**ANALYSIS OF DEVONIAN BLACK SHALES IN KENTUCKY FOR
POTENTIAL CARBON DIOXIDE SEQUESTRATION AND ENHANCED
NATURAL GAS PRODUCTION**

**Eleventh Quarter
January 1, 2005 to March 31, 2005**

Brandon C. Nuttall

Report Issued: April 26, 2005

DE-FC26-02NT41442

**Kentucky Geological Survey
228 Mining and Mineral Resources Building
University of Kentucky
Lexington, Kentucky 40506-0107**

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service mark by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The view and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Abstract

Devonian gas shales underlie approximately two-thirds of Kentucky. In the shale, natural gas is adsorbed on clay and kerogen surfaces. This is analogous to methane storage in coal beds, where CO₂ is preferentially adsorbed, displacing methane. Black shales may similarly desorb methane in the presence of CO₂.

Drill cuttings from the Kentucky Geological Survey Well Sample and Core Library were sampled to determine CO₂ and CH₄ adsorption isotherms. Sidewall core samples were acquired to investigate CO₂ displacement of methane. An elemental capture spectroscopy log was acquired to investigate possible correlations between adsorption capacity and mineralogy.

Average random vitrinite reflectance data range from 0.78 to 1.59 (upper oil to wet gas and condensate hydrocarbon maturity range). Total organic content determined from acid-washed samples ranges from 0.69 to 14 percent. CO₂ adsorption capacities at 400 psi range from a low of 14 scf/ton in less organic-rich zones to more than 136 scf/ton. There is a direct correlation between measured total organic carbon content and the adsorptive capacity of the shale; CO₂ adsorption capacity increases with increasing organic carbon content.

Initial estimates based on these data indicate a sequestration capacity of 5.3 billion tons of CO₂ in the Lower Huron Member of the Ohio Shale of eastern Kentucky and as much as 28 billion tons total in the deeper and thicker parts of the Devonian shales in Kentucky. Should the black shales of Kentucky prove to be a viable geologic sink for CO₂, their extensive occurrence in Paleozoic basins across North America would make them an attractive regional target for economic CO₂ storage and enhanced natural gas production.

Table of Contents

DISCLAIMER	I
ABSTRACT	II
TABLE OF CONTENTS	III
LIST OF FIGURES	IV
EXECUTIVE SUMMARY	1
TECHNOLOGY TRANSFER SUMMARY	3
INTRODUCTION	3
STUDY AREA	4
REGIONAL GEOLOGY	4
STRATIGRAPHY	4
PRODUCTION	5
METHODS	6
Drill Cuttings	6
Total Organic Carbon	7
Vitrinite Reflectance	8
Adsorption Isotherms	8
Sidewall Cores for Adsorption and Methane Displacement	10
Mineralogy: Elemental Capture Spectroscopy and X-Ray Diffraction	10
Geophysical Logs	10
Sequestration Capacity of the Shale	11
RESULTS TO DATE	12
PRELIMINARY CONCLUSIONS	13
ACKNOWLEDGEMENTS	14
REFERENCES CITED	15
TABLES	17
FIGURES	20
FIGURES	20
BIBLIOGRAPHY	37
APPENDIX A: SUMMARY OF ADSORPTION ISOTHERMS	59
APPENDIX B: GIS ANALYSIS OF THE DISTRIBUTION AND ESTIMATED CO₂ STORAGE VOLUME OF THE DEVONIAN SHALE IN KENTUCKY	74
APPENDIX C: CNR 24752 ELK HORN COAL	81

LIST OF TABLES

Table 1. Gas storage capacity, total carbon (TC), total organic carbon (TOC), and vitrinite reflectance data for completed samples.	17
Table 2. Summary of CO ₂ adsorption capacity in standard cubic feet per ton at selected pressures.	18
Table 3. Summary of CH ₄ adsorption capacity in standard cubic feet per ton at selected pressures	19

LIST OF FIGURES

Figure 1. Distribution of the Devonian shale in Kentucky, showing the occurrence of deeper and thicker shale with possibly greater potential for geologic sequestration of CO ₂	20
Figure 2. General structure of the Devonian shale, showing presence of shale in the subsurface (shading).	20
Figure 3. Distribution and nomenclature of Devonian shales of Kentucky (Hamilton-Smith, 1993, p. 3).	21
Figure 4. General geologic column showing approximately 3,800 feet of overlying Mississippian and Pennsylvanian lithologies adequate for ensuring reservoir integrity in the Devonian shale. Note: Devonian shale is underlain by Devonian carbonates.	22
Figure 5. Nomenclature of Mississippian and Devonian shales of eastern Kentucky and key to names and codes used for intervals sampled.	23
Figure 6. Eastern Kentucky Devonian shale natural-gas production (proprietary data), showing long-term increase. Dotted line is exponential best fit of observed rate-time data.	24
Figure 7. Location of selected wells in eastern Kentucky.	25
Figure 8. Location of the Columbia Natural Resources 24752 Elk Horn Coal Company well, permit 94539, Knott County, Ky., Carter coordinate 11-K-81, latitude 37.37019° N, longitude 82.76441° W (NAD 1983).	26
Figure 9. Mean random reflectance ($R_{0 \text{ random}}$)	27
Figure 10. Summary of adsorption isotherms.....	28
Figure 11. Distribution of observed CO ₂ (green) and CH ₄ (blue) adsorption capacity.	29
Figure 12. Average calculated adsorption capacities by formation at selected pressures.	30
Figure 13. Section of elemental capture spectroscopy log through the Lower Huron section of the Columbia Natural Resources No. 24752 Elk Horn Coal well, Knott County, Ky., showing relative abundance of species related to mineral and lithologic identification. Asterisks denote depths where sidewall cores were recovered.....	31
Figure 14. Typical whole rock X-ray diffraction trace of the Devonian shale (upper part, well id 107928, Figure 7).	32
Figure 15. Relationship between total organic content and adsorption capacity of shale at 400 psia.....	33
Figure 16: West (left) to east (right) cross section of Big Sandy Gas Field color-shaded based on density. Low densities (cooler colors) indicate organic-rich zones.	34
Figure 17. Gamma-ray density cross plots showing variation by general lithotype: all wells combined (top) and the CNR #24526 Bush (bottom).....	35
Figure 18. Preliminary estimated CO ₂ storage capacity per square kilometer (in million tons) in the areas of deeper (>=1,000 feet) and thicker (>=50 feet) Devonian shale.....	36

Executive Summary

Increased emissions of CO₂, especially from the combustion of fossil fuels, are being linked to global climate change and are of considerable global concern. These concerns are driving initiatives to develop carbon management technologies, including geologic sequestration of CO₂. One option for sequestration may be Devonian black shales, organic-rich rocks that serve as both the source and trap for natural gas. Most of the natural gas is adsorbed on clay and kerogen surfaces, very similar to the way methane is stored within coal beds. It has been demonstrated in gassy coals that, on average, CO₂ is preferentially adsorbed, displacing methane at a ratio of two for one. Black shales may similarly desorb methane in the presence of adsorbing CO₂. If this is the case, black shales may be an excellent sink for CO₂ and have the added benefit of serving to enhance natural-gas production. A bibliography of Devonian shale has been compiled to identify previous work and provide supporting data for continued research.

Because of the volume of material lost during washing the sampling protocol was modified to collect cuttings before washing. Unwashed candidate samples have been selected and are being prepared for total organic carbon, vitrinite reflectance, and petrographic and CO₂ adsorption analyses to determine the gas-storage potential of the shale and to identify shale facies with the most sequestration potential. For the Devonian shale, average total organic carbon is 3.71 (as received) and mean random vitrinite reflectance is 1.16.

Columbia Natural Resources (CNR) has provided access to a selected drill hole of opportunity for collecting sidewall cores and an elemental capture spectroscopy (ECS) logging suite for correlation and mineralogical analysis. Sidewall cores were submitted for methane and CO₂ adsorption isotherms and methane displacement analyses. The results of the displacement and flow through experiments are pending.

All samples were submitted for TOC and CO₂ adsorption analyses including samples from the New Albany Shale (Illinois Basin) and the Battelle deep well in Mason County, West Virginia (AEP #1). Methane adsorption isotherms are being obtained on all most recently submitted samples. X-ray diffraction analyses have been conducted to assist in mineral characterization and correlating results from electron capture spectroscopy logging.

Gamma ray and density log data has been digitized for 18 wells in the Big Sandy Gas field. These data have been correlated and models are being developed to calculate CO₂ sequestration capacity as adsorbed gas in place estimates from the observed shale density data.

In cooperation with Interstate Natural Gas, Pikeville, Kentucky, an ECS log was acquired for a shale well in Martin County. Schlumberger has developed a shale gas analytical model and has applied their to the ECS log for this well. Sidewall cores were acquired for this well and have been submitted for CO₂ adsorption and other analyses. It has been requested that Schlumberger donate their analytical services to run this new model on the ECS log for the CNR well.

Adsorption capacity reported as measured langmuir volumes ranges from 37 to 2,078 standard cubic feet CO₂ per ton of shale (scf/ton) at langmuir pressures ranging from 243 to 14,284 psia. These values represent the range of values for coefficients of the selected langmuir model. At a constant pressure of 400 psia indicate the CO₂ adsorption capacity ranges from 14 to 136 scf/ton with a median value of 40 scf/ton. Methane adsorption capacity ranges from 2 to 38 scf/ton with a median value of 8 scf/ton. At 400 psia, CO₂ adsorption exceeds CH₄ adsorption by a factor of 5. These data are being correlated with data from nuclear log suites for modeling TOC and CO₂ storage capacity for individual wells.

Initial estimates at 68 scf/ton indicate a sequestration capacity of 5.3 billion tons CO₂ in the Lower Huron Member of the Ohio shale in parts of eastern Kentucky. At 500 psia, adsorption capacity of the Lower Huron Member of the shale averages 72 scf/ton. Assuming a thickness weighted average adsorption capacity of 40 scf/ton (at 400 psia), as much as 28 billion tons total in the deeper and thicker portions of the Devonian shales in Kentucky. The black shales of Kentucky could be a viable geologic sink for CO₂, and their extensive occurrence in Paleozoic basins across North America would make them an attractive regional target for economic CO₂ storage and enhanced natural gas production.

Accomplishments this quarter:

- Digitize logs for 18 wells
- Pick stratigraphic tops and correlate digital well logs
- Compile and review stratigraphic and structural cross sections
- Compile and analyze gamma-ray and density log cross plots
- Collect ECS log and sidewall cores from the Interstate #3 Jude well, Martin County
- Compute TOC and gas-in-place curves (statistics and analysis pending)
- Submit abstracts for NETL and Eastern Section AAPG meetings
- Compile poster for NETL meeting

Technology Transfer Summary

- NE/SE Combined GSA Section Meeting, April 2-5, 2002, Lexington, KY
- 2nd National Conference on Carbon Sequestration (NETL), May 5-8, 2003, Alexandria, Virginia: (poster session)
- Kentucky Oil and Gas Association Annual Meeting, June 23-25, 2003, Louisville, Kentucky
- 2003 GSA Annual Meeting and Exposition, November 2-5, 2003, Seattle, Washington
- NE/SE Combined GSA Section Meeting, March 25-27, 2004, Washington, DC
- DOE/NETL Carbon Sequestration Project Review, March 29 to April 1, 2004, Pittsburgh, Pennsylvania
- AAPG Annual Meeting, April 18-21, 2004, Dallas, Texas.
- 3rd Annual Conference on Carbon Sequestration (NETL), May 2-6, 2004, Alexandria, Virginia.
- 7th International Conference on Greenhouse Gas Control Technologies, September 5-9, 2004, Vancouver, British Columbia, Canada
- AAPG Eastern Section, October 3-7, 2004, Columbus, Ohio
- Regional Carbon Sequestration Partnership Geologic Characterization Working Group Workshop, Houston, Texas
- 2004 GSA Annual Meeting and Exposition, November 7-10, Denver, Colorado
- 4th Annual Conference on Carbon Sequestration (NETL), May 2-5, 2005, Alexandria, Virginia: (upcoming, poster accepted)
- AAPG Annual Meeting, June 19-22, 2005, Calgary, Alberta, Canada: (upcoming, abstract accepted)
- AAPG Eastern Section, October 18-20, 2005, Morgantown, West Virginia: (upcoming, abstract submitted)

Introduction

Carbon dioxide (CO₂) is an efficient heat-trapping gas occurring in Earth's atmosphere. Over the past decades, there has been a growing concern that anthropogenic emissions of CO₂ are contributing to a systematic warming of Earth's climate; that is, global warming. The majority of anthropogenic emissions of CO₂ are from fossil fuel combustion. Electric power generation, transportation fuels, and industrial applications are highly dependent on coal, crude oil, and natural gas. It is estimated that the reliance on fossil fuel combustion will extend well into the 21st century (EIA, 2000). In Kentucky, 95 percent of the total electric generation capacity relies on fossil fuels (EIA, 2002, Table 4), with annual emissions of 87 million metric tonnes of CO₂ (EIA, 2002, Table 7).

CO₂ emissions can be decreased by increasing the efficiency of fossil fuel combustion processes, switching to alternate and renewable fuels (biomass, nuclear, solar, wind), and capturing and sequestering CO₂. Each of these methods will undoubtedly be used to achieve goals for addressing global warming and meet increasing energy demands. For sequestering CO₂, marine and terrestrial options are being researched, but geologic sequestration is the focus of this project. Geologic sequestration includes long-term carbon storage in old oil and gas fields, coals, saline aquifers, and unconventional reservoirs.

Usually considered to be the seal for conventional oil and gas reservoirs, gas shales warrant study as a possible sequestration option. This research tests the hypothesis that organic- and gas-rich black shales can adsorb significant amounts of CO₂. In carrying out the research, the Devonian black shales of Kentucky are being tested in the laboratory to determine their CO₂ sorption capacity using powdered drill cuttings and sidewall cores. The ability of

sorbed CO₂ to displace methane is being tested on sidewall cores in order to assess the potential for enhanced natural gas production from the shales.

Organic matter in the Devonian gas shales has large surface areas similar to that found in coal. Coal seams are currently being investigated as potential sequestering sites for CO₂, the most important greenhouse gas (IEA Coal Research, 1999). Naturally occurring organic matter (kerogen) is a microporous material that possesses a very high surface area and hence sorption capacity for gas. In the subsurface, coal commonly has economically significant amounts of sorbed methane (coalbed methane). Because organic matter has a greater sorption affinity for CO₂ than methane, injection of CO₂ with simultaneous production of methane may be viable (see Reznik and others, 1982; Bachu and Gunter, 1998). Currently a pilot CO₂ injection project is under way in Alberta, led by the Alberta Research Council and a consortium of petroleum companies. In the San Juan Basin, New Mexico, Amoco has carried out a pilot investigation of CO₂ injection, and Burlington Resources is currently evaluating the utility of CO₂ injection to enhance recovery of methane from coal. Results from these tests have shown that CO₂ injection and co-production of coalbed methane is technically and economically feasible. Since 1996, over 57 million m³ of CO₂ has been sequestered in Cretaceous coal of the San Juan Basin, New Mexico. The question is: can Devonian gas shales adsorb sufficient amounts of CO₂, making them significant targets for CO₂ sequestration?

Study Area

The study area is primarily confined to the major gas-producing area of the Ohio Shale in the Big Sandy Gas Field, eastern Kentucky (Figure 1, main concentration of producing localities). As key wells and available samples are identified, wells in deep (at least 1,000 feet) and thick (at least 50 feet) areas will be included. The Devonian New Albany Shale in two Illinois Basin wells in Indiana have been sampled. Battelle has contributed drill cuttings through the Devonian Lower Huron Member of the Ohio Shale from their deep AEP CO₂ sequestration project well in Mason County, W. Va.

Regional Geology

Thinly bedded, fissile shales of Early Mississippian and Late Devonian age occur in the subsurface of nearly two-thirds of Kentucky. In general, the shales are thicker and deeper in eastern and western Kentucky (Figure 1) and are absent in the Bluegrass Region of central Kentucky and the Mississippi Embayment Region in the Jackson Purchase area of extreme western Kentucky. Along the axis of the Cincinnati Arch in central Kentucky, the thickness of the shale is usually 50 feet or less. The shale thickens eastward to more than 1,700 feet in Pike County. The shale is exposed in outcrop around the margin of the Jessamine Dome (along the perimeter of the Inner and Outer Bluegrass Regions of central Kentucky) and along the Cumberland River drainage in south-central Kentucky. A subcrop of the shale has been identified beneath the Cretaceous sediments of the Mississippi Embayment Region of western Kentucky. Figure 2 shows the elevation of the top of the Devonian shale in Kentucky and illustrates the progressive deepening of the shale east and west of the Cincinnati Arch area of central Kentucky.

Stratigraphy

Figure 3 shows the distribution of the Devonian shales in Kentucky, known variously as the New Albany (Illinois Basin), Chattanooga (central Kentucky, Cincinnati Arch area), and Ohio (Appalachian Basin) Shales. Reservoir integrity for CO₂ sequestration is a concern. Figure 4 provides a composite general geologic column illustrating more than 3,800 feet of Mississippian and Pennsylvanian lithologies, including carbonate, sand, shale, and coal that have proven an

effective seal for existing shale gas resources. The assumption that sequestration will take place in the shale at depths of at least 1,000 feet recognizes the possible limitations of a fractured reservoir to act as an effective seal. Testing the integrity of this seal with respect to CO₂ is beyond the scope of this project and will be the subject of any subsequent CO₂ injection demonstration project.

The Ohio Shale is subdivided into seven recognizable units (Figure 5): Cleveland Shale, Three Lick Bed, Upper, Middle, and Lower Huron, Olentangy, and Rhinestreet. In the subsurface, these units have been differentiated based on gamma ray and density differences that are essentially related to the organic-matter content of the shale. The upper most black, carbonaceous shales (Cleveland and Upper Huron) pinch out eastward into gray, more clastic sequences correlative to the Three Lick Bed, herein called the Chagrin Shale. The Olentangy and Rhinestreet black shales correspond to the Java Formation of West Virginia, and thin and pinch out westward. Some authors consider that the Olentangy and Rhinestreet are members of the Devonian Ohio Shale. Although they are not everywhere present in the subsurface in the study area, the units are included in the analyses where samples are available.

Production

The first Devonian shale gas wells were drilled between 1863 and 1865 in Meade County, west-central Kentucky, and were used to fuel street lamps and provide heat in Louisville. Shale gas was discovered in eastern Kentucky circa 1892 in Floyd County (Hoeing, 1905). Overall, cumulative Devonian shale gas production in Kentucky probably exceeds 84.9 billion cubic meters (bm³); gas in place is estimated by various investigators to be between 26 trillion cubic meters (tm³) and 73 tm³ (Hamilton-Smith, 1993, p. 5). According to production data on file at the Kentucky Geological Survey, the giant Big Sandy Gas Field of Floyd, Knott, Letcher, Martin, and Pike Counties produced 77 percent of the nearly 2.5 bm³ of natural gas produced in Kentucky in 2003.

