Stratigraphy, Depositional Environments and Coalbed Methane Resources of Cherokee Group Coals (Middle Pennsylvanian)--Southeastern Kansas

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Abstract

The Cherokee basin of southeast Kansas, part of the western region of the Interior Coal Province, is a hydrocarbon-bearing foreland province. Middle Pennsylvanian Cherokee Group coals form a large portion of an estimated 48 billion metric tons of deep coal resources (greater than 30 meters) in eastern Kansas. Cherokee coals are of high-volatile bituminous A and B rank. With sufficient overburden and thick seals they have high potential for coalbed gas production. In Kansas, economic coalbed gas production requires coals of higher quality (low ash, high Btu, and high gas content), seams generally thicker than 0.3 meters, and multiple coals within close proximity to pipeline infrastructure.

Structure and isopach maps, along with cross sections constructed from cores, outcrops and well logs, provide a better understanding of the lateral variability and extent of the major coal bearing sequences. Integration of core descriptions with well logs was used to correlate depositional environments across the Cherokee basin. Cherokee Group coals accumulated in a variety of depositional settings such as, marshes, non-barred and back barrier coastlines, estuaries, and fluvial flood basins. Variations in coal quality, thickness, and lateral distribution can be understood by placing Cherokee Group coals within a sequence stratigraphic framework. Thicker and laterally extensive coals developed toward the end of the transgressive systems tract, and beginning of the highstand systems tract. Pre-existing topography played a major role in the growth, distribution and quality of peatlands that developed into coal.

Desorption of coal and shale samples from core holes within the study area determined total gas content. Gas contents varied from 3 to more than 300 standard cubic feet/ton (scf/ton). Black shale gas contents range from 3 scf/ton to 35 scf/ton. Within the study area, an estimated 6.6 trillion cubic feet of original gas in place is estimated from twelve coals and two black shales. An improved geologic understanding of the Cherokee Group coals can aid in coalbed gas exploration and development in southeastern Kansas.

The Cherokee basin of southeast Kansas, part of the western region Interior Coal Province, is a hydrocarbon-bearing foreland province with abundant resources of deep coal (>100 ft; >30 m burial depth), predominately within the Cherokee Group (Desmoinesian Stage, Middle Pennsylvanian Series). Estimates of total deep coal resource within eastern Kansas are on the order of 48 billion metric tons of predominately bituminous coal (Brady, 1990). The major Cherokee Group coal beds make up the largest portion of this resource and include the Riverton, "Aw" (informal subsurface name), Weir-Pittsburg, Mineral, and Bevier coals (Brady, 1997; Figure 1.01). Typical Cherokee Group coals are of high-volatile A and B bituminous rank. Medium-volatile bituminous coal is the ideal rank for coal bed generated methane (Stoeckinger, 1989). Sufficient overburden, and a

competent seal provided by thick shale, generated and trapped quantities of methane in the high-volatile A and B bituminous Cherokee Group coals (Stoeckinger, 1989).

This study of major Cherokee Group coals in southeast Kansas addresses the following:

- distribution of coals within the Cherokee basin;
- the location of coals within a sequence stratigraphic framework;
- depositional environments of the coals;
- gas content of Cherokee Group coals;
- linkage between depositional environment and coal quality;
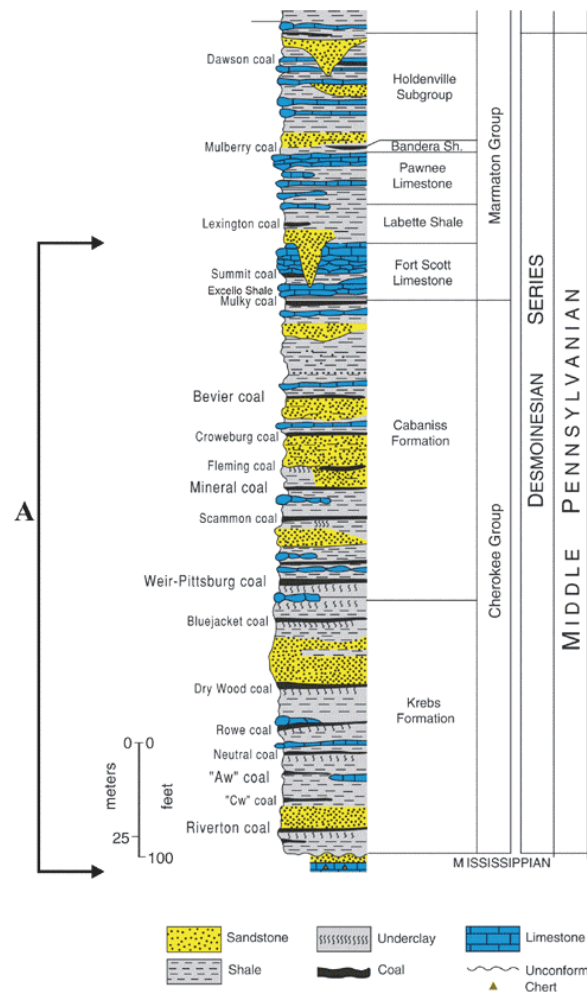- potential for coalbed methane exploitation in southeast Kansas.

