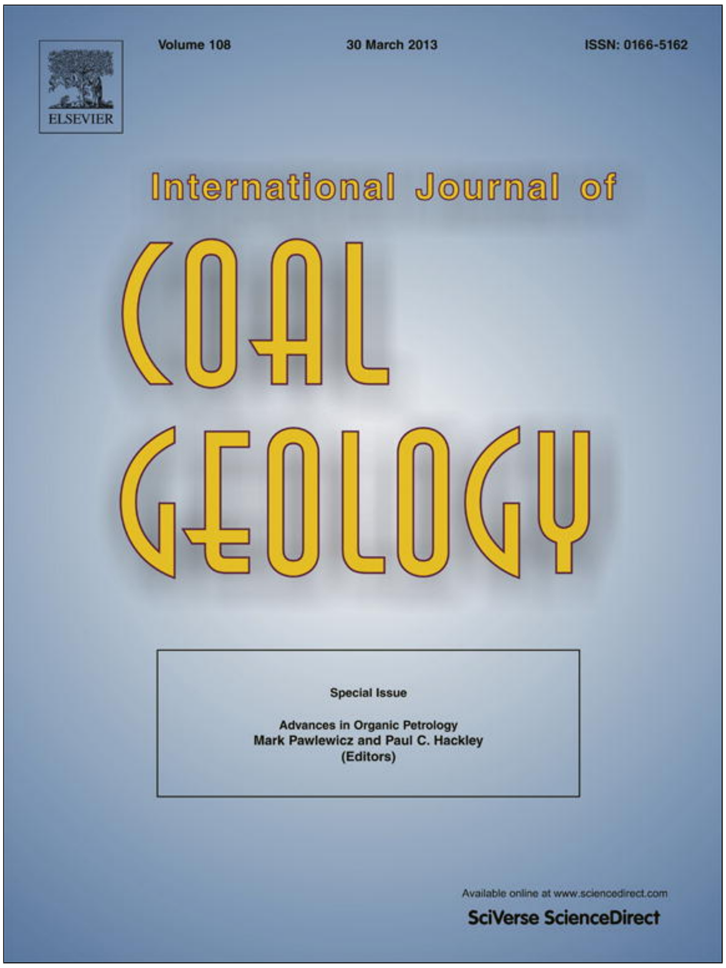
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Hartshorne coal rank applied to Arkoma Basin coalbed methane activity, Oklahoma, USA

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ABSTRACT

Coal rank, generalized for all coal beds at or near the surface, in the eastern Oklahoma coalfield has been known since 1915. Near the surface (depths <305 m, <1000 ft), coal rank increases from high volatile bituminous to low volatile bituminous from west to east in the Arkoma Basin in Oklahoma. The rank of subsurface (depths >305 m, >1000 ft) coals in Arkoma Basin coalbed methane (CBM) prospects was previously unknown. A new Hartshorne coal (Middle Pennsylvanian) rank map is based on mean maximum vitrinite reflectance values of 0.76% to 2.41% R_{max} from 70 coal samples from vertical depths of 0 (surface) to 1327 m (4355 ft). Hartshorne coal rank in the subsurface increases from high-volatile bituminous to semianthracite from west to east in the Arkoma Basin in Oklahoma. Bituminous rank boundaries changed considerably from earlier surface rank maps (primarily by increasing the area of medium volatile bituminous rank coal in the subsurface) and revealed a previously unknown semianthracite rank area. This discrepancy is significant because the rank of deep (>305 m, >1000 ft) coal resource assessments and CBM exploration projects have been based on shallow coal rank assignments.

A total of 2635 Hartshorne (Hartshorne, Lower Hartshorne, and Upper Hartshorne) CBM wells have been completed in Oklahoma since 1988. Most (1610) wells are horizontal with lateral lengths ranging from 4 to 1498 m (14 to 4914 ft; an average of 669 m [2195 ft]). Coal in most Hartshorne CBM wells is medium volatile bituminous rank. Hartshorne coal is semianthracite rank in about 160 CBM wells in Le Flore County. The four Hartshorne CBM wells with the highest initial potential (IP) gas rates (48 to 65 thousand cubic meters per day, Mcmd; 1.7 to 2.3 million cubic feet per day, MMcfd) are medium volatile bituminous rank from horizontal wells in Haskell and Pittsburg counties. IP gas rates <28.3 Mcmd (<1 MMcfd) in low volatile bituminous and semianthracite rank Hartshorne horizontal CBM wells may be low due to complications in drilling into high rank coals with cleat spacing <1 cm, to stimulation differences, or to gas migration into adjacent sandstone channels.

