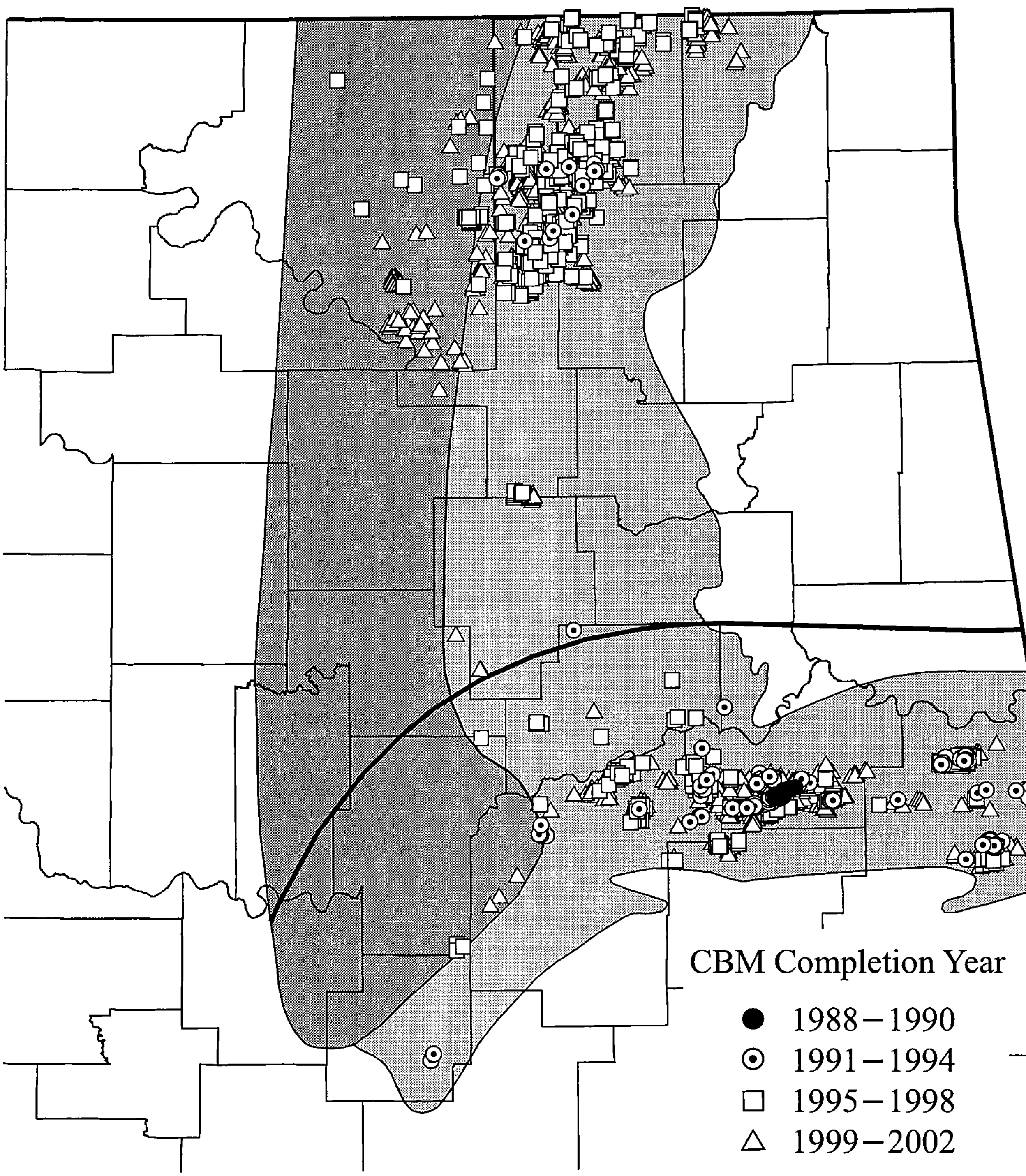
OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 9-2002

FOURTH ANNUAL OKLAHOMA COALBED-METHANE WORKSHOP



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FOURTH ANNUAL OKLAHOMA COALBED-METHANE WORKSHOP

Compiled by
Brian J. Cardott

Co-sponsored by
Oklahoma Geological Survey
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(South-Midcontinent Region)

Moore Norman Technology Center
Norman, Oklahoma
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Geologic factors controlling producibility of sorbed-gas reservoirs

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Levine, J.R., 2002, Geologic factors controlling producibility of sorbed-gas reservoirs, *in* Fourth annual Oklahoma coalbed-methane workshop: Oklahoma Geological Survey, Open-File Report 9-2002, p. 1-33.

Oklahoma Geological Survey and
Petroleum Technology Transfer Council

4th Annual Oklahoma Coalbed-Methane Workshop

October 10, 2002
Norman, Oklahoma

Geologic Factors Controlling Producibility of Sorbed-Gas Reservoirs

presented by:

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Main Points – 1 of 3

1) **Economic CBM production is influenced by *many* factors acting *in combination* with one another. No *single* factor will dictate success or failure.**

2) **Production trends in established U.S. basins indicate that overall, geology has a greater impact than engineering in contolling production rates.**

Main Points – 2 of 3

3)Coal composition has an important impact on many of the most significant characteristics of sorbed gas reservoirs, yet is usually inadequately characterized

4) Coal is comprised of a mixture of geochemical constituents, many of which are free molecules that are physically bonded to other coal constituents. Methane is one such constituent. Also included are other gases such as CO_2, and liquids such as water and oil.

Main Points 3 of 3

5) To properly understand the behavior of sorbed gas reservoirs, one must understand how coal evolves geochemically during its geologic history, and the nature of the intra- and intermolecular forces that bind coal together.

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"Sorbed Gas Reservoirs"

- Most of the producible gas in place exists in a "sorbed" state, in association with organic matter in the rocks
- Reservoir drainage depends (in <u>most</u> cases!) upon a network of interconnected fractures
- Drilling-Completion-Production technologies are similar

Sorbed Gas Reservoirs

Gas Shales		"Coalbed Methane"
• Devonian Antrim, Chattanooga etc. of Appalachian basin • Cretaceous Lewis, Pierre, etc. of Rocky Mountain region • Miss. Barnett of Ft. Worth Bas.		• Carboniferous Coals of Eastern & Mid-continent • Cretaceous Coals of Rocky Mt. Region • Tertiary of Powder River Basin
Typically 5-20%	←OM Content→	Typically 70-95%
May be Type I or III	←OM Composition→	Usually Type III & IV
Joints (~10 ~ 100 cm)	←Fracturing→	Cleat (~5 ~ 20 mm)

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Shales & Coals are Already Important Sources of Produced Gas in North America

- Together represent ~10% of U.S. production (CBM: 7%; Shale Gas: 3%)
- Shale gas is an active emerging play
- Gas from shales and gas from coal are typically co-mingled in "CBM" production. Shale component estimated at 30-40% for BWB & Drunkard's Wash CBM fields.

Geological Issues Bearing on the *Economic* Producibility of CBM Reservoirs Influenced by Coal Composition

Issues Bearing on the "Gas Resource Density":

- Gas Content
- Gas Capacity
- Reservoir Dimensions (Thickness & Lateral Extent)
- Reservoir Temperature
- Reservoir Pressure
- Gas Composition

Issues Bearing on the "Gas Deliverability":

- Cleat Permeability
  - fracture spacing
  - fracture openness
  - fracture mineralization
- Matrix Shrinkage Effect
- Relative Permeability
- Reservoir Pressure
- Reservoir Continuity
- Gas Diffusivity

Practical Applications of Coal Petrology to CBM Exploration & Production

- **Exploration** - Assist in determining *where* to look for good CBM prospects and *what* to look for
- **Drilling & Completion** - Helping to understand reservoir behavior during drilling and determine the best completion practices
- **In Production Analysis & Remediation** - Helping to understand well performance, diagnose problems & recommend appropriate solutions

"the power of science is to explain what we observe, and to predict what we have not yet observed"

Overview of Coal Composition & Coalification

Some Keys to Understanding Coal Composition

- The term "coal" refers to a diverse class of sedimentary rocks comprised mostly of the organic remains of once-living plants. Coals vary widely in their composition and characteristics.
- Coal represents a heterogeneous mixture of constituents. Compositional heterogeneity occurs at many different scales, ranging from centimeter-scale banding, visible to the unaided eye, down to molecular scale.
- Mineral matter is a natural constituent of all coals, the relative proportion of which is an important parameter of coal composition. The term "coal" refers to the whole rock, not solely to the organic fraction.
- The composition of coal undergoes a continual evolution throughout its history, in response changes in its chemical and biological environment, especially temperature and pressure. These changes continue up to present day.
- Petroleum substances (incl. oil and gas) are generated within coal during coal formation. These products are partly retained and partly expelled into surrounding strata. The retained portion becomes part of "molecular fraction" of coal.
- On a molecular scale, coal is a loose aggregation of molecules of varying size and complexity, bound together by several different types of forces, including: covalent bonds (strong), hydrogen bonds (weak), and van der Waals bonds (very weak).
- Coal has the bulk characteristics of a solid, but is actually comprised of a multiphase mixture of substances in a variety of physical states.

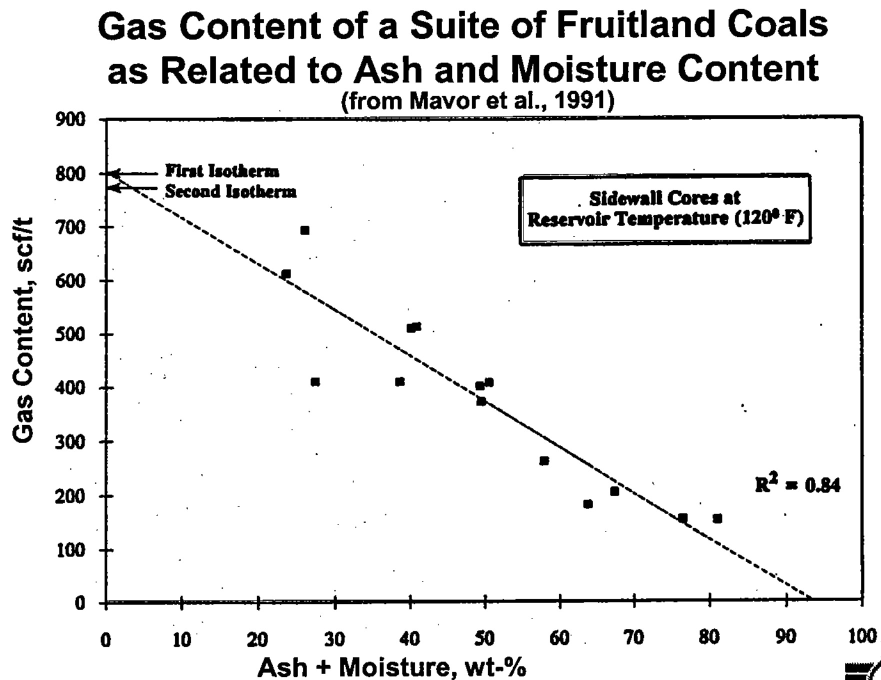
The Three Fundamental Variables of Coal Composition

- Grade
- Rank
- Type

Grade:
- represents the relative proportion of organic vs. inorganic constituents
- is the sole criterion by which coal is distinguished from all other rocks
- Other rocks may contain some organic matter or no organic matter, but "coal" is mostly organic matter

Shale	OM-Bearing Shale	OM-Rich Shale	Shaley or "Boney" Coal	Dirty or High Ash Coal	Coal	Clean Coal

T.O.C. (wt-%) ←→ Ash (wt-%)



Gas Resource Density Calculation

Gas Resource Density = Gas Content x Density x Thickness

Parameter	U.S. System	Metric System
Thickness	ft	cm_c
Density	tons/ac-ft	g_c/cm_c^3
Gas Content	ft^3/ton	cm_g^3/g_c

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Example Summation of G.R.D. Values

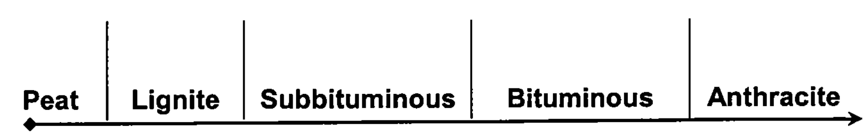
Rock Type	Thickness cm	Gas Content cm/g	Density g/cm³	GRD cm³/cm²	% of Tot.
Carb Shale	50	1.7	2.35	200	15
Coal	50	5.5	1.45	400	30
Shale	25	0.0	2.50	0	0
Shaley Coal	80	3.5	1.79	500	37
Rich Carb Shale	50	2.5	2.00	250	18

Total GRD = 1350 cm^3/cm^2
= 1.23 BCF/mi^2

The Three Fundamental Variables of Coal Composition

- Grade
- Rank
- Type

Rank:
- represents the level of organic metamorphism
- is the principal criterion by which different varieties of coal are distinguished



Parameters:
BTU Yield (wt-%)
Fixed Carbon (wt-%)
Ro,vit (%)

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ASTM Coal Rank Classification System
(ASTM D-388)

Class	Group	Ab-brevi-ation	Fixed Carbon limits		Volatile Matter Limits		Calorific Value Limits (moist, min. matter-free basis		Agglom-erating Char-acter
			wt-%, dry, mineral matter-free basis		wt-%, dry, mineral matter-free basis		Btu/lb, moist,[1] min. mat.-free basis		
			Greater than or equal to	Less than	Greater than	Less than or equal to	Greater than or equal to	Less than	
I. Anthracite	1. Meta-anthracite	ma	98			2			No
	2. Anthracite	an	92	98	2	8			No
	3. Semianthracite[2]	sa	86	92	8	14			No
II. Bituminous	1. Low volatile bituminous coal	lvb	78	86	14	22			Usually[4]
	2. Medium volatile bituminous coal	mvb	69	78	22	31			Usually[4]
	3. High volatile A bituminous coal	hvAb		69	31		14,000[3]		Usually[4]
	4. High volatile B bituminous coal	hvBb					13,000[3]	14,000	Usually[4]
	5. High volatile C bituminous coal	hvCb					11,500	13,000	Usually[4]
							10,500	11,500	YES
III. Subbituminous	1. Subbituminous A coal	subA					10,500	11,500	NO
	2. Subbituminous B coal	subB					9,500	10,500	No
	3. Subbituminous C coal	subC					8,300	9,500	No
IV. Lignite	1. Lignite A	ligA					6,300	8,300	No
	2. Lignite B	ligB						6,300	Non-

[1]Moist refers to coal containing its natural inherent moisture, but not including visible water on the surface of the coal.
[2]If agglomerating, classify in low volatile group of the bituminous class.
[3]Coals having 69% or more fixed carbon on the dry, mineral matter-free basis shall be classified according to fixed carbon, regardless of calorific value.
[4]It is recognized that there may be nonagglomerating varieties in these groups of the bituminous class.

The Three Fundamental Variables of Coal Composition

- Grade
- Rank
- Type

Type:
- represents the various kinds and categories of organic constituents
- provides a secondary criterion by which different varieties of coal are distinguished

Examples:

Humic Coal vs. Sapropelic Coal
Vitrinite-Rich vs. Liptinite Rich
"Oily" Coal

from Papp, A.R. et al., 1998, Atlas of Coal Geology, v. 2
Coal Petrology: AAPG Studies in Geology #45, CD-ROM

The Three Principal Maceral Groups

Coal Maceral Group	Kerogen Type	Microscopic Appearance (Low Rank, Refl. Light)	Characteristic Atomic Composition
Liptinite	Type I Type II	Dark Gray	Hydrogen-Rich
Vitrinite	Type III	Medium Gray	Oxygen-Rich
Inertinite	Type IV	Light Gray to White	Carbon-Rich

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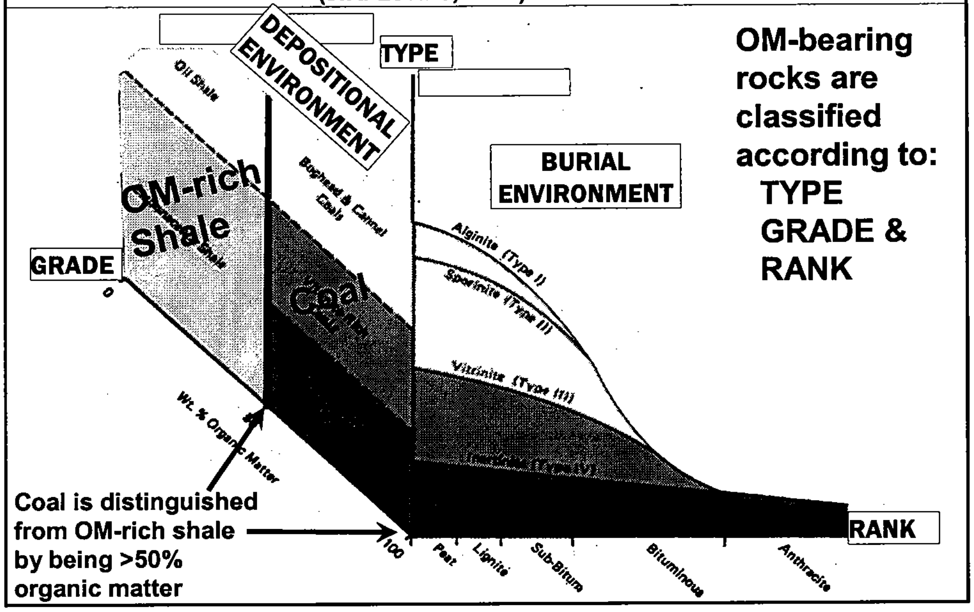
Diagram Depicting Classification of Organic Matter-Rich Rocks

(J.R. Levine, 1992)



Understanding the Chemical Composition and Molecular Structure of Sedimentary Organic Matter:

1. Atomic Composition
2. Chemical vs. Physical Bonds
3. Adsorption or Absorption?
4. Porosity vs. "Accessibility"
5. Energetics of Sorption
6. Dynamics of Sorption
7. Kinetics of Sorption

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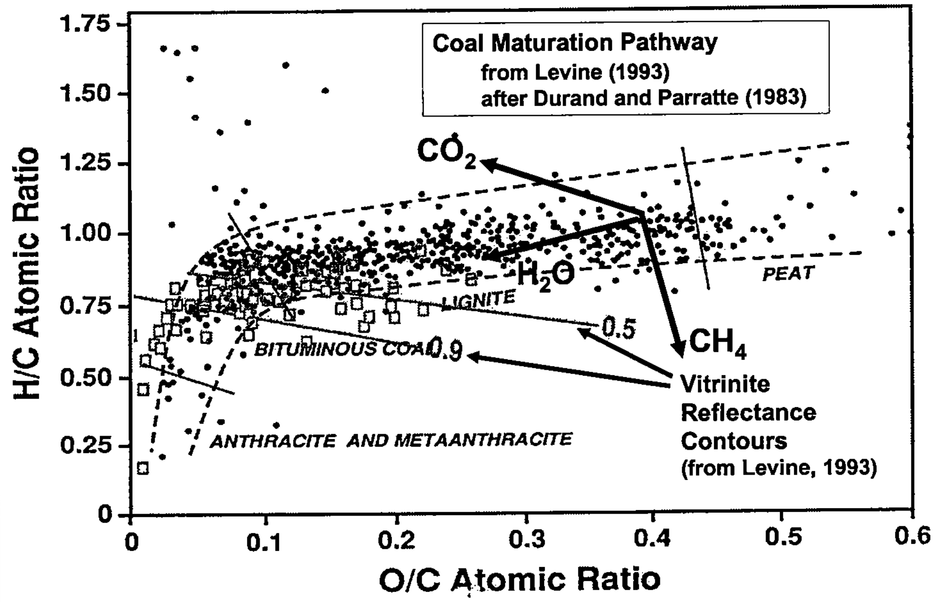
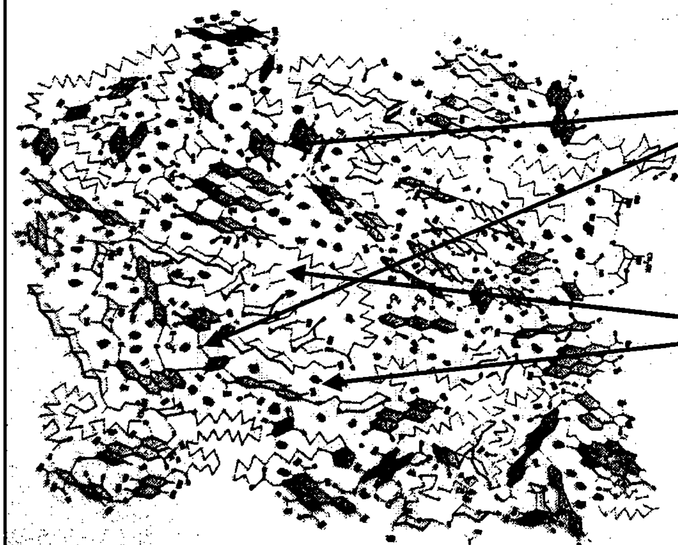


Molecular Bonding Mechanisms

Chemical Bonds (Electrons are shared)
- Covalent
- Ionic

Physical Bonds based on natural *or* induced electrical potential: (Electrons not shared)
- Coulombic forces ($\propto 1/r$)
  - "Hydrogen bonds"
- van der Waals ($\propto 1/r^6$)
  - Keesom interaction
  - Debye, induction interaction
  - London, dispersion interaction, etc?

Nanometer-scale Variability: Coal Molecular Composition

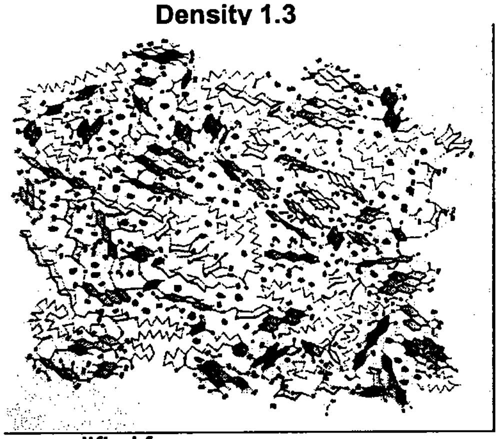


(modified from Behar and Vandenbroucke, 1987)

Comparison of Vitrinite and Graphite Density

Vitrinite or "Type III" Kerogen:

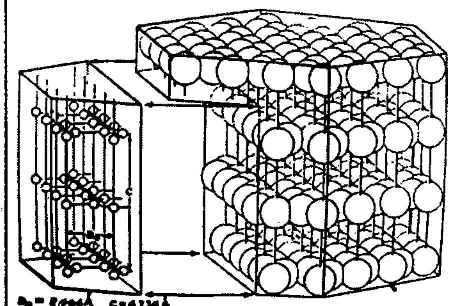
Density 1.3



modified from
Behar and Vandenbroucke, 1987

Graphite:

Density 2.3



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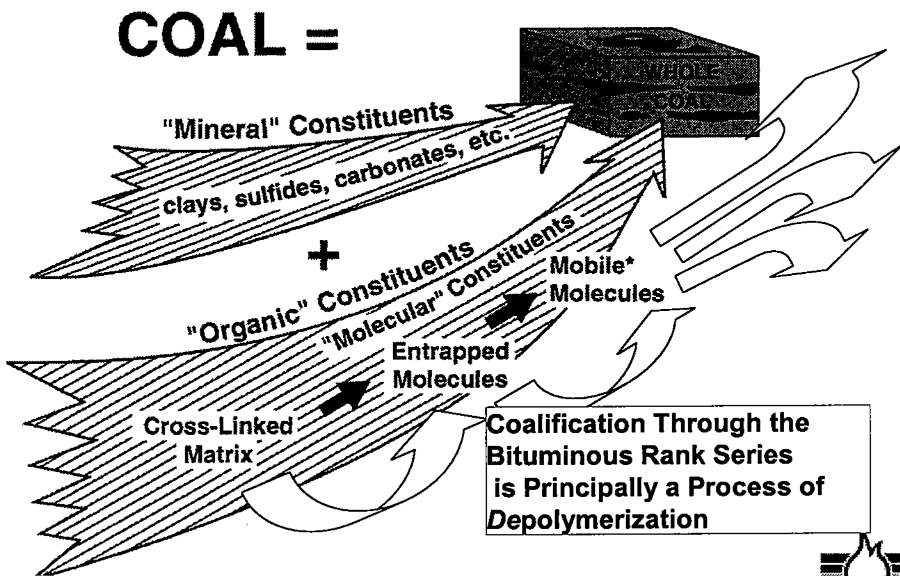
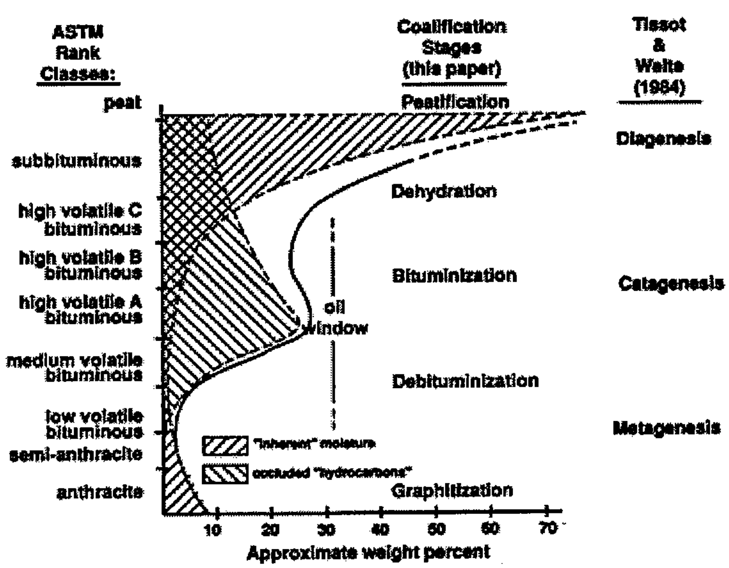
Coal is best understood not as a 'solid', but as a multiphase, multicomponent 'mixture'



Changing Composition of the "Molecular Fraction" of Coal during Coalification



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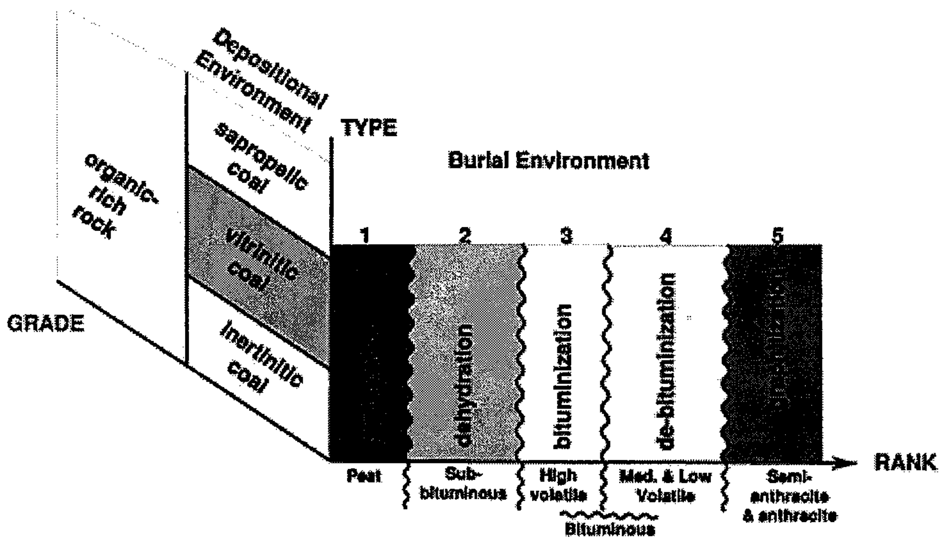
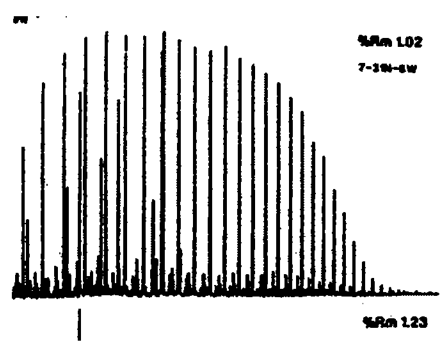
The 3-Axis Diagram of Coal Composition, Showing the Five Major Stages of Coalification



Coal Composition:
Is coal a "solid"?

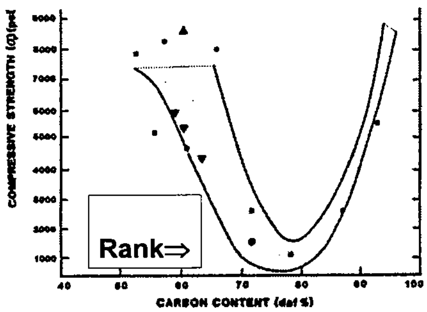
- Depends on "scale" of view
- Depends on word usage & meaning



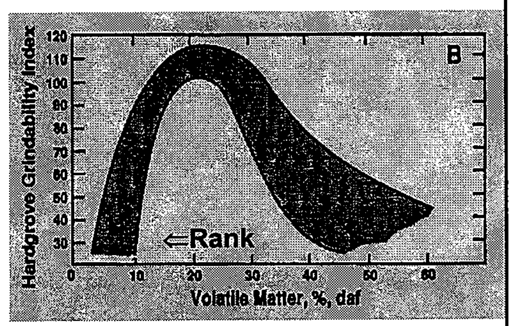
Evidence:

- Petrography (fluid macerals)
- Organic Geochemistry (esp. thermal & solvent extraction)
- Mechanical behavior/Rhealogy
  (vitrinite is a highly viscous fluid at some coal ranks)

Change in of mechanical strength of coal vs. rank

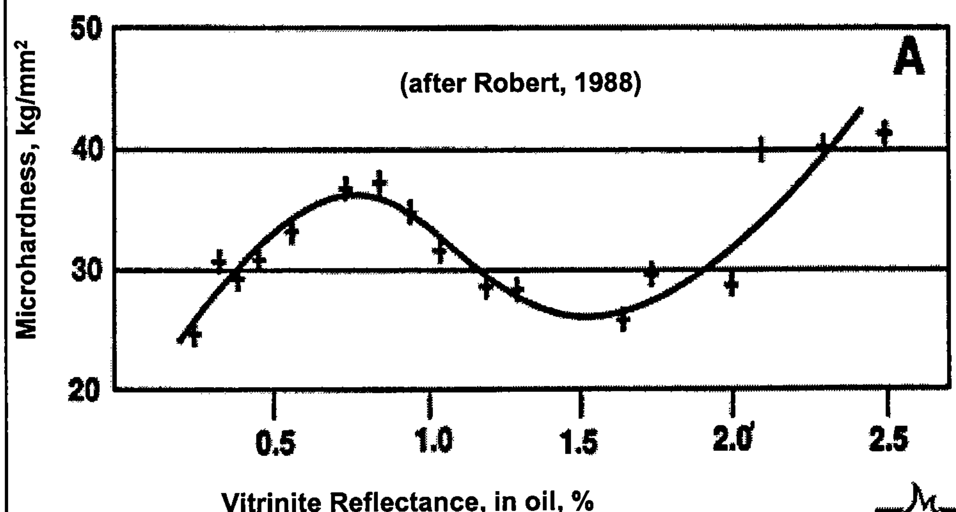


Unconfined compressive strength
vs. wt-% carbon
(mod. from Pomeroy & Foote, 1960)



Hardgrove Grindability Index
vs. wt-% volatile matter
(Berkowitz, 1979)

Microhardness increases, decreases, then increases again with rank, possibly related to bituminization, debitumini-zation, and graphitization of the molecular structure



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So What?

Mechanical strength influences coal's response to ambient stresses....

...which will impact the "style" of structural deformation (brittle vs. ductile)

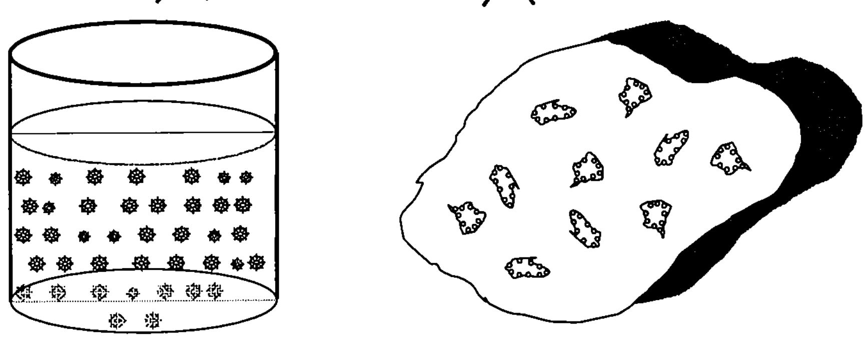
...and influences well bore stability

...and influences the openness of fractures

...and influences "matrix shrinkage effect"

Understanding the Nature of "Sorption": Sorption

1. ~~Ab~~sorption vs. ~~Ad~~sorption



Solution
Solvation

But... Which model is appropriate for sedimentary organic matter???

Answer: Both!... Together!!

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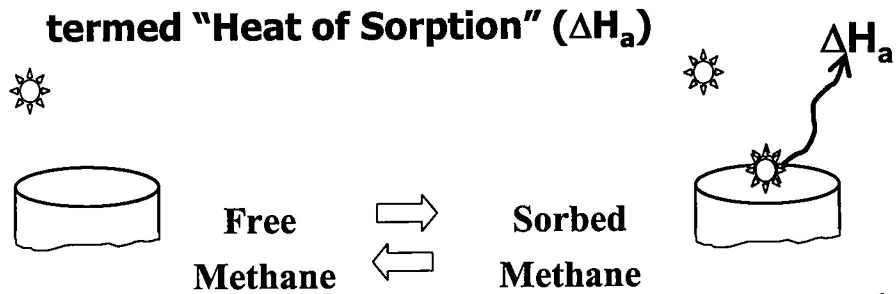
Internal Surface Area??!!

Coal does not have an "internal surface area" in the strict sense. Rather coal has a certain "accessibility" to sorbates, that is, in part, related to the open "cage-like" structure of some of it's molecular constituents. But a substantial proportion of coal does not have a fixed structure, but rather is a liquid. Accessibility to these regions of the coal structure is via solvation.

Energetics of Sorption: 3.b. Heats of Sorption

Just as in the transition from gas to liquid, or liquid to solid, sorption is, in general, an exothermic process, and provides evidence of the strength of the interaction between sorbant and sorbate. The heat liberated is termed "Heat of Sorption" (ΔH_a)



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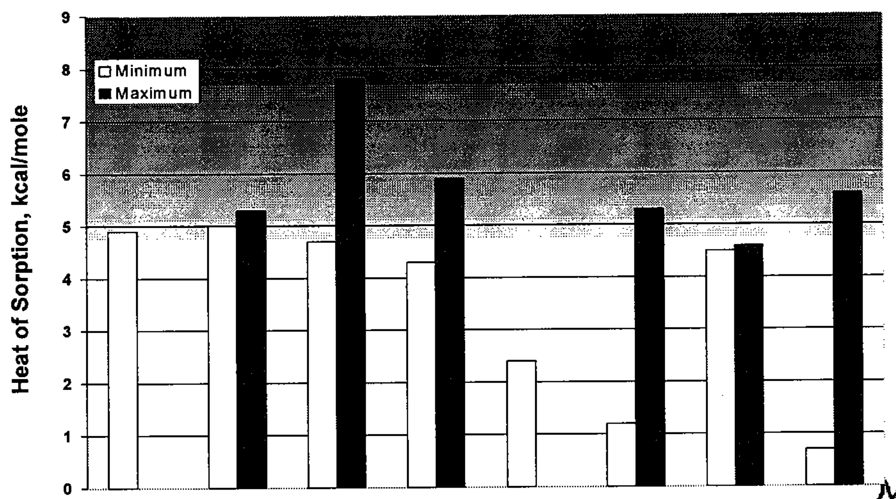
Isothermal or Isosteric Heats of Sorption of Methane with Coal

(data from various authors compiled by Yee, Amoco Production Company, 1993)



Le Chatelier's Principle is Applicable to Methane Sorption in Coal

Free Methane ⇔ **Sorbed Methane**

In chemistry we are dealing with reactions, and at equilibrium, the forward and reverse reaction rates are equal.

"Any change in one of the variables that determines the state of a system in equilibrium causes a shift in the position of equilibrium in a direction that tends to counteract the change in the variable under consideration."

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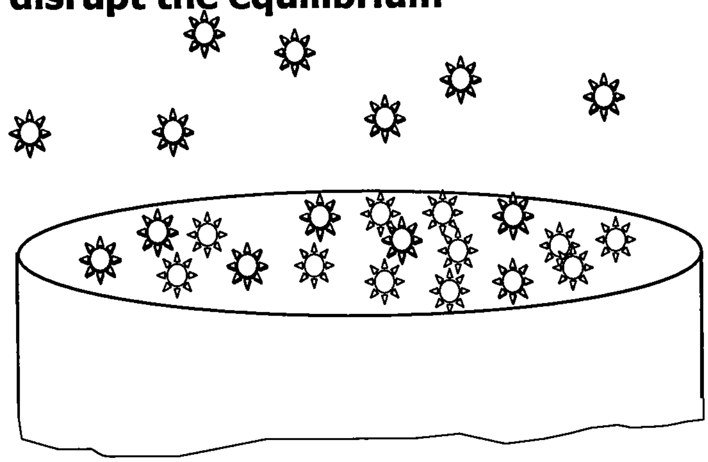
Understanding the Nature of Sorption:

Sorbates exist in dynamic equilibrium

Changes in pressure temporarily disrupt the equilibrium



Understanding the Nature of Sorption: "Sorption Time"

(de Boer, J.H., 1953)

$$\tau = \tau_0 e^{Q/RT}$$

τ - average residence time on surface

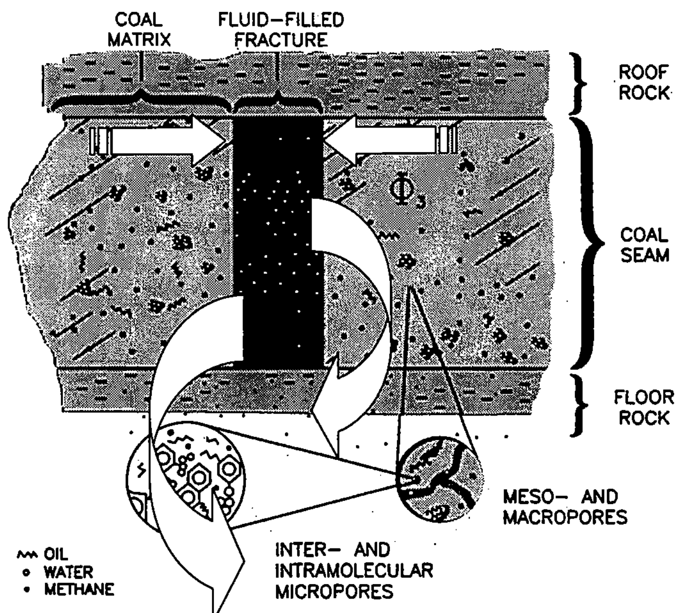
τ_0- vibration period of molecule (generally 10^{-12} to 10^{-13} sec)

Q- Heat or enthalpy of sorption

"Sorption Time"
(Adamson & Gast, 1997)

Q	τ @ 25°C	Comments
kcal/mol	sec	
0.1	10^{-13}	Adsorption nil; specular reflection
1.5	10^{-12}	Region of physical adsorption
3.5	$4x10^{-11}$	
9.0	$4x10^{-7}$	
20.0	100	Region of chemisorption
40.0	10^{17}	

Representation of Production of Water and Gas from Coal Bed Reservoirs



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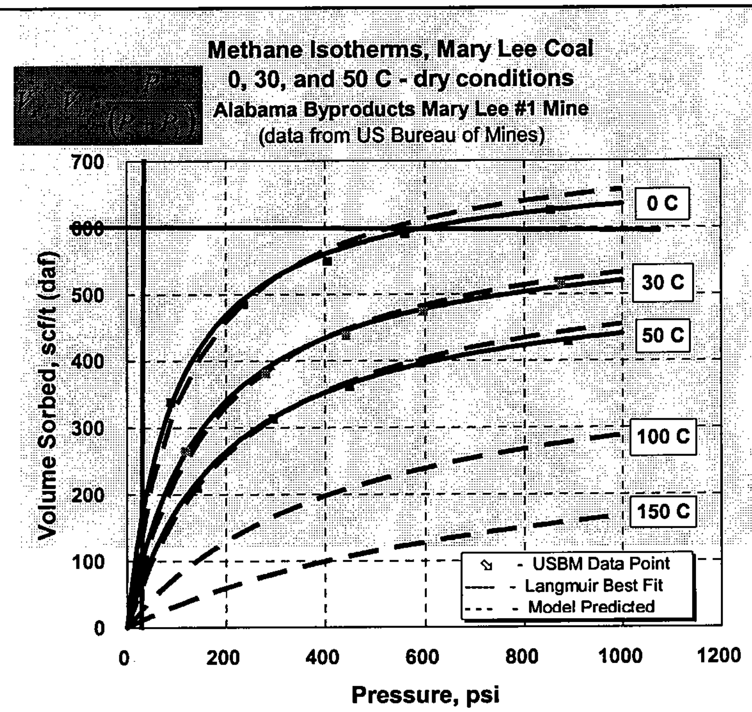
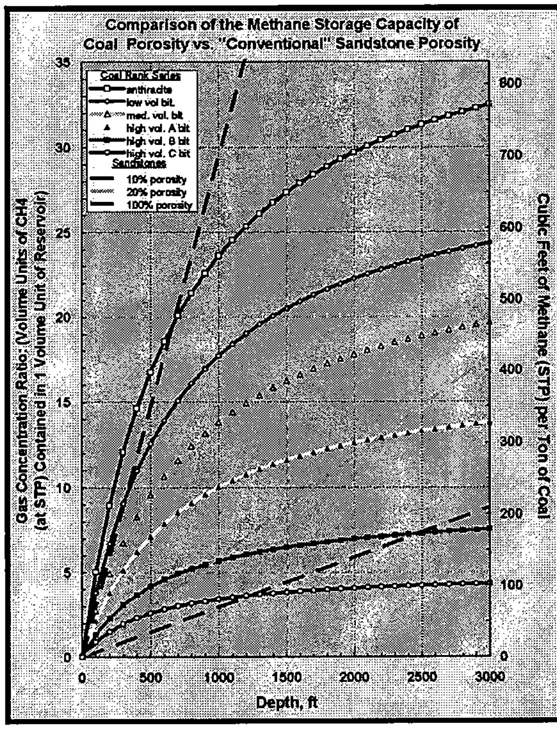
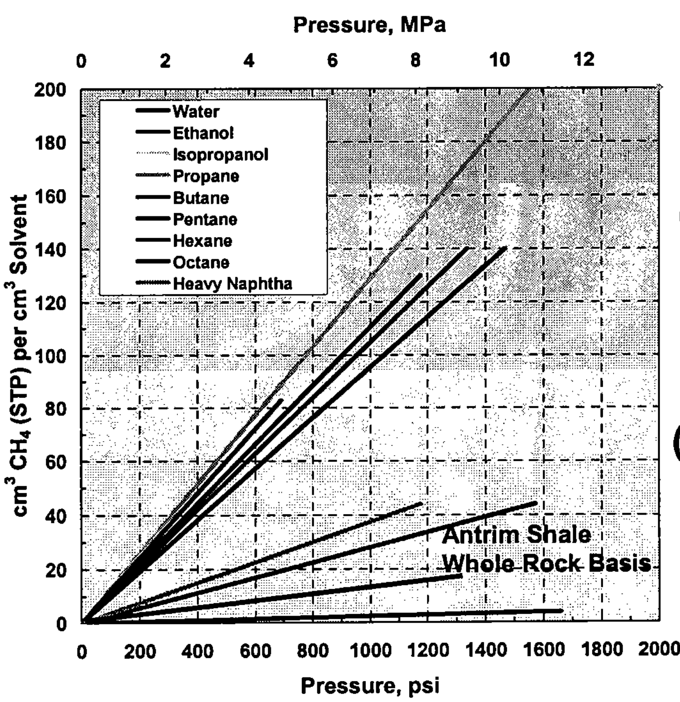


Heat of Vaporization
Boiling Points @ P_i=1 atm
Solubility in Water @ P_i=1 atm & 298°K
for Various Gases

Gas		Heat of Vaporization kcal/mole	(Boiling Point) T°K	Solubility Mole Fraction
Helium	He		4.4	0.70×10^{-5}
Nitrogen	N_2	1.33	77.2	1.18×10^{-5}
Argon	Ar	1.54	87.4	2.52×10^{-5}
Methane	CH_4	1.95	111.5	2.55×10^{-5}
Ethane	C_2H_6		184.4	3.401×10^{-5}
Carbon Dioxide	CO_2	6.02	194.8	61.50×10^{-5}
Water	H_2O	9.70	373.0	



Changing Methane Sorption Capacity of Coal as a Function of Coal Rank



Measured Solubility of CH_4 in Various Solvents vs. Pressure

(after Frolich et al., 1931)