Figure 1.01 - Stratigraphic classifications of the Desmoinesian Series (modified from Zeller, 1968). (A) Stratigraphic limits of this study

1.2 Hydrocarbon Significance

Conventional petroleum production in the Cherokee basin began in the late 19th century and continues to present. Production has been in decline for the past fifty years and is presently dominated by stripper production (Newell et al., 2002). Production of shale gas in eastern Kansas from carbonaceous black shales from the Fort Scott member of the Marmaton Group dates back to 1910, where wells are reported to have produced more than 200 million cubic feet (MMCF; Charles

and Page, 1929). Today, these carbonaceous black shales are known as the Little Osage and Excello Shale, and occur in association with thin underlying coals (Summit and Mulky, respectively; fig. 1.01). Exploration for shale and coal gas briefly resurged in the late 1980's due to tax incentives and then subsided in the early 1990's during persistent low commodity prices. In the first three years of the 21st century, recent demands for natural gas, increased price, and new technologies have turned unconventional gas in the Cherokee basin into an active energy play (Figure 1.02). Up to 14 relatively thin coals beds may be encountered in any one well (Brady, 1997). The key to a successful coalbed play is to identify numerous coals of sufficient thickness with higher adsorbed gas contents (greater than 100 standard cubic feet per ton) located near pipeline infrastructure (Figure 1.02).

Coals in the Cherokee basin are generally less than 2,500 feet deep (760 m), so drilling costs are relatively low. Top reported completion intervals are in the Mulky coal and overlying Excello Shale, Weir-Pittsburg coal, and Riverton coal.

Many producers are producing gas from coals that are less than 2 feet (0.6 m) thick with promising results. Current unconventional gas production in southeast Kansas is rapidly increasing and exceeds 1.5 BCF per year (billion cubic feet; Priestman, 2003).
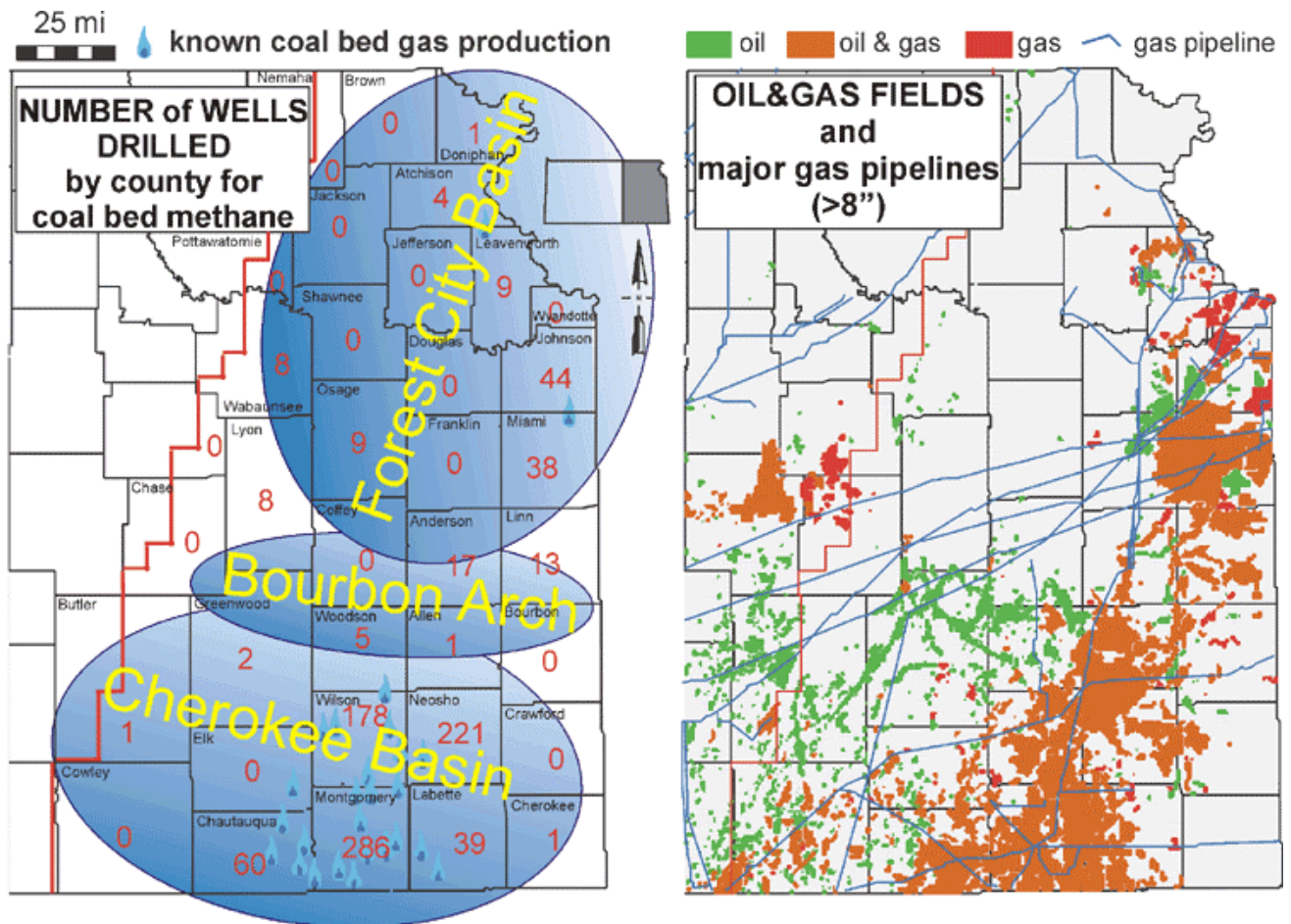

Figure 1.02 Coalbed methane wells drilled and major pipeline infrastructure

1.3 Area of Investigation

The study area covers approximately 4,000 square miles (approximately 10,300 sq km) within an eight-county area in southeastern Kansas (Figure 1.03). It includes all of Cherokee, Crawford, Neosho, Labette, Wilson, Montgomery, Elk and Chautauqua counties. Cherokee Group rocks are present in the subsurface throughout most of the study area and crop out in a northeast-southwest-trending belt along the southeastern edge of the study area. For over 145 years coal deposits of eastern Kansas have been mined with a total production of approximately 300 million short tons (272 million metric tons; Brady, 1997). During this time major peaks in production corresponded with World War I and II (Brady, 1997). For the past 25 years coal production has followed a steady decline due to low commodity prices and the demand for higher quality coal from other regions.