Reservoir parameters for the Big Sandy Gas Field were summarized in the "Atlas of Major Appalachian Gas Plays" (Boswell, 1996). The average completed interval exceeds 500 feet in thickness. Average porosity is 4.3 percent, with a maximum of 11 percent. Reservoir temperature averages 84°F, with an initial reservoir pressure of 800 psi or more. Current reservoir pressure averages 400 psi. Limited permeability data are available, but indicate less than 0.1 millidarcy of matrix permeability. Fracture permeability may exceed several hundred millidarcies.

Drilling and completions target organic-rich intervals with abundant natural fractures, mostly in the Lower Huron Member of the Ohio Shale (Figure 5) of eastern Kentucky. The completion often consists of multiple completions including the Sunbury to Upper Huron interval with the Lower Huron completed separately. Completions in the gray, more clastic, shale intervals (Three Lick Bed/Chagrin and Middle Huron) are typical only where temperature, density, and audio anomalies indicate fracturing of the shale. Nitrogen is typically used as the carrier fluid in hydraulic fracturing stimulations, which are intended to intersect with and enhance any natural fractures. Sand is employed as a proppant to maintain an open fracture system. The industry rule of thumb is that a shale well can be expected to produce 300 million cubic feet of natural gas (MMcf). Some wells often produce from 500 MMcf to more than 1 billion cubic feet. Devonian shale gas production tends to be long-term. This long-term production (with many wells exhibiting flat, or inclining production; see Figure 6) and high organic content suggest the shale contains a large component of adsorbed methane.

Methods

Drill Cuttings

Drill cuttings on file at the Kentucky Geological Survey Well Sample and Core Library and sidewall cores are the main source of material for analysis. Unwashed sets of recently acquired drill cuttings were used to minimize weathering of material and to maximize volume of material for analysis. Drill cuttings are commonly collected during drilling in 5- to 10-foot intervals and consist of a mix of chipped rock fragments and powder. Distribution and stratigraphy of the Devonian shale in eastern Kentucky suggest dividing well cuttings into up to three samples for adsorption analysis. The upper part of the shale from the Cleveland Member to the Middle Huron is generally less organic-rich, as indicated by the gamma-ray response on standard geophysical well logs (Figure 5). Drill cuttings of this sequence generally have a lighter gray color and more recognizable quartz material than the darker gray to black samples with sparse pyrite that are characteristic of the Lower Huron Member. In some areas of the Big Sandy Gas Field, the Olentangy and Rhinestreet Members of the Ohio Shale are present but have a somewhat lesser organic content as indicated by gamma-ray logs. Where present, these shales were composited as a separate sample. Some wells have an insufficient volume of cuttings available to analyze the individual members of the Ohio Shale; in these cases the entire shale sequence was composited into a single sample. The rock chip and powder samples were divided into two splits: one for TOC, vitrinite reflectance, and X-ray diffraction analyses, and one for determination of CO₂ isotherms. Each split was then milled and sieved to the specifications of the respective analytical technique.

DEVSHALE - CO₂ Sequestration in the Devonian Shale

Figure 7 shows the location of wells sampled to date in eastern Kentucky.

Total Organic Carbon

To investigate any relation between organic content and CO₂ sorption capacity, total organic carbon content (TOC) is being determined. For total organic carbon analyses, samples were first crushed to a maximum particle size of 200 microns (-60 mesh). Samples were run in duplicate. One split was run "as is." Another split was treated with 30 percent hydrochloric acid (HCl) for 12 to 24 hours to remove any carbonate minerals from the matrix, prior to analysis. Although carbonate minerals are typically a rare component of Devonian shales, they present a possible bias in the calculation of TOC. Like organic material, carbonate minerals dissociate in the combustion chamber and form CO₂. The hydrochloric acid was removed by repeated

washings with distilled water, followed by centrifugation. The samples were then placed in a drying oven (50°C).

Total organic carbon was measured on a LECO SC-144 DR dual range sulfur and carbon analyzer, which is a nondispersive, infrared, digitally controlled instrument designed to measure sulfur and carbon in a wide variety of organic and inorganic materials. The unit combusts samples in a pure oxygen environment at 1,350°C. Sulfur compounds are immediately oxidized and form sulfur dioxide (SO₂); carbon compounds are oxidized to CO₂. From the combustion system, sample gases pass through two tubes containing magnesium perchlorate (MgClO₄), which removes moisture, and then are routed to the infrared (IR) detection cells. A sulfur IR cell measures the amount of SO₂ present in the gas stream, and a carbon IR cell does the same for CO₂. All molecules, with the exception of bipolar species (e.g., N₂, H₂, O₂), absorb energy in the infrared region. As radiant energy is projected through the sample material an IR absorption spectrum is produced. Since no two molecules produce the same spectrum, the identity and quantity of a compound can be readily, and accurately, determined.

An anomaly was noted in the last group of samples submitted for TOC determination; the carbon content after acid washing was consistently higher than the content as received. A new TOC standard has been selected and the samples are were reanalyzed. It was determined that the observed difference in TOC content before and after washing were smaller than instrument error. This indicated that very little, if any, inorganic carbon was present in the samples

Vitrinite Reflectance

Vitrinite reflectance is used as a measure of the maturity of the organic matter in shale and that maturity may influence CO₂ sorption capacity. Mean random reflectance (R_{0random}) on dispersed vitrinite particles in the samples was determined on a Zeiss USMP incident light microscope calibrated using glass standards of known reflectance. Depending on the amount of vitrinite in the samples, 50 or 100 grains were measured at a magnification of 640x to determine mean reflectance. Mean random reflectance was used because it eliminates the need to rotate the stage to determine maximum and minimum reflectance values. As the vitrinite particles in the analyzed samples were quite small (usually less than 10 microns), stage rotation simply wasn't practical, because it often resulted in the reflectance measuring spot moving off the grain. Maximum vitrinite reflectance values (R_{0max}) can be estimated by multiplying the mean random measurements by 1.066 (Ting, 1978).

Adsorption Isotherms

The classic theory used to describe the type I isotherm for microporous materials with small external surface area is based on the Langmuir equation (1916). The type I isotherm displays a steep increase in adsorption at low relative pressures due to enhanced adsorption caused by the overlapping adsorption potentials between the walls of pores whose diameters are commensurate in size with the adsorbate molecule. The type I isotherm then flattens out into a plateau region at higher relative pressure, which is believed to be caused by the completion of a monolayer of adsorbed gas. The micropore volume is thought to then be filled by only a few molecular layers of adsorbate, and further uptake is limited by the dimensions of the micropores.

The Langmuir model assumes that a state of dynamic equilibrium is established between the adsorbate vapor and the adsorbent surface and that adsorption is restricted to a single monolayer. The adsorbent surface is thought to be composed of a regular array of energetically homogeneous adsorption sites upon which an adsorbed monolayer is assumed to form. The rate of condensation is assumed to be equal to the rate of evaporation from the

adsorbed monolayer at a given relative pressure and constant temperature. The Langmuir equation was developed with these assumptions and takes the following form:

$$\frac{P}{V} = \frac{1}{BV_m} + \frac{P}{V_m}$$

where P is the equilibrium pressure, V is the volume of gas adsorbed at equilibrium, V_m is the volume of adsorbate occupying the monolayer, and B is an empirical constant. A plot of P/V vs. relative pressure should yield a straight line whose slope will yield V_m , from which the surface area may be obtained.

The Langmuir isotherm can be written:

$$V(P) = \frac{V_L P}{P_L + P}$$

P = gas pressure
 $V(P)$ = predicted amount of gas adsorbed at P
 V_L = Langmuir volume parameter
 P_L = Langmuir pressure parameter

The difference between the measured amount of gas adsorbed ($V(P)$) and that predicted using the Langmuir equation ($V_i(P)$) is a measure of error and is given as:

$$Err(P) = V_i(P) - V(P)$$

This error may be positive or negative. The square of the error is always positive and is a measure of how well the calculated isotherm matches the data. This error can be calculated for each point and summed giving a measure of the overall error:

$$SSE = \sum_{i=1}^N Err_i^2$$

N = number of measured points

The goodness of fit of the isotherm is expressed by calculating the correlation coefficient between the measured points and the calculated points. The results generally yield correlations that are better than $r^2 = 0.99$, and standard errors of Langmuir volumes of ± 2 percent. The reported CO_2 sorption capacity and corresponding pressure are calculated coefficients of the Langmuir model and are used to determine the sorption capacity at reservoir-appropriate pressures.

Adsorption analyses were performed using a high-pressure volumetric adsorption technique similar to that described by Mavor and others (1990). Isotherms were measured on a custom-made apparatus modeled after a similar module designed and built at CSIRO in Lucas Heights, Australia. The apparatus is based on Boyle's Law. In simple terms, a known volume of gas within a reference cell is used to dose a sample cell that contains the sample. The amount of gas adsorbed in the sample cell is then determined, based on a change in pressure in the sample cell using the Real Gas Law. Following dosing of the sample cell, the pressure drops until equilibrium is reached (i.e., no more gas can be adsorbed by a sample at a particular

pressure). When equilibrium is reached, the sample is dosed at a higher pressure. Typically, 11 separate pressure points are selected and measured so that a Langmuir regression curve can be accurately generated. The pressures in the reference and sample cells are measured using pressure transducers that are interfaced to a computer equipped with special boards and software. The computer monitors the transducers and determines when equilibrium is reached; it also controls valves and switches for dosing and purging the cells.

Sidewall Cores for Adsorption and Methane Displacement

Laboratory investigation of methane displacement in the presence of CO₂ is being performed on whole rock core samples. In cooperation with Columbia Natural Resources, access to a well in Knott County, eastern Kentucky, was obtained for logging and collection of sidewall cores. Schlumberger Oilfield Services provided elemental capture spectroscopy logging for mineral identification and obtained the sidewall cores. The sidewall core plugs are being saturated with methane. To test the potential for enhanced natural gas production, the cores are being subjected to simulated injection of CO₂, and the amount of methane displaced during injection is being measured. Laboratory setup and analyses are similar to the standard procedure for obtaining adsorption isotherms. The results from this flow-thru experiment are pending.

Mineralogy: Elemental Capture Spectroscopy and X-Ray Diffraction

Elemental capture spectroscopy (ECS) is an advanced tool used for lithology and mineral determination that uses the same technology employed by NASA on the Mars Rover missions. An AmBe neutron source is used to activate a formation. Relative elemental yields are derived using fourier transform infrared spectroscopy analysis to identify 23 elements. Primary elements measured include: Si, Ca, Fe, S, Ti, Gd, Cl, and H. The relative abundance of these elements has been correlated with particular minerals and sedimentary lithologies (Herron and Herron, 1997 and Schlumberger, 2000). To supplement the ECS log, x-ray diffraction (XRD) data are being acquired. Samples for XRD analysis are pulverized to 200 mesh or smaller and side packed.

Geophysical Logs

A gamma-ray density (GRD) log suite is typically available for shale wells drilled within the past few decades. More recently, the standard open-hole log suite has expanded to include temperature, audio, density porosity, and lithology (photoelectric effect) determinations. Schmoker (1979, 1993) developed a model for determining TOC of the shale from formation density log data. Shale can be considered a mixture of three components: clay minerals, quartz-feldspar-mica, and organic matter. Schmoker (1979) suggests the organic matter content is the main contributing factor to observed variations in shale density. Using Schmoker's (1993, p. J4) method, TOC for intervals can be estimated from density logs using the equation:

$$TOC = 55.822 \left[\frac{\rho_B}{\rho} - 1 \right]$$

ρ_B = maximum density of gray shale intervals
(typically 2.67 to 2.72 g/cm³)

ρ = formation density from log

Sequestration Capacity of the Shale

ArcView GIS software was used to develop a method to compile an estimate of the sequestration capacity of the shale. The method uses a cell-based approach that enables combining shale thickness and depth information in the form of continuous grids with shale density and spatially variable CO₂ adsorption capacity data. Preliminary estimates were compiled using a uniform, minimum CO₂ adsorption capacity and include data projected into the Illinois Basin portion of western Kentucky.

Results to Date

Thirty-three samples have been collected from 11 wells, including three cuttings samples and 10 sidewall cores from the Columbia Natural Resources No. 24752 Elkhorn Coal Corporation well in Knott County (Figure 8). Data for completed analyses are presented in Table 1. In recognition of the regional nature of the potential reservoir, both the Midwest Geologic Sequestration Consortium (Illinois Basin, ISGS) and the Midwest Regional Carbon Sequestration Partnership (Appalachian Basin, Battelle) were contacted to obtain shale samples. Illinois Basin core samples and drill cuttings from the Battelle AEP test well have been acquired and submitted for analysis.

$R_{0\text{random}}$ values (Table 1) range from a minimum of 0.78 to 1.59 with a median of 1.1 and a mean of 1.2. This places the shale in the upper oil to wet gas and condensate maturity range as measured by reflectance. In Figure 9. Mean random reflectance ($R_{0\text{random}}$), axis labels refer to the upper (right) end of the graphed class.

The currently available adsorption isotherms are presented in Figure 10. The Langmuir volume and pressure data reported in Table 1 must be compared on a uniform pressure basis by formation. These summary data are shown in Table 2 which provides calculated adsorption capacities at three pressure values that are expected to be typical of the range of observed Devonian shale gas reservoir conditions. To effectively compare capacity data derived from adsorption isotherms, three pressure conditions were selected: 200, 400, and 600 psia. These comparison data are presented in Figure 12.

Columbia Natural Resources (CNR, now owned by Triana) drills a number of Devonian shale gas wells in eastern Kentucky as a normal part of their resource development program. A drill hole of opportunity was identified and sidewall cores and logs were obtained from the well. An elemental capture spectroscopy (ECS) log was obtained. The cores have been submitted for laboratory analysis by saturation with CH_4 and analysis of CH_4 displacement efficiency as CO_2 is injected into the core. The CNR well number 24752 Elk Horn Coal Company is located in eastern Knott County (Figure 8).

The ECS log presents dry weight fractions of major lithologic components including silicates (quartz, feldspar, and mica), clay minerals, and carbonates. Figure 13 shows a portion of the ECS log through the Lower Huron Member of the Devonian Ohio Shale in the CNR well 24725 Elk Horn Coal. As measured on the ECS log through the complete Ohio Shale interval, the dry weight fraction of clay ranges from a minimum of 25 percent to a maximum of 71 percent. The mean clay content is 55 percent and the mode is 63 percent. Figure 14 shows a typical whole rock x-ray diffraction trace indicating the presence of Illite, Kaolinite, Pyrite, and Quartz. Another clay mineral (indicated by "M" in the figure) is most likely an authigenic Smectite (possibly Montmorillonite). Hosterman and Whitlow (1983) reported an Illite-Smectite mixed layer clay (consistent with Montmorillonite).

Ten sidewall cores were recovered and are summarized in Appendix C. Of these cores, 7 were intact and have been submitted for CO_2 adsorption and methane displacement analysis. The three broken cores are being analyzed for solvent extraction for chromatographic analysis identify any light hydrocarbons present and for petrographic analysis. Appendix C also includes sections of the litho-density and elemental capture spectroscopy logs acquired. Adsorption capacity reported as measured langmuir volumes ranges from 37 to 2,078 standard cubic feet CO_2 per ton of shale (scf/ton) at langmuir pressures ranging from 243 to 14,284 psia (

Table 2). These values represent the range of values for coefficients of the selected langmuir model. At a constant pressure of 400 psia, the indicated CO_2 adsorption capacity ranges from 14 to 136 scf/ton with a median value of 40 scf/ton. Methane adsorption capacity

ranges from 2 to 38 scf/ton with a median value of 8 scf/ton (Table 3). At 400 psia, CO₂ adsorption exceeds CH₄ adsorption by a factor of 5.3 (Figure 11).

A direct relationship has been observed between total organic content and the adsorption capacity of the shale. Figure 15 shows the relation by formation analyzed. (It should be noted that the Indiana Selmeir (New Albany Shale) samples were specifically chosen for their high organic content.) It was observed that two samples are enriched with respect to the amount of CO₂ that can be adsorbed based on organic carbon content. When these outliers are included in regression analysis, the correlation coefficient is 0.80 (at the 95 percent level of confidence). Excluding the outliers, the correlation coefficient improves to 0.96 (at the 95 percent level of confidence).

Gamma ray and density logs have been digitized for 18 shale wells including all wells for which adsorption data were acquired and supplemental wells needed to construct a detailed cross section sub-parallel to regional dip through the main part of the Big Sandy Gas Field. The cross section, Figure 16, was compiled using the Petra software from GeoPlus Corporation and shows the facies transition from predominantly black, carbonaceous shales in the west to predominantly clastic-rich gray shales toward the basin center (eastward). Gamma ray versus density cross plots have been made for these 18 wells. Two plots of this type are shown in Figure 17. With reference to the top plot in the figure, the general pattern of sandstone units, in this case the Berea sandstone, data are clustered between densities of 2.4 to 2.8 grams per cubic centimeter (g/cm³) with the natural gamma-ray being less than 200 API units. Gray shales with little organic matter (the Three Lick Bed, Middle Huron, and Chagrin) cluster between densities of 2.55 and 2.82 g/cm³ and a gamma-ray reading generally between 150 and 250 API units. The black, organic rich units, however, show a wide variation along a broad, linear trend supporting Schmoker's assumptions. The same pattern holds for individual wells (see bottom cross plot in Figure 17). For calculating TOC from the density curve using the method of Schmoker (1993) a bulk density of 2.82 g/cm³ for the maximum density of the gray shale sections of the Ohio.

Initial estimates of CO₂ sequestration capacity have been calculated using selected data. An initial estimate of the sequestration volume of the Lower Huron was compiled using areal distribution and thickness data from Dillman and Ettensohn (1980). Initial calculations indicate that 91×10^{12} cubic feet (2.6×10^{12} cubic meters) of CO₂ could be sequestered in the Lower Huron using a Langmuir volume of 67.6 scf/ton (2.1 m³/tonne; raw data from sample 107928-2 (Table 1) and an average thickness of 150 feet over the area of Boyd, Breathitt, Floyd, Johnson, Knott, Lawrence, Leslie, Magoffin, Martin, Perry, and Pike Counties combined. Assuming 30 percent of this theoretical saturation, approximately 1.6 billion tons (1.5 billion metric tonnes) of CO₂ could be sequestered. Using a 1-kilometer grid, a depth to top of shale of 1,000 feet or greater, a shale thickness of 50 feet or more, and a constant adsorption capacity equal to a thickness-weighted average of 40 scf/ton (1.2 m³/tonne; raw data from samples 107928-1, 107928-2, and 107928-3, Table 1), estimated initial CO₂ sequestration capacity of the Devonian shale in Kentucky is 27.7 billion tons (25.1 billion metric tonnes) (Figure 18).