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1. Introduction

The eastern Oklahoma coalfield is in the southern part of the western region of the Interior Coal Province of the United States (Campbell, 1929). The coal region continues northward into Kansas and eastward into Arkansas (Tully, 1996). Friedman (1974) divided the Oklahoma coalfield into the northeast Oklahoma shelf and Arkoma Basin based on physiographic and structural differences (Fig. 1). The commercial coal belt is where coal beds are mineable at more than 25 cm (10 in.) thick. 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 strip mining. The western boundary of the noncommercial coal-bearing region is uncertain (Wood and Bour, 1988). Coalbed methane (CBM) drilling has occurred in both the commercial coal belt and the noncommercial coal-bearing region.

About 40 named banded coal beds of Desmoinesian to Missourian age (Middle to Late Pennsylvanian) in the eastern Oklahoma coalfield are <0.3 to 3 m (<1 to 10 ft) thick (Hemish, 1988). Since 1915, numerous maps have shown rank generalized for all coal beds at or near the surface (depths <305 m, <1000 ft) of high-volatile bituminous in the northeast Oklahoma shelf and high-volatile bituminous to low-volatile bituminous (increasing from west to east) in the Arkoma Basin (Fig. 1). Prior to CBM drilling, coal rank in the subsurface was known regionally only imprecisely from widely distributed underground coal-mine samples and coal exploration core samples. As in the deepest underground coal mine in Oklahoma (Lone Star Steel Co. Carbon No. 5 mine at 488 m (1600 ft) deep to the McAlester coal), the rank of deep coal in Oklahoma is often unknown (Friedman, 2010).

A Hartshorne coal-rank map based on mean maximum vitrinite reflectance (R_{max}) can be applied to the influence of rank on Arkoma Basin CBM activity and a more accurate assignment of rank to future Oklahoma deep (>305 m, >1000 ft) coal resource assessments. The rank of deep coal beds was previously extrapolated to the subsurface in an

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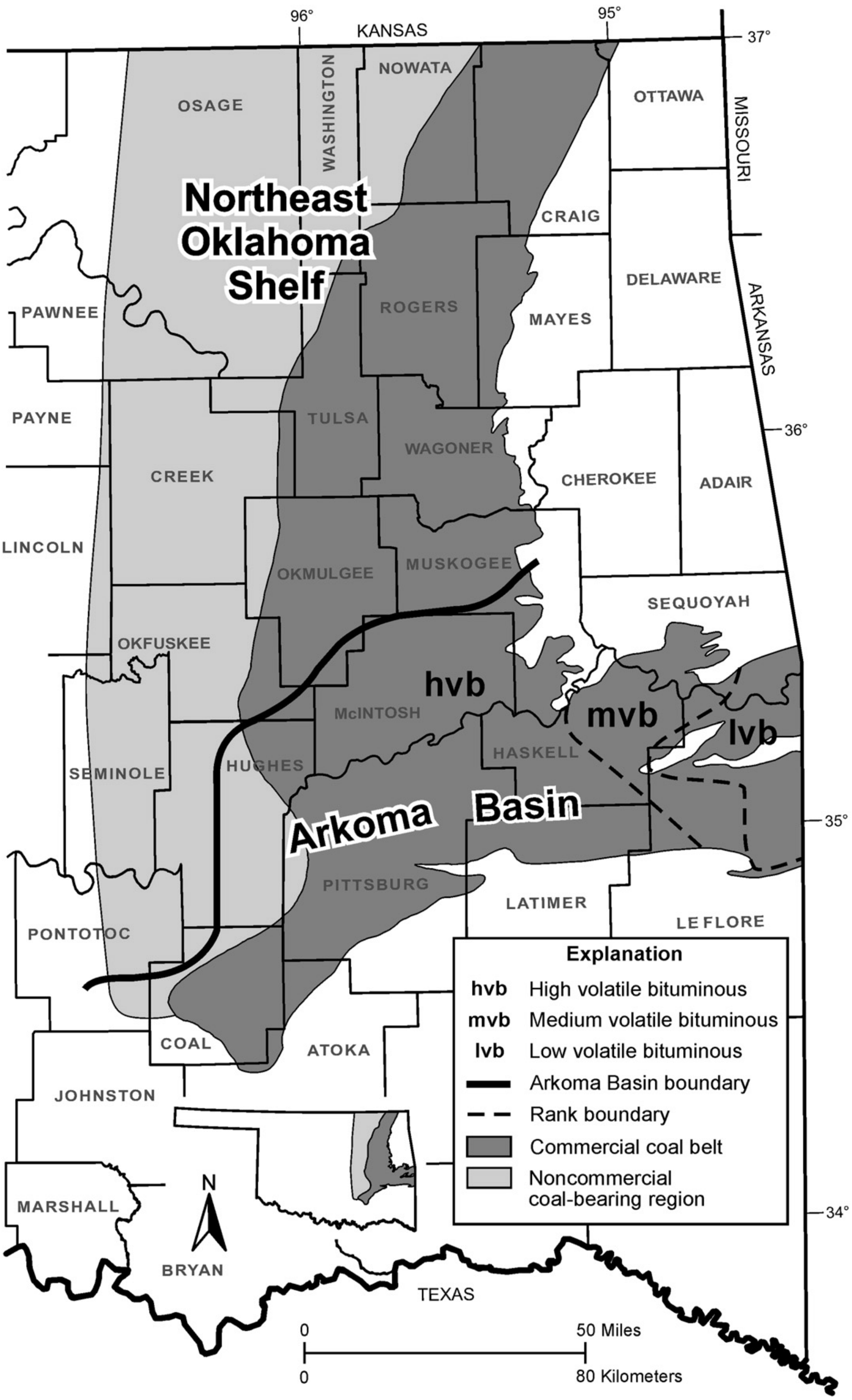