1.4 Previous Investigations

Previous studies have dealt with the stratigraphy and distribution of coal beds or sandstones within the Cherokee Group (Abernathy, 1936; Searight et al, 1953; Howe, 1956; Branson, 1957; and Searight and Howe, 1961). The first reference to the Cherokee Group concerned outcrops along the banks of the Neosho River in southeastern Kansas (Haworth and Kirk, 1894). Subsequently, the Cherokee Group was subdivided into fifteen cyclothems (Abernathy, 1936). Howe (1956) subdivided the Cherokee Group from the top of one coal bed to the next overlying coal bed and designated these units as formations. These earlier works, supplemented by the work of others, were the basis of the current accepted stratigraphic classification (Jewett et al., 1968; Figure 1.01). Previous work on the Cherokee Group centered on the major sandstones that formed the traditional "shoestring" oil reservoirs of southeastern Kansas and northeastern Oklahoma.

Figure 1.03 - Location of study area in state of Kansas

Recent studies have focused on the stratigraphy and/or depositional environments of the Cherokee Group relating to strippable coal reserves, and conventional sandstone petroleum reservoirs. Early work calculated the strippable coal reserves of eastern Kansas (Brady et al., 1976), while more recent work involved the first identification of coalbed methane resources (Brady, 1990, 1997). Harris (1984) examined the Krebs Formation in southeastern Kansas, and described the stratigraphy and depositional environments. Staton (1987) completed a similar study for all of the Cherokee Group in the central Cherokee basin. Walton (1995) applied sequence stratigraphic concepts to the Cherokee Group, and identified twenty-two sequence boundaries, of which some have a regional extent while others are only considered to be local. This study overlaps the areas of both Staton (1987) and Harris (1984). However, the focus is on coal deposits as a nonconventional gas reservoir, whereas previous work was centered on major sandstone deposits of the Cherokee Group (Figure 1.04).

Interpretation of depositional environments for units of the Cherokee Group (primarily sandstone deposits) have evolved and changed many times since the original interpretations (Bass, 1934). Bass (1934) concluded that the major "shoestring" sandstones were deposited in offshore barrier-bar environments. Following this interpretation, Hayes (1963) re-interpreted the sandstone units that crop out in Missouri as tidal-flat or tidal channel environments based on the presence of bi-directional cross-bedding. Cole (1969), and Visher et al. (1971) interpret most of the Cherokee Group sandstones to be fluvial-deltaic environments
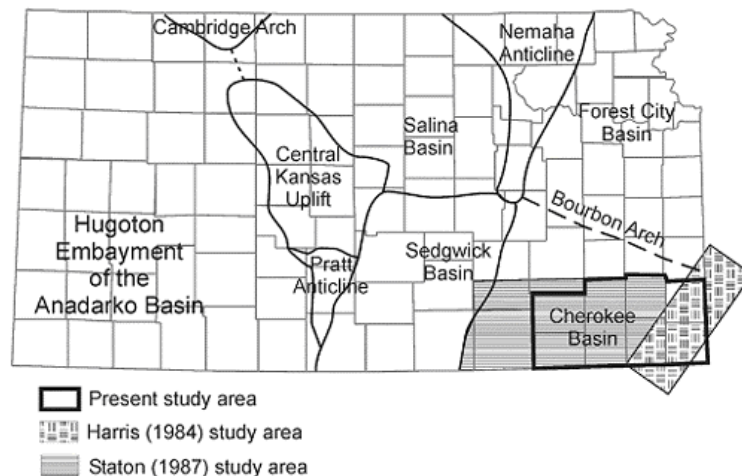

Figure 1.04 - Location of study area in relation to the study area of Harris (1984) and Staton(1987), and to the major structural features of Kansas.

1.5 Regional Geology

1.5.1 Geological Setting

The Cherokee basin is located on the western flank of the Ozark dome, which is part of the northward extension of the elongated Oklahoma platform (Cole, 1969; Moore, 1979; Figure 1.05). The Cherokee basin is bounded by the Bourbon arch to the north, the Nemaha uplift to the west, and the Ozark dome to the east. During the early to mid-Desmoinesian, the Cherokee basin was influenced by the orogenic activity of the convergent Ouachita system in present-day southeastern Oklahoma (Ham and Wilson, 1967; Harris 1984; Figure 1.05). During the Pennsylvanian, sediment of the Cherokee Group was deposited disconformably upon the karst surface of the Mississippian limestone in southeastern Kansas and adjacent areas (Saueraker, 1966). The Cherokee Group was deposited while