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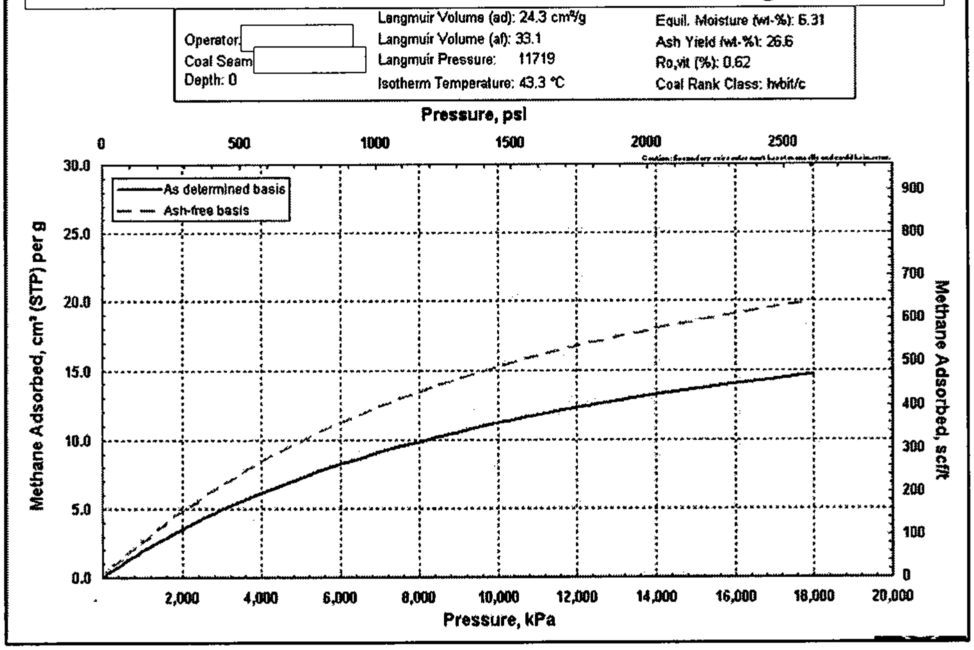
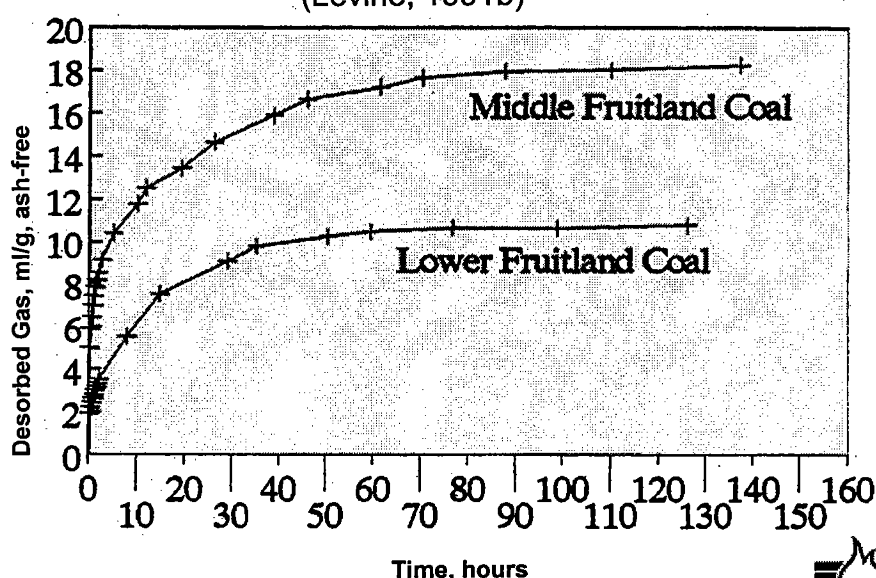
Methane Sorption Isotherm of an Apparently Oily Cretaceous Coal from Canada Plains Region



Two different Fruitland coal horizons from the same well showed markedly different gas contents & diffusion rates (Levine, 1991b)



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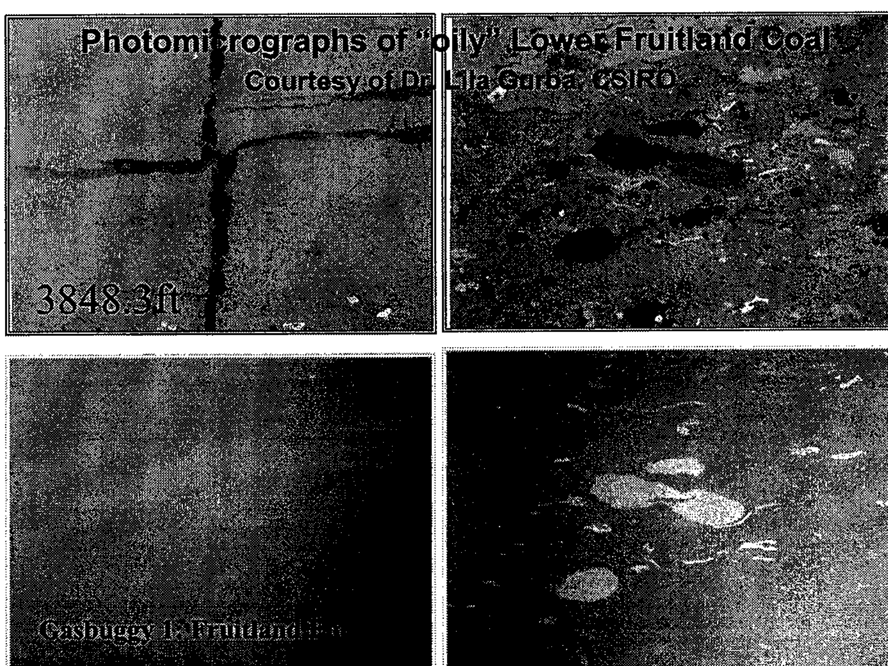
Selected Compositional Variables and Reservoir Characteristics of Fruitland Coals from the 13-CX and SUIT 15-4 (B/EA) Wells, Northwestern San Juan Basin, Colorado.(Levine, 1991b)

Parameter Description:	Data:			
Core hole name:	13-CX		15-4	
Fruitland seam	Upper	Lower	Middle	[illegible]
Sample ID #	1053	1054	1060	[illegible]
Depth to top (ft)	236	341	2989	[illegible]
$R_{o,vit}$, %	0.68	0.70	0.94	[illegible]
Fix.Carb., wt-%, daf	57.1	58.1	67.4	[illegible]
"Relative Oilyness"	Less oily	More oily	Less oily	[illegible]
Rock-Eval S_1, mg/g*	6.1	20.2	10.7	[illegible]
CH_2Cl_2 Extract, ppm*	16,431	19,545	17,126	[illegible]
Hydrocarbons, ppm*	8,872	11,003	7,523	[illegible]
Equil. Moisture, wt-%*	4.37	3.17	2.16	[illegible]
CO_2 Surface area, m^2/g*	70.6	42.5	136.5	[illegible]
N_2 Surface area m^2/g*	3.05	0.85	0.28	[illegible]
Desorbed Gas ml/g	n.d.	n.d.	21.5	[illegible]
CH_4 capacity at 2000 psia, 30°C, (from isotherm), scf/t*	542	n.d.	725	[illegible]



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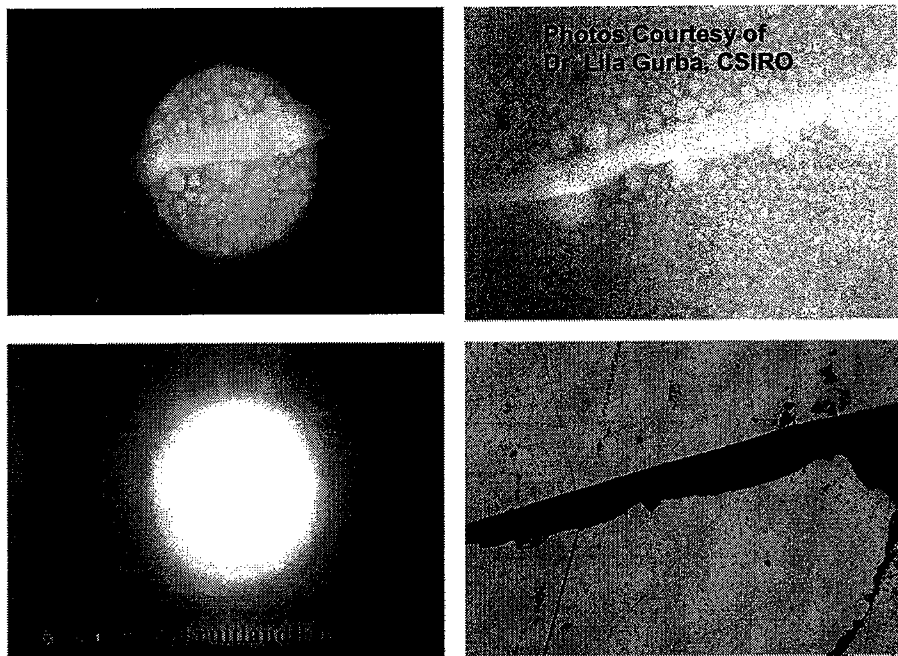
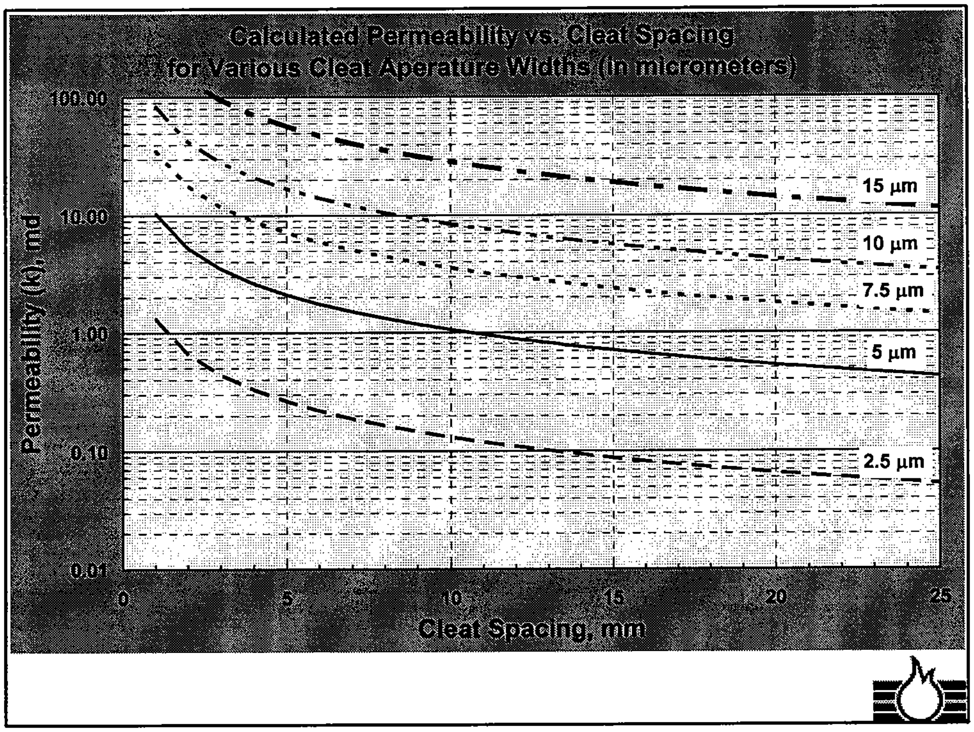
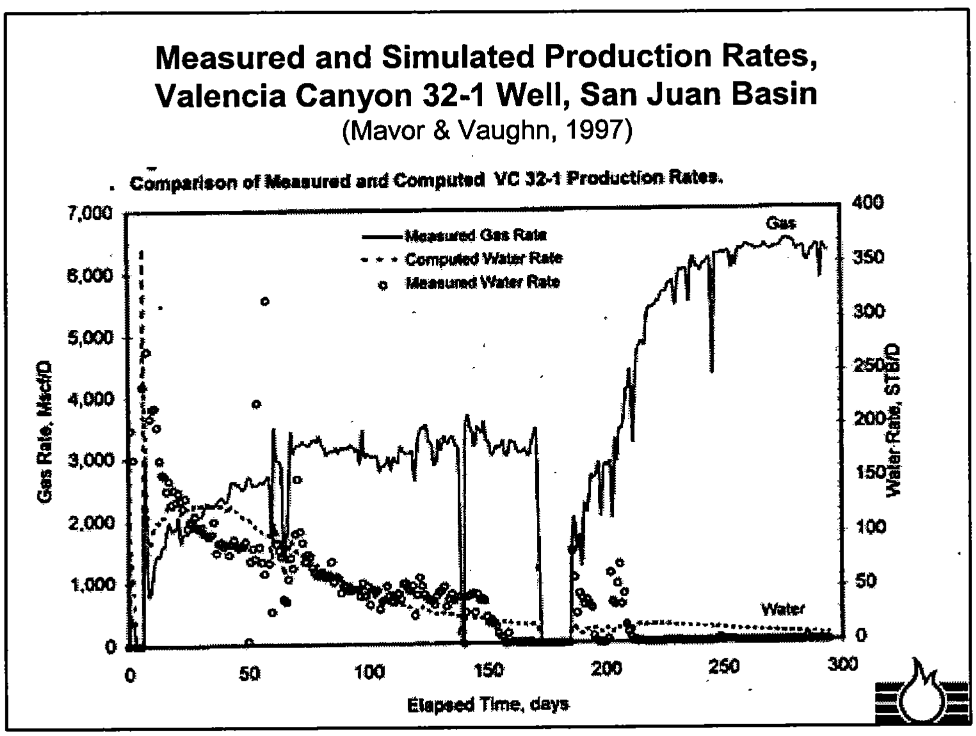


Matrix Shrinkage Effect





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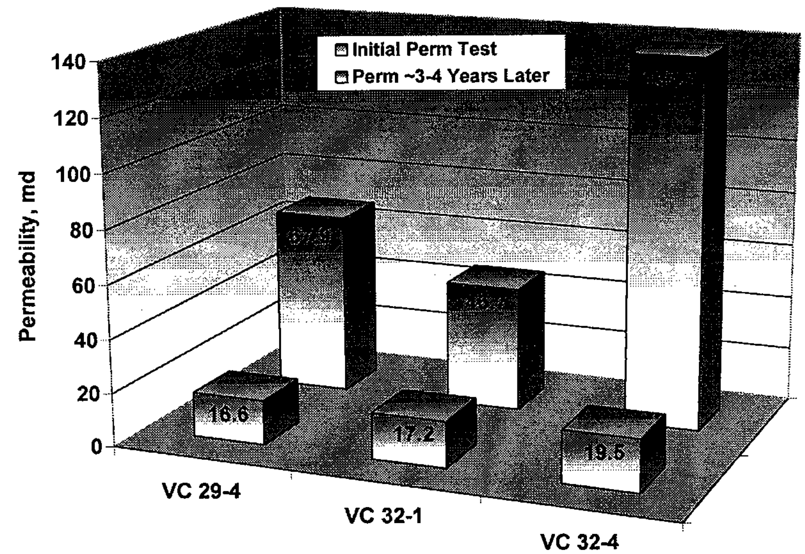
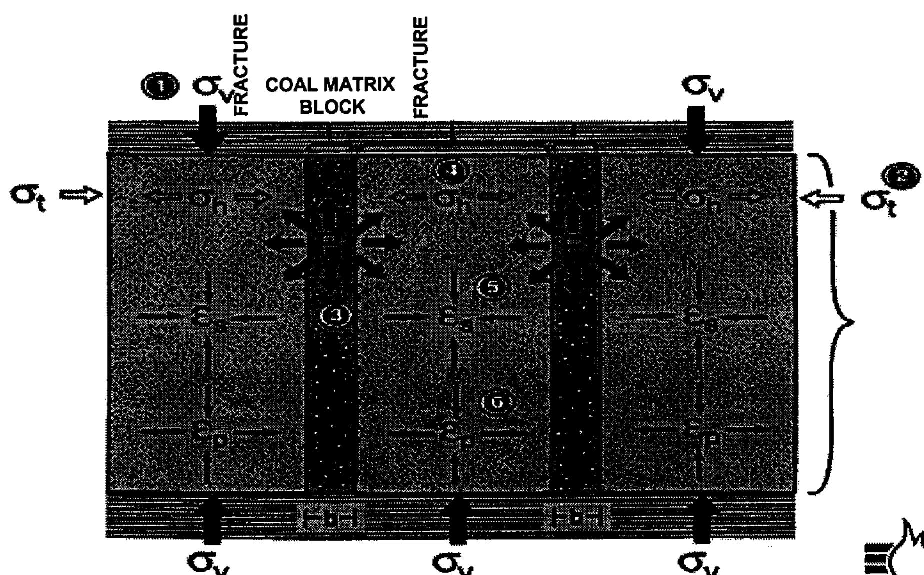
Change in Absolute Permeability with Time for 3 Example CBM Wells in the San Juan Basin

(data from Mavor, 1998)



Rock Mechanics Model of the Effect of Matrix Shrinkage on Permeability (Levine, 1996)



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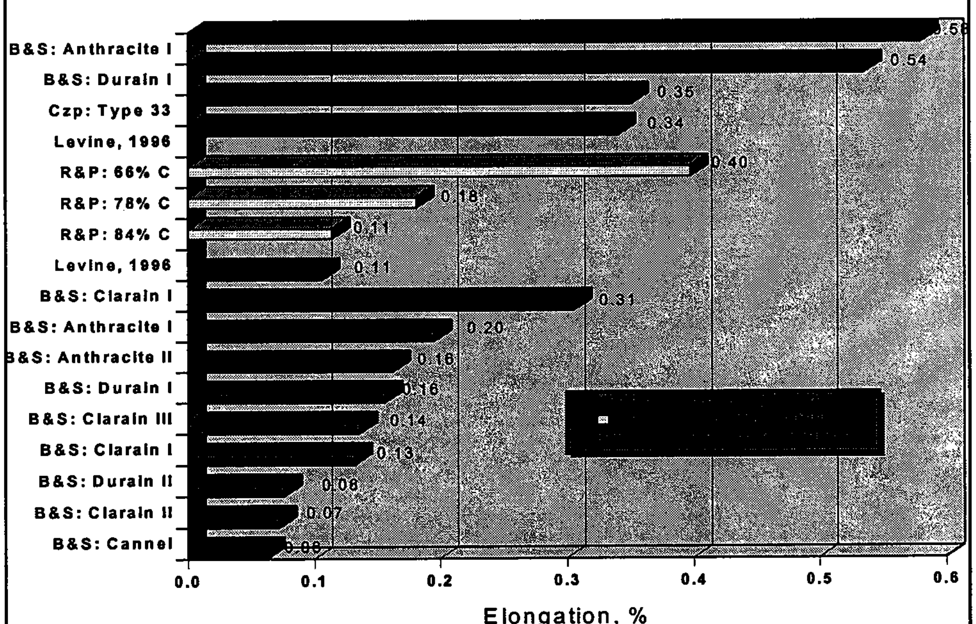
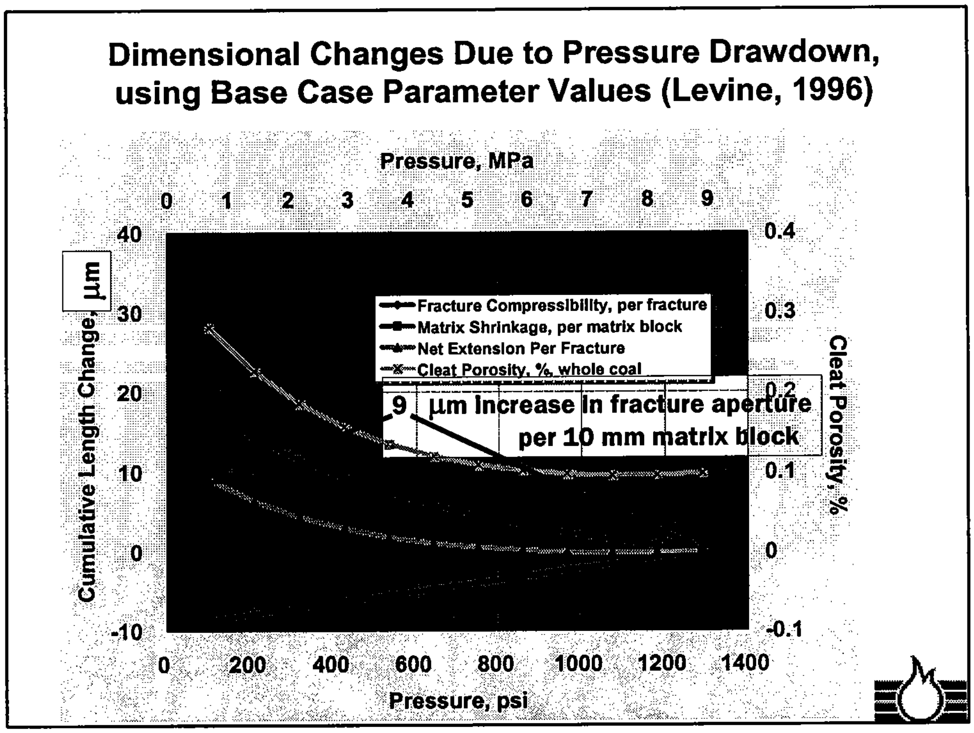
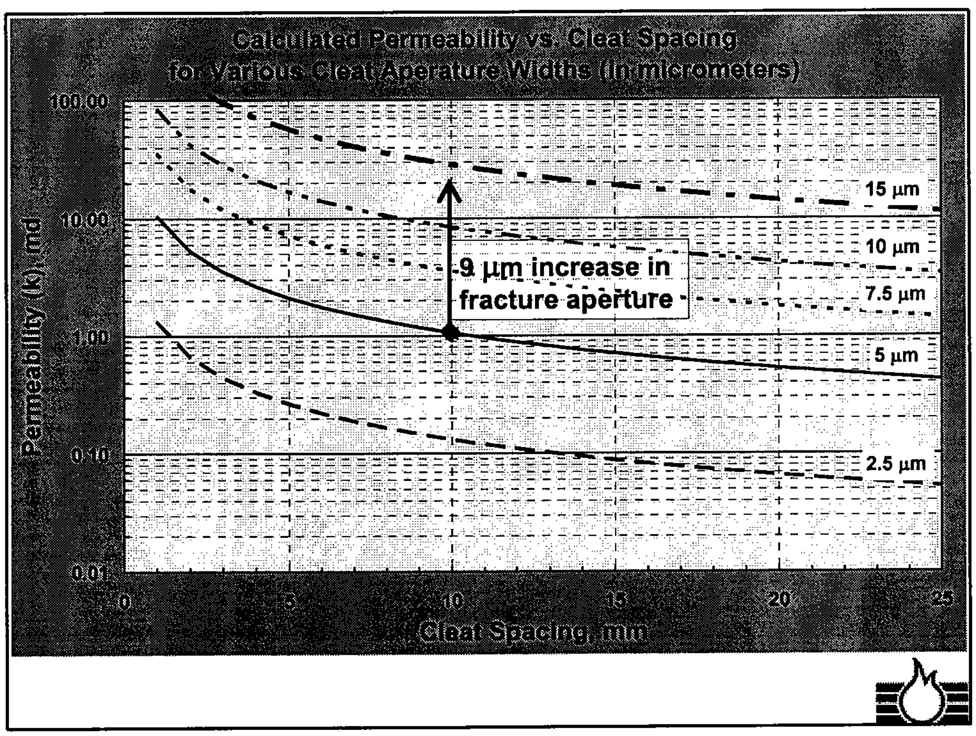
Values Selected for Matrix Shrinkage
Parameter Sensitivity Study (Levine, 1996)

Parameter	Symbol	Lower Case	Base Case	Upper Case
Cleat Spacing	s	5 mm	10 mm	20 mm
Initial Permeability	k	0.1 md	1 md	10 md
Young's Modulus	E	300,000 psi^{-1}	493,000 psi^{-1}	725,000 psi^{-1}
Poisson's Ratio	ν	0.22	0.32	0.42
Shrinkage Coefficient: ε_{max}	ε_{max}	1995 microstrains	3414 microstrains	6647 microstrains
Shrinkage Coefficient: P_{50}	P_{50}	212 psi	697 psi	1407 psi

Matrix Elongation of Coal with Gas Sorption
(data from various sources: Levine, 1996)







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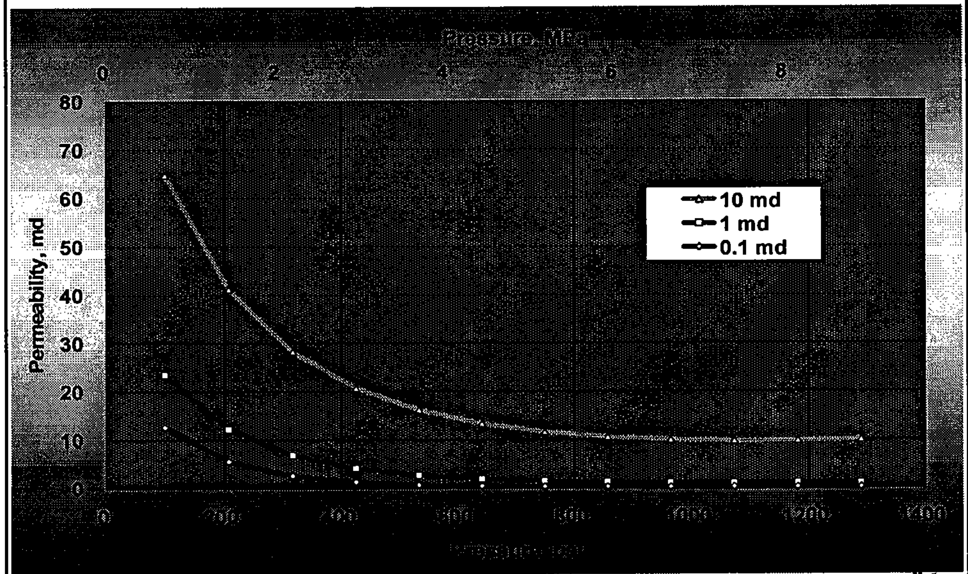
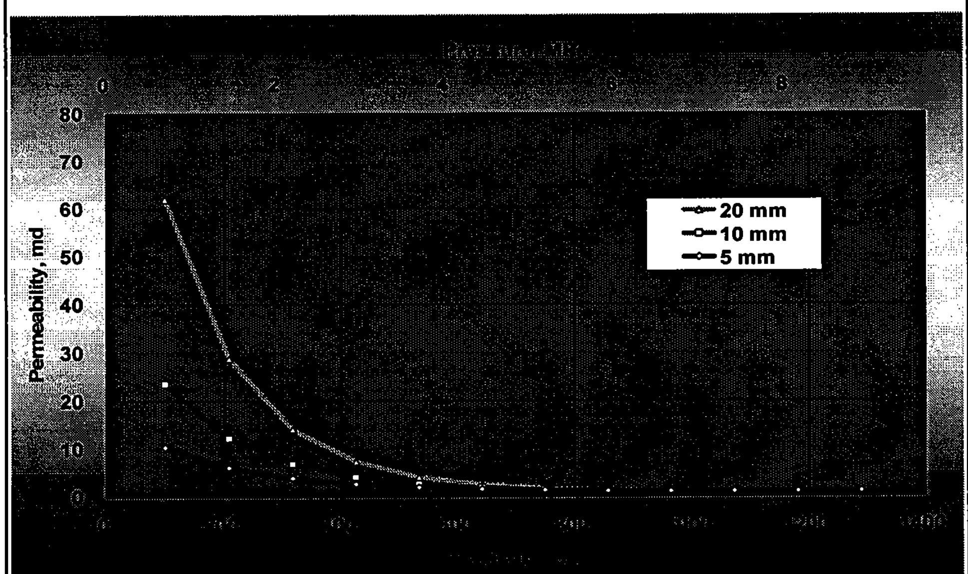
Sensitivity to Variation in Initial Permeability (Levine, 1996)



Sensitivity to Variation in Cleat Spacing (Levine, 1996)



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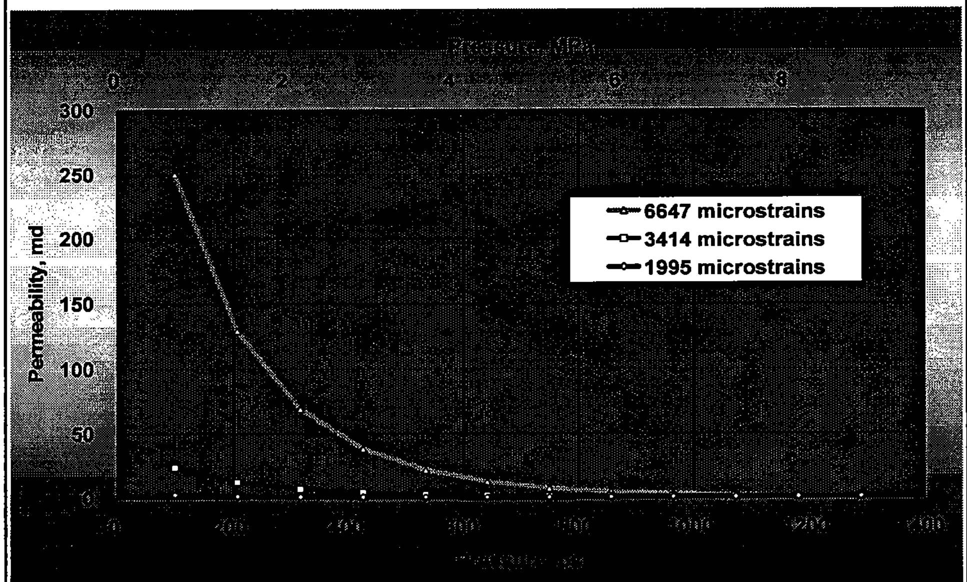
Sensitivity to Variation in Shrinkage Coefficient ε_{max} (Levine, 1996)



May You Degas Successfully!

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2

Introduction to coal geology of Oklahoma

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Introduction to Coal Geology of Oklahoma

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INTRODUCTION

The Oklahoma coalfield is in the eastern part of the State and occupies the southern part of the Western Region of the Interior Coal Province of the United States (Campbell, 1917; Friedman, 2002). The coal region continues northward into Kansas and eastward into Arkansas (Tully, 1996). The Oklahoma coalfield is bounded on the northeast, south, and southwest by the Ozark, Ouachita Mountain, and Arbuckle Mountain Uplifts, respectively, and on the west by noncommercial coal-bearing strata of Missourian to Wolfcampian age (**Figure 1**). Some noncommercial Pennsylvanian-age coal resources occur in the Anadarko Basin (Wood and Bour, 1988) and Ardmore Basin (Trumbull, 1957; Tomlinson, 1959), but these are not part of the Oklahoma coalfield.

Friedman (1974) divided the Oklahoma coalfield into the northeast Oklahoma shelf and the Arkoma Basin based on physiographic and structural differences (**Figure 2**). The commercial coal belt contains coal beds ≥ 10 in. (25 cm) thick that are mineable by surface methods at depths < 100 ft (30 m) and coal beds ≥ 14 in. (36 cm) thick that are mineable by underground methods (Hemish, 1986). The noncommercial coal-bearing region has limited information on coal thickness and quality or contains coals that are too thin, of low quality, or too deep for surface mining. The western boundary of the noncommercial coal-bearing region is uncertain. Coalbed methane (CBM) production has been developed in both the commercial coal belt and the noncommercial coal-bearing region.

Figure 3 shows coal outcrop and potentially strippable areas in the Oklahoma coalfield (Friedman, 1982b). Coal beds in the northeast Oklahoma shelf strike northeast in outcrop and dip as much as 2° westward and northwestward from the outcrop to depths > 2,500 ft (760 m; **Figure 4**). Coal beds in the Arkoma Basin are present at the surface and to depths > 6,000 ft (1,830 m)(Iannacchione and Puglio, 1979a); they are faulted and folded into narrow, northeastward-trending anticlines and broad synclines (Figure 4). Coal beds in the Arkoma Basin dip from 3° to nearly vertical (Friedman, 1982b, 2002). Major deformation of the Oklahoma coalfield occurred during the peak of the Ouachita orogeny (Middle to Late Pennsylvanian)(McBee, 1995).

COAL STRATIGRAPHY

The age of commercial coal-bearing strata in the Oklahoma coalfield is Desmoinesian (Middle Pennsylvanian). Thin, noncommercial coal beds occur in Morrowan, Atokan, Missourian, Virgilian, and Wolfcampian strata (Cardott, 1989). **Figures 5 and 6** are generalized stratigraphic columns of the northeast Oklahoma shelf and Arkoma Basin, showing about 40 named and several unnamed coal beds and their range in thickness measured from outcrops, mines, and shallow core samples. Coal beds are 0.1 to 6.2 ft (0.03 to 1.9 m) thick in the shelf and 0.1 to 7.0 ft (0.03 to 2.1 m) thick in the basin. The thickest known occurrence of coal in the Oklahoma coalfield is an exposure of the Hartshorne coal (10 ft) in Latimer County (sec. 35, T. 6 N., R. 18 E.; Wilson, 1970; Hemish, 1999). The thickest known occurrence of coal in the shelf is the Weir-Pittsburg coal (6.2 ft) in a coal-company drill hole at a depth of 408 ft (124 m) in Craig County (sec. 28, T. 29 N., R. 18 E.; Hemish, 1986, Plate 4; Hemish, 2002).

Hemish (2001, p. 78) described the following differences in the coal-bearing strata between the Arkoma Basin and the northeast Oklahoma shelf: "1) Coal-bearing rocks present above the Senora Formation in the shelf area are absent in the Arkoma Basin; 2) Stratigraphic units are generally much thicker in the Arkoma Basin; 3) Commercial coal beds in the northern shelf area pinch out to the south and are absent in the basin; conversely, certain well-developed commercial coals in the Arkoma Basin, such as the Hartshorne coal, pinch out to the north, or have no commercial value in the shelf area, owing to thinness; 4) Quality of the same coal in the two regions often varies because of different depositional environments. Additionally, strata in the Arkoma Basin are much more deformed than they are in the shelf area. Beds have been folded into broad, northeast-trending synclines and narrow anticlines, resulting in steep dips of the beds in some areas. Faulting is also common throughout the Arkoma Basin."

In ascending order, the coal beds yielding commercial methane in the northeast Oklahoma shelf include the Riverton and McAlester (McAlester Formation), Rowe and Drywood (Savanna Formation) and Bluejacket and Wainwright (Boggy Formation) in the Krebs Group; Weir-Pittsburg, Tebo, Croweburg, Bevier, Iron Post, and Mulky (Senora Formation) in the Cabaniss Group; and Dawson (Holdenville Formation) in the Marmaton Group of Desmoinesian age. Hemish (2002) correlated coals from the surface to subsurface in a 2,700-mi^2 area in the northeast Oklahoma shelf to assist operators in correctly identifying methane-producing coal beds. Two type logs were designated in the northern and southern parts of the study area. The northern type log is in **Figure 7.** Persistent marker beds are identified to correlate the coal beds.

The nomenclature of Oklahoma and Kansas coal-bearing strata and coal beds differ slightly. The Kansas Geological Survey includes the Krebs and Cabaniss Formations in the Cherokee Group (Brady, 1997), whereas the Oklahoma Geological Survey assigns the Krebs and Cabaniss to group level in the Desmoinesian Series. The Rowe coal of Kansas and Missouri is equivalent to the Keota coal of Oklahoma, whereas the Drywood coal of Missouri and Dry Wood coal of Kansas are equivalent to the Spaniard coal of Oklahoma (Hemish, 1990b).

The Mulky coal is one of the most important CBM reservoirs in the northeast Oklahoma shelf (Cardott, 2002b). The Mulky, the uppermost coal in the Senora Formation, occurs at the base of the Excello Shale Member and varies in composition from pure to impure coal with increasing amounts of mineral matter. (As defined by Schopf (1956), carbonaceous shale contains >50% mineral matter by weight or <30% carbonaceous matter by volume. According to the ASTM (1994), impure coal contains 25 to 50 weight % mineral matter as ash.) Hemish (1986, p. 18) recognized the Mulky coal in three drill holes in northern Craig County, where its maximum thickness is 10 in. Hemish (2002, p. 3) indicated that "The occurrence of the Mulky coal downdip to the west in Nowata, Washington, and Osage Counties has not been verified by the OGS from coring. It seems probable that the methane is being produced from the Excello black shale."

In ascending order, the methane-producing coal beds in the Arkoma Basin are the Hartshorne (undivided), Lower Hartshorne, and Upper Hartshorne (Hartshorne Formation), McAlester and "Savanna" (interpreted to be the McAlester coal, McAlester Formation; a CBM completion in Coal County reported to be in the "Lehigh" coal is equivalent to the McAlester coal), Secor (Boggy Formation), and unnamed coal in the Krebs Group of Desmoinesian age. The McAlester coal and Stigler coal are correlative (Friedman, 1974, p. 29).

The Hartshorne coals are the most important CBM reservoirs in the Arkoma Basin (Cardott, 2002b). The Hartshorne coal contains a thin claystone parting and splits into two beds (Upper and Lower Hartshorne coals) where the parting is thicker than 1 ft (Friedman, 1982a). The coal is a single bed north and west of the coal split line (**Figure 8**). South and east of the line, two beds are identifiable. The interval between the upper and lower coal beds increases southeastward to a maximum of 120 ft (37 m)(Friedman, 1978, p. 48; Iannacchione and Puglio, 1979a, p. 5). The top of the Hartshorne coal or Upper Hartshorne coal, where present, marks the top of the Hartshorne Formation in Oklahoma. The nomenclature of Oklahoma and Arkansas coal beds differ slightly. The Arkansas Geological Commission includes the Upper and Lower Hartshorne coals in the McAlester Formation (Prior and White, 2001), whereas the Oklahoma Geological Survey includes the Hartshorne coals in the Hartshorne Formation (Hemish and Suneson, 1997). The Paris and Charleston coals (Savanna Formation; Prior and White, 2001) of Arkansas are not present in Oklahoma.

COAL RESOURCES, RESERVES, AND PRODUCTION

Remaining identified bituminous coal resources (using measured, indicated, and inferred resource categories of reliability) in beds ≥ 10 in. (25 cm) thick total 8.09 billion short tons in 19 counties in eastern Oklahoma, an area of approximately 8,000 mi^2. Approximately 76% of these resources are in the Arkoma Basin and 24% are in the northeast Oklahoma shelf (Friedman, 2002).

Identified coal resources were determined by S.A. Friedman and L.A. Hemish of the Oklahoma Geological Survey. Friedman (1982b) showed the distribution of strippable coal resources to depths of 100 ft (30 m) or 150 ft (46 m), and areas where coal has been mined by surface methods. Friedman (1974) summarized the coal resources and reserves in 7 counties (Atoka, Coal, Haskell, Latimer, Le Flore, Pittsburg, and Sequoyah) in the Arkoma Basin. County coal reports with updated estimates of strippable coal resources and reserves in the northeast Oklahoma shelf are available for the following 12 counties: Craig and Nowata (Hemish, 1986), Rogers and Mayes (Hemish, 1989), Tulsa, Wagoner, Creek, and Washington (Hemish, 1990a), Okmulgee and Okfuskee (Hemish, 1994), Muskogee (Hemish, 1998a), and McIntosh (Hemish, 1998b).

The demonstrated reserve base (economically recoverable portion of identified coal resource from measured and indicated resource categories for beds ≥ 28 in. (71 cm) thick at depths to 1,000 ft) for Oklahoma is 1.57 billion short tons of coal (Energy Information Administration, 2002, table 33). Oklahoma ranks 19th of 32 coal-bearing states in the U.S. demonstrated reserve base.

From 1873–2001, 281.3 million short tons of coal were produced in Oklahoma (Federal and State data). Peak annual coal production was 5.73 million short tons in 1981, with smaller production peaks during and immediately following World War I and World War II (**Figure 9**). Coal was mined in Oklahoma exclusively by underground methods until 1915. The predominant mining method shifted from underground to surface in 1943. Oklahoma produced 1.59 million short tons of coal from 11 mines in 2000 (Oklahoma Department of Mines, 2001). Oklahoma imported 18.0 million short tons of low-sulfur, subbituminous coal from Wyoming in 2000 for electricity generation at five Oklahoma public-utility power plants (Energy Information Administration, 2002, tables 64, 65).

Abandoned underground coal mines are areas where coal has been removed by room-and-pillar type mining in Oklahoma. Coal mine methane migrates to mine workings and is vented to the atmosphere during mining (Diamond, 1994; Brunner, 2000). Mine and gob gas (in caved zone of mine) may be present in abandoned underground mines. Maps showing the location of abandoned underground coal mines in Oklahoma are in Hendricks (1937, 1939), Knechtel (1937, 1949), Dane and others (1938), Oakes and Knechtel (1948), Hemish (1990a), and Friedman (1978, 1979, 1994, 1996).

COAL STRUCTURE AND THICKNESS

Maps showing structure, overburden (to depths >100 ft (30 m)), coal isopach, and mined areas in the northeast Oklahoma shelf are in Hemish (1986, 1989, 1990a, 1994, 1998a, 1998b). **Figure 10** shows the regional structure on the top of the Hartshorne Formation. Additional structure and/or overburden maps of the Hartshorne Formation are in Dane and others (1938), Hendricks (1939), Oakes and Knechtel (1948), Knechtel (1949), Catalano (1978), Agbe-Davies (1978), Craney (1978), Donica (1978), Williams (1978), Iannacchione and Puglio (1979a, 1979b), Iannacchione and others (1983), and Gossling (1994). A structure map on the McAlester coal is in Knechtel (1937).

Hartshorne coal isopach maps of limited coverage are in Catalano (1978), Agbe-Davies (1978), Craney (1978), Donica (1978), Williams (1978), Iannacchione and Puglio (1979a, 1979b), Iannacchione and others (1983), Brady (1981a-c; 1983a,b), and Brady and Querry (1985a-i). Hartshorne coal isopach maps in parts of Haskell, Latimer, Le Flore, McIntosh, and Pittsburg Counties are in Gossling (1994). An isopach map of the Stigler (McAlester) coal is in Karvelot (1973).

RANK

Coal rank, generalized for all coals at or near the surface, ranges from high-volatile bituminous in the shelf and western Arkoma Basin to medium- and low-volatile bituminous in the eastern Arkoma Basin in Oklahoma (**Figure 11**). Rank increases from west to east and with depth in the Arkoma Basin, attaining semianthracite in Arkansas (Prior and White, 2001). For example, the Hartshorne coal is medium-volatile bituminous at 2,574 ft (785 m) in Continental Resources' 1-3 Myers well in Pittsburg County (sec. 3, T. 7 N., R. 16 E.) in the high-volatile bituminous area in Figure 11.

CLEAT

Cleat is a miners' term for the natural, opening-mode fractures in coal. Two orthogonal cleat sets, perpendicular to bedding, are the face cleat (primary, well developed; extends across bedding planes of the coal) and the butt cleat (secondary, discontinuous; terminates against face cleat). Cleats control the directional permeability of coal beds (Diamond and others, 1988). Vertical CBM wells drain gas from an elliptical area elongated in the face-cleat direction. Horizontal coalbed-methane wells drilled perpendicular to oblique to the face cleat drain more gas from a larger area than would a vertical well. Cleat spacing is closest in medium- and low-volatile bituminous coals (Close, 1993).

Coal beds in the northeast Oklahoma shelf exhibit average face-cleat directions of N39°–47°W and butt-cleat directions of N46°–56°E (Andrews and others, 1998; Hemish, 2002; **Figure 12**). Face and butt cleats in the Hartshorne coal beds in the eastern Arkoma Basin trend N17°–32°W and N52°–77°E, respectively (**Figure 13**). In general, face cleats are oriented parallel to the axis of compression and butt cleats are oriented subparallel to the structural fold axes (McCulloch and others, 1974). **Figure 14** is a map summarizing face-cleat direction in the Oklahoma coalfield.

Secondary mineralization (e.g., authigenic minerals) in cleats decrease the permeability of coal. Clay, carbonate, quartz, and sulfide minerals are common cleat-filling minerals (Close, 1993; Gamson and others, 1996). **Figure 15** illustrates the distribution of common cleat-filling minerals in Oklahoma coals.

CONCLUSIONS

The Oklahoma coalfield contains bituminous-coal resources in about 40 coal beds of Middle Pennsylvanian age in 19 counties. Commercial coal beds range from 10 in. to 7 ft thick from the surface to depths > 6,000 ft in the Arkoma Basin. Coal beds in the northeast Oklahoma shelf dip gently westward and northwestward, whereas coals in the Arkoma Basin are folded and faulted. Coal and coalbed-methane resources in Oklahoma are suitable and available for combustion, carbonization, and gasification.