Preliminary Conclusions

Preliminary data indicate that black, organic-rich gas shales can serve as targets for sequestration of significant volumes of anthropogenic CO₂. TOC data may be used as a proxy to estimate adsorptive capacity of the shale. TOC content of the shale can be estimated from density log data. At Kentucky's current rate of power plant emissions, the organic-rich, black shale in the state could sequester more than 300 years' worth of that carbon. Enhanced production of natural gas displaced by the injected CO₂ would contribute to a long-term increase in the supply of what is considered a "greener" fuel.

Acknowledgements

The authors want to thank the University of Kentucky Research Foundation and the Office of Sponsored Projects Administration for their assistance and support. Ed Rothman of Columbia Natural Resources (Triana) and Jay Terry of Schlumberger were instrumental in providing access to a drill hole and obtaining advanced well logs. Henry Francis, Laboratory Services Manager, is conducting x-ray diffraction analyses. Dr. Sue Rimmer, Associate Professor, Department of Geological Sciences, University of Kentucky, has assisted with analysis and interpretation of the x-ray diffraction data. Dr. Frank Ettensohn, Professor, Department of Geological Sciences, University of Kentucky, has reviewed and commented on stratigraphy and correlation within the Devonian Shale. Bob Cluff, Discovery Group, Denver, Colorado, suggested the use of density log interpretation. Joe Meglen, Interstate Natural Gas, Pikeville, Kentucky, contributed the ECS log and analysis for their well in Martin County and gave us access to obtain additional sidewall cores. Jackie Silvers of the Kentucky Geological Survey kept our budget straight and Leah Barth spent many dusty hours sampling well cuttings.

References Cited

- Bachu, S., and Gunter, W.D., 1998, Storage capacity of CO₂ in geological media in sedimentary basins with application to the Alberta Basin: 4th International Conference on GHG Control Technologies, Interlaken, Switzerland, September 1999.
- Boswell, R., 1996, Play Uds: Upper Devonian black shales, *in* Roen, J.B. and Walker, B.J., eds., Atlas of major appalachian gas plays: West Virginia Geologic and Economic Survey, Publication V-25, p. 93–99.
- Dillman, S.B., and Ettensohn, F.R., 1980, Isopach map of the Lower Huron Shale Member (unit 5) of the Ohio Shale in eastern Kentucky: U.S. Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 518, scale 1:370,000.
- Energy Information Administration (EIA), 2000, Annual energy outlook 2001 with projections to 2020: U.S. Department of Energy, Energy Information Administration DOE/EIA-0383(2001), 262 p., [www.eia.doe.gov/oiaf/aeo/pdf/0383\(2001\).pdf](http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2001).pdf) [visited 11-Nov-2001].
- Energy Information Administration (EIA), 2002, State Energy Profiles, Kentucky: U.S. Department of Energy, Energy Information Administration, www.eia.doe.gov/cneaf/electricity/st_profiles/kentucky.pdf [visited 4-Mar-2004].
- Hamilton-Smith, T., 1993, Gas exploration in the Devonian shales of Kentucky: Kentucky Geological Survey, ser. 11, Bulletin 4, 31 p.
- Herron, M. M., and Herron, S. L., 1997, Log Interpretation Parameters Determined from Chemistry, Mineralogy and Nuclear Forward Modeling, in International Symposium of the Society of Core Analysts, Calgary, Alberta, CA, p. 14.
- Hoeing, J.B., 1905, The oil and gas sands of Kentucky: Kentucky Geological Survey, ser. 3, Bulletin 1, 233 p.
- Hosterman, J. W., and Whitlow, S. I., 1983, Clay mineralogy of Devonian Shales in the Appalachian Basin: Washington, D.C., United States Geological Survey Professional Paper 1298, 31 p.
- IEA Coal Research, 1999, CO₂ reduction—Prospects for coal: London, IEA Coal Research, 84 p.
- Langmuir, I., 1916, The constitution and fundamental properties of solids and liquids: Journal of the American Chemical Society, v. 38, p. 2221–2295.
- Mavor, M.J., Owen, L.B., and Pratt, T.J., 1990, Measurement and evaluation of isotherm data: Proceedings of the 65th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, SPE 20728, p. 157-170.
- Reznik, A., Singh, P.K., and Foley, W.L., 1982, An analysis of the effect of carbon dioxide injection on the recovery of in-situ methane from bituminous coal: An experimental simulation: Society of Petroleum Engineers/U.S. Department of Energy 10822.
- Schlumberger, 2000, Elemental Capture Spectroscopy Sonde: Houston, Texas, Schlumberger, 3 p.
- Schmoker, J. W., 1979, Determination of Organic Content of Appalachian Devonian Shales from Formation-Density Logs: American Association of Petroleum Geologists Bulletin, v. 63, p. 1504-1537.

- Schmoker, J. W., 1993, Use of formation-density logs to determine organic-carbon content in Devonian shales of the western Appalachian Basin and an additional example based on the Bakken Formation of the Williston Basin, in J. B. Roen, and R. C. Kepferle, eds., Petroleum geology of the Devonian and Mississippian black shale of eastern North America, U. S. Geological Survey Bulletin 1909, U.S. Government Printing Office, p. J1-J14.
- Ting, F.T.C., 1978, Petrographic techniques in coal analysis, *in* Karr, C., Jr., ed, Analytical methods for coal and coal products: New York, Academic Press, v. 1, p. 3–26.

Tables

Table 1. Gas storage capacity, total carbon (TC), total organic carbon (TOC), and vitrinite reflectance data for completed samples.

Sample	Formation	Langmuir Coefficients		Langmuir Coefficients		TOC (Acid*)	R _{0random}	Sulfur%
		CH ₄ scf/ton	CH ₄ PSIA	CO ₂ scf/ton	CO ₂ PSIA			
107928-1	Upper Ohio	4.6	377.8	37.5	681.1	0.69	1.55	Not analyzed
	Lower							
107928-2	Huron	34.6	443.2	67.6	243.7	2.95	1.48	
107928-3	Lower Ohio	4.9	176.2	34.6	253.1	1.60	1.59	
121774-1	Ohio Shale	Not analyzed		126.5	989.8	3.66	1.1	
124789-1	Upper Ohio			740.8	6419.1	3.26	0.78	
	Lower							
124789-2	Huron			2077.6	14283.5	4.62	0.81	
124789-3	Lower Ohio			116.2	957.9	1.78	0.83	
123486-1	Upper Ohio			228.9	2230.4	2.44	0.78	
123486-2	Lower Ohio			309.3	2106	4.13	0.82	
121162-1	Ohio Shale			164.2	1561.3	2.37	0.85	
121464-1	Upper Ohio			52.6	708.9	1.18	1.52	
	Lower							
121464-2	Huron			248.7	751.2	3.60	1.52	
121464-3	Lower Ohio			108	819	2.31	1.51	
IGSID-	Selmier	Not analyzed						Pending
107310-1	Shale			172.6	1428.1	607.3	1390.3	14.7
IGSID-	Blocher							
107310-2	Shale			118.7	2097.6	408.5	1456.5	3.69
IGSID-	Selmier							
119139-1	Shale			109.5	1148.7	321	781.5	11.79
IGSID-	Blocher							
119139-2	Shale			68.4	1513.2	283	1444.1	5.37
123957-1	Upper Ohio			33.5	2170.8	218.7	1977.5	2.34
	Lower							
123957-2	Huron			43.7	1126.7	271	1742	4.73
125651-1	Upper Ohio			36.7	1497.9	90.7	455.4	1.96
	Lower							
125651-2	Huron	22.7	1445.3	146.1	978.5	3.05		2.4
125651-3	Lower Ohio	4.5	936.4	79.5	493.4	0.73		1.79
	Lower							
AEP#1-1	Huron	26	1566.7	111.7	810	1.54		1.87

* Samples washed in HCl to remove carbonate (inorganic carbon)

Scf/ton = standard cubic feet per ton

psia = pressure, pounds per square inch absolute

Table 2. Summary of CO₂ adsorption capacity in standard cubic feet per ton at selected pressures.

Sample ID	Formation	PSIA		
		200	400	600
121774-1	Ohio Shale	21.26	36.41	47.74
121162-1	Ohio Shale	18.65	33.49	45.58
121162-1	Ohio Shale	18.65	33.49	45.58
AEP#1-1	Ohio Shale	22.12	36.93	47.53
Average	Ohio Shale	20.17	35.08	46.61
107928-1	Upper Ohio	8.51	13.87	17.56
124789-1	Upper Ohio	22.38	43.45	63.32
121464-1	Upper Ohio	11.57	18.97	24.11
123486-1	Upper Ohio	18.84	34.81	48.52
123957-1	Upper Ohio	20.09	36.79	50.91
125651-1	Upper Ohio	27.68	42.41	51.56
Average	Upper Ohio	18.18	31.72	42.67
107928-2	Lower Huron	30.47	42.01	48.07
124789-2	Lower Huron	28.69	56.60	83.75
121464-2	Lower Huron	52.29	86.41	110.44
123957-2	Lower Huron	27.91	50.61	69.43
125651-2	Lower Huron	24.79	42.39	55.53
Average	Lower Huron	32.83	55.60	73.45
107928-3	Lower Ohio	15.27	21.19	24.33
124789-3	Lower Ohio	20.07	34.23	44.75
121464-3	Lower Ohio	21.20	35.44	45.67
123486-2	Lower Ohio	26.83	49.37	68.58
125651-3	Lower Ohio	22.93	35.59	43.63
Average	Lower Ohio	21.26	35.16	45.39
IGSID-107310-2	Blocher Shale	49.32	88.02	119.18
IGSID-119139-2	Blocher Shale	34.43	61.38	83.07
Average	Blocher Shale	41.87	74.70	101.13
IGSID-107310-1	Selmier Shale	76.38	135.69	183.08
IGSID-119139-1	Selmier Shale	65.41	108.68	139.41
Average	Selmier Shale	70.89	122.18	161.25

Table 3. Summary of CH₄ adsorption capacity in standard cubic feet per ton at selected pressures

Sample ID	Formation	PSIA		
		200	400	600
AEP#1-1	Ohio Shale	2.94	5.29	7.20
Average	Ohio Shale	2.94	5.29	7.20
107928-1	Upper Ohio	1.59	2.37	2.82
123957-1	Upper Ohio	2.83	5.21	7.25
123957-2	Upper Ohio	6.59	11.45	15.19
125651-1	Upper Ohio	4.32	7.73	10.50
Average	Upper Ohio	3.83	6.69	8.94
107928-2	Lower Huron	10.76	16.41	19.90
125651-2	Lower Huron	2.76	4.92	6.66
Average	Lower Huron	6.76	10.67	13.28
107928-3	Lower Ohio	2.60	3.40	3.79
125651-3	Lower Ohio	0.79	1.35	1.76
Average	Lower Ohio	1.70	2.37	2.77
IGSID-107310-2	Blocher Shale	10.33	19.01	26.40
IGSID-119139-2	Blocher Shale	7.99	14.30	19.42
Average	Blocher Shale	9.16	16.66	22.91
IGSID-107310-1	Selmier Shale	21.20	37.77	51.06
IGSID-119139-1	Selmier Shale	16.24	28.28	37.57
Average	Selmier Shale	18.72	33.02	44.32

Figures

Figure 1. Distribution of the Devonian shale in Kentucky, showing the occurrence of deeper and thicker shale with possibly greater potential for geologic sequestration of CO₂.

Figure 2. General structure of the Devonian shale, showing presence of shale in the subsurface (shading).

Figure 3. Distribution and nomenclature of Devonian shales of Kentucky (Hamilton-Smith, 1993, p. 3).

Figure 4. General geologic column showing approximately 3,800 feet of overlying Mississippian and Pennsylvanian lithologies adequate for ensuring reservoir integrity in the Devonian shale. Note: Devonian shale is underlain by Devonian carbonates.

Figure 5. Nomenclature of Mississippian and Devonian shales of eastern Kentucky and key to names and codes used for intervals sampled.

Figure 6. Eastern Kentucky Devonian shale natural-gas production (proprietary data), showing long-term increase. Dotted line is exponential best fit of observed rate-time data.

DEVSHALE - CO₂ Sequestration in the Devonian Shale

Figure 7. Location of selected wells in eastern Kentucky. Small dots are existing gas wells completed in the shale since 2000. Yellow highlight indicates LAS files. Red highlight indicates adsorption data gathered by the project. Blue line is line of cross section.

Figure 8. Location of the Columbia Natural Resources 24752 Elk Horn Coal Company well, permit 94539, Knott County, Ky., Carter coordinate 11-K-81, latitude 37.37019° N, longitude 82.76441° W (NAD 1983).

Figure 9. Mean random reflectance ($R_{0 \text{ random}}$)

Figure 10. Summary of adsorption isotherms.

Figure 11. Distribution of observed CO₂ (green) and CH₄ (blue) adsorption capacity.

Figure 12. Average calculated adsorption capacities by formation at selected pressures.

Figure 13. Section of elemental capture spectroscopy log through the Lower Huron section of the Columbia Natural Resources No. 24752 Elk Horn Coal well, Knott County, Ky., showing relative abundance of species related to mineral and lithologic identification. Asterisks denote depths where sidewall cores were recovered.

Figure 14. Typical whole rock X-ray diffraction trace of the Devonian shale (upper part, well id 107928,

Devonian Shale Adsorption at 400 PSIA

Figure 15. Relationship between total organic content and adsorption capacity of shale at 400 psia.

Figure 16: West (left) to east (right) cross section of Big Sandy Gas Field color-shaded based on density. Low densities (cooler colors) indicate organic-rich zones.

Figure 17. Gamma-ray density cross plots showing variation by general lithotype: all wells combined (top) and the CNR #24526 Bush (bottom).

Figure 18. Preliminary estimated CO₂ storage capacity per square kilometer (in million tons) in the areas of deeper ($\geq 1,000$ feet) and thicker (≥ 50 feet) Devonian shale.

Bibliography

- 1996, CO₂ Recovery Not Feasible: Power, v. 140, no. 6, p. 62.
- 1997, Big Canadian Miscible CO₂ EOR Project, Pipeline Advanced: Oil & Gas Journal, no. 7 July, p. 23-24.
- 1998, Kansas Fields Screened for CO₂ Pilot Program, CO₂ Bulletin (Shell CO₂ Company, Ltd.).
- 1999, DOE Eyes Research to Sequester Carbon Dioxide, Oil & Gas Journal, p. 53-54.
- Abelson, P. H., 2000, Future Supplies of Electricity: Science, v. 287, p. 971.
- Acomb, B., 1979, The petrology, stratigraphy and origin of phosphatic nodules in Upper Devonian and Lower Mississippian rocks of the eastern interior [Thesis]: University of Cincinnati, unknown p.
- Adewusi, V. A., and Ikwuka, N. A., 1998, Tertiary Oil Recovery Potential from CO₂-Miscible Flooding of Agbada Viscous Oil Reservoir: Petroleum Science and Technology, v. 16, no. 5&6, p. 477-501.
- Akai, M., Kagajo, T., and Inoue, M., 1995, Performance Evaluation of Fossil Power Plant with CO₂ Recovery and a Sequestering System: Energy Conversion and Management, v. 36, no. 6-9, p. 801-804.
- Akai, M., Nomura, N., Waku, H., and Inoue, M., 1997, Life-Cycle Analysis of a Fossil-Fuel Power Plant with CO₂ Recovery and a Sequestering System: Energy, v. 22, no. 2/3, p. 249-255.
- Anderson, L. G., Olsson, K., Jones, E. P., Chierici, M., and Fransson, A., 1998, Anthropogenic carbon dioxide in the Arctic Ocean; inventory and sinks: Journal of Geophysical Research, C, Oceans, v. 103, no. 12, p. 27.
- Anonymous, 1996, New Albany shale gas flow starts in western Indiana: Oil and Gas Journal, v. 94, no. 18, p. 69-70.
- Arco, N. d., 1981, Regional and local geochemical variation in the Devonian Black shales of Eastern Kentucky [Thesis]: University of Kentucky, unknown p.
- Bachu, S., 1999, Geological disposal of carbon dioxide emitted by the upstream energy industry; the potential for the Alberta Basin, in Program and Abstracts of the 1999 Annual Convention American Association of Petroleum Geologists, San Antonio, TX, April 11-14, 1999, p. A8.
- Bachu, S., 2000, Sequestration of CO₂ in geologic media: criteria and approach for site selection in response to climate change: Energy Conservation and Management, v. 41, no. 9, p. 953-970.
- Barden, C., Corlay, P., and Longeron, D., 1991, Interpretation of a CO₂ Huff'n'Puff field case in a light-oil-depleted reservoir: SPE 22650, p. 551-562.
- Barnett, S. F., 1995, The Portwood Member (upper Middle Devonian) of the New Albany shale of central Kentucky; nature and origin [PhD Dissertation thesis]: University of Kentucky, 545 p.
- Barnett, S. F., and Ettensohn, F. R., 1992, Portwood Member of the New Albany shale and the Boyle Dolostone, in Ettensohn, F. R., Barnett, S. F., Greb, S. F., Chesnut, D. R., Jr., Lierman, R., Eble, C. F., Mason, C. E., Pasin, J. C., Goodman, P. T., and Schumacher, G. A., eds., Changing interpretations of Kentucky geology; layer-cake, facies, flexure, and eustasy: Miscellaneous Report—Ohio, Division of Geological Survey, p. 42-44.
- Barnett, S. F., Ettensohn, F. R., and Norby, R. D., 1995, The Carpenter Fork Bed, a new- and older-black-shale unit at the base of the New Albany shale in central Kentucky; characterization and significance: Southeastern Geology, v. 35, no. 4, p. 187-210.