the area was part of a slowly subsiding, intracratonic basin (Staton, 1987). Since onset of Cherokee deposition, approximately 4,900 feet (1,500 m) of Pennsylvanian and Permian sediments were deposited in the Cherokee basin (Barker et al., 1992). The Cherokee Group gradually thickens to the south into the deeper Arkoma foreland basin (Gould, 1927; Ham and Wilson, 1967; Jewett, 1951; Figure 1.05). Today, parts of these late Paleozoic deposits are stripped away leaving a homoclinal middle and upper Pennsylvanian succession dipping less than 0.5 degrees to the west (Walton, 1995).
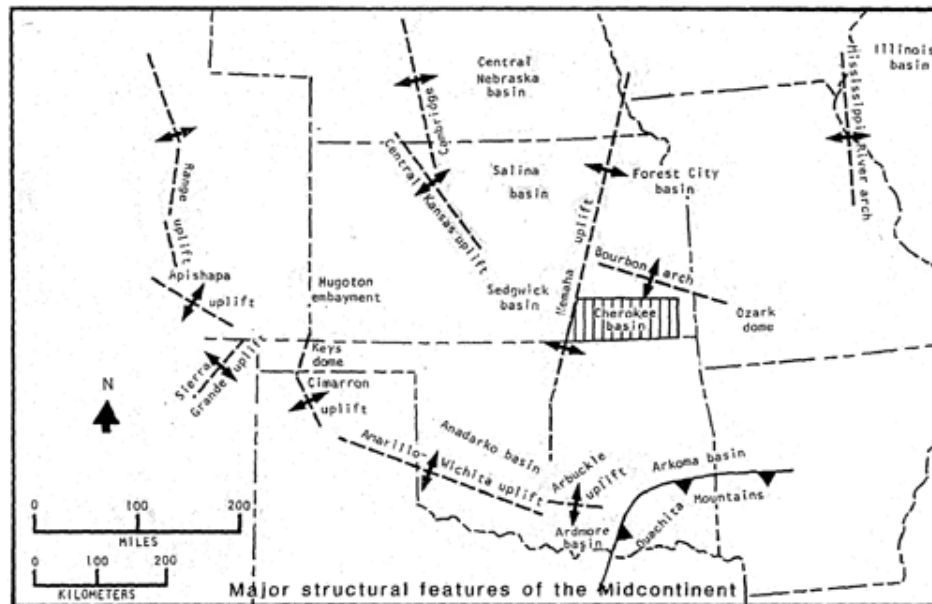

Figure 1.05 - Location of Cherokee basin and major structural features of the Midcontinent (modified from Wanless, 1969)

1.5.2 Stratigraphy

In southeastern Kansas, the Cherokee Group (Desmoinesian Stage, Middle Pennsylvanian Series) is divided into the Krebs Formation and the overlying Cabaniss Formation (Jewett et al., 1968; Figure 1.01). It is composed of numerous repetitive successions of interbedded gray to dark gray shale, rippled sandstone and siltstone, underclay, thin coal, and thin argillaceous limestone that have been interpreted as classic megacyclothems (Moore, 1931) and Illinois cyclothems (Wanless, 1931). The Cherokee Group is interpreted as consisting of a number of cyclothems that onlap positive structural features (Ham and Wilson, 1967; Visher et al., 1971, and Rascoe and Adler, 1983). Cherokee Group cyclothems were interpreted as deposited during minor progradational pulses of sedimentation that punctuate a major transgression during the Desmoinesian (Staton, 1987).

A typical Pennsylvanian cyclothem includes beds of nonmarine transitioning to marine sediments in the lower half of the cyclothem, with beds of marine transitioning to nonmarine sediments dominating the upper half of the cyclothem (Heckel, 1977). A transgressive-regressive sequence comprising a typical "Kansas" cyclothem consists of:

1. relatively thick, nearshore to terrestrial, sandy "outside" shale, and localized coal;
2. thin, transgressive "middle" limestone;
3. thin, offshore, nonsandy dark gray to black "core" shale;
4. thicker, upward grading regressive "upper" limestone; and
5. thick, nearshore to terrestrial, sandy "outside" shale (Heckel, 1977; Figure 1.06).
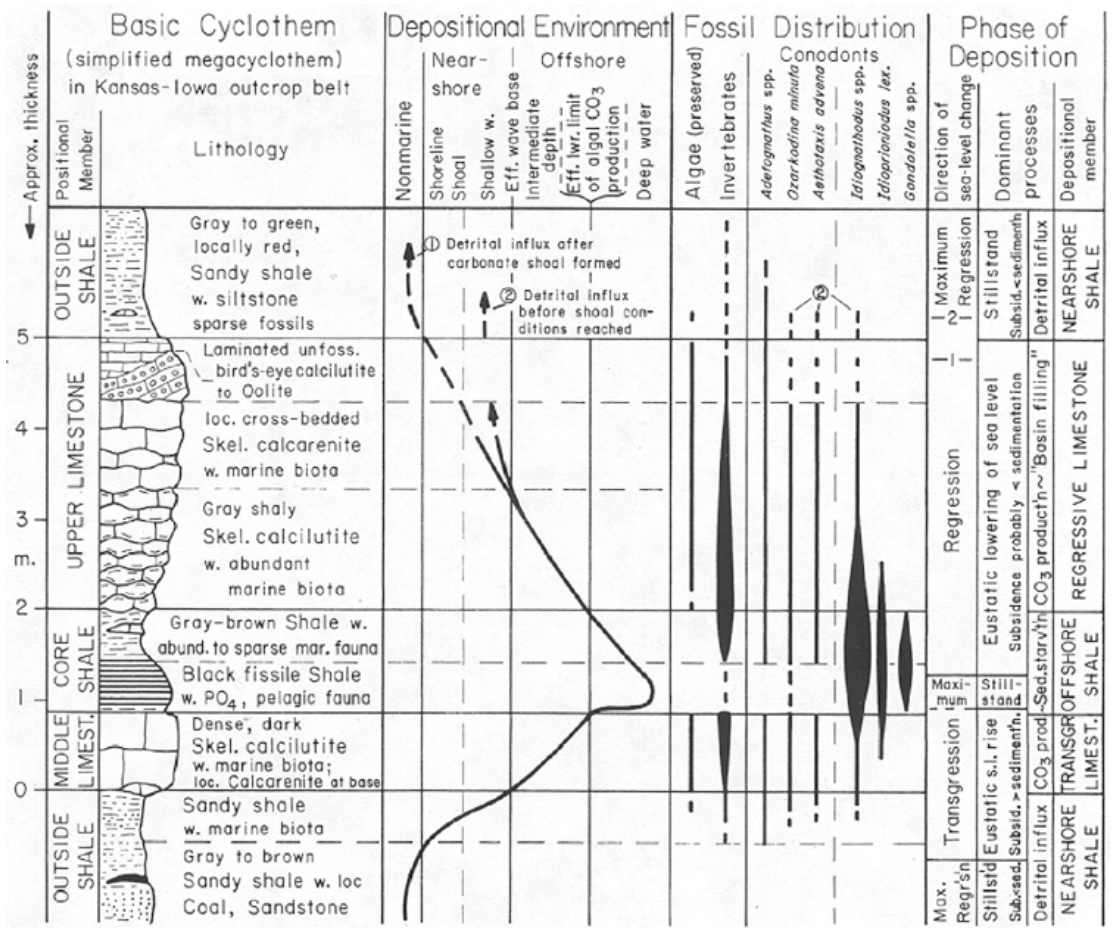
Figure 1.06 - The major components of a typical "Kansas" cyclothem and their relation to geologic properties such as depositional environment, fossil distribution, and phase of deposition (from Heckel, 1977).