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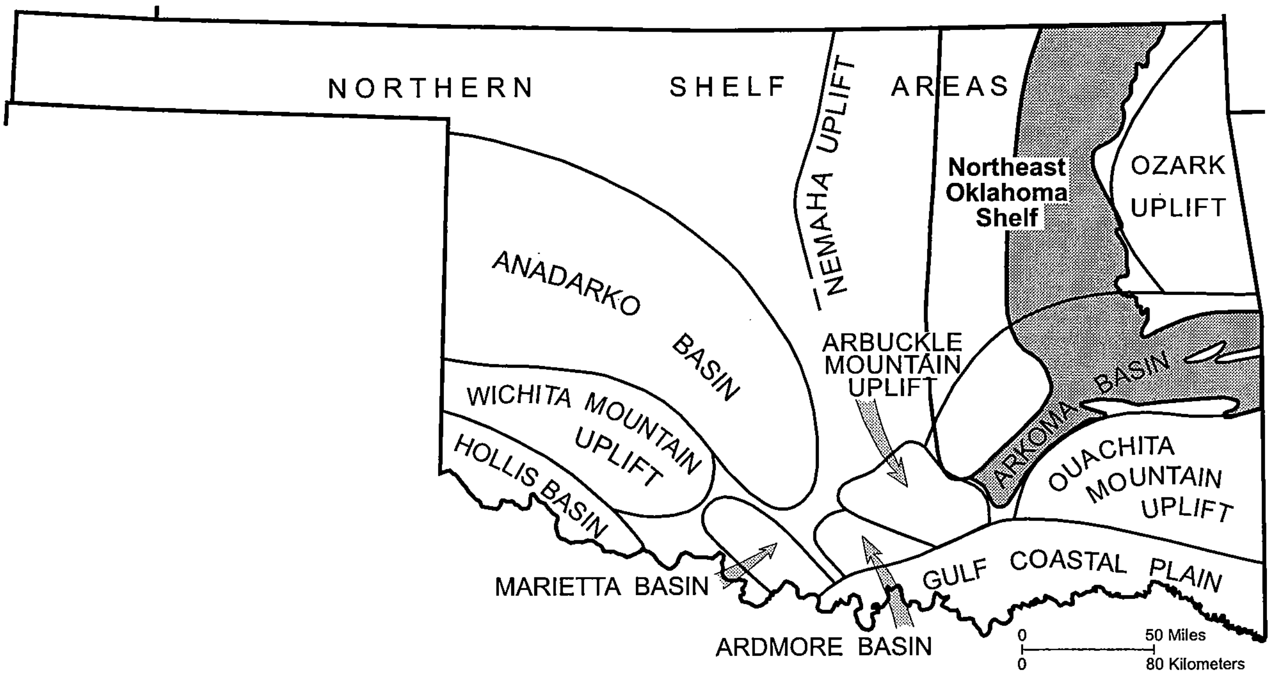


Figure 1. Map of Oklahoma coalfield (modified from Friedman, 1974) in relation to the major geologic provinces of Oklahoma (modified from Johnson and Cardott, 1992).

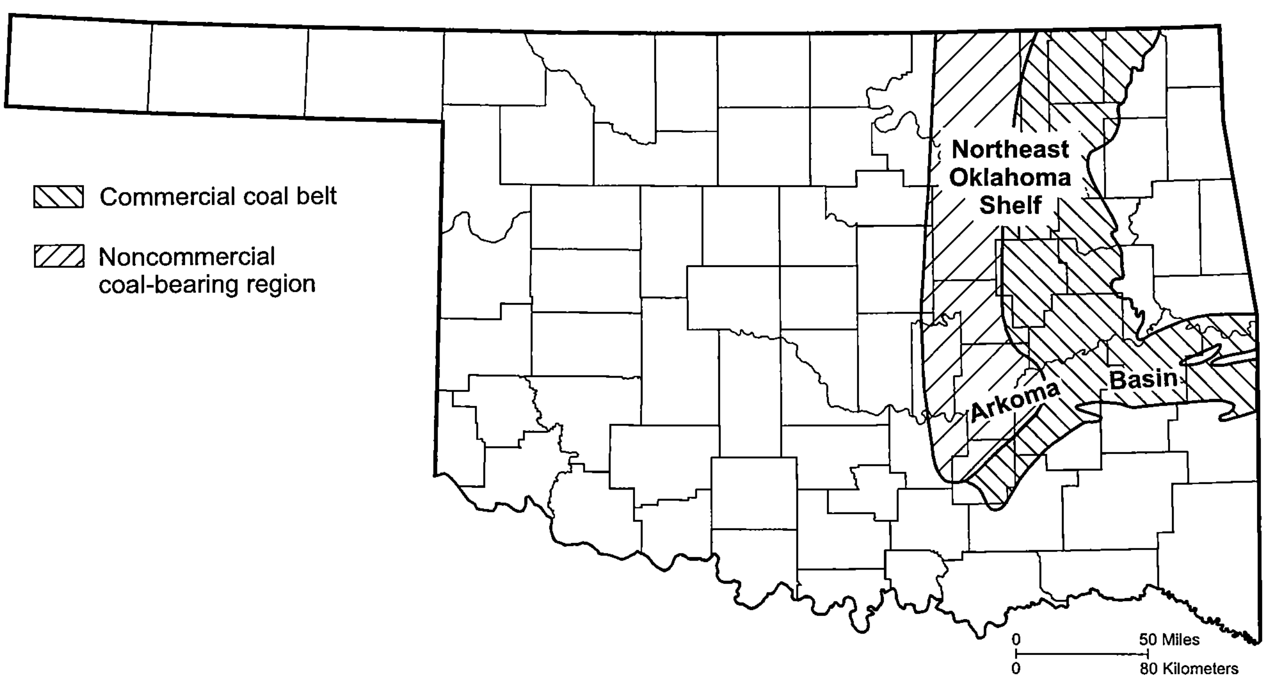


Figure 2. Map of Oklahoma coalfield. Modified from Friedman (1974).

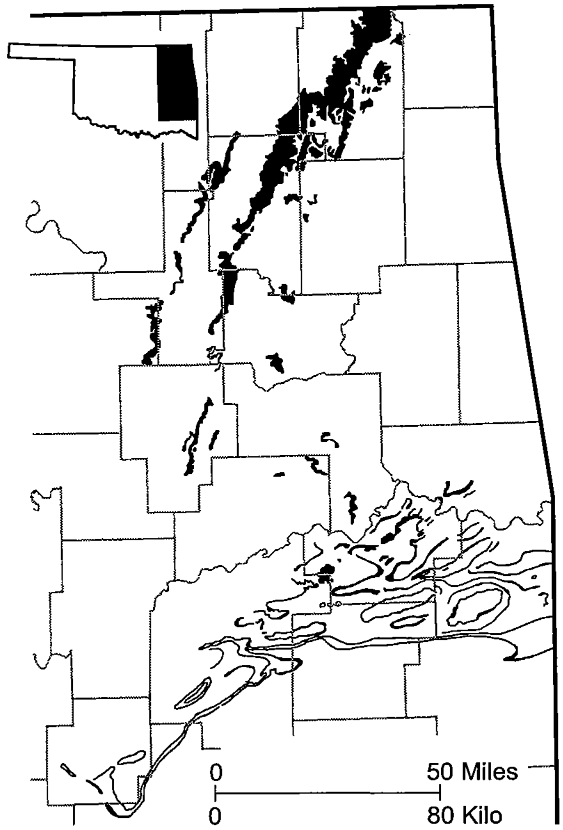


Figure 3. Map showing potentially strippable coal beds in eastern Oklahoma (modified from Friedman, 1982b).

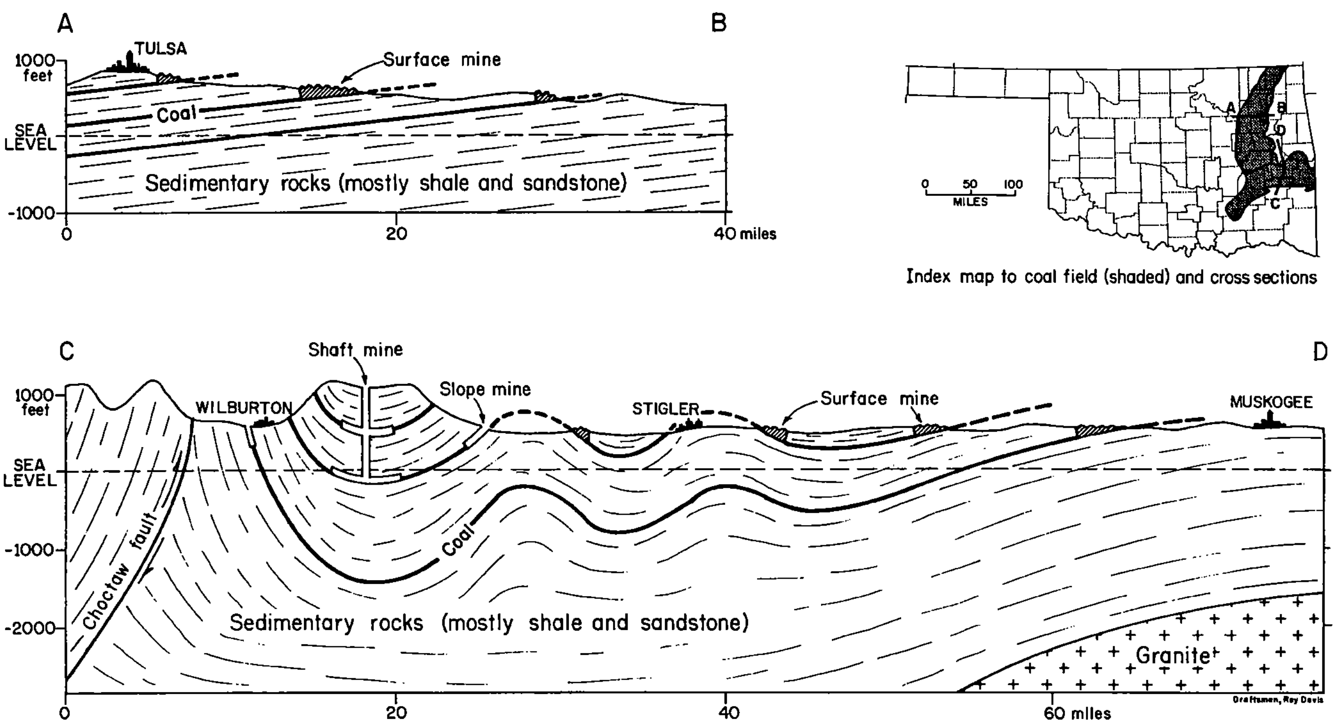


Figure 4. Schematic sections showing geologic structure and types of mines in the Oklahoma coalfield (from Johnson, 1974).

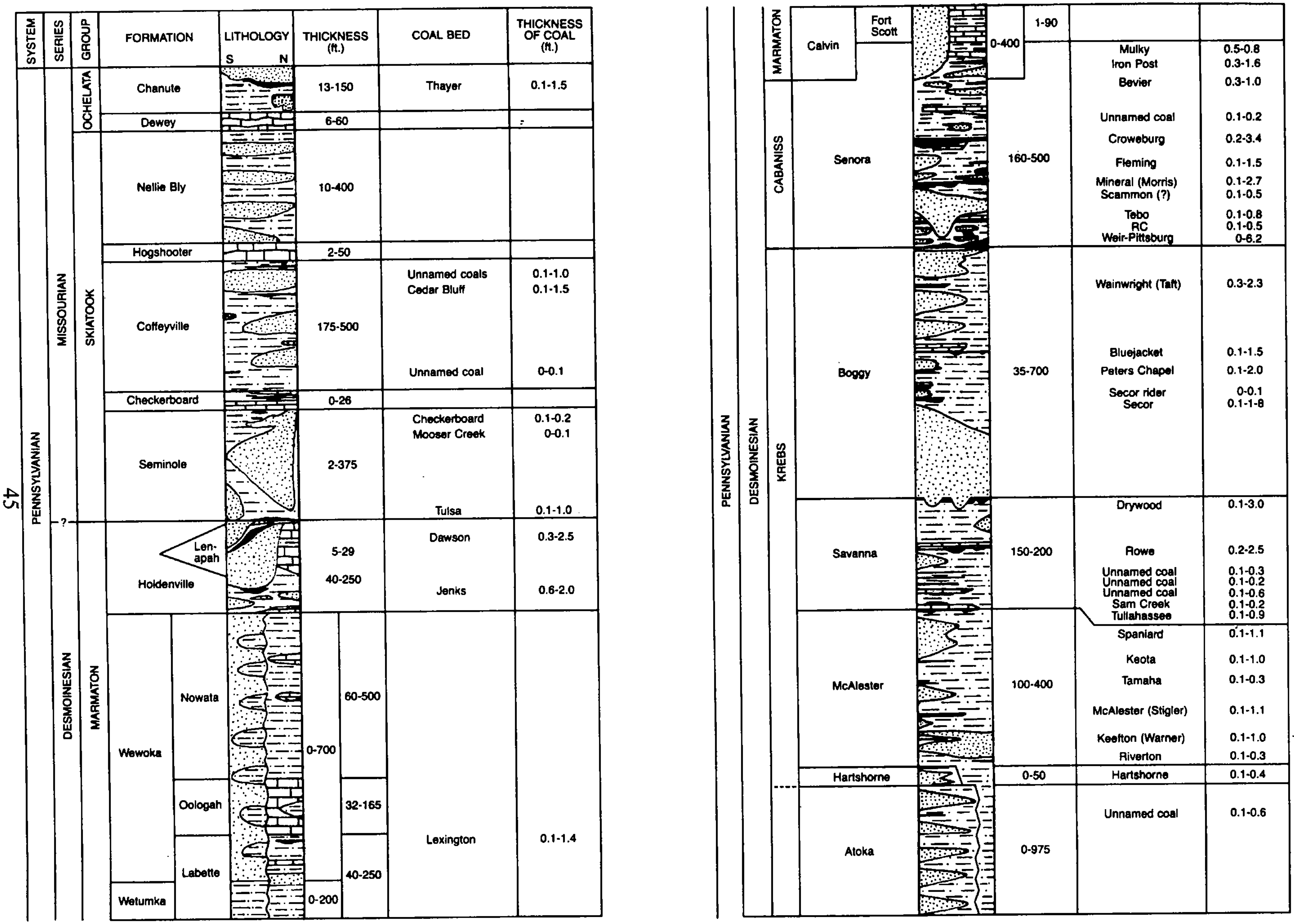


Figure 5. Generalized stratigraphy of coal-bearing strata of the northeast Oklahoma shelf (from Hemish, 1988).

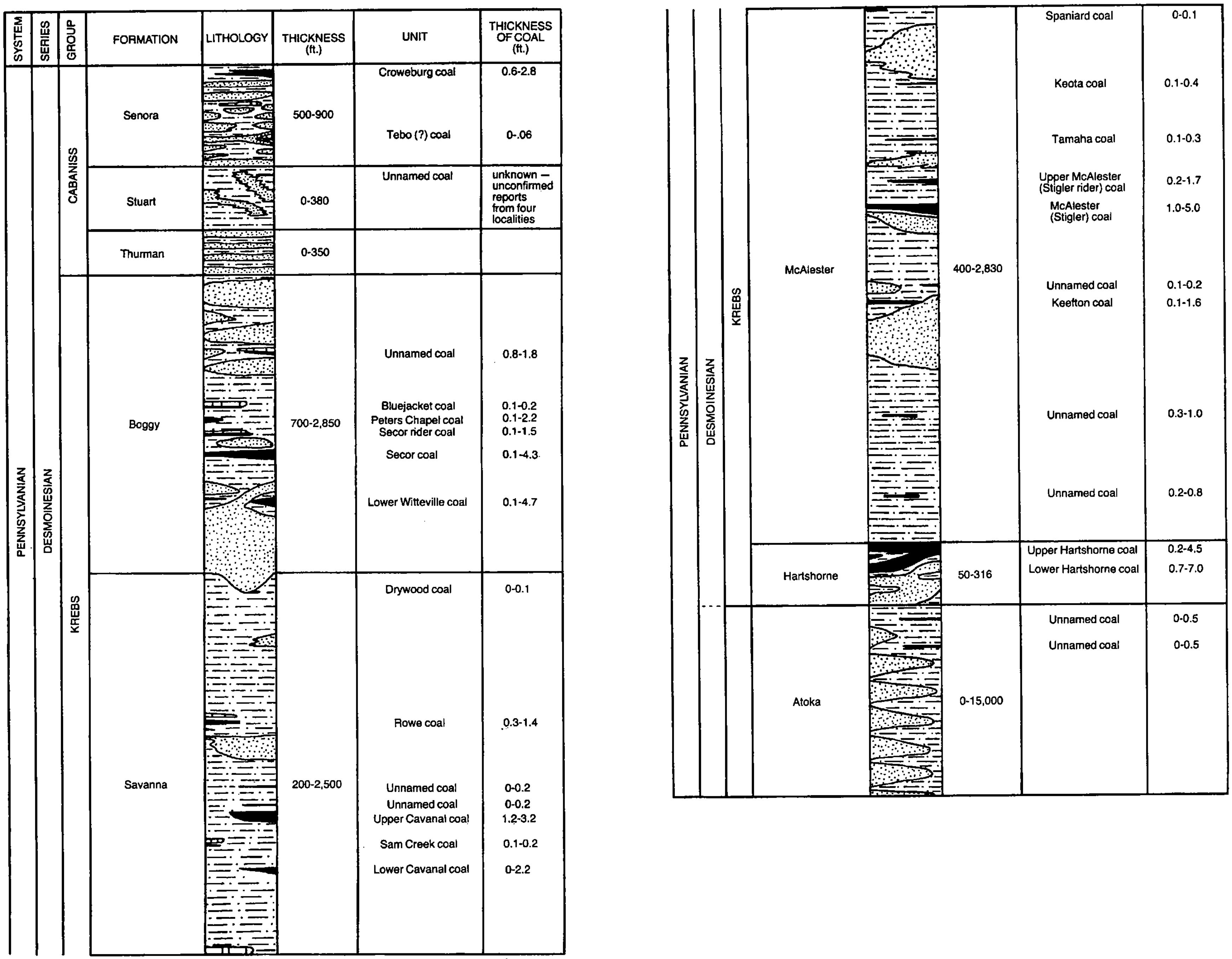


Figure 6. Generalized stratigraphy of coal-bearing strata of the Arkoma basin (from Hemish, 1988).

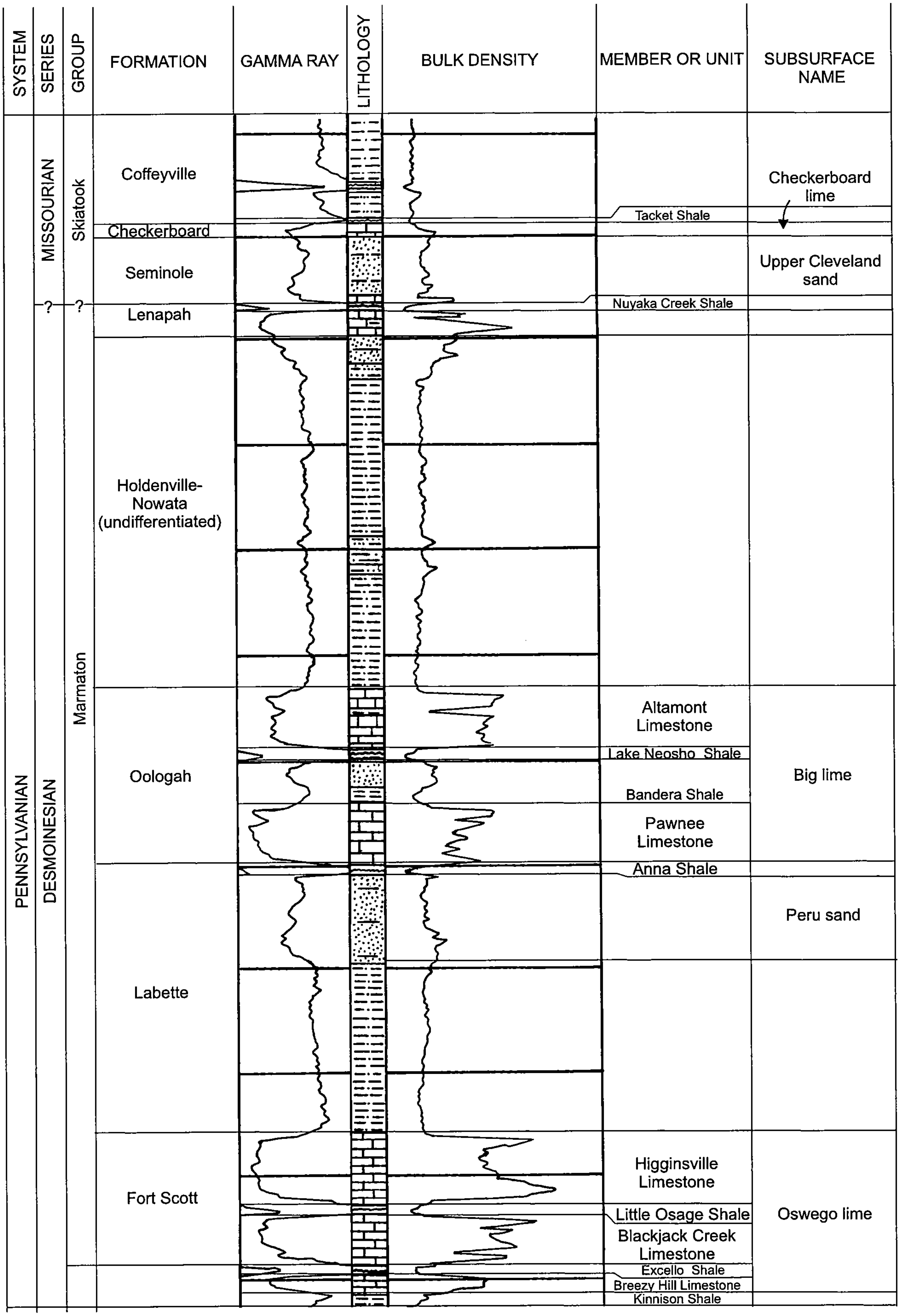
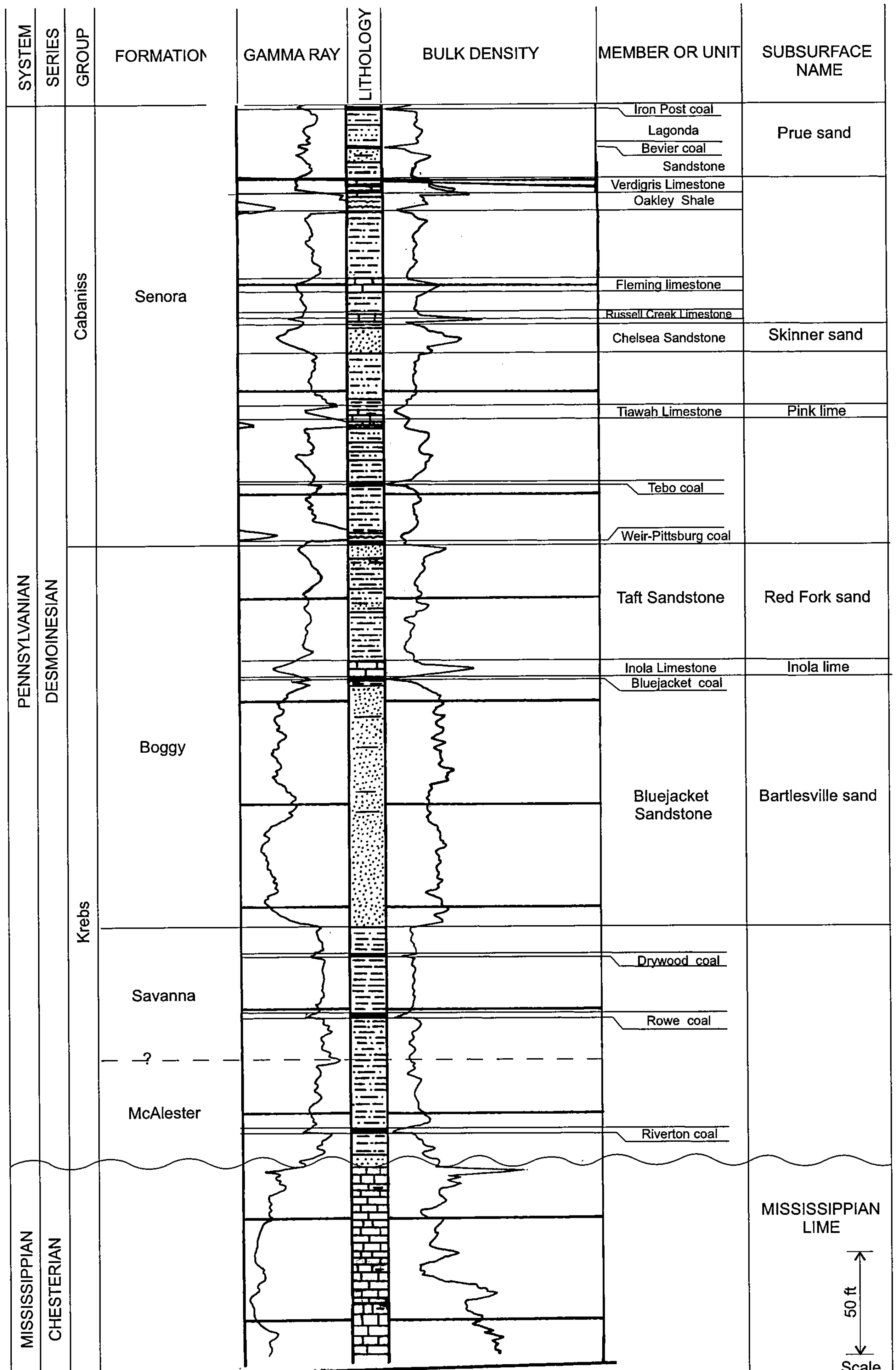


Figure 7. Type log for northern part of northeast Oklahoma shelf (from Hemish, 2002, fig. 18).


SYSTEM
SERIES
GROUP
FORMATION
GAMMA RAY
LITHOLOGY
BULK DENSITY
MEMBER OR UNIT
SUBSURFACE NAME
PENNSYLVANIAN
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Cabaniss
Senora
Iron Post coal
Lagonda
Bevier coal
Sandstone
Prue sand
Verdigris Limestone
Oakley Shale
Fleming limestone
Russell Creek Limestone
Chelsea Sandstone
Skinner sand
Tiawah Limestone
Pink lime
Tebo coal
Weir-Pittsburg coal
Boggy
Taft Sandstone
Red Fork sand
Inola Limestone
Inola lime
Bluejacket coal
Bluejacket Sandstone
Bartlesville sand
Krebs
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Rowe coal
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CHESTERIAN
MISSISSIPPIAN LIME
50 ft
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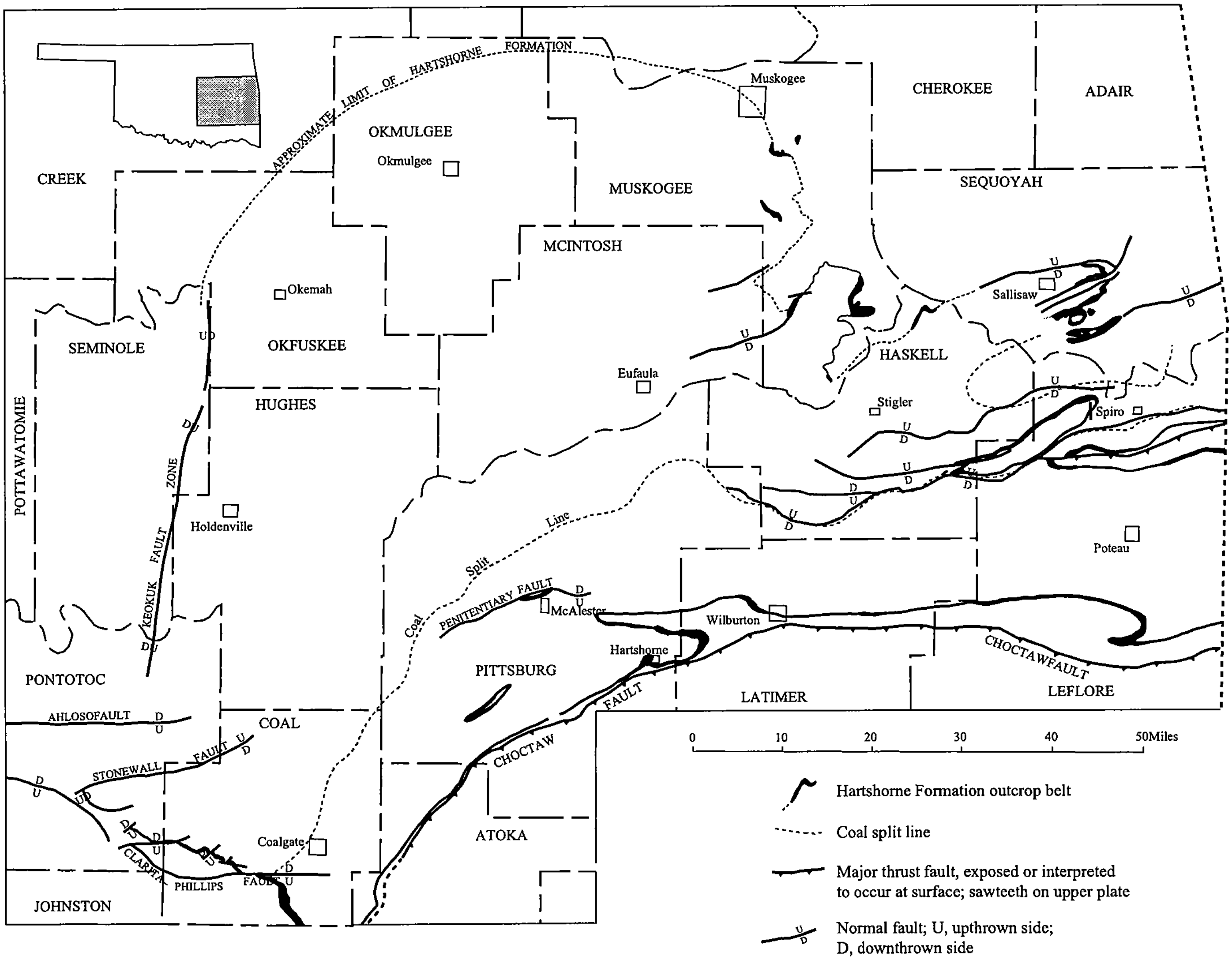

Figure 8. Distribution of the Hartshorne coal in the Arkoma basin, showing the coal split line (from Cardott, 2002a)

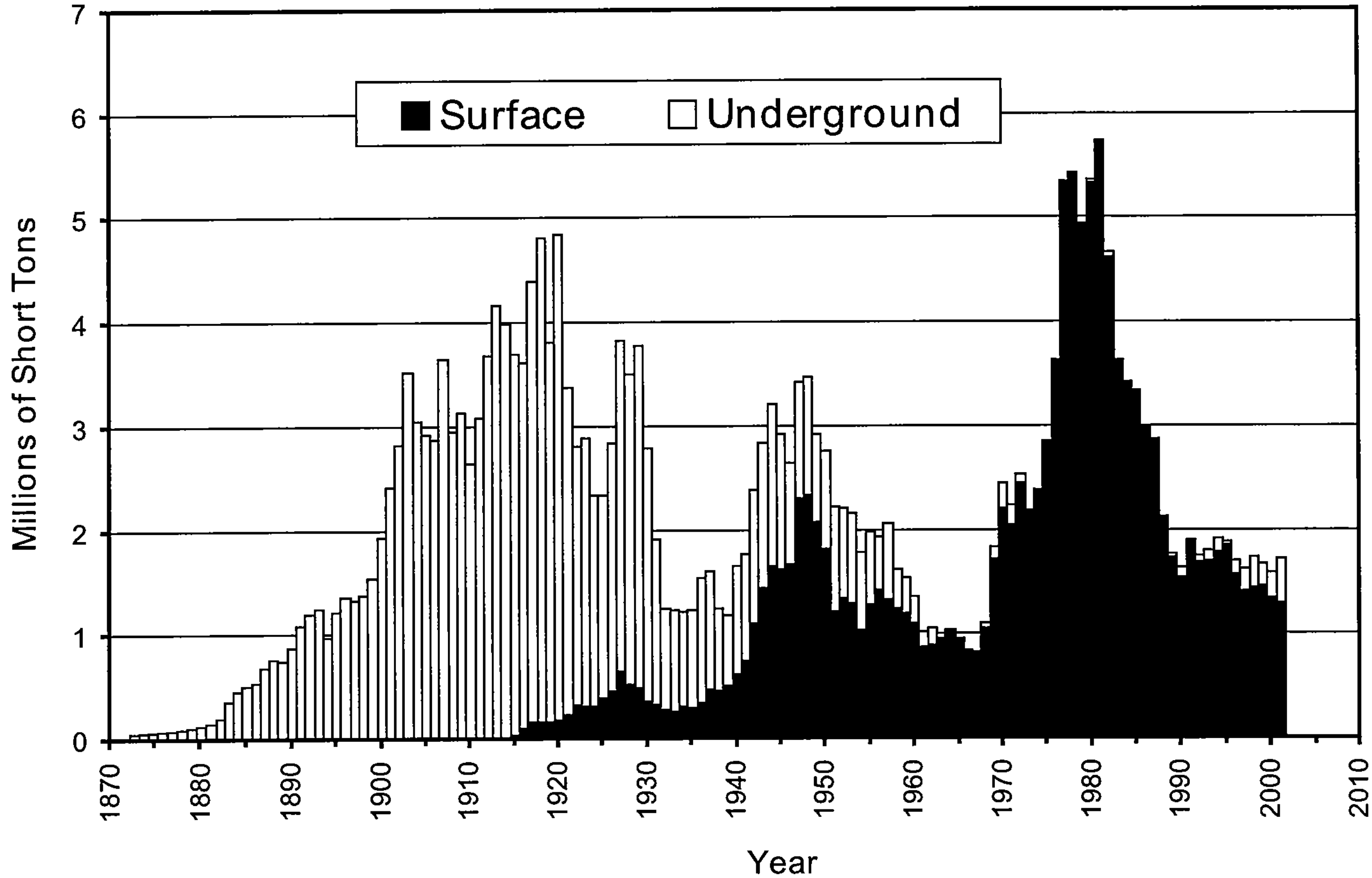

Figure 9. Coal production in Oklahoma, 1873-2001
(from Federal and State data).

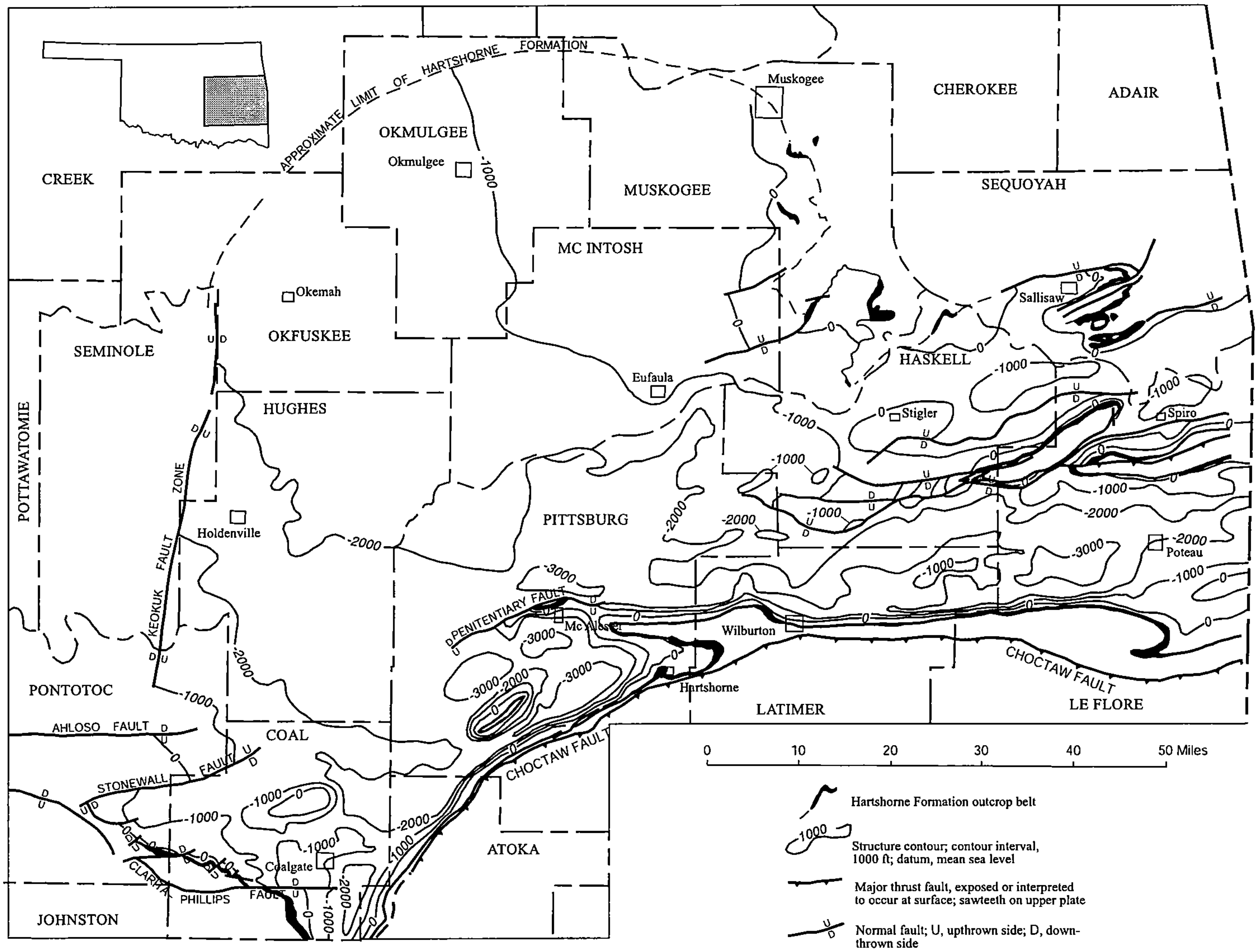

Figure 10. Regional structure on the top of the Hartshorne Formation (from Cardott, 2002a).

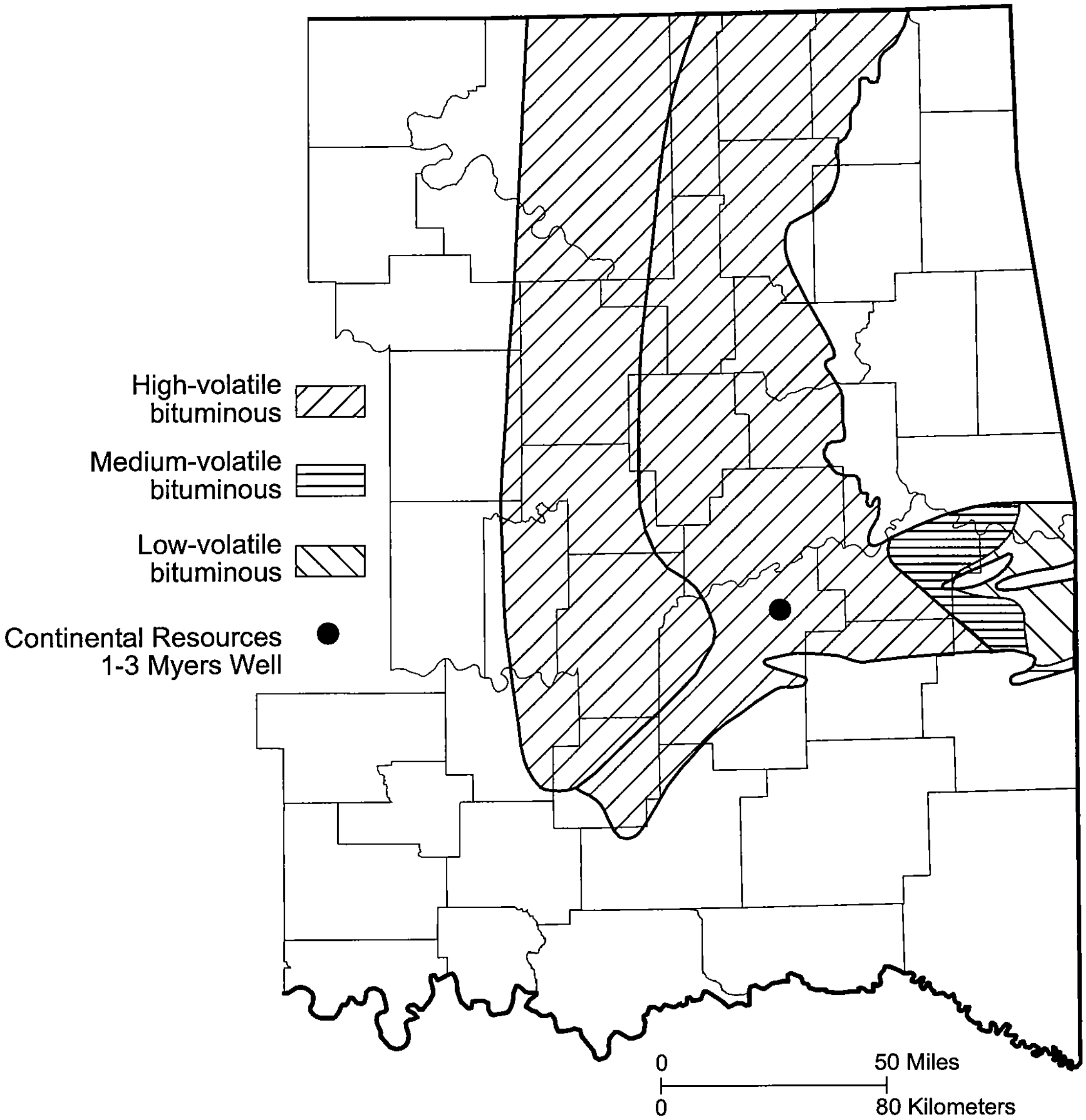

Figure 11. Generalized rank of all coal beds at or near the surface in the Oklahoma coalfield. Modified from Friedman (1974) and Andrews and others (1998).

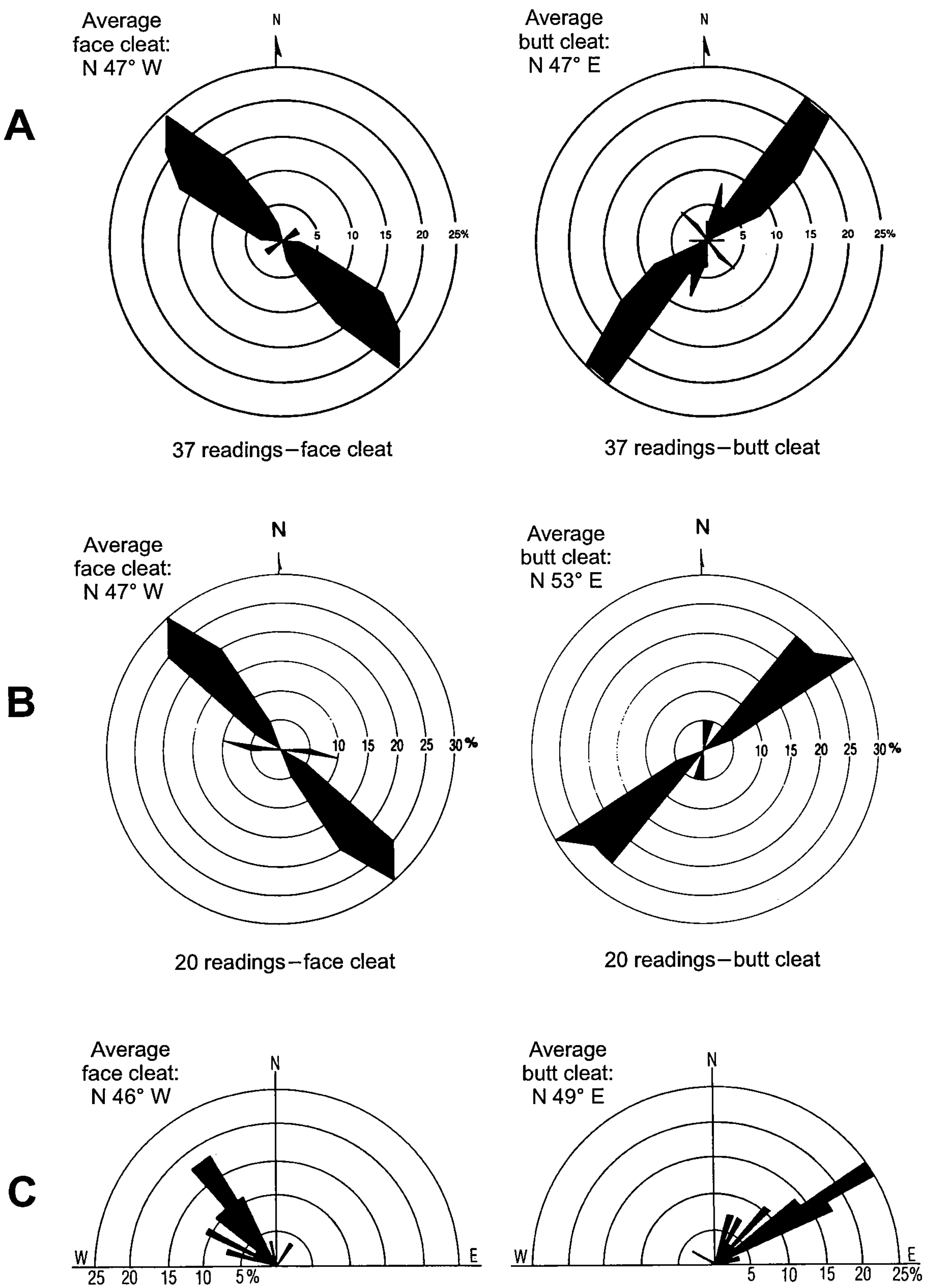

Figure 12. Rose diagrams of cleat orientations in coal beds (from Hemish, 2002). A. Craig and Nowata Counties. B. Rogers and Mayes Counties. C. Tulsa and Wagoner Counties.