- Barron, L. S., 1982, The paleoecology of the Upper Devonian-Lower Mississippian black shale sequence in Eastern Kentucky [Thesis thesis]: University of Kentucky, unknown p.
- Bayan, M. R., and Etensohn, F. R., 1993, Supergene alteration of substrates below Devonian-Mississippian oil and gas shales: origin and significance, in 1993 Eastern Oil Shale Symposium, Lexington, Kentucky, p. 376-380.
- Beard, J. G., 1980, Devonian black shale study of western Kentucky: Final status report: Lexington, Kentucky Geological Survey, Open File Report OF-80-02, 113 p.
- Beato, B. D., Yost, R. A., Van Berkel, G. J., Filby, R. H., and Quirke, J. M. E., 1991, The Henryville Bed of the New Albany shale; III, Tandem mass spectrometric analyses of geoporphyrins from the bitumen and kerogen: Organic Geochemistry, v. 17, no. 1, p. 93-105.
- Beran, M. A., 1995, Carbon sequestration in the biosphere: processes and prospects: Berlin, New York, Springer, p. 305.
- Bethke, C. M., Reed, J. D., and Oltz, D. F., 1991, Long-range petroleum migration in the Illinois Basin: American Association of Petroleum Geologists Bulletin, v. 75, no. 5, p. 925-945.
- Boberg, W. S., Lumm, D. K., Frankie, W. T., and Hamilton-Smith, T., 1994, Cross sections showing members of the New Albany shale (Devonian and Mississippian) in the Illinois Basin, in Hasenmueller, N. R., and Comer, J. B., eds., Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, plate 5.
- Booras, G. S., and Smelser, S. C., 1991, An Engineering and Economic Evaluation of CO₂ Removal from Fossil-Fuel-Fired Power Plants: Energy, v. 16, no. 11/12, p. 1295-1305.
- Boswell, R., 1996, Play UDs: Upper Devonian black shales, in Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: Morgantown, WV, West Virginia Geological and Economic Survey, Publication V-25, p. 93-99.
- Bownocker, J. A., and Dean, E. S., 1929, Analyses of the coals of Ohio, Ohio Division of Geological Survey, Bulletin 34, 360 p.
- Broadhead, R. F., 1990, Bravo Dome carbon dioxide gas field, in Beaumont, E. A., and Foster, N. H., eds., Structural Traps I, AAPG Treatise of Petroleum Geology - Atlas of Oil and Gas Fields: Tulsa, Oklahoma, American Association of Petroleum Geologists, p. 213-232.
- Browne, R., Conkin, J., Conkin, B., and MacCary, L. M., 1958, Geological Society of Kentucky field trip, sedimentation and stratigraphy of Silurian and Devonian rocks in the Louisville area, Kentucky: Lexington, KY, Kentucky Geological Survey, 46 p.
- Burruss, R. C., 1999, Options for sequestration of carbon dioxide; an energy resource perspective [abs]: Abstracts with Programs Geological Society of America, v. 31, no. 7, p. 29-30.
- Byrer, C. W., and Guthrie, H. D., 1999, Carbon dioxide sequestration potential in coal deposits, in Program and Abstracts of the 1999 Annual Convention American Association of Petroleum Geologists, San Antonio, TX, April 11-14, 1999, p. A18.
- Byrnes, A. P., and Cluff, R. M., 1992, Lopatin analysis of maturation and petroleum generation in the Illinois Basin: American Association of Petroleum Geologists Bulletin, v. 76, no. 8, p. 1272.
- Caramanica, F. P., 1995, Relationships between gas production and natural fractures in the Antrim shale—Applications to the New Albany shale, in Gas potential of the New Albany shale workshop, Evansville, Indiana, p. M1, illustrated.

- Casey, G. D., 1992, Preliminary hydrogeologic framework of the Silurian and Devonian carbonate aquifer system in the Midwestern basins and arches region of Indiana, Ohio, Michigan, and Illinois: Abstracts with Programs, Geological Society of America, v. 24, no. 7, p. 281-282.
- Chohji, T., Tabata, M., and Hirai, E., 1997, CO₂ Recovery from Flue Gas by an Ecotechnological (Environmentally Friendly) System: Energy, v. 22, no. 2/3, p. 151-159.
- Clarkson, C. R., and Bustin, R. M., 1996, Variation in micropore capacity and size distribution with composition in bituminous coal of the Western Canadian Sedimentary Basin: Implications for coalbed methane potential: Fuel, v. 75, no. 13, p. 1483-1498.
- Cluff, R. M., 1993, Source rocks and hydrocarbon generation in the New Albany shale (Devonian-Mississippian) of the Illinois Basin; a review, in Roen, J. B., and Kepferle, R. C., eds., Petroleum geology of the Devonian and Mississippian black shale of eastern North America: U. S. Geological Survey Bulletin, p. I1-I15.
- Cluff, R. M., Cluff, S. G., and Murphy, C. M., 1996, Devonian shale gas resource assessment, Illinois Basin: Annual Meeting Abstracts, American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, v. 5, p. 28.
- Cluff, R. M., Reinbold, M. L., and Lineback, J. A., 1981, The New Albany Shale Group of Illinois: Champaign, Illinois, Illinois State Geological Survey, Circular 518, 83 p.
- Comer, J. B., 1995, Thermal maturity of the New Albany shale (Devonian and Mississippian) in the Illinois Basin, in Gas potential of the New Albany shale workshop, Evansville, Indiana, p. E1-E2, illustrated.
- Comer, J. B., Hamilton-Smith, T., and Frankie, W. T., 1994, Source rock potential, in Hasenmueller, N. R., and Comer, J. B., eds., Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, p. 47-54.
- Comer, J. B., Hasenmueller, N. R., Frankie, W. T., and Hamilton-Smith, T., 1993, Gas potential of New Albany shale (Devonian-Mississippian) in the Illinois Basin [abs], Eastern Oil Shale Symposium Abstracts, November 16-19, 1993: Lexington, Kentucky, Institute for Mining and Minerals Research, p. 71.
- Comer, J. B., Hasenmueller, N. R., Frankie, W. T., and Hamilton-Smith, T., 1994, Gas potential of New Albany shale (Devonian-Mississippian) in the Illinois Basin, in Schultz, A. P., and Rader, E. K., eds., Studies in eastern energy and the environment; AAPG Eastern Section special volume: Virginia Division of Mineral Resources, Publication 132, p. 178-179.
- Comer, J. B., Hasenmueller, N. R., Frankie, W. T., and Hamilton-Smith, T., 1994, Gas potential of New Albany shale (Devonian-Mississippian) in the Illinois Basin [abs]: American Association of Petroleum Geologists Bulletin, Eastern Section Meeting Abstracts, v. 77, no. 8, p. 1467.
- Comer, J. B., Smidchens, Z., Irwin, P. N., Sowder, K. H., Frankie, W. T., Lumm, D. K., and Hamilton-Smith, T., 1994, Map showing mean random vitrinite reflectance (Ro) for New Albany shale (Devonian and Mississippian) gas fields in the Illinois Basin, in Hasenmueller, N. R., and Comer, J. B., eds., Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, plate 7, scale 1:1,000,000.
- Concha, M. A., Quirke, J. M. E., Beato, B. D., Yost, R. A., Mercer, G. E., and Filby, R. H., 1991, The Henryville Bed of the New Albany shale; IV, Tandem mass spectrometric analyses of geoporphyryns from the bitumen of the demineralised shale: Chemical Geology, v. 91, no. 2, p. 153-168.

- Currie, M. T., 1981, Subsurface stratigraphy and depositional environments of the "Corniferous" (Silurian-Devonian) of Eastern Kentucky [Thesis]: University of Kentucky, unknown p.
- Department of Energy, 1999, Energy Department to Fund Further Studies of Six Concepts for Capturing, Disposing of Greenhouse Gases, DOE Techline Press Release.
- Desborough, G. A., 1992, Mineralogical and geochemical analysis of the metal- and organic-rich Grassy Creek shale of the New Albany Group (Upper Devonian and Lower Mississippian) in Hardin County, southern Illinois, in Day, W. C., and Lane, D. E., eds., Strategic and critical minerals in the Midcontinent region, United States: U. S. Geological Survey Bulletin, p. C1-C9.
- Diagne, D., Goto, M., and Hirose, T., 1995, Parametric Studies on CO₂ Separation and Recovery by a Dual Reflux PSA Process Consisting of Both Rectifying and Stripping Sections: Industrial & Engineering Chemistry Research, v. 34, no. 9, p. 3083-3089.
- Dias, R. R., Freeman, K. H., Lewan, M. D., and Franks, S. G., 1997, Kerogen maturation and the delta 13C of organic acids in oil-associated waters: American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, Annual Meeting Abstracts, v. 6, p. 27-28.
- Dillman, S. B., 1980, Subsurface geology of the Upper Devonian-Lower Mississippian black shale sequence in Eastern Kentucky [M.S. thesis]: University of Kentucky, unknown p.
- Dillman, S. B., 1980, Subsurface geology of the Upper Devonian-Lower Mississippian black shale sequence in Eastern Kentucky [M.S. thesis]: University of Kentucky, unknown p.
- Dillman, S. B., and Ettensohn, F. R., 1980a, Isopach map of the Cleveland shale member (Unit 1) of the Ohio shale in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 522, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980b, Isopach map of the Devonian black-shale sequence (New Albany-Chattanooga-Ohio shale) in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 515, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980c, Isopach map of the Lower Huron shale member (Unit 5) of the Ohio shale in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 518, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980d, Isopach map of the Middle Huron shale member (Unit 4) of the Ohio shale in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 519, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980e, Isopach map of the Rhinestreet shale (Unit 7) in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 516, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980f, Isopach map of the Three Lick bed (Unit 2) of the Ohio shale in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 521, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980g, Isopach map of the Upper Huron Shale member (Unit 3) of the Ohio shale in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 520, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980h, Isopach map of the Upper Olentangy shale (Unit 6) in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 517, scale 1:370,000.

- Dillman, S. B., and Ettensohn, F. R., 1980i, Structure contour map on the base of the Cleveland shale member (Unit 1) of the Ohio shale in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 514, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980j, Structure contour map on the base of the Java formation/Olentangy shale (Unit 6) in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 509, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980k, Structure contour map on the base of the Lower Huron shale member (Unit 5) of the Ohio shale in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 510, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980l, Structure contour map on the base of the Middle Huron shale member (Unit 4) of the Ohio shale in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 511, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980m, Structure contour map on the base of the Ohio shale in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 507, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980n, Structure contour map on the base of the Three Lick bed (Unit 2) of the Ohio shale in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 513, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980o, Structure contour map on the base of the Upper Huron Shale member (Unit 3) of the Ohio shale in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 512, scale 1:370,000.
- Dillman, S. B., and Ettensohn, F. R., 1980p, Structure contour map on the base of the West Falls Formation (Rhinstreet shale, Unit 7) in eastern Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 508, scale 1:370,000.
- Doctor, R. D., Molburg, J., Brockmeier, N. F., and Chess, K., 1998, Engineering Assessment of CO₂ Recovery, Transport, and Utilization: Argonne National Laboratory.
- Drahovzal, J. A., Harris, D. C., Wickstrom, L. H., Walker, D., Baranoski, M. T., Keith, B. D., and Furer, L. C., 1992, The East Continent Rift Basin, a new discovery, Kentucky Geological Survey, Series 11, Special Publication 18, 25 p.
- Dubois, M. K., Byrnes, A. P., Pancake, R. E., Willhite, G. P., and Schoeling, L. G., 2000, Economics show CO₂ EOR potential in central Kansas: Oil and Gas Journal, June 5, 2000, v. 98, no. 23, p. 37-41.
- Dyman, T. S., Schmoker, J. W., and Root, D. H., 1998, Emerging U.S. gas resources 2-USGS assesses deep undiscovered gas resource: Oil & Gas Journal, April 20, 1998, p. 99-104.
- Energy Information Administration, 1996, Annual Energy Outlook 1997 with projections to 2015: Washington, DC, Government Printing Office, DOE/EIA-0383(97), 212 p.

- Energy Information Administration, 1996, Annual Energy Outlook 1997 with projections to 2015: Washington, DC, U.S. Department of Energy, Government Printing Office, DOE/EIA-0383(97), p. 212.
- Energy Information Administration, 1997, Annual Energy Outlook 1998 with projections to 2020: Washington, DC, U.S. Department of Energy, Government Printing Office, DOE/EIA-0383(98), p. 227.
- Energy Information Administration, 1997, Annual Energy Outlook 1998 with projections to 2020: Washington, DC, Government Printing Office, DOE/EIA-0383(98), 212 p.
- Energy Information Administration, 1998, Annual Energy Outlook 1999 with projections to 2020: Washington, DC, U.S. Department of Energy, Government Printing Office, DOE/EIA-0383(99), p. 233.
- Energy Information Administration, 1998, Annual Energy Outlook 1999 with projections to 2020: Washington, DC, Government Printing Office, DOE/EIA-0383(99), 233 p.
- Energy Information Administration, 1999, Annual Energy Outlook 2000 with projections to 2020: Washington, DC, U.S. Department of Energy, Government Printing Office, DOE/EIA-0383(2000), 250 p.
- Energy Information Administration, 1999, Annual Energy Outlook 2000 with projections to 2020: Washington, DC, U.S. Department of Energy, Government Printing Office, DOE/EIA-0383(2000), p. 250.
- Energy Information Administration, 2000, Emissions of greenhouse gases in the United States 1999, Energy Information Administration, U. S. Department of Energy, EIA/DOE-0573(99).
- Erga, O., Juliussen, O., and Lidal, H., 1995, Carbon Dioxide Recovery by Means of Aqueous Amines: Energy Conversion Management, v. 36, no. 6-9, p. 387-392.
- Ettensohn, F. R., Barnett, S. G., and Norby, R. D., 1994, Late-Middle to Late Devonian (Givetian-Famennian) tectonic and stratigraphic history of central Kentucky: Geological Society of America, Abstracts with Programs, v. 26, no. 5, p. 14-15.
- Ettensohn, F. R., 1998, Compressional tectonic controls on epicontinental black-shale deposition; Devonian-Mississippian examples from North America, in Scheiber, J., Zimmerle, W., and Sethi, P. S., eds., Shales and mudstones; I, Basin studies, sedimentology, and paleontology: Stuttgart, E Schweizerbart'sche Verlagsbuchhandlung Naegle u. Obermiller, p. 109-128.
- Fallin, J. A., ed., 1984, Carbon dioxide and its applications to enhanced oil recovery, Petroleum Frontiers, 63 p.
- Felty, K. K., 1989, Stratigraphy of the Silurian and Devonian in Western Marion and Southern Nelson Counties [Thesis thesis]: University of Kentucky, unknown p.
- Foerste, A. E., 1910, Oil, gas, and asphalt rock, in Meade and Breckinridge Counties, in Norwood, C. J., ed., Report on the Progress of the Survey for the years 1908 and 1909: Lexington, Kentucky, Kentucky Geological Survey, p. 69-85.
- Foster, R. W., and Jensen, J. G., 1972, Carbon dioxide in northeastern New Mexico, New Mexico Geological Society Guidebook to 23rd field conference, p. 192-200.
- Frankie, W. T., Lumm, D. K., Boberg, W. S., Comer, J. B., and Hamilton-Smith, T., 1994, Data and Methods, in Hasenmueller, N. R., and Comer, J. B., eds., Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, p. 5-8.

- Frankie, W. T., Lumm, D. K., Boberg, W. S., Hamilton-Smith, T., and Noger, M. C., 1994, Map showing major structural features in the Illinois Basin, in Hasenmueller, N. R., and Comer, J. B., eds., Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, plate 1, scale 1:1,000,000.
- Frankie, W. T., Lumm, D. K., Boberg, W. S., Hasenmueller, N. R., Smidchens, Z., and Hamilton-Smith, T., 1994, Map showing elevation of the top of the New Albany shale (Devonian and Mississippian) in the Illinois Basin, in Hasenmueller, N. R., and Comer, J. B., eds., Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, plate 3, scale 1:1,000,000.
- Frankie, W. T., Lumm, D. K., Boberg, W. S., Hasenmueller, N. R., Smidchens, Z., and Hamilton-Smith, T., 1994, Map showing total thickness of the top of the New Albany shale (Devonian and Mississippian) in the Illinois Basin, in Hasenmueller, N. R., and Comer, J. B., eds., Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, plate 4, scale 1:1,000,000.
- Frankie, W. T., Moody, J. R., and Kemper, J. R., 1986, Geologic and hydrocarbon report of Letcher County: Part 1 of 5, Hydrocarbon production from the Devonian Shale in Letcher, Knott, Floyd, Martin, and Pike Counties, eastern Kentucky: Lexington, Kentucky, Kentucky Geological Survey, Gas Research Institute contract report, contract 5084-213-0990, 59 p.
- Frankie, W. T., Moody, J. R., Kemper, J. R., and Johnston, I. M., 1986, Geologic and hydrocarbon report of Floyd County: Part 3 of 5, Hydrocarbon production from the Devonian Shale in Letcher, Knott, Floyd, Martin, and Pike Counties, eastern Kentucky: Lexington, Kentucky, Kentucky Geological Survey, Gas Research Institute contract report, contract 5084-213-0990, 52 p.
- Frankie, W. T., Moody, J. R., Kemper, J. R., and Johnston, I. M., 1986, Geologic and hydrocarbon report of Knott County: Part 2 of 5, Hydrocarbon production from the Devonian Shale in Letcher, Knott, Floyd, Martin, and Pike Counties, eastern Kentucky: Lexington, Kentucky, Kentucky Geological Survey, Gas Research Institute contract report, contract 5084-213-0990, 94 p.
- Freeman, L. B., 1939, A sample study of the Devonian of Western Kentucky: Lexington, Department of Mines and Minerals, Geological Division, [Kentucky Geological Survey] Series 8, Bulletin 4, 27 p.
- Freeman, L. B., 1951, Regional aspects of Silurian and Devonian stratigraphy in Kentucky: Lexington, Kentucky Geological Survey, Series 9, Bulletin 6 (reprinted 1959), 575 p.
- Fronts, J. H., Jr., 1995, Economics of drilling and completing New Albany shale wells, in Gas potential of the New Albany shale workshop, Evansville, Indiana, p. L1-L2, illustrated.
- Frost, J. K., 1996, Geochemistry of black shales of the New Albany Group (Devonian-Mississippian) in the Illinois Basin: relationships between lithofacies, and the carbon, sulfur and iron contents, Illinois State Geological Survey Circular 557: Urbana, Illinois, Illinois State Geological Survey, 24 p.
- Frost, J. K., and Shaffer, N. R., 1994, Mineralogy and geochemistry, in Hasenmueller, N. R., and Comer, J. B., eds., Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, p. 41-45.
- Fullerton, D. S., 1961, The geology of the Silurian and Devonian in the subsurface of Larue County, Kentucky [Thesis thesis]: University of Kentucky, unknown p.