Fig. 1. Oklahoma coalfield and surface coal rank generalized from all coal beds (modified from Andrews et al., 1998, and Friedman, 1974). Arkoma Basin province northern boundary is from Northcutt and Campbell (1998).

Table 1
Hartshorne coal sample information and vitrinite reflectance data arranged by increasing township and range. (OPL = Oklahoma Geological Survey Organic Petrography Laboratory; PSOC = Pennsylvania State University, Penn State Office of Coal Research; hvAb = high volatile A bituminous; mvb = medium volatile bituminous; lvb = low volatile bituminous; sa = semianthracite; NA = not available).

Sample	Sample ID	Operator Name	Well/Mine Name	Sample Type	Latitude	Longitude	County	Coal Name	Depth (FT)	R_{max}	R_{max} Range	n	Standard Deviation	Rank
1	OPL 1237	Orion Exploration	1–5 Claudine	Cuttings	34.93	−95.84	Pittsburg	Upper Hartshorne	1806	0.85	0.77–0.96	100	0.04	hvAb
2	OPL 419	P&K Coal Company	Gowen Pit (strip mine)	Channel	34.87	−95.46	Latimer	Lower Hartshorne	Surface	0.76	0.62–0.86	100	0.04	hvAb
3	OPL 457	OGS Core C-LA-1		Core	34.93	−95.15	Latimer	Lower Hartshorne	165	0.80	0.65–0.92	100	0.06	hvAb
4	OPL 1167	Fractal Operating	1–5 Noggle	Cuttings	34.94	−95.11	Latimer	Lower Hartshorne	1252	0.98	0.87–1.09	100	0.05	hvAb
5	OPL 1043	Farrell-Cooper Mining	Pine Mountain (strip mine)	Channel	34.88	−94.62	Le Flore	Lower Hartshorne	Surface	1.34	1.22–1.47	100	0.04	mvb
6	OPL 934	Farrell-Cooper Mining	Pine Mountain Bowman Pit (strip mine)	Channel	34.87	−94.63	Le Flore	Lower Hartshorne	Surface	1.28	1.21–1.38	100	0.03	mvb
7	OPL 662	Turner Brothers	Heavener (strip mine)	Channel	34.87	−94.67	Le Flore	Lower Hartshorne	Surface	1.27	1.16–1.38	100	0.04	mvb
8	OPL 1039	Highway 59 Roadcut	Outcrop	Grab	34.87	−94.62	Le Flore	Lower Hartshorne	Surface	1.27	1.18–1.37	100	0.03	mvb
9	PSOC 142	Howe Mining Company	Howe Mine No. 1 (underground mine)	Channel	34.92	−94.61	Le Flore	Lower Hartshorne	350	1.46	1.37–1.55	100	NA	mvb
10	OPL 1169	El Paso Production Co.	GBP 1-13H	Cuttings	34.9	−94.52	Le Flore	Hartshorne	2068	1.70	1.58–1.84	100	0.04	lvb
11	OPL 1145	Farrell-Cooper Mining	Heavener East No. 2 (auger mine)	Grab	34.88	−94.51	Le Flore	Lower Hartshorne	Surface	1.38	1.30–1.45	100	0.03	mvb
12	OPL 1346	Farrell-Cooper Mining	HE 09-1	Core	34.91	−94.45	Le Flore	Lower Hartshorne	144	1.41	1.36–1.50	100	0.03	mvb
13	OPL 1153	Farrell-Cooper Mining	Heavener East (auger mine)	Grab	34.9	−94.46	Le Flore	Lower Hartshorne	Surface	1.43	1.35–1.52	100	0.04	mvb
14	OPL 1227	Chesapeake Operating	1–13H Blevins	Cuttings	34.99	−96.1	Hughes	Hartshorne	3239	0.90	0.82–0.99	100	0.03	hvAb