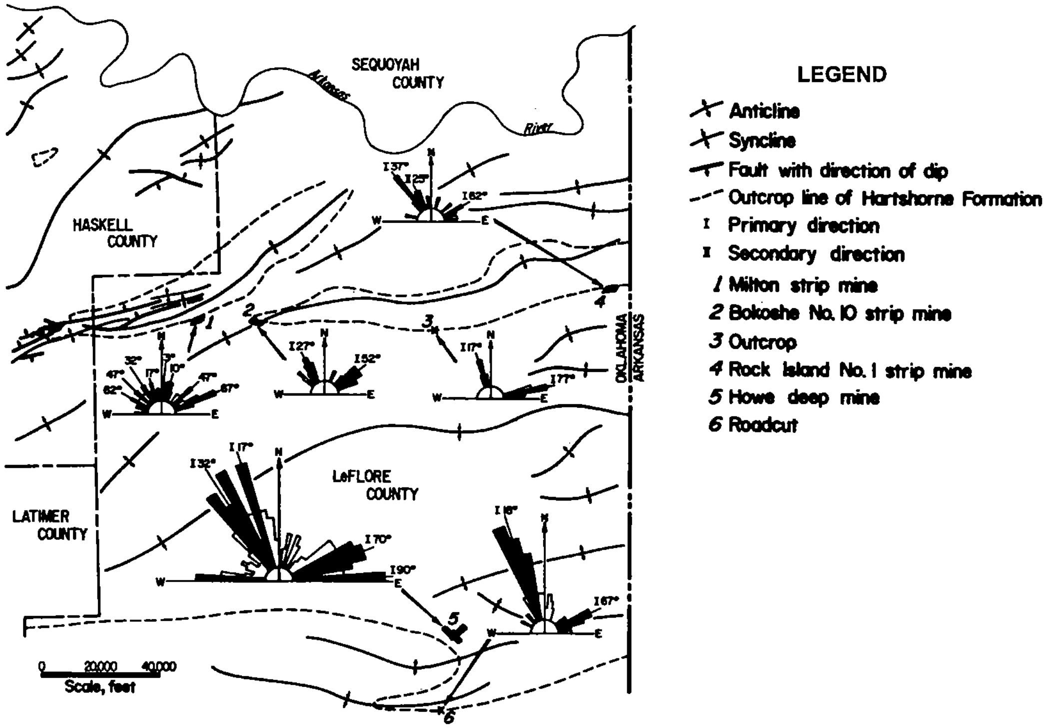

Figure 13. Coal cleat orientations of the Hartshorne coal, Le Flore County, Oklahoma (from Iannacchione and Puglio, 1979a).

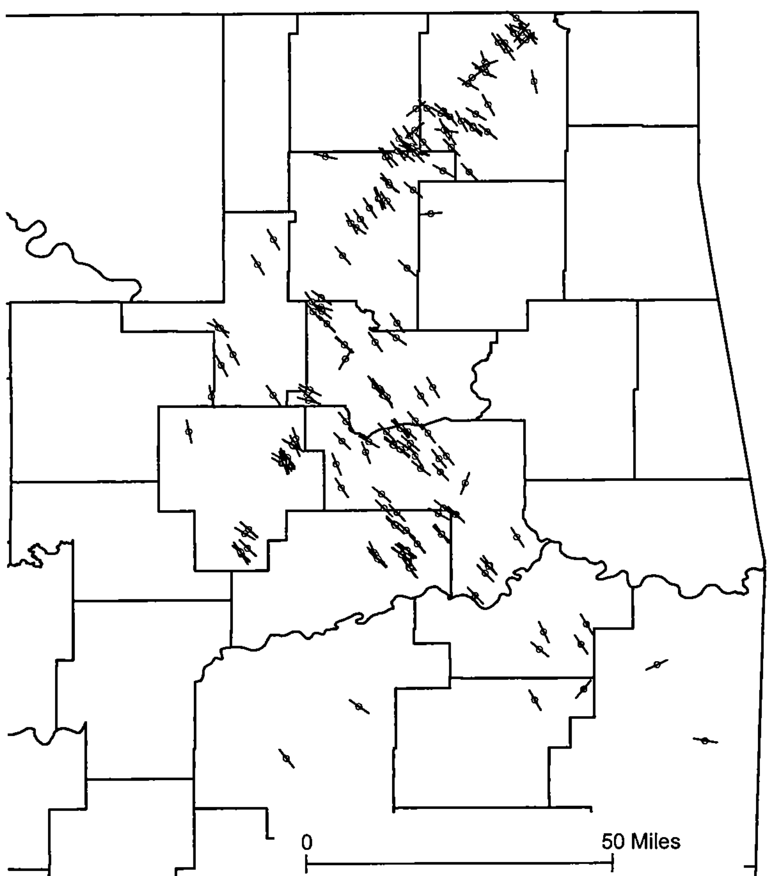

Figure 14. Map of face-cleat orientations in the Oklahoma coalfield from data in Hemish (1986, 1989, 1990a, 1994, 1998a, 1998b) and Friedman (unpublished).

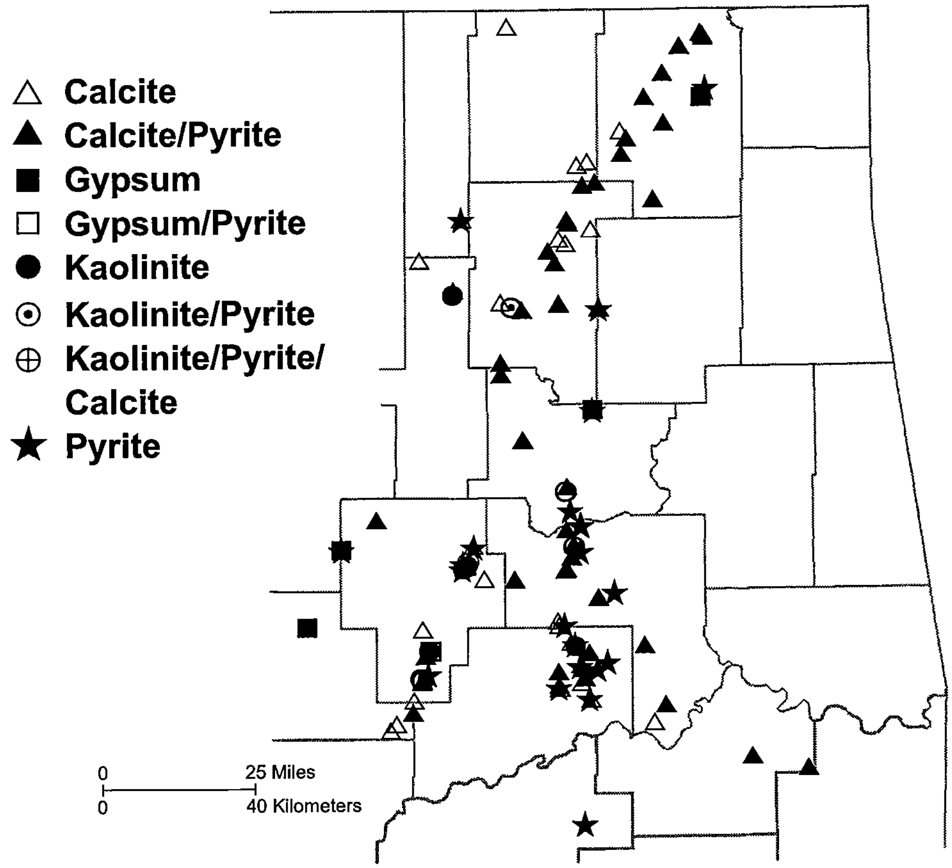

Figure 15. Map showing the distribution of cleat-filling minerals in northeast Oklahoma coal beds from data in Hemish (1986, 1988, 1989, 1990a, 1990b, 1994, 1997, 1998a, 1998b) and Friedman (unpublished).

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OPEN-FILE REPORT 9-2002

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Coalbed-methane activity in Oklahoma, 2002 update

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Coalbed-Methane Activity in Oklahoma, 2002 Update

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ABSTRACT.— Nearly 1,900 wells in the Oklahoma coalfield have been drilled exclusively for coalbed methane (CBM) since 1988, in part for the Federal Section 29 tax credit. A database of CBM completions records 1,167 completions in the northeast Oklahoma shelf and 707 completions in the Arkoma Basin. Operators presently target thirteen coal objectives in the shelf and five in the basin. The primary CBM objectives, all Desmoinesian (Middle Pennsylvanian) in age, are the Mulky (380 wells) and Rowe (433 wells) coals in the shelf and the Hartshorne coals (664 wells) in the basin.

In general, coals in the Arkoma Basin are deeper and thicker than those in the northeast Oklahoma shelf and have higher initial gas rates and lower initial produced-water rates. Many horizontal CBM wells have been drilled in the Arkoma Basin since 1998, the more successful wells following improvements in completion techniques. Much is known about the coal geology of the Oklahoma coalfield (e.g., number of coals, age, depth, thickness, rank, quality). The present emphasis is on finding permeable sweet spots and matching coal characteristics to optimum completion techniques.

INTRODUCTION

Mine explosions from gas and dust caused more than 500 deaths in 19 major coal-mining disasters in Indian Territory and Oklahoma from 1885 to 1945 (Oklahoma Department of Mines, 2002). Gas explosions in underground coal mines and safety studies of underground coal mines by the U.S. Bureau of Mines (Deul and Kim, 1988) have demonstrated that Oklahoma coals contain large amounts of methane. Applied research by the U.S. Bureau of Mines, U.S. Department of Energy, and Oklahoma Geological Survey, advances in coalbed methane (CBM) completion technology through studies of coals in the Black Warrior and San Juan Basins by the Gas Research Institute, and Federal non-conventional fuel tax credit (Section 29 of the IRS Code; Sanderson and Berggren, 1998) all promoted interest in development of the Oklahoma CBM industry.

The CBM play in Oklahoma began in 1988 with the first completions in the Arkoma Basin (**Figure 1**). Bear Productions reported initial-potential (IP) gas rates of 41 to 45 Mcfd (thousand cubic feet of gas per day) per well from seven wells in the Hartshorne coal at depths ranging from 611 to 716 ft (186 to 218 m) in the Kinta gas field (sec. 27, T.8N., R.20E., Indian Meridian) in Haskell County. Bear Productions was the only CBM operator in Oklahoma from 1988–1990. Following a peak of 72 completions in 1992, activity declined for several years before rising to 180 completions reported in the basin in 2001. CBM completions in the shelf began in 1992 with one well. Shelf completions totaled 231 and 257 in 1998 and 2001, respectively. More CBM wells per year have been drilled in the shelf than in the basin since 1995. Through July 2002, 1,874 CBM completions have been reported in Oklahoma — 707 in the Arkoma Basin and 1,167 in the northeast Oklahoma shelf. **Figure 2** shows the distribution of coalbed-methane fields in eastern Oklahoma.

The Oklahoma coalfield is in the eastern part of the State and occupies the southern part of the Western Region of the Interior Coal Province of the United States (Campbell, 1929; Friedman, 2002). The coalfield is divided into the northeast Oklahoma shelf and the Arkoma Basin (Friedman, 1974; **Figure 3**). Cardott (2002) summarized the coal geology of Oklahoma. The remainder of this report will discuss the coalbed methane activity of the northeast Oklahoma shelf and the Arkoma Basin.

SOURCE OF DATA

The following discussion of Oklahoma CBM activity is based on information reported to the Oklahoma Corporation Commission and Osage Indian Agency. The names of coal beds are as reported by the operator. For the most part, coal names assigned by operators have not been verified with electric logs, and may not conform to usage accepted by the Oklahoma Geological Survey. Since not all the wells are reported as CBM wells, some interpretation or verification with the operator was necessary. Dual completions in sandstone and coal beds, including perforations of more than one coal bed, were made in some wells. Therefore, not all the wells are exclusively CBM completions. Dual completions were included only if gas rates were reported for the coal beds.

This summary is incomplete inasmuch as some wells were not known to be CBM wells or were not reported as such at the time of this compilation. This evaluation is based on reported CBM completions, which may or may not have been connected to a gas pipeline. Likewise, some completions may have produced gas but have since been plugged.

The Coalbed-Methane Completions table of the Oklahoma Coal Database was used to summarize data in this report. Each record (well completion) in the table lists operator, well name, API number, completion date, location (county, gas field, township-range-section, latitude-longitude), coal bed, production depth interval, initial gas potential and water rates, pressure information, and comments. Incomplete copies of Oklahoma Corporation Commission Form 1002A limited the data summaries for coal depth, initial gas potential, and produced water in this report. The database is available for viewing at or purchase from the Oklahoma Geological Survey. A searchable version of the Coalbed-Methane Completions table is accessible on the Internet through a link on the OGS web site, http://www.ou.edu/special/ogs-pttc.

COALBED METHANE ACTIVITY

Northeast Oklahoma Shelf

There have been 1,167 CBM well completions reported in the shelf by 54 operators through July 2002 (**Figure 4**). Completions are distributed across Craig, McIntosh, Nowata, Okfuskee, Okmulgee, Osage, Rogers, Tulsa, and Washington Counties. About 38% of the wells are workovers or recompletions of older conventional gas and oil wells and coalbed methane wells. In ascending order (with number of completions with coal as uppermost bed in parentheses), the coal beds yielding commercial methane include the Riverton (144) and McAlester (1) (McAlester

Formation), Rowe (433) and Drywood (1) (Savanna Formation), and Bluejacket (15) and Wainwright (1) (Boggy Formation) in the Krebs Group; Weir-Pittsburg (62), Tebo (5), Croweburg (29), Bevier (15), Iron Post (43), and Mulky (380) (Senora Formation) in the Cabaniss Group; and Dawson (34) (Holdenville Formation) in the Marmaton Group of Desmoinesian age. Note that the Rowe coal of Kansas and Missouri is equivalent to the Keota coal in Oklahoma, while the Drywood coal of Missouri and Dry Wood coal of Kansas are equivalent to the Spaniard coal of Oklahoma (Hemish, 1990, p. 10).

Figure 5 shows the depth range of CBM completions in 1,162 wells in the shelf. Coal beds were perforated at depths-to-top of coal of 256 to 2,459 ft (78 to 750 m), for an average depth of 1,014 ft (309 m). Three modes are apparent. First, the shallower mode represents the Mulky coal (380 wells; includes commingled wells with the Mulky as the shallowest perforated coal) completed over a depth range of 256 to 1,733 ft (78 to 528 m); 292 of 380 wells that perforated the Mulky coal were completed in only the Mulky coal.

The second mode represents the Rowe coal (433 wells), completed over a depth range of 542 to 2,459 ft (165 to 750 m). The deepest coal completion (2,459 ft) is in the Rowe coal in Osage County (Amvest West, 99 Drummond II well, sec. 23, T.21N., R.9E.).

The third mode represents the Riverton coal (144 wells), completed over a depth range of 630 to 1,970 ft (192 to 600 m). Although two to seven coal beds were perforated in 166 completions, only the shallowest coal depth was used in Figure 5.

Initial-potential gas rates from 1,040 wells range from a trace to 278 Mcfd and average 30 Mcfd (**Figure 6**). However, as will be shown in production-decline curves below, IP rates do not demonstrate the full potential of a CBM well because they reflect only the first of the three stages of a typical CBM production-decline curve: dewatering, followed by stable production and decline (Schraufnagel, 1993; **Figure 7**). **Figure 8** shows the relationship of depth and initial-potential gas rate for CBM wells in the shelf. The shallowest coals (256-322 ft; 78-98 m) had IP rates of 1-12 Mcfd. The shallowest coal with a moderate IP rate of 28 Mcfd was at a depth of 326 ft (99 m). Coals with the highest IP rates (>100 Mcfd) were from depths of 433 to 1,500 ft (132 to 457 m). The maps in **Figures 9 to 11** highlight the Mulky, Rowe, and Riverton CBM wells, respectively, that exhibit the generally higher rates—34 (12%) of 292 Mulky-only wells with initial gas rates of 50 to 145 Mcfd, 90 (21%) of 429 Rowe-only wells with initial gas rates of 50 to 260 Mcfd, and 45 (31%) of 144 Riverton-only wells with initial gas rates of 50 to 150 Mcfd.

Monthly gas production by well is reported on Form 1004/1005 (Measured Volume Report) by the Oklahoma Corporation Commission Oil & Gas Conservation Division. The information will be available from the Oklahoma Corporation Commission web site (http://www.occ.state.ok.us/) in September, 2002. Production-decline curves for four CBM wells in Nowata and Washington Counties are illustrated in **Figure 12**. Their IP rates range from 73 to 210 Mcfd and 30 to 90 bwpd. Depths-to-top of coal for the four selected wells is 1,223 ft (Figure 12a), 1,172 ft (Figure 12b), 1,178 ft (Figure 12c), and 1,375 ft (Figure 12d). Gas content and composition data are unavailable for coals on the northeast Oklahoma shelf.

Initial water rates in the shelf range from 0 to 5,061 bwpd and average 63 bwpd from 1,018 wells (**Figure 13**, excluding two wells with 1,201 and 5,061 bwpd). Most of the water is believed to be formation water and not water from fracture stimulation. Because of generally poor water quality, these wells require disposal wells for the produced water. In general, water volumes are not metered; therefore, the volume of disposed water and the effect of water production on gas rate are unknown. Data on water quality is not available.

Arkoma Basin

Figure 14 shows the locations of 707 CBM completions in the basin reported by 50 operators through July 2002. Completions have been reported in Coal, Haskell, Hughes, Latimer, Le Flore, McIntosh, Muskogee, and Pittsburg Counties. In ascending order, the methane-producing coals include the Hartshorne (undivided), Lower Hartshorne, and Upper Hartshorne (Hartshorne Formation), McAlester and "Savanna" (interpreted to be the McAlester coal, McAlester Formation; a completion in Coal County reported to be in the "Lehigh" coal is equivalent to the McAlester coal), Secor (Boggy Formation), and unnamed coal in the Krebs Group of Desmoinesian age. Most (664 completions) of the CBM completions in the Arkoma Basin are in Hartshorne coals.

Figure 15 shows the depth range of CBM completions in the basin. Coals in 676 wells were perforated at depths-to-top of coal of 347 to 3,726 ft (106 to 1,136 m), for an average of 1,440 ft (439 m). Three of the four deepest completions, 3,632 to 3,726 ft (1,107 to 1,136 m), were made in the Hartshorne coal in Hughes County (T.4N., R.11E.). Although 19 completions have perforated two to three coals, only the shallowest coal depth was used in Figure 15.

IP gas rates from 592 wells range from a trace to 2,300 Mcfd (average 127 Mcfd)(**Figure 16**). Most (412 completions) wells produced 10 to 120 Mcfd. The highest IP rates (> 330 Mcfd) were reported from 57 horizontal CBM wells in the Hartshorne coal. Based on 563 completions with depth and initial potential pairs, **Figure 17** shows no relationship between initial-potential gas rate and depth in the Arkoma Basin (depth of horizontal wells is based on vertical depth-to-top of coal). Low gas rates (<50 Mcfd) span the entire depth range. The 160 wells (28% of 563) with the highest gas rates (>99 Mcfd) are from depths of 636–3,031 ft (194-924 m), not associated with the deepest completions. Theoretically, gas content increases with increasing rank, depth, and reservoir pressure (Kim, 1977; Scott and others, 1995; Rice, 1996). However, gas production depends on many variables, including gas content, coal thickness, water volume, cleat mineralogy, permeability, porosity, and stimulation method.

The first horizontal CBM well in Oklahoma was completed by Bear Productions in August 1998. By the end of July 2002, 108 horizontal CBM wells (15% of 707 completions) had been completed in Haskell, Le Flore, and Pittsburg Counties reported by 6 operators—Bear Productions Inc., 5 wells; Brower Oil & Gas Co. Inc., 2 wells; Continental Resources, one well; Mannix Oil Co. Inc., 91 wells; Questar Exploration & Production Co., 7 wells; Williams Production Co., 2 wells (**Figure 18**). IP gas rates in 104 horizontal CBM wells were 15 to 2,300 Mcfd (average of 434 Mcfd) at true vertical depths-to-top of coal of 752 to 3,031 ft (229 to 924 m). Higher gas rates are possible in a horizontal well than in a single-bed vertical well by drilling at a high angle (perpendicular to oblique) to the face cleat to drain a larger area (Diamond and others, 1988). Horizontal CBM wells can drain as much as seven times the area of a vertical CBM well, depending on the lateral length (Stayton, 2002). Vertical CBM wells exhibit an elliptical drainage pattern, elongated parallel to the face cleat, as a result of the directional (anisotropic) permeability of the cleat (Diamond and others, 1988). Horizontal CBM wells are completed openhole. The lateral distance within the coal for 88 horizontal CBM wells ranged from 439 to 2,523 ft (134 to 769 m), with an average of 1,531 ft (467 m). **Figure 19** shows that higher initial gas rates are related to longer horizontal lateral lengths.

The map in **Figure 20** shows Hartshorne CBM wells that have the highest initial gas rates—163 (25%) of 664 Hartshorne (including Upper and Lower Hartshorne) CBM wells with initial gas rates of 100 to 2,300 Mcfd. A comparison with Figure 18 shows that many of the Hartshorne CBM wells with high gas rates are horizontal CBM wells.

Figure 21 illustrates gas-production-decline curves for three vertical and three horizontal CBM wells in different areas in the Arkoma Basin, using monthly production data. IP rates range from 43 to 513 Mcfd and 0 to 8 bwpd. Depths-to-top of coal for five of the six selected wells is 2,271 ft (Figure 21a), 637 ft (Figure 21b), 1,351 ft (Figure 21c), 2,856 ft (Figure 21d), and 922 ft (Figure 21f). The lateral distance within the coal for the horizontal CBM wells in Figures 21d-e is 1,876 ft and 1,636 ft, respectively. Figure 21c extends the data presented in Andrews and others (1998, p. 57, Figure 45a).

Initial produced-water rates from 557 wells range from 0 to 320 bwpd (average 21 bwpd)(**Figure 22**). Most (382 completions) produced less than 20 bwpd. An undisclosed amount of initial water production is frac water introduced during fracture stimulation. Most Arkoma Basin CBM well completions are situated on the flanks of anticlines (**Figures 23-24**) and tend to produce relatively little water.

Andrews and others (1998) summarized published information on gas resources, gas content, gas composition, and cleating in Hartshorne coals. Measured gas contents in the Arkoma Basin range from 70 to 560 cf/ton in high-volatile to low-volatile bituminous coal cores from depths of 175 to 3,651 ft (53 to 1,113 m). **Figure 25** shows the location of available Oklahoma coal-core desorption samples. The gas-content data are plotted against depth in **Figure 26**.

CONCLUSIONS

The Oklahoma CBM play began in the Arkoma Basin in 1988. The play then spread to the northeast Oklahoma shelf in 1992. Through July 2002, 1,874 CBM completions were reported in Oklahoma — 707 in the Arkoma Basin and 1,167 on the northeast Oklahoma shelf. The primary objectives are Hartshorne coals in the basin and the Mulky and Rowe coals in the shelf. Fourteen percent (166 of 1,167) of the CBM completions in the shelf were multiple-coal completions with two to seven coal beds, while most of the CBM completions in the basin were single-coal completions.

Coal completion depths range from 256 to 2,459 ft (78 to 750 m) and average 1,014 ft (309 m) in 1,162 wells in the shelf, and 347 to 3,726 ft (106 to 1,136 m), averaging 1,440 ft (439 m) in 676 wells in the basin.

Initial-potential gas rates range from a trace to 278 Mcfd (average 30 Mcfd) from 1,040 wells in the shelf, and a trace to 2,300 Mcfd (average 127 Mcfd) from 592 wells in the basin. The maximum initial gas rate was reported in the Hartshorne coal at a true vertical depth of 2,543 ft (775 m) from a horizontal well in Pittsburg County.

Produced-water rates range from 0 to 5,061 bwpd (average 63 bwpd) from 1,018 wells in the shelf, and 0 to 320 bwpd (average 21 bwpd) from 557 wells in the basin.

Low initial gas rates and minimal initial increase in gas production during dewatering are often attributed to formation damage caused by well stimulation, including the generation of coal fines that plug permeability. Present industry emphasis is on matching the completion techniques to the specific coal.

Future development of CBM in Oklahoma is promising. Applications of horizontal drilling and established completion practices have demonstrated the potential for CBM in the Midcontinent USA.

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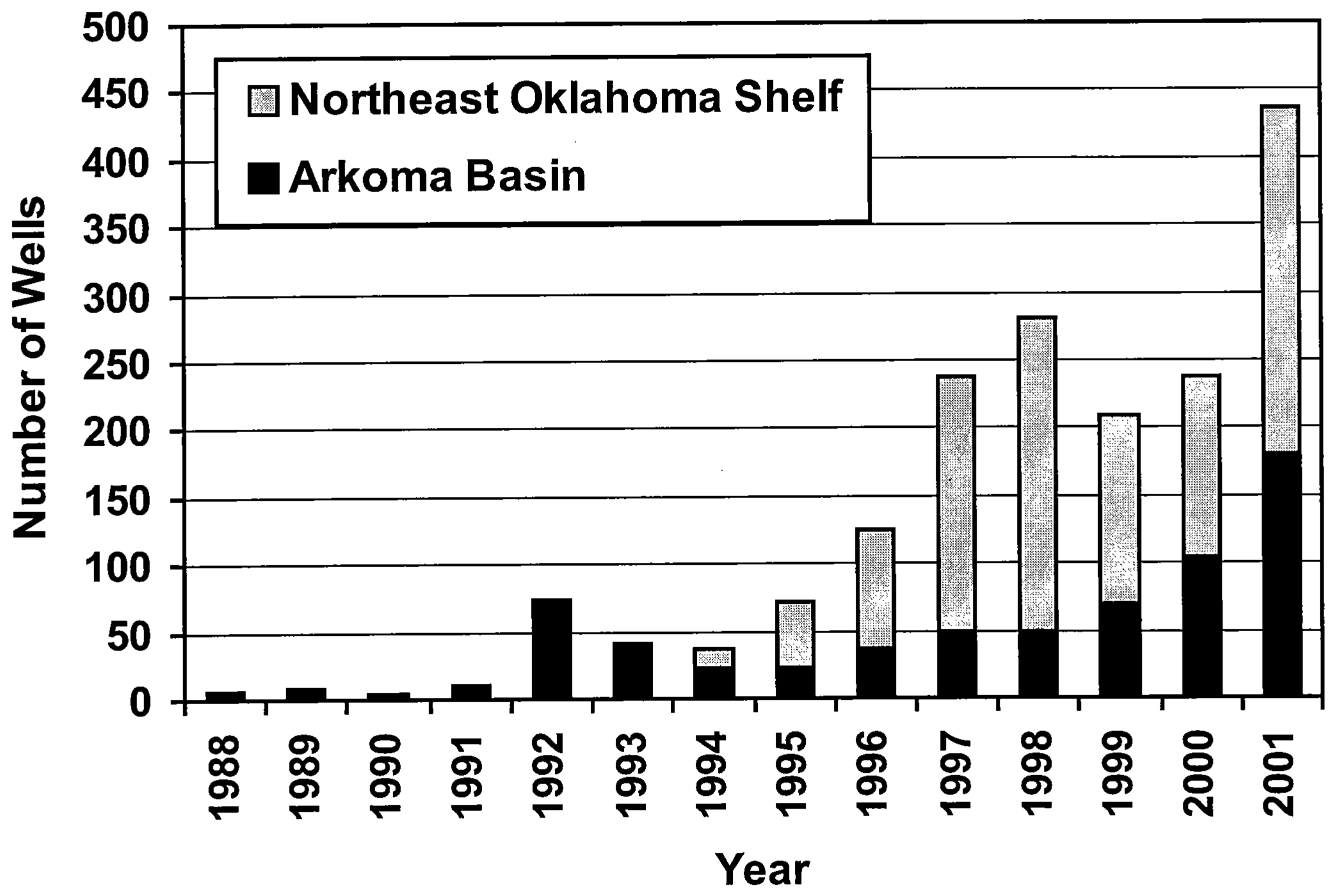

Figure 1. Histogram showing numbers of Oklahoma coalbed-methane well completions, 1988 to 2001.

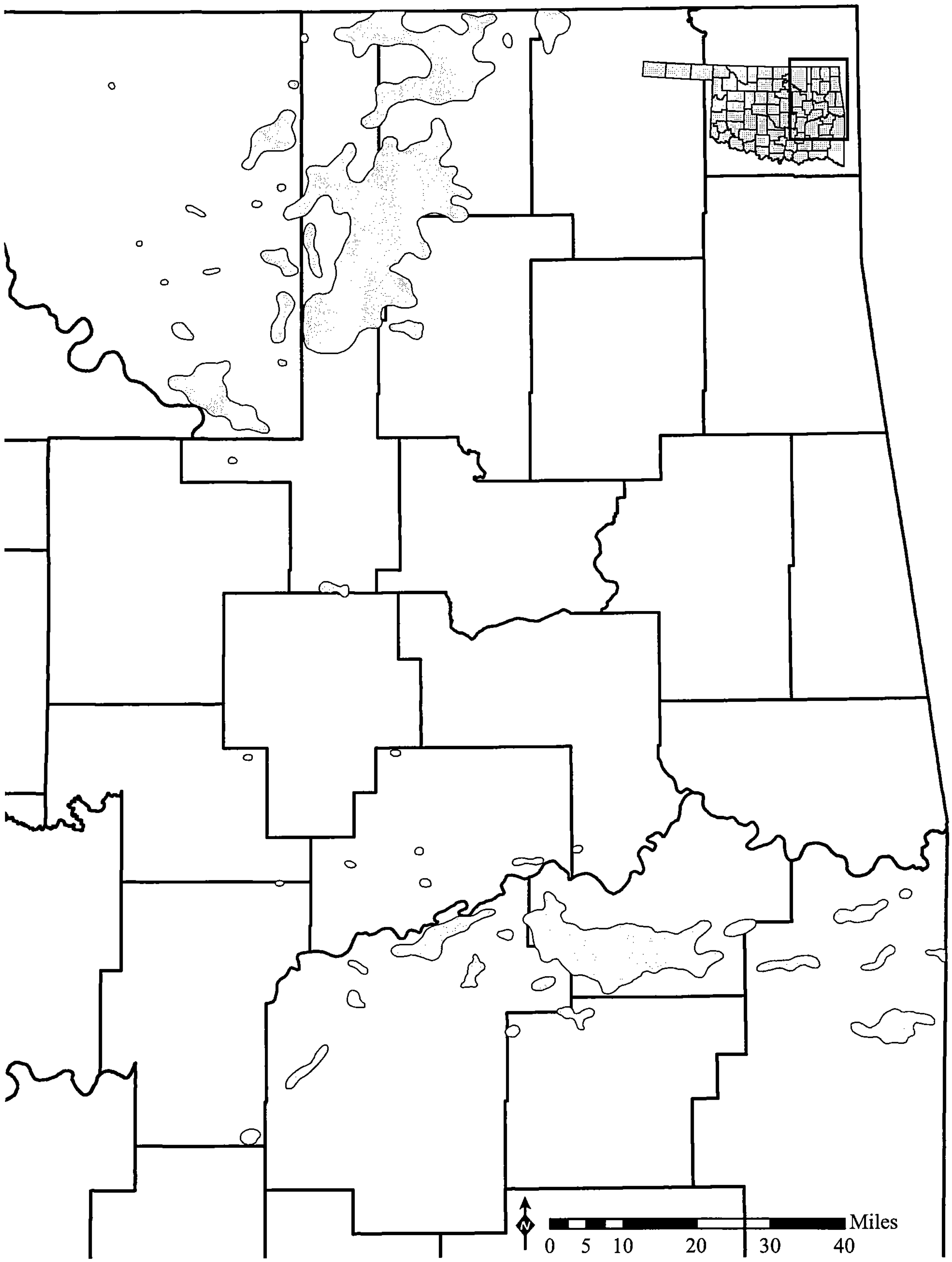

Figure 2. Map of Oklahoma coalbed methane fields (modified from Boyd, 2002).

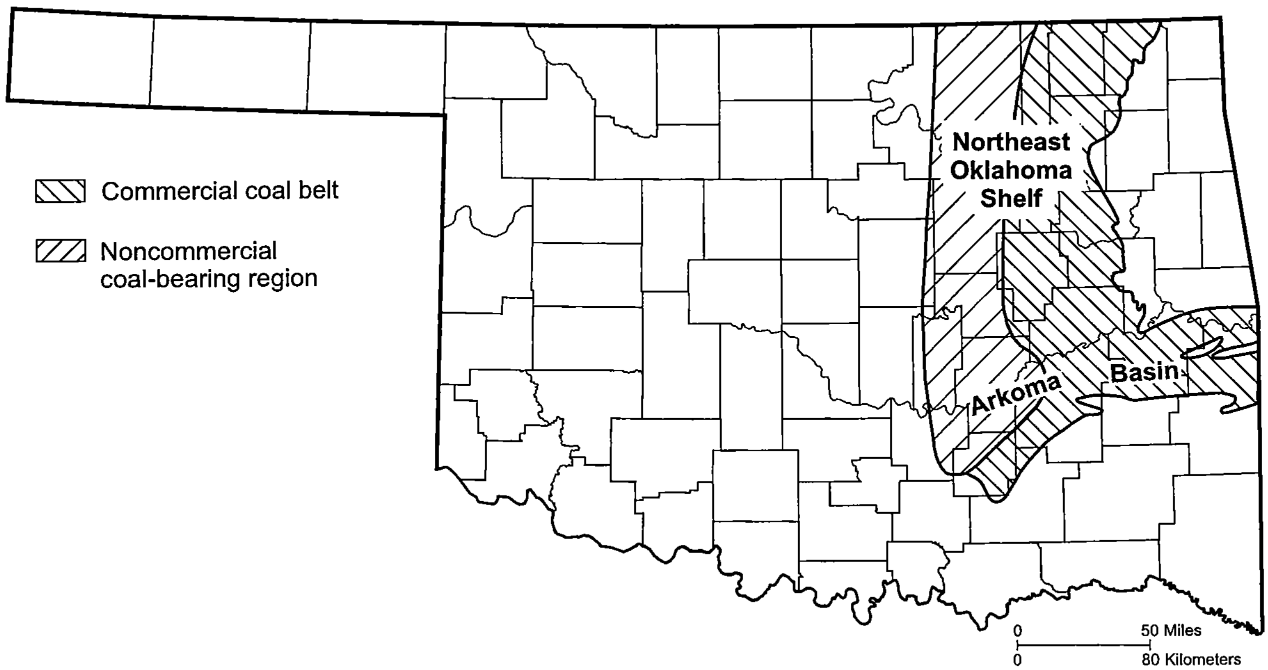

Figure 3. Map of Oklahoma coalfield (modified from Friedman, 1974).

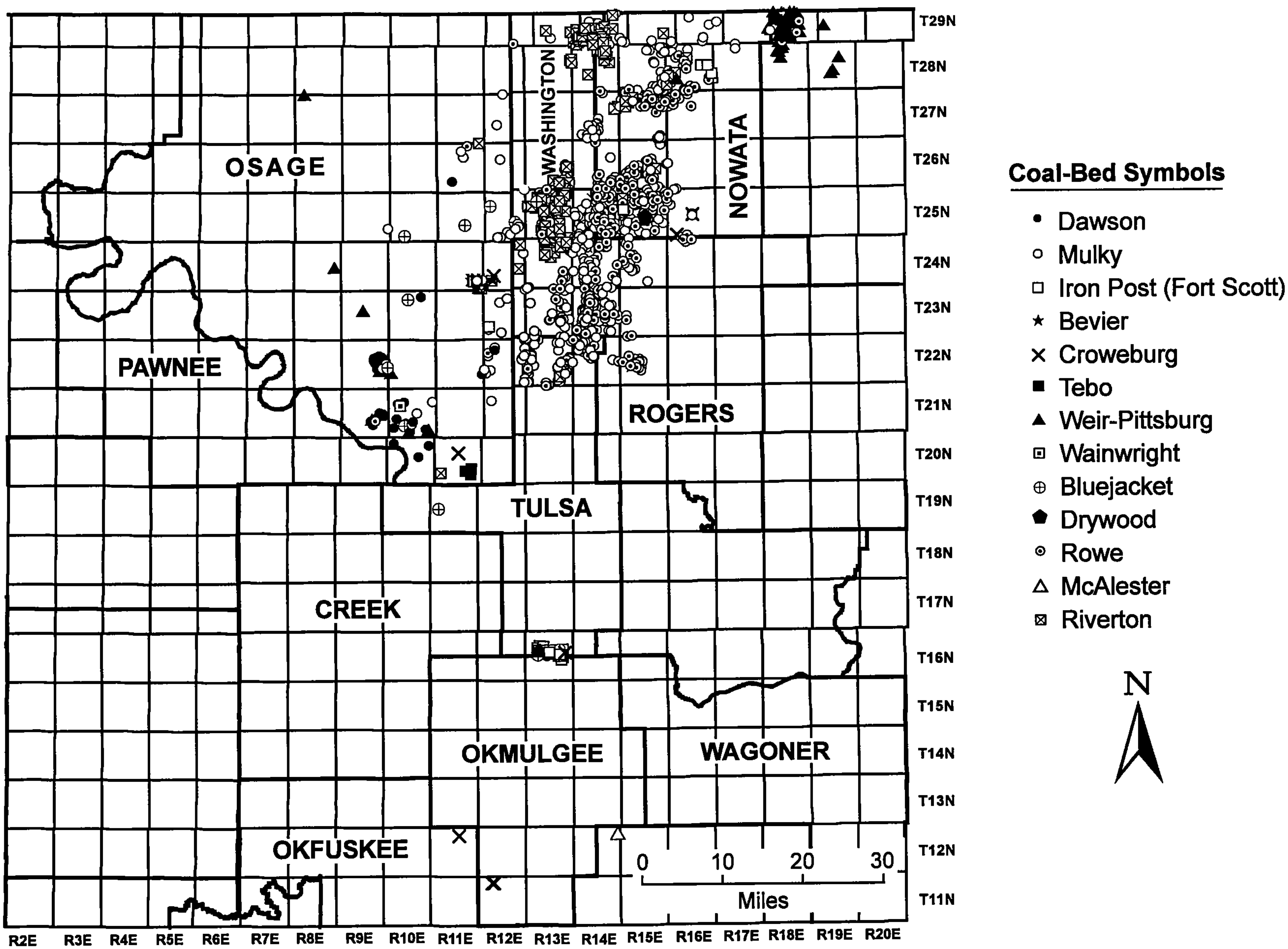

Figure 4. Distribution of coalbed-methane well completions by coal bed in the northeast Oklahoma shelf.

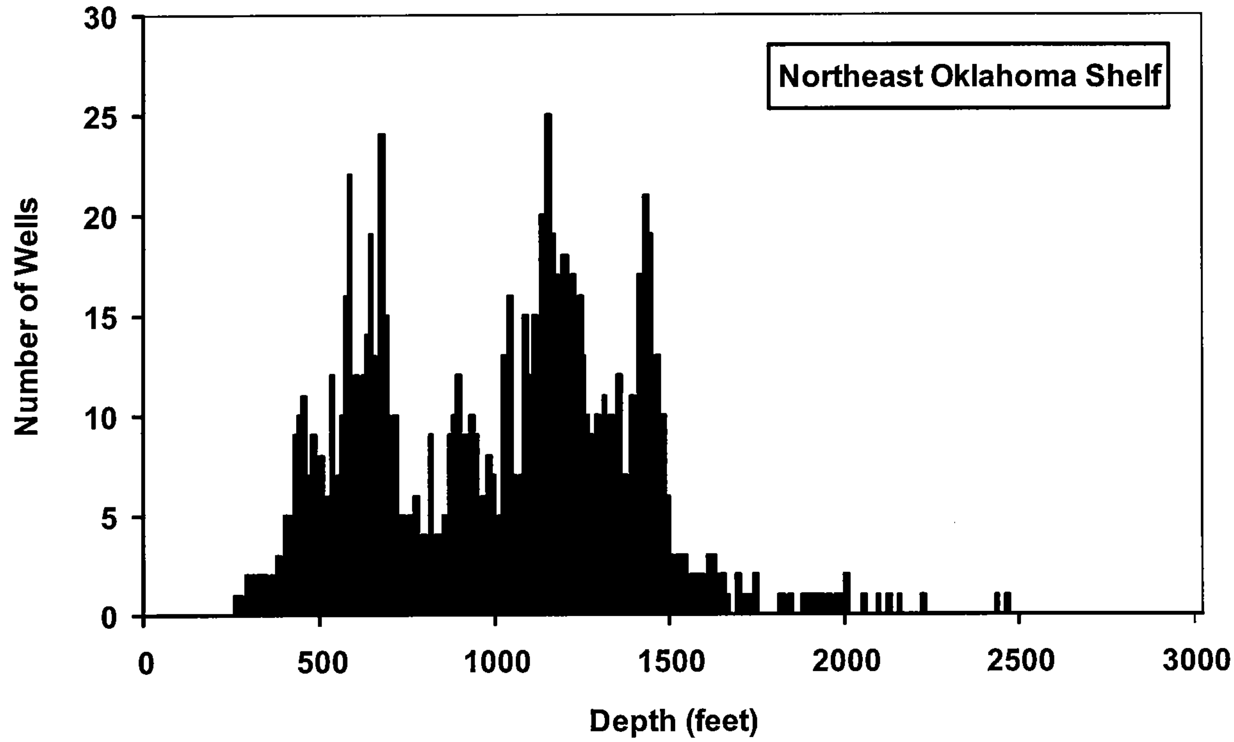

Figure 5. Histogram of coalbed-methane well completion depths in the northeast Oklahoma shelf.

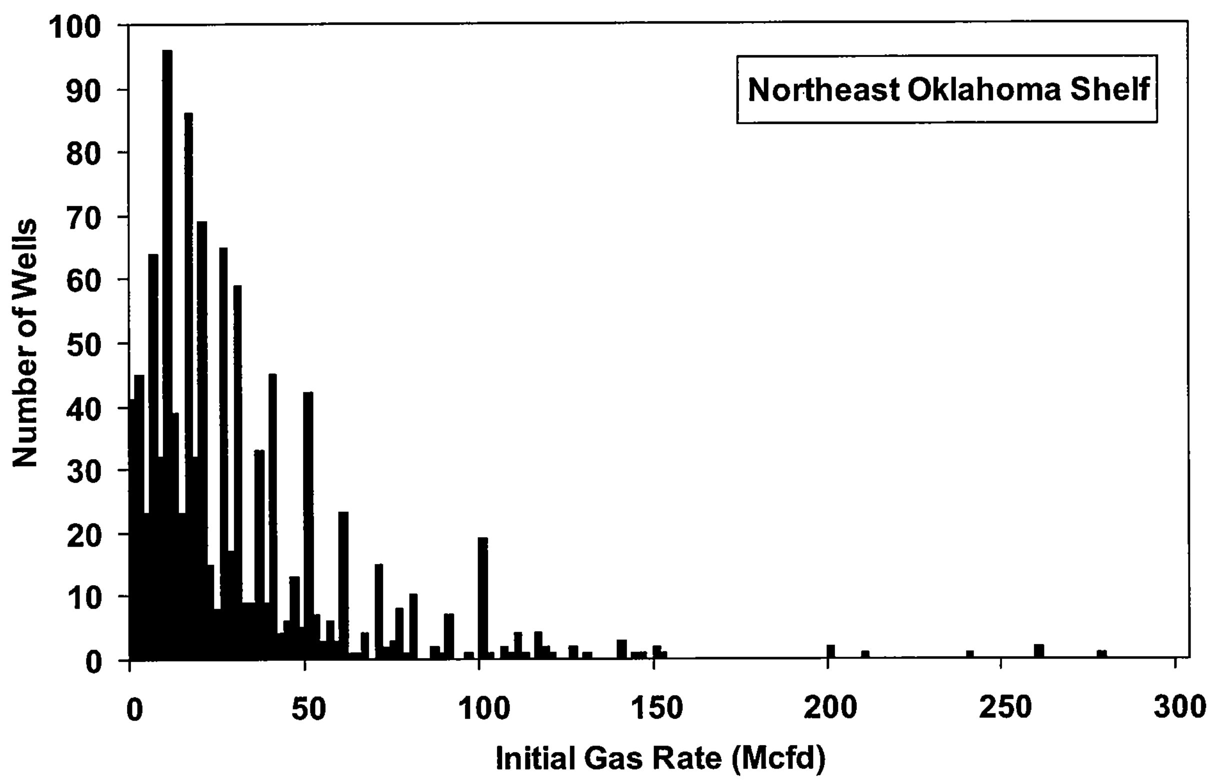

Figure 6. Histogram of initial-potential-gas rates in coalbed-methane well completions in the northeast Oklahoma shelf.