1.6 Methodology

Data from the Kansas Geological Survey, including well logs, cores, and driller's logs were used to generate structure and isopach maps, and cross sections to study the geographic variability and stratigraphic geometries of coals and related facies in the Cherokee Group. A subsurface geographic information system (GIS) program was used to digitally map the structure and thickness of the main lithologies and to build a series of regional sequence stratigraphic and structural cross sections. Cores were described and tied to well log response for a well-by-well analysis. Cores of coals were sampled and desorbed to determine total gas content. After termination of the desorption process, samples were selected for proximate and sulfur analyses.

1.6.1 Well Log Analysis

The bulk of the subsurface data available for this project are geophysical well logs. Logs from a total of 930 wells, with an average spacing of eight wells per township, were interpreted and correlated (Figure 1.07). Since neutron-density is the preferred logging tools for identification and evaluation of coal, all available neutron/density porosity logs were used. Due to the paucity of neutron/density logs, gamma ray/neutron logs (the dominant geophysical well logs within the study area), were used to

broaden the aerial coverage. Gamma ray/neutron logs were found to have a distinct and correlatable response that could be used to identify lithologies and sequence stratigraphic packages and surfaces.
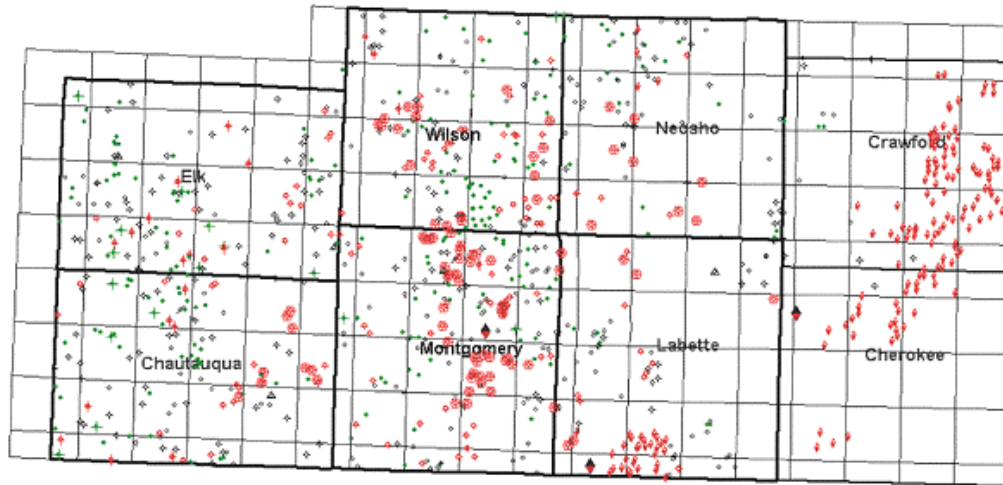

Figure 1.07 - Locations of examined and analyzed well logs in this study exceeds 930. 150 drillers logs (⬖), 3 cores (♦), cbm wells (⊙), all other symbols are oil and gas wells.

A combination of gamma ray and gamma ray/neutron porosity logs were used to identify coals and provide a qualitative evaluation. Low-ash coals, lacking naturally occurring radioactive elements, exhibit a low gamma-ray count, while high ash coals contain clay minerals that register a moderate gamma-ray count. The gamma ray/neutron tool is sensitive to both high-energy captive gamma rays and thermal neutrons. The response of the tool is primarily to the amount of hydrogen in the formation that is interpreted as porosity. The high hydrogen content of coals is reflected as a high apparent porosity on the neutron log since hydrogen is regarded as an indication of porosity (Table 1.1; Scholes and Johnston, 1993). Interpretations of coal seams were made using the coincidence of low gamma-ray deflections with higher neutron porosity deflections (Figure 1.08). In addition, stratigraphic position was helpful in recognizing coals. Many Kansas coals are located just below black phosphatic "core" shales with very high gamma radiation counts (Figure 1.08). Radioactive black "core" shales were used as marker beds to focus the evaluation of possible coal development.