- Fulmer, J. E., 1992, Geologic and production comparisons of the New Albany shale of the Illinois Basin with the Michigan Basin's Antrim shale and the Appalachian Basin's Ohio shale: American Association of Petroleum Geologists Bulletin, Eastern Section Meeting Abstracts, v. 76, no. 8, p. 1274.
- Fulton, L. P., 1979, Structure and isopach map of the New Albany-Chattanooga-OHio shale (Devonian and Mississippian) in Kentucky, eastern sheet: Kentucky Geological Survey, Series 10, scale 1:250,000 (with correction sheet).
- Furer, L. C., 1996, Basement tectonics in the southeastern part of the Illinois Basin and its effect on Paleozoic sedimentation, in van der Pluijm, B. A., and Catcosinos, P. A., eds., Basement and basins of eastern North America: Geological Society of America, Special Paper 308, p. 109-126.
- Gatens, J. M., III, 1995, Practical reservoir engineering in the New Albany shale, in Gas potential of the New Albany shale workshop, Evansville, Indiana, p. 11, illustrated.
- Gautier, D. L., Dolton, G. L., Takahashi, K. I., and Varnes, K. L., 1996, 1995 national assessment of United States oil and gas resources--results, methodology, and supporting data: Washington, DC, United States Geological Survey, Digital Data Series DDS-30, release 2, CD-ROM.
- Geller, K. L., 1985, Stratigraphic relationships between the Devonian-Mississippian black shale sequence in the Appalachian and Illinois Basins [Thesis thesis]: University of Kentucky, unknown p.
- Gentzis, T., 2000, Subsurface sequestration of carbon dioxide; an overview from an Alberta (Canada) perspective: International Journal of Coal Geology, v. 43, no. 1-4, p. 287-305.
- Gerling, C. R., 1983, McElmo dome Leadville carbon dioxide field, Colorado, in Fassett, J. E., ed., Oil and gas fields of the Four Corners area, Four Corners Geological Society, p. 735-739.
- Gharrabi, M., and Velde, B., 1995, Clay mineral evolution in the Illinois Basin and its causes: Clay Minerals, v. 30, no. 4, p. 353-364.
- Goff, F., Guthrie, G., Counce, D., Kluk, E., Bergfeld, D., and Snow, M., 1997, Preliminary investigations on the CO₂ sequestering potential of ultramafic rocks, Los Alamos National Laboratory Report LA-13328-MS.
- Goff, F., and Lackner, K. S., 1998, Carbon dioxide sequestering using ultramafic rocks: Environmental Geosciences, v. 5, no. 3, p. 89-101.
- Gognat, T. A., Payne, G. A., Swenson, A., and Shurr, G. W., 1995, Exploration for and evaluation of the hydrocarbon potential of the New Albany shale, Illinois Basin, USA, in Gas potential of the New Albany shale workshop, Evansville, Indiana, p. N1.
- Grover, J., and Dupuis-Nouille, E. M., 1992, Orientation of tectonic stresses in central Kentucky during U. Devonian/L. Mississippian times; evidence from quartz veins (after gypsum) in NE-trending, systematic joints in shales: Geological Society of America, Abstracts with Programs, v. 24, no. 7, p. 183.
- Grover, J., and Dupuis-Nouille, E. M., 1995, Tectonic stress directions in the central Mid-continent and the systematic orientation of lineaments and joints; a correspondence that has endured since Devonian time: Geological Society of America, Abstracts with Programs, v. 27, no. 6, p. 384.
- Gunderson, L. C. S., Schumann, R. R., Otton, J. K., Owen, D. E., and Dubiel, R. F., 1991, Geologic radon potential of the United States: Geological Society of America, Abstracts with Programs, v. 23, no. 1, p. 39.
- Gunter, W. D., Bachu, S., Law, D. H.-S., Marwaha, V., Drysdale, D. L., MacDonald, D. E., and McCann, T. J., 1996, Technical and economic feasibility of CO₂ disposal in aquifers within the Alberta sedimentary basin, Canada: Energy Conservation and Management, v. 37, no. 6-8, p. 1135-1142.

- Gunter, W. D., Gentzis, T., Rottenfusser, B. A., and Richardson, R. J. H., 1997, Deep coalbed methane in Alberta, Canada: A fuel resource with the potential of zero greenhouse gas emissions: *Energy Conservation and Management*, v. 38, p. 217-222.
- Gunter, W. D., Wong, S., Cheel, D. B., and Sjoström, G., 1998, Large CO₂ sinks: Their role in the mitigation of greenhouse gases from an international, national (Canadian) and provincial (Alberta) perspective: *Applied Energy*, v. 61, p. 209-227.
- Hall, V. S., 1980, An eastern gas shales bibliography selected annotations gas, oil, uranium, etc., citations in bituminous shales worldwide: Morgantown, WV, United States Department of Energy, Morgantown Energy Technology Center, DOE/METC/12594-12, 532 p.
- Hamilton-Smith, T., 1992, Gas production from the New Albany shale: *American Association of Petroleum Geologists Bulletin, Eastern Section Meeting Abstracts*, v. 76, no. 8, p. 1276-1277.
- Hamilton-Smith, T., 1993, Gas exploration in the Devonian shales of Kentucky, *Kentucky Geological Survey, Series 11, Bulletin 4*, 31 p.
- Hamilton-Smith, T., 1994, Temperature and pressure controls on the fractured Devonian shale gas play of the Appalachian Basin, in Berg, T. M., and Baranoski, M. T., eds., *Ohio Geological Society Second annual symposium, Major natural gas plays of the Appalachian Basin of Ohio and surrounding areas: Ohio Geological Society, Canton, Ohio, Annual Technical Symposium*, p. unpaginated.
- Hamilton-Smith, T., 1995, History of gas production from the New Albany shale, in *Gas potential of the New Albany shale workshop*, Evansville, Indiana, p. F1-F2.
- Hamilton-Smith, T., 1996, Fractured shale reservoirs; towards a realistic model: *American Association of Petroleum Geologists Bulletin, Eastern Section meeting abstracts*, v. 80, no. 9, p. 1524.
- Hamilton-Smith, T., 1998, Deep, water-free gas potential in upside to New Albany shale play: *Oil and Gas Journal*, v. 96, no. 7, p. 70-71.
- Hamilton-Smith, T., Boberg, W. S., Smidchens, Z., Frankie, W. T., and Lumm, D. K., 1994, Map showing average initial potential (IP) for New Albany shale (Devonian and Mississippian) gas fields in the Illinois Basin, in Hasenmueller, N. R., and Comer, J. B., eds., *Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2*, plate 6, scale 1:1,000,000.
- Hamilton-Smith, T., Hasenmueller, N. R., Boberg, W. S., Smidchens, Z., and Frankie, W. T., 1994, Gas Production, in Hasenmueller, N. R., and Comer, J. B., eds., *Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2*, p. 23-40.
- Hamilton-Smith, T., Walker, D., and Nuttall, B. C., 1991, Fractured gas reservoirs in the Devonian shale of the Illinois and Appalachian basins: *American Association of Petroleum Geologists Bulletin, Eastern Section meeting abstracts*, v. 75, no. 8, p. 1383.
- Hancock, S. K., 1999, Project brings commercial-scale CO₂ miscible flooding to Canada: *Oil and Gas Journal*, no. Oct. 18, 1999, p. 70-75.
- Haney, D. C., 1979, *Geology and Energy Resources of Kentucky: The Interstate Oil Compact Commission Committee Bulletin*, v. XXI, no. 1, p. 59-62.
- Hanisch, C., 1999, Exploring Options for CO₂ Capture and Management: *Environmental Science and Technology*, v. 33, no. 3, p. 66.

- Hasenmueller, N. R., 1993, New Albany shale (Devonian and Mississippian) of the Illinois Basin, in Roen, J. B., and Kepferle, R. C., eds., *Petroleum geology of the Devonian and Mississippian black shale of eastern North America*: U. S. Geological Survey Bulletin 1909, p. C1-C19.
- Hasenmueller, N. R., Boberg, J., Lumm, D. K., Frankie, W. T., Hamilton-Smith, T., and Comer, J. B., 1994, Stratigraphy, in Hasenmueller, N. R., and Comer, J. B., eds., *Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin*: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, p. 13-21.
- Hasenmueller, N. R., Boberg, W. S., Comer, J., Smidchens, Z., Frankie, W. T., Lumm, D. K., Hamilton-Smith, T., and Walker, J. D., 1991, Study of gas production potential of New Albany shale (Group) in the Illinois Basin: American Association of Petroleum Geologists Bulletin, Eastern Section meeting abstracts, v. 75, no. 8, p. 1383.
- Hasenmueller, N. R., Boberg, W. S., Comer, J., Smidchens, Z., Frankie, W. T., Lumm, D. K., Hamilton-Smith, T., and Walker, J. D., 1991, Study of gas production potential of New Albany shale (Group) in the Illinois Basin, in Goldhaber, M. B., and Eidel, J. J., eds., *U. S. Geological Survey, Open-file Report*, 19 p.
- Hasenmueller, N. R., Boberg, W. S., Comer, J. B., Smidchens, Z., Frankie, W. T., Lumm, D. K., Hamilton-Smith, T., and Walker, J. D., 1991, Study of gas production potential of New Albany shale (Group) in the Illinois Basin [abs], Eastern Oil Shale Symposium Abstracts, November 16-19, 1993: Lexington, Kentucky, Institute for Mining and Minerals Research, p. 78.
- Hasenmueller, N. R., and Comer, J. B., 1994, Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin, Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, p. 83.
- Hasenmueller, N. R., and Comer, J. B., 1995, Gas potential of the New Albany shale workshop: Evansville, Indiana, March 1, 1995, Gas Research Institute and Illinois Basin Consortium, p. 274.
- Hasenmueller, N. R., Comer, J. B., Irwin, P. N., Sowder, K., Zuppann, C. W., Carpenter, J., Morse, D. G., Nuttall, B. C., and Hill, D. G., 1999, A new GIS compilation of "Final Report GRI92-0391/Illinois Basin Studies 2: Gas potential of New Albany shale (Devonian and Mississippian) in the Illinois Basin": American Association of Petroleum Geologists Bulletin, v. 83, no. 8, p. 1369.
- Hasenmueller, N. R., Comer, J. B., Morse, D. G., Nuttall, B. C., DeChurch, D., Hill, B. T., Hill, R. T., Irwin, P. N., Like, K. K., Sowder, K., Thompson, T. A., and Zoltin, A., 2000, GIS compilation of gas potential of the New Albany shale in the Illinois Basin, Illinois Basin Consortium, Gas Research Institute CD-ROM GRI-00/0068.
- Hasenmueller, N. R., Shaffer, N. R., and Comer, J. B., 1995, Cores of the New Albany shale from wells in Indiana, in *Gas potential of the New Albany shale workshop*, Evansville, Indiana, p. O1-O42.
- Haugan, P. M., and Drange, H., 1992, Sequestration of CO₂ in the deep ocean by shallow injection: *Nature*, v. 357, no. 6376, p. 318-320.
- Helton, W. L., 1963, The Silurian-Devonian stratigraphy of Pulaski County, Kentucky, and some features of the pre Mid-Devonian unconformity [Thesis thesis]: University of Kentucky, unknown p.
- Hendriks, C., 1994, Carbon Dioxide Removal from Coal-Fired Power Plants, *Energy & Environment*: Boston, Kluwer Academic Publishers, 233 p.
- Herzog, H., 1998, The Economics of CO₂ Capture, in *Fourth International Conference on Greenhouse Gas Control Technologies*, Interlaken, Switzerland.

- Herzog, H., Drake, E., and Adams, E., 1997, CO₂ Capture, Reuse, and Storage Technologies for Mitigating Global Climate Change: Energy Laboratory, MIT, DOE Order No. DE-AF22-96PC01257.
- Herzog, H., Eliasson, B., and Kaarstad, O., 2000, Capturing greenhouse gases: *Scientific American*, v. 282, no. 2, p. 72-79.
- Herzog, H., Schmidt, C., and Drake, E., 1998, CO₂ Sequestration: Opportunities for Government-Industry-Academia Partnerships, in Fourth International Conference on Greenhouse Gas Control Technologies, Interlaken, Switzerland.
- Herzog, H., and Vukmirovic, N., 1999, CO₂ Sequestration: Opportunities and Challenges, in 7th Clean Coal Technology Conference, Knoxville, TN.
- Hill, D. G., 1995, An overview of productive gas shales, in Gas potential of the New Albany shale workshop, Evansville, Indiana, p. G1-G2, illustrated.
- Hitchon, B., 1996, Aquifer disposal of carbon dioxide: hydrodynamic and mineral trapping, in Hitchon, B., ed., Proof of Concept: Sherwood Park, Alberta, p. 165.
- Hitchon, B., Gunter, W. D., Gentiz, T., and Bailey, R. T., 1999, Sedimentary basins and greenhouse gases: a serendipitous association: *Energy Conservation and Management*, v. 40, no. 8, p. 825-843.
- Holbrook, C. E., 1964, Stratigraphic relationships of the Silurian and Devonian in Clark, Powell, Montgomery and Bath Counties [Thesis thesis]: University of Kentucky, unknown p.
- Holloway, S., 1996, An overview of the Joule II project "The underground disposal of carbon dioxide": *Energy Conservation and Management*, v. 37, no. 6-8, p. 1149-1154.
- Holloway, S., Rochelle, C. A., and Pearce, J. M., 1999, Geological sequestration of carbon dioxide; implications for the coal industry: *Institution of Mining and Metallurgy, Transactions, Section B: Applied Earth Science*, v. 108, p. 19-22.
- Hopkins, C., 1995, Completion technology, in Gas potential of the New Albany shale workshop, Evansville, Indiana, p. K1-K2, illustrated.
- Hornbrook, M. W., Dehghani, K., Qadeer, S., Ostermann, R. D., and Ogbe, D. O., 1991, Effects of CO₂ Addition to Steam Recovery of West Sak Crude Oil: *SPE Reservoir Engineering*, v. 63, p. 278-286.
- Hover, V. C., Peacor, D. R., and Walter, L. M., 1996, Relationship between organic matter and authigenic illite/ smectite in Devonian black shales, Michigan and Illinois basins, USA, in Crossey, L. J., Loucks, R., and Totten, M. W., eds., *Siliciclastic diagenesis and fluid flow; concepts and applications: SEPM (Society for Sedimentary Geology), Special Pub. 55*, p. 73-83.
- Hover, V. C., Peacor, R. R., and Walter, L. M., 1993, Shale microstructure and chemistry in cratonic basins; does shale authigenesis follow the Gulf Coast paradigm?: *American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, Annual Meeting Abstracts*, p. 121.
- Hover, V. C., Peacor, R. R., and Walter, L. M., 1996, STEM/AEM evidence for preservation of burial diagenetic fabrics in Devonian shales; implications for fluid/rock interaction in cratonic basins (U.S.A.): *Society of Economic Paleontologists and Mineralogists, Journal of Sedimentary Research, Section A: Sedimentary Petrology and Processes*, v. 66, no. 3, p. 519-530.
- Hovorka, S. D., and Dutton, A. R., 1999, Exploring for optimal geological environments for carbon dioxide disposal in saline aquifers in the United States, in *Program and Abstracts of the 1999*

- Annual Convention American Association of Petroleum Geologists, San Antonio, TX, April 11-14, 1999, p. A63.
- Hughes, J. D., Dawson, F. M., Duggan, J., Hallas, D. F., Khitrova, G., Marchioni, D. L., Richardson, R., and Wynne, D., 1999, Regional analysis of the Ardley coal zone, Alberta, for coalbed methane production and CO₂ sequestration, Geological Survey of Canada, Open-File Report, 116 p.
- Hughes, R. E., Olive, W. W., Reuff, A. W., Baxter, J. W., Anderson, W. H., McFarland, M., and Stiff, B. J., 1992, Assessment of the clay and shale resources of the Paducah Quadrangle, in Goldhaber, M. B., and Eidel, J. J., eds., Mineral resources of the Illinois Basin in the context of basin evolution: U. S. Geological Survey, Open-file report, p. 28-29.
- Hunter, C. D., and Young, D. M., 1953, Relationship of natural gas occurrence and production in eastern Kentucky (Big Sandy Gas Field) to joints and fractures in Devonian Bituminous shale: Lexington, Kentucky, Kentucky Geological Survey, Series 9, Reprint 7, 18 p.
- Hunter, C. D., and Young, D. M., 1953, Relationship of natural gas occurrence and production in eastern Kentucky (Big Sandy Gas Field) to joints and fractures in Devonian bituminous shale: Bulletin of the American Association of Petroleum Geologists, v. 37, no. 2, p. 282-299.
- IEA Greenhouse Gas R&D Programme, SACS Project.
- IEA Greenhouse Gas R&D Programme, Saline Aquifer CO₂ Storage (SACS).
- Iijima, M., 1996, A Feasible New Flue Gas CO₂ Recovery Technology for Enhanced Oil Recovery: Society of Petroleum Engineers, SPE 39686.
- Ipsen, K. H., and Jacobsen, F. L., 1996, The Linde Structure, Denmark an example of a CO₂ depository with a secondary chalk cap rock: Energy Conservation and Management, v. 37, no. 6-8, p. 1161-1166.
- Ivy, S. M., and Fox, C. E., 1997, Improvements enhance CO₂ flooding technology, planning maximize oil recovery using CO₂ floods, Shell CO₂.
- Jenkins, J. L., 1981, Petrology and related studies of the Upper Devonian black shales in Eastern Kentucky [Thesis thesis]: West Virginia University, 115 p.
- Jillson, W. R., 1932, The next oil pool; a general consideration of some of the undeveloped areas of outstanding merit in Kentucky: Lexington, Kentucky, Transylvania press, xiv , 1 ., 116 p.
- Johnson, R. E., 1983, Bravo dome carbon dioxide area, northeast New Mexico, in Fassett, J. E., ed., Oil and gas fields of the Four Corners area, Four Corners Geological Society, p. 745-748.
- Jordan, D. W., 1979, Trace fossils and stratigraphy of the Devonian Black Shale in east-central Kentucky [Thesis thesis]: University of Cincinnati, unknown p.
- Jordan, D. W., 1985, Trace fossils and depositional environments of upper Devonian Black Shales, east-central Kentucky, U S A: The Society of Economic Paleontologists and Mineralogists., v. 35, p. 279-298.
- K&A Energy Consultants, I., 1988, Significance of Geology to Gas Production from Devonian Shales of the Central Appalachian Basin: An Underdeveloped Asset: Chicago, Illinois, Gas Research Institute, Topical Report October 1, 1987--July 30, 1988, GRI Contract No. 5087-213-1617, 121 p.
- Kaiser, J., 1998, Possibly Vast Greenhouse Gas Sponge Ignites Controversy: Science, v. 282, p. 386-387.
- Kalafant, J. R., and Boyer, C. M., 1988, A geologic assessment of natural gas from coal seams in the central Appalachian Basin, topical report (January 1988-November 1988): Fairfax, VA, ICF-

