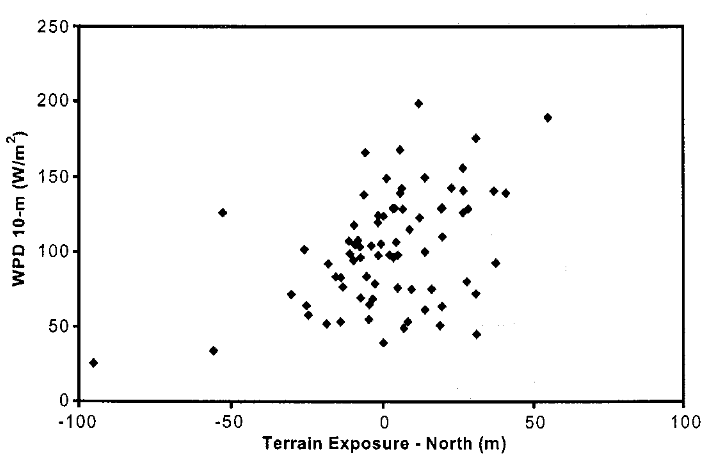

Figure 8. Correlation between north terrain exposure and calculated 10-m WPD at Mesonet stations with good to excellent fetch conditions.

(north and south), and roughness lengths (north and south). Values for corresponding cells from each of the grids were plugged into the formula. The resulting grid covered the entire State and provided an estimate of WPD at 10 m with a resolution of 60 m.

Extrapolating WPD from 10 to 50 Meters

The power-law method is a simple model used for extrapolating wind speeds from a height where wind speed is known to another height where it is an unknown, and is as follows:

$$U/U_r = (Z/Z_r)^m$$

where U_r represents the known wind speed at the reference height Z_r (10 m), and U represents the estimated wind speed at height Z (50 m). The exponent m is dependent on the values of surface roughness and stability. Typically, the exponent is chosen on the basis of long-term averages of measurements collected at two different heights. Such measurements were not available for use in these models, but an estimate can be made on the basis of terrain and vegetative types and general stability conditions in the area.

The power m was estimated to be one-sixth, which represents a compromise between that for relatively flat terrain with low roughness (one-seventh) and that for forested or hilly areas (one-fifth). Because WPD is proportional to the cube of the wind speed, the relationship between WPDs at the two heights can be reduced to the following:

$$WPD_{50m}/WPD_{10m} = (Z/Z_r)^{3m} = (50/10)^{(3/6)} = 5^{1/2} = 2.236$$

or

$$WPD_{50m} = 2.236 \cdot WPD_{10m}.$$

A correction factor was applied to the entire map in order to reduce underestimation. The 10-m WPD grid was multiplied by 1.23. The correction factor was based on a scalar discrepancy in the fit of model output versus calculated wind-power densities at 10 m (i.e., the slope of the trend is increased to equal 1; Fig. 9). The result was a map with significantly more class 3, 4, and 5 wind-power areas (see Fig. 10 for these areas).

Results

Figures 10 and 11 illustrate the results from the two models at 50 m. Note that both models agree relatively well regarding the large-scale variation of wind energy across the State. That is, the wind increases from east (classes 1 and 2) to west (classes 4 and 5) for both models. Aside from this similarity, the models appear very different from each other. For example, WindMap produced broad areas of winds with similar WPDs, whereas the neural-network (NN) model's output closely adheres to changes in topography and hence reflects more local variation in WPDs. Some of the detail can be attributed to the better resolution of the NN model (i.e., 60 vs. 372 m). However, experiments that incorporate higher resolution roughness and elevation data with WindMap did not account for most of the discrepancies between the models.

On the basis of 12 months of data collected from a 40-m tower in northwestern Oklahoma (near Buffalo), the wind resource for the tower's location was calculated to be 500 W/m² at the 40-m level. To determine if this value represents

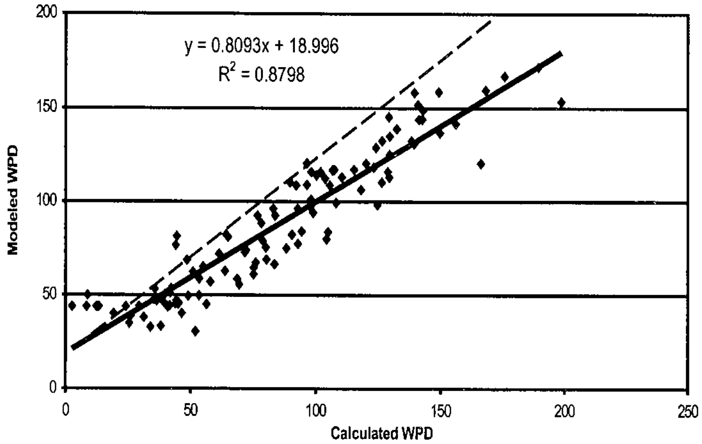

Figure 9. Model output versus calculated WPD at 10 m for 114 Mesonet stations. Dashed line represents adjusted linear trend after application of the correction factor of 1.23.

a long-term average value, it was benchmarked against a nearby Mesonet station and found to be quite close. That is, the WPD value was calculated for the benchmark station over the same data-collection period and was found to be within 0.5% of that station's average WPD, calculated by using 7 years of data. Hence, the value of 500 W/m² could be assumed representative of long-term values. Then, using the power law and average measured wind shear between 10 and 40 m, the 50-m WPD was estimated to be 550 W/m². According to the adjusted NN model's output (with correction factor applied), the 50-m WPD for the grid cell containing the tower was 477 W/m², whereas the WindMap model estimated a 50-m WPD of 456 W/m².

WPD estimates from both models appear to be quite conservative, especially for ridges and hills. Although one validation point is not enough to justify a conclusion, informal discussions with wind-farm developers seem to substantiate that OWPI's models may underestimate true WPD by >10%.

There may be at least two reasons for the models' low results. One is that when Mesonet stations were sited, there was a conscious effort to avoid placement on the tops of hills or ridges, and yet river valleys or other areas with poor terrain exposure (low relative elevation) were considered perfectly acceptable. This distribution may lead to a bias on the low side because no high-end WPDs would be associated with the very tops of hills and ridges, but many low-end WPDs would be associated with low relative-elevation sites.

The second possible reason for the models' underestimations is that a value of one-sixth (or 0.1667) was used for the exponent *m* in the power-law equation (1) to approximate WPDs at 50 m on the basis of estimates at 10 m.

Preliminary results from data taken at the Buffalo tower and from instruments on another tower near Hobart indicate that a value of 0.18 to 0.20 may be more appropriate for a long-term average. Using 0.18 for *m*, for example, would increase the estimates for WPDs at 50 m by about 7%.

To determine the accuracy of the models' WPD estimates and to improve the output, more wind data are needed from heights of ~50 m. Recently, OWPI installed instruments on an existing tall tower to a height of 100 m. Future plans are to instrument more tall towers. These towers are likely to be in areas with the greatest potential for development of wind energy, but attempts will be made to use towers throughout the State to provide optimal validation. Further adjustments in the power-law exponent and further comparison against 5 to 10 tall-tower measurements of WPD will aid significantly in improving the models.

It should be noted that, as stated in the caption for Figure 9, calculated and modeled WPDs were used for all 114 Mesonet stations in determining the correction factor for the NN model adjustment. This procedure has since been determined to be in error. Since only sites with good and excellent fetch ratings were used in developing the model, a better practice would be to recalculate the correction factor by using only the same 76 stations. Preliminary results indicate that this method will lower the correction factor somewhat, but not significantly.

ECONOMIC ANALYSIS USING OWPI'S PRODUCTS

After obtaining a reasonable model of Oklahoma's wind resource, GIS tools were used to approximate potential economic development from this energy source.

Oklahoma has several prime areas for potential wind-energy development. Starting with the neural-network-model resource map, six regions were identified (Fig. 12), and GIS tools were used to evaluate the land area in those regions. Table 1 lists the six prime areas and gives an approximation for wind-power development potential in each, as well as the total for all six areas.

The following are important assumptions for this development model: (1) transmission capacity is not a limiting factor; (2) 30% of the area with a class 4 or better (good to excellent) wind resource is developed; (3) 9 MW of rated wind-generator capacity will be installed per square mile of developed area, on average; (4) capital investments are based on $0.8 million per MW installed nameplate capacity (Wayne Walker, Zilkha Renewable Energy, LLC, Houston, Texas, personal communication, 2001); (5) gross annual revenues (GAR) are estimated, using benchmark figures from wind farms in existence and scaled by MW nameplate capacity; (6) GARs are based on a $30 per MW-hour wholesale rate, assuming a 33%-capacity factor and a 95% turbine average availability; and (7) estimated annual lease payments are calculated by assuming 3% of GAR.

Under these assumptions, OWPI's resource map gives an estimate of total developable wind power of 13,790-MW nameplate capacity, corresponding to a capital investment of >$11 billion, >$1.1 billion in GAR, and >$34 million per year in landowner payments.

Assuming a 33%-capacity factor and a 95% availability, a 13,790-MW nameplate capacity corresponds to almost 4,400 MW of average production, which would provide >38.5 billion kilowatt-hours every year. This amount of electricity corresponds to roughly two-thirds of Oklahoma's entire electricity generation in 2000 (see www.eia.doe.gov/cneaf/electricity/epavl/ta7p2.html). Clearly, this demonstrates a potential for Oklahoma's winds to deliver a tremendous amount of power for sale here and out of State, but only under special conditions. For one thing, the estimate assumes no transmission constraints, and this is far from the case for Oklahoma. Without improvements to transmission facilities, Oklahoma will see less than 1,000-MW nameplate wind-generation capacity installed. Still, this model provides a useful figure to help estimate the potential development if means for transmission of electricity, or hydrogen fuel, are significantly upgraded.

WIND-RESOURCE-ASSESSMENT TIES TO GEOLOGY

One may very well ask how geology comes into play when determining the best areas for wind resource. Clearly, wind prospecting does not entail a knowledge of subsurface geology the way oil and gas exploration does. In a sense, wind prospecting is much more straightforward than mineral

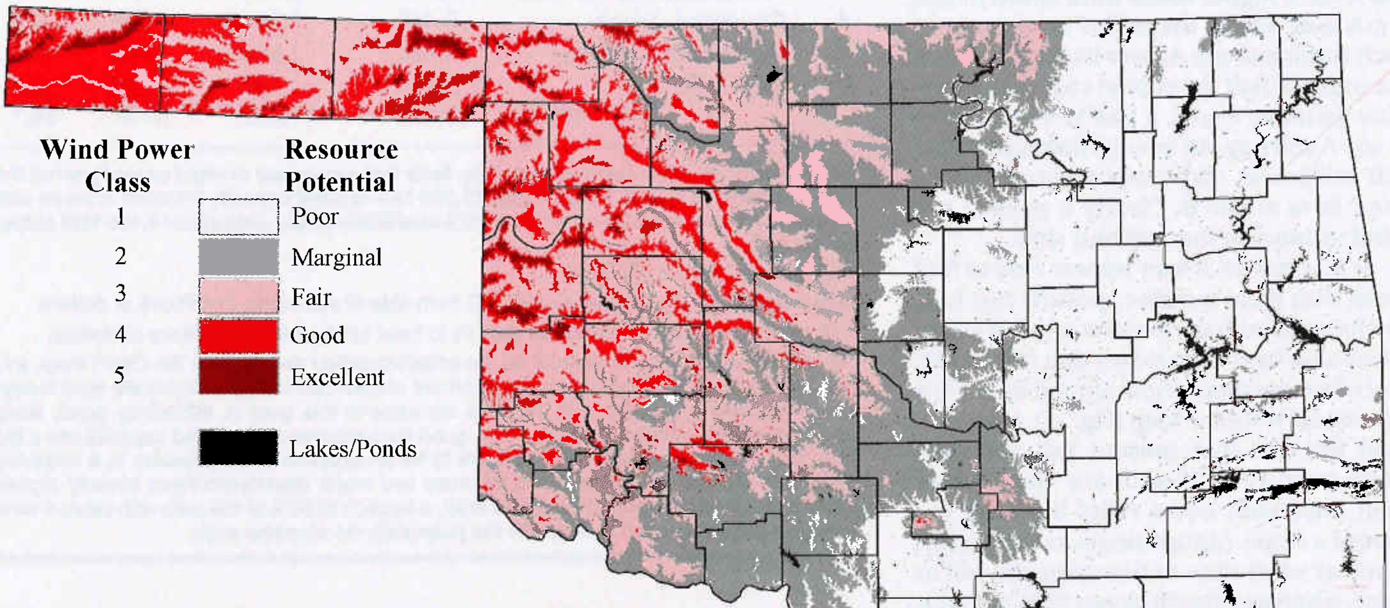

Figure 10. Map showing current estimate of long-term average WPD at 50 m above ground level, based on neural-network model (with slope correction factor of 1.23 and altitude-adjustment factor of 2.236 applied to 10-m results).

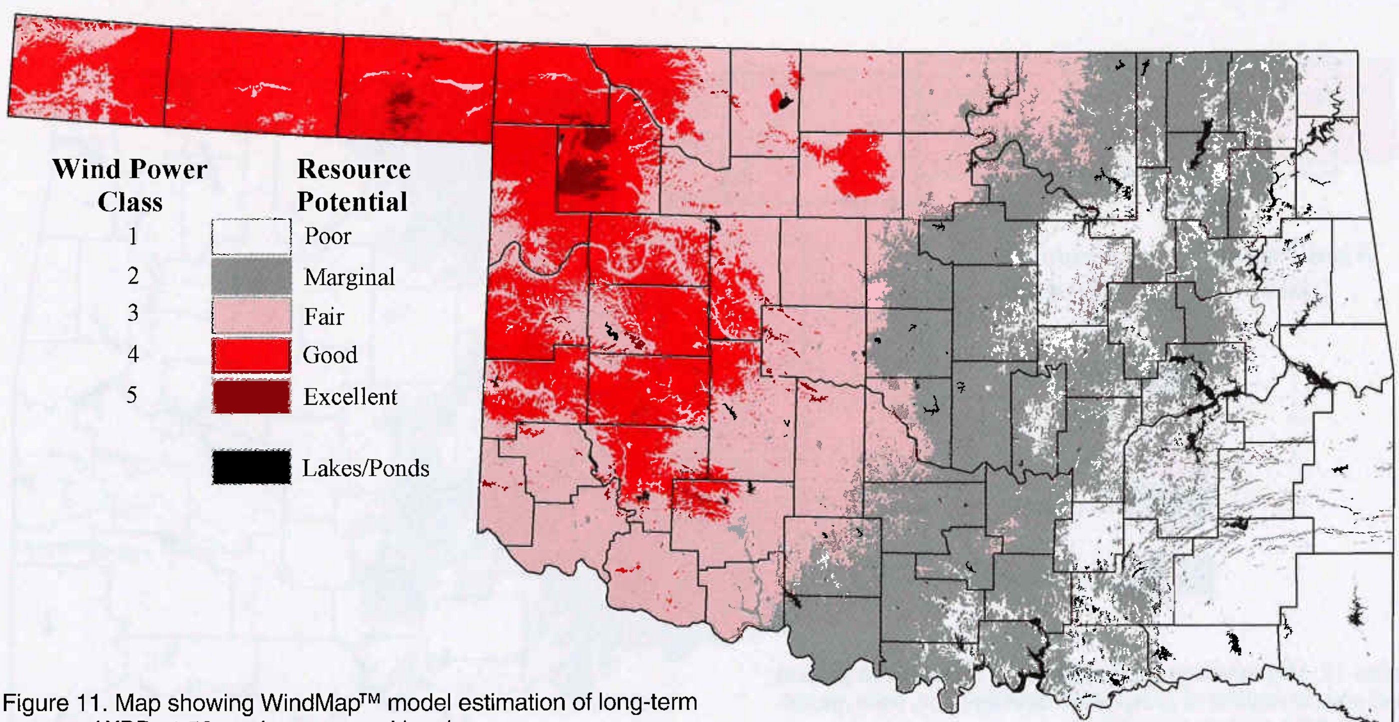

Figure 11. Map showing WindMap™ model estimation of long-term average WPD at 50 m above ground level.

prospecting. However, a knowledge of rock units that help to define topography can still be valuable.

Because of the strong dependence of wind energy on wind speed (recall that WPD is proportional to the sum of the *cube* of wind speed), even a small increase in wind speed means a significant increase in the energy produced. To give an example, if site A has a higher mean wind speed of just 1 m/s over site B, the *added* revenue from each turbine at site A, over its lifetime, is on the order of half the capital cost of that turbine. In other words, a 100-MW wind farm at site A will pay out over its lifetime at least $50 million in additional revenue over a wind farm at site B. Clearly it pays to put wind turbines at the very best sites.

At first glance, it may appear easy to find areas with great terrain exposure: just look for the areas with the greatest relief. Western Oklahoma has many ridges that fill the bill, and of course these show up well in OWPI's NN-model resource map (Fig. 12). However, land features that present just the right slope to prevailing winds are much better than ones with equal relief but with too abrupt a slope. Abrupt slopes create turbulence as wind rises to flow over the hill or ridge, whereas smooth slopes help to maintain laminar (i.e., nonturbulent) flow of the airstream. One can imagine the difference between wind flowing over an aircraft wing (maximizing laminar flow and minimizing turbulent flow) in comparison to winds encountering an object with a similar height but which is situated at a right angle to the wind flow, forming a "wall" of sorts. The latter object will create turbulent eddies, which decrease the energy captured from the wind. Furthermore, turbulent conditions create more wear and tear on turbines, increasing

TABLE 1. — SIX PRIME AREAS FOR WIND DEVELOPMENT IN OKLAHOMA (FIG. 12)

Key	Region	MW capacity[a]	Capital investment[b]	GAR[c]	EALP[d]
1	Texas/Cimarron Cos.	4,910	3,928	405	12.1
2	Beaver Co.	1,890	1,512	156	4.7
3	Woodward–Buffalo–Alva	2,320	1,856	191	5.7
4	Cheyenne–Arnett	2,460	1,968	203	6.1
5	Weatherford–Hobart	1,970	1,576	162	4.9
6	Slick Hills[e]	240	192	20	0.6
	Totals:	13,790	11,032	1,137	34.1

[a]Estimates for installed megawatt capacity. Note that nameplate or rated capacity is not the same as average output. For example, 13,790 MW of rated capacity installed in areas with an average capacity factor of 33% and 95% availability would yield about 4,400 MW output on average.

[b]Estimates in millions of dollars.

[c]Estimated gross annual revenues (GAR) from sale of electricity, in millions of dollars.

[d]Estimated annual lease payments (EALP) to local landowners, in millions of dollars.

[e]Although the Slick Hills area is by far the smallest region depicted on the OWPI map, this area is likely a lead candidate for development of 200–500 MW of utility-scale wind farms. Unofficial reports indicate that the wind resource in this area is especially good, likely owing to special terrain influences. Also, good transmission access and capacity are a big plus for the area. Because there appears to be an excellent wind resource in a relatively small and unpopulated region, and because two major developers have already signed lease rights for a significant part of this area, a fraction or 50% of the area with class 4 wind power or greater is used to estimate the potentially developable area.

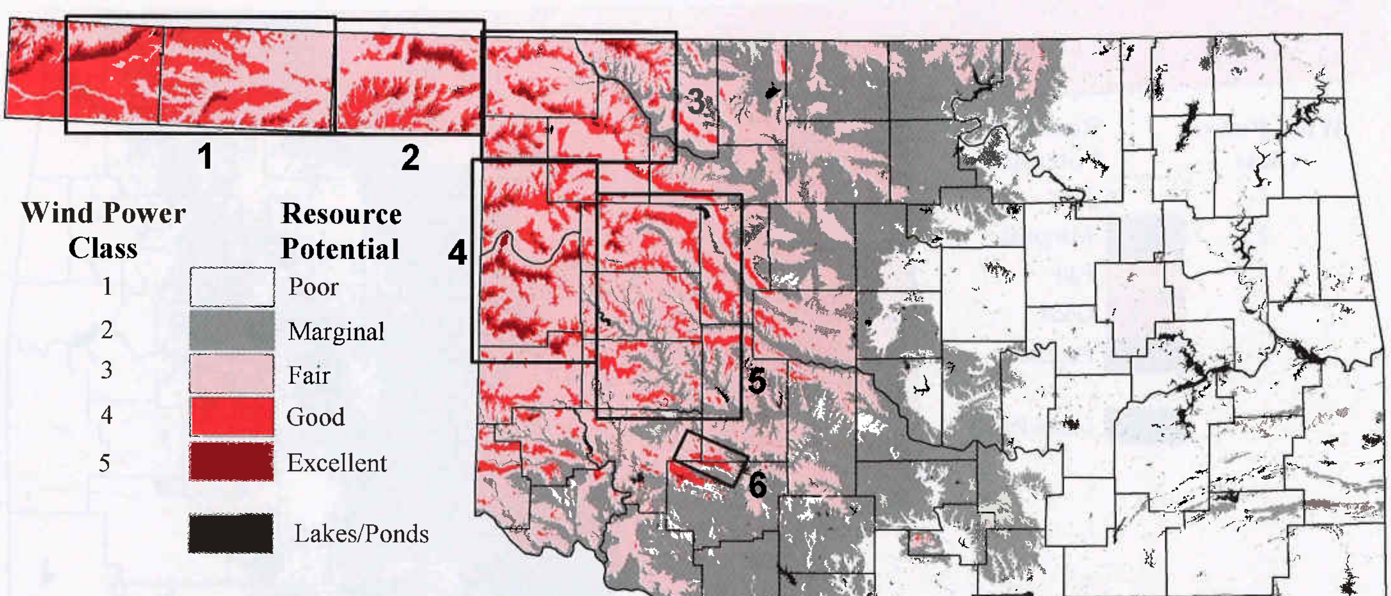

Figure 12. Map showing wind resource at 50 m above ground level and six regions of prospective development, from neural-network (NN) computer model.

maintenance costs. Figure 13 illustrates the airflow over two kinds of terrain features with similar relief but with sharp versus smooth slopes.

Clearly, the use of GIS software to analyze terrain features is one way to search for areas with optimal profiles. A knowledge of geologic features that correlate with these desirable terrain features can be valuable as well.

INDICATORS FOR WIND'S FUTURE ROLE IN ENERGY DIVERSIFICATION

It is expected that the future development of Oklahoma's wind resource will unfold in a variety of ways, depending on what happens in the Federal and State capitals. If Federal energy policy creates a national renewables portfolio standard (RPS), mandating that utilities provide a predetermined percentage (e.g., 10%, the rate in the U.S. Senate's version of the current National Energy Bill) of electricity from renewable sources, wind power will become immensely attractive to developers. Should the Oklahoma Legislature promulgate a State-based RPS, such as the one now in place in Texas, the competition to develop the most attractive local sites will likewise quicken. Other issues that are likely to influence the development of Oklahoma wind resources include (1) transition to a competitive market in electric power, (2) growth in distributed energy resources, (3) growth in demand for hydrogen fuel to power fuel cells, (4) development of an emissions trading scheme to reduce carbon dioxide emissions from fossil-energy combustion, and (5) economic-development benefits that will accompany the growth of a new industry in the State.

Transition to a Competitive (Deregulated) Market

While the transition to a more competitive market in electric power has been put on hold by many States in the wake of California's recent energy crisis, Congress has been deliberating the prospects for facilitating the development of a more competitive market in power supply. Since policy makers recognize that the national electric grid was never envisioned to transfer power from a large number of generators to an equally large numbers of consumers, widespread development of wind power may have to wait until the grid is improved.

Advocates of wind-energy development are now actively pushing for grid-improvement plans that pay attention to utilizing the tremendous wind resource available in the Great Plains and moving its energy to large markets across the country. With fair access to an improved nationwide grid, and hence to distant areas with large appetites for energy, wind's environmental and competitive advantage (including its value as a hedge against fuel-cost spikes) will spur development immensely.

Distributed Energy

Continued reductions in the cost of wind power have made it economically attractive to developers who may wish to enter a distributed market for energy supply. Distributed generation offers opportunities for small wind farms to serve local users directly, and small wind farms offer opportunities for local ownership, thereby increasing economic returns to in-State concerns. Furthermore, while feeding into electrical distribution systems offers technical challenges, one large advantage is that wind-farm development will not be restricted to proximity to transmission lines with capacity. This offers more opportunity for economic development in remote rural communities.

Small, locally owned, utility-scale wind farms (with 1–10-MW capacity) have been in place in Europe for some time. Minnesota offers a recent model for such development that is working in the United States (Miller, 2002); owners of large wind turbines there expect to earn 10 to 15 times the income they would realize as landowners selling wind rights, or up to $30,000 per year per turbine. After loans are retired, the annual income from each turbine jumps to $80,000.

Production of Hydrogen for Fuel Cells

In addition to producing electricity, developers in windy regions in the Great Plains may also find it attractive to store energy in the form of hydrogen, made by splitting water into

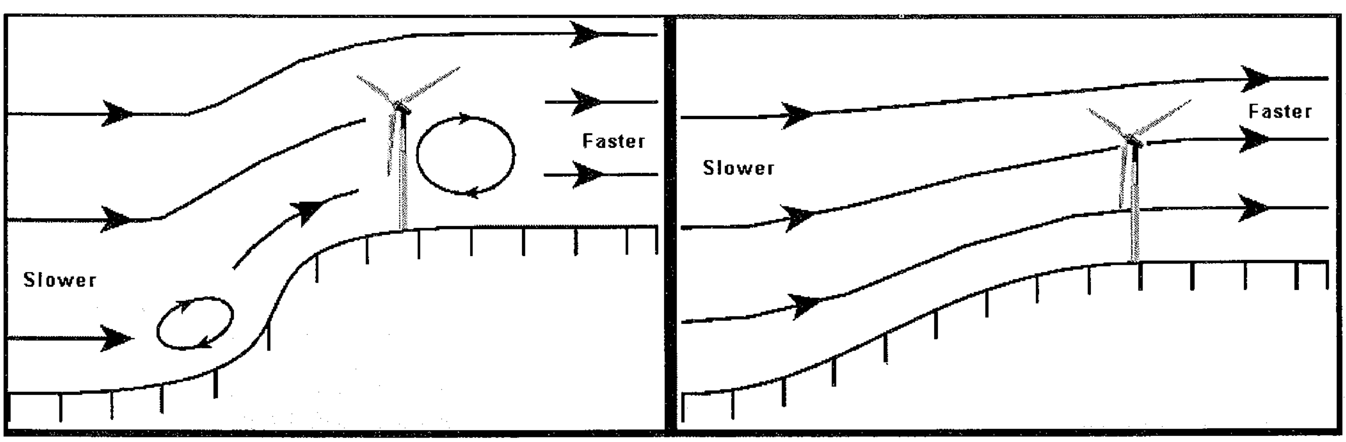

Figure 13. Diagram showing airflow over two terrain characteristics. The sharp escarpment on the left causes turbulent eddies to form, reducing wind energy captured by the turbine and putting stress on its rotor and blades. The smooth uphill slope on the right causes acceleration of the winds, as indicated by the streamlines coming closer together; but the flow remains laminar, so no energy is lost to turbulence.

its component elements. With the emergence of hydrogen-powered fuel cells for mobile as well as stationary power use, parts of the Great Plains could emerge as important sources of fuel for automobiles and for fuel cells sized to provide power to houses. For Oklahoma, the rapid emergence of fuel-cell usage over the coming decade would lead the next boom in a storied history of energy supply.