15	OPL 1242	Tilford Pinson Exploration	1H–19 Stewart	Cuttings	34.97	−95.98	Pittsburg	Hartshorne	3390	0.99	0.90–1.07	100	0.04	hvAb
16	OPL 1238	Orion Exploration	2–25 Hotubbee	Cuttings	34.96	−95.57	Pittsburg	Upper Hartshorne	3660	1.38	1.30–1.49	100	0.03	mvb
17	OPL 1217	Jay Petroleum	7–9 Hyla	Cuttings	35.01	−95.52	Pittsburg	Hartshorne	2111	1.23	1.17–1.33	100	0.03	mvb
18	OPL 1225	Samson Resources	1–11H Lake Wayne	Cuttings	35.01	−95.38	Latimer	Hartshorne	3246	1.28	1.21–1.37	100	0.03	mvb
19	OPL 1246	Samson	1–17H Mollie	Cuttings	34.99	−95.33	Latimer	Hartshorne	3026	1.17	1.12–1.22	100	0.02	mvb
20	OPL 1165	Fractal Operating	1–31 Booth	Cuttings	34.94	−95.13	Latimer	Lower Hartshorne	1570	0.89	0.78–1.01	100	0.05	hvAb
21	OPL 1166	Fractal Operating	1–32 Thrift	Cuttings	34.94	−95.12	Latimer	Lower Hartshorne	1516	0.98	0.90–1.05	100	0.03	hvAb
22	OPL 1163	Williams Company	3–8 Wil E Coyote	Cuttings	35.01	−94.8	Le Flore	Hartshorne	4355	2.41	2.31–2.53	100	0.06	sa
23	OPL 1164	Williams Company	1A–18 Penelope	Cuttings	35	−94.81	Le Flore	Hartshorne	4233	2.32	2.13–2.47	100	0.07	sa
24	OPL 1203	Vectra	1H–30 Gist	Cuttings	34.96	−94.8	Le Flore	Lower Hartshorne	2267	1.75	1.68–1.85	100	0.04	lvb
25	OPL 1204	Vectra	32H Morris	Cuttings	34.96	−94.8	Le Flore	Lower Hartshorne	1700	1.59	1.53–1.71	100	0.04	lvb
26	OPL 1384	Farrell-Cooper Mining	Bull Hill (strip mine)	Grab	34.95	−94.81	Le Flore	Lower Hartshorne	Surface	1.28	1.23–1.36	100	0.03	mvb
27		El Paso	CH 2–16	Core	35	−94.67	Le Flore	Hartshorne	2357	2.16	2.03–2.30	NA	NA	sa
28	OPL 1241	El Paso Production Co.	7–21H Kerr	Cuttings	34.98	−94.68	Le Flore	Lower Hartshorne	2394	2.22	2.05–2.39	100	0.07	sa
29	OPL 1247	Aztec Energy	10–11 Barnes	Core	35	−94.55	Le Flore	Upper Hartshorne	1522	2.06	1.93–2.21	100	0.05	sa
30	OPL 1127	Bear Productions	2 Hudgins	Cuttings	34.98	−94.57	Le Flore	L. Hartshorne	1022	1.83	1.72–1.95	100	0.06	lvb
31	OPL 1136	Bear Productions	1 Gatlin	Cuttings	34.97	−94.55	Le Flore	L. Hartshorne	1105	1.81	1.71–1.96	100	0.05	hvAb
32	OPL 1137	Bear Productions	1 Christopher	Cuttings	34.97	−94.56	Le Flore	Hartshorne	946	1.83	1.69–1.95	100	0.06	hvAb
33	OPL 1288	Panther Energy	2H–34 Maddy	Cuttings	35.04	−96.23	Hughes	Hartshorne	3176	0.82	0.72–0.90	100	0.03	hvAb
34	OPL 1208	Chesapeake Operating	1–16H Riner	Cuttings	35.09	−96.04	Pittsburg	Hartshorne	2492	0.90	0.82–1.02	100	0.03	hvAb
35	OPL 1231	Ardmore Production & Exploration	1H–15 Quick Draw	Cuttings	35.08	−95.93	Pittsburg	Hartshorne	2595	0.90	0.81–0.97	100	0.03	hvAb