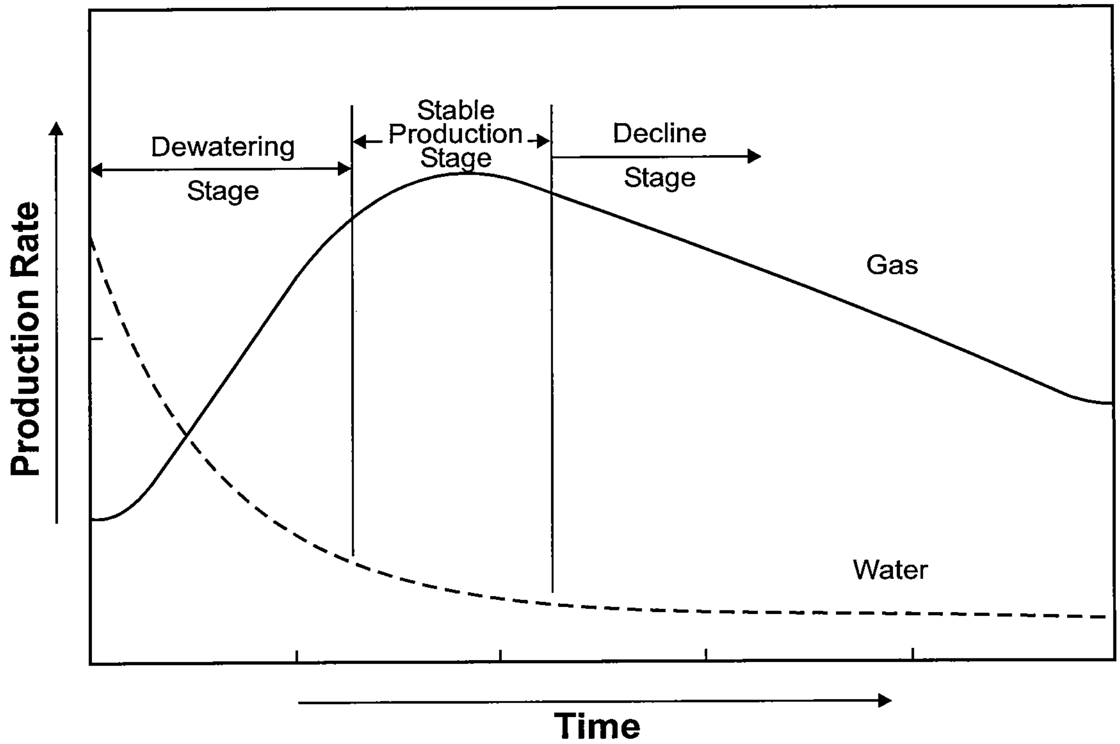

Figure 7. Theoretical production decline curve for a coalbed methane well (from Schraufnagel, 1993).

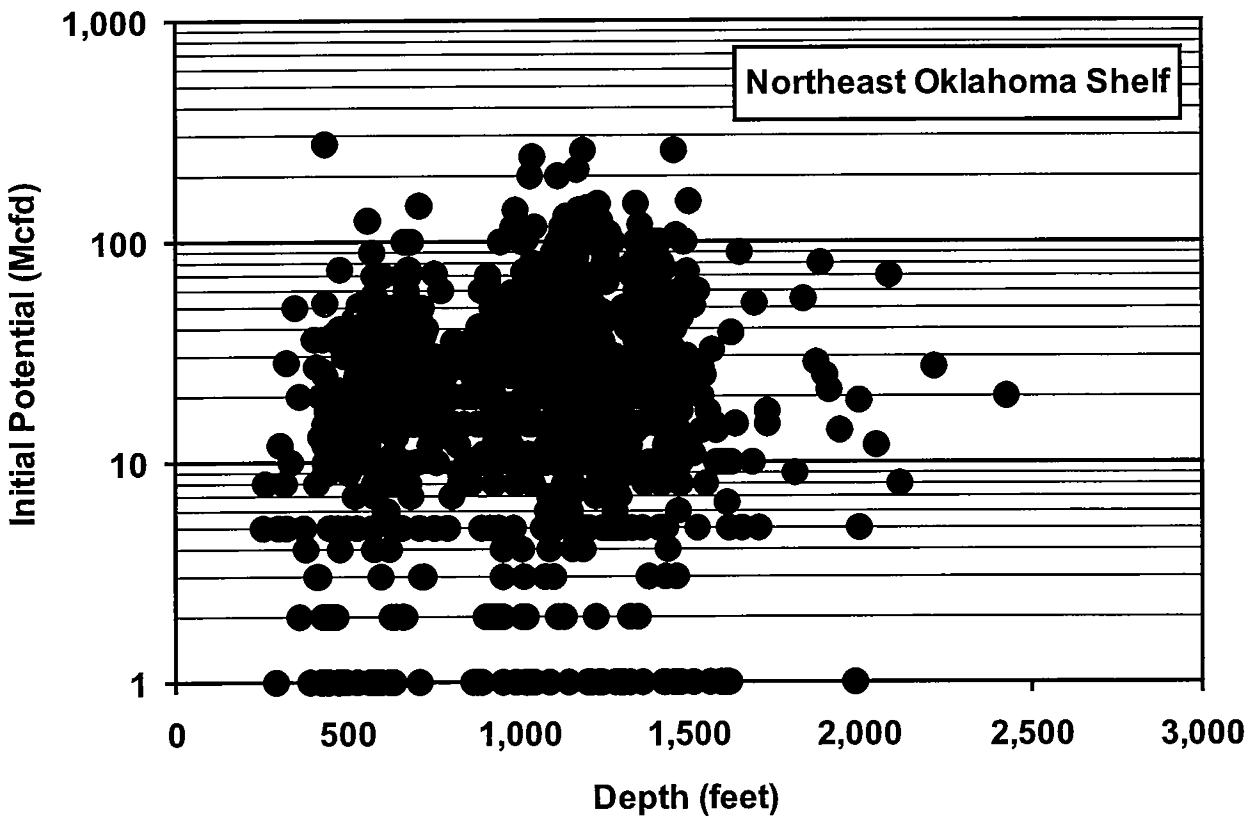

Figure 8. Scatter plot of initial-potential-gas rate (in thousand cubic feet of gas per day—Mcfd) and depth (in feet) to top of coal in the northeast Oklahoma shelf.

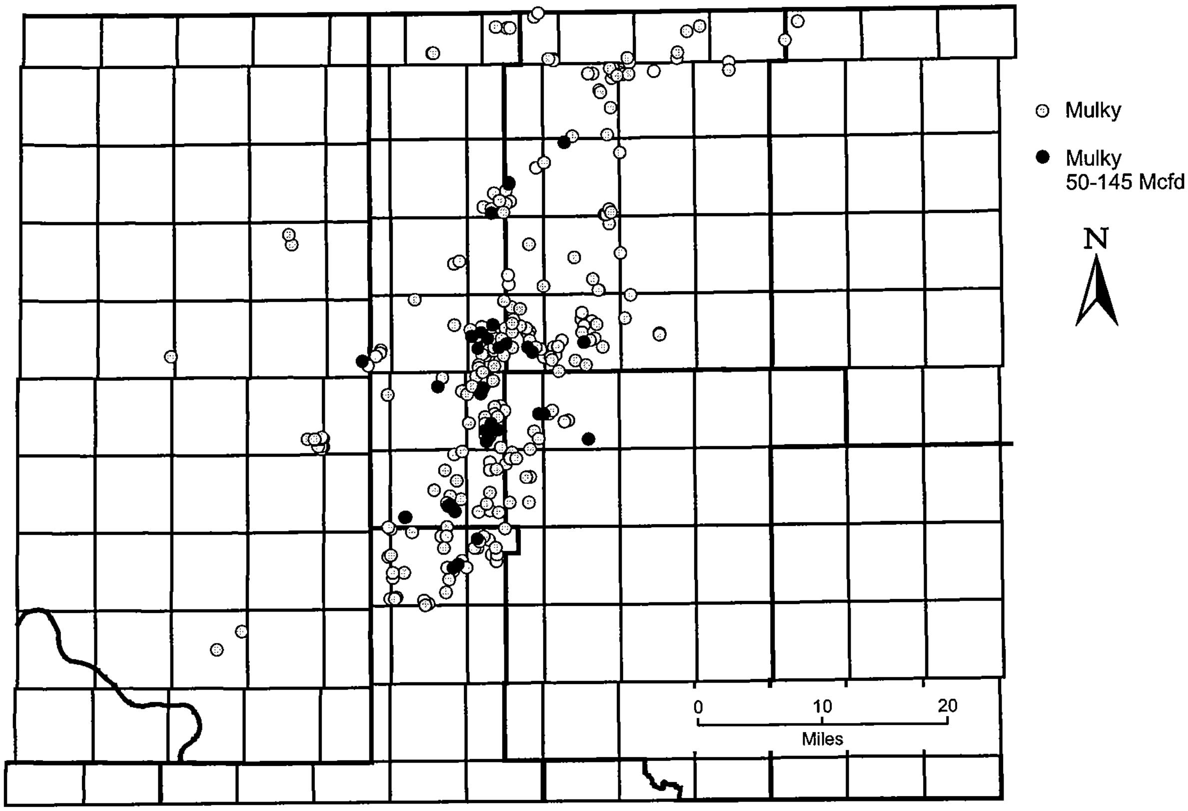

Figure 9. Distribution of well completions in the Mulky coal in the northeast Oklahoma shelf, showing wells with relatively high IP gas rates.

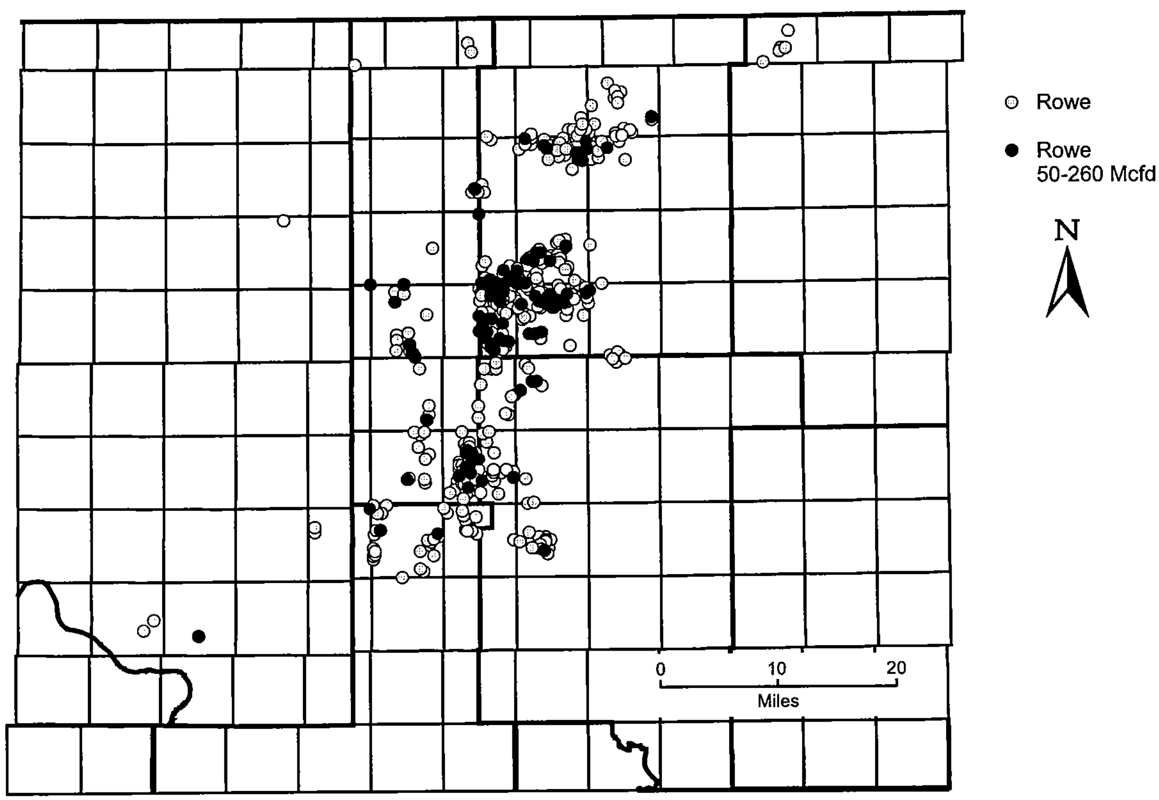

Figure 10. Distribution of well completions in the Rowe coal in the northeast Oklahoma shelf, showing wells with relatively high IP gas rates.

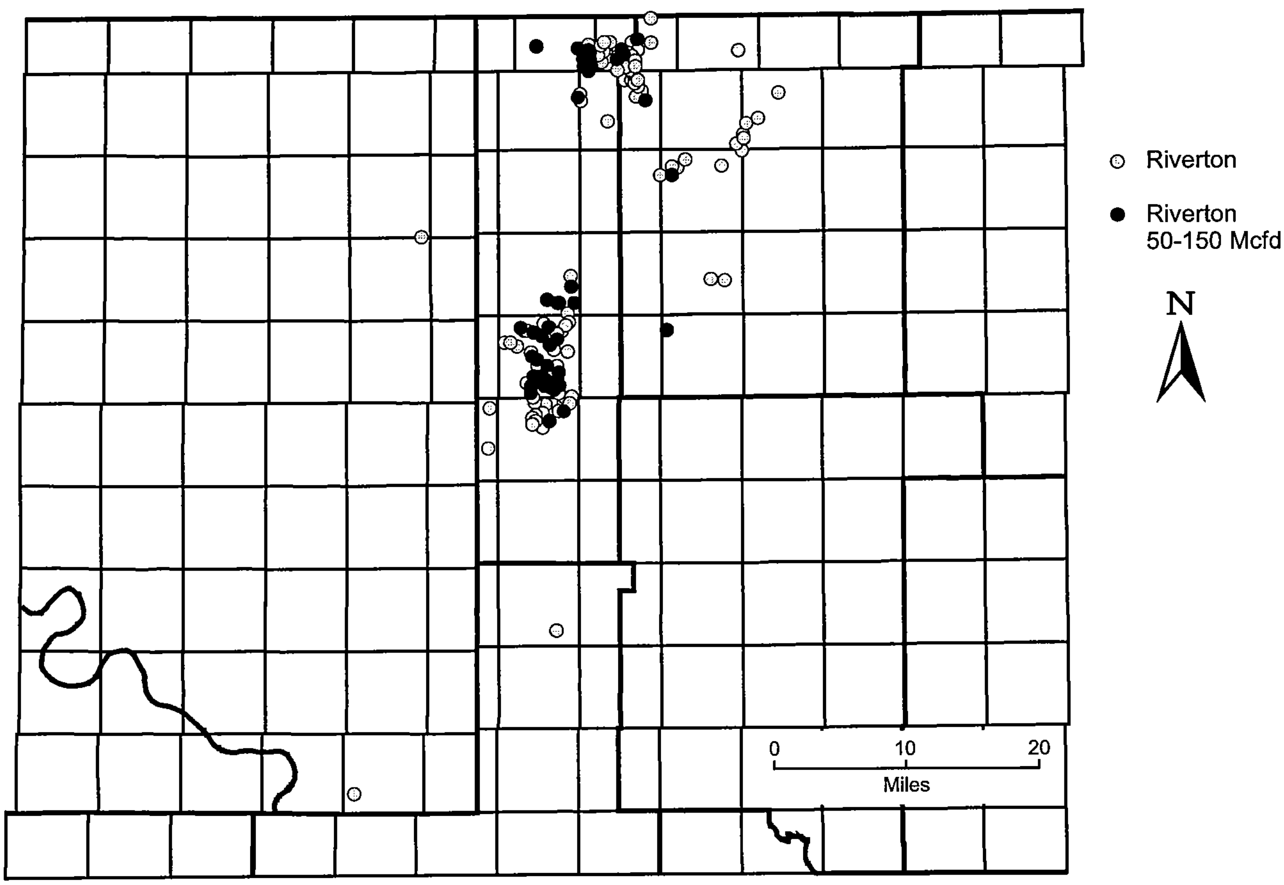

Figure 11. Distribution of well completions in the Riverton coal in the northeast Oklahoma shelf, showing wells with relatively high IP gas rates.

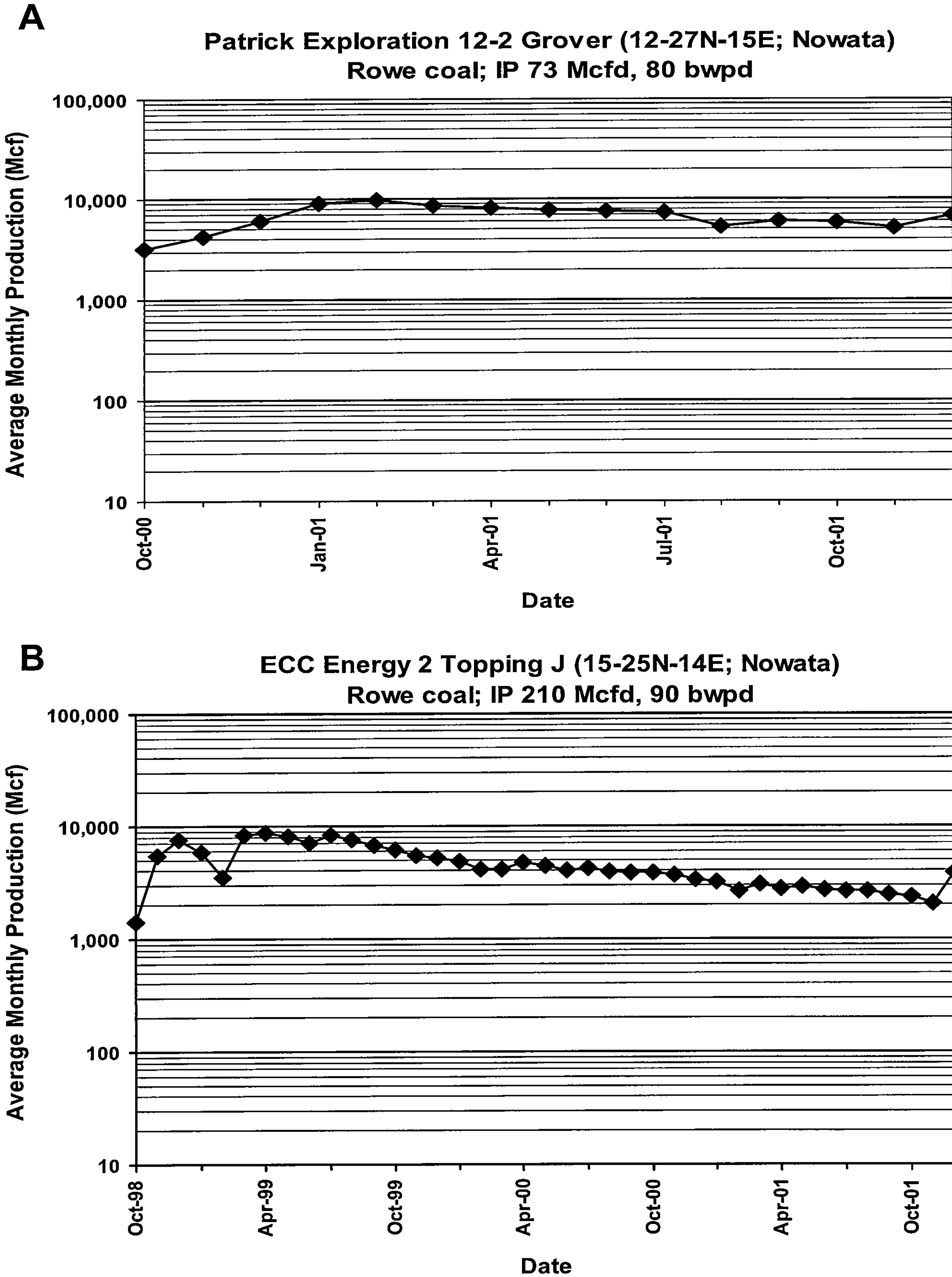

Figure 12. Gas-production-decline curves. (A) Patrick Exploration 12-2 Grover well; (B) ECC Energy 2 Topping J well. Monthly gas production by well is from Oklahoma Corporation Commission, operator, or IHS Energy Group.

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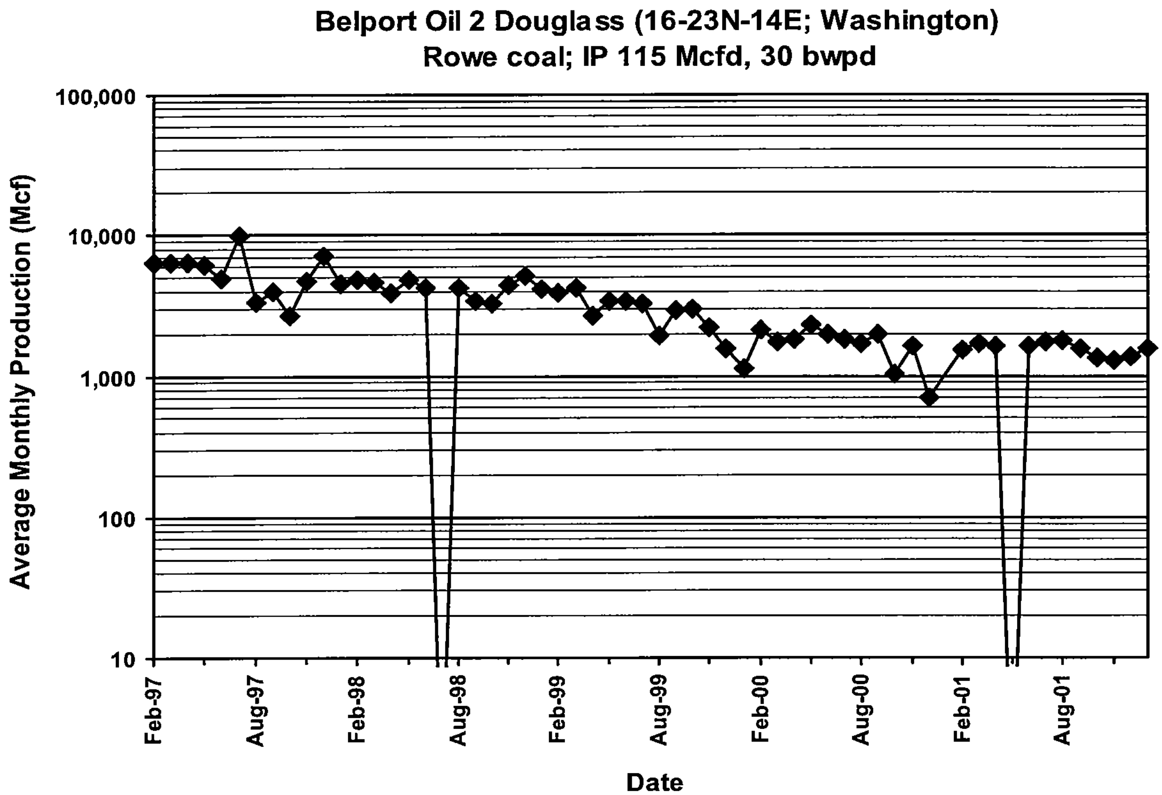

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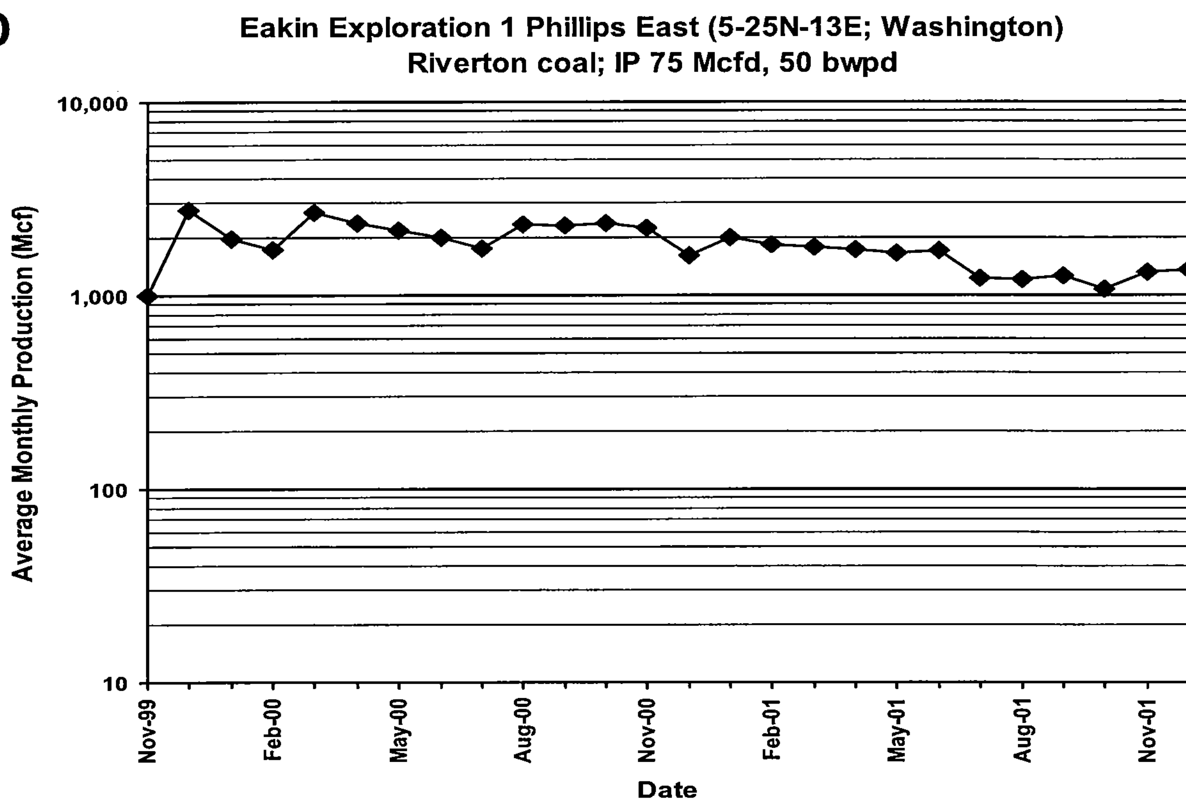


Figure 12. (cont.) Gas-production-decline curves. (C) Belport Oil 2 Douglass well; (D) Eakin Exploration 1 Phillips East well. Monthly gas production by well is from Oklahoma Corporation Commission, operator, or IHS Energy Group.

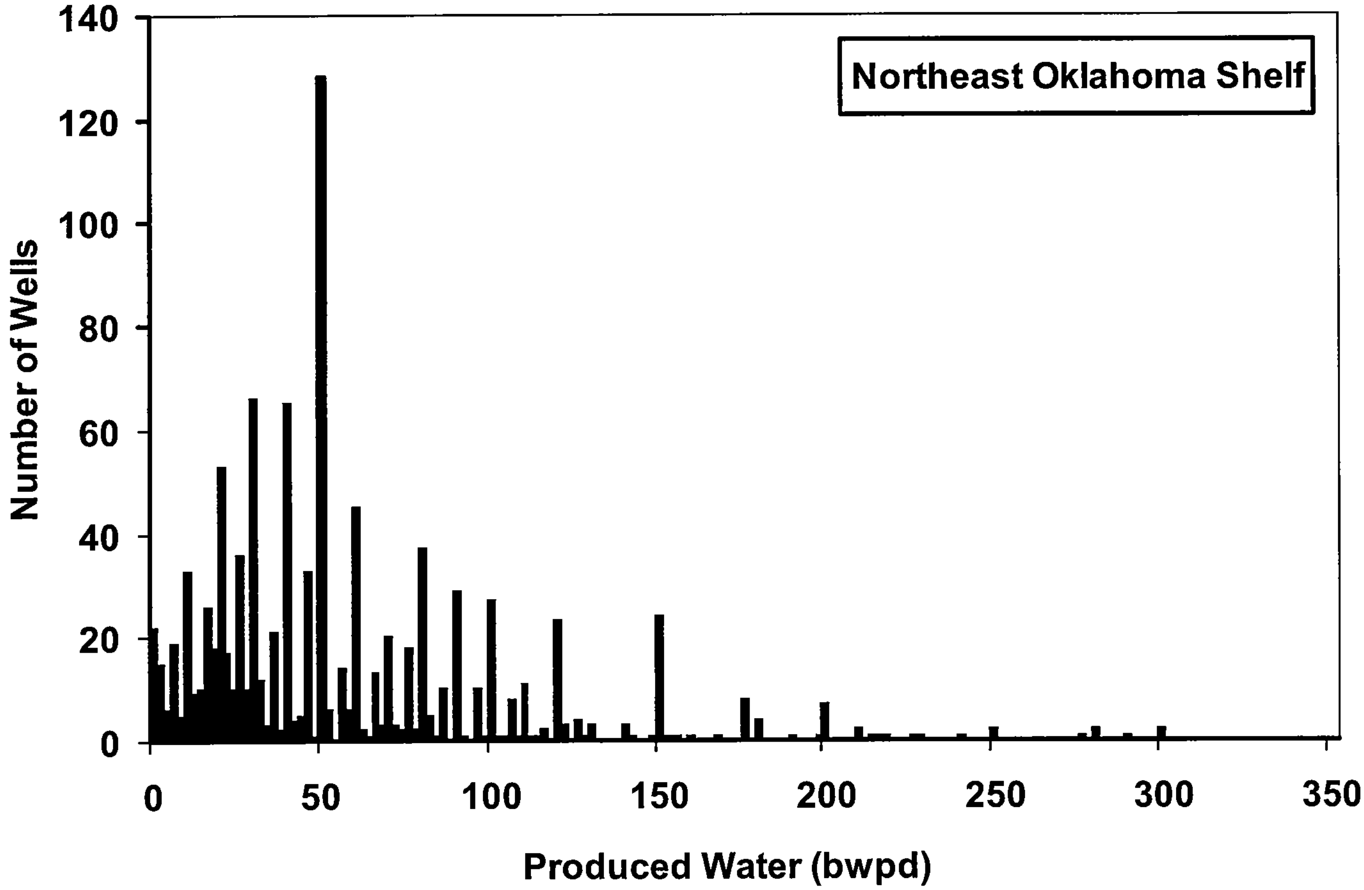


Figure 13. Histogram of initial water production rates from coalbed-methane wells in the northeast Oklahoma shelf (excluding two wells with 1,201 & 5,061 bwpd).

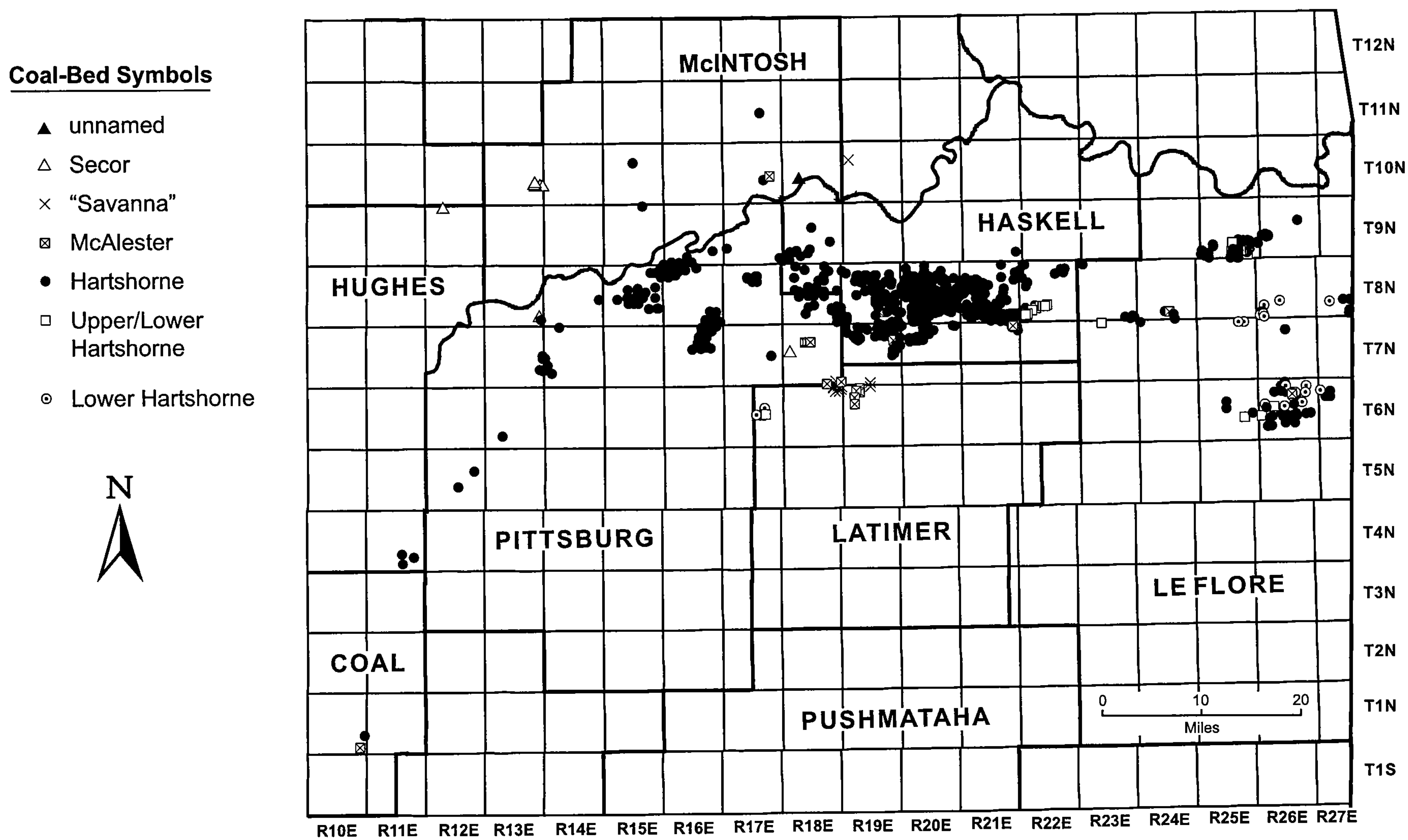


Figure 14. Distribution of coalbed-methane well completions by coal bed in the Arkoma basin.

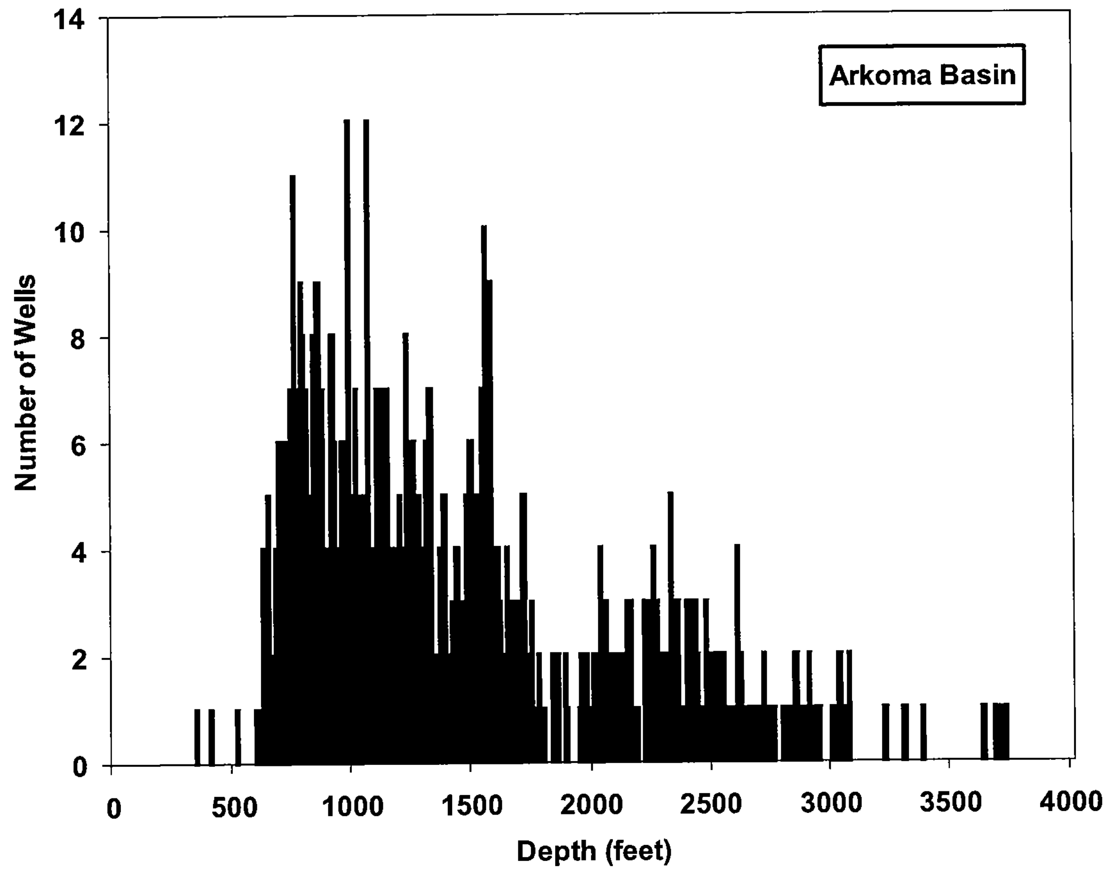


Figure 15. Histogram of coalbed-methane well completion depths in the Arkoma basin.

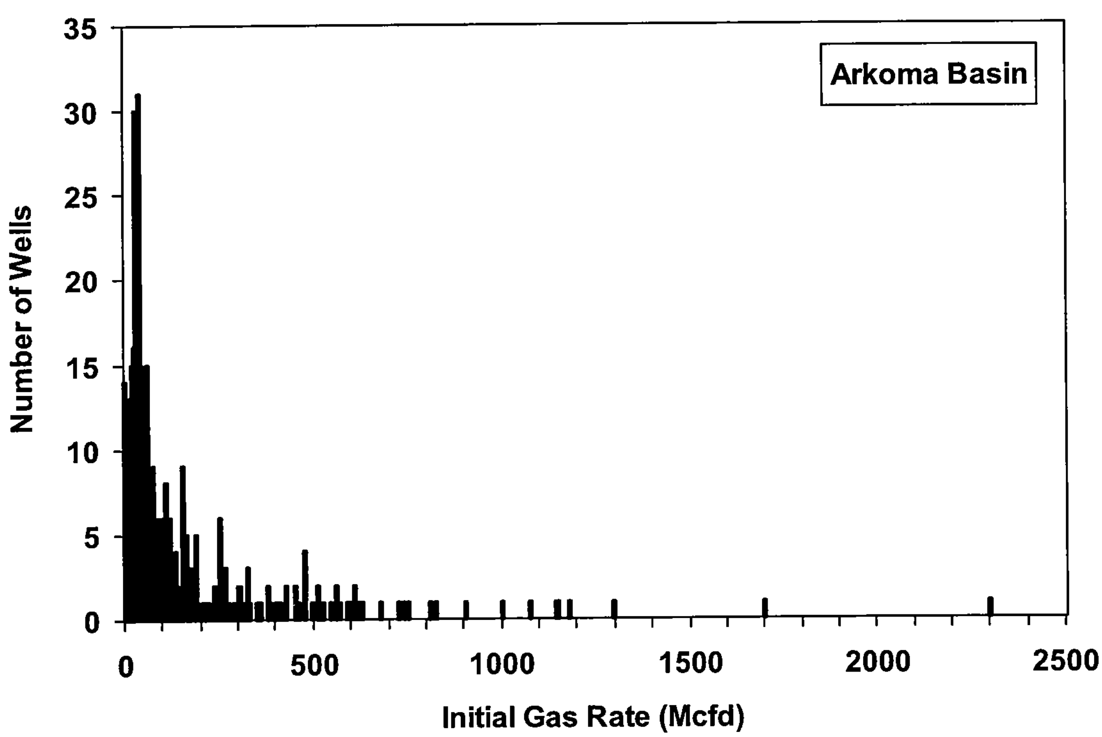


Figure 16. Histogram of initial-potential-gas rates in coalbed-methane well completions in the Arkoma basin.

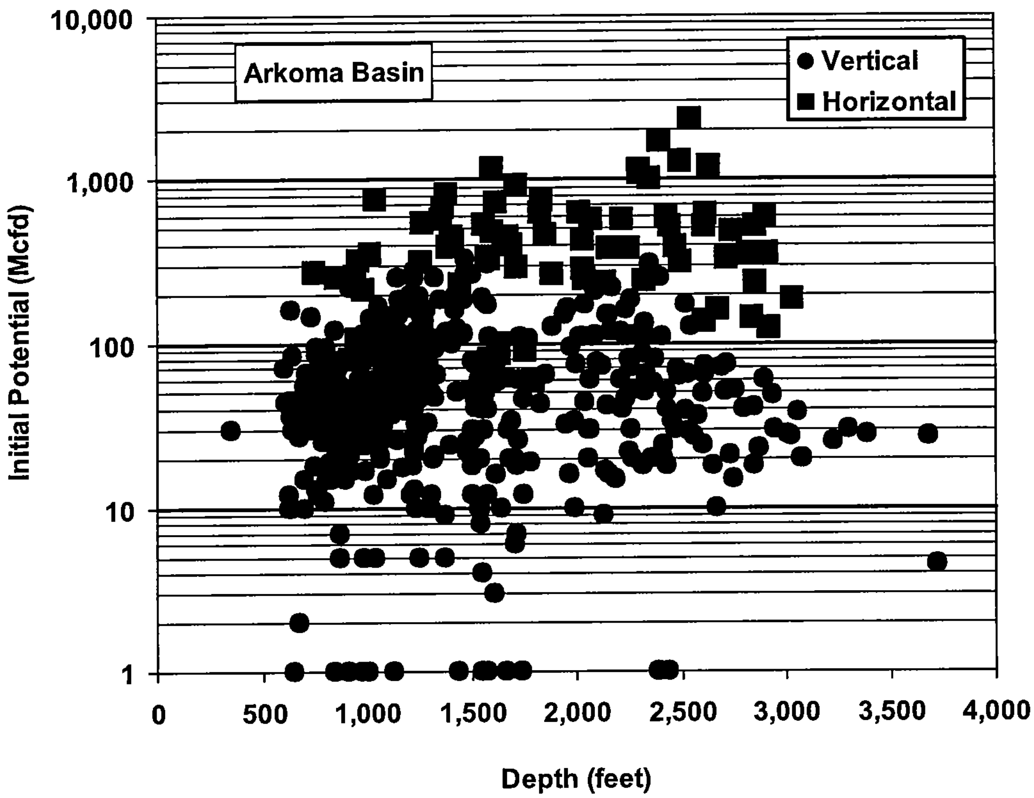


Figure 17. Scatter plot of initial-potential-gas rate (in thousand cubic feet of gas per day–Mcfd) and depth (in feet) to top of coal in the Arkoma basin.

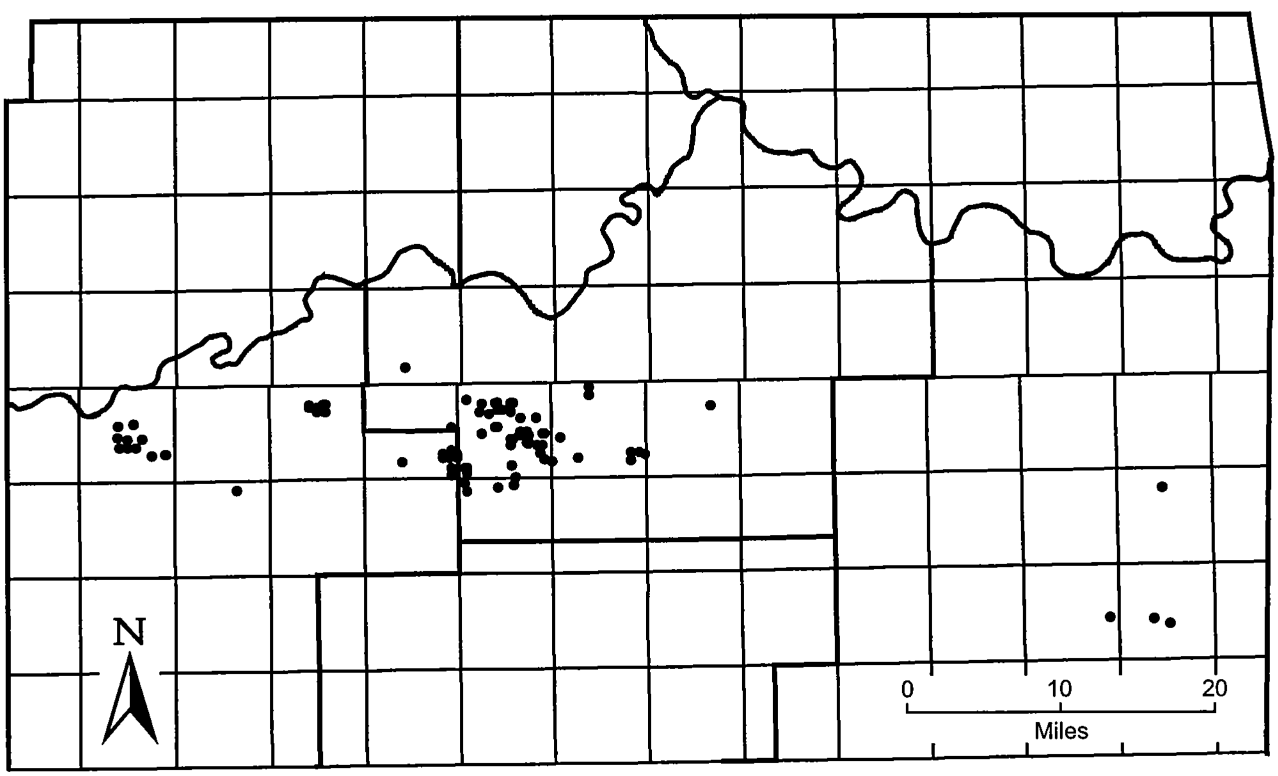


Figure 18. Distribution of horizontal coalbed-methane well completions in the Arkoma basin.