Carbon Dioxide–Emissions Trading

Growing concern about global climate change has led a number of companies to search for ways to reduce their emissions of carbon dioxide. While many strategies exist for sequestering carbon dioxide, such as pumping it underground for storage in partly empty oil and gas reservoirs, the lack of gaseous emissions associated with wind power makes it especially attractive to industries that are looking for cost-effective ways to purchase carbon credits. The emergence of a national market in carbon credits, similar to the international market that was created by the Kyoto Protocol, will enhance the domestic appeal of wind-power development.

Economic Development

Wind-power development has direct local economic benefits that can be captured by landowners and communities where land is leased by developers. For landowners, annual royalty payments in the range of $2,000 to $5,000 per turbine can be realized. Communities may see increased revenue from property taxes—revenues that would benefit their schools, roads, and other infrastructure needs. Because wind-power systems are the most competitive of the renewable-energy technologies, wind-rich regions also have the potential to become key sites in the design and development of the next generation of these systems. In Oklahoma, the success of Bergey Windpower Company in Norman, a manufacturer of small wind turbines sold throughout the world, is a good example of the economic-development opportunities that can accrue to proactive planning and management.

An important State policy incentive is now in place to boost production and sales of small turbines. If an effective policy incentive is also put into place in Oklahoma to promote wind-farm development, Oklahoma's rural landowners and communities will reap immediate economic gains. Furthermore, the demand for wind turbines in this area will make Oklahoma more attractive to the wind-turbine industry when it comes to locating facilities for the manufacture and maintenance of turbines and turbine parts.

SUMMARY AND CONCLUSIONS

Two models were developed by OWPI to investigate Oklahoma's wind resource. Owing to a lack of observations near 50 m above ground level, the industry-standard observing height for large turbines, the wind resource at this height is difficult to characterize exactly when using 10-m data. However, OWPI's models give good indications of the *relative* wind resource—that is, where the best areas appear to be for near-term development. These models also provide reasonable inputs for estimating potential economic development, showing that billions in capital investment is well within reach over time.

Although extensive validation work remains to be done, preliminary results indicate that both of OWPI's models underestimate the true wind resource. The preferred model for now, the neural-network model, does a better job of correlating changes in wind power to topography. Results clearly show that significant parts of western Oklahoma and the Panhandle have wind resources that make the development of large utility-scale wind farms economically feasible. These wind farms could potentially bring billions of dollars to Oklahoma in economic development.

In view of finite fossil-fuel reserves, an expected increase in demand for hydrogen fuel, and expected advances in wind, solar, and bioenergy technologies, renewable energy appears as a viable and sustainable path for energy diversification. Wind energy is the fastest growing source of electricity in the world right now because it addresses environmental concerns while doing so at a competitive cost. With continued improvements in wind-turbine technology, economies of scale, transmission grids, and techniques for long-term energy storage (e.g., hydrogen generation and large fuel cells), wind power grows more attractive daily as an energy resource.

ACKNOWLEDGMENTS

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Oklahoma Natural Gas: Past, Present, and Future

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This is the second of three articles examining the oil and gas industry in Oklahoma. The first, "Oklahoma Oil: Past, Present, and Future," was published in the Fall 2002 issue of *Oklahoma Geology Notes*; it reviewed the history and projected future of oil in the State. This article does the same for natural gas. The final article, "Oklahoma Oil and Gas: Our Place in the Big Picture," will build on the first two and focus on Oklahoma's part in the bigger national and international energy landscape. These non-technical papers review the evolution and status of Oklahoma's oil and gas industry and attempt to predict its long-term future.

INTRODUCTION

Oil put Oklahoma on the map. This is true both figuratively and literally, as in 1907 oil was the driving force behind turning the Oklahoma Territory into the State of Oklahoma. Industry's early success in finding abundant oil, and later natural gas, has made these our primary sources of energy. Relatively inexpensive energy is one of the largest factors responsible for the unprecedented levels of prosperity now enjoyed by the United States and the rest of the developed world. Although both U.S. and Oklahoma oil and gas production are past their peak, we continue to be a key producing state, ranking fifth nationally in oil and third in natural gas.

Natural gas is especially important to Oklahoma because it alone maintains a positive State energy budget that would otherwise be strongly negative. In spite of our national ranking, oil consumption in Oklahoma is about 50% higher than production, and local coal production accounts for less than 10% of State consumption. For oil, the possibility of discoveries that could significantly impact State production is very low, making enhanced recovery in existing fields the only way to meaningfully affect production declines (Boyd, 2002a). Coal in Oklahoma is another resource that has largely been defined, but in order to meet strict sulfur-emission requirements, the vast bulk of coal burned in the State now comes from Wyoming. In marked contrast, gas production is still three times the State's consumption, and Oklahoma continues to be an area where gas exploration and development can bring large rewards.

Oil and gas are formed by alteration of microscopic organisms that are deposited with the sediment that composes sedimentary rocks. The sediment and organic remains reach maximum thickness where they accumulate in large, gradually subsiding depressions called geologic basins (Fig. 1). With increasing temperature and pressure that result from

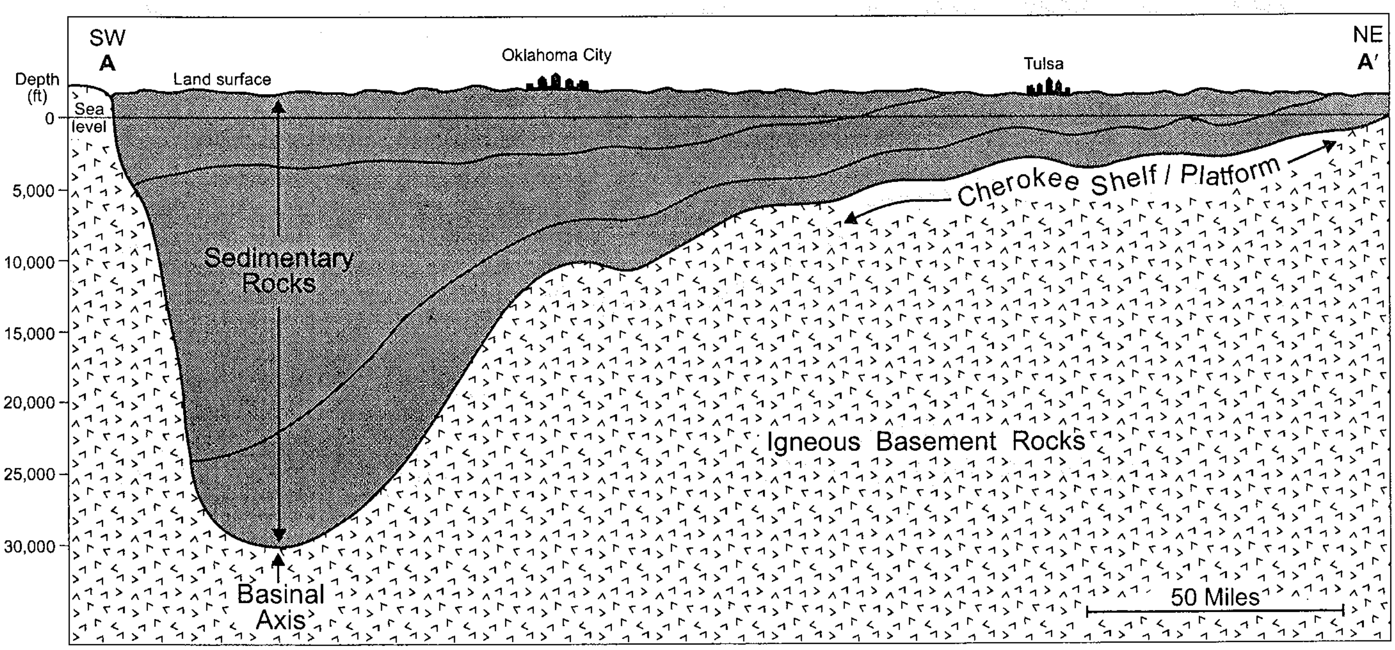

Figure 1. Cross section of the Anadarko geologic basin. Modified from Witt and others (1971). Vertical exaggeration 14:1. Figure 4 is the base map.

increased burial depth, organic remains slowly change into oil and natural gas. Those compounds consist dominantly of hydrogen and carbon, and hence are called hydrocarbons. As oil and gas are less dense than the water in which the sediment was deposited, where permeable rock permits they migrate upward. The upward movement ends where impermeable rock blocks the migration path, creating a seal that may form a hydrocarbon trap. A key factor in the size of the petroleum accumulation thus formed is the extent and sealing ability of the impermeable rock.

Gas is almost always associated with oil, as it represents the lighter chemical fraction (shorter molecular chain) formed when organic remains are converted into hydrocarbons. Therefore, in addition to being found underground as discrete gas reservoirs, much natural gas is also found dissolved in subsurface oil. As this oil is brought from reservoir conditions to the surface, and its pressure is reduced to the atmospheric level, dissolved gas comes out of solution much like carbonation from a soft drink when the cap is lifted.

Natural gas that comes from produced oil is classified as associated gas. When subsurface oil has been saturated with gas, any additional gas that migrates into the trap must exist as free gas; being less dense than oil, it occupies the top of the hydrocarbon trap and forms what is called a gas cap (Fig. 2). This gas, or any gas not directly associated with oil, is called non-associated gas.

The chemistry of certain types of organic matter (for example, those high in plant material) can make hydrocarbon source rock more likely to generate gas. A source rock is rock containing enough organic remains to generate an appreciable quantity of hydrocarbons—given adequate heat, pressure, and time. An example of a gas-prone source rock is coal, which in Oklahoma is important in mining and also in the rapidly expanding coalbed-methane industry.

Regardless of the type of source rock involved or the relative volumes of oil and gas that are initially generated, temperatures and pressures invariably rise with increasing burial depth. As the thermal energy in a subsurface system increases, the longer-chained hydrocarbons present in oil begin to break into progressively smaller pieces. Eventually a critical depth is reached below which liquid hydrocarbons are no longer stable. Although oil cannot exist anywhere below this critical depth, natural gas can still be present in large quantities. This is important for Oklahoma because many of the State's source rocks and reservoirs are, or were in the geologic past, located below the depth at which oil is stable. The combination of deep sedimentary basins and a source rock chemistry that is dominantly gas-prone has made large parts of Oklahoma almost exclusively gas producing (Fig. 3).

Oklahoma's prominent place in the oil and gas industry is a fortuitous result of its encompassing the bulk of the hydrocarbon-rich Anadarko, Arkoma, and Ardmore geologic basins and their associated platforms (also called shelves). A platform, unlike a basin, is a stable, relatively flat-lying area with a thinner blanket of sediment. Figure 4 shows the State's major basins and adjacent areas; it also shows the 11

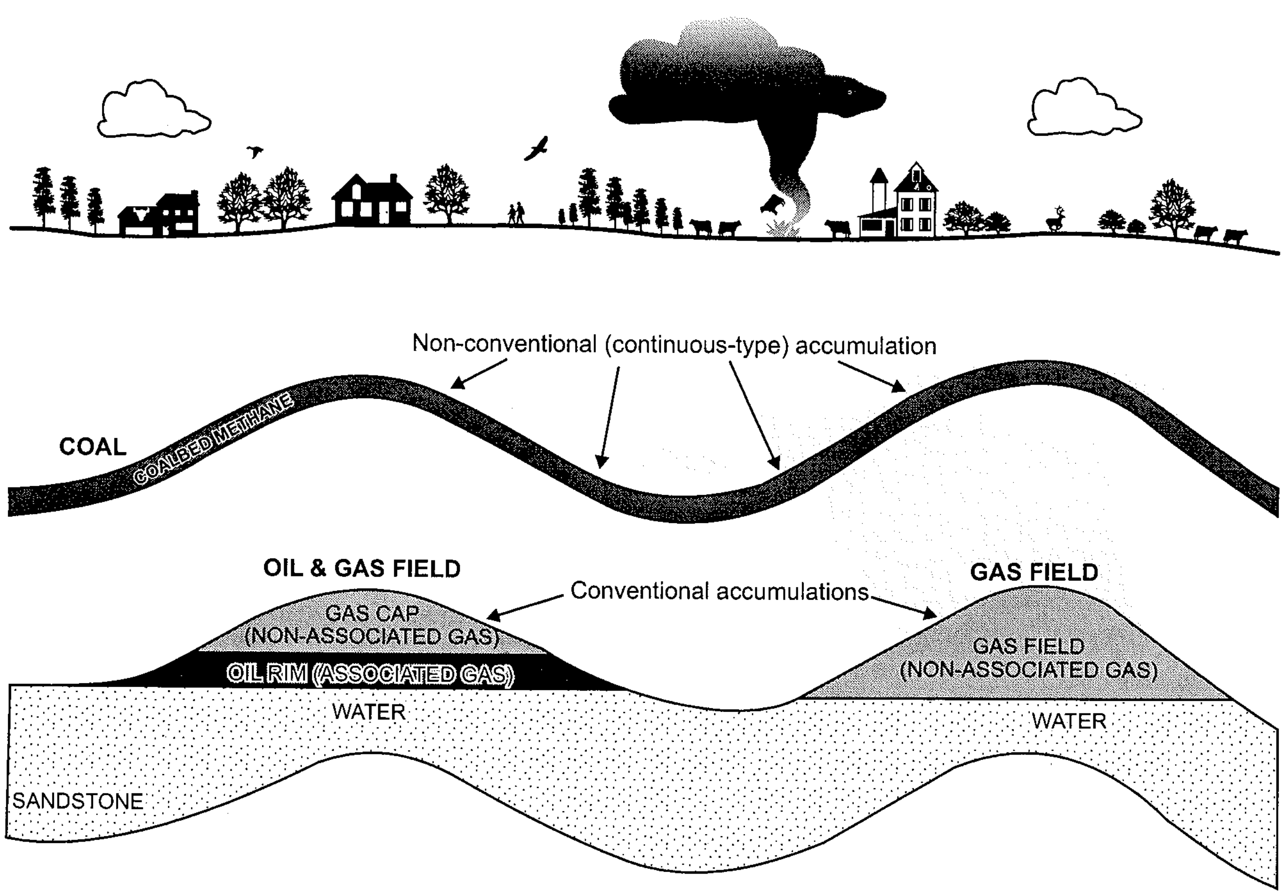

Figure 2. Some types of subsurface natural gas accumulation.

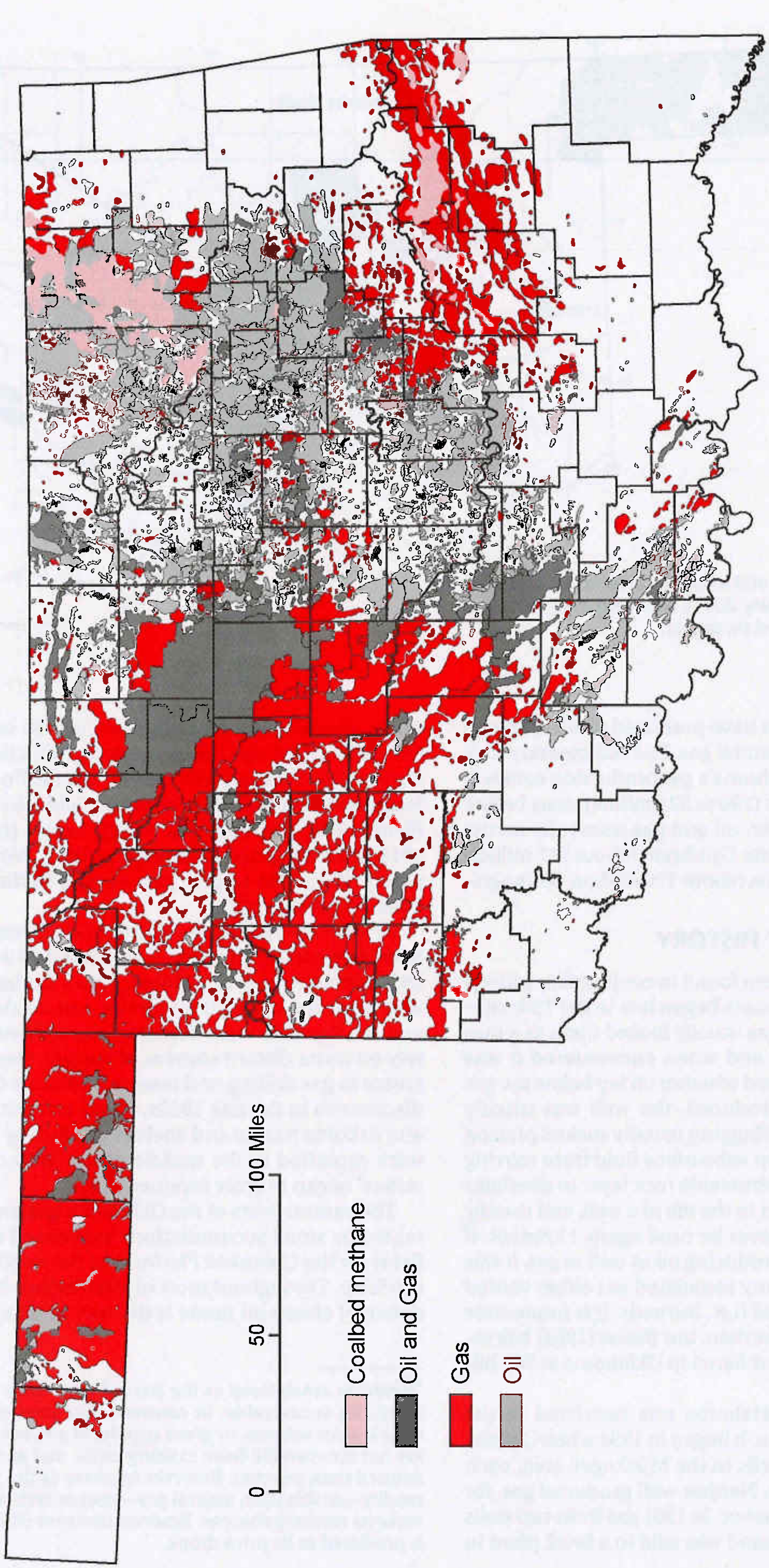

Figure 3. Oklahoma oil and gas fields distinguished by gas-oil ratio (G.O.R.) and conventional gas vs. coalbed methane. Modified from Boyd (2002b).

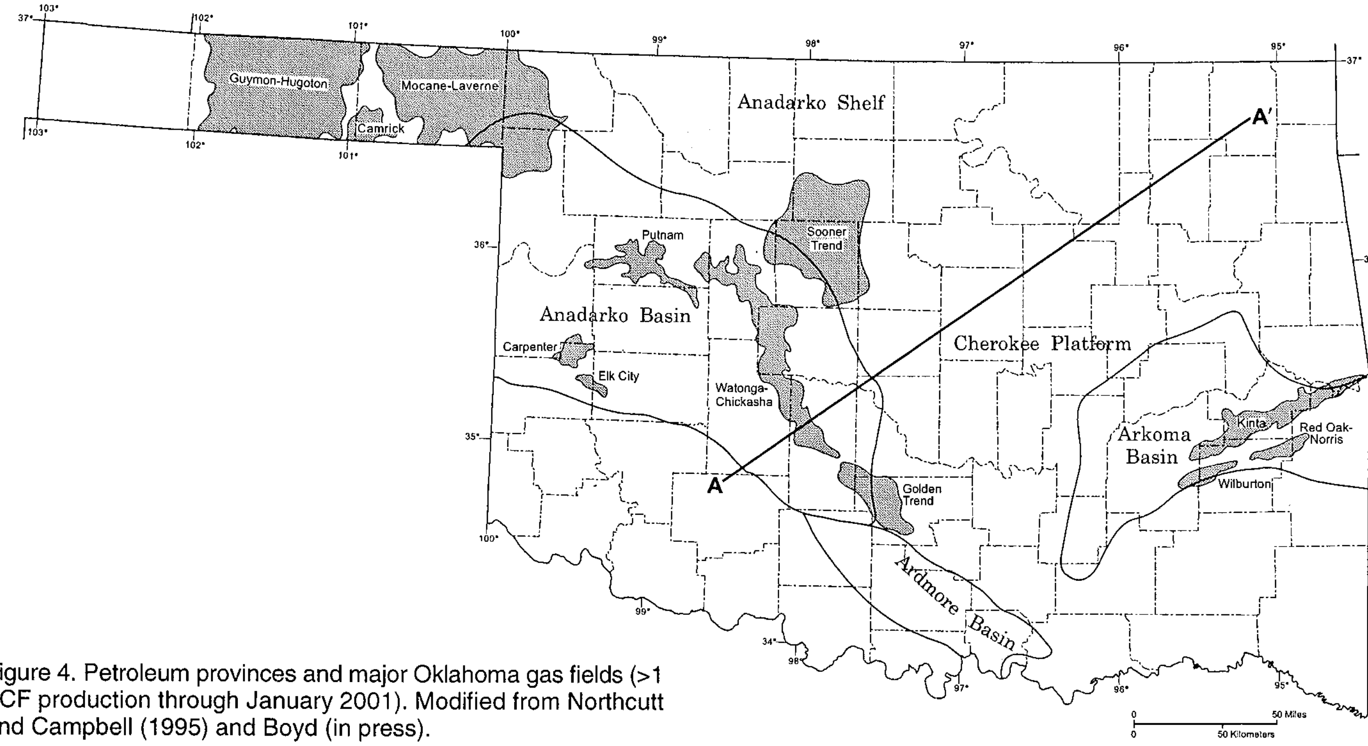

Figure 4. Petroleum provinces and major Oklahoma gas fields (>1 TCF production through January 2001). Modified from Northcutt and Campbell (1995) and Boyd (in press).

major gas fields—those that have produced more than one trillion cubic feet (TCF) of natural gas. The sedimentary rock from which the bulk of Oklahoma's gas production comes is largely Pennsylvanian in age (290 to 323 million years before the present; Fig. 5). However, oil and gas reservoirs across the State range in age from late Cambrian (about 517 million years ago) to early Cretaceous (about 100 million years ago).

EARLY HISTORY

Natural gas has always been found in conjunction with oil exploration, which in Oklahoma began late in the 19th century. In the early days, gas was usually looked upon as a nuisance or a drilling hazard, and when encountered it was vented until it was determined whether oil lay below the gas (Fig. 2). If only gas was produced, the well was usually plugged and abandoned. (Plugging usually means placing cement in a borehole to keep subsurface fluid from moving to the surface or from one permeable rock layer to another.) Abandonment is the final act in the life of a well, and usually ensures that the well can never be used again. However, if the well eventually started producing oil as well as gas, it was treated as an oil well, with any associated gas either vented into the atmosphere or flared (i.e., burned). It is impossible to say how much gas was lost then, but Beebe (1962) has estimated the volume vented or flared in Oklahoma at 500 billion cubic feet (BCF).

Initial gas activity in Oklahoma was restricted to the northeastern part of the State. It began in 1894 when Cudahy Oil Company drilled two wells in the Muskogee area, each with commercial gas shows. Neither well produced gas, for no local market existed. However, in 1901 gas from two wells completed in the Red Fork sand was sold to a brick plant in Tulsa, marking the first commercial use of natural gas in Oklahoma. After this milestone, gas production was added in Bartlesville-Dewey Field (1904), Glenn Pool Field (1905), Hogshooter Field (1906), Boynton Field (1910), and Cushing Field (1912). Depew Field, which began producing gas in 1912, was converted to storage in 1951. With 63 BCF of capacity, it was the largest gas-storage facility in the United States (Koontz, 1962).

In 1906 the Oklahoma Natural Gas Company, today the State's dominant supplier, was formed to deliver gas to the Oklahoma City market (Moore, 1962). At the time, gas fields were near the towns they served, but, as demand climbed and nearby wells were depleted, the industry was forced to rely on more distant sources of supply. Despite a rapid increase in gas drilling and reserve additions due to a spate of discoveries in the late 1920s, it was not until the Anadarko and Arkoma basins and shelves (including the Panhandle) were exploited in the middle of the 20th century that reserves* began to grow exponentially.

The earliest years of the Oklahoma gas industry were sustained by small accumulations associated with shallow oil fields on the Cherokee Platform in the northeastern part of the State. Throughout most of Oklahoma's history an abundance of cheap oil made it the fuel of choice, keeping the

*Reserves are defined as the part of a resource base that is economically recoverable. In contrast, resources are defined as the total known volume, or gross supply, of a commodity. Resources are not recoverable from existing wells, and as such are less well defined than reserves. Reserves increase as the price of the commodity—in this case, natural gas—rises or technological advances make its recovery cheaper. Reserves decrease when the commodity is produced or its price drops.

DIVISIONS OF GEOLOGIC TIME				Age (approx.) in millions of years
Eon	Era	Period	Epoch	
Phanerozoic	Cenozoic	Quaternary	Holocene	0.010
			Pleistocene	1.6
		Tertiary	Pliocene	5
			Miocene	23
			Oligocene	35
			Eocene	57
			Paleocene	65
	Mesozoic	Cretaceous	Late	97
			Early	146
		Jurassic	Late	157
			Middle	178
			Early	208
		Triassic	Late	235
			Middle	241
			Early	245
	Paleozoic	Permian	Late	256
			Early	290
		Carboniferous: Pennsylvanian	Late	303
			Middle	311
			Early	323
		Carboniferous: Mississippian	Late	345
			Early	363
		Devonian	Late	377
			Middle	386
			Early	409
		Silurian	Late	424
			Early	439
		Ordovician	Late	464
			Middle	476
			Early	510
		Cambrian	Late	517
			Middle	536
			Early	570

Figure 5. Geologic time scale. From Harland and others (1990) and Hansen (1991).

demand for natural gas low, and thus its price and drilling activity. Another factor was the regulation of natural gas by the federal government through 1978, which kept prices low relative to oil. Also underlying low demand in the early days was a lack of pipelines. Although crude oil can be transported anywhere there are roads, gas requires a gathering system that usually entails huge up-front costs. In a classic Catch-22 scenario, the economic justification for a pipeline requires that a threshold of production rate and reserves be met, and that, in turn, means money must be spent in drilling wells. However, even if the wells justify the expenditure, they must remain shut-in (generating no cash flow) for a prolonged period during construction of the gathering system. Once this hurdle is overcome and pipelines are in place, drilling and production commonly increase exponentially. Drilling success then spurs expansion of the system, which in turn opens more-distant areas to exploration and development.