Density and neutron/density porosity logs are the most dependable for coal identification, and were used to provide a guide to interpretation of the much more abundant gamma/ray neutron logs. Coals generally have a low matrix density (1.33 gm/cc) and density logs will read relatively low density, which translates to very high apparent porosity (Figure 1.09). With increasing ash content (eg., clay minerals), density will increase and apparent porosity will decrease (see Table 1.1; Scholes and Johnston, 1993).
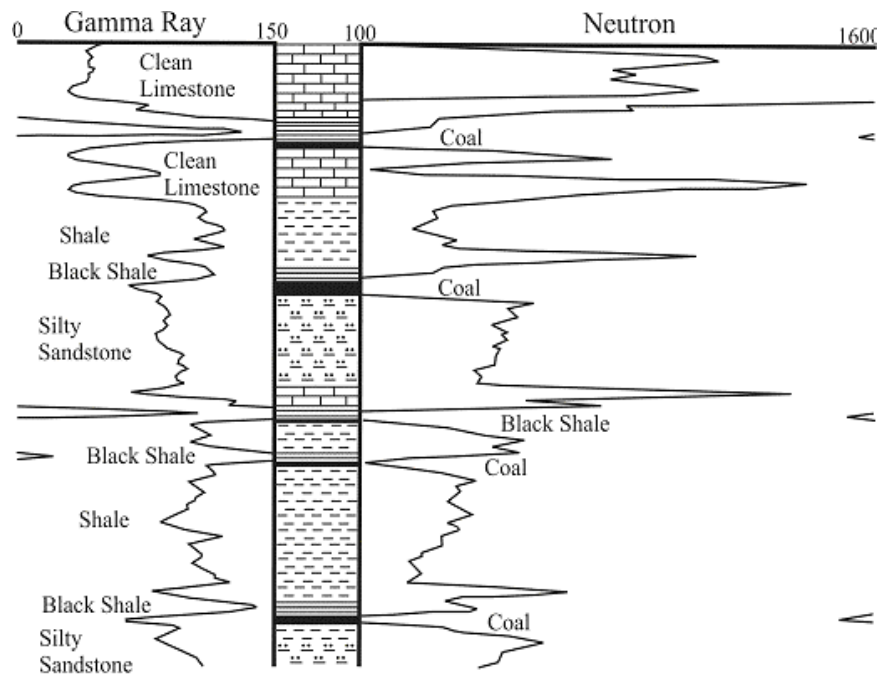
Figure 1.08 - Lithologic responses on a typical gamma-ray - neutron log from the Hinthorn CW#1 well 14=T32S-R16E. Coals are typically located beneath black phosphatic "core" shales with high gamma-ray counts (180-300 API units). Coals have relatively low gamma-ray counts (<100 API) and high apparent porosity resulting from the high hydrogen content measured by the gamma-ray/neutron log.

	Gamma Ray	Neutron	Density	Density Porosity
Low Ash Coal	Low API ~ 45 - 75 API	High Porosity ~ 35 - 45 %	Low Density < 1.75 g/cc	High DPHI > 40 %
High Ash Coal	Moderate API ~ 75 - 105 API	High Porosity < 35 %	Low Density < 2.0 g/cc	High DPHI ~ 30 - 40 %

Table 1.1 Log responses for low and high ash coals from southeastern Kansas

During the 1910's and 1920's coal exploration and extraction companies drilled numerous shallow core holes primarily in Cherokee and Crawford counties to evaluate potential for mineable coal. To supplement the sparse coverage of oil and gas wells in the eastern part of the study area, approximately 150 driller's logs from shallow borings were examined (Figure 1.07). Drillers logs from shallow borings were tied to outcrop maps and wells logs in order to better interpret the lithologies and stratigraphic position. The shallow borings provided a link between the stratigraphy from the deeper oil and gas wells and the surface stratigraphy in extreme eastern Cherokee and Crawford counties.

1.6.2 Lithologic Analysis

To supplement sparse natural outcrops and coal mines in the study area, two surface-to-total-depth cores were drilled and logged by the Kansas Geological Survey (KGS). The KGS core holes provide sedimentological, stratigraphic, and coal quality information. A total of two cores (KGS), representing the entire Fort Scott Formation and Cherokee Group, were described. Detailed descriptions of cores are in Appendix One. Another previously described core, the P&M core #20

(SE NE NE, sec.8-T23S-R22E) was reviewed and compared against the other two cores (description in Harris, 1984). Cores were examined for lithology, color, texture, cement(s), bedding, sedimentary structures, and fossil content.

Selected intervals of the core were slabbed and polished due to their brittle nature in order to better study and identify sedimentary features and fossil content. Underclays were slabbed by placing them in cardboard mailing tubes cut to length and filled with casting resin. Once the resin set up, the underclay sample was slabbed and described.