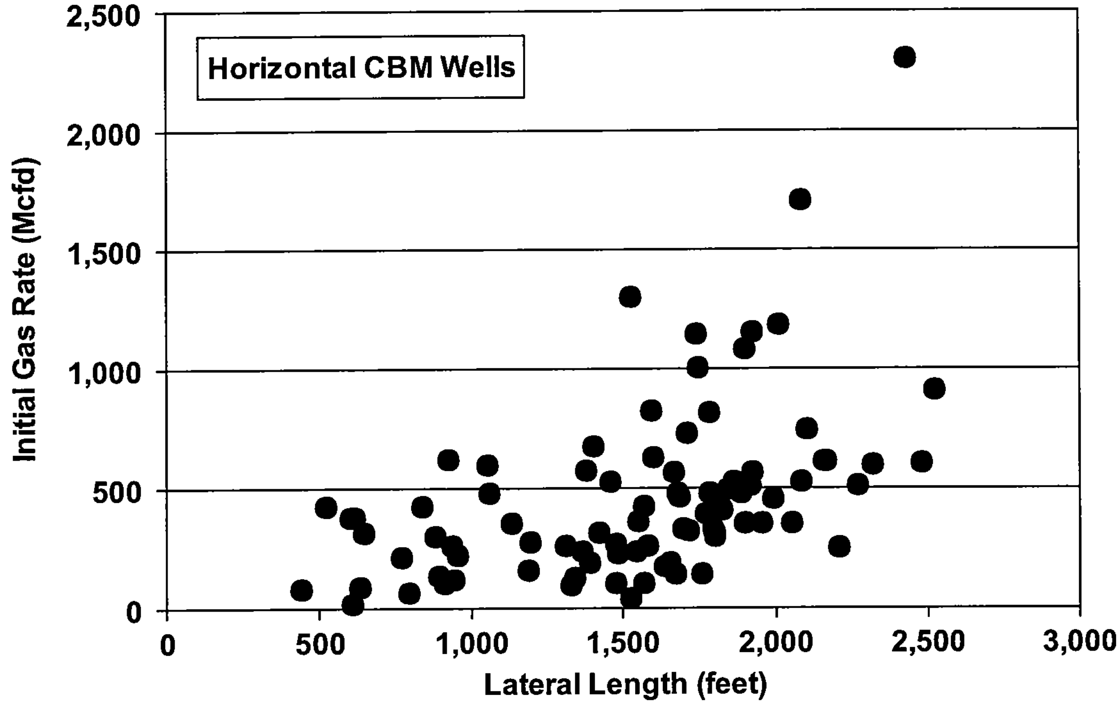


Figure 19. Scatter plot of initial-potential-gas rate and horizontal lateral length in the Arkoma basin.

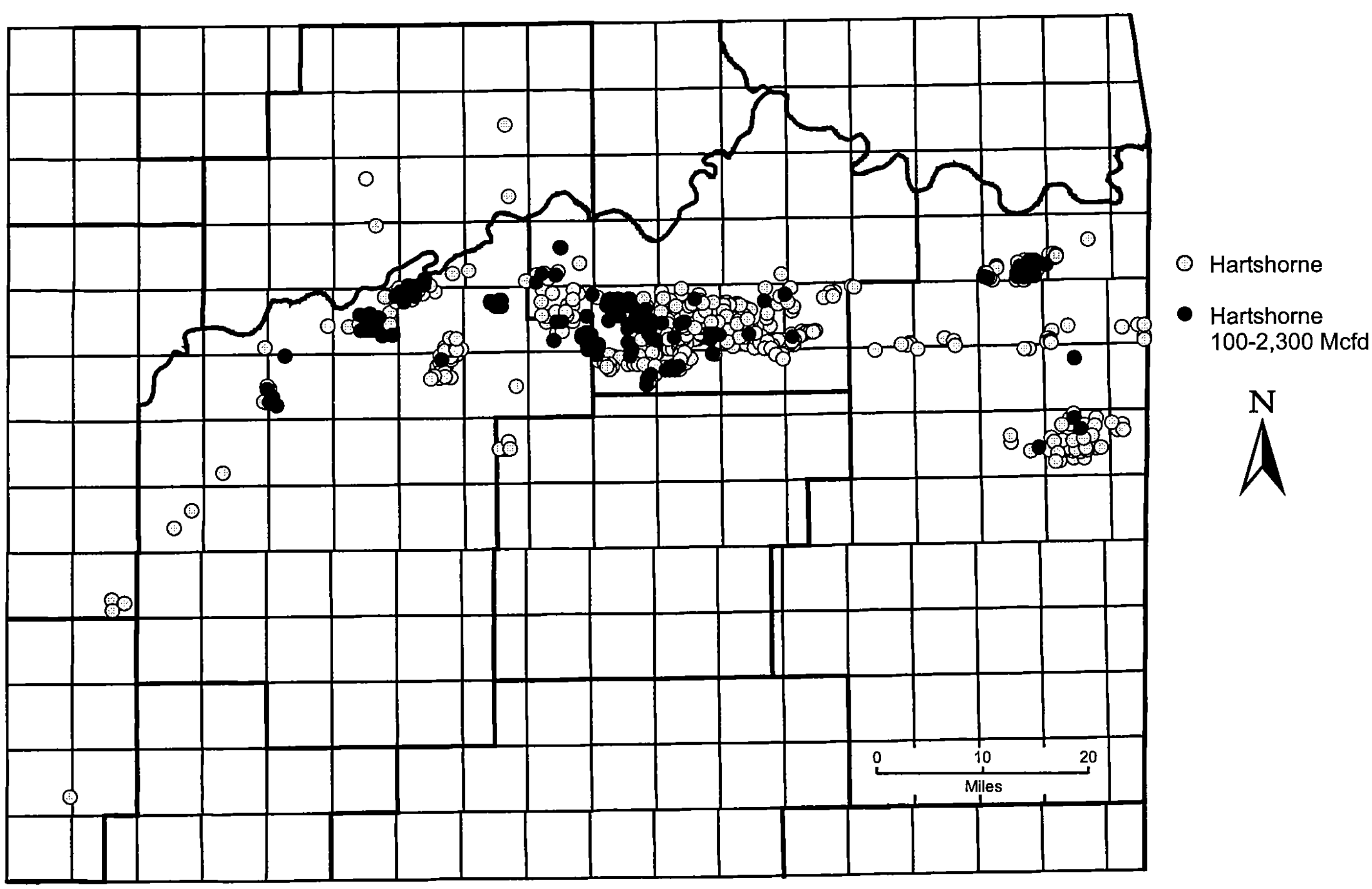
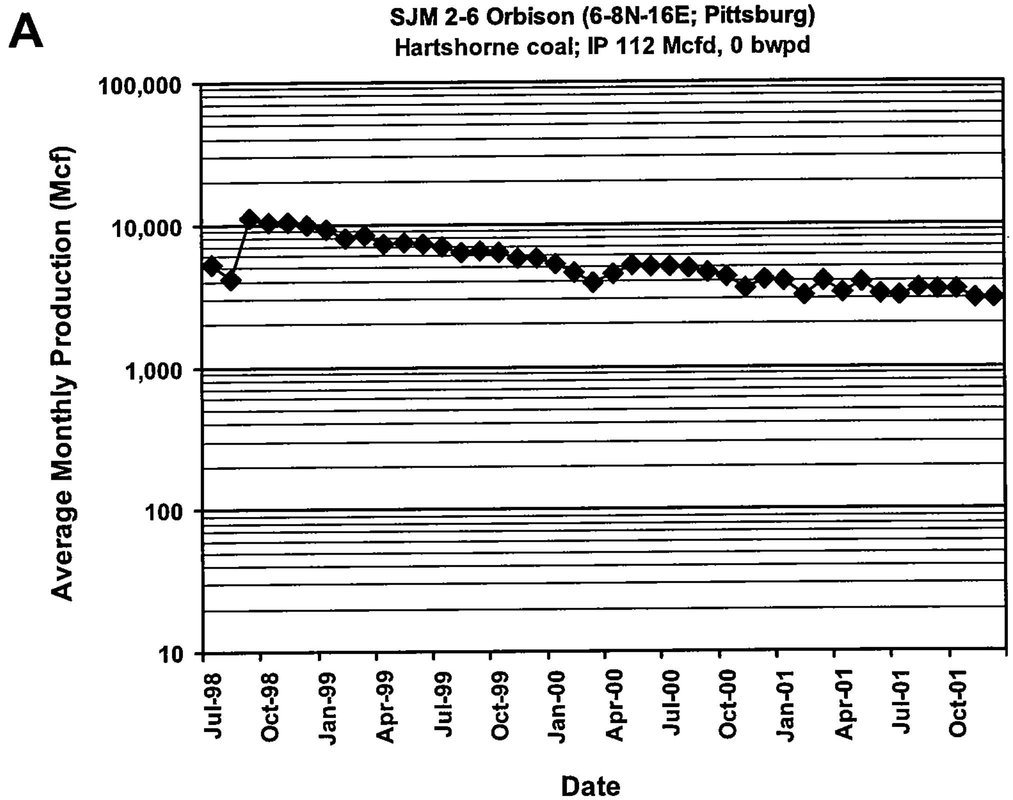


Figure 20. Distribution of well completions in the Hartshorne coal in the Arkoma basin, showing wells with relatively high IP gas rates.



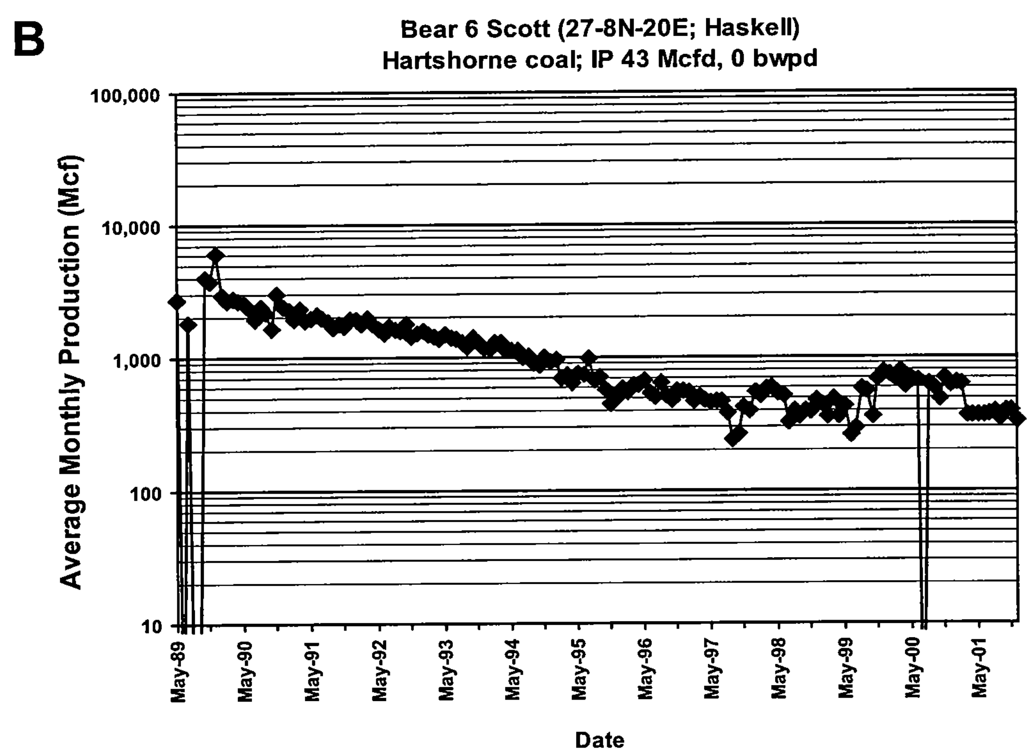


Figure 21. Gas-production-decline curves. (A) SJM Inc. 2-6 Orbison well; (B) Bear Productions 6 Scott well. Monthly gas production by well is from Oklahoma Corporation Commission, operator, or IHS Energy Group.

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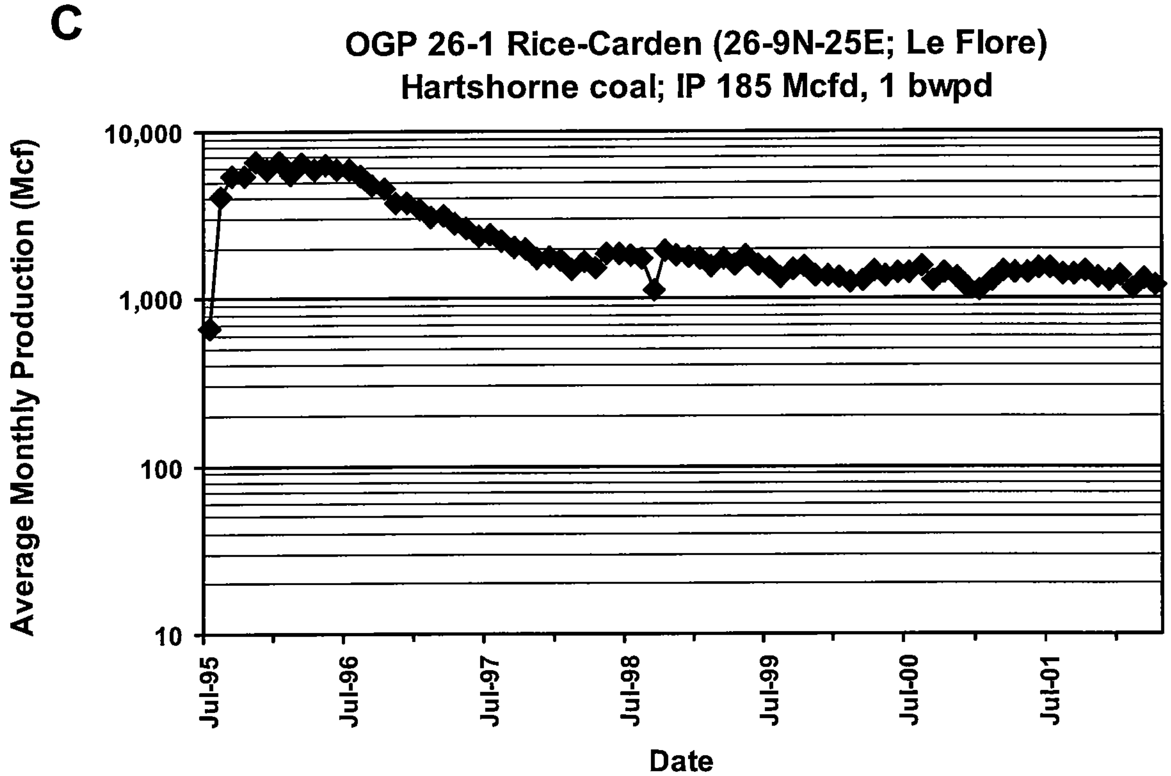

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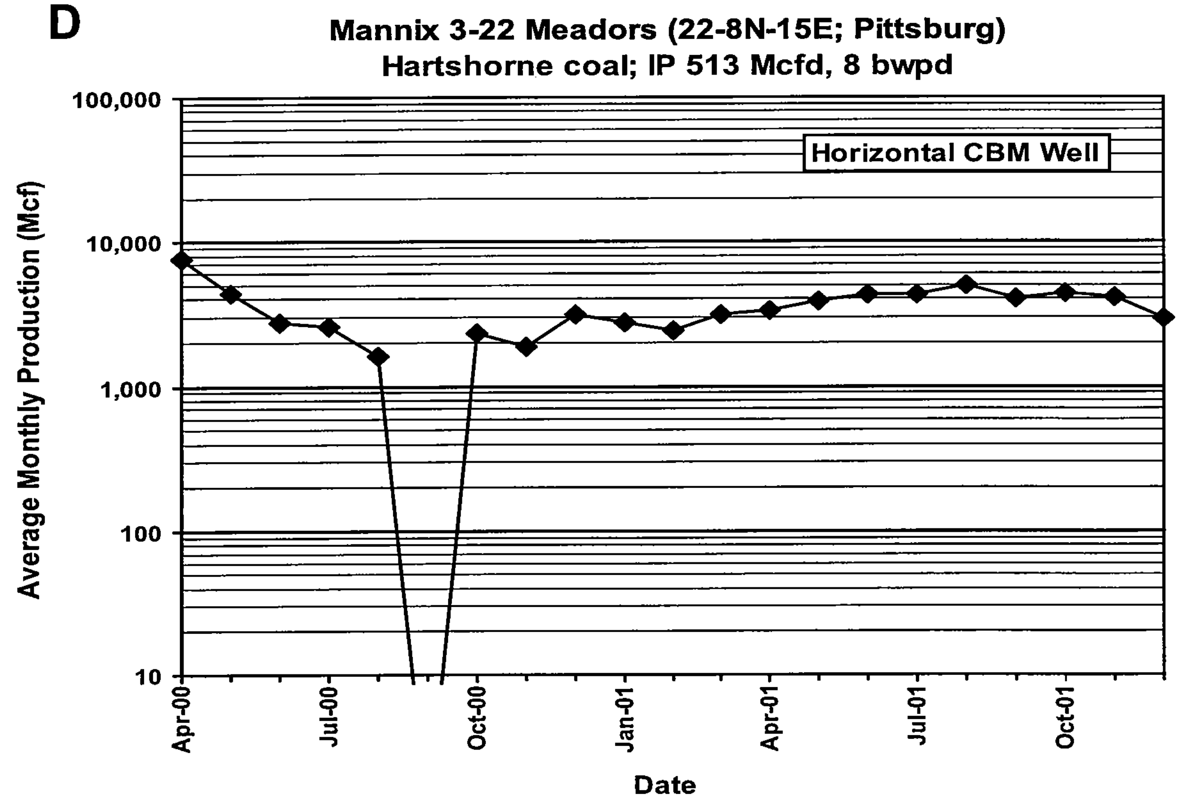
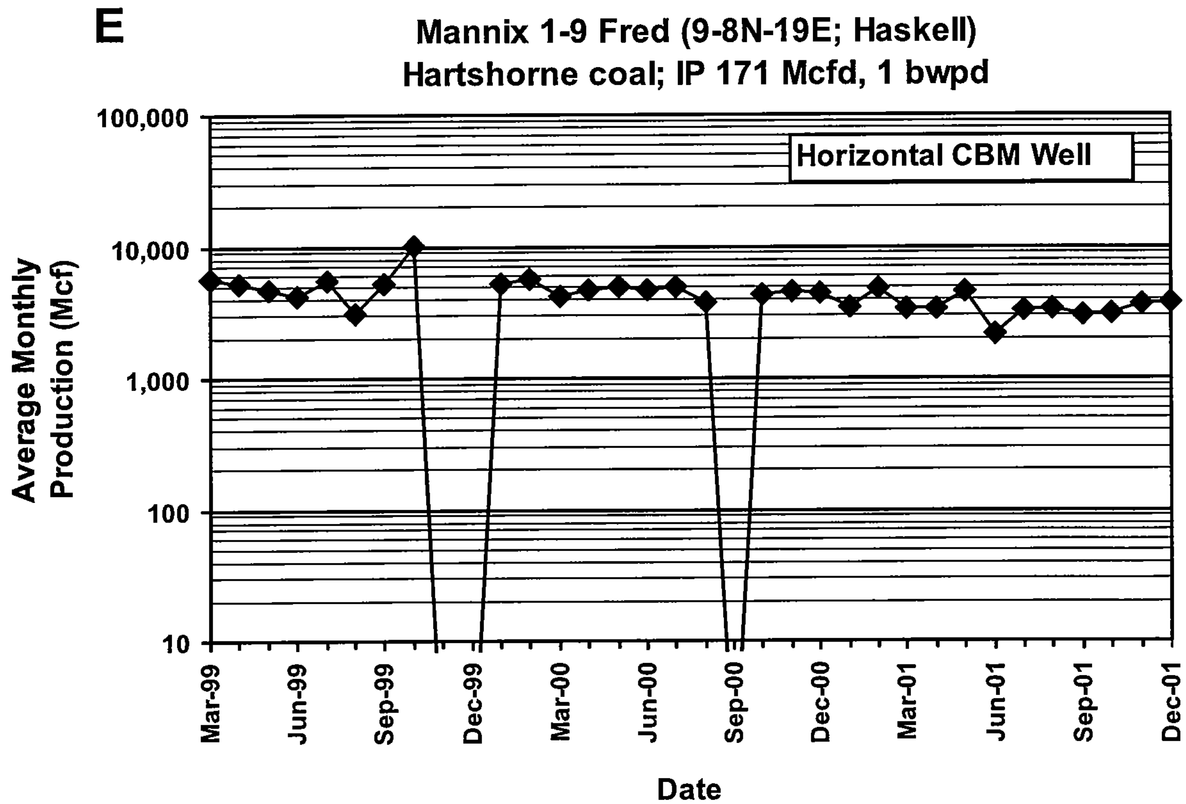


Figure 21. (cont.) Gas-production-decline curves. (C) OGP Operating 26-1 Rice-Carden well; (D) Mannix Oil 3-22 Meadors well. Monthly gas production by well is from Oklahoma Corporation Commission, operator, or IHS Energy Group.



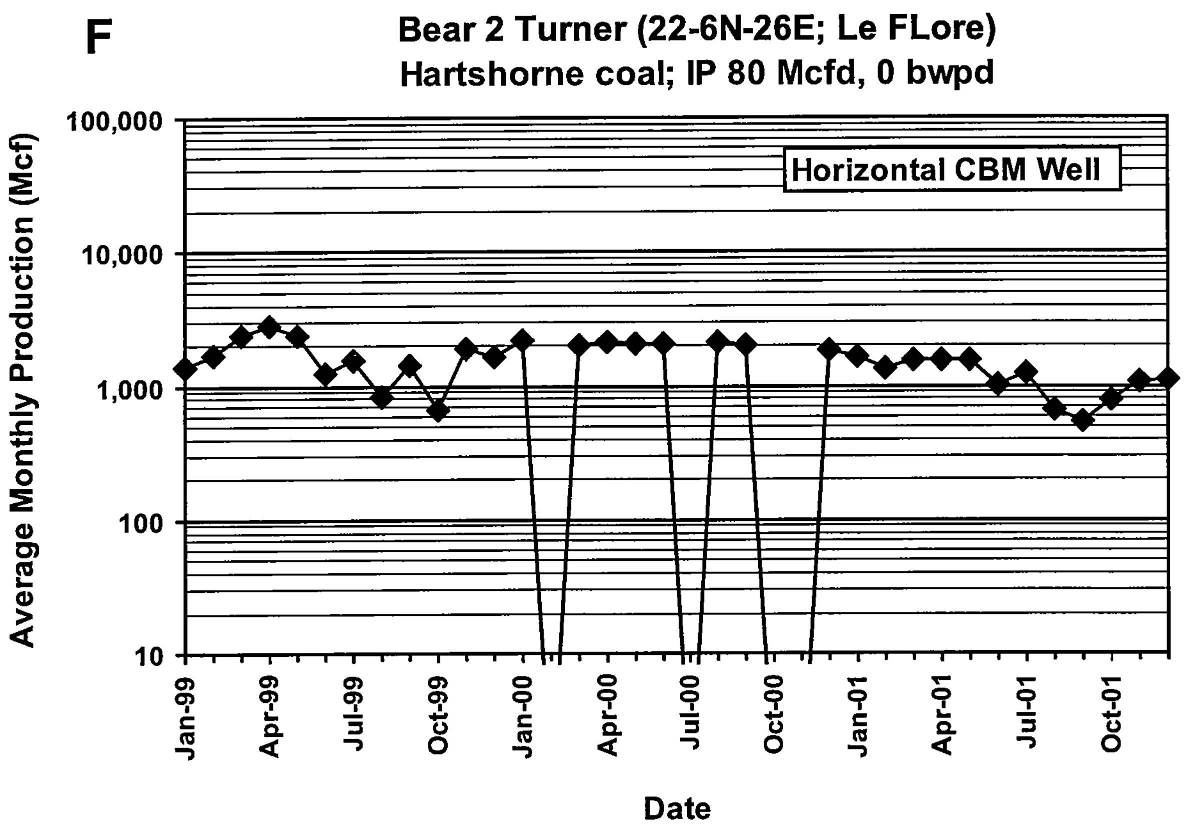


Figure 21. (cont.) Gas-production-decline curves. (E) Mannix Oil 1-9 Fred well; (F) Bear Productions 2 Turner well. Monthly gas production by well is from Oklahoma Corporation Commission, operator, or IHS Energy Group.

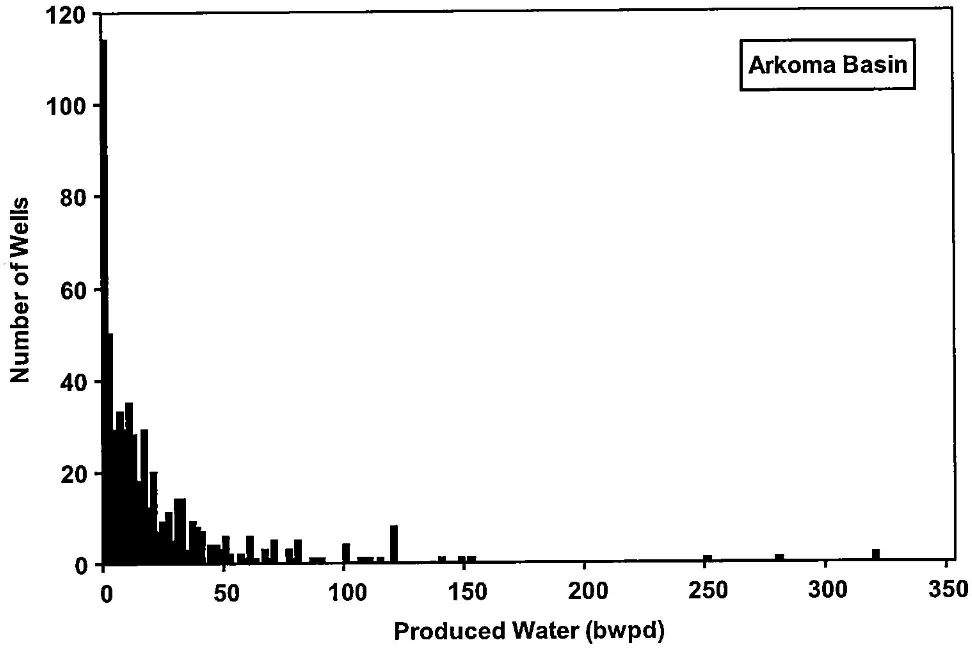


Figure 22. Histogram of initial water production rates from coalbed-methane wells in the Arkoma basin.

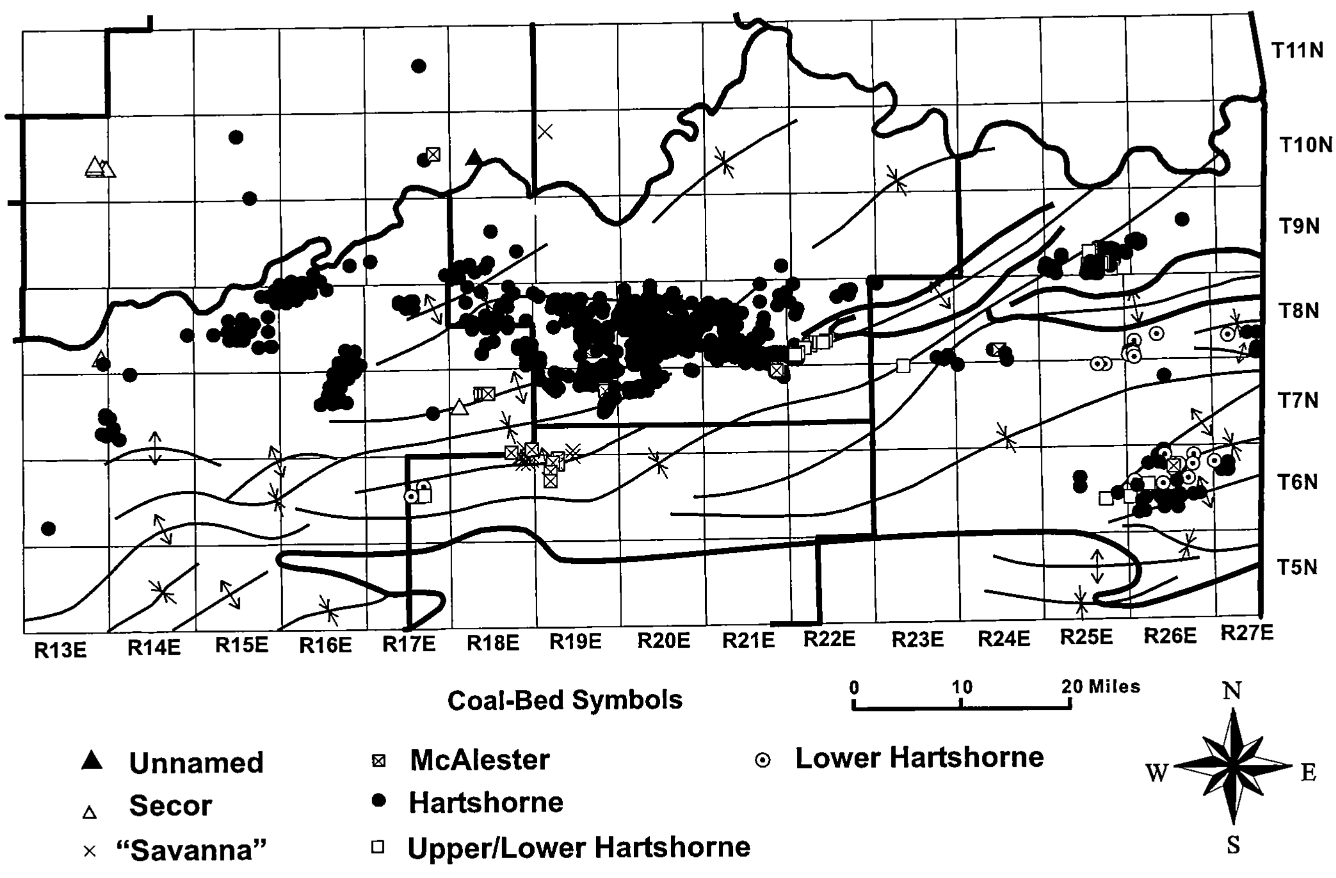


Figure 23. Major surface folds, Hartshorne coal outcrop, and coalbed-methane well completions in the Arkoma basin, Oklahoma. Structure modified from Arbenz (1956, 1989), Berry and Trumbly (1968), and Suneson (1998).

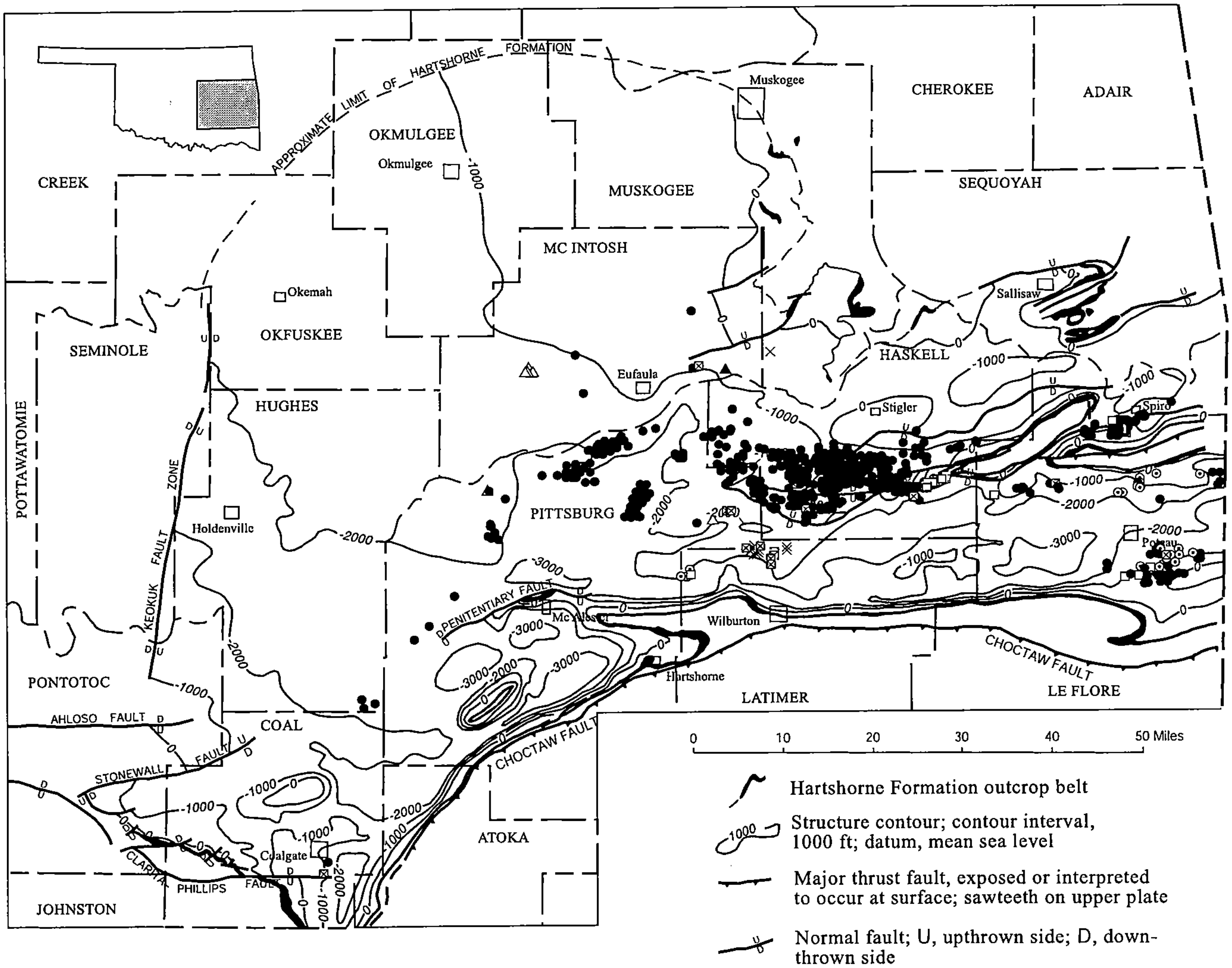


Figure 24. Map of coalbed-methane wells on Hartshorne structure map (modified from Cardott, 2002).

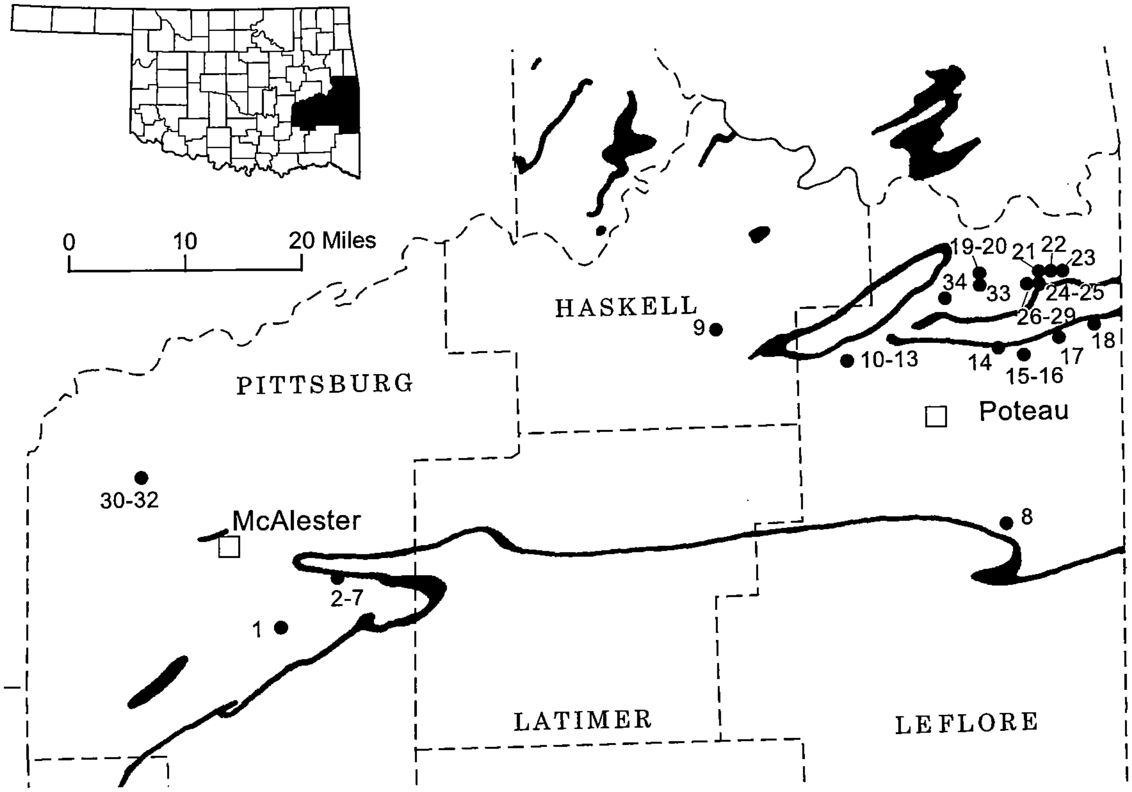


Figure 25. Map showing location of Oklahoma coal-core desorption samples and outline of Hartshorne coal outcrop (modified from Andrews and others, 1998, refer to Table 7 for desorption analyses).

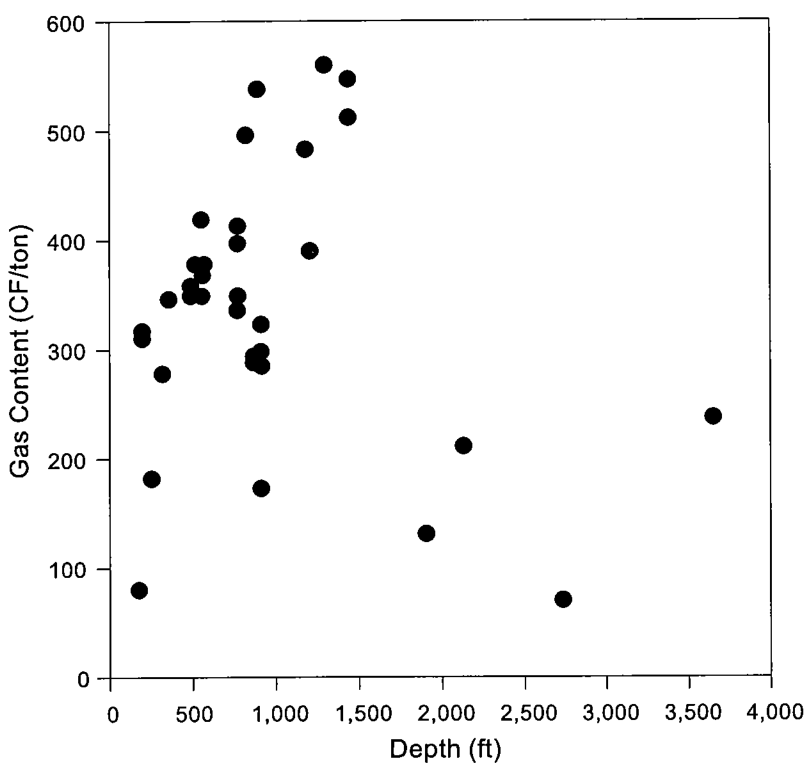


Figure 26. Oklahoma coal-gas content versus depth (from Andrews and others, 1998).

OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 9-2002

4

Geophysical well-log interpretation for coalbed methane

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Hall, R.V., 2002, Geophysical well-log interpretation for coalbed methane, *in* Fourth annual Oklahoma coalbed-methane workshop: Oklahoma Geological Survey, Open-File Report 9-2002, p. 83-110.

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R. Vance Hall 10/10/02

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- Gas Technology Institute
- Oklahoma Geological Survey, Brian Cardott
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- Tucker Wireline Services, Jeff Formica

Without their suggestions, feedback, permissions to reproduce copyrighted materials, and in some instances slides, this presentation would have been quite difficult.

INTRODUCTION

The purpose of this presentation is to provide an overview of the wireline logging methods that have been used in coal exploration and coalbed gas exploration. I am not a log analyst. For ten years early in my career, I explored for coal throughout the U.S. I had the opportunity to describe many thousands of feet of core in coal-bearing sequences, and routinely compared the core descriptions with wireline logs. My views on well-log interpretation for coalbed gas reflect this experience.

A new cycle of coal exploration is taking place, this time with new criteria and constraints. The natural gases contained within the coal matrix, referred to here as CBM, are the resource of interest rather than the coal. However, most of the logging methods now used for coalbed gas evaluation were developed many years ago in the search for mineable coal resources.

My objectives are:

1. To provide an introduction to evaluating coal with geophysical well logs.
2. To raise some issues that should be considered in designing a logging program and in interpreting logs.
3. To review some log examples from Tixier and Alger (1967), one of the classic papers on interpreting wireline logs for coal evaluation.
4. To review examples of (slimhole) coal logging in the mining industry since 1972, with an emphasis on the benefits of core description for improving log interpretations.
5. To review the logging methods most commonly used for CBM exploration.

The wireline log examples presented here are mostly logs of bituminous coals, because these are the coals most commonly exploited for CBM. Examples of the logging methods most commonly used for CBM exploration are provided.

More emphasis is given to the density log than other methods. Geophysics entails the sensing of contrasts in rock properties. The density log is one of the most commonly used methods in CBM exploration because the low density of coal contrasts markedly with the densities of other rock types that commonly occur in coal-bearing sequences.

EARLY COAL LOGGING

Schlumberger was among the first to recognize the value of geophysical well logs in mineral exploration (Tixier and Alger, 1967). Even though Schlumberger did not pursue the mining market, their groundbreaking research did encourage the use of wireline logs by the mining industry. Of particular importance to us are the observations by Tixier and Alger that::

- "Coal beds are characterized by high resistivities, and by high apparent porosities on sonic, neutron, and density logs."
- "Density logs are particularly suited for evaluation of yield from oil shales."

Both of these observations, and the excellent examples that Tixier and Alger provided, led to the widespread use of geophysical well logging for coal exploration.

The examples from Tixier and Alger illustrate the responses of numerous logging methods to coal:

- **Slide 5** – normal resistivity, lateral log, caliper, sonic.
- **Slide 6** – caliper, gamma ray, density, sonic, SP, induction, normal resistivity.
- **Slide 7** – gamma ray, density, sonic, neutron.

Additional examples from Tixier and Alger illustrate the good correlations between organic matter, oil shale yield, and density (**Slide 8**).

Slimhole logging tools were widely available to the mineral industries by the late 1960s. Century Geophysical Corporation may have offered slimhole logging services as early as the 1950's. By the time that I began my career in the spring of 1973, service companies that offered slimhole services were well established as the mainstay of coal exploration, at least in the Rockies and Gulf Coast. Some mining companies, a few in the west but especially the eastern mining companies, were reluctant to accept the technology and continued to rely on coring for another decade.

Two of the key topics for improving well log interpretations during the early years of coal logging were:

- Correlating the log responses to the rocks.
- Understanding some of the basic principles involved in logging for coal.

These remain important topics today.

LOG-ROCK CORRELATION

When you look at the well logs for a pay zone, your "mind's eye" sees a rock, or at least it should. You want to be able to recall the rocks that produced a log response similar to the one you are viewing. The importance of experience comparing core to well log responses cannot be overemphasized. (See **Slide 9**.)

Some generalized core-log comparisons are presented (**Slides 10 and 11**), not to illustrate the details, but to illustrate how one can gain confidence in the interpretation of log responses. These examples show generalized written or graphic descriptions of coal sequences drawn directly on logs. This is how I learned to interpret the subtle inflections on coal logs, and I remain an advocate of such study to improve core description and log interpretation skills.

Probably during the early 1970's, mining companies and wireline companies observed a correlation between log responses and the proximate analysis of coal. Generally, the relationship between ash content and density was excellent for a specific coal seam and area. By the late 1970's, at least one wireline company was computing ash content from density logs.

This may constitute preaching to the choir, but is too important to overlook. The tight budgets in the CBM industry commonly do not permit coring for the purpose of studying coal facies or log-rock relationships. But how else will we learn to recognize the feather edge of an overbank splay in a coal seam, or the difference between a very thin zone that may be carbonaceous shale or coal too thin for the density tool to fully resolve, or the difference between coal lithotypes that may be more or less prone to cleating? Such subtle changes may not be fully resolved by the logs, but important clues may be present. If the gas-analysis team immediately removes all coal that is cored, then lacking an opportunity to correlate a detailed description to the logs, we will never see the rock in our mind's eye.

VINTAGE SLIMHOLE LOGS

The slimhole log examples presented (**Slides 10-14**) have a purpose beyond the illustration of the importance of log-rock correlation. Your company may one day acquire vintage logs from a mining company. Such logs are often found in mining company files, and commonly do not exist anywhere else. The log presentations are not so standardized as those in the oil and gas industry. The units may not be the same either, because the slimhole tools may differ.

Two logs that may not be familiar to some are the "gamma-gamma" density tool and the single-point resistance tool. The gamma-gamma tool was commonly a free-swinging omnidirectional tool that measured backscattered gamma rays from all directions. This is sometimes referred to as a 4-π (4 pi) tool. The units are counts per second per inch of deflection. The curve may be plotted with counts increasing to the left or right, depending on company conventions. As with modern density tools, the gamma-gamma tool was sensitive to washouts.