Despite early difficulties, all major gas fields in the greater Anadarko and Arkoma Basins were discovered before natural gas deregulation (Figs. 4, 6). Some of the fields were discovered quite early, but they were not close to main population centers. As a result they were usually not fully developed (or their size appreciated) until much later, when gas became a primary drilling objective rather than an unintended consequence of oil exploration.

RECENT HISTORY

Although commercial gas production in Oklahoma began in 1901, annual production did not begin growing until the 1940s (Claxton, 2001). Growth continued through the early 1960s, with production rates more than doubling between 1960 and 1970 (Fig. 7). As measured by the standard average energy equivalence of 6 thousand cubic feet (MCF) per barrel (42 U.S. gallons) of oil, Oklahoma's primary production shifted in 1963 from oil to gas. The change occurred despite the fact that oil production in 1963 was still well over 500,000 barrels per day. In the year 2000, Oklahoma's cumulative production of gas (measured in sales) exceeded cumulative oil for the first time. Although these are important milestones, the critical point is that natural gas has been Oklahoma's primary energy resource for almost 40 years. In addition, because oil production has declined to one third of the level in 1963, and is still falling, the importance of gas in the State's energy mix continues to increase.

As is true of any commodity, the effort expended in the search for natural gas has increased as its value increased. The wellhead price (the price received by the operator) remained low and changed little during the first 73 years of commercial production in the State (Fig. 8). Then in 1974, for the first time, the price of natural gas began rising more than a penny per year. The change resulted from the deregulation of gas prices, which hitherto had been a part of an elaborate system that kept interstate below intrastate prices. This caused shortages to develop in gas-importing states, while surpluses were generated in major gas-producing states such as Oklahoma.

In response, the Natural Gas Policy Act was enacted in 1978 to deregulate the price that pipeline companies paid for gas, and the average annual price of gas rose from 23¢ per MCF in 1974 to $1.49 in 1980. The rapid increase is significant because it encouraged gas-targeted exploration and development and because the 1980 price has essentially remained the floor price for gas ever since. In the succeeding 21 years, the average annual wellhead price for Oklahoma natural gas was lowest in 1995. The value, $1.43 per MCF (unadjusted for inflation), is about the same as in 1980. Even in constant dollars this historic low still exceeds the price through most of the State's history (Fig. 8). However, it must be emphasized that the average annual price is not the net value realized by gas producers, and it in no way conveys the degree of volatility with which operators must contend. In any given year, the price low can be a fraction of the annual value shown. Although they average out in the long term, successful operators must be able to weather many short-term dips in price.

As we might expect, the number of wells drilled for gas has closely tracked the gas price (Figs. 9, 10). After the Arab

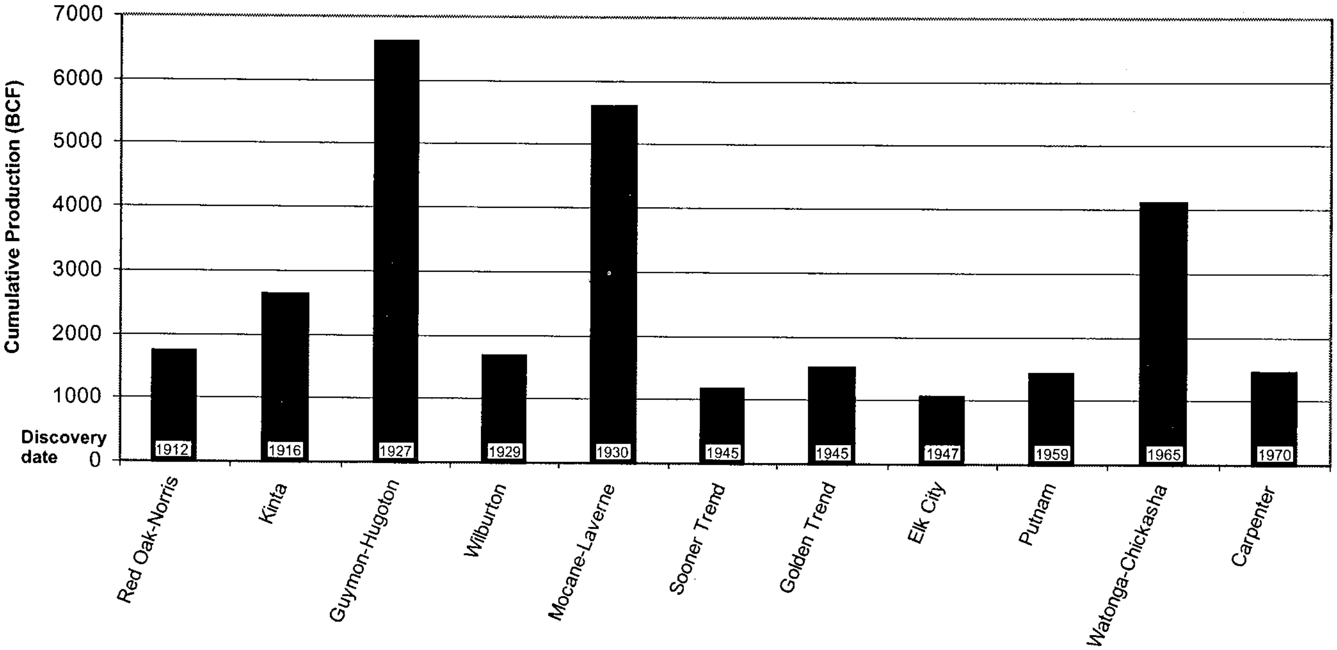

Figure 6. Major gas fields in Oklahoma: their cumulative production and discovery dates. Cumulative production >1 TCF through January 1, 2000. Data from Lay (2001).

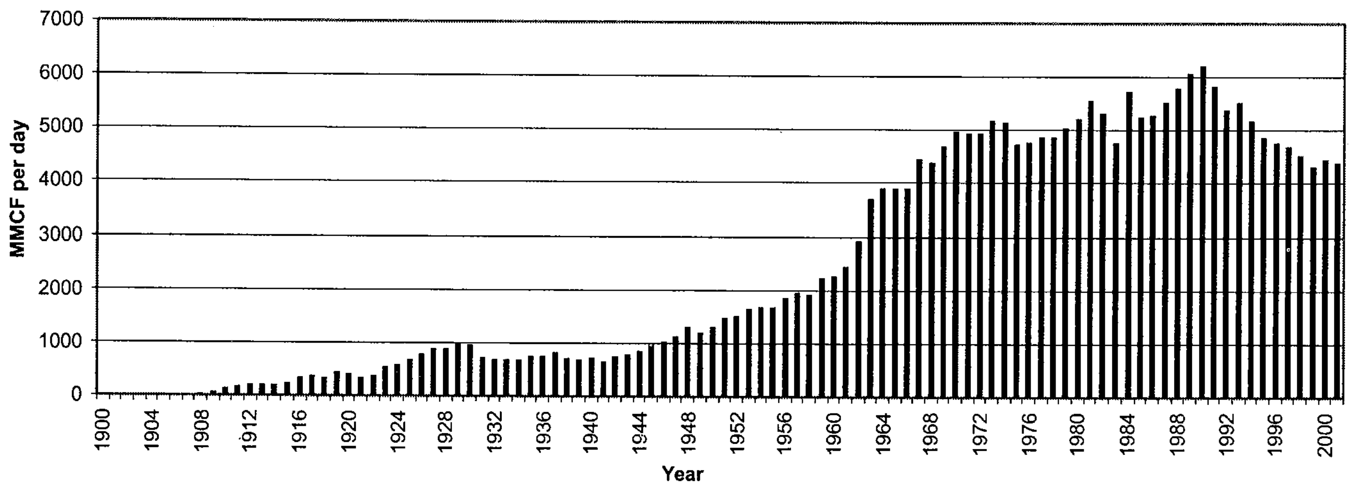

Figure 7. Natural-gas production in Oklahoma (1900–2001). Data from Claxton (2001).

oil embargo of 1973, which sent oil prices to record highs, the resulting increased demand for gas helped push prices higher for this commodity too. A combination of domestic deregulation and international politics precipitated a large increase in completions of gas wells from 1977 through 1985, a peak period in the last important drilling boom (Boyd, 2002a). However, with deregulation and eased political tension, market forces gradually have resumed control—resulting in moderate to low prices that suppressed gas drilling activity from 1986 through 1999.

Mirroring a dramatic rise in gas prices in 2000 (above $3.50 per MCF) and 2001 (above $4.00), the number of gas completions recorded for those complete calendar years was the highest in the State since the early 1980s. Many factors were responsible for this increase, primarily the markedly higher oil prices in the same period (Fig. 10). Upward pressure on the price of natural gas continued as the industry found itself unable to keep pace with peak seasonal demand. Because gas-storage facilities and their high delivery rates are key to meeting demand in winter, when storage levels drop significantly, concern for supply is heightened, and prices rise. Figures 8 and 10 show how closely the price trends for oil and gas have tracked through time.

In oil, additions to reserves in Oklahoma now come almost exclusively from improved recovery from previously defined traps: in gas, the discovery of new or incompletely drained reservoirs is still common. Recent activity directed toward finding and producing natural gas has succeeded in both conventional and non-conventional settings. Conventional accumulations occur in discrete reservoirs of limited

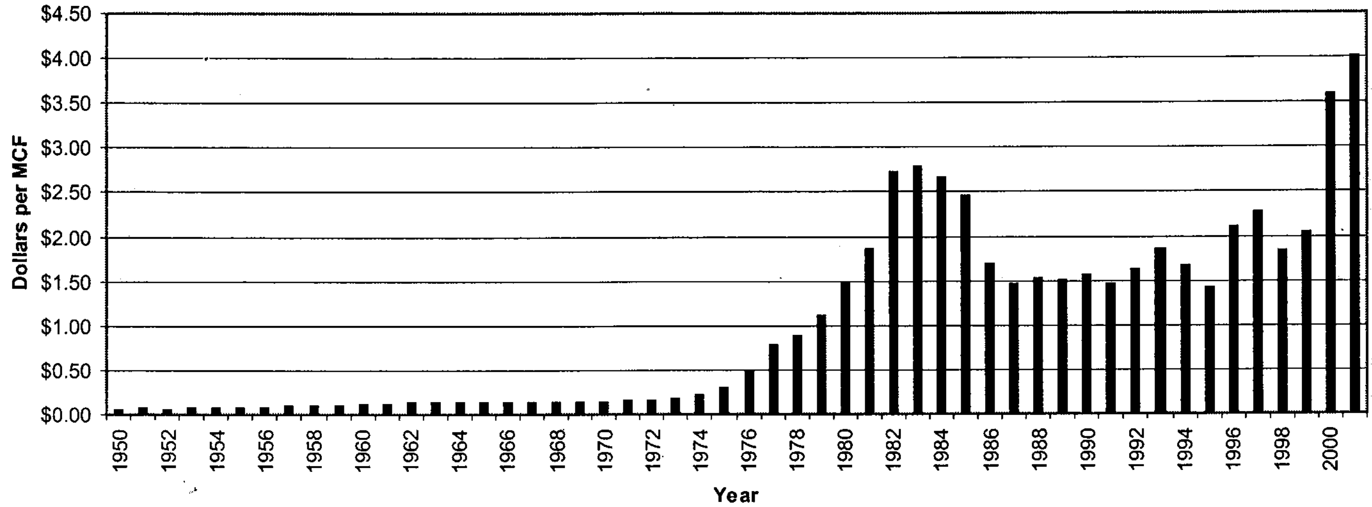

Figure 8. Average annual price of natural gas at the wellhead (unadjusted for Inflation) in Oklahoma (1950–2001). Data from Claxton (2001).

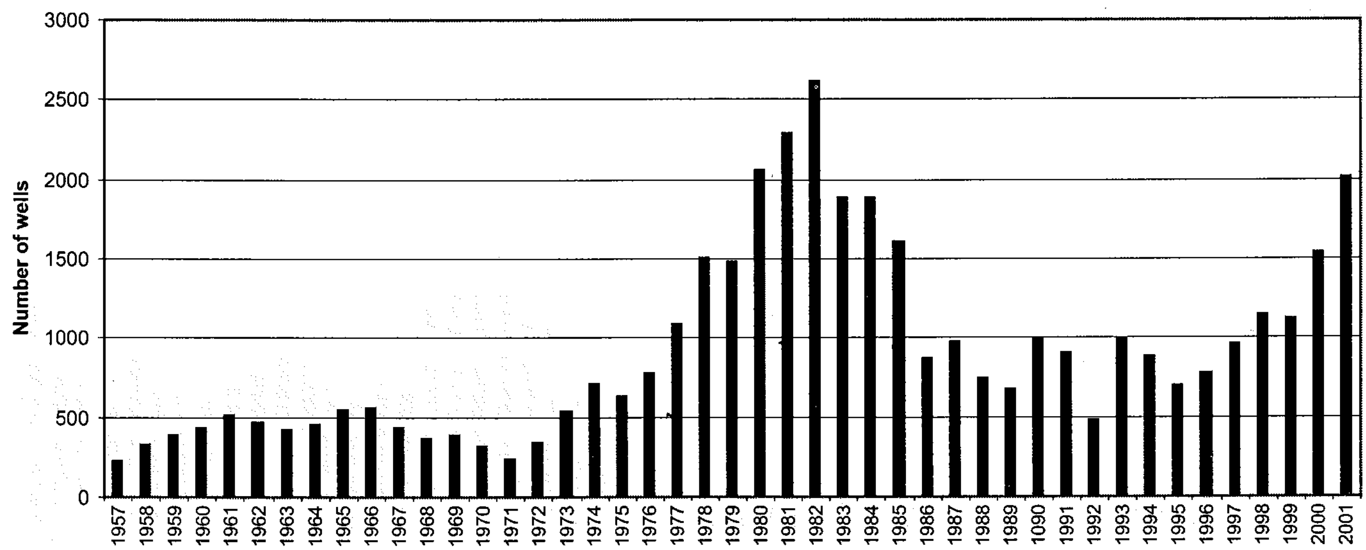

Figure 9. Gas-well completions in Oklahoma (1957–2001). Data from Claxton (2001).

aerial extent—mostly in sandstones, limestones, and dolomites, which are relatively permeable and represent the vast majority of Oklahoma's gas fields and reserves. Non-conventional accumulations, which are designated continuous-type by the U.S. Geological Survey (1995), do not occur in discrete reservoirs; they tend to cover large areas and include accumulations in coalbeds and in low-permeability (or tight) sandstones, shales, and chalks (Fig. 2).

An example of an important conventional gas discovery in Oklahoma is the Potato Hills Field, which is in a structurally complex area of southeastern Oklahoma. It was a marginal producer from its discovery in 1960 through January 1987, when it went off production after making less than 1 BCF of gas. There was no further activity in the area until 1997, when a well drilled in the same section as a dry hole drilled in 1961 established new gas production in the Jackfork Sandstone and initiated a spate of drilling that continues today. Since recently drilled wells went on line in late 1998, Potato Hills has produced more than 100 BCF of gas. Although production appears to be in decline, in the first 4 months of 2002 the field still produced an average of 61 million cubic feet (MMCF) per day.

The production added by Potato Hills Field is among the most significant in decades. As the State has nearly 500,000 wells, entirely new discoveries have become increasingly rare. However, this field shows that Oklahoma's gas potential, even in areas that have been drilled intensively, is still far from fully defined.

A non-conventional gas resource, coalbed methane, is a comparatively recent addition to Oklahoma's energy mix. As plant material is heated and compressed into what will eventually become coal, methane is released. The generation of methane turns coal into a source rock from which gas sometimes migrates into adjacent, permeable rock (such as sandstone) where the gas can be produced as in a conventional reservoir. More often, the gas has no way to escape and stays locked in the coalbed. Because coal is inherently impermeable, its quality as a reservoir depends on the spacing and interconnectivity of the fractures (cleats) that are formed during the coalification process. Where the cleats are pervasive and interconnected, it is possible to drill gas wells that are low-rate, but economic and long-lived. Production of coalbed methane is unusual because the coal acts as both source rock and reservoir, and rather than producing from reservoir pores, the gas is extracted from the coal itself.

The coalbed-methane play in Oklahoma is little more than 10 years old, and continues to be quite active. Because the productive coals have been penetrated many times by deeper wells targeting conventional oil and gas, the location, depth, and thickness of prospective coals are usually well established. The principal unknown is producibility—the rate at which gas will flow from the coal—but that cannot be ascertained until the well has been drilled and completed.

Because coalbed methane is considered non-conventional by regulators, its production is not merged with the existing, conventional field areas. However, by use of the same criterion as for conventional production (combining wells within ~1 mile of each other into one field), 50 coalbed-methane fields have been discovered thus far (Fig. 11). As these fields grow, many will be merged into larger fields or regional gas areas.

At mid-2002, about 2,000 coalbed-methane wells had been drilled in Oklahoma (Cardott, 2002), with new ones being added at a rate of about one per day. As coalbed methane is not distinguished from conventional gas, it is difficult to estimate its contribution to State production. However, if initial production is 60 MCF per well per day (Cardott, 2002), Oklahoma's production at the end of 2002 is about 120 MMCF per day, or about 44 BCF per year. Although this represents slightly less than 3% of the total gas production for the State, large prospective coalbed-methane areas remain undrilled or under-drilled. Consequently, coalbed methane's share of the State's natural gas production will undoubtedly continue to increase.

Shallow, low-cost coalbed-methane wells are suited to the small operators that dominate in Oklahoma. Although stabilized production rates are typically low (50–100 MCF per day), risk of a dry hole is low because the targeted coals are pervasive. In addition, coal acts as both reservoir and source rock, so areas with methane potential are vast. Another in-

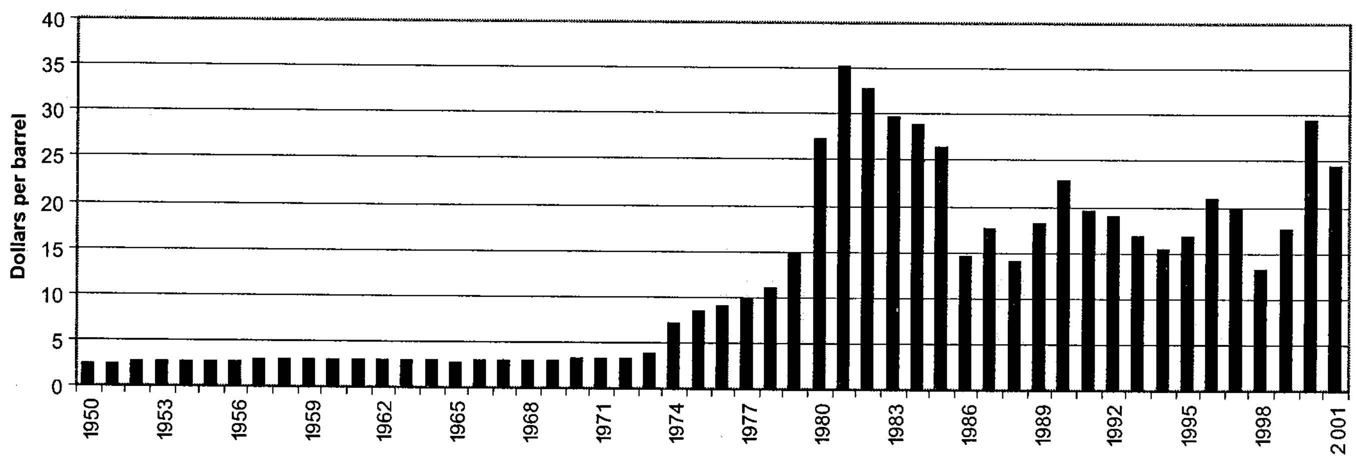

Figure 10. Average annual crude-oil price (unadjusted for inflation) in Oklahoma (1950–2001). Data from Claxton (2001).

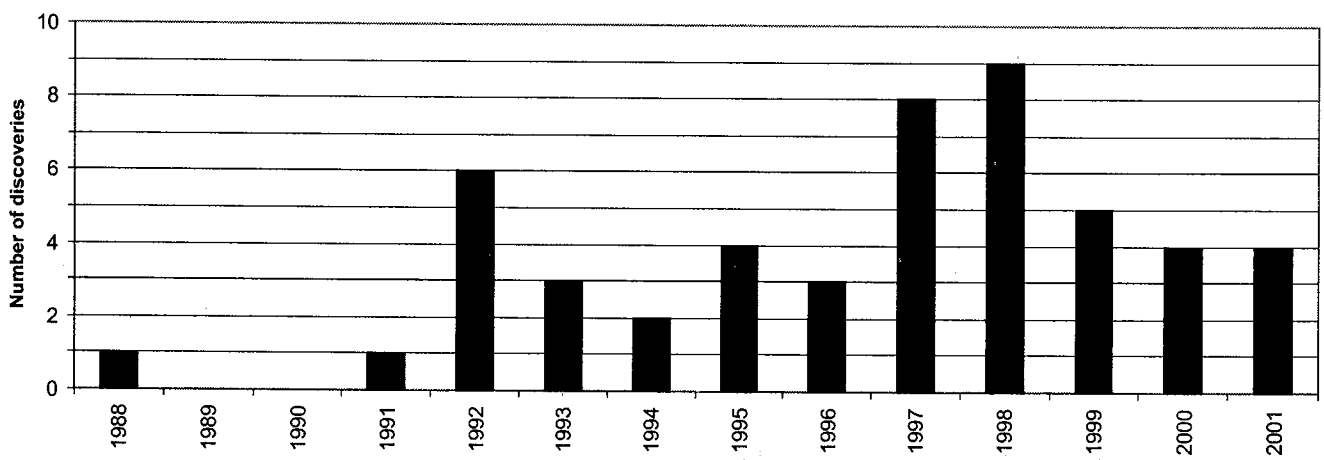

Figure 11. Provisional coalbed-methane fields in Oklahoma. From Boyd (2002b). Data from Cardott (2002).

centive for some operators is a federal tax credit applied to coalbed methane. As part of the Crude Oil Windfall Profits Tax Act of 1980, the credit (Section 29) was designed to encourage production of non-conventional fuels. These include shale oil, tar sands, tight gas, and coalbed methane.

Areas that produce coalbed methane in Oklahoma include parts of 15 counties on the eastern margin of the Cherokee Platform and the northern half of the Arkoma Basin (Figs. 3, 4). In 1995 the USGS estimated the mean, proved coalbed-methane reserves for the Cherokee Platform and Arkoma Basin at 4.6 TCF. Although these provinces (and reserves) are shared by Kansas and Arkansas, the estimate demonstrates the magnitude of the coalbed-methane play. Judging by experience in other basins, as drilling and production continue, estimates of coalbed-methane reserves will likely rise markedly.

Drilling and completion activity is an excellent indicator of the industry's focus on adding reserves. Changes in price, success rate, economics, tax incentives, and technology are all reflected in these data that show where the money has gone. In the last half century, the percentage of wells completed as dry holes in the State has fallen from almost 40% to under 10% (Fig. 12). This shows that as well density has increased and the number and size of productive fields has grown, dry-hole risk has fallen and drilling has become more developmental in nature.

We could infer from the current dry-hole percentage that the areas with the lowest risk have been drilled, and that risk-to-reward analyses make most of the undrilled areas unappealing. Exclusive of enhanced recovery projects, the reserve size of new oil prospects is almost universally low. However, because gas can exist at greater depths than oil and flow from less-permeable rock, it is still possible to find important new reserves of natural gas in densely drilled areas. Also, the value of gas, relative to oil, has increased, prompting the percentage of gas-well completions in the State to rise dramatically, from less than 5% in 1957 to nearly 70% today. Well-completion statistics clearly show that the industry in Oklahoma has undergone a pronounced change in focus, mostly in the last 15 years, from oil to gas (Fig. 12).

If completion marks the birth of a productive well, then abandonment marks its demise. From 1971 through 2001, former oil wells accounted for more than 80% of all abandonments (Fig. 13). In that period about 47,000 oil wells were plugged and abandoned, compared with about 11,000 gas wells. Not only are more gas wells being drilled each year in Oklahoma, but proportionately fewer are being abandoned.

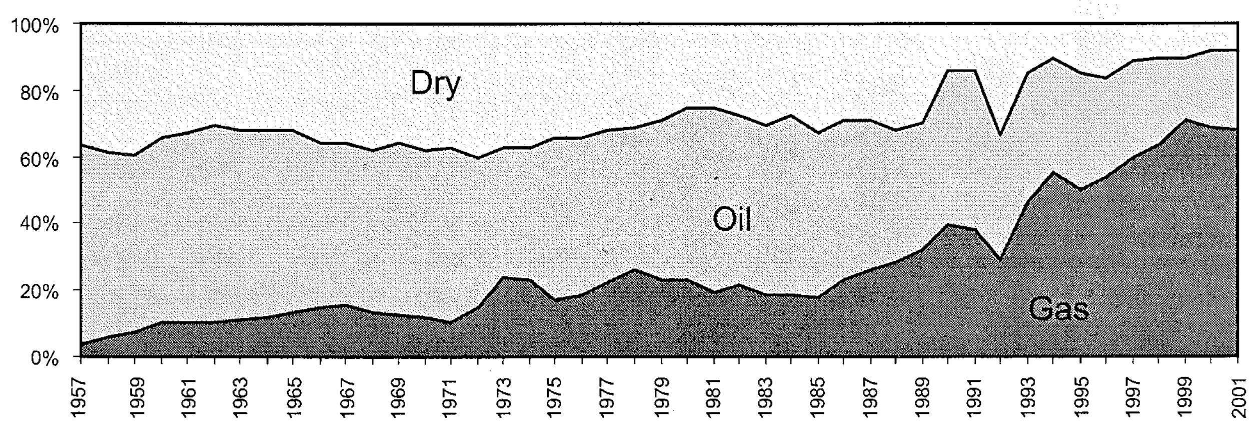

Figure 12. Oklahoma's well-completion history (all wells, 1957–2001). Data from Claxton (2001).