- Lewan, prepared for the Gas Research Institute, contract number 5084-214-1066, GRI No. 88/0302, 66 p.
- Keith, D. W., and Parson, E. A., 2000, A breakthrough in climate change policy?: *Scientific American*, v. 282, no. 2, p. 78-79.
- Kelebeev, A. S., Akinfiev, N. N., and Shvets, V. M., 1996, Carbon dioxide utilization in aquifer: method for mitigation greenhouse effect: *Energy Conservation and Management*, v. 37, no. 6-8, p. 1143-1148.
- Kepferle, R. C., 1986, Devonian and Mississippian black shales of Kentucky: *Geological Society of America Centennial Field Guide - Southeastern Section*, v. 6, no. Southeastern Section of the Geological Society of America, p. 31-36.
- Kikkinides, E. S., Yang, R. T., and Cho, S. H., 1993, Concentration and Recovery of CO₂ from Flue Gas by Pressure Swing Adsorption: *Industrial & Engineering Chemistry Research*, v. 32, no. 11, p. 2714-2720.
- Kikkinides, E. S., Yang, R. T., and Cho, S. H., 1994, Response to Comments on "Concentration and Recovery of CO₂ from Flue Gas by Pressure Swing Adsorption": *Industrial & Engineering Chemistry Research*, v. 33, no. 11, p. 2881.
- Kimura, N., Omata, K., Kiga, T., Takano, s., and Shikisima, S., 1995, The Characteristics of pulverized coal combustion in O₂/ CO₂ mixtures for CO₂ recovery: *Energy Conversion and Management*, v. 36, no. 6-9, p. 805-808.
- Knauss, K. G., Copenhaver, S. A., Braun, R. L., and Burnham, A. K., 1997, Hydrous pyrolysis of New Albany and Phosphoria shales; production kinetics of carboxylic acids and light hydrocarbons and interactions between the inorganic and organic chemical systems: *Organic Geochemistry*, v. 27, no. 7-8, p. 477-496.
- Kuuskraa, V. A., Schmoker, J. W., and Dyman, T. S., 1998, Diverse gas plays lurk in gas resource pyramid: *Oil and Gas Journal*, v. 96, no. 23, June 8, 1998, p. 123-130.
- Kuuskraa, V. A., and Wicks, D. E., 1983, Technically recoverable Devonian shale gas in Ohio, U.S. Department of Energy, Morgantown Energy Technology Center, DOE/MC/19239-1525, 101 p.
- Lancaster, D., and Gatens, J. M. III, 1989, Research targets Devonian shales: *Northeast Oil World (NOW)*, p. 12-15.
- Lang, W. B., 1959, The origin of some natural carbon dioxide gases: *Journal of Geophysical Research*, v. 64, p. 127-131.
- Latil, M., 1980, Enhanced oil recovery: Paris, France, French Institute of Petroleum Publications, translation distributed by Gulf Publishing, Houston, 236 p.
- Law, D. H.-S., and Bachu, S., 1996, Hydrogeological and numerical analysis of CO₂ disposal in deep aquifers in the Alberta sedimentary basin: *Energy Conservation and Management*, v. 37, no. 6-8, p. 1167-1174.
- Lenhart, S. W., 1985, Structural and paleogeographic control of Devonian carbonate litho-stratigraphy of the adjacent to the Cincinnati Arch in south-central Kentucky [Thesis thesis]: University of Kentucky, unknown p.
- Leventhal, J. S., and Shaw, V. E., 1980, Organic matter in Appalachian Devonian Black Shale: I. comparison of techniques to measure organic carbon, II. short range organic carbon content variations: *Journal of Sedimentary Petrology*, v. 50, no. 1, p. 0077-0081.

- Lewan, M. D., Comer, J. B., Hamilton-Smith, T., Hasenmueller, N. R., Guthrie, J. M., Hatch, J. R., Gautier, D. L., and Frankie, W. T., 1995, Feasibility study of material-balance assessment of petroleum from the New Albany shale in the Illinois Basin, U.S. Geological Survey Bulletin 2137, 31 p.
- Lewan, M. D., Henry, M. E., Higley, D. K., and Pitman, J. K., 1998, Material-balance approach to petroleum systems: New Albany shale/Chesterian of the Illinois Basin: American Association of Petroleum Geologists, Annual Convention Extended Abstracts, p. A401.
- Lewis, J. O., 1949, A study of the geology of Preston (Boyle) ore in Bath County, Kentucky [Thesis thesis]: University of Kentucky, unknown p.
- Los Alamos National Labs, 1998, Zero Emission Coal.
- Lumm, D. K., 1995, Relationships between structural features, fracture orientations, and current stress in the Illinois Basin, in Gas potential of the New Albany shale workshop, Evansville, Indiana, p. D1-D3, illustrated.
- Lumm, D. K., Frankie, W. T., Hasenmueller, N. R., and Hamilton-Smith, T., 1994, Illinois Basin geologic setting, in Hasenmueller, N. R., and Comer, J. B., eds., Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, p. 9-12.
- Lyle, D., 1999, CO₂ for Kansas: Oil and Gas World, v. 91, no. 5, p. 25-26.
- Malin, C. B., 2000, Petroleum industry faces challenge of change in confronting global warming: Oil and Gas Journal, August 28, 2000, v. 98, no. 35, p. 58-63.
- Markowitz, G., 1979, A geochemical study of the Upper Devonian-Lower Mississippian black shales in Eastern Kentucky [Thesis thesis]: University of Kentucky, unknown p.
- Martini, A. M., Walter, L. M., Ku, T. C. W., and Budai, J. M., 1997, Genetic and temporal relations between black shale formation waters and biogenic methane in Mid-Continent sedimentary basins: Geological Society of America, Abstracts with Programs, v. 29, no. 6, p. 156.
- Maslowski, A., 1986, Logs help decipher Devonian shales: Northeast Oil World (NOW), p. 18-20.
- Maslowski, A., 1986, Multi-well frac performed in Kentucky: Northeast Oil World (NOW), p. 29-30.
- McPherson, B. J. O. L., and Cole, B. S., 2000, Multiphase CO₂ flow, transport and sequestration in the Powder River basin, Wyoming, USA: Journal of Geochemical Exploration, p. 65-70.
- Mercer, G. E., 1992, The distribution and association of trace elements in the bitumen, kerogen, and pyrolysates from New Albany oil shale [PhD Dissertation thesis]: Washington State University, 160 p.
- Miller, B. J., 1990, Design and results of a shallow, light oilfield-wide application of CO₂ Huff'n'Puff process: SPE/DOE 20268, p. 925-932.
- Miller, B. J., and Hamilton-smith, T., 1998, Field Case: Cyclic gas recovery for light oil using carbon dioxide/nitrogen/natural gas: SPE 49169, p. 501-507.
- Miller, M. L., 1978, A petrographic study of the Upper Devonian-Lower Mississippi black shales in Eastern Kentucky [Thesis thesis]: University of Kentucky, unknown p.
- Mines, U. S. B. o., 1965, Joint Committee on Petroleum-Impregnated Rocks, 29; 73-149 p.
- Minihan, E. D., and Buzzart, R. D., 1995, Modern Devonian shale gas search starting in southwestern Indiana: Oil and Gas Journal, v. 93, no. 9, p. 58-62.

- Minihan, E. D., and Buzzart, R. D., 1996, Gas sales starting from Indiana's fractured New Albany shale: *Oil and Gas Journal*, v. 94, no. 36, p. 96-97.
- Moody, J. R., Kemper, J. R., Johnston, I. M., and Elkin, R. R., 1987, Geologic and hydrocarbon report of Pike County: Part 5 of 5, Hydrocarbon production from the Devonian Shale in Letcher, Knott, Floyd, Martin, and Pike Counties, eastern Kentucky: Lexington, Kentucky, Kentucky Geological Survey, Gas Research Institute contract report, contract 5084-213-0990, 51 p.
- Moody, J. R., Kemper, J. R., Johnston, I. M., and Elkin, R. R., 1987, The geology and the drilling and production history of the Upper Devonian Shale of Whitley, Knox, Bell, and Harlan Counties, southeastern Kentucky: Lexington, Kentucky, Kentucky Geological Survey, Gas Research Institute contract report, contract 5084-213-0990, 30 p.
- Moody, J. R., Kemper, J. R., Johnston, I. M., Elkin, R. R., and Smath, R. A., 1988, The geology and the drilling and production history of the Upper Devonian Shale of Breathitt, Clay, Johnson, Leslie, Magoffin, Perry, and Wolfe Counties, east-central Kentucky: Lexington, Kentucky, Kentucky Geological Survey, Gas Research Institute contract report, contract 5084-213-0990, 50 p.
- Moody, J. R., Kemper, J. R., Johnston, I. M., Elkin, R. R., Smath, R. A., and Frankie, W. T., 1988, The geology and the drilling and production history of the Upper Devonian Shale of Boyd, Carter, Elliott, Greenup, Lawrence, Lewis, Menifee, Morgan, and Rowan Counties, north-eastern Kentucky: Lexington, Kentucky, Kentucky Geological Survey, Gas Research Institute contract report, contract 5084-213-0990, 37 p.
- Moody, J. R., Kemper, J. R., Johnston, I. M., Frankie, W. T., and Elkin, R. R., 1987, Geologic and hydrocarbon report of Martin County: Part 4 of 5, Hydrocarbon production from the Devonian Shale in Letcher, Knott, Floyd, Martin, and Pike Counties, eastern Kentucky: Lexington, Kentucky, Kentucky Geological Survey, Gas Research Institute contract report, contract 5084-213-0990, 50 p.
- Moritis, G., 2001, New companies, infrastructure, projects reshape landscape for CO₂ EOR in US: *Oil & Gas Journal*, v. 99.20, no. 14-May-2001, p. 68-73.
- Morse, D. G., 1995, Distribution and lithologic (organic) facies of the New Albany shale in the Illinois Basin, in Gas potential of the New Albany shale workshop, Evansville, Indiana, p. C1-C3, illustrated.
- Morse, D. G., 1996, Sedimentology, diagenesis, and trapping style, Chesterian Tar Springs Sandstone at Inman Field, Gallatin County, Illinois: *American Association of Petroleum Geologists Bulletin*, Eastern Section Abstracts, v. 80, no. 9, p. 1528-1529.
- Murray, J. B., 1971, Silurian and Lower Devonian deposition in the Southern Appalachian Mountains: a stratigraphic and environmental analysis [Thesis thesis]: Case Western Reserve University, 442 p.
- Nadelhoffer, K. J., Emmett, B. A., Gundersen, P., Kjonaas, O. J., Koopmans, C. J., Schlegel, P., Tietema, A., and Wright, R. F., 1999, Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests: *Nature*, v. 398, no. 6723, p. 145-148.
- Negus-deWys, J., 1979, The eastern Kentucky gas field: a geological study of the relationships of Ohio Shale gas occurrences to structure, stratigraphy, lithology, and inorganic geochemical parameters, UGR file #262: Morgantown, West Virginia, 199 p.
- Nicholson, T. J., 1983, Geology and the accumulation of hydrocarbons in the "Big Lime" and Borden group (Mississippian) and Pre-Chattanooga (Silurian-Devonian) of Knox, Laurel and Whitley Counties, south-east Kentucky [Thesis thesis]: University of Kentucky, unknown p.

- Norby, R. D., and Ettensohn, F. R., 1992, Stratigraphy and biostratigraphy of the New Albany shale (Devonian-Mississippian) in the Illinois basin: American Association of Petroleum Geologists Bulletin, Eastern Section Abstracts, v. 76, no. 8, p. 1282.
- Norman, C., 1994, CO₂ for EOR is Plentiful But Tied to Oil Price: Oil & Gas Journal, v. 92, no. 6, p. 44-50.
- Nosow, E., 1962, Kentucky, in Research Committee of the Interstate Oil Compact Commission, ed., Underground Storage of Natural Gas in the United States: Oklahoma City, Oklahoma, Interstate Oil Compact Commission, p. 156-162.
- Nuccio, V. F., 1994, Thermal history modeling in the Illinois Basin, in Ridgely, J. L., Drahovzal, J. A., Keith, B. D., and Kolata, D. R., eds., Proceedings of the Illinois Basin energy and mineral resources workshop: U. S. Geological Survey, Open-file report, p. 28-29.
- Nuccio, V. F., and Hatch, J. R., 1994, Potential problems using vitrinite reflectance to calibrate thermal history models in the Illinois Basin: American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, Annual Meeting Abstracts, p. 226.
- Nuccio, V. F., and Hatch, J. R., 1996, Vitrinite reflectance suppression in the New Albany shale, Illinois Basin; vitrinite reflectance and Rock-Eval data, U. S. Geological Survey, Open-file report, 37 p.
- O'Brien, N. R., Slatt, R. M., and Sneftle, J., 1993, The significance of oil shale fabric in primary hydrocarbon migration, in Lau, F. S., and Bonner, W. P., eds., 1992 Eastern oil shale symposium; proceedings: University of Kentucky, Institute for Mining and Minerals Research, Lexington KY, IMMR93-01, p. 294-299.
- O'Hare, A. T., 1982, A geochemical study of the partitioning of elements during retorting of oil shales from Lewis County, Kentucky [Thesis thesis]: University of Kentucky, unknown p.
- Oil and Gas Journal, 1998, Shell pressing CO₂ flood initiative in Kansas: Oil and Gas Journal, September 28, 1998, v. 96, p. 40.
- Oil and Gas Journal, 1999, Shell details Kansas CO₂ flood project: Oil and Gas Journal, July 26, 1999, v. 97, p. 42-43.
- Oil and Gas Journal, 2000, Seismic surveys provide baseline for CO₂ flood: Oil and Gas Journal, June 5, 2000, v. 98, no. 23, p. 41.
- Oil and Gas Journal, 2000, US greenhouse gas emissions growth slows: Oil and Gas Journal, v. 98, no. 7 (Feb. 14, 2000), p. 30-31.
- Oltz, D. F., Crockett, J. E., Mast, R. F., Howard, R. H., Rupp, J. A., and Noger, M. C., 1992, Oil and gas potential in Paducah Quadrangle, in Goldhaber, M. B., and Eidel, J. J., eds.: U. S. Geological Survey, Open-file report, p. 42-43.
- Orton, E., 1891, Report on the occurrence of petroleum, natural gas and asphalt rock in western Kentucky, based on examinations made in 1888 and 1889, Kentucky Geological Survey, Series 2, volume E, 233 p.
- Paquette, D. E., 1987, Depositional and diagenetic history of a Devonian coral and stromatoporoid biostrome, Falls of the Ohio River, Louisville, Kentucky [Thesis thesis]: Wright State University, 110 p.
- Parson, E. A., and Keith, D. W., 1998, Fossil Fuels Without CO₂ Emissions: Science, v. 282, no. 5391, p. 1053-1054.

- Pashin, J. C., 1985, Paleoenvironmental analysis of the Bedford-Berea sequence (Devonian-Mississippian), north-eastern Kentucky and south-central Ohio [Thesis thesis]: University of Kentucky, unknown p.
- Pashin, J. C., and McIntyre, M. R., In Press, Temperature-pressure conditions in coalbed methane reservoirs of the Black Warrior basin: implications for carbon sequestration and enhanced coalbed methane recovery: , p. 40.
- Pearce, J. M., Holloway, S., Wacker, H., Nelis, M. K., Rochelle, C., and Bateman, K., 1996, Natural occurrences as analogues for the geological disposal of carbon dioxide: *Energy Conservation and Management*, v. 37, no. 6-8, p. 1123-1128.
- Petroleum Tecnology Transfer Council, 1998, Shell initiates Kansas CO₂ study, North Midcontinent Region of the Petroleum Technology Transfer Council.
- Piccot, S. D., and Kirchgessner, D. A., 2000, EPA group verifies performance of greenhouse gas emissions-mitigation technologies: *Oil and Gas Journal*, August 28, 2000, v. 98, no. 35, p. 64-74.
- Potter, P. E., 1978, Structure and isopach map of the New Albany-Chattanooga-OHIO shale (Devonian and Mississippian) in Kentucky, central sheet: Kentucky Geological Survey, Series 10, scale 1:250,000.
- Potter, P. E., Maynard, J. B., and Pryor, W. A., 1980, Final report of special geological, geochemical, and petrological studies of the Devonian shales in the Appalachian Basin: Cincinnati, Ohio, H.N. Fisk Laboratory of Sedimentology, Department of Geology, University of Cincinnati, 86 p.
- Potter, P. E., Maynard, J. B., and Pryor, W. A., 1981, Sedimentology of gas-bearing Devonian shales of the Appalachian basin: Cincinnati, Ohio, H.N. Fisk Laboratory of Sedimentology, Department of Geology, University of Cincinnati, 20 p.
- President's Committee of Advisors on Science and Technology, 1997, Report to the President on federal energy research and development for the challenges of the twenty-first century, President's Committee of Advisors on Science and Technology, Panel on Energy Research and Development.
- Pyron, A. J., Viellenave, J. H., and Fontana, J. V., 2003, New York Devonian black shale: a Barnett-like play in waiting: *Oil and Gas Journal*, v. 101.2, January 13, 2003, p. 36-42.
- Quick, J. C., and Glick, D. C., 2000, Carbon dioxide from coal combustion: variation with rank of US coal: *Fuel*, v. 79, p. 803-812.
- Ramaswamy, G., 2001, Production history provides CBM insights: *Oil and Gas Journal*, April 2, 2001, v. 99, no. 14, p. 49-52.
- Ranganathan, V., 1992, Dissolved salt removal from Illinois Basin waters, in Kharaka, Y. K., and Maest, A. S., eds., *Proceedings of the 7th international symposium on water-rock interaction; Volume 2, Moderate and high temperature environments*: Edmonton, AB, International Association of Geochemistry and Cosmochemistry and Alberta Research Council Sub-group on Water-Rock Interaction, p. 1051-1054.
- Ranganathan, V., 1992, Maintenance of high TDS in pore waters above the New Albany shale of the Illinois Basin: *Geological Society of America, Abstracts with Programs*, v. 24, no. 7, p. 324-325.
- Ranganathan, V., 1993, The maintenance of high salt concentrations in interstitial waters above the New Albany shale of the Illinois Basin: *Water Resources Research*, v. 29, no. 11, p. 3659-3670.
- Ravizza, R., 1992, Applying the Re-Os and U-Th-Pb systems to black shale geochronology: *International Geological Congress, Abstracts- Congress Geologique, International, Resumes*, v. 29, p. 88.