The single-point resistance (not resistivity) tool measures an infinitely short-spaced resistance in ohms (not ohm-meters). The early designs used a button or ring on the tool as one electrode and an electrode in the mud pit to complete the circuit. Later designs used the sheath of the tool to complete the circuit. Bed boundary resolution is excellent, provided that the borehole conditions are good. The tool is extremely sensitive to hole rugosity.

Another example of a vintage slimhole log illustrates logging through pipe (**Slide 12**), and in the open-hole section, a gamma-gamma curve with counts increasing to the right (**Slide 13**). Mining companies rarely employed a sophisticated mud program. Where mud was used for circulation or to fill a hole to permit electrical logging, hole caving and bridging off was common. Here, an oil-patch technique was sometimes employed in lieu of tripping in to clean out the hole. If the comparatively small and lightweight slimhole tools could not be spudded through a bridge, the drill stem was circulated down past the bridge. Logs were then run through drill stem. Such logs may or may not be clearly marked, but the absence of the electric logs in the drill stem, and the density spikes at the pipe joints clearly indicate the presence of drill pipe.

MODERN COAL LOGGING FOR CBM

Rank and Lithotype

As is the case with other rock types, the log responses to coal vary with the different types of coal. Coal rank is one important factor (**Slide 16**). Both acoustic transit time and density vary with coal rank. Higher rank coal exhibits a slower transit time, and a higher density. Microporosity in coal is also rank dependent. **Slide 17** presents typical log responses for coals of varying rank. These data are from Davis (1976) and Tixier and Alger (1967).

Coal lithotype is another important factor controlling log responses. Varied plant communities produce material that is variably preserved and transformed by burial from peat to coal, to produce the coal lithotypes we observe (**Slide 18**). **Slide 20** is a table taken from Stach (1975, Table 14, p. 133) that defines the lithotypes vitrain, clarain, durain, fusain, cannel coal, and boghead coal. A wide variety of lithotypes exists that is transitional between coal and other rocks, from coal to many impure coal types to coaly and carbonaceous non-coal rocks. Coal lithotypes can provide clues to water depth (see Slide 18 and references to Tasch, 1960 in Stach, 1975, p. 310-312). In turn, water depth may have a bearing on the location of the margin of a coal deposit. Coal lithotype can be related to cleat development and gas production.

Density Log Calibration

I have compiled the densities of selected materials and several log calibration standards as reported by numerous sources in **Slide 21**. A good operational practice is to expand this list with laboratory-determined specific gravities of core samples from specific project areas. The density values shown can provide general guidelines for bituminous coal evaluation.

A shale that consists of 60% mineral matter (mineral matter = 1.08 ash + 0.55 sulfur) and 40% organic matter was reported to have a density of 2.0. An impure bituminous coal containing 20% mineral matter was reported to have a density of 1.5. The 1.5 density value is commonly considered to be a practical division between clean coal and impure coal. A relatively clean, bright, bituminous coal was reported to have a density of 1.35. Pure kerogen is reported to have a density of 0.95. These reported densities for coal, carbonaceous rocks, and kerogen, are lower than the densities of most Midcontinent rock types.

Density logs are commonly calibrated to aluminum, density 2.59, and magnesium, density 1.71. This calibration seems to be adequate for typical Midcontinent rocks. However, coal is less dense than the lower density standard, magnesium. Interpolation is generally better than extrapolation for estimating purposes. For this reason, some service companies use fresh water, density 1.0, to better calibrate for coal. Intuitively, this seems to me a good procedure to follow. Consider discussing the merits of using water as one of the calibration standards with your wireline services company.

Volume of Investigation, Resolution, Precision, Accuracy

Each specific logging method and tool has its unique measurement characteristics, including vertical resolution, volume of investigation, depth of investigation, etc. These terms have various theoretical and practical definitions, as discussed by Theys (1991, p. 47-52). Theys suggests the following definition of vertical resolution: "The minimum bed thickness for which the instrument measures, possibly on a limited portion of the bed, a value that gives the real value of the formation after the suitable environmental corrections." The volume of investigation has a theoretical shape and size, which may vary with the subsurface environment. Hypothetical volumes of investigation are shown in **Slides 22 and 23**. It is important to know a little about the measuring characteristics of each type of log that is run. **Slide 24** summarizes the density logging and processing parameters provided by two wireline service companies. These data have a bearing on the precision of bed boundary picks and the accuracy of the measurements within a bed.

For thin Midcontinent coals, an error of several inches in thickness has a significant impact on reserve calculations. The precision of bed boundary picks and the ability to correctly identify the lithologies of thin beds within a coal seam are also important for thick coals. Thin impermeable layers within a coal seam may affect fluid flowpaths.

Depth of investigation affects relative proportions of the formation and borehole environment in the measurement of interest. The usual tradeoff for tools that have a spherical or ellipsoidal volume of investigation is as follows. The shallow-investigating tools result in better bed boundary picks, but incorporate more borehole effects than the deep-investigating tools. The deep-investigating tools result in better estimates of formation properties, provided that the bed of interest is sufficiently thick that the measurement reflects just the bed of interest, not the adjacent beds. For focused resistivity logs such as the laterolog / guard log, a short array can provide good bed resolution and, in combination with a neutron log, resolve a coal seam precisely even with poor hole conditions. The disc-shaped volume of investigation of the laterolog / guard log permits good precision and relatively deep investigation.

In some instances, the difference in the vertical resolutions of the gamma-ray log and the density log can explain the apparent high gamma-ray in a thin coal seam. The vertical resolutions for the gamma-ray log that I have seen in the literature range from eight inches to three feet. If the gamma-ray measurement averages over a one to three foot radius, then a hot shale overlying a one-foot coal can prevent a low gamma-ray response from developing. **Slide 25**, an animated view of a logging tool passing through a thin coal and overlying black shale, illustrates the hypothetical volumes of investigation for a gamma-ray (large circle) and density (small circle) log.

High gamma-ray responses have been reported in coals from specific and sometimes very limited areas in Montana, North Dakota, Texas, Wyoming and probably other areas. In my experience, radioactive coals are uncommon. The most common occurrence I have observed is at the margins of a deposit or associated with adjacent sandstone beds in an area where uranium roll-fronts occur. In the southern Midcontinent, phosphatic black shales overlie some coals. The associated marine transgressions may introduce radioactive phosphate-bearing precipitates into the coal in the same manner that iron sulfide (pyrite and marcasite) is formed in these coals. I have not seen convincing evidence that this occurs, although I have not conducted a related literature search. I am uncertain as to whether such coals with no apparent low gamma-ray response contain some radioactive precipitates or whether this is an artifact of averaging over the gamma-ray tool's volume of investigation. This question might be answered with a series of gamma-ray core scans for a coal such as the Iron Post coal, overlain by the Kinnison Shale, from an area where the coal appears to have a moderately high gamma-ray response.

Consider the vertical resolution of your specific density tool when you interpret logs. This information should be provided by your wireline service company. Ask how your company defines vertical resolution. Source to detector spacing enters into the equation, as does the configuration of shielding and windows around the source and detector and other factors. Consider also that the resolution that is advertised for a specific tool may apply only if the tool is run at the optimal logging speed and with the maximum possible sampling rate.

<u>What is a High-Resolution Density Log?</u>

Modern slimhole density logging methods (for example **Slide 26**) and oilfield density logging methods have seen marked improvements during the past 25 years. High-resolution density logs are now available from many wireline service companies. Three definitions of high-resolution density log are:

- An expanded scale density log, for example, having a scale of two or five feet per inch.
- A density log run with a tool configured with an extremely near detector, for example, having a source-detector spacing of 1½ inches.
- A density log run with a CDL or LDT tool, with a sampling time of short duration, for example 50 to 250 milliseconds, run at a slow speed, and computer enhanced to improve the resolution.

I do not consider an expanded-scale presentation of a conventional oilfield density log to be a high-resolution density log. The logs produced by high-resolution density tools and by carefully designed and tested computer-enhanced density methods are legitimate high-resolution tools.

Slides 27 and 28 compare conventional density logs presented with an expanded scale, and computed high-resolution density logs. The shoulders on the high-resolution logs are noticably better defined. The thickness estimates from the high-resolution logs will be much more reliable than the estimates from the conventional, expanded scale logs.

Slide 29 compares a conventional density log and a density log acquired with a high-resolution density tool. The coal and partings thickness estimates from the high-resolution log are much more reliable than the estimates from the conventional expanded scale log.

Slide 30 compares a computer-enhanced high-resolution density log and a density log acquired with a high-resolution density tool. The two types of high-resolution logs compare quite favorably in this example. This is the only such example I have seen, and so I do not know whether this comparison is typical or the best example that Schlumberger had available.

The real test of vertical resolution is the direct comparison with detailed core descriptions. Without such a comparison, you must rely solely on the specifications provided by the various wireline companies, who may define vertical resolution differently.

Other Logs used in CBM Exploitation

Volumes have been written on well logging. Many logging methods other than the density log are used in CBM exploitation. The most important of these are illustrated in the several slide examples in this paper. The caliper, gamma-ray, neutron, resistivity, and microresistivity logs are valuable methods for CBM logging. The caliper indicates the washouts that may invalidate shallow investigation logs such as the density log. The caliper log may detect mudcake buildup at permeable zones. Washouts affect the neutron log less than the density log, so the neutron log can serve as an alternative to the density log for poor hole conditions. The microresistivity log detects mudcake buildup at permeable zones where coal cleat is well developed. Slides 34 and 35 compare micrologs for coals with good permeability and poor permeability.

The acoustic/sonic log and televiewer log, the temperature log, and the lithodensity photoelectric (pe) log also have potential uses. See **Slides 31-35** for examples of additional CBM logs. I have focused mostly on the density method in the interest of time and brevity. The principles that apply to density logs can be applied to other logging methods as well.

Slides 36 and 37 provide additional examples of density logs run in Oklahoma. These provide additional reference log examples for your review.

Quantitative Methods for Gas Content and Producibility

Other authors have demonstrated the relationships between density and coal ash, density and rank, rank and microporosity, lithotype and density, and lithotype and cleat development. I have been able to correlate ash and Btu's with log density using simple regression analysis, after having numerous core samples analyzed. These relationships suggest that gas content and producibility may be predicted with well logs, as several consultants and wireline service contractors claim. The calibration of log responses to local rocks and coals is likely to be required for valid quantitative log analysis. **Slide 38** is an example of the type of complex computed logs that Schlumberger is attempting, from Scholes and Johnston (1993, Figure 2) is shown. Logs that estimate coalbed gas content are available. I have no direct knowledge regarding the reliablity or cost of this type of analysis.

CONCLUSIONS

The oil and gas geologist or engineer should be able to adapt readily to the evaluation of coals with geophysical well logs. All the same principles and techniques apply, especially with regard to the thin-bed issues. A familiarity with the physical properties of the rocks you are evaluating is as important for CBM as it is for conventional oil and gas. Similarly, a familiarity with the logging methods used is important. Finally, the best way to gain an intimate feel for the log responses to coal-bearing rocks in a given area is to describe lots of core and compare the detailed core descriptions to the well logs.

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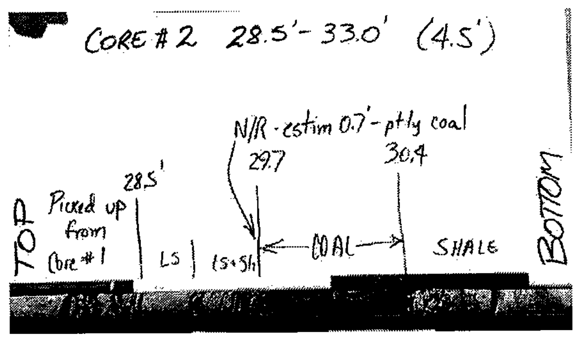
Slide 1

Geophysical Well-Log Interpretation for Coalbed Methane



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10/10/02

Slide 2

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- Society of Professional Well Log Analysts
- Tucker Wireline Services, Jeff Formica

Slide 3

Summary

- Background – the origins of wireline logging for coal
  - Early Schlumberger research, published in a groundbreaking paper that illustrates most of the methods we use today
- Slimhole logging for the coal-mining industry with examples from the 1960's and 1970's. Log-core comparisons.
- Modern logging methods
  - A few basic concepts to consider when interpreting logs
  - Examples
- Examples of conventional oilfield logs
- Suggested reading

Slide 4

Background

Groundbreaking work by Tixier and Alger (Schlumberger)

- Coal beds are characterized by high resistivities, and by high apparent porosities on sonic, neutron, and density logs.
- Density logs are particularly suited for evaluation of yield from oil shales.

From: Tixier and Alger (1967)

Slide 5

Coal Responses

Normal Resistivity

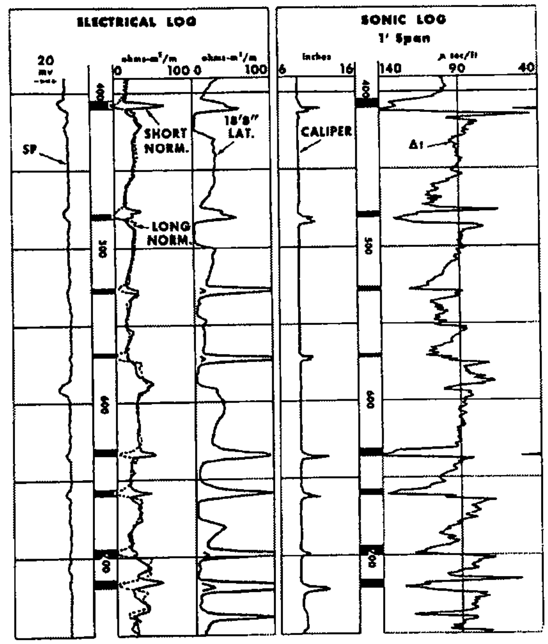
Lateral Log

Caliper Log

Sonic Log

Kentucky well

Probably bituminous



From: Tixier and Alger (1967), Fig. 13

Slide 6

Coal Responses

Caliper

Gamma Ray

Density

Sonic

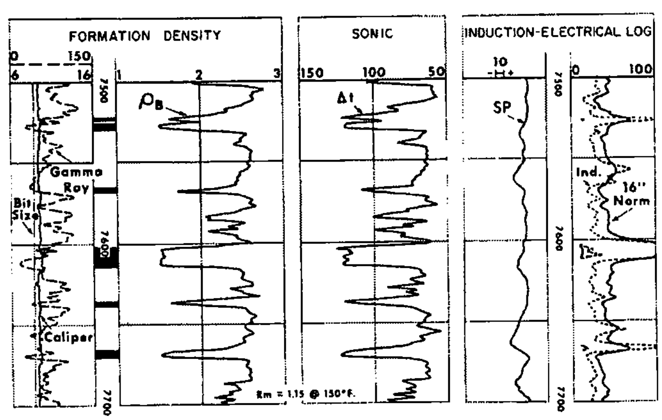
SP

Induction

Normal Res

Colorado well

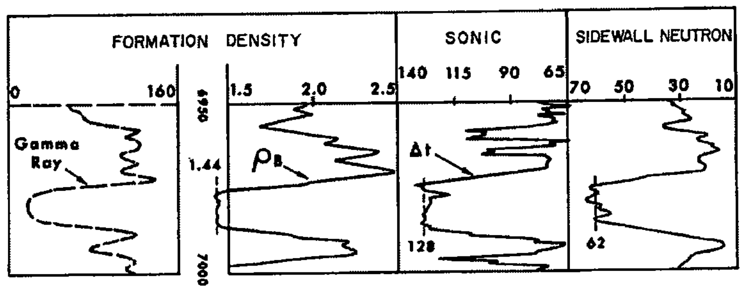
Unk. rank



From: Tixier and Alger (1967), Fig. 14

Slide 7

Coal Responses



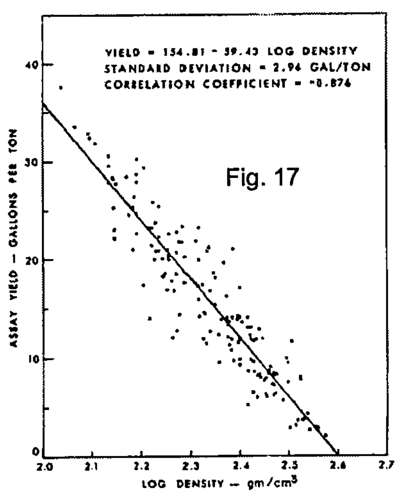
Gamma Ray Density Sonic Neutron

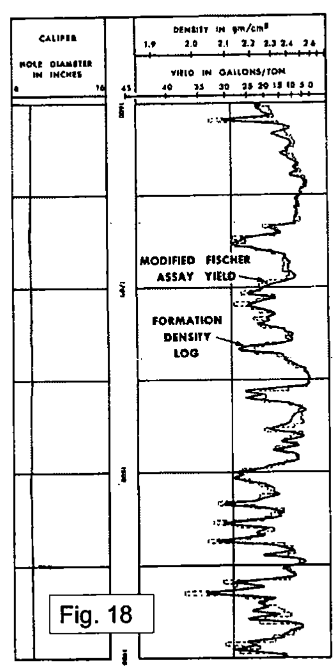
Wyoming well – Subbituminous

From: Tixier and Alger (1967), Fig. 16

Slide 8

OM Correlations

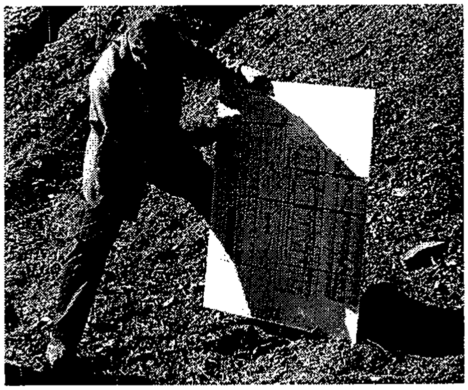




From: Tixier and Alger (1967), Fig. 17 & 18

Slide 9

Log-Rock Correlation — Why?



OGS Geologist Rick Andrews

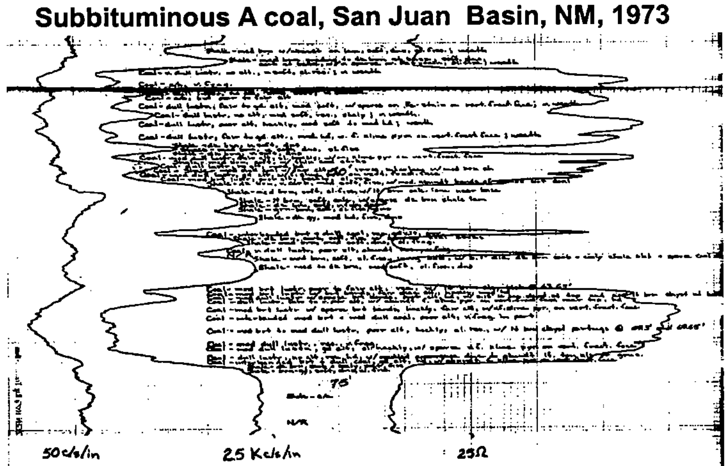
Correlating GR scan of measured section with nearby wireline log

- Why do we attend these field trips?
- Neil's jokes?
- Hunting Trilobites?
- Better exploration models?
- Better understanding of wireline log responses and how they translate to rock characteristics?

Slide 10

Log Response Study
Core – Log Comparison

Analog log by Century Geophysical
Subbituminous A coal, San Juan Basin, NM, 1973



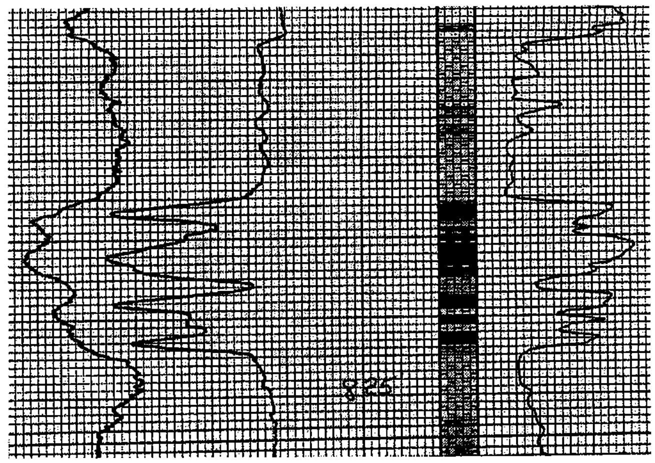
GR counts / sec — **γ-γ Density** counts / sec — **Single-Point Resistance** ohms (not ohm-m)

Slide 11

Coal Bed with Shale Partings

Analog log by Century Geophysical

HVA bituminous coal, Raton Basin, NM, 1974



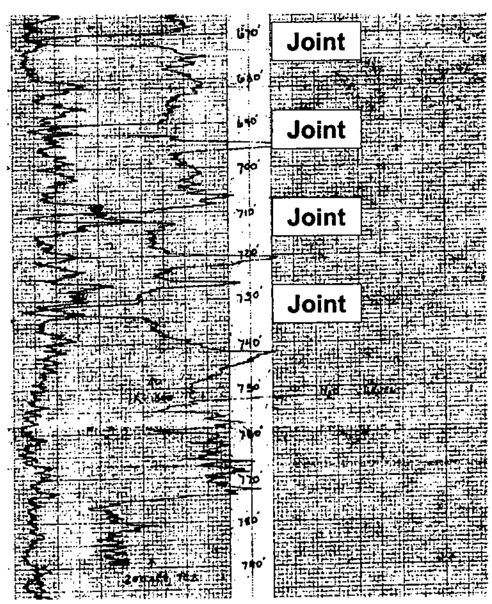
GR γ-γ Density Single-Point Resistance

Slide 12

Slimhole Logging through (2 $^{7}/_{8}$" I.F.) Drill Stem

Analog log by Nuclear Logging Service

HVC or B bituminous coal, S. Wasatch Plateau, UT, 1976



GR γ-γ Density

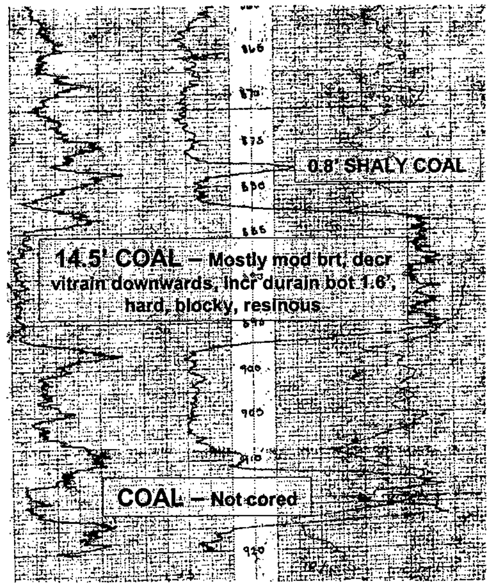
Slide 13

Coal Logging

(deeper, openhole section of well in Slide 12)

Analog log by
Nuclear Logging Service

HVC Bituminous coal,
S. Wasatch Plateau, UT,
1976

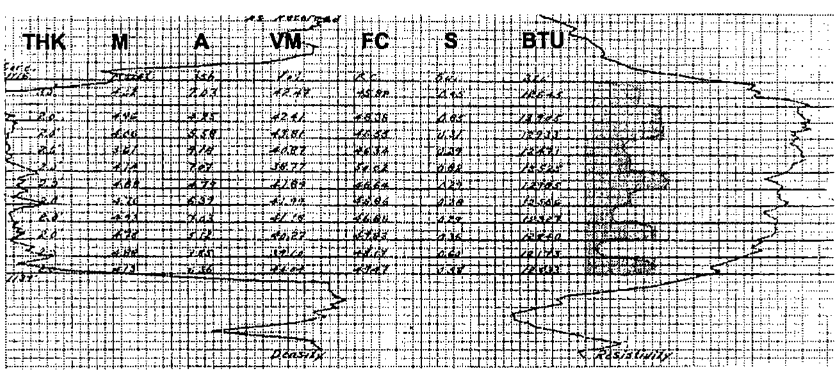


GR γ-γ Density Single-Point Resistance

Slide 14

Log Response Study Analysis – Log Comparison

Analog log by unknown contractor
Study by Helge Larsen
HVB Bituminous coal, Northern Wasatch Plateau, UT, NM, 1980



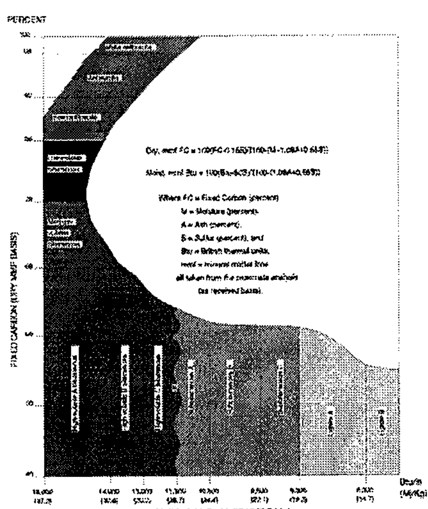
γ-γ Density **Single-Point Resistance**

Slide 15

Modern Coal Logging for Coalbed Methane / Gas

Selected properties of coal and related rocks
Considerations for log interpretation
Examples

Slide 16



BASIS OF RANK CLASSIFICATION OF COALS IN THE UNITED STATES, AND THE FORMULA USED IN MAKING APPROXIMATE RANK DETERMINATIONS

Coal Rank Classification (USA)

Lignite HVAB
MMMF BTU
(< 16000 BTU MMMF)

HVAB Anthracite
DMMF FC
(40 – 100 % FC DMMF)

U. S. Geological Survey

Slide 17

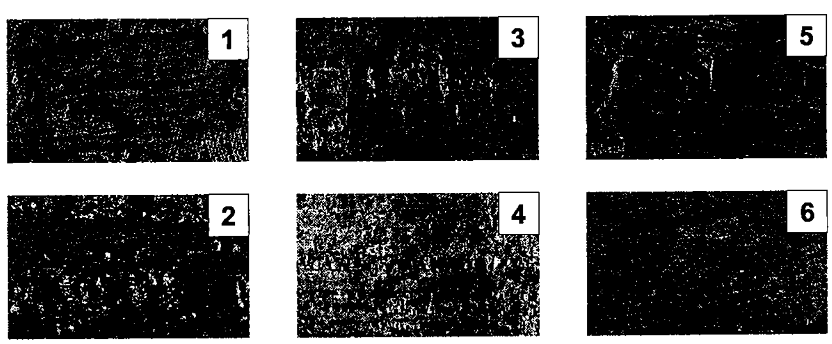
Log Characteristics of Coal

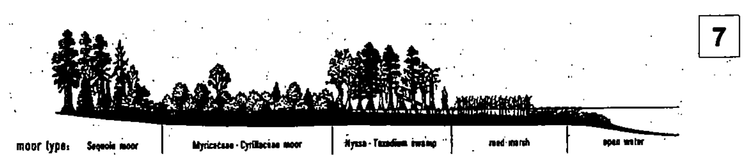
LOG TYPE	LIGNITE	BITUMINOUS	ANTHRACITE
Gamma Ray (API Units)[1]	Low 20-25	Low 20-25	Low 20-25
Resistivity (ohm-m)[2]	High 50-2000	High 50-2000	High 50-2000
Transit Time (μ-sec/ft)[3]	130-150	110-140	120 or less
Density (g/cc)[4]	0.7-1.5	1.2-1.5	1.4-1.8
Neutron (Porosity Index)	Very High 55-70	Very High 55-70	Very High 55-70

From: Davis (1976) and Tixier and Alger (1967)

Slide 18

Environments & Lithotypes





Slide 19

Sources for Figures in Slide 18

1. White and Thiessen, 1913, Plate XV
2. Parks, B.C. and O'Donnell, H.J., 1956, Figure 11
3. Theissen, R., 1920, Plate X
4. Schopf, J.M., 1960, Plate 6
5. White and Thiessen, 1913, Plate VIII
6. Parks, B.C. and O'Donnell, 1956, Figure 21
7. Teichmuller, M., 1975, Figure 88

Slide 20

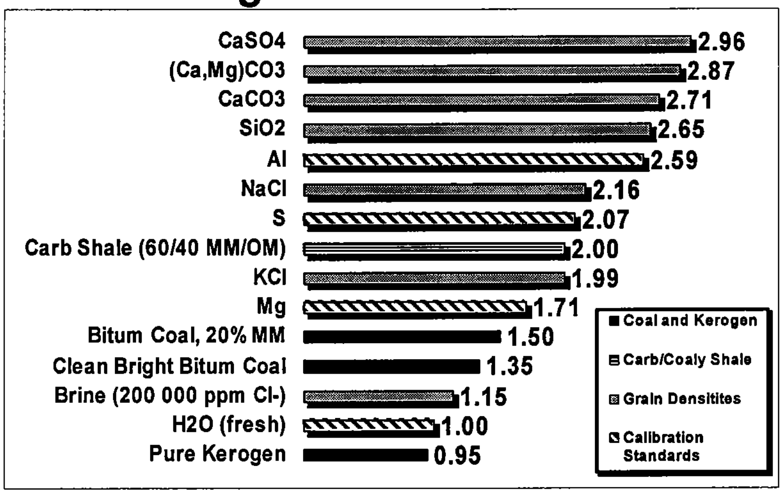
Types and Lithotypes of Bituminous Coals

Coal Type	Lithotype	Macroscopically Recognizable Features
Humic Coal	Vitrain	Bright, black, usually brittle, frequently with fissures
	Clarain	Semi-bright, black, very finely stratified
	Durain	Dull, black or gray-black, hard, rough surface
	Fusain	Of silky lustre, black, fibrous, soft, quite friable
Sapropelic Coal	Cannel Coal	Dull or of slight greasy lustre, black, homogeneous, unstratified, very hard, conchoidal fracture, black streak
	Boghead Coal	Like cannel coal, but of somewhat brownish appearance, brown streak

From: Stach (1975, Table 14)

Slide 21

Densities of Selected Materials and Log Calibration Standards

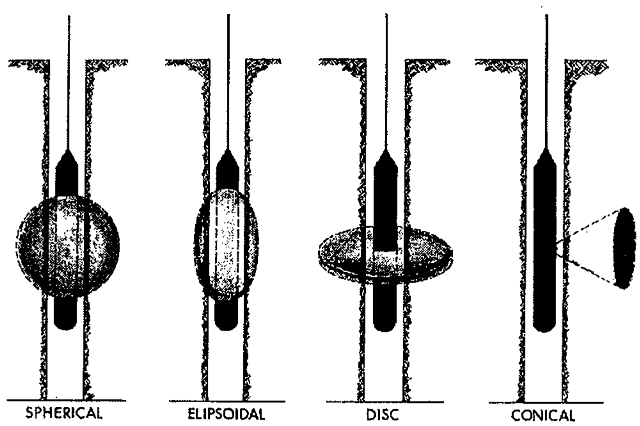


Values from numerous sources, all cited in References

Slide 22

Volumes of Investigation Hypothetical Shapes

Tool Design, Volume, Resolution

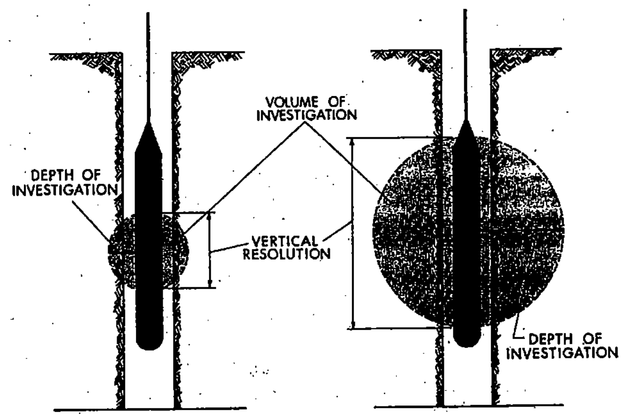


From: Hoffman, Jordan, and Wallis (1982)

Slide 23

Vertical Resolution, Depth of Investigation Spherical Volume of Investigation

Improved Tool Resolution = Increased Borehole Contribution



From: Hoffman, Jordan, and Wallis (1982)

Slide 24

Density Logging / Processing Parameters

Company A – Computed High Res from LDT
Company B – High Res Tool & CDL

PARAMETER	COMPANY A	COMPANY B
Logging Speed (ft/min)	15 – 60	10 – 30
Sample Time (msec)	50 – 250	100
CDL / LDT Spacing	12", 6½"	12", 6"
High-Res Spacing		1.5"
Resolution Advertised	8", 4"	24", 3"
Time Constant (sec)		0.5 – 2.0
Std Filter	15-pt (Gaussian)	
High-Res Filter	5-pt (Gaussian)	

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Tips

Consider the Effects of

Measure Point(s)

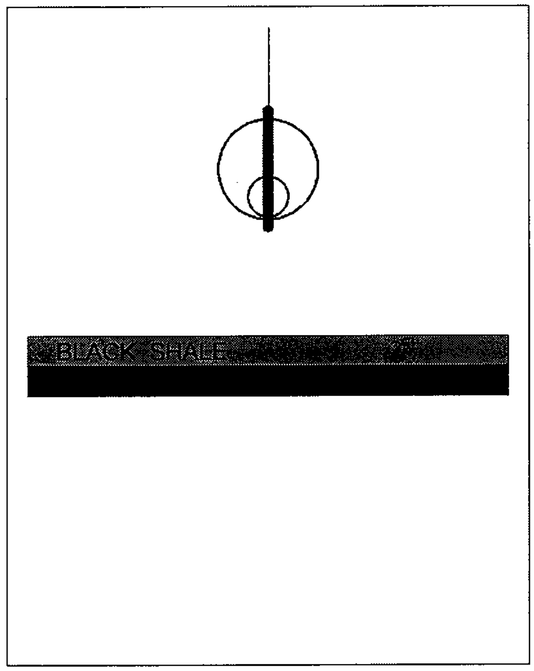
Vertical Resolution

Volume of Investigation

Logging Speed

Sample Time

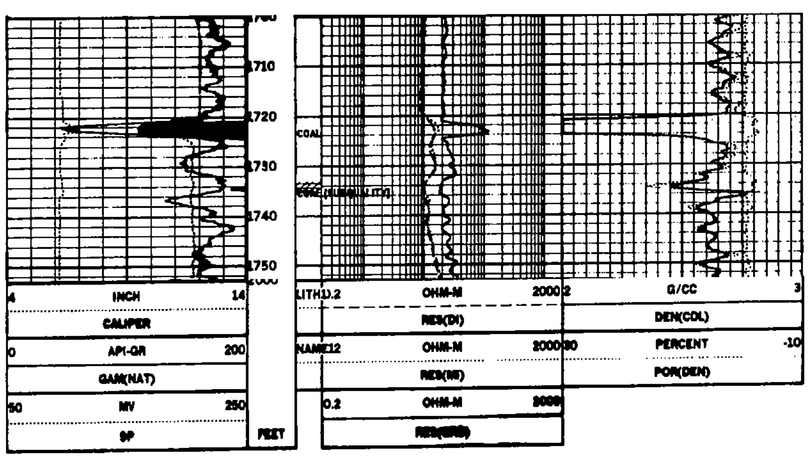
Time Constant & Filtering



Slide 26

Modern Slimhole Logs

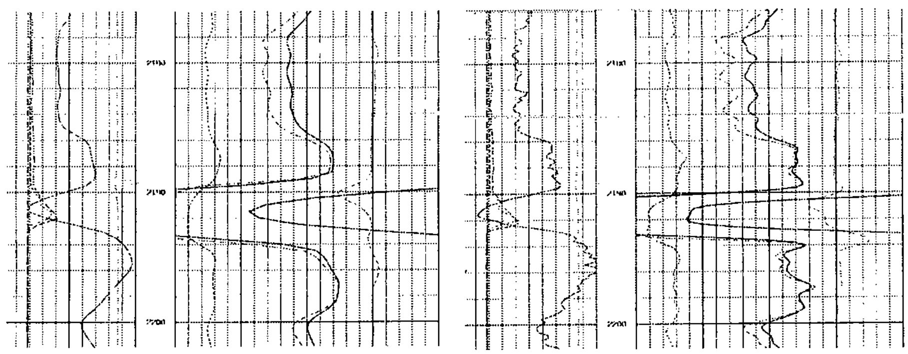
Digital log by ANLINE
HVA Bituminous coal, Okmulgee Co., OK, 1999



Courtesy of Don Andrews, ANLINE

Slide 27

Expanded-Scale Density vs Computed High-Resolution Density



Expanded Scale **Hres**

Tucker WIRELINE SERVICES

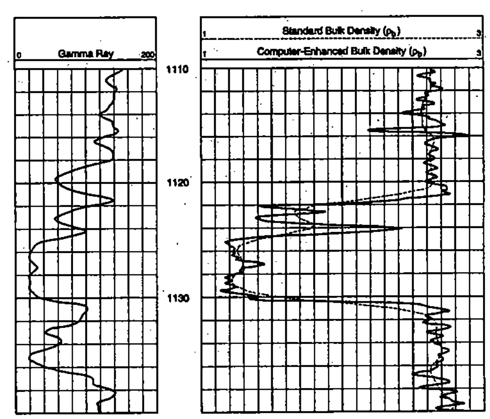
Courtesy of Jeff Formica

Slide 28

Oilfield Density vs Computed High-Resolution Density Showing Improved Resolution

Oilfield log by Schlumberger

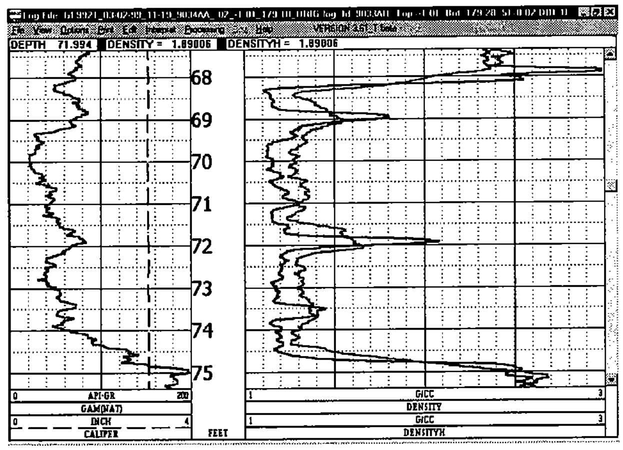
HVA bituminous coal, Greene Co., PA, before 1992



From: Olszewski and Schraufnagel (1992), Fig. 3

Slide 29

CDL vs High-Resolution Density Tool Showing Improved Resolution



Century Geophysical Corp.

Courtesy of Brian Peterson

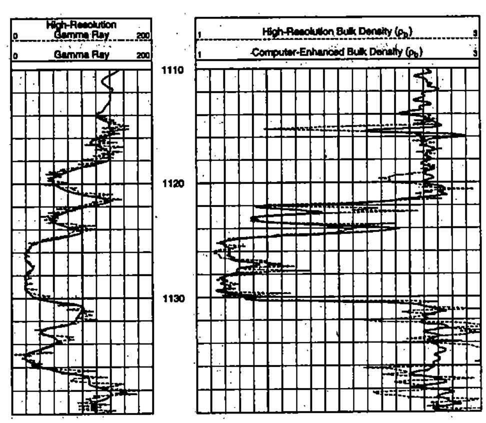
Slide 30

Computer-Enhanced Oilfield Density vs High-Resolution Density Tool

Oilfield log by Schlumberger

Slimhole log by Geological Logging Systems

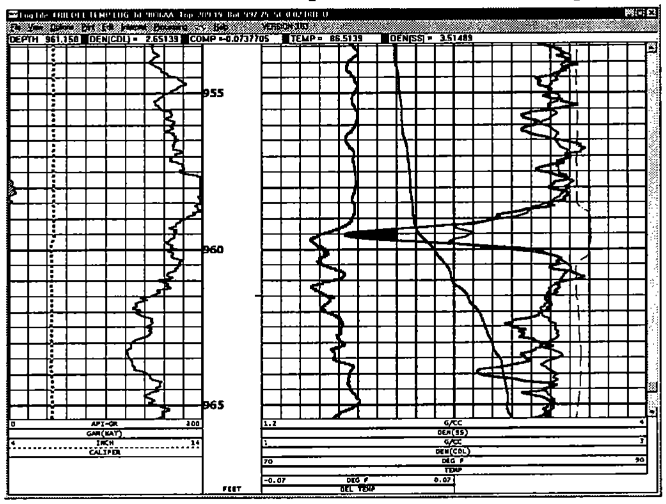
HVA bituminous coal, Greene Co., PA, before 1992



From: Olszewski and Schraufnagel (1992), Fig. 3

Slide 31

Expanded CDL/Temp with Short Spaced Density

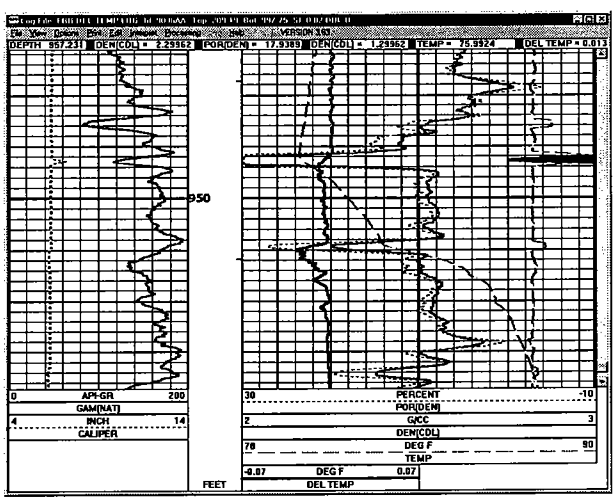


Century Geophysical Corp.

Courtesy of Brian Peterson

Slide 32

CDL and Temperature Air Filled Hole



Century Geophysical Corp.

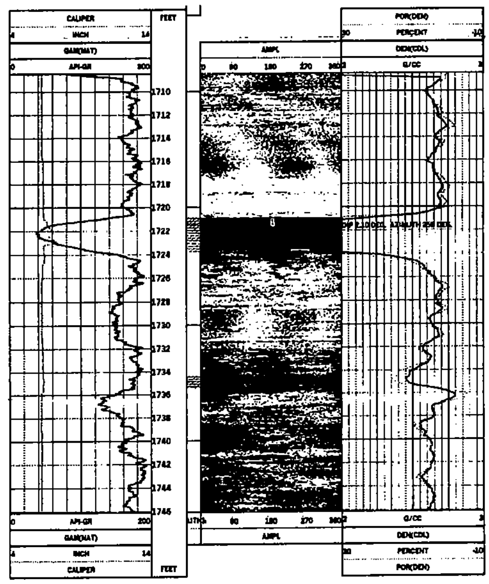
Courtesy of Brian Peterson

Slide 33

Sonic / Acoustic Televiewer

Digital log by ANLINE

HVA bituminous coal, Okmulgee Co., OK, 1999



Courtesy of Don Andrews
ANLINE

CAL GR Sonic Televiewer Density

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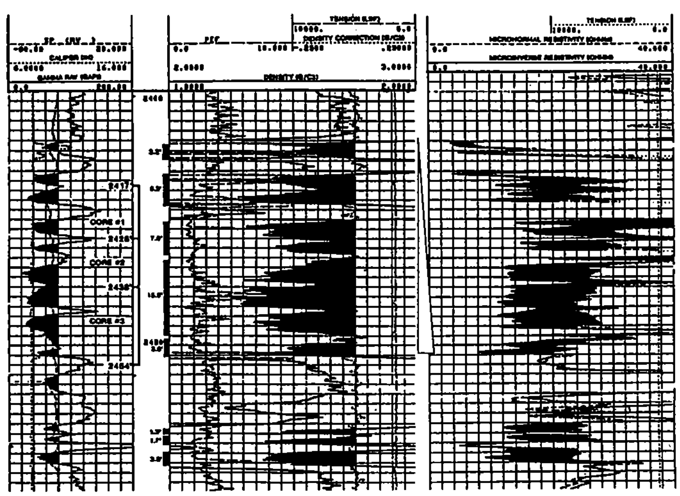
Microlog Response to Good Cleat Development DST 2408-2452 36 md



After: McBane and Mavor (1991), Fig. 1

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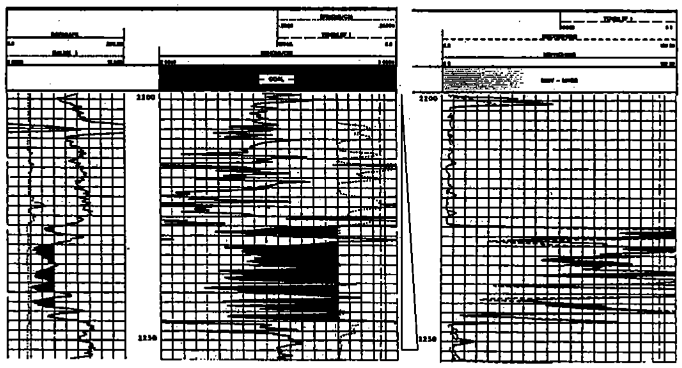
Microlog Response to Poor Cleat Development DST 2200-2252 .004 md



After: McBane and Mavor (1991), Fig. 2

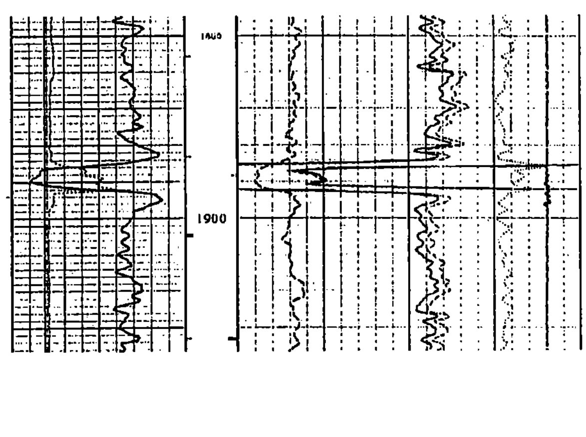
Slide 36

Reasonable Density ? Parting ? "Thick" Oklahoma Coal

Oilfield log by BPB

Bulk Density 1.3-1.5

HVA bituminous coal, Haskell Co., OK, 1996



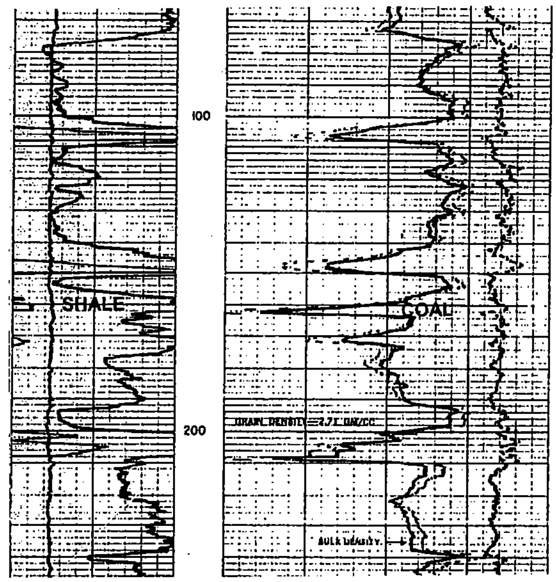
Slide 37

Example from Hemish (2002, in press)

Hot Shale and Underlying Coal

Oilfield log by GO

HVB bituminous coal, Craig Co., OK, 1979



Slide 38

The Future ?