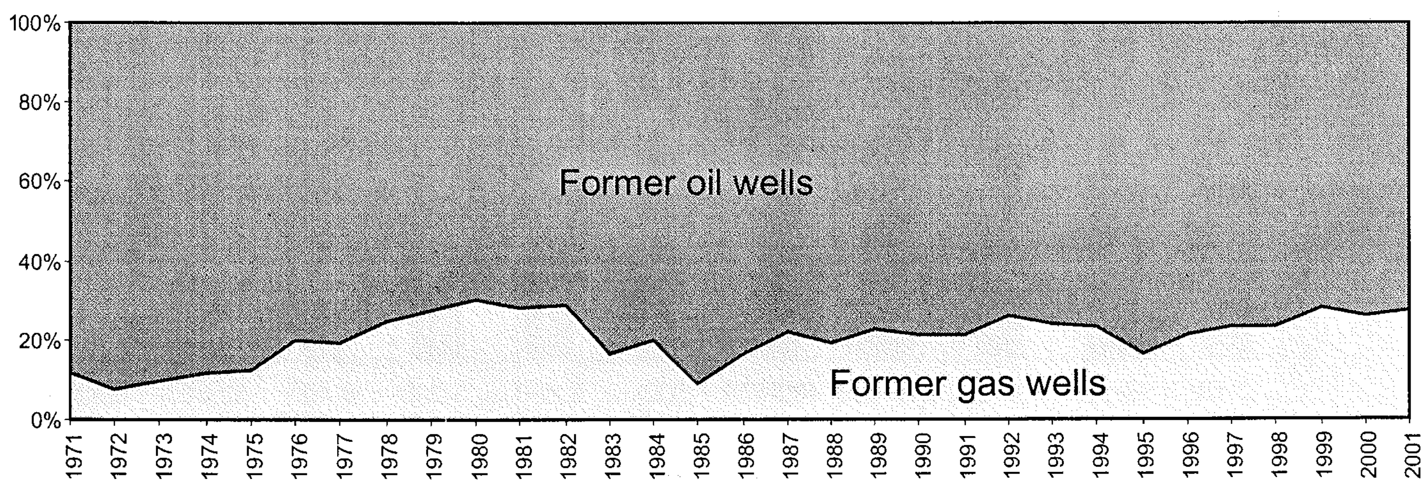

Figure 13. Well abandonments in Oklahoma (formerly productive wells). Data from Claxton (2001).

However, past drilling was so strongly directed toward oil that, despite recent activity, at the end of 2001 the ~84,000 active (unplugged) oil wells in the State still greatly outnumbered the ~33,000 active gas wells.

Of particular interest are the rate classes of wells that produce gas in Oklahoma. The Energy Information Administration (EIA) of the U.S. Department of Energy has classified the Oklahoma gas wells producing in 1999 by average production rate (Fig. 14), showing that 97% of the wells produced less than 800 MCF per day. In fact, about two thirds of the gas wells active in 1999 produced less than 100 MCF per day (Hinton, 2001). A review of the 11 well-production classes contributing to the 1999 State average of 4,356 MMCF per day shows that the class with 200–400 MCF per day contributed the most (~19%), followed closely by the 400–800 and 100–200 MCF per day classes (Fig. 15).

These data demonstrate that large numbers of low-rate wells produce most of Oklahoma's gas. As in oil (Boyd, 2002a), where the average well now produces only slightly more than 2 barrels per day, the average Oklahoma gas well in 1999 produced about 175 MCF per day. (This rate is undoubtedly quite close to today's gas wells.) Assuming that 6 MCF of gas yields energy equal to one barrel of oil, the average Oklahoma gas well, even at 175 MCF per day, still produces the equivalent of 29 barrels of oil per day. In terms of energy, this is more than 13 times the production of today's average oil well. This rate, unknown here since the mid-1960s, helps explain the dominance of gas in the State's energy production.

From a mechanical standpoint, maintaining a system of thousands of relatively low-rate producers is not as difficult or as expensive for gas as it is for oil. As oil wells are depleted, pumping equipment must be installed and maintained. As secondary recovery begins, water-injection wells must be drilled or converted from producers, and an elaborate pipeline system must be maintained to separate oil, associated

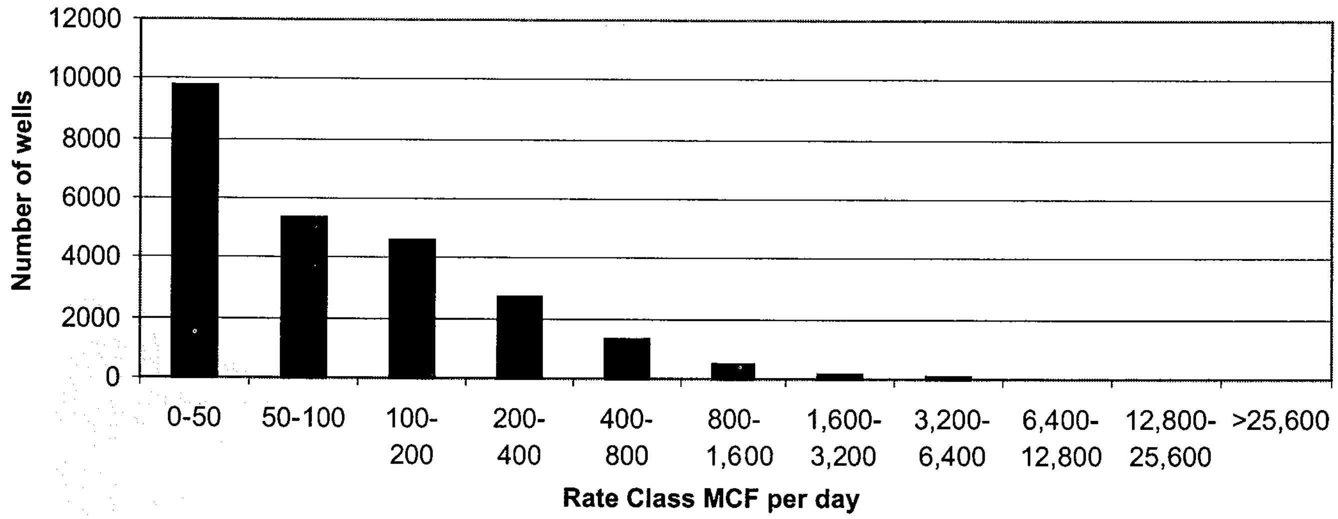

Figure 14. Gas-well production rates in Oklahoma (1999). Data from Hinton (2001).

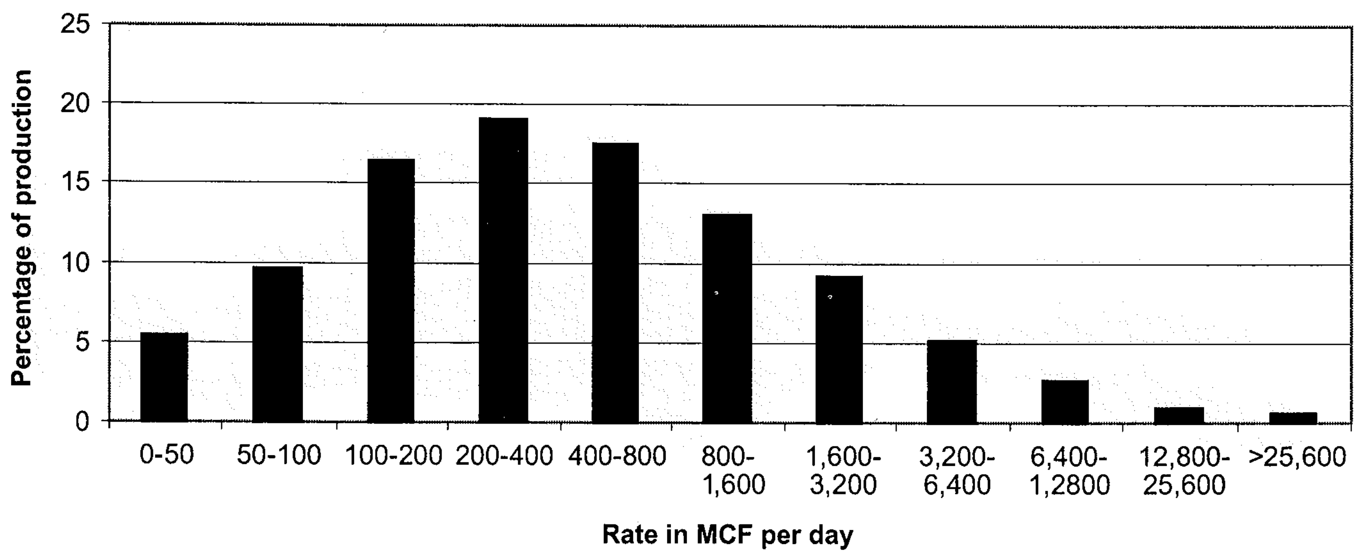

Figure 15. Oklahoma's gas production by rate class (1999). Data from Hinton (2001).

gas, produced water, and injected water. And equipment is subject to breakdown. Gas, which normally flows to the surface, requires less equipment. This ignores the need for compression, which arises when gas-pipeline pressure exceeds a well's surface flowing pressure, but a compressor usually serves multiple wells and so the maintenance expense is shared.

Clearly, in order to maintain production volume, wells must be kept active as long as possible. In 1992 the Oklahoma Legislature created the Oklahoma Commission on Marginally Producing Oil and Gas Wells for the express purpose of helping producers manage marginal oil and gas wells. The program was designed to help operators weather the inevitable price dips, and to minimize the long-term production decline. In addition, the Oklahoma Geological Survey offers low-cost geologic-play-based workshops and other programs to aid operators. Survey programs help identify practical techniques and technology for finding new fields, as well as means of efficient production in existing fields. They give local operators access to regional studies, technical insights, and resources usually available only to large companies. An example is the series of workshops coordinated by Brian Cardott designed to benefit Oklahoma's numerous small coalbed-methane operators.

WHERE DO WE STAND NOW?

The bulk of Oklahoma's energy production and more than 70% of its drilling focus on natural gas. Drilling in the State today, especially exploratory, is dominated by wells with gas objectives. The result is that from 1901 through mid-2002 a staggering 90 TCF of natural gas was produced and sold. However, the health of the industry must be measured by the volume of hydrocarbons that remain to be produced—the remaining reserves. That leads to the question: How much is left?

Estimating ultimate remaining reserves is difficult because it requires accurate knowledge of resources in the ground, as well as long-term price forecasts. This requires foreknowledge of demand, technical innovation, political stability, and other factors that may affect economics and is why predictions of remaining reserves can change dramatically from year to year. This complexity has led the industry to use a tiered system of estimates designed to convey differing levels of uncertainty. Although names and definitions commonly vary from company to company (a variety of subcategories also exist), reserves commonly comprise three tiers.

The top tier is called proved reserves; it is the key volume because its low technical and economic risk allows it to be given a monetary value. Proved reserves are defined by the EIA as the volume that geological and engineering data demonstrate with reasonable certainty to be recoverable from known reservoirs under existing economic and operating conditions. Other reserve categories that may eventually be upgraded to proved are, in increasing degree of uncertainty, probable reserves and possible reserves. Because all reserve categories are defined by analog production and subsurface data, they are understood better than any of the statistically defined categories under the heading of resources.

Because of the volume and complexity of data involved in thoroughly analyzing the thousands of fields and hundreds of formations that produce gas in Oklahoma, the EIA calculates remaining reserves by simply asking operators for their reserve volumes and then totaling the numbers reported. Assuming that operators do not invoke unrealistic recovery assumptions or price forecasts, such an analysis should give the minimum volume recoverable based on wells producing from known reservoirs in a particular year. However, the estimate reveals nothing about the impact of new discoveries, increased drilling, higher recovery in low-permeability reservoirs, new technology (in drilling, completion, and production), non-conventional gas such as coalbed methane, or changing prices.

We must remember that remaining (proved) reserves, when added to cumulative production, are not meant to approximate ultimate recovery. All types of reserves change continuously, the only certain reserves being those that have already been produced. To give an example, in 1946 Oklahoma's estimate of proved gas reserves was 10.1 TCF, an estimate that rose steadily to 18.3 TCF in 1962. But since 1962 more than 72.5 TCF has been produced, four times the proved reserves estimated in 1962. Clearly, the gas resource volume from which reserves come is finite. However, from year to year a combination of factors including new discoveries, greater efficiency in recovery, and higher prices, has repeatedly forced upward revisions in estimates.

Historical estimates of gas reserves, compiled by the EIA for Oklahoma (Hinton, 2001), are shown in Figure 16. From 1977 through 2000, reserves ranged from 12.5 to 16.7 TCF, with peak years in the 1980s, during and just after the last major drilling boom. For the same period, gas production ranged from 1.6 to 2.3 TCF per year. Where proved reserves go up from one year to the next, the volume increase is in addition to that year's production. The actual swing in ultimate-recovery estimates from one year to another is much larger than the graph suggests. Although it is not obvious from Figure 16, throughout Oklahoma's history the estimates of ultimate gas recovery have always gone up. However, when estimates rise more slowly than production, proved reserves go down, and this is shown as a net negative year for the State (Fig. 17). For example, in calendar-year 1999 additions totaled 0.5 TCF. Because production for the year was 1.6 TCF, the net effect was a reduction in reserves of about 1.1 TCF. In the following year, reserve additions totaled 2.7 TCF; when offset by that year's production of about 1.6 TCF, the net-reserve addition was 1.1 TCF, essentially balancing the previous year's net-reserve loss.

A common measure of reserve life is a comparison of reserve volume to production rate, usually expressed as the R/P ratio. This is the length of time that proved reserves can sustain the current production rate with no decline. For example, a state with 10 TCF of reserves that is currently producing them at 1 TCF per year has an R/P ratio of 10. Since 1977 for Oklahoma the ratio has averaged 7.7 years, ranging from a high of 9.3 years in 1983 to a low of 6.6 years in 1993. Based on the most recent reserve estimate (year-end 2000), Oklahoma's R/P of 8.5 years is above the 25-year average. However, we certainly have no reason to become complacent, as the main factor keeping reserve life stable is the

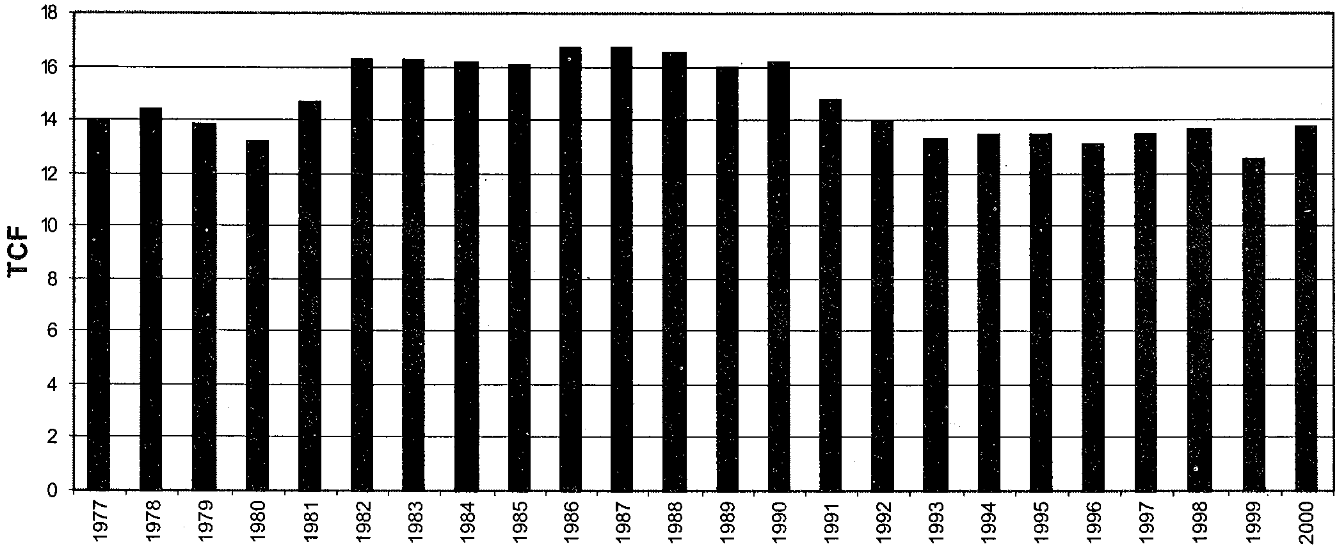

Figure 16. Proved gas reserves in Oklahoma (1977–2000). Data from Hinton (2001).

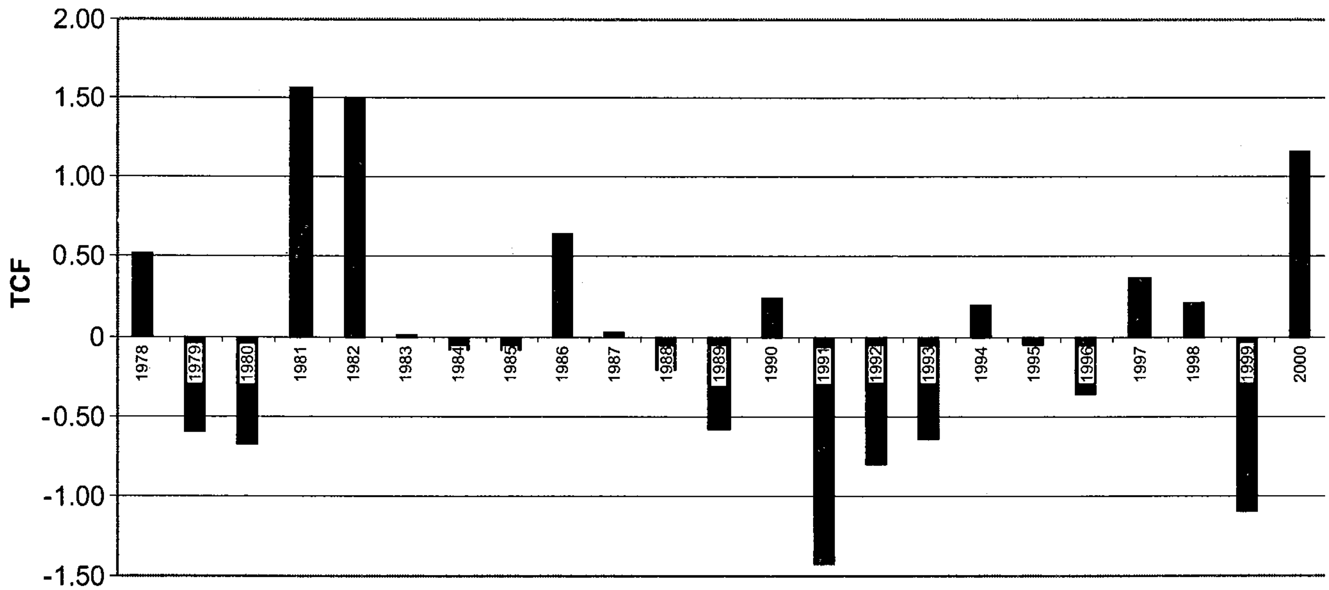

Figure 17. Changes in Oklahoma's net gas reserve (after production from the previous year). Data from Hinton (2001).

State's declining production rate. With production always at 100% of capacity, gas rates have slid from 1.9–2.3 TCF per year in the 1980s to 1.6–1.8 TCF per year since 1995.

Gas, unlike oil, has had no discernible long-term decline in annual estimates of the State's reserves (Fig. 16). Although Oklahoma's production rate is clearly declining in the long term, two years of increased prices and attendant higher drilling activity have, at least temporarily, slowed the decline (Fig. 7). How long current production rates can be maintained is impossible to determine, but if prices stay high, drilling should increase, and the inevitable long-term decline in production should be reduced. Price reductions do not usually cause gas wells to be shut-in, but they do slow the rate at which new wells are drilled. Because a new well typically has a steep initial production decline, less drilling invariably leads to lower gas deliverability. The resulting reduction in supply then pushes prices higher, usually dramatically so.

In 2001, Oklahoma's annual gas production of about 1.6 TCF (4,389 MMCF per day) was about two thirds of the peak rate in 1990, which was 2.3 TCF (6,200 MMCF per day). However, because the gas price in 2001 ($4.02 per MCF) was more than two and a half times that in 1990 ($1.57 per MCF), its gross value of $6.5 billion far exceeded 1990's $3.5 billion. Even inflated at the 2.79% rate calculated by the federal government for the period, 1990's record gas production was worth $1.9 billion less than 2001's production. This illustrates how the annual value of gas to the State of Oklahoma depends far more on its average price than on how much is produced. Much of the fall in State revenue for 2002 (relative to 2001) can be directly attributed to lower gas prices and proportionately lower tax revenues. The price of oil and gas, especially gas, is critical to Oklahoma's economic future.

THE FUTURE

The continued vitality of Oklahoma's natural gas industry relative to oil is due to many factors. The initial large-scale exploitation of gas occurred more recently than for oil, so proportionately more gas is left. From a regional perspective the State has more gas- than oil-prone areas, and many areas where drilling is sparse also tend to be strongly favorable for gas. In addition, gas can exist at much greater depths and flow through less-permeable rock, so that even where drilling is dense there are large areas in which deeper reservoirs are incompletely evaluated. At shallow depths in the eastern part of the State are many productive coal seams that have been penetrated by thousands of wells with deeper objectives. Although once ignored, the coal has now added important reserves and production to our natural-gas mix.

The primary factor affecting the health of Oklahoma's gas industry will always be price. Although we have little control over the value of gas, we can influence how much we produce. The most direct way to increase gas production is to discover large, long-lived fields. As history has shown repeatedly, in the early stages of exploration in a hydrocarbon-rich state like Oklahoma new discoveries are not difficult. Then, as more wells are drilled, large discoveries become less frequent. But even now the industry is not so mature that large gas reserves cannot be added.

In some parts of the State, both productive and unproductive, reservoirs with gas potential remain under-explored or under-developed. Due to their geologic complexity and correspondingly high risk, they may be largely untested. Or they may require only proper techniques of drilling, completion, or production to become viable. Although the State's gas production and reserves are declining, both conventional and non-conventional additions continue to be made. The Potato Hills Field is an example of a large, conventional accumulation, recently identified. Coalbed-methane recovery is a non-conventional play that is adding important reserves.

So new reserves continue to be added. However, generally low production rates for individual wells and steep declines mean that high levels of drilling activity are necessary to sustain Oklahoma's gas production. When drilling declines, reserves and production rates drop, as they did after 1990. In 2001 the EIA estimated proved reserves for the entire Mid-continent at 58 TCF. Perhaps more important, the agency also estimated the technically recoverable gas resources (both conventional and non-conventional) in the same region at 250 TCF. Although not all if this can be assigned to Oklahoma, the estimate does suggest that our area has at least four times as much undiscovered, recoverable gas as proved reserves.

These facts are encouraging, but as with any other commodity the primary driving force in the Oklahoma gas industry is economics. Any forecast presupposes that the industry will not be hurt by a price reduction that suppresses drilling for an extended period of time. Increases in demand show no sign of abating, and national and State production, even when drilling activity is high, struggles to stay flat. Even if we disregard warm winters, global warming, and fluctuations in gas-storage volumes, a large long-term price drop seems unlikely. Although such an occurrence could devastate the gas industry, as well as the State's overall budget, the resource must be produced eventually. Gas is environmentally friendly, relatively abundant, and its infrastructure can support substantial growth in the market. Oklahoma's location, geology, resource estimates, pipeline system, and the energy industry's strong history, all ensure that gas will be a key component of the State's economic future well into the 21st century.

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The Birth of the Seismic Reflection Method—An Oklahoma Story

Raymon L. Brown
Oklahoma Geological Survey

INTRODUCTION

The seismic reflection method used worldwide in exploration for oil and gas was developed in Oklahoma, yet, few Oklahomans know that the first seismic reflection surveys in history took place near Oklahoma City or that two University of Oklahoma (OU) graduates worked together to make geophysical history right here in Oklahoma. Even though I am a geophysicist, myself, I lived in the State for 12 years before I heard about it. I am grateful to Craig Ferris for giving me a copy of George Elliott Sweet's (1978) book, *The History of Geophysical Prospecting* (now out of print), which covers the subject thoroughly. Except where other references are cited, my information comes from Sweet (1978).

The history of the early lives of Everette Lee DeGolyer and John Clarence Karcher and of how they met and collaborated is a story worth telling. It chronicles the seismic reflection method's birth in Oklahoma and its development and application to exploration for oil and gas. In addition, it tells about the first use in U.S. oil exploration of two other geophysical methods—gravity mapping (using the Eötvös torsion balance) and seismic refraction. Along the way, the story highlights the role played by a network of OU graduates and faculty and also touches on the importance of sound-ranging research at the U.S. Bureau of Standards during World War I.

First, we'll follow DeGolyer's early life and professional career; next, we'll meet Karcher and learn of his early history. Then the two men meet and work together to prove—beyond any doubt—the great value of the seismic reflection method as a tool in oil and gas exploration.

EVERETTE LEE DEGOLYER

DeGolyer's Early Years

Everette Lee DeGolyer (Fig. 1) was born to John and Narcissa DeGolyer in a sod hut on their homestead near Greensburg, Kansas, in 1886. A tornado struck the house when Everette Lee was a year old and demolished half the roof. Luckily, he and his mother were huddled in the part of the house that survived the storm. (In Kansas and Oklahoma, one may have to survive not only the economic climate, but the weather, itself!) Two years later, the DeGolyers left the farm because of a drought. They put their meager holdings into a wagon and headed east toward the lead and zinc mining district in the southwestern corner of Missouri. (John DeGolyer had an amateur's interest in mining and geology.) Everette Lee was used to being rocked to sleep at night, so each evening during the trip, the rocking chair was unstrapped from the wagon and he and his mother rocked away under the stars.

To make a living in Missouri, the DeGolyers set up a family mill, but DeGolyer's father also roamed the hills of the area looking for a lead-zinc strike. (His father's interests in solid minerals may have led to Everette's later interest in liquid minerals.) In the middle of the 1890s, John DeGolyer and his brother operated The German Restaurant in Joplin, Missouri (Tinkle, 1970), and Everette started his first year of high school (1900–1901) there.

In 1901 the Kiowa-Comanche lands in Oklahoma were divided by lottery. DeGolyer's father bid for and received an allotment near Hobart, Oklahoma, where he once again became a farmer. The family relocated to Norman, and John DeGolyer ran Delmonico's Restaurant while Everette worked his way through the university's preparatory school and then OU (Tinkle, 1970).

While he was in Oklahoma City, Everette was encouraged by Mr. Vought, superintendent of schools. When Vought learned that Everette had some interest in mining, he took him to Norman and prevailed on Charles Newton Gould, head of the geology department, to give DeGolyer a job dusting off geological specimens among other janitorial duties. This contact may have influenced his choice of majors when he entered college.

Figure 1. Everette Lee DeGolyer (1886–1956), the father of modern exploration geophysics. From Karcher (1957, p. 463).