(continued on next page)

Table 1 (*continued*)

Sample	Sample ID	Operator Name	Well/Mine Name	Sample Type	Latitude	Longitude	County	Coal Name	Depth (FT)	R_{max}	R_{max} Range	n	Standard Deviation	Rank
36	OPL 1239	Orion Exploration	1–35 Orval	Cuttings	35.03	−95.81	Pittsburg	Hartshorne	3157	1.22	1.16–1.30	100	0.03	mvb
37	OPL 1224	Chesapeake Operating	1–8H Harper	Cuttings	35.09	−95.75	Pittsburg	Hartshorne	2999	1.28	1.2–1.36	100	0.03	mvb
38	OPL 1229	Petroquest Energy	3–22 Wood Trust	Cuttings	35.06	−95.71	Pittsburg	Hartshorne	3074	1.36	1.29–1.42	100	0.03	mvb
39		El Paso	CH 1–21	Core	35.07	−95.2	Haskell	Hartshorne	2450	1.34	1.29–1.38	NA	NA	mvb
40	OPL 1202	Panther Energy	2H–11 Gabriel	Cuttings	35.17	−95.9	McIntosh	Hartshorne	2228	1.05	0.96–1.14	100	0.03	hvAb
41	OPL 1182	Williams Company	1–23 Haley	Cuttings	35.15	−95.79	Pittsburg	Hartshorne	3451	1.42	1.34–1.49	100	0.03	mvb
42	OPL 1156	Williams Company	1–16 Jazzmyn	Cuttings	35.17	−95.73	Pittsburg	Hartshorne	2615	1.41	1.34–1.55	100	0.04	mvb
43	OPL 1157	Williams Company	3–26 Ivey	Cuttings	35.13	−95.7	Pittsburg	Hartshorne	3161	1.45	1.35–1.63	100	0.05	mvb
44	OPL 1234	Petroquest Energy	1–29H Kenny Leake	Cuttings	35.14	−95.65	Pittsburg	Hartshorne	2918	1.39	1.33–1.47	100	0.03	mvb
45	OPL 1181	Williams Company	3–4 Kobe	Cuttings	35.19	−95.52	Pittsburg	Hartshorne	2845	1.52	1.42–1.62	100	0.04	lvb
46	OPL 1158	Williams Company	2–10 Hook	Cuttings	35.18	−95.5	Pittsburg	Hartshorne	2300	1.36	1.26–1.60	100	0.06	mvb
47	OPL 1159	Williams Company	4–34 Izzy	Cuttings	35.13	−95.39	Pittsburg	Hartshorne	2562	1.19	1.13–1.33	100	0.03	mvb
48	OPL 1160	Williams Company	4–13 Brashears	Cuttings	35.17	−95.25	Haskell	Hartshorne	1571	1.20	1.13–1.32	100	0.03	mvb
49	OPL 1161	Williams Company	7–22 Domino	Cuttings	35.15	−95.3	Haskell	Hartshorne	1717	1.18	1.09–1.37	100	0.05	mvb
50	OPL 1162	Williams Company	4–32 Penny	Cuttings	35.13	−95.33	Haskell	Hartshorne	1650	1.09	0.99–1.26	100	0.04	hvAb
51	OPL 1265	Williams Production	2–25 Poncho	Cuttings	35.13	−95.05	Haskell	Hartshorne	1012	1.49	1.39–1.57	100	0.03	mvb
52	OPL 1266	Williams Production	4–25 Poncho	Cuttings	35.14	−95.05	Haskell	Hartshorne	884	1.42	1.33–1.49	100	0.03	mvb