The Cost ?

From: Scholes and Johnston (1993), Fig. 2

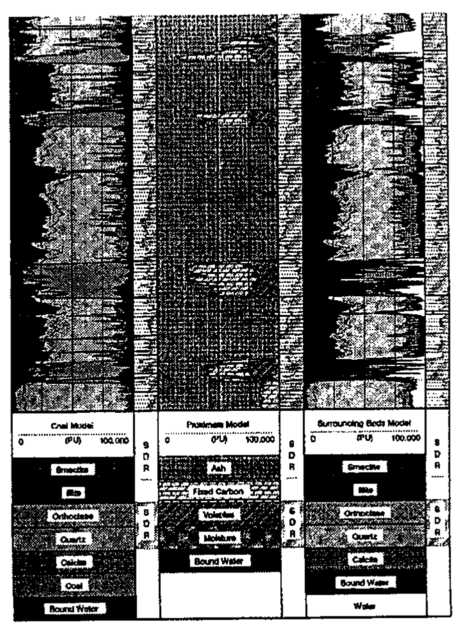


Figure 2. Proximate analysis model of coals through coal-bearing interval. The components of proximate analysis include volatiles, moisture, ash, and fixed carbon. Coals denoted in green.

OKLAHOMA GEOLOGICAL SURVEY
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5

Eastern Arkoma Basin coalbed-methane completions—A different perspective

John A. Ringhisen
Halliburton
Oklahoma City, OK

Ringhisen, J.A., 2002, Eastern Arkoma Basin coalbed-methane completions—A different perspective, *in* Fourth annual Oklahoma coalbed-methane workshop: Oklahoma Geological Survey, Open-File Report 9-2002, p. 111-116.

CEMENTING CBM WELLS
CONSIDER THIS

John A. Ringhisen
Halliburton

The cementing of production casings in conventional oil and gas wells is a relatively easy process when compared to CBM wells. Most conventional wells take advantage of being drill with a fluid in the wellbore. The drilling fluid, water based or oil based, is designed for the expected wellbore conditions during the drilling operation. One of the primary functions of the drilling fluid is to develop a barrier, filter cake, between the wellbore and any formations containing porosity and permeability. The filter cake minimizes damage to the producing interval by preventing the drilling fluid from invading the formation matrix. Conventional production wells produce from reservoirs containing both porosity and permeability. Naturally fractured wells have primary and secondary fractures which allow the formation matrix to produce reservoir hydrocarbons to the wellbore. The cementing procedure for these wells requires a mechanical process to remove the drilling mud and filter cake from the intervals of interest and successfully place the cement slurry. After a period of time the cement slurry cures and develops compressive strength. Successful zonal isolation will maximize the opportunity for trouble free completion techniques.

The cementing of the production casing in coal-bed methane wells have inherent characteristics to consider to obtain a successful cement job. The cleats, natural fractures in the coal, provide an excellent location for the entry of contaminating fluid into the producing matrix of the coal bed. Coal-bed methane wells are generally drilled with compressed air as the "drilling fluid". As a result, when the coal is penetrated by the bit, there is minimal damage to the coal reservoir. Since the pressure differential is from the coal to the wellbore, natural gas is produced to the surface and must be safely handled. Prior to logging the well, a thin fluid is added to the wellbore. The thin fluid can be "sucked" into the cleats of the coal through capillary action. The cleats act as small soda straws to pull a thin wellbore fluid into the coal. An additional source of damage to the coal reservoir may occur as the production casing is run into the well. The running speed of the casing can create a piston effect across the coal interval exerting additional pressure on the cleats and possibly force more wellbore fluid into the coal. The depth of penetration of the wellbore fluid as a result of either of these phenomenons is a function of the viscosity of the wellbore fluid and the height of the fluid in the wellbore above the coal interval. The cementing slurry for the coal wells is preceded by a viscous water pill. The viscous pill is designed to remove any cuttings left in the wellbore. The cement slurry is placed across the desired intervals. Even the cement slurry can damage the coal bed if the cement slurry is not correctly designed.

Improved technology and field experience have made horizontal coal-bed methane wells more economical. The cementing process for a casing string placed around the curve requires additional planning and design considerations. The cement sheath not only forms a barrier to isolate the coal production from the shallower intervals, but must survive the drilling process of the horizontal interval. The additional stress placed on the casing and cement sheath in the curvature of the casing are from the drill pipe movement during the drilling process. Additional stresses are encountered when the drilling assembly is run through the curve. This "banging around" can cause small cracks to develop in the cement sheath. In most instances these cracks do not create any problems for the operator during the life of the well. But, in a small number of wells, these cracks might weaken the cement sheath's ability to isolate the natural gas from the annulus. Should this problem become severe, natural gas could migrate into the annulus outside the production casing.

Additional design considerations will greatly improve the success of the primary cementing procedure for the production casing in both a vertical or horizontal coal-bed methane well. Here is a list of items to consider when planning the cementing of a coal-bed methane production casing.

- Spacer/flush - The current use of a gel pill ahead of the cement for an air drilled hole is sufficient to clean the wellbore of cuttings. The key is to remove the cuttings and not cause any damage to the producing intervals.
- Cement slurry weight – The slurry weight, density, of the slurry should be heavy enough to control the reservoir pressure from the production intervals, but light enough to control the total hydrostatic pressure exerted on of the coal interval. This total pressure must be lest than the bottom hole pressure required to initiate a fracture in the coal. The cement slurry weight has a direct correlation on the compressive strength of the set cement slurry.
- Compressive strength – The strength of set cement slurry is measured in pounds per square inch. The value indicates the amount of force required to cause a crack to develop in the cement. API standards require the compressive strength be measured at set time intervals at bottom conditions. The higher the compressive strength, the more brittle the cement sheath.
- Ductility – The set cement has sufficient compressive strength for zonal isolation. When a delta pressure or delta temperature is placed and then removed from the cement sheath, the cement sheath returns to its original position without deformation or cracking of the cement sheath. The integrity of the cement sheath of a horizontal well will greatly improve when ductility is designed into the cement slurry. The cement sheath will have a greater chance of surviving the additional stresses from the mechanical process of drilling the horizontal wellbore.
- API Fluid Loss – An API standardized test (API Document 10) to measure the amount of filtrate which is lost from the cement slurry when a specified differential pressure is placed across the unset cement. The test conditions are for 30 minutes at 100 and 1000 psi. The higher the fluid loss, the greater the potential to damage a formation.
- API Free Water – An API standardized test (API Document 10) to measure the percent of mixing water that does not stay in the cement slurry. The free water can migrate into the formation or form "water pockets" in the set cement slurry. This problem is magnified in high angle or horizontal wells where the free water

can collect on the high side of the wellbore. In these wells the free water only needs to travel a few inches rather than a few feet to collect in pockets. These pockets are most certain form in the highly deviated or horizontal wellbore an form a channel in the cement sheath.

- Thixotropic – A property applied to a cement slurry that achieves high gel strength during short periods of time when the cement slurry becomes static. Thixotropic cement slurries assist in "preventing" cement fall back in the annulus and minimize gas or fluid migration during the transition from a fluid to a set cement sheath.

STIMULATING CBM WELLS EVOLUTION CONTINUES

John A. Ringhisen
Halliburton

The evolutionary process for stimulating coal bed methane wells is continuing. The operators, consultants, and service providers are continually working together to develop the "cost effective silver bullet" to simplify and maximize the gas production and the Rate of Return. The Oklahoma CBM Industry's learning curve incorporates the best ideas from other CBM areas plus some homegrown innovative procedures in the quest for the "silver bullet".

Here is a brief outline of some of the stimulation techniques employed in our area.

From Brad Wilkins, Wilkins Engineering Supervision, Oklahoma Geological Survey Open-file Report 2-2000

- Brief History of Stimulation Techniques Imported from other CBM Areas
  - Straight Nitrogen Fracs with fluid or proppant. The results were not that impressive. The fracturing gradients were excessively high.
  - Gelled Water and Sand incorporated 20# or 30# and sand as the proppant. Again the results were not that impressive. StimLab analysis of the coal samples and materials indicated compatibility problems with foamers and permeability damage from the gel residue.
  - High rate sand/water fracs. High injections rates (+/- 40 BPM) were used to insure efficient proppant transport with the water system. The wells required 5 to 7 days of de-watering before natural gas production started. After a short period of time the wells suffered steep production decline. Post job analysis by the engineers and service companies determined the coals had fracturing gradients as high as 2 psi/ft and the treatments were generating multiple fractures. Further analysis by StimLab found an excessive amount of coal fines in the produced fluids. Their conclusion was the coal fines were plugging the permeability of the sand pack in the fracture system causing a decline in the gas production.
  - "Controlled Velocity Frac" – Eliminate the Fines, Eliminate the Problem - Tagged proppant indicated extensive fracture height growth. StimLab determined the coal fines were caused by high rate proppant eroding the fines from the sides of the cleats. The CVF increased the efficiency of the treating fluid, varied the injection rate to control the velocity of the proppant in the fractures. Real-time monitoring and analysis during the stimulation procedure were used to taylor the treatment to fit the well. CVF treatments generated initial production rates up to 2 ½ times greater than straight nitrogen fracs and water fracs. Results from the VF were up to 10 times greater than gelled water treatments. Maximum reported IP 100 to 130 MCFD.

From William T. Stoeckinger, Consulting Geologist, Oklahoma Geological Survey Open-file Report 2-2000

- Further Analysis to Find Area Specific Stimulation Guidelines
    - Near wellbore tortuosity is the source of high treating pressures and multiple fractures. The operator should incorporate real-time monitoring and analysis to make adjustments in the treatment to maximize the opportunity for success. Each CBM area is different.
    - Coals are friable. Consider the reservoir when designing the stimulation treatment, especially the completion costs and the ROR.
    - Damage to the coal reservoir can be caused during the cementing process. Calculate the hydrostatics of the cement column.

From Anthony Carpenter; Consolidated Oil Well Services, Inc; Oklahoma Geological Survey Open-file Report 3-2001

- Oklahoma Shelf Success
    - Acid ball-off treatment with mini-frac analysis to determine treatment design parameters specific to the individual well.
    - Frac treatments incorporating 2% KCL water and proppant.
    - Nitrogen fracs with water and proppant.
    - Hartshorne Coal Fracs – 2% KCL water and proppant.
    - Acid / water fracs – weak acid system in KCl water.

From Roger Marshall, Cudd Pumping Services, Oklahoma Geological Survey, Open-file Report 2-2001

- Follow the Learning Curve
    - "Eliminate the Fines, Eliminate the Problem"
    - Design your completion to fit your well.
    - Economics of CBM drilling and completion is the key to success
    - Oklahoma Shelf coals survive acid treatments

From John A. Ringhisen, Halliburton

- Paradigm Shift for the Eastern Arkoma Basin
    - Real-time monitoring and analysis of the treatment
    - Spearhead the treatment with hydrochloric acid to clean the cleats
    - Base fluid – water with clay control material
    - Gel system – low polymer loaded crosslinked gel
    - Bactericides
    - Surfactant
    - Proppant – 12/20 Brady Sand – maximum concentration 6 ppg
    - Conductivity enhancer – control fines migration and sand pack migration
    - Injection Rate – matched to coal interval height
    - Multiple stages, treat each productive interval by itself

- Results from the Paradigm Shift

	Initial Production	**30 Day**	**60 Day**
Well 1	104 MCFD	330 MCFD	250 MCFD
Well 2	52 MCFD	232 MCFD	307 MCFD
Well 3	16 MCFD	277 MCFD	

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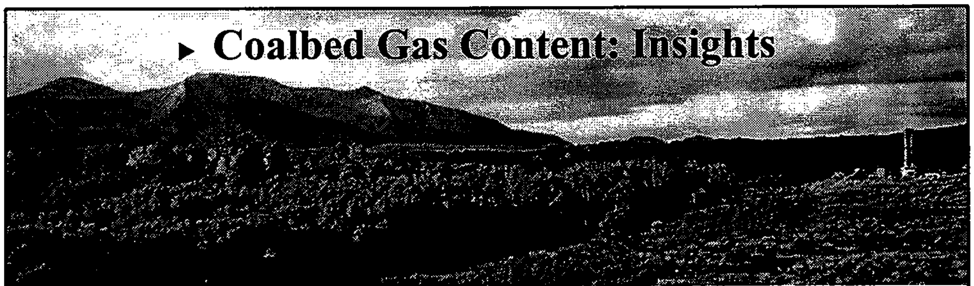
Coalbed gas content: Insights

Chris Hoffman
TICORA
Arvada, CO

Hoffman, C., 2002, Coalbed gas content: insights, *in* Fourth annual Oklahoma coalbed-methane workshop: Oklahoma Geological Survey, Open-File Report 9-2002, p. 117-128.



Presented to:

Fourth Annual Coalbed Methane Forum

October 10, 2002

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720/898-8200
chris-hoffman@gti-ticora.com

Coalbed Reservoir Gas Content

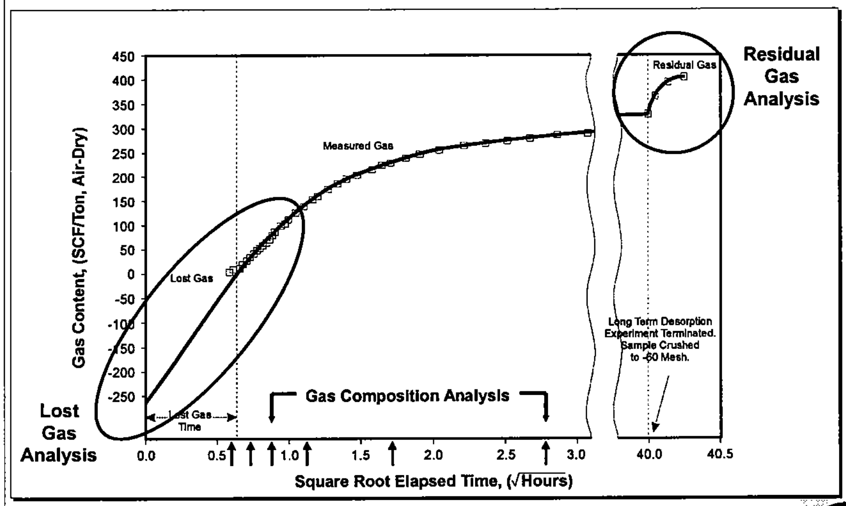
Gas Storage Mechanisms:

- Free gas within natural fractures.
- Dissolved gas in water within natural fractures.
- Adsorbed gas within the coal matrix.

Total Gas Volume = Free Gas Volume + Dissolved Gas Volume + Adsorbed Gas Volume

Adsorbed Gas Volume: Typically > 95%

Long Term Desorption: Best Practice Analysis Protocols



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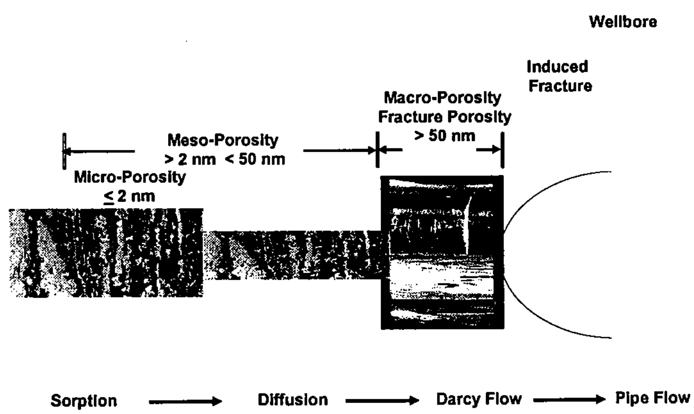
Coal Flow Mechanisms



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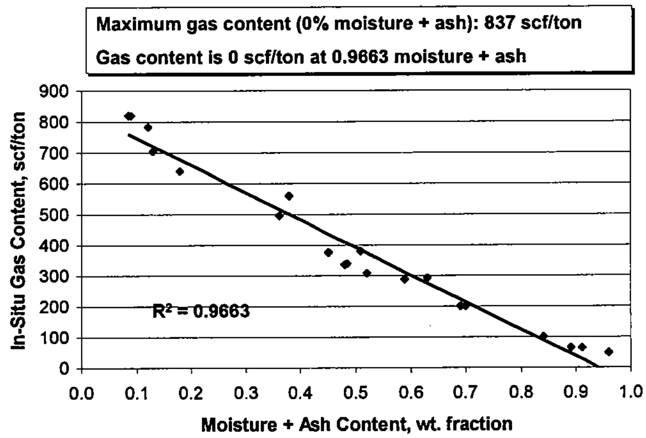
Gas Sorption Knowledge – It's a Good Thing



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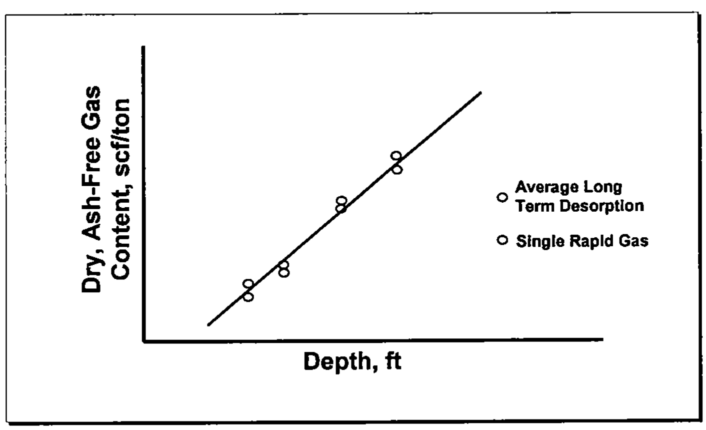
Gas Sorption Knowledge – It's a Good Thing



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Gas Resource - What We Get From Core

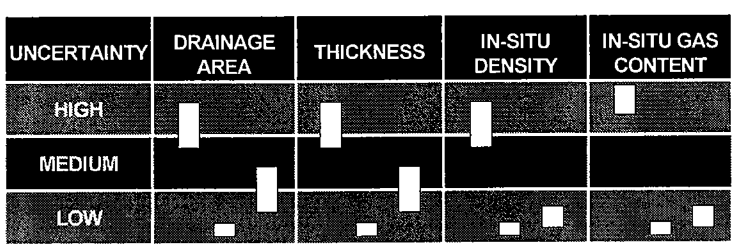
Coalbed Gas Reservoirs

Evaluate:

- In-situ Gas Content & Bulk Density
- % Gas Saturation
- Gas Composition
- Reservoir Pressure & Temperature
- Reservoir Volume (Area & Thickness)

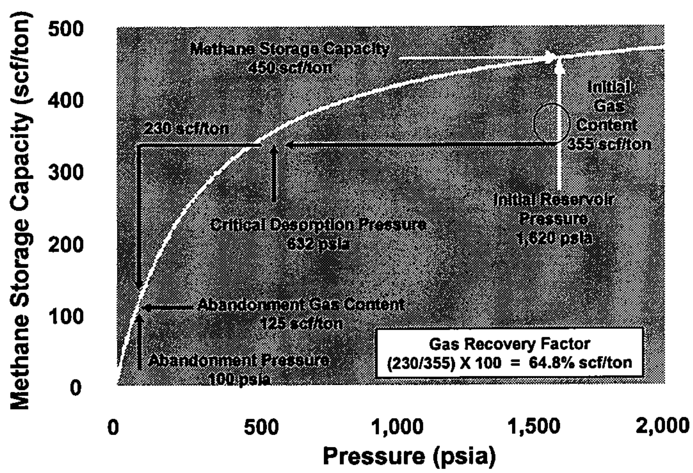
Data Confidence

$$GIP = Ah\bar{\rho}_c\bar{G}_c$$



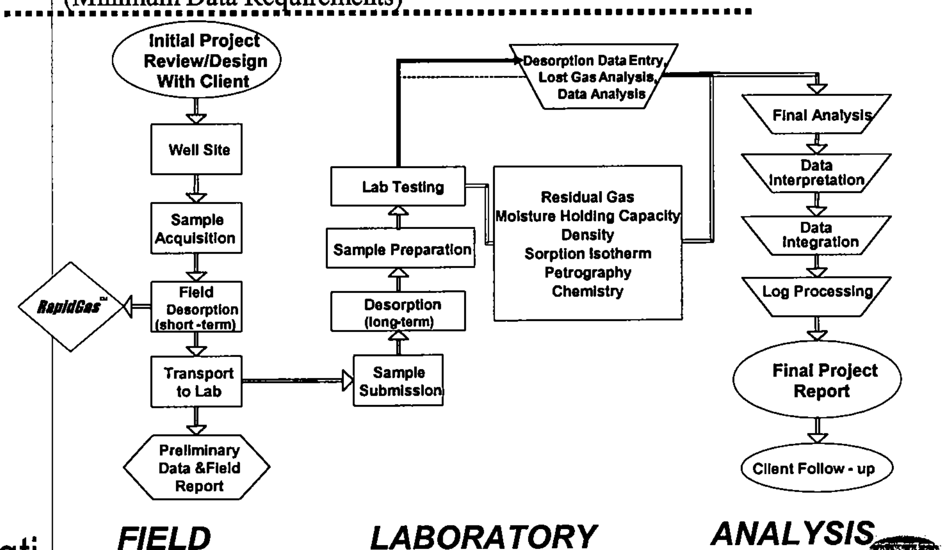
- Commonly Used Protocols
- Very High Sampling Density
- Best Practice Protocols

Typical Methane Isotherm

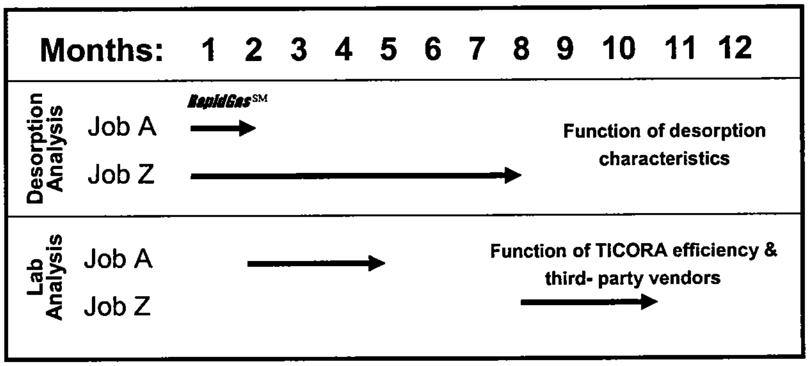


Coal Gas Analyses Flow Chart

(Minimum Data Requirements)

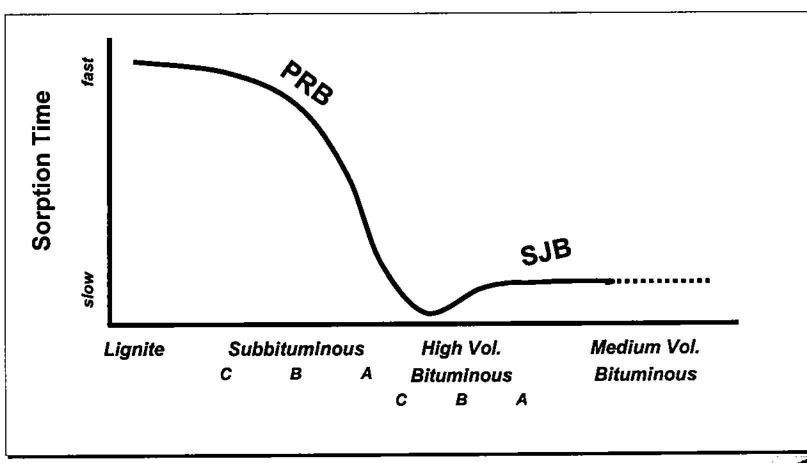


How Long Does The Job Last?

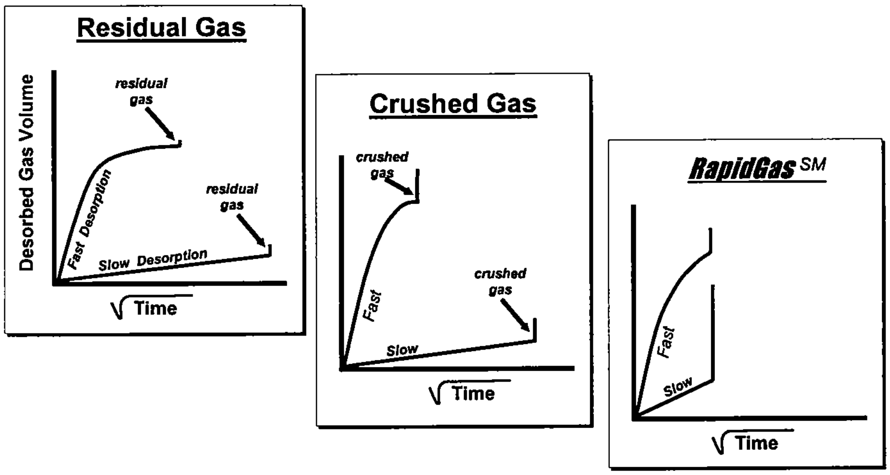


That depends on the coal desorption properties and the extent of the analysis program.

Gas Mobility (Movement Characteristics)



Residual Gas vs. Crushed Gas vs. *RapidGas*[SM]



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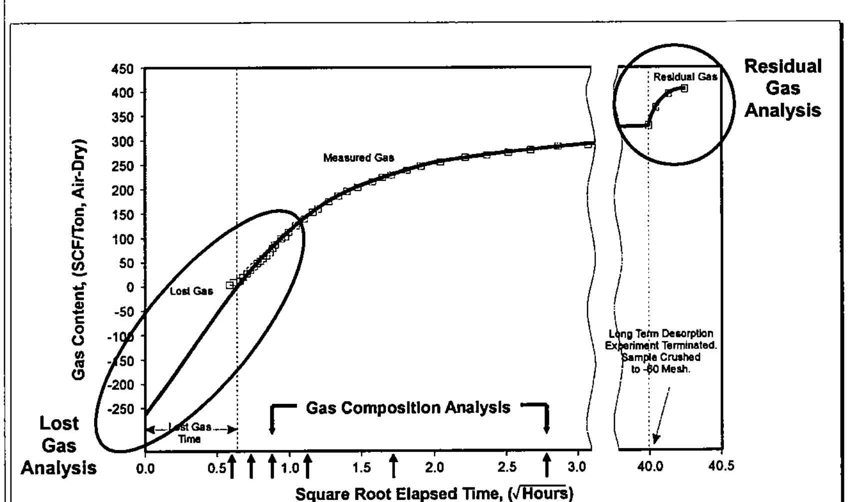
Long Term Desorption: Best Practice Analysis Protocols



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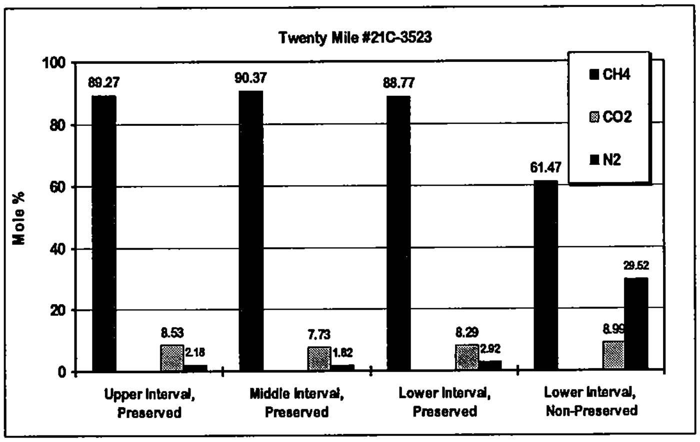
Sorbed Phase Gas Composition



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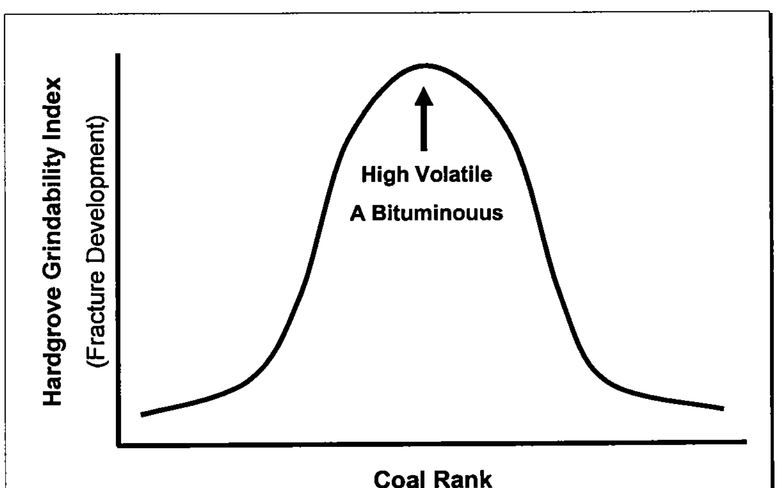
Natural Fracture Development (Tectonic) vs. Rank



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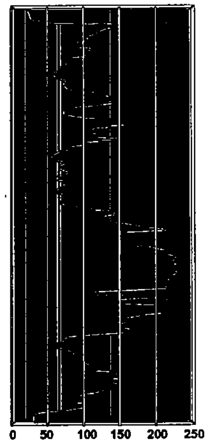
Generalized Graphic

Coal Gas Reservoir Systems

X-Ray Radiograph



Gray Level (0 - 255)
Density Profile

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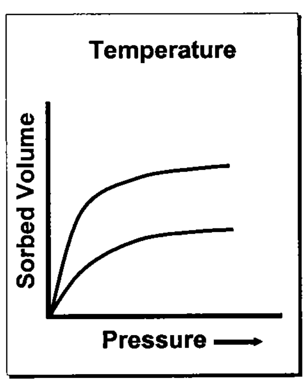
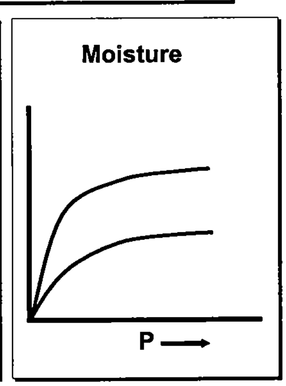
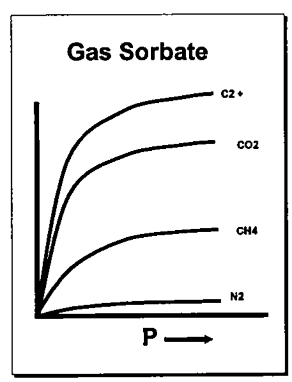
Sorption Isotherm Parameters

SAME COAL







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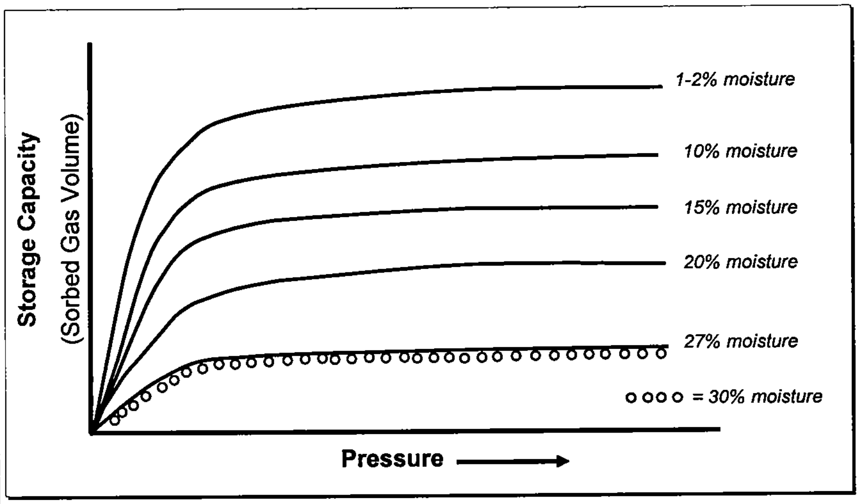
Storage Capacity Versus Moisture Content



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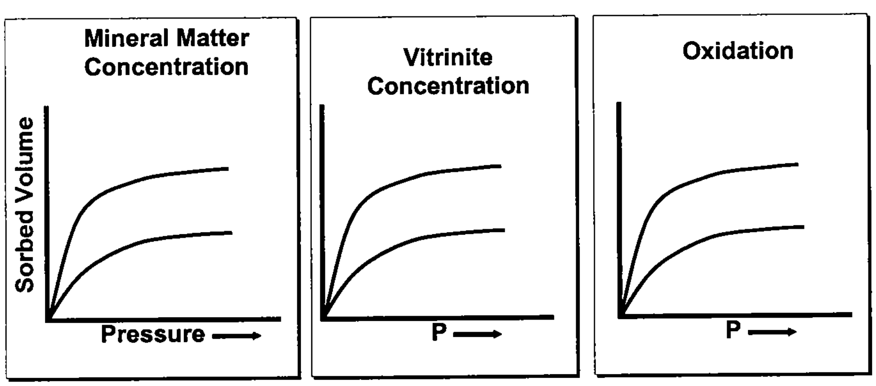
Sorption Isotherm Parameters

SAME RESERVOIR



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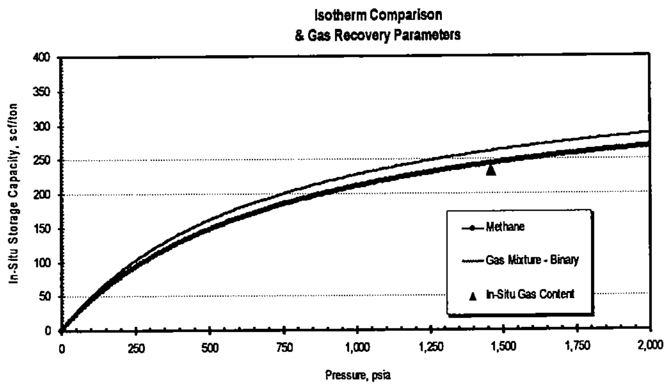
The Analytical Goal is to Construct Comprehensive and Critical Information...



Binary Storage Capacity: 262 scf/ton
(Modeled Sorbed Gas Composition: 86.1% CH_4 ; 13.9 % CO_2)
In-Situ Gas Content: 234.12 scf/ton
Reservoir Pressure: 1461.3 psia
Critical Desorption Pressure: 1,069.4 psia
Gas Recovery Factor (fraction, assumes abandonment pressure of 40 psia): 0.91

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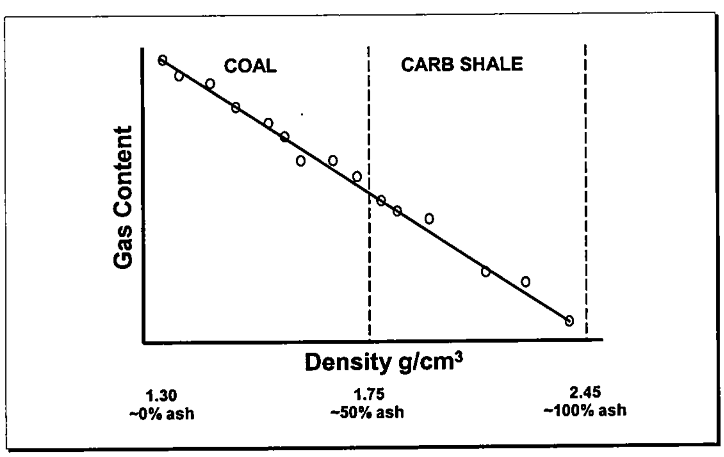
Reservoir Thickness - Inorganic Dilution



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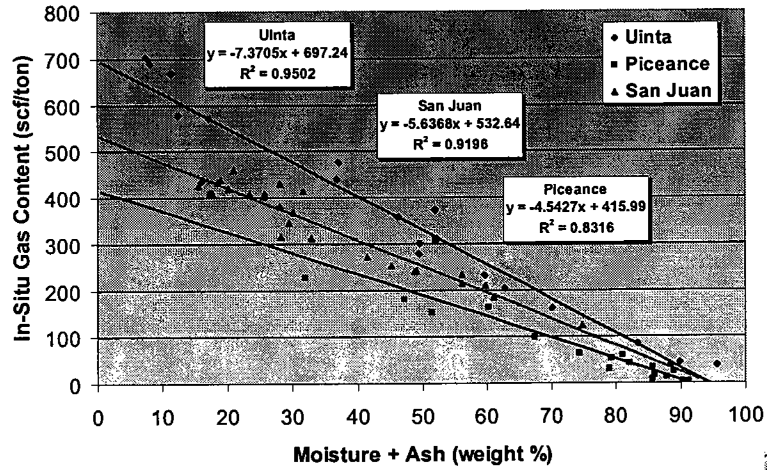
Gas Content Versus Coal Composition

Rule-of-thumb upper density limit: 1.75 g/cm³



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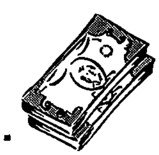
Creating Value with Gas Sorption Knowledge



- Exploration
  - Is the Resource Present – go/no go
  - Producibility – Economic Viability (when should the gas come)
  - Critical Reservoir Properties – Gas Mobility
- Asset Valuation
  - Resource In Place
  - Recovery Factor – Producible Reserves
  - Resource Quality – Sorbed Phase Gas Composition
- Asset Development
  - Optimum Flowing Pressure – Critical Desorption Pressure
  - Gas Processing – Gas Quality
  - Infield Development Potential

Assumption is that the data is collected, analyzed and reported using best practices protocols

gti

OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 9-2002

7

What your momma never told you about coal seams

John Eakin
Eakin Exploration, Inc.
Bartlesville, OK

Eakin, John, 2002, What your momma never told you about coal seams, *in* Fourth annual Oklahoma coalbed-methane workshop: Oklahoma Geological Survey, Open-File Report 9-2002, p. 129-133.

"WHAT YOUR MAMA

NEVER TOLD YOU

ABOUT COAL SEAMS"

Presented October, 2002

John L. Eakin III
Eakin Exploration, Inc.

I. INTRODUCTION

1. Introduce self and background
   a. Roughneck, roustabout
   b. BA degree in psychology
   c. Landman
   d. Operator of shallow wells in northeast Oklahoma
   e. BS geology
   f. Drilled, completed or plugged about 250 coal seam wells

2. "Resolution of some engineering and geological difficulties requires techniques not commonly found in textbooks." (Quote by Larry Connor, P.E., Ryder Scott Co., as a concluding statement on his technical paper presented at Mid-Continent Coalbed Methane Forum, August 2001.) Will attempt to present my understanding, or lack of understanding, of the coal seam gas business from an experience-based point of view.
   a. Looking for cookie cutter formula
      i. low-cost method
      ii. repeatable positive results
   b. Rule of thumb analysis
   c. Experience-based theory

II. HISTORY

1. Ancient – 1921 AAPG
   a. First shale well produced in southeast Kansas near Chanute about 1910
   b. By 1921, the shale gas industry had developed in eastern Kansas
   c. Coal producing area (picture of 1921 map)
   d. Coal seam industry declines with little knowledge of its existence

2. Recent
   a. In mid 1980's, some production reestablished in Montgomery County, Kansas
   b. In early 1990's, there were some recompletions of old wells, mostly Mulky coal
   c. By mid 1990, drilling of new wells occurred, mostly Riverton/Rowe coals
   d. By late 1990, many new operators, including large independents

III. PROSPECTS

1. Things to consider
   a. Acreage – 5,000 + acres
   b. Pipelines

c. Target coal with gas potential – e-logs and old driller's logs
    i. Weir-Pittsburg coal
    ii. Rowe coal
    iii. Riverton coal
d. Gas volume: average production 50 mcf/day or above
e. Structure
f. Depth

2. Quick economic analysis
    a. Parameters
        i. 5000 acres/80 acre spacing = 62 drill sites
        ii. 1500 ft wells
        iii. $40,000 well cost
        iv. $15,000 proportionate share of gathering and water disposal and acreage
        v. $800 per month operating cost including water disposal and gathering
        vi. $3.00 gas price - $2.40 to producer and gathering
        vii. 8 test wells

3. Quick payout analysis
    a. Cost: $55,000 per well
    b. Expenses: $800 per well per month
    c. Income: (50 mcf x $2.40 x 30.4 day/month)
       = $3,648 income - $800 month expenses
       = $2,848 net per well
    d. Payout: $55,000 well cost / $2,848 net monthly income
       = 19 month payout per well

4. Spacing and location orientation
    a. 80 to 160 acre spacing – larger wells, larger spacing
    b. Fracture orientation and elliptical drainage should be considered in well spot: face cleat N47°W primary, butt cleat N53°E, football shaped drainage orientation N47°W (diagrams)

IV. DRILLING & COMPLETION

1. Drilling
    a. Rig (photos)
    b. Samples
    c. Gas tests (photos)
    d. E-logs with gas tests

2. Completion
   a. Casing and cement
      i. cased hole vs. open hole
      ii. cement
         a. best coal most likely to take cement
         b. discuss cement
            i. cement in zone
            ii. gilsonite and flow seal
   b. Perfs and fracs – discussion and description of how we treat our wells
      i. photo of frac jobs
      ii. scoured tunnel theory
   c. Problems and Solutions
      i. cement invasion into coal – use lightweight cement and plenty of flow seal or gilsonite
      ii. frac out of zone – results from cement invasion into zone which was discussed above, or trying to force with too much rate and horsepower; be gentle to coals – they are unforgiving; use more water and less sand, particularly at beginning

V. PRODUCTION & GATHERING

1. Production (photos)
   a. Water disposal
      i. quote 1921 AAPG bulletin: "see page 378"
      ii. one central disposal – Arbuckle or recompletion of old well
   b. Gas volumes
      i. 10 to 400 mcf
      ii. (charts and decline curves)
      iii. cumulative gas and average decline
   c. Problems and solutions
      i. well produces black paraffin-looking substance – probably mixture of frac gel and coal fines; we have eliminated using gel in frac fluid
      ii. well that makes gas while drilling makes no gas or fluid after frac – probably cement in coal; trying to refrac well has never solved problem, just $10,000 poorer
      iii. well gas and water volumes decline rapidly; if no drainage from other wells, probably result of coal fine migration – pump into well with 200 bbls water then pump back slowly; may need to repeat process several times
      iv. when you think you have something figured out you're probably about to find out you're wrong

d. Gathering (photos)

   i. need major pipeline connection – too costly to move gas through small privately owned gathering
   ii. private gathering systems are used to control areas
   iii. low pressure – large pipe
   iv. gathering deals – between 25% and 35% of adjusted net revenue (line loss and fuel)

VI. CONCLUSION & QUESTIONS

OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 9-2002

8

Horizontal CBM development in the Hartshorne coal, Arkoma Basin, Oklahoma

Doug Rutter
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Rutter, Doug, 2002, Horizontal CBM development in the Hartshorne coal, Arkoma Basin, Oklahoma, *in* Fourth annual Oklahoma coalbed-methane workshop: Oklahoma Geological Survey, Open-File Report 9-2002, p. 134.

Horizontal CBM development in the Hartshorne coal, Arkoma basin, Oklahoma

Doug Rutter

NOTES

9

Appendixes

Appendix 1: Cardott, B.J., Selected coalbed methane references.

Appendix 2: Cardott, B.J., Bibliography of Oklahoma coalbed methane.

Appendix 3: Cardott, B.J., Bibliography of Oklahoma coal.

APPENDIX 1
Selected Coalbed Methane References
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APPENDIX 2
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