DeGolyer's Success Begins In College

DeGolyer entered OU in 1905. He helped pay for his board and room by waiting on tables at his fraternity house. For his books and spending money, he had his job with the OU geology department, where he began as janitor and ended as student assistant.

DeGolyer got his educational start with the fathers of Oklahoma geology. During DeGolyer's early years at OU, his mentor was Charles N. Gould, the first head of the geology department. When Gould left the department in 1908 to become the first director of the Oklahoma Geological Survey, Dr. Daniel Webster Ohern became head of the geology department. Ohern, too, left the department to serve as OGS director when Gould resigned that position in 1911. At that time, Charles Henry Taylor became head of the geology department, a position he held in 1911–1916. Taylor, an igneous petrologist, also taught the first course in petroleum geology at OU (M. Charles Gilbert, personal communication, 2002). It was Taylor who directed DeGolyer's baccalaureate thesis (Branson, 1957). Later, Taylor and DeGolyer together conceived the idea for the organization that became the American Association of Petroleum Geologists.

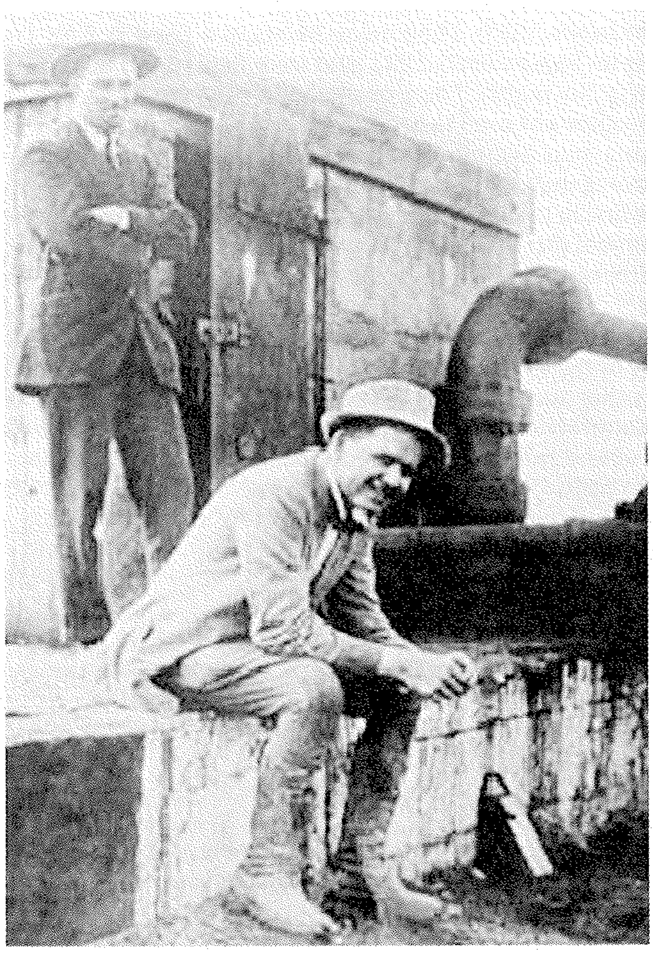

Figure 2. Everette DeGolyer takes it easy at his most famous discovery, the Potrero del Llano No. 4 well, near Tuxpam, Mexico. Associate geologist Leon Russ is standing behind DeGolyer. From Sweet (1978).

DeGolyer spent his summers making additional money by working for the U.S. Geological Survey (USGS); this practical experience may have been even more important to his career than his formal instruction. From 1906 to 1909, he progressed from cook to teamster to drilling-crew foreman to assistant geologist, and he significantly impressed every boss he had in the four USGS camps (Tinkle, 1970). They were some of the greatest names in American geology at the time: Nelson Horatio Darton (the dean of reconnaissance geologists), Dr. C. Willard Hayes, Carl D. Smith, and Willis T. Lee.

In the summer of 1907, DeGolyer was field assistant to E. G. Woodruff in the Big Horn Basin of Wyoming. He learned that Hayes, the chief geologist of the USGS, was going to visit the field party. He asked Woodruff what Hayes was like and found out that Hayes had a fondness for beer. DeGolyer managed to acquire a case of beer and stash it at a nearby spring. Alcoholic beverages were prohibited within any USGS camp. However, Hayes, young DeGolyer, and a few others spent many a pleasant hour at the nearby spring. Apparently, during discussions at the spring, Hayes made a mental note that DeGolyer had the makings of a fine geologist—an observation he later acted on when he offered DeGolyer a job. But that's jumping ahead of events.

Let's get back to our story. When DeGolyer returned from summer work in 1908, the OGS commissioned him to do field work in northeastern Oklahoma. He worked weekends and throughout the Thanksgiving and Christmas holidays. De Golyer's code of conduct seems to have included perseverance and long hours of work.

Another of DeGolyer's characteristics was his policy of leaving as little to chance as possible—perhaps a bit unusual for someone who would eventually work in the oil industry, where risk is a way of life! In his freshman year at OU, DeGolyer was taking German. To make sure that he got better grades, he made a point of meeting the grading assistant for the course. When the grading assistant turned out to be a beautiful girl, Nell Virginia Goodrich, he asked her for a date. They married in 1910.

DeGolyer's Most Famous Discovery

In January 1909, at the urging of E. G. Woodruff and Carl D. Smith, DeGolyer discontinued his studies at OU to go to Washington, D.C., and work toward obtaining permanent status with the USGS. He was needed as soon as possible to prepare maps of the Montana and North Dakota areas worked the previous summer. In June 1909, he was appointed junior geologist in the USGS.

One day, Dr. Willard Hayes called DeGolyer into his office. DeGolyer thought he was in trouble for his expense account, but instead Dr. Hayes wanted his assistance on a trip to Mexico to look over the properties of the Mexican Eagle Oil Company (Sweet, 1978). DeGolyer went to Tampico, Mexico, to join forces with Hayes and other geologists already working for the Mexican Eagle Oil Company. There, DeGolyer began to make his place in history. He located the fabulous Potrero del Llano No. 4 well (Fig. 2) in Mexico's Golden Lane, which blew in on December 27, 1910, and was not brought under control for 60 days (Robertson, 1986). Its initial production was 110,000 barrels a day (Robertson, 1986), and it produced more oil than any well in history up to that time! This discovery led to a close relationship between DeGolyer and one of the owners of the Mexican Eagle Oil Company, Sir Weetman Pearson (later Lord Cowdray) of England, who called DeGolyer, "my lucky charm" (Sweet, 1978, p. 116).

DeGolyer's Path to Amerada

A month after DeGolyer's famous oil discovery, he was back in the classroom at OU; Lord Cowdray had granted him leave at full pay to complete his degree in geology. DeGolyer received a B.A. in geology in June 1911 and returned to the Mexican Eagle Oil Company as Chief Geologist. He continued to work in Mexico until President Woodrow Wilson advised all Americans to leave Mexico because of the more and more chaotic revolution taking place. In 1914, DeGolyer returned to Oklahoma as a geological consultant. His first client was the Mexican Eagle Oil Company, and he devoted most of his time in 1914–15 to Cowdray enterprises.

Shortly after DeGolyer arrived in Norman, Lord Cowdray invited him (and C. W. Hayes) to London to form a worldwide oil company. These plans were interrupted by the advent of World War I. However, during this time in London, DeGolyer first became interested in the possibility of using applied geophysics as an aid to prospecting for petroleum (DeGolyer, 1935). He learned of gravity surveys in the great Hungarian Plain that had been made with the torsion balance, a new instrument invented by Baron Roland von Eötvös of Budapest. Such an instrument might be useful in prospecting for new salt domes in the coastal plain of Texas and Louisiana (DeGolyer, 1935). DeGolyer immediately contacted Eötvös for a bid on a torsion balance, but the war made delivery impossible.

During 1915 and the early part of 1916, DeGolyer's time was divided between his home in Norman, Oklahoma, where OU is located, and his Mexican office in Tampico. The Mexican Eagle Oil Company was still his first client, but he was adding others to his list. During this time, DeGolyer and Professor Charles H. Taylor (head of the OU Department of Geology, 1911–1916) discussed organizing the group that eventually became the American Association of Petroleum Geologists (AAPG), and DeGolyer played a prominent role in the first meeting in Norman on January 7 and 8, 1916. The name of the organization at that time was the Southwestern Association of Petroleum Geologists. In April 1916, DeGolyer moved to New York City because he thought that a consulting geologist should be in the financial capital of the country.

Vice President of Amerada

In October 1918, Royal Dutch Shell expressed serious interest in purchasing the Mexican Eagle Oil Company, and DeGolyer traveled to London at Lord Cowdray's request to help with the sale. The arrangement with Shell was finalized by spring 1919, and Shell retained DeGolyer as a consultant to help them get started in Mexico. In the same year, Lord Cowdray formed two new oil companies—the Amerada Petroleum Corporation to explore North America (America and Canada) and the Whitehall Petroleum Company, to explore the rest of the world. Thomas Ryder left Mexican Eagle to become the president of Amerada, and DeGolyer was named vice president and general manager. One of DeGolyer's first moves for Amerada was to hire Donald C. Barton (a Ph.D. from Harvard), who also became a very prominent figure in early geophysical exploration (Robertson, 1986). Later (in March 1930), Barton was elected the first president of the Society of Economic Geophysisists, subsequently renamed the Society of Exploration Geophysisists in 1937 (www.seg.org/).

In 1919, through Lord Cowdray, DeGolyer made contacts in the physics department at Cambridge University and had discussions about British sound ranging studies that had been conducted during the war. He also discussed the possibility of locating salt domes in coastal Texas and Louisiana with the Eötvös torsion balance and with some form of seismograph. In addition, DeGolyer discussed these ideas with a Dr. Th. Erb, a chief geologist for Shell.

DeGolyer had tried to get a torsion balance before the war. Now, in spite of setbacks due to the death of Eötvös in April 1919, he moved aggressively toward acquiring the new technology. Joint field research was arranged between Amerada and Mexican Eagle Oil Company, and two instruments were contracted with Ferdinand Süss, Budapest; construction began in August 1921 (DeGolyer, 1935). The torsion balances were standardized by Dr. Pekar of the Eötvös Institute, and Donald C. Barton was sent to Budapest to receive them in May 1922 and to learn how to operate them (DeGolyer, 1935). The torsion balances arrived in New York City on September 5, 1922, and were field tested near Houston in November. Then, one balance was sent to Mexico and the other was used to conduct a survey of the Spindletop salt dome near Beaumont, Texas, in early December 1922. According to DeGolyer (1935, p. 3), the Spindletop survey "was the first or one of the first surveys of an oil pool made by geophysical methods in the United States and appeared to be a brilliant success though it now seems, in light of our more extensive knowledge of gravity variations, to have been...a lucky accident, since it was a very definite gravity maximum, one of the very few in the entire coastal regions." The results of other surveys were vague; some prospects were drilled without success. The instruments and method were about to be abandoned when a survey in the Nash area in southern Fort Bend County, Texas, "gave a gravity maximum as brilliant and definite as that for Spindletop" (DeGolyer, 1935, p. 3). A well drilled in November 1924 struck cap rock, and oil was discovered on the flank of the dome on January 3, 1926 (DeGolyer, 1935, p. 3)—making Nash the first oil field in the world to be discovered by a geophysical method.

In addition to the gravity work, DeGolyer was pursuing the application of some type of portable electrical seismograph. Reginald A. Fessenden, chief physicist of the Submarine Signaling Company of Boston, held the fundamental patent on seismic exploration, which DeGolyer had heard about at Cambridge. Fessenden's 1917 patent, *Method and Apparatus for Locating Ore Bodies*, "covered the use of both reflected and refracted sound waves for locating mineral bodies" (Weatherby, 1940).

Shortly after DeGolyer returned from London in 1920 (after Amerada was formed), he traveled to Boston to meet with Fessenden. It was the first of many discussions between the two men, but Fessenden did not agree to sell his patent until John Clarence Karcher entered the picture.

JOHN CLARENCE KARCHER

Karcher's Early Years and OU Studies

John Clarence Karcher (Fig. 3) was on born April 15, 1894, in southern Indiana of German-French ancestry (Karcher [1987] is the source of information about Karcher's early life and OU years). When he was five, his parents, Leo and Mary, moved the family to a farming community near Hennessey, Oklahoma, ~50 mi northwest of Oklahoma City. (A student recently told me after I had presented this story to a group at OU that Karcher still has relatives living in Hennessey.) Karcher graduated from Hennessey High School in 1912 and entered OU that autumn to study electrical engineering. Although he later changed his major to physics, he still completed all lecture courses required for an electrical engineering degree. The contacts he made in both departments would be important to him later in life.

Karcher graduated from OU in 1916 with a B.S. in physics. A strong recommendation from W. P. Haseman, head of the physics department, helped Karcher obtain a graduate scholarship at the University of Pennsylvania, and he began studies in September. While still a student at Pennsylvania, Karcher spent about three weeks at the Thomas Edison Laboratory, where he often had talks with Mr. Edison, himself. Karcher always remembered two important points that Edison told him: (1) perseverance and persistence are important to make an idea work, and (2) make a note of any unusual phenomena because such things are often clues to some useful new device (Karcher, 1987, p. 10). Karcher learned these lessons well and applied both in developing the seismic reflection method.

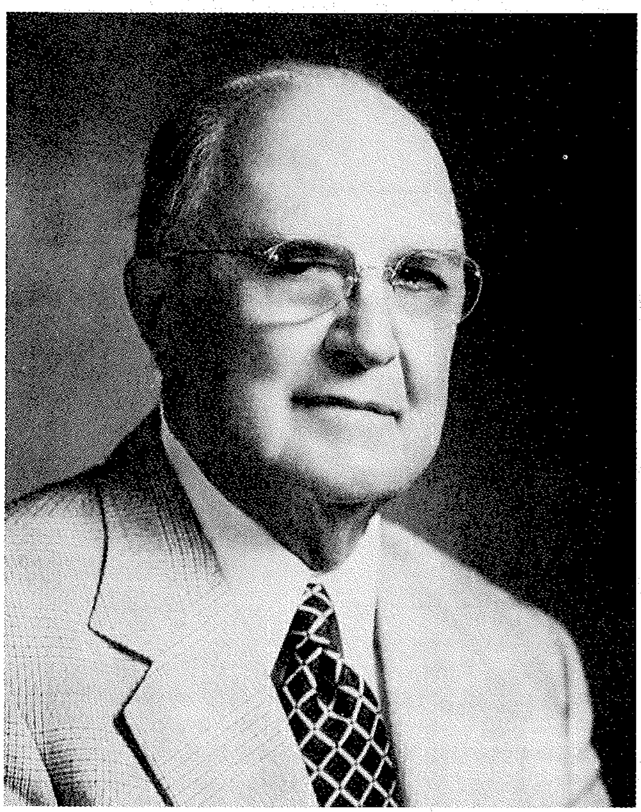

Figure 3. John Clarence Karcher (1894–1978), developer of the seismic reflection method used today in exploration for oil and gas. From Karcher (1987, p. 11).

The World War I Years

Karcher's graduate studies were just beginning when the U.S. entered World War I in April 1917. In June, Karcher left the university to work at the U.S. Bureau of Standards to help with the war effort. There he joined the investigation into the use of sound ranging to locate enemy artillery. Dr. W. P. Haseman, on leave from OU, was also at the Bureau of Standards. Initially, both men were assigned to the Sound Section under Dr. Frank Wenner. According to Sweet (1978, p. 83), during that time together, Karcher and Haseman discussed "the feasibility of utilizing reflected sound waves to determine probable oil field structure," and it was Haseman who initiated the discussion about oil structure. The original Sound Section was soon split up, however, before the ideas went any further than conversation (Sweet, 1978, p. 84). Haseman went to the Bureau's division at the University of Michigan, and Karcher became assistant to Dr. E. A. Eckhardt, who was in charge of reorganizing the Sound Section.

Karcher's recounting of events at the U.S. Bureau of Standards during this time (Karcher, 1987, p. 11–12), although not incompatible with Sweet's (1978), is somewhat different. According to Karcher, he was "assigned the problem of designing and constructing a device for detecting and recording the blast from the muzzle of field artillery pieces by the use of sound waves through the air" (Karcher, 1987, p. 11). While he and other project staff were testing the instruments he had designed, they discussed the possibility of recording seismic waves through the ground, since such waves would originate from the blast at a gun's muzzle, and seismic waves would not be affected by wind direction, or by temperature and pressure changes. They decided to test the idea and two types of geophones (not a term in use at that time) were built at the Bureau machine shop and connected into the recording circuit that was used for sound ranging through the air. During tests, he observed what he interpreted to be reflections from layers of rock inside the earth. Although the method of recording through the ground was abandoned for artillery ranging, Karcher followed Edison's advice to note any unusual phenomenon and followed up on the reflections later, with profound consequences for oil exploration.

The American air sound-wave method was developed into a relatively simple device, which was constructed and sent to the U.S. battlefront in France. Sound ranging had been used by the French as early as 1915, and the British, too, did studies and developed instrumentation under the direction of Lucien Bull and Sir Lawrence Bragg (Sweet, 1987). Dr. C. B Bazzoni (already in England when the U.S. entered the war) was the first American associated with sound ranging, under Bragg's direction. In March 1918, Bazzoni took charge of American Sound Ranging, which used British instruments.

Karcher was sent to France in May 1918 and served as a technical attaché to the U.S. Embassy in Paris for about the last eight months of the war. He spent most of his time in the field on various artillery problems, and observed sound ranging under Bazzoni (Sweet, 1987).

Karcher's Return to Graduate Studies— The Growth of an Idea

In January 1919, Karcher returned to his graduate studies in physics at the University of Pennsylvania, but he also continued to think about the seismic waves that had been observed as reflections (Karcher, 1987). During his undergraduate studies at the University of Oklahoma, Karcher had shared required science classes with geology students through whom he had learned something about "dome-like reservoirs, anticlinal structures, and how oil accumulates in porous rocks or in sands lying under impervious limestone beds" (Karcher, 1987, p. 12). Thus, in early 1919, he thought that it was feasible to use reflected waves to measure the depths to the tops of subsurface layers of limestone, and he discussed the possibility with Dr. Johan August Udden, professor of geology at the University of Texas (Sweet, 1978, p. 84), and with Dr. D. W. Ohern, who had been an OU geology professor (1908–1911) and director of the Oklahoma Geological Survey (1911–1913). Both agreed that the idea had merit.

During the summer of 1919, while again at the U.S. Bureau of Standards, Karcher had the opportunity on weekends to conduct more tests. He recorded dynamite blasts in a rock quarry and proved the existence of seismic reflections (Fig. 4). The next challenge was to "devise a practical procedure that could be developed into a useful device to identify reflections from a hard rock layer and to determine its depth below the surface" (Karcher, 1987, p. 12).

Karcher returned to the University of Pennsylvania in the fall and completed his Ph.D. thesis before the beginning of his final semester. Then he devoted his time to designing instruments for "measuring the depths of rock layers by means of seismic reflections generated by charges of dynamite" (Karcher, 1987, p. 12). He made several patent applications during this period and communicated with Dr. Haseman (who had returned to OU in January 1919), as well as with Ohern and Udden. Haseman and Ohern thought that the results of Karcher's experiments in the rock quarry might interest oil producers in the Oklahoma City area.

Schriever (1964) and Sweet (1978, p. 84–86) describe events in 1919 somewhat differently from Karcher (1987). They indicate that Haseman wrote to Karcher early in 1919, either about the possibility of using reflected seismic waves for prospecting purposes (Schriever) or to ask Karcher if he would be interested in joining him in an oil exploration company that Haseman wished to form (Sweet). According to Schriever, Haseman wrote to Karcher in the winter proposing to organize a company to exploit their ideas concerning reflection seismographs. Both Schriever and Sweet indicate that, in 1919, E. A. Eckhardt and Burton McCollum were involved in discussions with Karcher about the possibility of working together, either with Karcher alone (Schriever) or with Karcher and Haseman (Sweet). Sweet also indicates that McCollum joined Karcher in four patent applications, two relating to refractions and two to reflections.

Whatever the sequence of discussions and correspondence was, it is clear that Karcher's colleagues from OU and the U.S. Bureau of Standards were key players in the story. The stage was set for the formation of the Geological Engineering Company, the first seismic reflection company in history.

Geological Engineering Company

Karcher received his Ph.D. in physics in June 1920 and joined the U.S. Bureau of Standards to work in the acoustics laboratory. In the meantime, Haseman left his position at OU in summer 1919, moved to Oklahoma City, and got busy raising funds for the company that he wanted to form (Sweet, 1978). The OU network certainly seems to have played a big part in his success. He had discussions with Dr. Irving Perrine and Dr. D. W. Ohern* (both former OU geology professors). With their help, Haseman was able to interest Oklahoma City oilmen in the project. Frank Buttram* (OU graduate, former OGS staff, independent oil operator) and the brothers Walter R. and William E. Ramsey joined Haseman, Ohern, and Perrine in forming the Geological Engineering Company (GEC) (www.ok-history.mus.ok.us/enc/seismograph.htm). The company was incorporated in Oklahoma in April 1920 as the very first seismic reflection company: 85% of the corporation stock went to the contributors

*Ohern (director) and Buttram (assistant director) worked together at the Oklahoma Geological Survey. They left the Survey together around 1913 to form Fortuna Oil Company. Both retired as wealthy oil men.

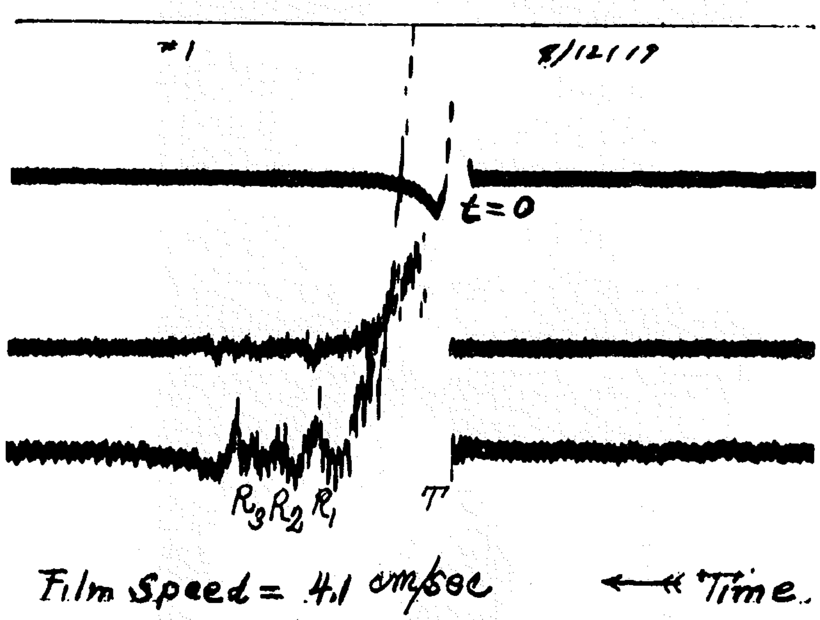

Figure 4. Seismic data that Karcher recorded at the U.S. Bureau of Standards in Washington, D.C., convinced him that reflections from interfaces between rock layers could be observed. On the top trace, t=0 marks the explosion instant. On the bottom trace, T marks the instant of the arrival of the ground wave, and R_1, R_2, and R_3 record the arrivals of reflected waves after the explosion. From Schriever (1964, p. 21).

and 15% was distributed among Karcher, Eckhardt, and McCollum (Sweet, 1978). A total of $28,000 had been subscribed for GEC early in 1921. Funds were sent to Karcher in Washington, D.C., who put together the equipment that would be needed for experimental work to be done in the spring.

Seismic Reflection Experiments by the Geological Engineering Company, Oklahoma City

In May 1921, Karcher took a six-month leave from the U.S. Bureau of Standards. He shipped the equipment to Oklahoma City and went directly there, himself. On June 4, 1921, in what was then the outskirts of Oklahoma City, ~1.25 mi west of Belle Isle, he joined the first seismic reflection crew in history intent on finding petroleum structures. The field party consisted of Karcher, observer; Haseman, shooter; Irving Perrine, helper; and William C. Kite, helper. It is interesting to note that all four men were part of the OU network (former students or faculty) (Table 1).

TABLE 1. — FIRST SEISMIC REFLECTION CREW JUNE 4, 1921

Name	Duty	OU Association
J. C. Karcher	Observer	B.S., Physics (OU); Ph.D., Physics (U. of Penn.)
William P. Haseman	Shooter	Former head of OU Physics Department; Ph.D., Physics (U. of Penn.)
Irving Perrine	Helper	Former OU geology professor
W. C. Kite	Helper	Geologist; former student of Dr. Perrine; OU graduate

Note: Field tests were made near Belle Isle, in what was then the outskirts of Oklahoma City.

Experimental reflection work continued in the vicinity of Oklahoma City throughout June and into early July. They shot nine profiles and spent intervening days calculating the data and improving their equipment (Karcher, 1987). Schriever (1964) shows a schematic diagram of the apparatus used in 1921 (Fig. 5). The basic idea was to set off dynamite charges at the surface; seismic waves were transmitted down through the layers of rock beneath the explosion. At the interfaces between different rock layers, the waves were reflected back to the surface. The reflected waves were detected using several receivers located at different distances from the dynamite source. The basic geometry—a source separated from a group of receivers—used on this first experiment was not very different from that used today to record what is called single-fold data. A great deal of single-fold data is available throughout Oklahoma today, but modern processing adds the results of multiple experiments to create multiple-fold data. This process gives modern seismic data an improved signal-to-noise ratio, but the basic idea is the same.