53	OPL 351	Great National Corp.	Federal Pit (strip mine)	Channel	35.16	−94.96	Haskell	Upper Hartshorne	Surface	1.35	1.21–1.48	100	0.05	mvb
54	OPL 1152	Georges Colliers Inc.	Milton (strip mine)	Grab	35.15	−94.89	Le Flore	Hartshorne	Surface	1.59	1.50–1.78	100	0.04	lvb
55	OPL 1344	Farrell-Cooper Mining	Rock Island (strip mine)	Channel	35.18	−94.48	Le Flore	Lower Hartshorne	Surface	1.83	1.74–1.93	100	0.05	lvb
56	OPL 1257	IRIS Resources	31-4 Dubois	Cuttings	35.12	−94.49	Le Flore	Upper Hartshorne	1347	1.85	1.77–1.99	100	0.05	lvb
57	OPL 1287	Panther Energy	1H-27 Tanner	Cuttings	35.23	−95.81	McIntosh	Hartshorne	3345	1.44	1.39–1.50	100	0.03	mvb
58	OPL 1230	Mahalo Energy	4-3H CBM Skip	Cuttings	35.28	−95.72	McIntosh	Hartshorne	1955	1.30	1.23–1.35	100	0.02	mvb
59	OPL 1249	G.M. Oil Properties	1H-8 Hunton Season	Cuttings	35.26	−95.75	McIntosh	Hartshorne	2160	1.27	1.22–1.35	100	0.02	mvb
60	OPL 844	K&R Coal Company	Ryan No. 2 (strip mine)	Channel	35.23	−95.11	Haskell	Hartshorne	Surface	1.17	1.10–1.23	100	0.03	mvb
61	OPL 513	K&R Coal Company	Ryan (strip mine)	Channel	35.21	−95.09	Haskell	Hartshorne	Surface	1.22	1.14–1.33	100	0.04	mvb
62	OPL 454	OGS Core C-HA-2	Ritter Property	Core	35.22	−94.83	Haskell	Hartshorne	134	1.39	1.33–1.50	100	0.03	mvb
63	OPL 845	K&R Coal Company	Sunset Corners Test Burn (strip mine)	Channel	35.23	−94.72	Le Flore	Hartshorne	Surface	1.78	1.69–1.91	100	0.04	lvb
64	OPL 1252	IRIS Resources	34–2 Dale	Cuttings	35.2	−94.75	Le Flore	Hartshorne	1039	1.87	1.76–2.00	100	0.05	lvb
65	OPL 1243	Coal Creek Minerals	Red Bank Creek (underground mine)	Grab	35.25	−94.7	Le Flore	Hartshorne	Surface	1.85	1.74–1.97	100	0.04	lvb
66	OPL 1378	CWF Associates	27–9 G.W. Eagleton	Core	35.22	−94.64	Le Flore	Lower Hartshorne	1186	2.02	1.87–2.15	100	0.06	lvb
67	OPL 1379	CWF Associates	31–8 L.W. Stiles	Core	35.21	−94.69	Le Flore	Lower Hartshorne	1214	2.00	1.90–2.10	100	0.04	lvb
68	OPL 1131	Georges Colliers Inc.	Pollyanna No. 8 (underground mine)	Grab	35.22	−94.57	Le Flore	Hartshorne	300	1.84	1.74–2.03	100	0.05	lvb
69	OPL 1324	Rio Vista Operating	2-29 Urquhart	Cuttings	35.31	−95.53	McIntosh	Hartshorne	1390	1.18	1.09–1.26	100	0.03	mvb
70	OPL 319		Outcrop	Grab	35.47	−95.15	Muskogee	Hartshorne	Surface	1.03	0.94–1.11	100	0.03	hvAb