During the drilling process, cores of coals were measured and photographed before quickly placing the coals in pressurized canisters to determine gas content. Following termination of gas release, the coals were decanistered, examined for mineral and cleating development, and crushed for proximal analysis.
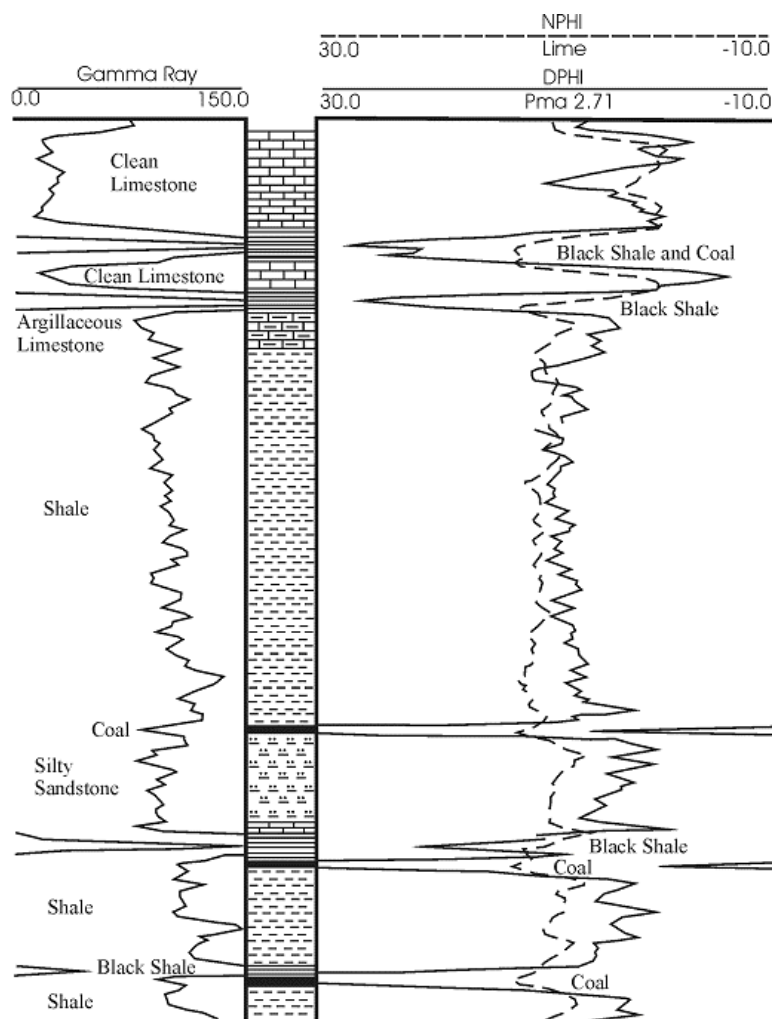

Figure 1.09 - Lithological responses on a typical gamma-ray - neutron density porosity log from southeastern Kansas. Coals have relatively low gamma-ray counts in combination with very high apparent porosity (low density). Apparent porosity in many typical coals exceeds 30 percent.

1.6.3 Computer Applications

A subsurface geographical information system (PETRA) was used to map the structure and thickness of the main stratigraphic units along with constructing regional sequence stratigraphic and structural cross sections. A digital dataset project, consisting of a series of spreadsheets (Microsoft Excel), was built through custom queries to the KGS relational database management system using Microsoft Access 2000 to generate special query language (SQL). Data selected includes general well data (eg., well name, location, elevation), producing formation, formation tops, and production for coalbed methane wells. In order to map the main lithologies and build cross sections over the study area, paper logs were selected and scanned (Neurolog scanner). Raster images of the logs were calibrated and imported into a GIS workstation for lithologic analysis. Spreadsheets were used to record and analyze all coal desorption data such as the volume, time, temperature, and barometric pressure of each measurement. Desorbed gas was summed over the time period for which the coal samples evolved all of their gas. All data generated or modified as part of this study, including horizon tops, raster wells images and identification of coalbed methane wells was uploaded into the Kansas Geological Survey's online databases.

1.6.4 Desorption Method

In cooperation with local independent oil and gas companies, cuttings and core samples of coals were obtained from wells within the major areas of coalbed methane exploration and production. Additional coal core samples were obtained by the Kansas Geological Survey's core drilling operations (Figure 1.10). Dave Newell and I collected and placed coal samples in desorption canisters immediately following extraction from the well bore (Figure 1.11). Cutting samples were caught with a kitchen strainer at the end of the buoy line. Core samples were obtained and quickly moved from the boring to the surface by use of a wire-line core barrel.
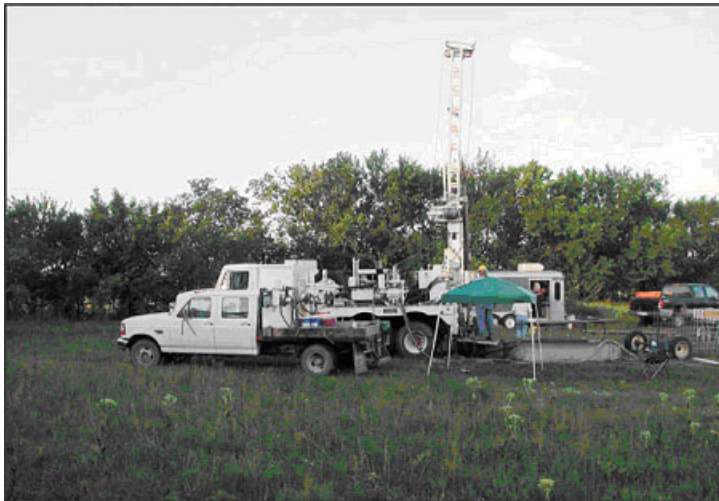

Figure 1.10 - Kansas Geological Survey's core drilling operations

Figure 1.11 Collection and canistering of coal core samples

Desorption canisters were made at the KGS, using PVC pipe and plumbing materials available at hardware stores, or purchased commercially (SSD, Inc. in Grand Junction, CO). On average, the canisters were approximately 12.5 inches long (32 cm), 3 1/2 inches (9 cm) in diameter, and enclosed a volume of approximately 150 cubic inches (2450 cm3; Figure 1.12).