The Arbuckle Reflection Experiment—Proof of Concept

After the initial seismic reflection shooting at Oklahoma City, GEC's seismic reflection crew needed to work in an area where more was known about the geology. They moved their experiments to the Arbuckle Mountains, where both Ohern and Perrine had taken groups of students on geology field trips. Over a number of days, they calculated the velocities of the Hunton Limestone (11,680 ft/sec), the Sylvan Shale (5,780 ft/sec), and the Viola Limestone (14,070 ft/sec). Together, Karcher, Haseman, Perrine, and Ohern (who had taken Kite's place as a helper on the crew) correctly surmised that the interface between the Sylvan Shale and the Viola Limestone would be ideal for obtaining sharp and usable reflections because of the radical velocity change between the two formations. Ohern then directed the crew to an area in Murray County known as Vines Branch (7 mi north of Dougherty and about halfway between Dougherty and Sulphur, Oklahoma), where a structural dome was known to exist. The caprock of the dome is the Viola; on the flanks of the dome, the Sylvan overlies the Viola (Schriever, 1964). The

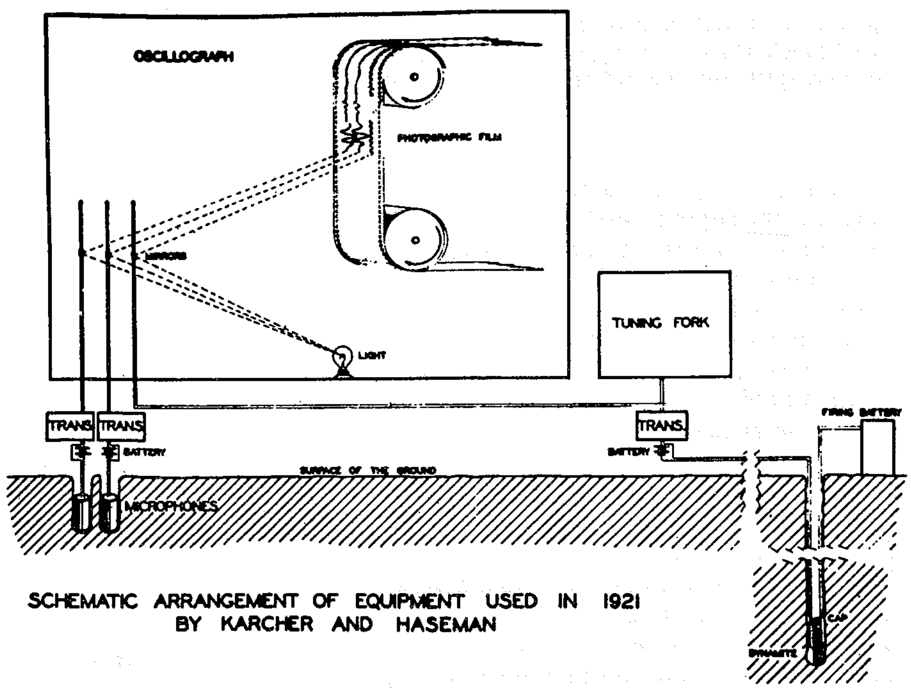

Figure 5. Schematic diagram of the equipment used by the Geological Engineering Company in 1921 for the first seismic reflection exploration in history. The first experiment was carried out near Belle Isle, in what was then the outskirts of Oklahoma City, on June 4, 1921. From Schriever (1964, p. 21).

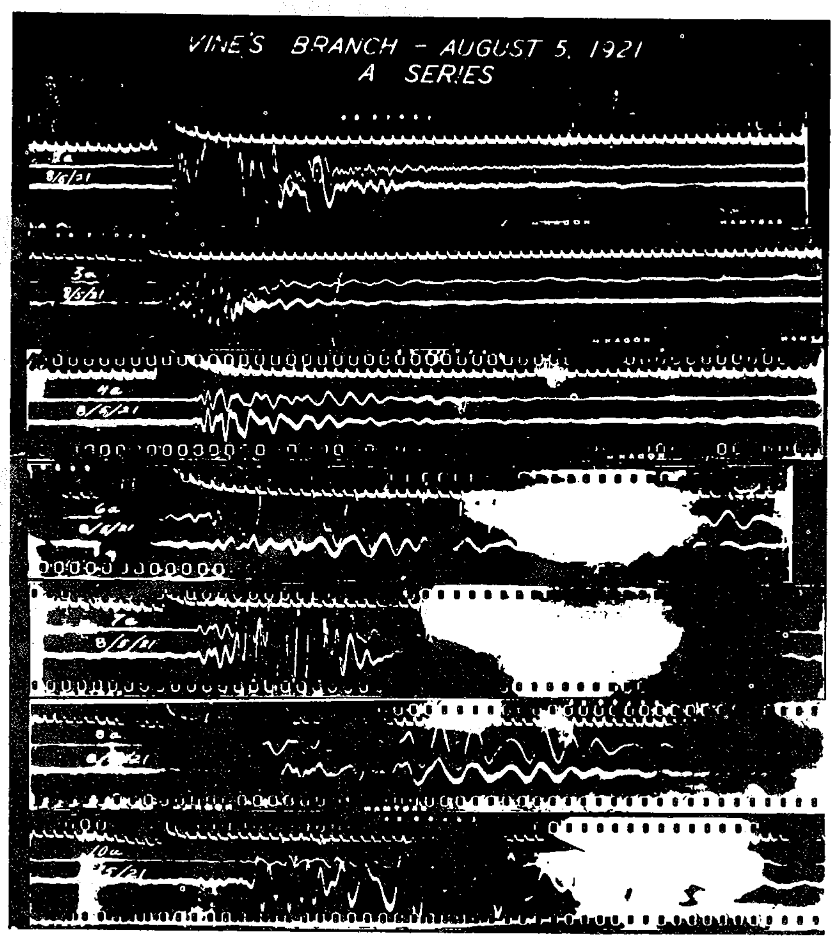

Figure 6. A photostatic copy of data recorded in the Arbuckle Mountains at Vines Branch, Murray County, Oklahoma, by the Geological Engineering Company in August 1921. From Karcher (1987, p. 13).

Two More Firsts for Oklahoma—A Contract for Seismic Reflection Exploration and a Seismic Structure Map

The Arbuckle experiment had given GEC convincing proof that the seismic reflection method worked, but the company needed additional funding to keep operating. Ohern and Perrine left at once for Ponca City to talk to their personal friend, E. W. Marland, about establishing a contract between Marland Refining Company (later Conoco) and GEC. Perrine was the ideal person to contact Marland. He had consulted for Marland Refining for approximately three years (1912–1915) and personally had instructed Marland in the fundamentals of geology. The two men often talked late into the night. It is said that they walked every road in Kay County so Marland could actually see the geology for himself.

In spite of this warm friendship, Marland only promised to underwrite the bare cost of operating the reflection crew for two months of work in the Ponca City area. (Sweet [1978] suggests that Marland—who was known for trying new technology—had over extended his finances at that time.) It was not as much support as GEC was expecting, but it kept the effort alive. It was another first historically, too—the first contract for seismic reflection exploration.

While Perrine and Ohern were in Ponca City, Haseman, Karcher, and Reginald Ryan (Dr. Ohern's nephew) did some additional testing near Oklahoma City (Fig. 8). On September 1, the crew moved to the Ponca City area. The GEC crew (Haseman, Karcher, Ryan, and field labor; Paul Johnson replaced Ryan in September) to-

Viola plunges steeply to the east away from the dome, and the depth to the Sylvan increases as the distance from the dome increases. This prospect was shot from July 22 to early August 1921 to try to define the Vines Branch Dome. According to Karcher (1987, p. 14), the records were of good quality and easy to read (Fig. 6). He timed all the records and calculated the dip slope of the Viola beneath the Sylvan; the calculations agreed well with the dip slope as determined by the geologists with alidade and plane table (Karcher, 1987, p. 14). Figure 7 is a geological cross section of the depth of the Viola prepared from the data. Note that Karcher was swinging arcs of equal traveltime to account for the dip of the reflector (Schriever, 1964, p. 21–22). Today, this method of finding the true position of a reflector is called "migration." Apparently, Karcher was migrating his data long before the subject became popular in the 1960s and 1970s.

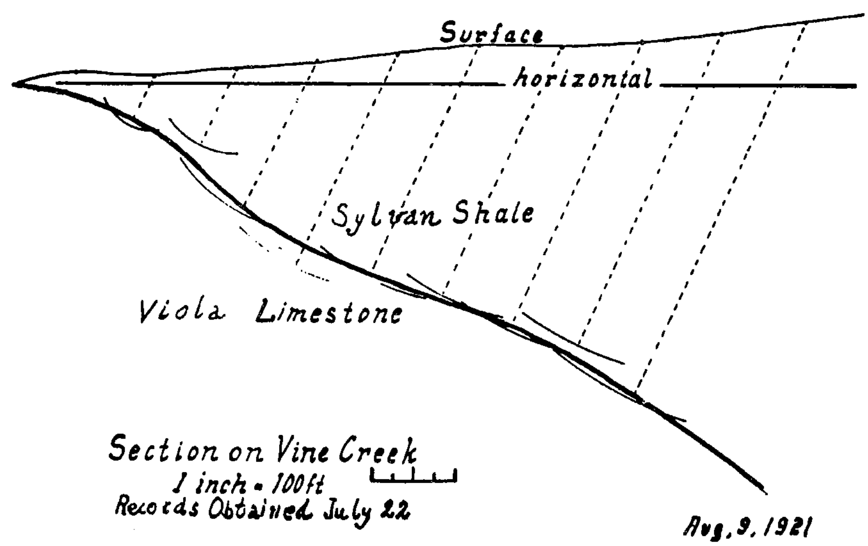

Figure 7. A geological cross section of the depth of the Viola Limestone, prepared from the seismic reflection data recorded by J. A. Karcher, W. P. Haseman, Irving Perrine, and D. W. Ohern at Vines Branch, Murray County, Oklahoma, on July 22, 1921. From Schriever (1964, p. 22).

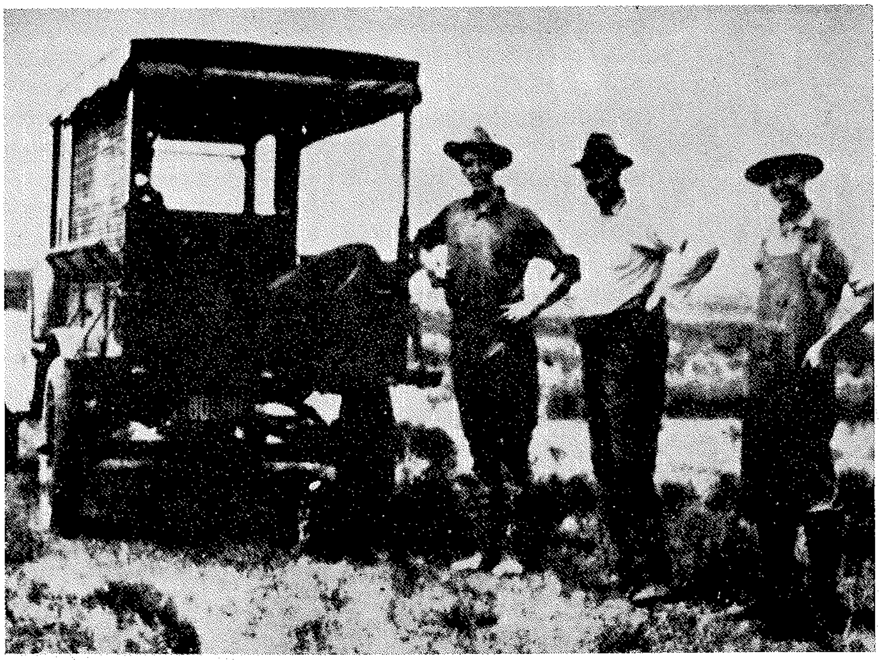

Figure 8. Geological Engineering Company field crew—Reginald G. "Rex" Ryan (Dr. D. W. Ohern's nephew), W. P. Haseman, and J. C. Karcher—shooting data near Oklahoma City, August 1921. From Schriever (1964, p. 23).

gether with Marland geologists (F. Park Geyer, chief geologist; Fritz L. Aurin, assistant chief geologist; Glen Clark; and E. C. Parker) explored in Kay and Grant Counties in September and October (Fig. 9). During this effort, Aurin made the first structure map in history to be based on seismic reflection data (Fig. 10).

In mid-October, Burton McCollum arrived in Ponca City and joined the shooting efforts. Sweet (1978) speculates that McCollum had made an instant decision—based on the Vines Branch data, which he first saw in September—to make seismic exploration his life's work.

In late October, there was another meeting between Marland and GEC personnel, at which Marland offered a somewhat better contract price for continued operations but wanted an exclusive contract. Reluctantly, GEC turned down the offer. Karcher (1987, p. 15) adds that oil companies and producers lost interest in GEC's new method because of the discovery of the large Garber and Burbank fields in July and August. The price of oil dropped to 15¢ per barrel, and no one believed that GEC could find oil at a cost of less than 50¢ per barrel. GEC stopped work on December 22, 1921, and Karcher returned to his job at the U.S. Bureau of Standards. McCollum, Haseman, and Johnson did about three months work in the Ponca City area in the spring of 1922 but could secure no profitable contract. The company was liquidated and the assets eventually became the property of Burton McCollum.

Feast or Famine

A famine in oil prices brought the first phase in the development of the seismic reflection method to a close. Karcher had seen no return for his hard work on seismic reflections, but he could return to his job at the U.S. Bureau of Standards, and within six months he had been offered a better paying position with the American Telephone and Telegraph Company (AT&T). For the next three years, he worked for Western Electric Company (a subsidiary of AT&T).

By March 1925, the price of oil had rebounded to more than $3 per barrel, and people started contacting Karcher about the seismic reflection method. One of those people was Everette Lee DeGolyer.

DEGOLYER AND KARCHER, TOGETHER

Geophysical Research Corporation

In 1925, the time was ripe for DeGolyer and Karcher to meet. The price of oil had rebounded, and DeGolyer was actively looking for someone to develop seismic methods. In 1924, the brilliant German scientist, Dr. Ludger Mintrop, proved that his seismic refraction method was "one to be reckoned with" (DeGolyer, 1935). A crew from Mintrop's Seismos Company—under contract to Gulf Production Company—had used Mintrop's mechanical seismograph to locate the Orchard Dome in Texas. It was "the first seismic discovery on the Coast and possibly the first in the world" (DeGolyer, 1935). DeGolyer went in search of someone competent to develop seismic methods.

Once more, the OU network had a role to play. DeGolyer called Harold V. Bozell, who had been a professor in the School of Electrical Engineering at OU when Karcher was a student, and asked if Bozell knew where Karcher could be

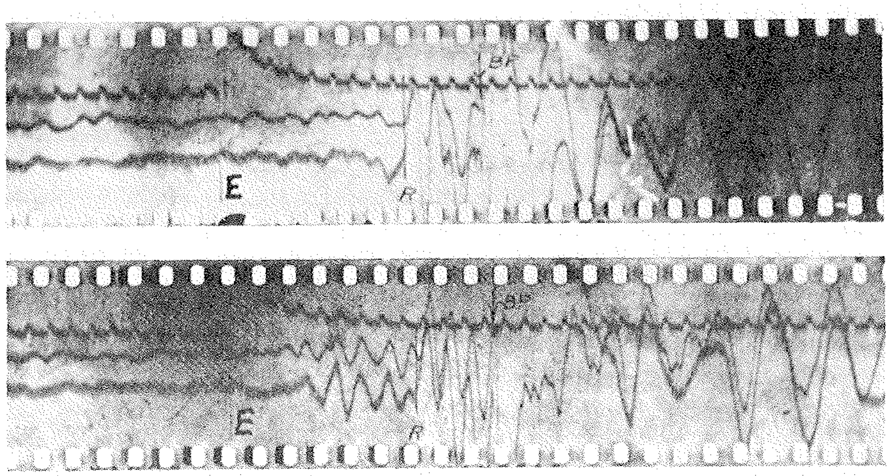

Figure 9. Two reflection seismograph records from a survey made by the Geological Engineering Company under contract to Marland Refining Company, September 1921. From Schriever (1964, p. 22).

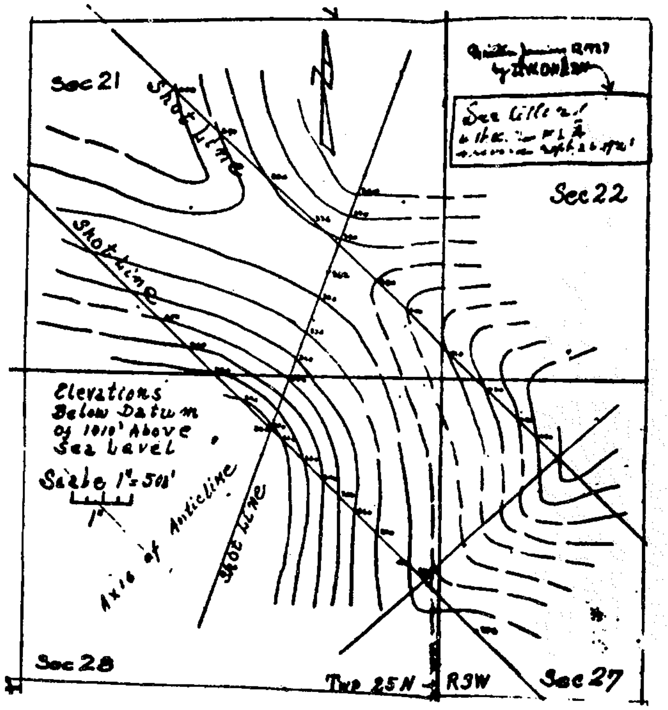

Figure 10. History's first seismic structure map, based on data recorded near Ponca City in September 1921 for Marland Refining Company. The map was made by Fritz L. Aurin, assistant chief geologist for Marland. From Schriever (1964, p. 22).

located. He did. Bozell arranged a meeting between DeGolyer and Karcher, and, in March 1925, DeGolyer, Bozell, Karcher, and Dr. Donald C. Barton had lunch together at the Banker's Club in New York City, where they discussed the experimental work in the seismic reflection method. The meeting led to a lifetime friendship and long-term partnership between DeGolyer and Karcher.

The Geophysical Research Corporation (GRC) was incorporated in May 1925 as a subsidiary of Amerada; DeGolyer became the president and Karcher was vice president. The first laboratory was a large room over a drug store in Bloomfield, New Jersey. Karcher recruited an exceptional technical staff—Eugene McDerMott, E. E. Rosaire, Fabian Kannenstine, Benjamin Weatherby, Ted Born, and H. Bates Peacock (Robertson, 1986).

DeGolyer introduced Karcher to Reginald Fessenden and turned further discussions about Fessenden's patent over to Karcher. The two physicists met many times and, after a thorough investigation, Karcher and DeGolyer mutually agreed that Fessenden's patent was fundamental and should be acquired for GRC (Sweet, 1978, p. 73). Through negotiations with Karcher, Fessenden finally agreed to sell his patent, and the way was clear for GRC to develop the seismic reflection method.

At first, however, in response to Ludger Mintrop's success with refraction exploration, GRC fielded refraction crews in "the intensive campaign of searching for shallow salt domes which swept the Gulf Coast of Texas and Louisiana from 1924 to 1930" (DeGolyer, 1935, p. 5). Of the approximately 60 domes found in the region during that period, GRC discovered about 40 (Robertson, 1986). During that time, Karcher improved the refraction technique by introducing the radio time-break, sound surveying, and electrical recording (DeGolyer, 1938).

Even during the refraction years, GRC's primary interest was in developing the seismic reflection method, which promised to provide better data—and require much less dynamite (Robertson, 1986). They had a viable method in operation by the late 1920s. On September 13, 1928, Amerada spudded the No. 1 Hallum well in Pottawatomie County, Oklahoma (center NE¼SE¼SE¼ sec. 1, T. 8 N., R. 4 E.). It was completed as a commercial producing well on December 4, 1928. The No. 1 Hallum was the first well in history drilled on structure that had been mapped by seismic reflection data (Karcher, 1987, p. 17). Seismic exploration history was again made in Oklahoma. The discovery of the prolific Edwards field, among other discoveries in Oklahoma, soon convinced the entire industry that the reflection method was an important exploration tool. GRC's place in history was secure.

In 1929, DeGolyer moved from the presidency of Amerada to chairman of its board of directors, and Alfred Jacobsen became president. When Jacobsen decided that all GRC reflection parties would be limited for the sole use of Amerada, DeGolyer disagreed. He sent in his letter of resignation as chairman of the board in 1929, 1930, and 1932. When it finally was accepted in 1932, DeGolyer also ceased to be the president of GRC. By then, his vision of the vast potential for seismic reflection exploration was being realized through another company.

Geophysical Services, Inc.

In 1930, DeGolyer made a bold move. He made a secret financial arrangement with Karcher to form a new exploration company, Geophysical Services, Inc. (GSI). DeGolyer provided $100,000 and took a 50% interest; the other 50% was divided among key staff (Sweet, 1978, p. 147). Nobody in the industry except Karcher knew of DeGolyer's involvement. (As late as 1941, Cecil Green only learned of DeGolyer's part ownership in GSI when Green and his partners purchased the company [Robertson, 1986].) Karcher became the president of GSI and Eugene McDermott became vice president; both left GRC to take up their new positions. The new company had well-known reflection expertise and was an immediate success. In March 1930, Karcher sold 10 reflection seismograph contracts to 10 different oil companies in less than a month! GSI became one of the largest seismic reflection contractors of its time. By the end of 1933, the company had nearly 40 crews in the field. The seismic reflection method of exploration, born in Oklahoma a dozen years earlier, had come of age!

SUMMARY

The seismic reflection method should have "Oklahoma" stamped on it. John Clarence Karcher and Everette Lee DeGolyer, two OU graduates, played key roles in developing the method, and Oklahoma was the scene of many firsts for seismic reflection exploration.

The Geological Engineering Company (GEC), the first seismic reflection company in history, was incorporated in

Oklahoma in 1920. On June 4, 1921, a GEC crew used instrumentation developed by John Clarence Karcher to carry out the world's first seismic reflection exploration near Belle Isle, in what was then the outskirts of Oklahoma City. All members of that first crew were OU alumni or former OU faculty: J. C. Karcher, W. P. Haseman, Irving Perrine, and W. C. Kite. In the spring of 1971, to commemorate the 50th anniversary of the advent of the reflection seismograph, the Society of Exploration Geophysicists dedicated a monument at Oklahoma City's Belle Isle Library (Fig. 11).

In another historic seismic experiment, at Vines Branch in the Arbuckle Mountains, a GEC crew proved that seismic reflections could be used to map the geology. Dr. D. W. Ohern, the second head of geology at OU and the second director of the Oklahoma Geological Survey, pointed out this ideal location for proving the method. In addition, in August 1921, E. W. Marland (Marland Refining Company) gave history's first contract for seismic reflection exploration to GEC. In conjunction with that contract to shoot in the Ponca City area, Fritz Aurin (an OU graduate) made the first seismic

Figure 11. John Clarence Karcher, spring 1971, standing near the monument at Oklahoma City's Belle Isle Library that honors the first seismic reflection crew in history. The Society of Exploration Geophysicists dedicated the monument to commemorate the 50th anniversary of the advent of the reflection seismograph. From Karcher (1987, p. 18).

structure map in history to be based upon seismic reflection data.

Plummeting oil prices forced GEC out of business in 1922. Nevertheless, in the short time that it operated, GEC secured a place for Oklahoma in the history of the seismic reflection method.

A few years later, the Oklahoma story gathered momentum again. As the price of oil went up, Everette L. DeGolyer of Amerada Petroleum Corporation sought out Karcher, and, in 1925, the two put together Geological Research Corporation (GRC) under the umbrella of Amerada. In 1928, GRC made the first commercial discovery that used the seismic reflection method—in Oklahoma! After Amerada limited all GRC reflection parties for Amerada's sole use in 1929, DeGolyer secretly financed Geophysical Services, Inc. (GSI), a new exploration company to be led by Karcher. The new company became one of the most successful seismic reflection contractors of its time.

The seismic reflection method continues to play a vital role in today's oil and gas exploration. Its history is so rich with Oklahoma connections that the method can truly be called a product of Oklahoma.

ACKNOWLEDGMENTS

As noted in the introduction, much of the material for this article comes from George Elliott Sweet's (1978) book, *The History of Geophysical Prospecting.* Funds from the Society of Exploration Geophysics (SEG) allowed Sweet to travel worldwide interviewing people about the early history of exploration geophysics. SEG member, Craig Ferris, encouraged Sweet to write the history. Dr. M. Charles Gilbert, School of Geology and Geophysics at the University of Oklahoma, supplied additional information and edited an earlier version of this article. Thanks go to L. C. (Lee) Lawyer and to M. Charles Gilbert for their constructive reviews of the article. The author's interest in this topic was sparked by a suggestion from Dr. Charles J. Mankin.

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new OGS publications

STATEMAP Program: Geologic Maps of the Oklahoma City Metropolitan Area Available on CD-ROM

STATEMAP is a cooperative program funded by the Oklahoma Geological Survey (OGS) and the U.S. Geological Survey under the National Cooperative Geologic Mapping Program. As part of the STATEMAP program, the OGS has been mapping the Oklahoma City metropolitan area at a scale of 1:24,000 since 1997. Each year, starting in 1998, the OGS has published four 7.5′ quadrangles as part of its series of open-file reports. The maps published before 2001 are available only as author-prepared, black-and-white geologic maps. The 2001 and 2002 maps are being produced as read-only PDF files on CD-ROMs. Users of these maps will be able to download and print colored geologic maps of any area in the quadrangle at (almost) any scale.

These maps provide detailed information about the surface geology of the metropolitan area. Locations of outcrops, oil and gas wells, and municipal water wells are shown on the maps. In addition, the maps contain information of importance to city planning, including (1) the extent of the Garber-Wellington aquifer recharge area, (2) the extent of expansive clay-rich soils overlying the Hennessey Formation, and (3) the location of sand and gravel resources.

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(scale: 1:24,000; 7.5′ topographic base)

OF2-98. Geologic map of the Piedmont and Bethany NE quadrangles, Kingfisher, Logan, Canadian, and Oklahoma Counties, *by Neil H. Suneson and LeRoy A. Hemish.* B&W on paper, $4.80.

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AAPG Annual Convention

Salt Lake City, Utah

May 11–14, 2003

On behalf of the Utah Geological Association and the 2003 Coordinating Committee, I extend to you my sincere invitation to attend the 2003 Annual Convention of the American Association of Petroleum Geologists in Salt Lake City. Salt Lake City, in the heart of the country's most scenic and accessible geology, is located at the foot of the spectacular Wasatch Mountains on the east with its namesake, Great Salt Lake, to the west. As host of the 2002 Olympic Winter Games, Salt Lake City has entertained the world and again welcomes the AAPG.

Our convention logo, "Energy—Our Monumental Task," applies to the entire worldwide membership of the AAPG for the 21st century. The backdrop depicts the famous Monument Valley, located in Arizona and Utah, which represents the beauty and geology of the American West. Those who visit Monument Valley do so to be inspired by the beautiful vistas of the colorful buttes and mesas. We too, as geoscientists, need to be inspired to fulfill what is truly a monumental task—to provide energy to an energy-hungry world.

The convention offers the perfect opportunity to continue this task by attending technical sessions that cover a wide range of hot topics including new play concepts from the world's petroleum provinces, deep-water sequence stratigraphy and deposition, biostratigraphy, reservoir modeling, salt tectonics, lacustrine reservoirs, and emerging gas plays. The popular e-poster and core sessions will also return. Each of the AAPG divisions is sponsoring specific sessions and forums including coalbed methane, carbon dioxide sequestration, remote sensing, methane hydrates, environmental best practices, and national security as it pertains to petroleum.