estimate of remaining coal resources of Oklahoma (Friedman, 1974). Knowing the rank of coal is important in selecting high rank coals for combustion, carbonization, gasification, and CBM exploration (e.g., gas-in-place generally increases with increasing coal rank). Lessons learned from the successes and challenges of drilling into thin (<3 m, <10 ft thick), Pennsylvanian-age, banded bituminous and semianthracite rank coals of Oklahoma may be applied to other CBM projects.

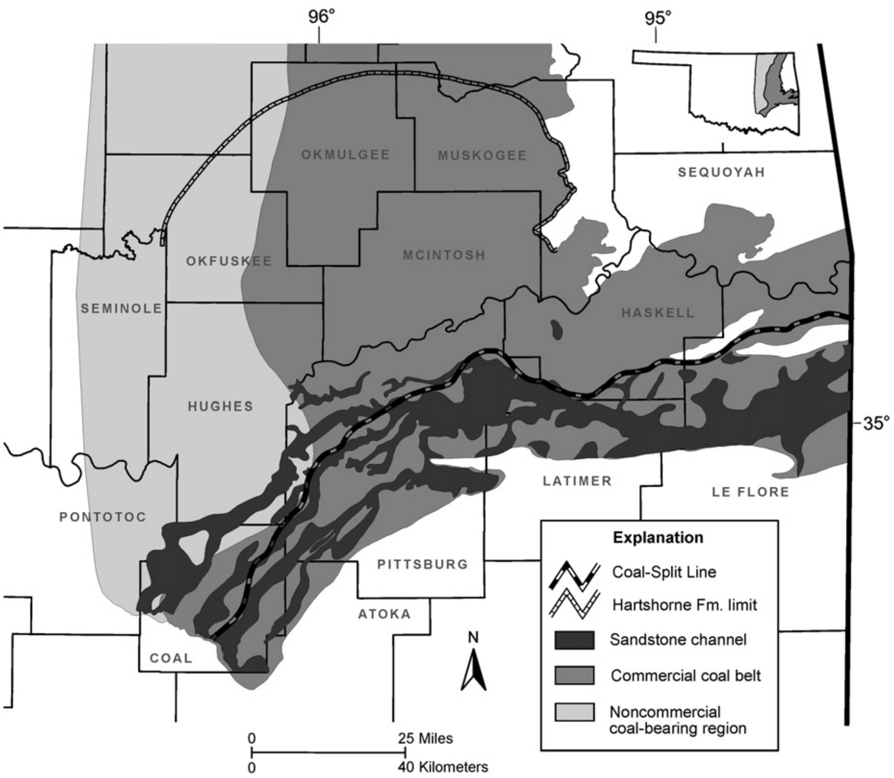

Fig. 2. Distribution of the Hartshorne Formation in the Arkoma Basin, showing the approximate limit of the Hartshorne Formation, coal-split line, and sandstone channels (modified from Andrews et al., 1998).

2. Surface coal rank

The first surface-coal-rank map of the Oklahoma coalfield was based on fixed-carbon content (White, 1915). Subsequent surface-coal-rank maps refined the isocarb contours (Croneis, 1927; Damberger, 1974; Fuller, 1920; Hendricks, 1935; Iannacchione et al., 1983; Miser, 1934; Thom, 1934; Wilson, 1971). Burgess (1974) prepared a thermal-alteration-isocarb map of the Arkoma Basin interpreted from kerogen and

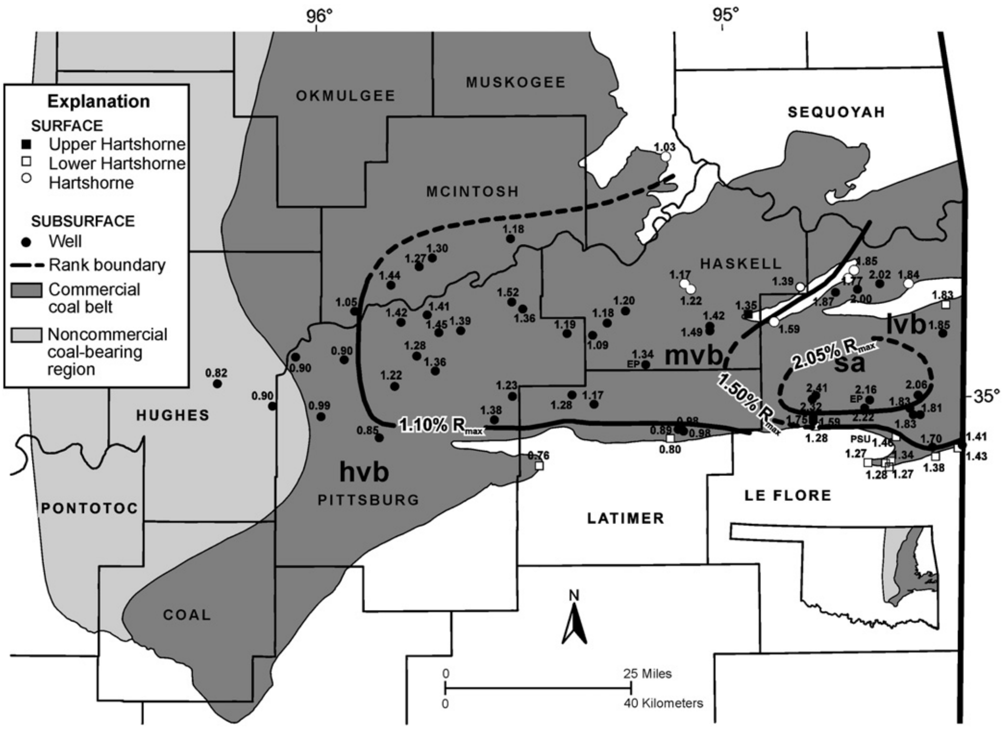

Fig. 3. Rank of Hartshorne coal based on mean maximum vitrinite reflectance (hvb = high volatile bituminous; mvb = medium volatile bituminous; lvb = low volatile bituminous; sa = semianthracite). Numbers are mean maximum vitrinite reflectance values (%R_{max}). PSU = Pennsylvania State University samples; EP = El Paso samples.