- Rawn-Schatzinger, V., 1999, CO₂ Recovery from Flue Gas for Use in EOR: Eye On Environment (DOE's Oil & Gas Environmental Research Program), v. 4, no. 1, p. 6-7.
- Reeves, S., 2002, Field studies of enhanced methane recovery and CO₂ sequestration in coal seams: World Oil, v. 223, no. 12, p. 56-60.
- Reichle, D., Houghton, J., Kane, B., Ekmann, J., Benson, S., and al., e., 1999, Working Paper on Carbon Sequestration Science and Technology: U.S. Department of Energy.
- Reynolds, D. W., Jr., 1997, Evidence for the presence of hydrocarbon charge in the Knox and pre-Knox rocks of the Rough Creek Graben [abs]: American Association of Petroleum Geologists Bulletin, Eastern Section and the Society for Organic Petrology meeting abstracts, v. 81, no. 9, p. 1562.
- Reynolds, D. W., Jr., 1997, Reservoirs and hydrocarbons of the Narge Creek Block; anatomy of a field extension in a mature area: American Association of Petroleum Geologists Bulletin, Eastern Section and the Society for Organic Petrology meeting abstracts, v. 81, no. 9, p. 1662.
- Rice, G. S., 1962, Silurian-Devonian stratigraphy of southern Madison, southern Garrard and eastern Lincoln Counties [Thesis thesis]: University of Kentucky, unknown p.
- Ridgley, J. L., and Nuccio, V. F., 1994, Mississippian St. Louis Limestone; a new source-rock play in the Illinois Basin?: American Association of Petroleum Geologists and Society of Paleontologists and Mineralogists, Annual Meeting Abstracts, p. 243.
- Roen, J. B., and Kepferle, R. C., 1993, Petroleum Geology of the Devonian and Mississippian Black Shale of eastern North America, U. S. Geological Survey Bulletin 1909, various p.
- Roth, G., 1983, Sheep Mountain and Dike Mountain fields, Huerfano County, Colorado; a source of CO₂ for enhanced oil recovery, in Fassett, J. E., ed., Oil and gas fields of the Four Corners area, Four Corners Geological Society, p. 740-744.
- Rubarts, W. E., 1959, the Boyle-Duffin-New Albany relationships in northern Casey and western Lincoln Counties [Thesis thesis]: University of Kentucky, unknown p.
- Rudnicki, J. W., and Wawersik, W. R., 1999, Report looks at sequestering CO₂ beneath Earth's surface: Eos, Transactions, American Geophysical Union, v. 80, no. 50, p. 607-608.
- Runge, E. J., 1959, An analysis of the microfauna of the Kiddville layer of the Devonian Boyle Limestone, Marion County, Kentucky [Thesis thesis]: Miami University, 86 p.
- Rushing, S. A., 1994, CO₂ Recovery Improves Cogen Plant Economics: Power Engineering, v. 98, no. 4, p. 46-47.
- Rushing, S. A., 1995, Business Opportunity: Power Projects Profit from CO₂ Recovery: Electrical World, v. 209, no. 3, p. 48.
- Rutledge, H. M., 1957, The Boyle Formation of southern Boyle County, Kentucky [Thesis thesis]: University of Kentucky, unknown p.
- Ryder, R. T., Burruss, R. C., and Hatch, J. R., 1998, Black shale source rocks and oil generation in the Cambrian and Ordovician of the Central Appalachian Basin, USA: AAPG Bulletin, v. 82, no. 3, p. 412-441.
- Salkever, A., 1999, Turning the Ocean into a Giant Soda Pop, The Christian Science Monitor: Boston, MA, p. 2.
- Salmon, G. L., Risatti, J. B., and Whitaker, S. T., 1992, Geochemical characterization of dissimilar-sourced oils from upper Knox and Middle Devonian rocks, Wayne County, Illinois: American Association of Petroleum Geologists Bulletin, Eastern Section Abstracts, v. 76, no. 8, p. 1284.

- Sandararaman, P., and Robl, R. I., 1993, Use of activation energy of maceral concentrate in predicting product composition of generated oil: American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, Annual Meeting Abstracts, p. 187.
- Sandberg, C. A., Hasenmueller, N. R., and Rexroad, C. B., 1993, Conodont zonation, biofacies, and correlations of lower part of New Albany shale (Devonian), central and southern Indiana: Geological Society of America, North-Central Section, Abstracts with Programs, v. 25, no. 3, p. 77.
- Sandberg, C. A., Hasenmueller, N. R., and Rexroad, C. B., 1994, Conodont biochronology, biostratigraphy, and biofacies of Upper Devonian part of New Albany shale, Indiana: Courier-Forschungsinstitut Senckenberg, v. 168, p. 227-253.
- Sargent, M. L., Rupp, J. A., and Noger, M. C., 1992, Structure and morphology of the top of Precambrian crystalline rocks in the Illinois Basin region: Geological Society of America, Abstracts with Programs, v. 24, no. 7, p. 178.
- Sasaki, A., Matsumoto, S., Fujitsuka, M., Shinoki, T., Tanaka, T., and Ohtsuki, J., 1993, CO₂ Recovery in Molten Carbonate Fuel Cell System by Pressure Swing Adsorption: IEEE Transactions on Energy Conversion, v. 8, no. 1, p. 26-32.
- Schieber, J., 1996, Early diagenetic silica deposition in algal cysts and spores; a source of sand in black shales?: Journal of Sedimentary Research, Section A: Sedimentary Petrology and Processes, v. 66, no. 1, p. 175-183.
- Schmoker, J. W., 1981, Determination of Organic-Matter Content of Appalachian Devonian Shales from Gamma-Ray Logs: American Association of Petroleum Geologists Bulletin, v. 65, p. 1285-1298.
- Schoeling, L., 1999, Enhanced coalbed methane production with carbon dioxide injection [abs], in Interstate Oil and Gas Compact Commission Annual Meeting Presentation Notes, New Orleans.
- Schoeling, L., and Fox, C. E., 1998, CO₂ floods look good in Mid-Continent, Shell CO₂.
- Schoeling, L. G., Green, D. W., and Poyser, L. A., A Survey of Waterflooding Performance, Lansing-Kansas City/ CO₂ Potential: , p. 95-109.
- Schulmeister, M. K., 1993, A study of the first row transition elements as a group in a section of the New Albany shale (Devonian- Mississippian) of southern Indiana [Masters Thesis thesis]: Michigan State University, 99 p.
- Schultz, R. B., 1991, Metalliferous black shales; accumulation of carbon and metals in cratonic basins, in Force, E. R., Eidel, J. J., and Maynard, J. B., eds., Sedimentary and diagenetic mineral deposits; a basinal analysis approach to exploration: Society of Economic Geologists, Reviews in Economic Geology volume 5, p. 171-176.
- Schütz, M., Daun, M., Weinspach, P.-M., Krumbeck, M., and Hein, K. R. G., 1992, Study on the CO₂-Recovery from an ICGCC Plant: Energy Conversion and Management, v. 33, no. 5-8, p. 357-363.
- Schwalb, H., and Norris, R. L., 1980, East-west cross sections north and south of Rough Creek Fault system: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 900, scale 2 sheets.
- Schwalb, H., and Norris, R. L., 1980, Isopach map of Blocher member of New Albany shale, western Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 902, scale 1:500,000.
- Schwalb, H., and Norris, R. L., 1980, Isopach map of Grassy Creek member of New Albany shale, western Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 905, scale 1:500,000.

- Schwalb, H., and Norris, R. L., 1980, Isopach map of Sweetland Creek member of New Albany shale, western Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 903, scale 1:500,000.
- Schwalb, H., and Norris, R. L., 1980, North-south cross section east side of area: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 904, scale 2 sheets.
- Schwalb, H., and Norris, R. L., 1980, North-south cross section west side of area: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 901, scale 2 sheets.
- Schwalb, H., and Norris, R. L., 1980, Occurrence of natural gas in the New Albany shale, western Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 906, scale 1:500,000.
- Schwalb, H., and Norris, R. L., 1980, Structure map on the base of the new Albany shale, western Kentucky: United States Department of Energy, Morgantown Energy Technology Center, Eastern Gas Shales Project, METC/EGSP Series 907, scale 1:500,000.
- Schwalb, H. R., and Potter, P. E., 1978, Structure and isopach map of the New Albany-Chattanooga-Ohio shale (Devonian and Mississippian) in Kentucky, western sheet: Kentucky Geological Survey, Series 10, scale 1:250,000.
- Shell CO₂, 1998, CO₂ floods may enhance Kansas oilfield recovery, Shell CO₂.
- Shell CO₂, 1999, What is a CO₂ flood?, Shell CO₂.
- Shirley, A. I., 1994, Comments on "Concentration and Recovery of CO₂ from Flue Gas by Pressure Swing Adsorption": Industrial & Engineering Chemistry Research, v. 33, no. 11, p. 2879-2880.
- Shumaker, R. C., 1987, Structural parameters that affect Devonian shale gas production in West Virginia and eastern Kentucky, Appalachian Basin Industrial Associates, 133-201 p.
- Shumaker, R. C., 1993, Structural parameters that affect Devonian shale gas production in West Virginia and eastern Kentucky, in Roen, J. D., and Kepferle, R. C., eds., Petroleum geology of the Devonian and Mississippian black shale of eastern North America, U. S. Geological Survey Bulletin 1909, p. K1-K38.
- Skinner, L., 2003, CO₂ blowouts: an emerging problem: World Oil, v. 224, no. 1, p. 38-42.
- Smidchens, Z., Boberg, W. S., Frankie, W. T., Lumm, D. K., and Hamilton-Smith, T., 1994, Map showing locations of cores of the New Albany shale (Devonian and Mississippian) in the Illinois Basin, in Hasenmueller, N. R., and Comer, J. B., eds., Gas potential of the New Albany shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Gas Research Institute 92-0391/Illinois Basin Studies 2, plate 2, scale 1:1,000,000.
- Sneftle, J. T., Yordy, K. L., Barron, L. S., and Crelling, J. C., 1991, Whole rock and isolated kerogen characterization studies; observations of sample type preparations upon petrographic and chemical characterization of New Albany shale, in Baker, E. W., and Douglas, A. G., eds., Organic Geochemistry: Collected papers from the Fifth annual meeting of the Society for Organic Petrology and the Society for Organic Petrology/ American Association of Stratigraphic Palynologists symposium, p. 275.
- Spirakis, C. S., 1995, Problems with applying topographically driven flow to genesis of the Upper Mississippi Valley zinc-lead district and to fluid flow in the Illinois Basin, U. S. Geological Survey Bulletin 2094-C, 12 p.

- Stankiewicz, B. A., 1995, Geochemistry and petrology of coal and kerogen macerals [PhD Dissertation thesis]: Southern Illinois University, 272 p.
- Stephens, S. H., and Gale, J., 2000, Geologic CO₂ sequestration may benefit upstream industry: Oil & Gas Journal, v. 98, no. 20, p. 40-44.
- Stephenson, J. T., 1979, Petrology, lithofacies and depositional analysis of the Boyle dolomite, Middle Devonian in east-central Kentucky [Thesis thesis]: University of Cincinnati, unknown p.
- Stevens, S. H., Schoeling, L., and Pekot, L., 1999, CO₂ Injection for enhanced coalbed methane recovery: project screening and design, in University of Alabama, C. o. C. S., ed., Proceedings of the 1999 International Coalbed Methane Symposium: Tuscaloosa, AL, University of Alabama, p. 309-318.
- Stevens, S. H., Spector, D., and Riemer, P., 1998, Enhanced coalbed methane recovery using CO₂ injection: Worldwide resource and CO₂ sequestration potential: Society of Petroleum Engineers, SPE 48881, p. 489-501.
- Suda, T., Fujii, M., Yoshida, K., Iijima, M., Seto, T., and Mitsuoka, S., 1992, Development of Flue Gas Carbon Dioxide Recovery Technology: Energy Conversion and Management, v. 33, no. 5-8, p. 317-324.
- Swager, D. R., 1978, Stratigraphy of the Upper Devonian-Lower Mississippian shale sequence in the Eastern Kentucky outcrop belts [Thesis thesis]: University of Kentucky, unknown p.
- Takano, S.-I., Kiga, T., Endo, Y., Miyamae, S., and Suzuki, K., 1995, CO₂ Recovery from PCF Power Plant with O₂/ CO₂ Combustion Process: Ihi Engineering Review, v. 28, no. 4, p. 160-164.
- Talmage, S. B., and Andreas, A., 1942, Carbon dioxide in New Mexico, in Bates, R. L., ed., The oil and gas resources of New Mexico (2nd ed), New Mexico Bureau of Mines and Mineral Resources Bulletin 18, p. 301-307.
- Teng, H. H., Dove, P. M., DeYoreo, J. J., and Orme, C., 1998, Thermodynamic controls on calcite growth; determining foundations of biomineral formation: Abstracts with Programs Geological Society of America, v. 30, no. 7, p. 156.
- The Society for Organic Petrology, 1998, Coalbed Methane (full list).
- Thomas, Jr., Josephus., and Frost, R. R., 1980, Adsorption/Desorption Studies of Gases through Shales, in Bergstrom, R. E., Shimp, N. F., and Cluff, R. M., eds., Geologic and Geochemical Studies of the New Albany Shale Group (Devonian-Mississippian) in Illinois, Final Report: Urbana, Illinois, Illinois State Geological Survey, DOE/METC/12142-26, p. 143-183.
- Thomas, R. N., 1951, Devonian shale gas production in central Appalation area: Lexington, Kentucky, Kentucky Geological Survey, Series 9, Reprint 4, 8 p.
- Tontiwachwuthikul, P., Chan, C. W., Kritpiphat, W., DeMontigny, D., Skoropad, D., Gelowitz, D., Aroonwilas, A., Mourits, F., Wilson, M., and Ward, L., 1998, Large Scale Carbon Dioxide Production from Coal-Fired Power Plants for Enhanced Oil Recovery: A New Economic Feasibility Study: Journal of Canadian Petroleum Technology, v. 37, no. 11, p. 48-55.
- Tontiwachwuthikul, P., Chan, C. W., Kritpiphat, W., Jordan, C., Skoropad, D., Gelowitz, D., Aroonwilas, A., Mourits, F., Wilson, M., and Ward, L., 1996, Carbon Dioxide Production from Coal-Fired Power Plants for Enhanced Oil Recovery: A Feasibility Study in Western Canada: Energy, v. 21, no. 10, p. 857-869.
- Tontiwachwuthikul, P., Chan, C. W., Kritpiphat, W., Skoropad, D., Gelowitz, D., Aroonwilas, A., and Jordan, C., 1996, New feasibility study of carbon dioxide production from coal-fired power plants for enhanced oil recovery: a Canadian perspective: Energy Conservation and Management, v. 37, no. 6-8, p. 1129-1134.

- Treworgy, C. G., Prussen, E. I., Justice, M. A., Chenoweth, C. A., Bargh, M. H., Jacobson, R. J., and Damberger, H. H., 1997, Illinois coal reserve assessment and database development: final report: Champaign, Illinois, Illinois State Geological Survey, Open File Series 1997-4, 105 p.
- Turner, J. A., 1999, A Realizable Renewable Energy Future: *Science*, v. 285, no. 5427, p. 687-689.
- U. S. Department of Energy, 1993, CO₂ Prophet: water and CO₂ flood prediction software, Texaco Exploration and Production Technology Department (DOE Contract No. DE-FC22-93BC14960).
- U. S. Department of Energy, O. o. S., 1999, Carbon sequestration: State of the science, U.S. Department of Energy, various p.
- Vella, A. J., and Holzer, G., 1992, Distribution of isoprenoid hydrocarbons and alkylbenzenes in immature sediments; evidence for direct inheritance from bacterial/algal sources: *Organic Geochemistry*, v. 18, no. 2, p. 203-210.
- Vergano, D., 2000, Defusing the Carbon Dioxide Threat, *USA Today*, p. 9D.
- Waku, H., Tamura, I., Inoue, M., and Akai, M., 1995, Life Cycle Analysis of Fossil Power Plant with CO₂ Recovery and Sequestering System: *Energy Conversion and Management*, v. 36, no. 6-9, p. 877-880.
- Walter, L. M., Budai, J. M., Martini, A. M., Richards, J. C., and Abriola, L. M., 1995, Geology and hydrogeochemistry of the Michigan Basin with implications for exploration in the New Albany shale, in Gas potential of the New Albany shale workshop, Evansville, Indiana, p. H1, illustrated.
- Wawersik, W. R., and Rudnicki, J. W., 1998, Terrestrial sequestration of CO₂-An assessment of research needs: Washington, D.C., U. S. Department of Energy, Office of Science., p. 67.
- Welch, R. N., 1937, A study and description of two cores from the "Corniferous" of western Powell County, Kentucky [Thesis thesis]: University of Kentucky, unknown p.
- Wells, B. E., and Mills, J. G., Jr., 1992, Orientation of principle paleostress directions in Mississippian strata of Warren County, Illinois, Kistler Quarry and Biggsville Quarry: Geological Society of America, North-Central Section, Abstracts with Programs, v. 24, no. 4, p. 71.
- Wilson, M. A., Wrubleski, R. M., and Yarborough, L., 1992, Recovery of CO₂ from Power Plant Flue Gases Using Amines: *Energy Conversion and Management*, v. 33, no. 5-8, p. 325-331.
- Wojick, D. E., 1999, Carbon storage in soil, the ultimate no-regrets policy?, Greening Earth Society.
- Wolsky, A. M., Daniels, E. J., and Jody, B. J., 1991, Recovering CO₂ from Large- and Medium-Size Stationary Combustors: *Journal of the Air & Waste Management Association*, v. 41, no. 4, p. 449-454.
- Woock, R. D., 1982, The quantitative mineralogy and mineral stratigraphy of the Late-Devonian, Early-Mississippian black shales of east-central Kentucky [Thesis thesis]: University of Kentucky, unknown p.
- Zaback, D. A., and Pratt, L. M., 1992, Clarification of C-S relationships of marine black shales using stable isotopic composition of reduced sulfur: Geological Society of America, Abstracts with Programs, v. 24, no. 7, p. 168.
- Zuber, M. D., 1995, Production characteristics and practices, in Gas potential of the New Albany shale workshop, Evansville, Indiana, p. J1, illustrated.

Appendix A: Summary of Adsorption Isotherms

107928-1 3600-4000 ft. Ohio Shale (upper part)

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
61	2.6
141	6.1
209	8.6
262	11.0
326	13.1
395	15.0
484	16.7
589	17.9
811	18.6

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	37.5
Pressure (PSIA)	681.1

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.88 Density g/cc 2.756

107928-2 4400-4600 ft. Lower Huron Member

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
47	8.9
109	19.7
172	27.6
252	35.9
315	41.2
383	45.1
469	46.8
572	48.0
803	48.7

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	67.6
Pressure (PSIA)	243.7

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.97 Density g/cc 2.660

**107928-3 4600-5000 ft. Rhinestreet and
Olentangy Members**

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
49	5.3
109	9.9
177	13.5
248	17.4
320	19.5
391	22.4
483	24.1
590	24.8
806	25.0

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	34.6
Pressure (PSIA)	253.1

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.98 Density g/cc 2.749

**121774-1A 3500-3720 ft. Ohio Shale
(Undifferentiated)**

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
23	2.9
50	6.4
82	9.8
103	11.8
130	14.2
185	18.9
251	24.8
321	31.3
392	37.2
512	48.4
705	68.9

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	126.5
Pressure (PSIA)	989.8

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.91 Density g/cc 2.550

RN124789 1A 2680-2990 ft.

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
26	3.1
55	6.2
76	8.3
111	12.1
133	15.4
191	22.3
259	29.6
334	37.7
402	43.2
517	54.9
595	61.6

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	740.8
Pressure (PSIA)	6419.1

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.49 Density g/cc 2.597

RN124789 S2A 2990-3110 ft.