One does not come to Utah without seeing some of the best outcrops in the world. The field trips will visit the classic Utah geology that serves so well as outcrop reservoir analogs. Participants can examine thrust and extensional faulting, modern and ancient lake deposits, fluvial deltaic sequences, carbonate mounds, eolian facies, salt tectonics, dinosaurs, coal and coalbed geology, and sequence stratigraphy. Many of these trips will take place in national parks such as Zion, Arches, Canyonlands, Lake Powell, and the Grand Canyon, which were established because of their geologic scenic beauty. The field trips are complimented by a wide variety of excellent and timely short courses.

We look forward to hosting the 2003 Annual Convention of the AAPG and geoscientists from around the world. Please join us in Salt Lake City for what will truly be a monumental event!

Thomas C. Chidsey, Jr.
General Chairman

Convention Agenda

Technical Program

Monday, May 12

Frontiers in Coalbed Methane Development
New Play Concepts: Asia
Management : Technology Trends in Exploration and Production
Evaluating Controls on Depositional Elements of Deep-Water Deposits: Climate, Sea-Level, Physiography, Sediment Supply
Global Salt Tectonics
The Influence of Stress Regimes on Fluid Migration and Entrapment
Burial/Thermal History of Sedimentary Basins: Low-Temperature Thermochronology, Fluid Inclusions, and Other Methods
Forum: Bullish Commodities, Crises in Investor Confidence, and Meeting Regulatory Challenges
Forum: The Earthscope Initiative—A New View into the Earth
Future Gas Plays: Tight Gas, Basin-Centered Gas, and Other Unconventional Gas Targets
New Play Concepts: Atlantic Margins
Near-Surface Hydrocarbon Migration: Mechanisms and Seepage Rates (from Hedberg Conference)
Comparative Salt Tectonics: Similarities and Differences between Salt Basins
Governmental Affairs Forum: Public Lands Access in the Rocky Mountains
How to Thrive (and Survive) as an Independent Geologist

Tuesday, May 13

Interactive E-Poster: 3-D Interpretation Techniques Using 3-D Visualization Software
SEPM Research Symposium: Processes and Images of Incised Valley and Lowstand Deposits
Biostratigraphic and Paleoenvironmental Analyses in Deep-Water Settings
Allocyclic Versus Autocyclic Processes in Depositional Systems
Sedimentary, Thermal, and Structural Evolution of Extensional Basins
Canadian Oil and Gas Resources
Approaches and Measurement of Uncertainty in Reservoir Modeling–Reservoir Characterization
Depositional Processes, Facies, and Sequence Stratigraphy in Foreland Basin Settings
New Discoveries
Sequence Stratigraphy of Giant Fields from Around the World
Deep-Water Siliciclastic Sequence Stratigraphy Applications—Successes and Failures
Mechanics and Dynamics of Thrust Belts—Impact on Evolving Petroleum Systems
Quantitiative Stratigraphy and Geostatistics: New Approaches and Applications

Impact of Structural and Stratigraphic Uncertainty in Reservoir Modeling—Approaches to Define Uncertainty in Faulted Reservoirs

Wednesday, May 14

Intrabasinal Influence of Paleotopography on Deposition in Deep-Water Siliciclastic Settings

Application of Seismic Attribute Analysis to Reservoir and Exploration Studies

Geological Sequestration of CO_2

Shale Diapirs, Mud Volcanoes, and Hydrocarbon Systems

Geochemical Exploration: Strategies for Success

Styles of Intraplate Deformation and Associated Sedimentary Basins

Experimental and Numerical Modeling of Deposition on Continental Margins

3-D Interpretation Techniques Using 3-D Visualization Software

Current Research in Microbial Carbonates

Global Methane Hydrate Resources

Porosity Evolution within a Sequence Stratigraphic Framework

New Developments in Reservoir-Scale Geochemistry—Organic and Inorganic

Quantifying Flow Structures (Porosity and Permeability) around Faults

Short Courses

Pre-Convention

Geochemical Exploration for Oil and Gas—Strategies for Success, *May 10*

Thrustbelts: Structural Architecture, Thermal Regimes, and Petroleum Systems, *May 10–11*

Shale Gas Potential of the Western Interior of North America, *May 11*

Introduction to the Petroleum Geology of Deep-Water Clastic Depositional Systems, *May 8–10*

Coalbed Methane: Geologic and Engineering Principles, *May 10*

Principles of Play Risk Analysis, *May 10–11*

Desktop Applications for the Petroleum Geoscientist: Excel, Access, and Database Fundamentals, *May 10*

Desktop Applications for the Petroleum Geoscientist: PowerPoint and Effective Use of Graphics in Geologic Reports, *May 11*

Tips on Becoming a Successful Consultant, *May 11*

Mapping for Environmental, Facility, and Exploration Applications, *May 11*

3-D Seismic Interpretation for Geologists, *May 10–11*

Applied Biostratigraphy for Geologists, Geophysicists, and Engineers, *May 11*

Complex Well Technology for Earth Scientists and Engineers: A Multi-Discipline Review of Application Screening, Design, Implementation, and Intervention of Horizontal and Complex Wells, *May 11*

Subsurface Fluid Pressures and Their Relation to Oil and Gas Generation, Migration, and Accumulation, *May 11*

Pennsylvanian Heterogeneous Shallow-Shelf Carbonate Buildups of the Paradox Basin, Utah: A Core Workshop, *May 10*

Post-Convention

E&P Methods and Technologies: Selection and Application, *May 15–17*

Carbonate Sequence Stratigraphy and Reservoir Characterization: Concepts and Applications, *May 15–16*

Deep-Water Sands: Integrated Stratigraphic Analysis—A Workshop Using Multiple Data Sets, *May 15–16*

Seismic Imaging of Subsurface Geology, *May 15–16*

Field Trips

Pre-Convention

Fluvial-Deltaic Sequence Stratigraphy—Upper Ferron Sandstone, *May 7–11*

Classic Geology of Zion National Park and Cedar Breaks National Monument, *May 8–10*

Extensional and Contractual Crustal Architecture in the Southern Nevada Area, *May 8–10*

Facies Asymmetry in Alluvial-Lacustrine Basins: A Transect Across the Uinta Basin, Eastern Utah and Western Colorado, *May 8–11*

Central Utah, To Thrust or Not to Thrust, *May 10*

Geology Along the Wasatch Front, *May 10*

Antelope Island and Great Salt Lake, Utah, *May 10*

Grand Canyon Geology Via the Colorado River, Arizona, *May 4–11*

Great Salt Lake Cruise: Hazards and the Ecosystem, *May 11*

Characterization and Modeling of Shallow-Marine and Coastal Reservoirs, Book Cliffs, Utah, *May 7–10*

Late Cretaceous Facies Tract, Book Cliffs Area, Utah, *May 10*

Post-Convention

Reservoir-Scale Faults: Hydraulic Structure and Implication for Modeling and Prediction, *May 14–16*

Pleistocene Lake Bonneville, Utah—Stratigraphy and Sediment Response to Climate, Lake Level, Sediment Supply, and Tectonic, *May 15–17*

Timeless Geologic Scenes of Glen Canyon and Rainbow Bridge via Lake Powell, Utah-Arizona, *May 15–18*

Structure, Salt Tectonics, and Stratigraphy of Arches and Canyonlands National Parks and Vicinity, Utah, *May 15–18*

Structural Continuity of the Sevier Thrust Belt Across the Uinta Arch, *May 15–16*

Carbonate Reservoir Characterization: From Rocks to Fluid Flow Simulation Using Sequence Stratigraphy, Paradox Basin, Utah, *May 15–19*

Coalbed Gas Deposits of Central Utah, *May 14–16*

Deep-Water Reservoirs, California, *May 14–17*

Paleozoic and Mesozoic Eolian Systems of Southeastern Utah, *May 14–17*

Sedimentology and Sequence Stratigraphic Response to Changes in Accommodation: Predicting Reservoir Architecture, Book Cliffs, Utah, *May 14–18*

Morrison Formation Sequence Stratigraphy—Grand Junction, Colorado, to Ticaboo, Utah, *May 14–18*

Late Jurassic–Early Cretaceous of the Dinosaur Diamond, Eastern Utah and Western Colorado, *May 15–17*

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Preregistration deadline: April 8, 2003

upcoming meetings

MAY

Interstate Oil and Gas Compact Commission, Mid-Year Meeting, May 18–21, 2003, Williamsburg, Virginia. Information: IOGCC, P.O. Box 53127, Oklahoma City, OK 73152; (405) 525-3556; fax 405-525-3592; e-mail: iogcc@iogcc.state.ok.us. Web site: http://www.iogcc.state.ok.us/.

American Wind Energy Association, WINDPOWER 2003 Conference, May 18–21, 2003, Austin Texas. Information: AWEA, 122 "C" Street, N.W., Suite 380, Washington, DC 20001; (202) 383-2500; fax 202-383-2505; e-mail: windmail@awea.org. Web site: http://www.awea.org/conference/.

39th Forum on the Geology of Industrial Minerals, May 18–24, 2003, Sparks, Nevada. Information: Terri Garside, Nevada Bureau of Mines and Geology, Mail Stop 178, University of Nevada, Reno, NV 89557; (775) 784-6691, ext. 126; fax 775-784-1709; e-mail: tgarside@unr.edu. Web site: http://www.nbmg.unr.edu/imf/.

Oklahoma Geological Survey and Sarkeys Energy Center Symposium

INTERPRETING RESERVOIR ARCHITECTURE USING SCALE-FREQUENCY PHENOMENA

Oklahoma City, June 19–20, 2003

A two-day symposium will examine Scale-Frequency Phenomena and the application of these phenomena to defining reservoir architecture. Many of the presentations will look at rocks with different frequency information that can be equated to viewing rocks in color.

Specifically, the symposium will focus on the frequency-dependence of physical properties (rheological and transport) of rocks as well as the scale-dependence of these properties. The idea is to bring "color" to an otherwise black-and-white view of rocks currently used.

Although the industry has lived for years dealing with measurements at different scales (e.g., the log scale or the reservoir scale), new ideas are available for a better understanding of the physical relationships between measurements at different scales and how to utilize them to find more oil and gas. For example, understanding the physical relationship between surface seismic measurements at one frequency and sonic measurements at another frequency offers potentially new ways of recognizing hydrocarbon zones where other logs fail to detect such hydrocarbons.

An important objective of this symposium is to transfer information to the industry to aid in the search for and production of oil and gas resources. The emphasis will be upon those new technologies and ideas that can contribute to exploration/production success.

Information: Raymon Brown, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 or (800) 330-3996; fax 405-325-7069; e-mail: raybrown@ou.edu. Web site: http://www.ogs.ou.edu/.

JUNE

Oklahoma Wind Power and Bioenergy Conference, June 19, 2003, Norman, Oklahoma. Information: Tim Hughes, Oklahoma Wind Power Initiative, 3200 Marshall Ave., Suite 110, Norman, OK 73072; (405) 447-8412; fax 405-447-8455; e-mail: thughes@ou.edu. Web site: http://www.seic.okstate.edu/owpi.

American Water Resources Association, International Congress: "Watershed Management for Water Supply Systems," June 29–July 2, 2003, New York City. Information: Peter E. Black, Organizing Chair, pebchair@esf.edu. Web site: http://www.awra.org/meetings/NewYork2003/index.html.

JULY

XVI INQUA Congress, July 23–30, 2003, Reno, Nevada. Information: Marjory Jones, Congress Secretary, Division of Hydrologic Sciences, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512; e-mail: inqua03@dri.edu. Web site: http://www.inqua2003.dri.edu.

AUGUST

Applied Geology for the Petroleum Engineer, August 7, 2003, Norman, Oklahoma, co-sponsored by the Oklahoma Geological Survey and Petroleum Technology Transfer Council. Information: Michelle Summers, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 or (800) 330-3996; fax 405-325-7069; e-mail: mjsummers@ou.edu. Web site: http://www.ogs.ou.edu/.

SEPTEMBER

APPEX: AAPG Prospect and Property Exposition, September 9–11, 2003, Houston, Texas. Information: Michelle Mayfield Gentzen, phone (918) 560-2618 *or* (888) 945-2274 ext. 618; e-mail: mmayfiel@aapg.org. Web site: http://www.aapg.org.

American Association of Petroleum Geologists, International Conference and Exhibition, September 21–24, 2003, Barcelona, Spain. Information: AAPG Convention Dept., P.O. Box 979, Tulsa, OK 74101; (918) 560-2679; fax 918-560-2684; e-mail: convene@aapg.org. Web site: http://www.aapg.org.

OCTOBER

Society of Petroleum Engineers, Annual Technical Conference and Exhibition, October 5–8, 2003, Denver, Colorado. Information: SPE, P.O. Box 833836, Richardson, TX 75083; (972) 952-9393; fax 972-952-9435; e-mail: SPEDAL@spe.org. Web site: http://www.spe.org/.

American Association of Petroleum Geologists, Mid-Continent Section, Annual Meeting, October 12–14, 2003, Tulsa, Oklahoma. Information: Bob Merrill, Samson, Two West Second St., Tulsa, OK 74102; (918) 591-1816; fax 918-591-7816; e-mail: rmerrill@samson.com. Web site: http://www.aapg.org/meetings/mcs03/.

Interstate Oil and Gas Compact Commission, Annual Meeting, October 19–21, 2003, Reno, Nevada. Information: IOGCC, P.O. Box 53127, Oklahoma City, OK 73152; (405) 525-3556; fax 405-525-3592; e-mail: iogcc@iogcc.state.ok.us. Web site: http://www.iogcc.state.ok.us/.

Oklahoma abstracts

The Oklahoma Geological Survey thanks the Geological Society of America for permission to reprint the following abstracts of interest to Oklahoma geologists.

Evolution of a Hyperpycnal Lacustrine Delta, Red River/ Lake Texoma, Texas-Oklahoma

CORNEL OLARIU, ROBERT J. STERN, and *JANOK P. BHATTACHARYA,* Dept. of Geosciences, University of Texas at Dallas, Richardson, TX 75083

The Red River where it flows into Lake Texoma provides a natural laboratory for studying how deltas evolve. This delta prograded into Lake Texoma more than 15 km since 1940 when the lake was impounded. Growth of the delta and change in its morphology was observed using aerial photos and satellite images collected from 1955 to 2002. Because basin energy is negligible compared with river energy, river processes dominate delta formation. A correlation between morphology variation and river discharge variation was established for hyperpycnal Red River delta built into Lake Texoma. From 1940 to 1981 annual discharge averaged around 100 m^3/sec, with values of 50 m^3/sec between 1958 and 1981. Annual discharge since 1981 averaged between 150 and 250 m^3/sec with the exception of 4 years when it was between 50 and 100 m^3/sec. When river discharge was low (pre 1981), the delta was lobate. When river discharge was high (post 1981) the delta is elongate (finger type). Input of sediments and delta progradation is controlled by river discharge. At 5 m^3/sec water discharge the sediment flux is 1.8*103 m^3/sec. At extreme water discharge (1.2*103 m^3/sec) the sediment flux is 9*105 m^3/sec. This volume of sediments approximates 150 m daily delta progradation into a basin similar to Lake Texoma (3 km wide and 2 m depth). River discharge also controls water density. Because Permian and Pennsylvanian evaporites deposits underlie much of the watershed, at low discharge the river water is saline (4.9 g/l TDS), river water is denser than lake water. During high discharges salinity is diluted by rainwater but, because suspended sediment concentration increases (21.1 g/l for a river discharge of 1022.2 m^3/sec), river water is still denser than lake water. As a consequence of salinity/suspended sediments interplay, the Red River frequently has a hyperpycnal type flow. Internal architecture of delta deposits can be inferred from delta morphology. During low discharges lobate shape will produces tabular, basinward dipping bodies, during high discharge more elongate, channel type bodies form.

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Channel Geometry and Morphology of the Dry Cimarron River of New Mexico and Oklahoma

JOSEPH C. CEPEDA, Dept. of Life, Earth, and Environmental Sciences, West Texas State University, P.O. Box 60162, Canyon, TX 79016

This study is part of a project comparing the geometry, morphology, and erosional and depositional history of two river basins, the Canadian River of Texas and New Mexico and the Dry Cimarron.

The upper segment of the Dry Cimarron in the volcanic highlands of the Raton-Clayton Volcanic Field decreases in elevation from about 2500 to 1700 meters above sea level and has an average gradient of 17.5 m/km. The width of the river valley is generally 1–2 km wide in this segment.

The middle segment of the river valley is carved into Mesozoic shales, sandstones, and siltstones, and channel elevation decreases from 1700 m to 1220 m above sea level with an average channel gradient of 4 m/km. The lower segment studied, upstream from the Kansas/Oklahoma line, lies within the High Plains Province, underlain by the late Tertiary Ogallala Formation. In this segment the channel elevation decreases from 1220 m to 1130 m above sea level with an average channel gradient of 1.9 m/km.

Although width of the valley generally increases downstream, the greatest valley widths are achieved in the Mesozoic section segment where width may exceed 3 km. The width of the active channel, at bank full discharge, increases downstream from 2 to 4 m wide in the volcanic highlands segment; to 6 to 15 m in the middle segment; to 15 to 60 m wide in the High Plains segment. Moderately sinuous reaches alternate with relatively straight reaches in all three segments studied. In the more sinuous reaches, sinuosity ranges from 1.5 to 1.7 in all segments. Within a relatively short stretch within the Mesozoic segment sinuosity exceeds 2.1. Radius of curvature of meanders generally increases downstream correlative with increase in channel width. Radius of curvature in the upper, volcanic highlands segment, ranges from 20 to 60 m, increases to 60–150 m in the middle segment, and dramatically increases to 600 to 900 m in the High Plains segment and in the transition zone between the Mesozoic and High Plains segments. Valley sinuosity ranges from 1.0 to 1.1 along the segments studied except for a small reach at the transition zone between the middle and lower segments where the sinuosity is approximately 1.8.

Although bedrock canyons are most abundant in the upper segment, all segments of the Dry Cimarron River Valley contain moderate amounts of alluvial fill. Dating of terrace material is underway to decipher the history of erosion and infilling.

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Change in Water in Storage in the High Plains Aquifer, 2000

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The High Plains aquifer, which underlies about 174,000 square miles in parts of eight states—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—is the principal source of water in one of the major agricultural areas in the United States. Water-level declines began soon after extensive ground-water irrigation. The U.S. Geological Survey, in cooperation with numerous federal, state, and local water-resource agencies, monitors ground-water levels in the High Plains aquifer using periodic and continuous water-level measurements from wells. Water levels are measured primarily in irrigation wells in winter to early spring, when water levels have generally stabilized. The water-level elevation for predevelopment conditions was determined using water-level measurements from more than 20,000 wells. The water-level elevation in the year 2000 was determined using water-level measurements from more than 7,000 wells; 127 of these wells are instrumented with continuous recorders.

The water-level measurements were analyzed to determine the change in water-level elevation from predevelopment to the year 2000. The change in the volume of water in the aquifer was calculated using the mapped area in each water-level change interval and an average specific yield value for the aquifer in each state. The results indicate that the water in storage in the aquifer decreased about 200 million acre-feet from predevelopment to the year 2000. This decline is about 6 percent of the predevelopment volume in the aquifer. In the 26,000-square-mile area with greater than 25 feet of water-level declines, the water in storage in the aquifer decreased about 190 million acre-feet from predevelopment to 2000. This represents a decline of about 34 percent of the predevelopment volume in that part of the aquifer.

The states' ground-water-management approaches for the High Plains aquifer are designed to prevent aquifer depletion, manage aquifer development, or to attempt to insure the availability of aquifer resources for a specified period. In some states, the management approaches are also designed to limit water-level declines to maintain an acceptable amount of ground-water discharge to rivers and streams.

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Downstream Grain-Size Change in a Modern Sand-Bed River and Implications for Regional Quality of Reservoirs and Aquifers: Canadian River Drainage, Oklahoma, USA

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Recent developments in reservoir-quality technology suggest that improved prediction of reservoir quality requires better pre-drill estimates of sandstone texture and composition. In response to this need, we are integrating some GIS-based topographic analysis and mapping tools with conventional techniques for the characterization and analysis of sediment in modern sand-bed rivers. The intent of this work is to identify and document the controls on changes in bed material with distance along the drainage system. The study design enables us to evaluate changes in sediment as functions of (a) transport distance, (b) bedrock lithology, and (c) changes in near-channel slope. In contrast to gravel-bed rivers, few studies of this nature have been conducted in sand-bed rivers even though sand-bed rivers constitute the bulk of hydrocarbon production from fluvial systems. We are particularly focused on reasons for changes in particle size because of the strong control that grain size exerts on the permeability of granular aggregates.

Our results indicate that fining does occur in the Canadian River (1,027 km along-channel-length). However, the fining is best recognized in sediments obtained from positions high on the sand bars. These samples correspond to high-discharge events when most particle-size attrition occurs. Samples obtained at lower positions on the bars also show a downstream decrease in grain size, though this along-river change is less pronounced. Samples from the main channel (mean low-flow channel) show no change. Other findings from this work with implications for permeability of sandstones: (1) Grain size appears to vary systematically with bedrock lithology. This relationship suggests that changes in bedrock character beneath an incisement can influence the texture of the overlying valley fill. (2) Mean minimum particle size in the downstream portion of the riverbed is about 0.1 mm. This mean grain size is the same documented to occur in the lower reaches of the Mississippi and Amazon drainage systems. Similarity in grain size for all three drainages suggests the occurrence of a physical lower limit to particle size in active channelized systems. (3) Similar to studies conducted in gravel-bed rivers, we document a very rapid transition from sand to gravel in the up-dip reach of the study area.

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Evaluation of Ground Water in the Arkansas River Alluvial and Terrace Aquifers, Osage Reservation, Oklahoma, 2002

SHANA L. MASHBURN, *CALEB C. COPE*, and *JAMES O. PUCKETTE*, School of Geology, Oklahoma State University, Stillwater, OK 74078; and *MARVIN M. ABBOTT*, U.S. Geological Survey, Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116

Increasing demand for water on the Osage Reservation led to an evaluation of shallow ground-water resources contained within alluvial and terrace deposits along the Arkansas River. The Osage Reservation is located in north-central Oklahoma and covers about 2,350 square miles (6,090 square kilometers). The Arkansas River valley forms the southern and western boundaries of the reservation.

The thickness of the alluvium and terrace deposits ranged from 20 to 93 feet (6 to 28 meters). The alluvial deposits were composed of sand, silt, clay, and gravel, and all alluvial boreholes produced water. The terrace deposits were predominantly sand, but most terrace boreholes were dry. A direct push tool was used to drive an electrical conductivity probe and extract cores. Data from 20 cores and 75 electrical conductivity logs were used to determine sediment types and thickness of the alluvium and terrace deposits along the Arkansas River. The cores were collected from the surface to total depth of the borehole. Electrical conductivity measurements taken in boreholes were calibrated to cores and used to estimate sediment compositions in non-cored boreholes.

Water samples were collected using the direct push tool with a slotted screen. Water quality was determined through field measurements of pH, specific conductivity, dissolved oxygen, and nitrates. Several specific conductivity values were greater in areas near oilfield production facilities. Nitrate concentration decreased with depth. Several greater nitrate concentrations occurred in areas near cultivated crops. Dissolved oxygen and pH measurements were relatively homogeneous in the alluvial aquifer.

Water quality in the Arkansas River alluvium is variable and concentrations of dissolved constituents may be locally influenced by land use. This research is part of a joint study of the U.S. Geological Survey, Bureau of Indian Affairs, and Osage Tribe.

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Resistivity/Conductivity Anomalies at the Norman, Oklahoma, Landfill Site

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A resistivity survey was carried out between the months of April and June 2002 at a landfill site near Norman, Oklahoma. The essence was to determine the extent of migration of the leachate plume emanating from the landfill, and flowing downgradient toward the Canadian River. This plume has contaminated a part of the alluvial aquifer that underlies the landfill site. A total of five profiles, each covering a length of 135 m, were surveyed using a combination of Dipole-dipole, Wenner, and Wenner-Schlumberger electrode configurations on each profile. Three of the profiles were oriented in an E–W direction and placed 150 m from each other, covering a total distance of about 350 m downgradient from the landfill. The remaining two profiles ran N–S. As a control measure, electrical conductivity logging was performed on selected portions along each profile using the Geoprobe conductivity tool. The EC logs gave a good picture of the lithologic units that constitutes the aquifer. Two-dimensional modeling of the resistivity data was done using the RES2DINV software. The resistivity anomalies generated correlated well with the EC logs. Thus it was possible to delineate both the lateral and vertical extent of the leachate plume.

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Arsenic Occurrence in the Central Oklahoma Aquifer, Oklahoma, USA

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Changes in national drinking water standards for arsenic have fueled renewed interest in factors affecting arsenic levels in municipal groundwater wells in the Central Oklahoma Aquifer in and around Norman, Oklahoma. Hypotheses explaining elevated concentrations range from various types of water-rock interaction, water residence time effects, influences of pumping schedules or well construction and completion techniques. To discern among these hypotheses a study combining water chemical analyses, GIS, well log and core sample analysis and hydrological/geochemical modeling is being conducted on a portion of the aquifer system. Major and trace elemental analyses, including a rapid colorimetric technique for arsenic determination (sensitive to 4 ppb and adaptable for well-head analysis) is being conducted and examined for As correlations with variables such as alkalinity, redox potential, temperature, dissolved oxygen, pH, etc. New geological mapping by the Oklahoma Geological Survey is being used to develop a 3-D GIS combining aquifer geology, water table/potentiometric surfaces, well location and perforated intervals, and major, minor and trace groundwater chemical changes through time. Well log and core sample analysis is being conducted to examine patterns of arsenic occurrence with lithological variation and to determine any influence made by water well construction and completion techniques. Finally, hydrological/geochemical modeling is being used to simulate existing pumping schedules, determine groundwater residence times and to predict arsenic desorption as a function of space and time in the aquifer system. The overall goal of this study is to provide a comprehensive view of how and why elevated arsenic concentrations exist in this aquifer and to suggest additional aquifer management methods needed to ensure drinking water standard compliance.