Standard methods and equipment were used for measuring desorbed gas (McLennan et al., 1995). I measured evolved gas with a volumetric displacement apparatus, consisting of a set of connected dispensing burettes, one of which measures the gas evolved from the desorption canister. The other burette compensates for the compression effects that occur when the desorbed gas displaces the water in the measuring burette (Figure 1.12). The amount of gas evolved is determined by first adjusting the water levels in the two cylinders to the same level, then after releasing the gas from the desorption canister, reading the difference in water level using the volumetric scale on the side of the burette.

Desorbed gas collected in the desorption canisters was periodically released into the volumetric displacement apparatus and measured as a function of time, temperature and atmospheric pressure. Ideally, original temperature at the formation depth should be maintained for the period of desorption. To control temperature, desorption samples were placed in isothermal baths immediately after being canistered. Isothermal baths were constructed using plastic and Styrofoam coolers filled with water. For measurements in the field, original formation temperature was maintained using ice, or water heated either by an aquarium heater and/or boiling pot

Figure 1.12 - Desorption apparatus and canisters

For measurements in the lab, water was heated with aquarium heaters and circulated with aquarium pumps for formation temperatures greater than 70 °F. For temperatures less than 70 °F, the samples were kept in a room with an ambient temperature varying from 65 to 68 °F.

I measured time and atmospheric pressure in the field and laboratory using a portable weather station (Oregon Scientific, model BA928). The atmospheric pressure was measured in millibars. However, this measurement was not the actual barometric pressure, but rather an altitude-compensated barometric pressure, automatically converted to a sea-level-equivalent pressure within the instrument. In order to translate this measurement to actual atmospheric pressure, a regression correlation was determined by recording and comparing barometric readings displayed from a pressure transducer in the Petrophysics Laboratory in the Kansas Geological Survey in Lawrence, Kansas. The regression equation, corrected the millibar reading to barometric pressure.

Barometric pressure for the desorption measurements was used in a spreadsheet (written by K.D. Newell, Kansas Geological Survey) to determine gas volumes at standard temperature and pressure. Conversion of gas volumes to standard temperature and pressure was applied by the ideal-gas equation (Equation 1).

$$n = PV/RT \qquad\qquad (1)$$

where n is moles of gas, T is degrees Kelvin (i.e., absolute temperature), V is in liters, and R is the universal gas constant, which has a numerical value depending on the units in which it is measured (for example, in the metric system R = 0.0820 liter atmosphere per degree mole). The number of moles of gas (i.e., the value n) is constant in a volumetric conversion. Therefore the conversion equation is derived from the ideal gas equation (Equation 2).

$$(P_{stp}V_{stp})/(RT_{stp}) = (P_{obs}V_{obs})/(RT_{obs}) \qquad\qquad (2)$$

Customarily, standard temperature and pressure for gas volumetric measurements in the oil industry are 60° F and 14.7 psi (Dake, 1978). P_{stp}, V_{stp}, and T_{stp}, respectively, are pressure, volume and temperature at standard temperature and pressure, where standard temperature is degrees Rankine (° R = 460 + ° F). P_{obs}, V_{obs}, and T_{obs}, respectively, are ambient pressure, volume and temperature measurements observed on well site or in the desorption laboratory.

Universal gas constant R drops out as this equation is simplified and the determination of V_{stp} becomes (Equation 3):

$$V_{stp} = (T_{stp}/T_{obs}) \ (P_{obs}/P_{stp}) \ V_{obs} \qquad\qquad (3)$$

Conversion calculations in the spreadsheet were carried out in the english-metric system, as this is the standard measure system used in U.S. coal and oil industry. V is therefore converted to cubic feet; P is psia; T is ° R.

Desorbed gas was summed over the time period for which the coal samples continued to evolve gas. In the case of cores, this time could be six or more months. Cuttings desorbed faster, typically in a matter of days or weeks. Lost gas (i.e., the gas lost from the sample from the time it was drilled, brought to the surface, to time of canistering) was determined using the direct method (Kissel et al., 1975; McLennan et al., 1995). Cumulative gas evolved is plotted against the square root of elapsed time. I carefully recorded time zero during drilling operations and assumed it be the instant the core sample is lifted from the bottom of the hole, or in the case of cuttings, when the drilled rock is cut and circulated off bottom. Characteristically, the cumulative gas evolved from the sample, when plotted against the square root of time, is linear for a short time period after the sample reaches ambient pressure conditions. As a result, lost gas can be estimated by a line projected back to time zero. The period of linearity generally is 4 to 6 hours for a core sample, and less than an hour for cuttings samples.

The termination of evolved gas was defined as two consecutive weeks of zero volume of desorbed gas. After termination of gas evolution, the canisters were opened and coal samples were removed. Samples were weighed for their wet weight and allowed to dry for one to two weeks. At the end of the drying period, samples were weighed again to obtain dry weight. A portion of the dry coal sample was crushed and sent to a commercial laboratory to determine moisture, ash, sulfur, calorific value (BTU), fixed carbon, and volatile matter (Luman's Laboratories).