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
29	3.9
45	6.7
68	10.4
94	14.0
122	17.4
176	24.4
240	34.0
309	44.4
380	54.0
496	69.8
602	96.9

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	2077.6
Pressure (PSIA)	14283.5

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.04 Density g/cc 2.579

RN124789 3A 3110-TD

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
32	4.2
49	6.0
74	8.2
110	11.4
136	13.6
193	17.9
253	23.6
326	30.4
394	35.6
512	45.7
663	60.3

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	116.2
Pressure (PSIA)	957.9

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.77 Density g/cc 2.679

RN123486 #1 341OHIOU 2600-3700 ft.

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
22	2.4
45	4.5
73	7.0
99	9.2
126	12.0
183	17.4
249	23.8
321	29.2
394	34.0
515	42.9
593	54.7

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	228.9
Pressure (PSIA)	2230.4

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.66 Density g/cc 2.631

RN123486 S2 341OHIOL 3070-3210 ft.

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
25	3.6
49	7.2
82	11.6
116	16.1
146	20.1
196	26.4
256	33.7
321	40.5
390	48.4
508	61.6
571	75.3

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	309.3
Pressure (PSIA)	2106.0

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.96 Density g/cc 2.573

121162 OHIO UPPER 3410-3810 ft.

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
14	1.6
40	4.3
65	6.6
111	10.5
127	11.9
192	17.0
247	22.2
312	28.6
381	32.6
498	44.5

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	164.2
Pressure (PSIA)	1561.3

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.79 Density g/cc 2.669

121464 OHIO Upper 3200-3300 ft,

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
19	1.6
49	3.6
78	5.0
100	6.1
159	8.9
193	10.5
250	13.7
316	17.2
384	18.9
501	24.2

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	52.6
Pressure (PSIA)	708.9

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.82 Density g/cc 2.694

121464 HURNL 4300-4380 ft.

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
14	5.6
33	10.3
52	15.0
99	29.0
113	30.6
159	41.4
218	55.5
289	71.7
362	82.1
476	101.1

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	248.7
Pressure (PSIA)	751.2

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.79 Density g/cc 2.716

121464 OHIO Lower 4580-4980 ft.

Pressure (PSIA)	Adsorbed gas (ft ³ /ton)
	<i>In-Situ Conditions (Equilibrium Moisture)</i>
27	3.2
42	5.6
84	10.4
99	11.9
123	14.0
176	18.5
240	24.6
310	29.5
380	34.5
493	48.3

Langmuir Parameters

	<i>In-Situ Conditions (Equilibrium Moisture)</i>
Vol. (ft ³ /ton)	108.0
Pressure (PSIA)	819.0

SUMMARY OF ADSORPTION ANALYSES IMP. UNITS

Isotherm Temperature: 86.0 °F
 Goodness of fit of Langmuir regression: 0.93 Density g/cc 2.730

Appendix B: GIS Analysis of the Distribution and Estimated CO₂ Storage Volume of the Devonian Shale in Kentucky

Note: Grid data sets are indicated in matrix notation using the courier type face, i.e., [grid_data]

Geographic information system (GIS) software was used to perform an analysis of the thickness and distribution of the Devonian black shale in Kentucky. The initial goal is to calculate the number of tons of shale in place by county for those areas with drilling depths to the shale of at least 1,000 feet and a shale thickness of at least 50 feet. These cutoffs were selected to ensure reservoir integrity (deeper than the expected depth of surface fracturing) and gas reservoir potential. With the number of tons of shale being determined, a series of factors to calculate the sequestration potential in tons of CO₂ are derived based on measured CO₂ storage capacity and shale density. For GIS, ESRI's ArcView 3.2 and Spatial Analyst were used. The Kentucky Geological Survey uses a server running SQL-2000 for data storage. Data are accessed with tables linked to a graphic user interface implemented using Microsoft Access 97. Access queries were composed to compile point data sets consisting of the locations and values of Devonian shale stratigraphic tops and thickness. The formation tops data were maintained as drilling depth to the top of the formation rather than elevations with respect to sea level. Open database connectivity (ODBC) services are available from ArcView. The Access query results were added to the GIS as tables using the SQL Connect facility and then converted to shape files.

```
SELECT dbo_well_identification.record_number AS recno,
dbo_geographic_location.north_latitude AS lat,
dbo_geographic_location.west_longitude AS lon, dbo_formation_tops.pick_fm,
dbo_geographic_location.surface_elevation AS elev, dbo_formation_tops.fm_top,
dbo_formation_tops.fm_base, [fm_base]-[fm_top] AS thick
FROM ((dbo_geographic_location INNER JOIN dbo_geographic_region ON
dbo_geographic_location.location_index = dbo_geographic_region.location_index)
INNER JOIN dbo_well_identification ON dbo_geographic_location.location_index =
dbo_well_identification.location_index) INNER JOIN dbo_formation_tops ON
dbo_well_identification.record_number = dbo_formation_tops.record_number
WHERE (((dbo_formation_tops.pick_fm)="341OHIO" Or
(dbo_formation_tops.pick_fm)="341CHAT" Or
(dbo_formation_tops.pick_fm)="341NALB") AND ((dbo_formation_tops.fm_top) Is
Not Null) AND ((dbo_formation_tops.fm_base) Is Not Null) AND (([fm_base]-
[fm_top])>0) AND ((dbo_formation_tops.type_of_top)="s") AND
((dbo_geographic_location.ns_feet)>0) AND ((dbo_geographic_location.n or s) Is
Not Null) AND ((dbo_geographic_location.ew_feet)>0) AND
((dbo_geographic_location.e_or_w) Is Not Null) AND
((dbo_geographic_location.carter_section)>0) AND
((dbo_geographic_location.carter_letter)>=" A") AND
((dbo_geographic_location.carter_number) Is Not Null));
```

Sample SQL query composed with the Access GUI for compiling Devonian shale stratigraphic and location point data.

Existing polygon shape files of the Kentucky counties, faults, and the subsurface distribution of the Devonian shale in Kentucky ([Subsurf]) were employed in the analysis. The shape file of the subsurface distribution of the shale was converted to a grid for use in the spatial analysis. Each cell of this grid contained a value of 1 (true) if the shale existed in the subsurface over the area of the cell. All other cells were set to null, the no data value. All grids were computed with 1,000-meter (1 kilometer) cell dimensions. Analyses were performed using the North American Datum of 1927 (NAD27) with the projection set to UTM zone 16.

Subsurface distribution of the Devonian shale (blue, shaded) with stratigraphic data points.

Subsurface distribution of the Devonian shale (blue, shaded) with stratigraphic data points for the Lower Huron Member of the shale.

For deriving drilling depth and thickness maps, grids were interpolated from point data using the inverse distance weighted (IDW) nearest neighbor method. The interpolated data were processed to establish which grid cells fit the selection criteria of 1,000 feet or deeper drilling depths and a shale thickness of at least 50 feet.

```

Interpolate grid, [Depth], using drilling depth from point file
Interpolate grid, [Iso], using thickness data from point file
Map Query [Depth]>=1000 = [Deep]
Map Query [Iso]>=50 = [Thick]
Calculate [Deep]*[Thick] = [Temp01]
Calculate [Temp01]*[Subsurf] = [Temp02]
([Temp02] = 0.AsGrid).SetNull([Temp02]) = [DeepThick]

```

Method for deriving a grid dataset indicating the distribution of shale at least 50 feet thick and 1,000 feet deep.

To restrict the volume calculations to the limits of the distribution of thicker and deeper shale, the [Iso] and [DeepThick] grid data sets were multiplied together to produce a new grid, [Target].

To limit the number of calculation steps required to derive volume and sequestration potential estimates, conversion factors were derived to convert the thickness (isopach in feet) data in [Target] to million tons of shale and then directly to CO₂ tons. Tons of shale in place is a function of shale volume and density, thus:

$$Tons_{shale} = volume * density$$

and

$$MMTons_{shale} = \frac{thickness * area * density}{1000000}$$

Assuming thickness in feet, a 1 kilometer cell size, a density in g/cc million tons of shale in place can be calculated:

$$MMTons_{shale} = \frac{thickness * \frac{0.3048m}{ft} * (1000m)^2 * density * 1.102}{1000000} \quad \text{Eq. 1.}$$

where:

<i>thickness</i>	= thickness of shale in feet
1000	= cell size in meters
<i>density</i>	= bulk density from compensated density log
1.102	= density conversion factor to convert from grams per cubic centimeter to tons per cubic meter

For a specified density, the constants in equation 1 can be combined to obtain a direct conversion factor that is a function only of shale thickness. Substituting different shale densities, a factor, $CfMMTons$, would be one of:

2.5 g/cc (log estimated density for Lower Huron)	= 0.840
2.6 g/cc (log estimated density for upper part of shale)	= 0.873
2.65 g/cc (log handbook typical shale density)	= 0.890

To calculate million tons of shale per cell, the ArcView grid calculation would be:

$$[Target] * CfMMTons.AsGrid = [MMTons]$$

Different conversion factors could be derived for standard reservoir analysis (as opposed to assuming adsorbed gas). Distributions of porosity, water or oil saturation data, and others could be gridded and used to derive oil or gas in place estimates.

Converting tons of shale in place to estimated tons of CO₂ sequestered requires an additional factor based on the gas content per ton of shale from CO₂ adsorption data. Using a gas content of 1 standard cubic foot of CO₂ per ton and 17.25¹ thousand cubic feet (Mcf) CO₂ per ton of CO₂, there will be 57.97 tons of CO₂ per million tons of shale.

$$TonsCO_2 = \frac{ft^3_{CO_2}}{ton_{shale}} * 1000000 * \frac{Mcf}{1000 ft^3_{CO_2}} * \frac{ton_{CO_2}}{17.25 Mcf} = 57.97 \quad Eq. 2$$

The sequestration volume in tons of CO₂ can now be considered a function of thickness, shale density, and adsorbed gas content, or:

$$TonsCO_2 = 57.97 * CfMMTons * thickness * gascontent$$

Multiplying the 57.97 and $CfMMTons$ provides a single factor that varies only with density:

Factor = 48.69 at density equals 2.5 g/cc
Factor = 50.61 at density equals 2.6 g/cc
Factor = 51.59 at density equals 2.65 g/cc

In lieu of gridding gas content data, multiplying a measured gas content by one of these factors yields a final selection of factors for use in converting shale thickness data directly to tons of CO₂ sequestered. For example, using a gas content of 40 scf/ton, a shale density of 2.6 g/cc, and a 1000-meter cell size, the tons of CO₂ per cell is 2024.3 per foot of shale thickness, thus:

$$[Target] * (2024.3).AsGrid = [CO2Tons]$$

¹ 17.25 Mcf CO₂ per ton CO₂ is the conversion factor used by the U.S. EPA. Conversion is derived from gas laws and is valid for 60°F and 1 atmosphere pressure.

As additional gas content data are acquired, examining the distribution and gridding the data as appropriate will be used to refine the sequestration volume calculations.

The values calculated for each cell require summation for specific regions to obtain totals. With the county polygon theme active, the ArcView Summarize Zones procedure (available from the Analysis menu command) was used to summarize the data by county. The field defining the zones was the county name and the [CO2Tons] grid theme was selected for summarizing. A table of summary statistics was computed that could be joined to the original county table for mapping and additional analysis.

Summary by county of potential sequestration totals (gas content 40 scf/ton, shale density 2.6 g/cc, cell size 1,000 meters):

Name	Basin	Count	Min	Max	Mean	MMTonsCO2
BELL	160	949	0.24	1.52	0.51	486.8
BOYD	160	420	1.03	1.70	1.39	583.9
BREATHITT	160	1293	0.38	1.05	0.60	775.2
CARTER	160	329	0.34	1.26	1.05	346.6
CLAY	160	1236	0.24	0.48	0.35	433.2
ELLIOTT	160	292	0.29	1.14	0.92	267.2
FLOYD	160	1040	0.27	1.79	1.42	1,474.4
GREENUP	160	339	0.99	1.38	1.24	421.7
HARLAN	160	1211	0.31	1.17	0.76	918.6
JACKSON	160	275	0.21	0.34	0.25	69.4
JOHNSON	160	657	0.86	1.67	1.28	839.8
KNOTT	160	918	0.78	1.42	1.06	969.9
KNOX	160	1017	0.20	0.47	0.31	318.5

Name	Basin	Count	Min	Max	Mean	MMTonsCO2
LAUREL	160	1146	0.16	0.38	0.22	255.7
LAWRENCE	160	1089	0.20	1.85	1.37	1,490.6
LEE	160	232	0.22	0.50	0.35	81.6
LESLIE	160	1066	0.38	0.79	0.55	590.8
LETCHER	160	894	0.21	1.70	1.13	1,012.2
MAGOFFIN	160	793	0.63	1.20	0.92	730.8
MARTIN	160	631	1.23	2.32	1.76	1,113.1
MCCREARY	160	703	0.10	0.24	0.15	107.8
MENIFEE	160	16	0.37	0.42	0.39	6.2
MORGAN	160	710	0.25	1.19	0.70	496.8
OWSLEY	160	497	0.13	0.44	0.34	168.0
PERRY	160	892	0.37	1.04	0.71	630.4
PIKE	160	2056	0.82	3.60	2.17	4,467.3
POWELL	160	7	0.31	0.34	0.32	2.2
ROCKCASTLE	160	4	0.19	0.21	0.20	0.8
ROWAN	160	2	0.54	0.54	0.54	1.1
WHITLEY	160	1161	0.16	0.70	0.22	261.1
WOLFE	160	525	0.20	0.81	0.45	237.1
Appalachian	160 Total					19,558.9
MARSHALL	250	29	0.39	0.56	0.48	13.9
Jackson Purchase	250 Total					13.9
EDMONSON	300	670	0.12	0.40	0.24	157.5
HARDIN	300	220	0.13	0.18	0.16	35.3
HART	300	178	0.11	0.20	0.15	26.4
MEADE	300	106	0.18	0.22	0.20	21.6
PULASKI	300	58	0.14	0.18	0.16	9.3
WARREN	300	424	0.12	0.38	0.20	84.0
Cincinnati Arch	300 Total					334.2
BRECKINRIDGE	315	1426	0.10	0.26	0.19	274.8
BUTLER	315	1130	0.11	0.41	0.28	320.3
CALDWELL	315	898	0.27	0.67	0.48	430.0
CHRISTIAN	315	1870	0.11	0.58	0.25	470.0
CRITTENDEN	315	968	0.31	0.90	0.66	634.1
DAVISS	315	1255	0.12	0.46	0.32	404.1
GRAYSON	315	1277	0.12	0.49	0.27	343.6
HANCOCK	315	516	0.15	0.54	0.29	150.5
HENDERSON	315	1233	0.11	0.64	0.45	560.8
HOPKINS	315	1464	0.14	0.64	0.41	595.7
LIVINGSTON	315	696	0.42	0.67	0.60	415.6
LOGAN	315	966	0.12	0.25	0.19	183.1
LYON	315	620	0.28	0.59	0.46	284.8
MCLEAN	315	671	0.14	0.56	0.39	259.9
MUHLENBERG	315	1266	0.12	0.59	0.34	425.4
OHIO	315	1549	0.16	1.09	0.37	573.4
TODD	315	879	0.10	0.31	0.18	156.9
TRIGG	315	848	0.16	0.34	0.24	200.6
UNION	315	953	0.57	0.81	0.69	657.7
WEBSTER	315	878	0.17	0.68	0.51	445.1
Illinois Basin	315 Total					7,786.5
	Grand Total					27,693.5
Years sequestration available at 80,000,000 tons CO2 per year						346.2

The values shown in this table are provided to illustrate an application of the estimation method described in this appendix. The numbers are subject to revision and do not represent final conclusions of this project. Additional CO₂ adsorption capacity data will be acquired to refine the estimates. Consideration will be given to other adjustments to the total that might include evaluating areas likely to have little or no sequestration potential even though they are mathematically included in the area of deep and thick shale. These areas will be excluded. For example, based on experience in oil and gas field exploration and development, Marshall, Pulaski, and Rockcastle counties are areas of marginal potential that have a relatively small likely-hood of being developed for carbon sequestration.

Appendix C: CNR 24752 Elk Horn Coal

Recno: 125651
Permit: 94539
Name: Columbia Natural Resources 24752 Elk Horn Coal Corp
Loc: Knott County, KY, 1250 FSL 620 FWL 11-K-81
Lat: 37.3701 N (NAD27)
Lon: -82.764533 W

TD: 3004 feet

Log measured from KB @ 1011'

Era	Formation	Code	Top (feet)	Condition	Fluoresce	Comments	Shipped
Mssp	Little Lime	332LTLM	1698				
	Pencil Cave	332PCCV	1735				
	Big Lime	332BIGL	1739				
	Borden	337BRDN	1954				
	Sunbury	339SNBR	2249				
	Berea	339BREA	2283				
	Ohio Shale	341OHIO	2346				
Devonian	Cleveland Sh Mbr	341CLVD	2346				
	Core 10	341CLVD	2370	Intact	No	dry, faint odor	Yes
	Three Lick Bed	341TLBD	2452				
	Core 9	341TLBD	2455	Intact	No	light gray	Yes
	Core 8	341TLBD	2465	Intact	No	odor, dark oily black, slick, sticky feel, but not wet	Yes
	Upper Huron Mbr	341HURNU	2488				
	Core 7	341HURNU	2530	Intact	No	slight odor, dark oily black as in core 8	Yes
	Middle Huron Mbr	341HURNM	2543				
	Core 6	341HURNM	2630	Broken	No	slight odor, waxy feel, but not wet	No
	Lower Huron Mbr	341HURNL	2726				
	Core 5	341HURNL	2730	Intact	No	dry, somewhat mottled	Yes
	Core 4	341HURNL	2760	Intact	No	dry, somewhat mottled	Yes
	Core 3	341HURNL	2780	Intact	No	dry, approx. 0.5cm pyrite clast, possible faint odor	Yes
	Core 2	341HURNL	2835	Broken	No	oily, strong odor	No
	Olentangy	341OLNG	2838				
	Core 1	341OLNG	2900	Broken	No	oily, strong odor	No

Core samples are identified by their respective measured depth from KB (i.e., Top value in **bold**)

Sidewall core number 3 (0.25-inch grid).. This sample included a pyrite clast but is otherwise typical of the intact cores as submitted for analysis.

Sidewall core number 2 (0.25-inch grid). This sample exhibits an oily sheen characteristic of cores collected that were saturated with light hydrocarbons. This core is typical of the broken samples.

Annotated section of the litho-density log for the CNR 24752 Elk Horn Coal well, Knott County.

CNR 24752 Composite log suite through the (Devonian) Lower Huron showing locations of recovered cores (red arrows, right track of Litho-Density log).