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Sulfur Cycling in an Anoxic Surficial Spring

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Microbial sulfur cycling in an anoxic, sulfide bearing spring was studied as a model of processes occurring in the Archean biosphere. During the Archean and early Proterozoic periods, all microbial processes occurred anaerobically, but currently understood mesophilic surficial microbial communities are typically oxic or exist with oxic waters overlying anoxic sediments or bottom layers. A spring in Oklahoma discharges chemically anomalous springwater, containing abundant sulfide and no detectable oxygen. Sulfate concentration increases with distance from the source and apparently has its origins in the sulfide emerging from the spring. Microbial activity studies, in-situ experiments, molecular ecology and stable isotope studies suggest that as sulfide-rich water flows from the spring down a nearby stream, anaerobic phototrophic bacteria play a critical role in oxidizing sulfide to polysulfide and sulfate. Fine scale measurements of sulfate reduction within sediment cores show that sulfur cycling occurs within the microbial mats, as sulfate-reducing bacteria are closely associated with sulfide-oxidizing communities. Our characterization of this ecosystem suggests that the sulfide emerging from the spring supports a diverse phototrophic, primary producing community that then provides substrates (in the form of electron donor, electron acceptor, and organic carbon) for sulfate reducing and sulfur disproportionating bacteria. Within this rich and microbially diverse system, we find a modern analog for an Archaean aquatic environment.

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Integrated Subsurface Imaging Techniques for Detecting Cavities in Oklahoma Evaporite Karst

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Rapid dynamics of gypsum karst development constitutes a serious collapse hazard for surface structures, including highways, on a human rather than geological time scale. Gypsum and anhydrite deposits occur in the shallow subsurface (<30 m below ground surface; m.b.g.s.) in about 4% of Oklahoma, USA. This study presents preliminary results of an integrated study utilizing subsurface imaging techniques to non-intrusively detect and map solutional cavities in the Permian Blaine gypsum karst of western Oklahoma. The study employed electrical resistivity tomography (ERT), broadband electromagnetic induction (EMI), seismic reflection, and seismic refraction to detect, delineate and map karst geohazards within the Nescatunga cave system of northwestern Oklahoma. The combined use of several subsurface imaging techniques provides opportunities for evaluating the relative effectiveness of the methods in detecting cavities and minimizing uncertainty in the interpretation of subsurface features, especially where reasonable agreement was achieved among the methods. Subsurface cross sectional plots from the various methods were superimposed in ARCVIEW GIS and the Spatial Analyst tool was used to establish the magnitude of error in detected features from their true location. Interpreted cavern locations are compared to three dimensional digital maps of caverns obtained by a laser positioning method (discussed elsewhere in this session). The results provide a measure of relative accuracy of modeled cross sections. The approach adopted is superior to conventional site characterization methods, which typically involve intensive field drilling programs. The ultimate goal is to produce a methodology for locating sinkholes and cavities that constitute geohazards in the karst environments of Oklahoma, and perhaps elsewhere in the United States.

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Laser Positioning and 3-D Digital Mapping of Western Oklahoma Evaporite Karst

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Cavern morphology and distribution in three western Oklahoma evaporite karst systems were mapped using laser/global positioning systems. Portions of Jester Cave, the Corn Caves, and the Nescatunga cave system, all located within the gypsiferous Permian Blaine Formation, are being investigated in association with a series of surface geophysical studies in order to develop a cavern detection methodology. The Nescatunga system in particular has a history of highway collapse hazards. Digital mapping of cavern voids makes use of a reflectorless laser rangefinder with internal inclinometer linked to a digital compass and referenced to global positioning system receivers positioned outside the cavern entrances. This is a standard surveying technique for use under bridges and beneath heavy tree canopies. A series of control stations are laser-located along a cavern traverse at approximately 20-meter intervals and marked by mounted reflectors. Fifty or so additional laser positions of cavern floors and walls are taken as offsets from each station. Positioning data is downloaded onto a laptop computer and visualized with GIS and CAD software, enabling a real-time geo-referenced image of cavern shape to be developed. Sub-decimeter scale accuracy is achieved and verified by reoccupation of stations and by positioning from two or more GPS locations at different entrances. The resulting digital 3-D map of a portion of each cavern system investigated is used in interpretation of results of surface geophysical imaging techniques (discussed elsewhere in this session), both in order to provide "ground truth" for the geophysical surveys and to refine the methods for use in cavern detection in surface-inaccessible sites.

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Oxygen Isotope Values of Modern Spelean Carbonates and Source Waters: Non-Equilibrium Deposition is Status Quo

PENNY M. TAYLOR and *HENRY S. CHAFETZ*, Dept. of Geosciences, University of Houston, Houston, TX 77204; and *SEAN A. GUIDRY*, ExxonMobile Production Company, Houston, TX

Oxygen isotopic values of 35 modern calcite deposits and contemporaneous water samples from three Central Texas caves provide evidence that non-equilibrium deposition is common. All spelean sample pairs of calcite and immediately adjacent water are from streams and pools. Calcite precipitated on glass substrates, at the edge of pools, or on the water surface as floating rafts. Oxygen isotopic values range from –5.0 to –2.2 permil (PDB) and from –5.0 to 0.0 permil (SMOW) for calcite and water, respectively. Differences between theoretical and measured $\delta^{18}O$ values of these calcite samples range from –1.1 to +2.8 permil (mean=0.5; σ=1.01; n=35).

The temperature of the water from which a carbonate precipitated can be calculated assuming: (1) oxygen isotopic composition of the water, and (2) equilibrium fractionation between mineral and water. To assess the effect of observed disequilibrium fractionation on temperature calculations, the actual $\delta^{18}O$ values for carbonate and water sample pairs were used to calculate water temperature, treating temperature as an unknown. The resulting discrepancies ranged from –3.7 to +12.3°C relative to field-measured temperatures (mean=3.2; σ=4.4; n=31).

Evidence for non-equilibrium calcite deposition in three Central Texas caves is in agreement with data from a travertine-depositing stream within the same karst region as well as 6 carbonate-depositing surface streams from other areas (both am-

bient- and thermal-temperature) from which sample pairs of carbonate (aragonite and calcite) and water were analyzed. Without exception, non-equilibrium deposition is most common in these systems in California, Colorado, Oklahoma, Texas, Wyoming, and Italy. Collectively, these data provide strong evidence that equilibrium fractionation of oxygen isotopes is rare in these terrestrial environments. Thus, poor results from temperature calculations, using detailed isotope data (no assumptions) from natural systems, emphasize the potential for errors in interpretation of ancient depositional or climatic conditions.

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Correlating the Location of a Cave Passage in Gypsum Karst to a Highway Right-of-Way Using a Cave Radio

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The Oklahoma Department of Transportation plans to widen Highway 412 in western Oklahoma in an area underlain by the Blaine Gypsum Formation. The project would convert the highway from a two-lane divided to a four-lane divided highway and decrease the existing grades. One location of particular concern is in Major County where Nescatunga Cave passes under the highway at a relatively shallow (<30 meters) depth, but the location of the cave passage relative to the highway was not known. The preliminary plans for the highway-widening project specified lowering the grade by removing overburden in the vicinity of Nescatunga Cave. Concern regarding possible roadbed failure caused the Oklahoma Department of Transportation to seek methods to determine the location of Nescatunga Cave relative to the highway expansion project. Volunteers from the National Speleological Society used low-frequency radio direction finding equipment, commonly referred to as a cave radio, and a tape-and-compass survey to depict the position and dimensions of the Nescatunga Cave passages relative to the highway-widening project. A transmitter was placed sequentially at seven stations in the cave passage and a radio direction-finding receiver was used to identify and mark points on the surface directly above the transmitter stations. Transmitter stations, as well as the cave passage position and dimensions were surveyed using a tape and compass. The surface points were repeatable to within five centimeters. Subsequent core drilling by the Oklahoma Department of Transportation at three of the survey sites intercepted the cave passage—which ranged in width from 5.3 to 9.1 meters—at all three locations. Knowledge of the depth and location of the cave passages allowed the Oklahoma Department of Transportation to minimize drilling costs. The Oklahoma Department of Transportation is considering design changes for the highway-widening project to maintain more overburden above the cave passage.

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Gypsum Karst is a Major Factor in Siting of a Proposed Dam in Southwestern Oklahoma

KENNETH S. JOHNSON, Oklahoma Geological Survey, 100 East Boyd, Room N-131, Norman, OK 73019

Engineering-geology assessment of two proposed damsites in an area of gypsum karst in southwestern Oklahoma has shown that the first site should be abandoned, and the second site is acceptable, but with limitations. Both sites are on Salt Fork Red River, just upstream from the town of Mangum. The Upper Mangum Damsite, the first proposed site, has been studied since 1937 as a potential location for a compacted, earth-fill dam. Abutments for this dam would be in the Permian Blaine Formation, consisting here of 60 m of gypsum, with thin interbeds of dolomite and shale. The Blaine Formation locally has abundant gypsum-karst features, such as caves, sinkholes, disappearing streams, and springs. A final assessment, made in 1999, of the abutments at this site showed the following: open cavities, clay-filled cavities, and other karst features are abundant in and near the abutments; and fluid losses (per 3-m intervals) ranged from 60–250 L/min in most borehole pressure-tests, and in one borehole the losses were 1,600–5,300 L/min. As a result, the first site was abandoned, and a new study of the Lower Mangum Damsite was launched in 2002. This newly proposed damsite is 6 miles farther downstream on Salt Fork Red River, where the foundation and abutments would be in the thick Flowerpot Shale. Based upon geologic and hydrogeologic field studies, along with core study, pressure tests, and laboratory tests of cores, the foundation conditions at this damsite appear favorable. However, owing to the presence of the karstic Blaine Formation in the upper reaches of the reservoir that would be formed at this new site, there will be limitations on the lake level, size, and storage capacity of the Lower Mangum Reservoir. If the conservation-pool level here is too high, it will cause excess water to escape from the lake in the upper reaches; the water will enter a subsurface gypsum-karst conduit and flow as ground water into a different watershed. Investigations at these two sites demonstrate the importance of hydrogeological studies in areas of evaporite karst in order to plan location and size of potential damsites and reservoirs.

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Where Platform Limestone Meets Deltaic Deposits: Outcrop Stratigraphic Architecture of the Oread Cyclothem (Upper Pennsylvanian), SE Kansas and NE Oklahoma

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The ~{!0~}layer-cake~{!1~} model for late Paleozoic cyclothems cannot fully explain the juxtaposition between the Upper Pennsylvanian ~{!0~}Kansas-type~{!1~} Oread Cyclothem and the deltaic cycles at the southern margin of the Kansas Shelf in SE Kansas and NE Oklahoma. On the shelf, the Oread Cyclothem is composed of mixed marine and nonmarine siliciclastic and carbonate rocks. It juxtaposes with deltaic rocks in the south. We investigated the outcrop facies architecture of juxtaposition to understand the controlling processes. This study focused on the Leavenworth Limestone–Heebner Shale–Plattsmouth Limestone interval in the Oread Cyclothem, and documented facies and thickness changes by correlating 15 measured sections in a 10-km^2 area. From north to south in 5 km, the transgressive Leavenworth Limestone is persistent in lithology and thickness; the maximum-transgressive Heebner Shale changes from 2-m anoxic black shale to 30-m deltaic deposits; the regressive Plattsmouth Limestone changes from 8-m phylloidal algal mound-dominated facies to 1-m arenaceous grainstone, and pinches out into deltaic deposits. Syndepositional growth faulting and differential compaction of deltaic sediments increased local topographic relief. In detail, the Plattsmouth Limestone changes from arenaceous grainstone, shale, fossiliferous sandstone, limestone pebble conglomerate, to arenaceous packstone in 500 m from north to south. Specifically, the medium-grained sandstone with large-scale tabular cross-beds interfingers with the conglomerate. The conglomerate is 40 cm thick, composed of mixed quartz sand, limestone intraclasts, and skeletal fragments, in a 10-m-wide zone. Lithology, sedimentary structure, and bedding geometry suggest facies changes and mixing occurred in a syndepositional low with strong uni-directional current. We interpret that the facies juxtaposition and mixing were caused by hydrographic partitioning by alongshore currents associated with oceanic upwelling, similar to the modern analogs in offshore NW Africa and the Mahakam Delta region in Java Sea. Syndepositional topography and structural deformation also played important roles in determining the facies distribution, thickness, and boundary relationship in the transition zone.

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GIS as an Important Aid to Visualizing and Mapping Geology and Rock Properties in Regions of Subtle Topography: An Example from North-Central Oklahoma

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The purpose of this study is to assess the feasibility and practicality of using Geographic Information Systems (GIS) to visualize, quantify, and evaluate relationships between bedrock geology and topography. The study site is located in north-central Oklahoma where poorly consolidated Permian and Pennsylvanian-age sedimentary rocks of differing types and properties have been dissected by the regional drainage system. The erosion of these rock types has produced a subtle but well-defined topographic expression. Data for the analysis was obtained using 30m digital levation models (DEMs) available from the USGS National Elevation Dataset (NED). Using the DEMs, a slope was calculated for each pixel in the study area and a slope map was created with ESRI Spatial Analyst in ArcMap. Visual inspection of the slope map reveals that areas with common slope are frequently in close proximity and correspond closely, but not exclusively, with the properties of the underlying bedrock formations. This finding is significant for areas with subtle topographic expression because this variation in topography and the relationship with the underlying bedrock would normally not be recognized in most conventional multi-use mapping programs (soil, water, ecology, land use, or geology). Therefore, this GIS-based technique, when used in conjunction with conventional techniques, can quickly enhance the efficiency, accuracy, and applicability of multi-use mapping programs. An on-going field program is attempting to document and quantify the reasons for the observed correspondence between the bedrock formations and their characteristic topographic expressions. Field samples of bedrock at a select number of sites are being used to establish reasons why some formations or parts of formations are more (or less) susceptible to erosion than others. A major but unexpected finding of work to date is that the entire region appears to be riddled by two sets of closely-spaced, through-going, surface fractures (one set trending NE–SW, the other, NW–SE). It is possible that this system of fractures has previously eluded researchers due to the poorly consolidated nature of the regional bedrock and their concealment due to the development of gullies and other drainage systems (as determined by the fractures).

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Basement Control on Phanerozoic Structures and Tectonics—Midcontinent USA

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Modern-day structures of Midcontinent USA are relatively well known due to extensive surface mapping and individual state documentation of the geologic records from exploration for petroleum. The broader tectonic system that controlled these structures is revealed by geophysical data and the stratigraphic patterns of deposition and erosion through the Phanerozoic. The trends of most Phanerozoic structures, particularly those that exhibit repetitive movement, reflect the rejuvenation of the original architecture of the basement rather than a true directional response to the stress pattern imposed during any particular time frame.

In Midcontinent USA, much of the basement is contained within the Central Plains orogen and within the Transcontinental Proterozoic belt. This basement consists of a series of island arc terranes accreted during the period 1.8 to 1.6 Ga. Each arc within the series is delineated by an accretionary suture that has remained as a deep-seated zone of weakness in the basement. Four major island arc terranes and their bounding sutures are identified in Nebraska and adjacent areas. These sutures were reactivated into important Phanerozoic positive structures such as the White River fault system, the Wattenberg high, the Cambridge arch, the North Platte arch, the Ord arch, the Central Kansas uplift, the Rush rib, and the Las Animas arch.

The Proterozoic accretionary process also indirectly created the Nemaha boundary zone. This zone controlled a portion of the Midcontinent rift system (1.1 Ga) and the Phanerozoic Nemaha uplift. In the Nebraska region the Midcontinent rift system, and to some extent the older sutures, controlled the consecutive development of the Southeast Nebraska arch, the North Kansas basin, the Nemaha uplift, the Forest City basin, the Abilene anticline, and the Table Rock arch. Interrelating the stratigraphic studies of the Phanerozoic with the tectonic research on the Precambrian basement provides the insight necessary to explain and further understand the structures of Midcontinent USA.

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Old Rifts Never Die: Crustal Thickening Across the Midcontinent Rift and its Possible Role in Post-Rifting Tectonics

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One of the remaining first-order problems in geoscience is the origin of large-scale, long-lasting tectonic deformation in the interior of stable ectonic plates. An example of such deformation is the Nemaha Ridge in Nebraska, Kansas, and Oklahoma. The 550-km-long, 30–50-km-wide feature is about 50 km east of the 1.1-billion-years-old Midcontinent rift (MCR) and its proposed southward extension. Spatial variation in the thickness of Paleozoic and younger sedimentary rock layers implies that the Ridge has been continuously uplifting for at least 600 million years. Its eastern border, the Humboldt fault zone, is still producing notable and sometimes damaging earthquakes.

The force that has been driving the uplift must be persistent over a period of 600 m.y. or longer. While mantle convection is considered as the source of most large-scale tectonic movement, it may not be the direct cause of the uplifting of the Ridge because of the abnormally-long time-scale which is several times longer than the "over-turning" time of mantle convection. Thus the uplift might have a local or regional origin. Over the past several years we have been conducting a portable seismic experiment across Kansas. By stacking P-to-S converted seismic waves from the Moho, we have found that the crust beneath the MCR and the areas within about 120 km on each side of the rift axis is thickened by 5–12 km relative to the adjacent areas. The thickening was likely the result of the lateral compression during the closure of the MCR about 1.1 billion years ago. The Nemaha Ridge is located inside this zone of thickened crust, but outside the axis of the MCR, which is filled with a thick layer of high-density volcanic rocks that give characteristic gravity anomalies. Based on previous data and our new crustal thickness measurement, we hypothesize that the long-lasting uplift of the Nemaha Ridge is the result of the uplift of the Moho toward isostatic balance.

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Rare Earth Element Fractionation During Phosphate Nodule Diagenesis

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Phosphate nodules commonly occur in the marine Mississippian black shales of Oklahoma and Arkansas. These nodules often contain, at their cores, exceptionally well-preserved fossils and fecal pellets. The rare earth element (REE) chemistry of these nodules was analyzed to examine the conditions of diagenesis, which ultimately lead to ideal fossil preservation. Because REE abundance patterns in phosphate nodules are commonly enriched in the middle REE (MREE; Sm-Dy) the variations in this enrichment may provide clues as to the diagenetic history and perhaps to the paleoenvironment.

The ICP-MS based REE chemistry of phosphate nodules collected from the marginal marine to possibly non-marine Fayetteville Shale Formation in Arkansas differs from deeper marine facies in Arkansas and Oklahoma, particularly with regard to cores vs. rims of the phosphate nodules. In all of the nodules from the deeper facies, the cores are enriched in MREE when compared to the rims. The opposite trend occurs in the coastal nodules with greater MREE enrichments in the rim compared to the core. The relative loss of MREE is generally not accompanied by a commensurate loss in the light or heavy REE.

Several factors may explain the trends observed in our data. Mineralogical differences between the cores and rims may control the fractionation of MREE. Rims on near-shore nodules are generally richer in silicate material (clays) than their deeper marine counterparts. The higher electronegativity of the clays may encourage movement of the MREE away from the core in coastal nodules or towards the core in open marine nodules that are richer in lower electronegativity carbonates. High phosphate content may characterize clay-poor nodules, and this would probably favor higher overall REE abundance. MREE enrichment may correlate positively to total REE abundance. Redox variations may also be important in controlling intensity of MREE enrichment. Many of these hypothesized diagenetic factors may favor enhanced fossil preservation, but further exploration of the chemical and mineralogical differences within and among these phosphate nodules is needed.

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Widespread Late Ordovician Silicification Event on Laurentia: A Proxy for the Duration of Gondwana Glaciation?

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Late Middle to Late Ordovician bedded carbonate, chert and phosphate deposits of the U.S. Cordillera, southern Laurentia and the North American Midcontinent are unique in the Paleozoic because they represent the influx of cool oceanic waters, oftentimes hundreds of kilometers onto the interior of this continent. Late Middle to Late Ordovician subtidal ramp carbonates of New Mexico, Texas and Oklahoma contain abundant organic-rich chert, biogenic chert, phosphate and glauconite indicating these rocks formed in an extensive upwelling zone. Upwelling began in the Late Middle Ordovician (~454 Ma) and persisted until the end of the Ordovician. Late Ordovician cherty carbonates also occur along the U.S. Cordilleran margin, lying inboard of organic-rich graptolitic shale and chert. The widespread occurrence of Late Ordovician cherty and phosphatic carbonates on Laurentia, in addition to phosphate-rich, cool water carbonates over much of the North American Midcontinent suggests vigorous thermohaline circulation. Abundant Late Ordovician bedded chert deposits and the dearth of these units in the Middle Ordovician and during the Early Silurian suggests a global climatic or oceanographic origin for these deposits. The abundant evidence of widespread upwelling on Laurentia during the Late Middle to Late Ordovician fits well with recent oceanographic computer modelling indicating enhanced equatorial transfer of oceanic heat during the Late Ordovician glaciation. The initiation of upwelling in the Late Middle Ordovician also corresponds with cool (13–19°C) surface waters in the Appalachian Basin, a northward expansion of cool water trilobite faunas in North America, a shift to cool water benthic faunas across eastern North America, and the initiation of glaciogenic deposits in Africa. Thus, widespread upwelling around Laurentia over an ~14 Ma period suggests vigorous thermohaline circulation, that was likely driven by a prolonged glaciation on Gondwana.

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Use and Misuse of the Blackboard Web Program in Large College Earth Science Courses

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The Blackboard web site for curriculum management (www.blackboard.com) achieved its legendary status when it was a free web site for teachers. After becoming fee-based, many schools, including colleges such as Oklahoma State University, chose to independently license the software for their own servers, thus encouraging faculty to continue experimenting with the program. The School of Geology chose Blackboard to web-supplement its large lecture/lab courses; thus becoming the campus model for gen-ed deployment.

"Bb" has a steep learning curve, particularly if all the features are fully utilized. Despite hundreds of hours of development to make Bb work for large courses, we had problems with enrollment and password access (now automated via Central Computing), lack of student access to computers (the Bb server is now available throughout campus and beyond), inserting large AV and PowerPoint files (required learning proper web-conversion techniques), and in administering web-based exams and course assessments.

The following features of Bb were eventually disabled because of lack of use, misuse, or because they were duplicated by other services on campus: Calendar, Tasks, Email, Discussion board, Virtual classroom, and the Digital drop-box. These features function best for small classes; our sites would have required excessive work hours in order to be continually updated and properly supervised.

Online grading, assessment, and compilation of course statistics was also difficult to implement. Entering and revising exam questions is an unpleasant inefficient effort that Bb programmers need to improve. Furthermore, our attempt to set up supervised "testing labs" failed, thus we only offer auto-grading "practice" exams on the web.

An evaluation of our trial site was mostly negative because we tried to do too much poorly. Our current web-sites are less complex, more utilized and more appreciated.

Samples of our present Bb offerings will be demonstrated at the presentation. Copies may be obtained.

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Enhancing Science Education Through Research

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At the research frontier, be that frontier the realm of outer space or the inner space of Earth, scientists constantly generate new knowledge, all of which enters the educational system but at various levels and details. The nature of research, in part, determines the utility of the information and the speed at which it is applied. Within NASA, the focus of research occupies many niches, including science education. Platforms in space, such as the satellites or the Space Station, permit scientists to collect global data for a variety of purposes. The nature of research often determines how the data are employed and the impact they have on the educational processes and learning.

To communicate knowledge, it first must be acquired. Given its broad mission, NASA asks scientists to categorize their research such that the knowledge generated enhance learning throughout society. Six categories of research are embodied in the NASA mission. In basic research, scientists seek knowledge only for the sake of knowledge. The Hubble telescope provides images that often raise more questions than they answer. Fundamental research seeks useful knowledge, such as characteristics of the ocean. Exploratory research attempts to identify perceived useful knowledge, an example being the acquisition imagery to identify mineral composition of rocky surfaces. Applied research pursues practical objectives, such as experiments in space sent directly into K–12 classrooms. Programmatic research seeks and provides knowledge for a mission such as what sensors are capable of detecting buried ice. Finally, industrial research attempts to achieve economic benefits, such as interpreting geologic structure to enhance mineral exploration. The nature of research influences the knowledge created and how it can enhance science education. In all instances, learning contributes to the refinement of the processes and procedures in subsequent research and thereby expands the research frontier. Science education is a primary NASA mission.

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Geology Experiments in Space—Elementary Students Grow Crysyals

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One of the most basic methods to get children interested in science, especially earth science, is through conducting experiments. When experiments can be combined with the U.S. Space Program, then the chances for holding the interest of the children increases. Presented are the results of a volunteer effort dedicated to providing elementary students (Kindergarten through fifth grade) access to experiments involving the microgravity of space flight. Scientists from Lockheed Martin (and the children of one), Texas A&M, and Oklahoma State University, donate their time and act as mentors to the participating teachers and students. Most of the expenses related to the education about space flight are shouldered by Lockheed Martin Space Operations, Houston, Tex., and Instrumentation Technology Associates, Exton, Pa. This effort is centered on reaching children at an early age and exposing them to the challenges, especially the fun of science and mathematics. The current experimental design and overall learning processes concentrate specifically on crystal growth as geared to the elementary student. The crystal growth experiment is manifested on STS-107 (July 2002). Prior to conducting the experiment, we discuss various lesson plans with the teachers to hone their earth science lectures in regards to understanding/appreciating basic crystal growth and structure. The experiment is broken down into major topic sessions (usually six) of no more than one hour each. Again, the experiment is national with schools from several states participating. The poster/presentation displays lesson plans, experiment design, materials required, student hypotheses, control and experiment results as well as information on how elementary schools can become involved in future space experiments.

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Geoscience Research Partnerships as a Strategy for Engaging K–16 Students and Teachers in Inquiry-Based Learning

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Inquiry in the National Science Education Standards: From structured exercises to guided learning experiences to open-ended research.

The National Science Education Standards emphasizes the use of inquiry in the teaching of science. The Earth and space sciences section of the NSES stresses the importance of students developing the skills to think critically about Planet Earth and the global systems that have operated over long time to produce the world we see today. In preparing the national standards, the writers attempted to follow the cliché that "less is more" in terms of formally teaching students only the fundamentals and allowing the real science education come through experiment and investigation. Through careful analysis of observations and data collected in experiments, young people can learn essential scientific content and come to view the world from a scientific perspective. Central to such a perspective is "reasoning from the data."

One of the challenges faced by primary and secondary teachers and by those in the research community interested in supporting good K–12 instruction is designing a sequence of experiments, exercises, and fieldwork that are interesting, demanding, and instructive. For very young students, well-structured activities are necessary to teach basic concepts. For older students, more open ended, but still guided, explorations are needed to encourage "what if" questioning and subsequent experimentation to find out. For students in their last two years or so of secondary school, true research experiences are essential.

As experienced researchers know only too well, good research takes time. Unfortunately, K–12 education has become highly structured, with a strong focus of preparing students to succeed on mandated standardized tests. Devising guided explorations and developing meaningful research projects that in the available time communicate the essential content (to meet the demands of standardized testing) while providing valid research experience is the challenge.

This presentation will review the NSES from the perspective of their support for inquiry-based learning. Examples will be given of structured exercises for young students, guided learning experiences for middle school students, to open ended research projects suitable for high school students.

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