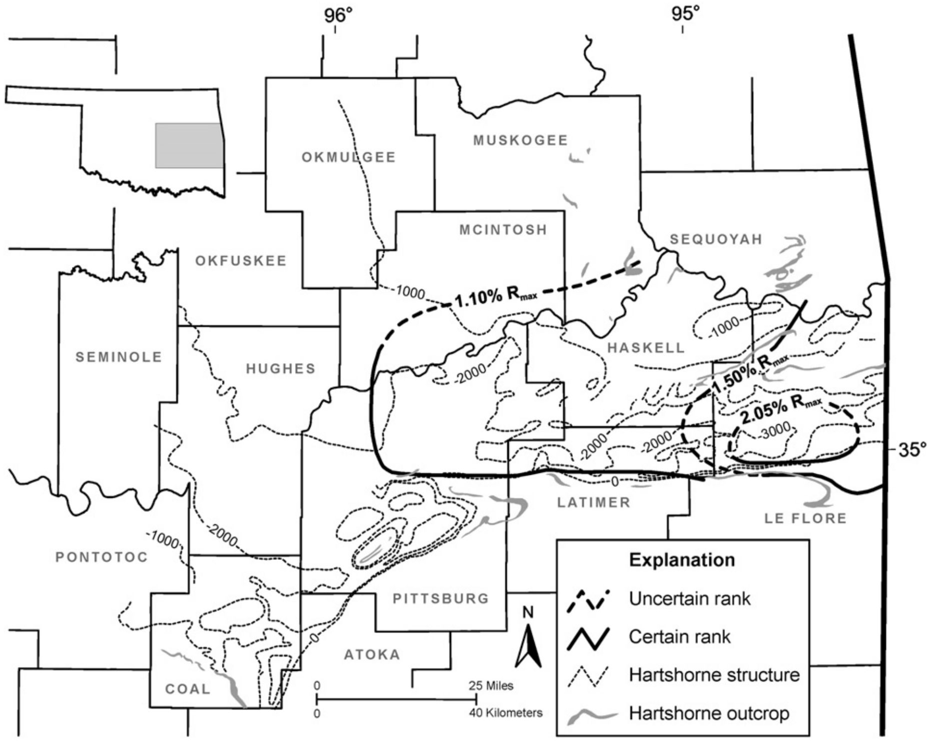

Fig. 4. Hartshorne coal rank on Hartshorne Formation structure (1000 ft contour interval; modified from Andrews et al., 1998).

coal fixed-carbon data. Houseknecht et al. (1992) prepared a Hartshorne coal isoreflectance map based on vitrinite reflectance, fixed carbon and Btu data (converted to equivalent vitrinite-reflectance values) from surface and shallow subsurface samples.

Coal-rank boundaries generalized for all coal beds at or near the surface (depths <305 m, <1000 ft) based on vitrinite reflectance and coal chemistry data are shown in Fig. 1. The rank of coal beds, determined from outcrop, coal strip mine, and shallow (<143 m, <470 ft) core samples, ranges from high volatile to low volatile bituminous, increasing from west to east in the Arkoma Basin in Oklahoma. Coal rank increases to semianthracite in Arkansas (Tully, 1996).

3. Methods

Grab and channel samples of Hartshorne coal were obtained from outcrop, coal strip and underground mines, shallow core, and well cuttings from CBM wells. Unwashed Hartshorne coal well cuttings were obtained directly from CBM well operators. Samples were washed with water in an 18-mesh sieve, dried, and prepared into crushed-particle pellets. Maximum vitrinite reflectance (R_{max}) measurements were made on polished pellets following ASTM D-2798-91 (ASTM, 2010). Sample information and data are in Table 1. Sample depths range from 0 (surface) to 1327 m (4355 ft; total vertical depths). Supplemental Hartshorne coal vitrinite reflectance data came from the Pennsylvania State University Penn State Coal Sample Bank and Data Base (PSOC, 1990) and Pratt and Mavor (2005; El Paso cores).

Wells drilled for CBM in Oklahoma were tabulated from completion reports (form 1002A) reported to the Oklahoma Corporation Commission by oil and gas operators. CBM well distribution maps were prepared based on information provided by the operator.

4. Subsurface Hartshorne coal rank

The Hartshorne coal (Hartshorne Formation; Desmoinesian age, Middle Pennsylvanian) is the oldest and thickest commercial coal bed in Oklahoma. The coal is a single bed in the northern part of the Arkoma Basin and splits into two members (Upper Hartshorne and Lower Hartshorne) in the southern part of the Arkoma Basin (Hemish and Suneson, 1997). The Hartshorne coal-split line is shown in Fig. 2. The Lower Hartshorne coal has a maximum thickness of 2 m (7.0 ft), while the Upper Hartshorne coal is up to 1.7 m (5.6 ft) thick (Hemish and Suneson, 1997). The thickest (3 m; 10 ft) occurrence of coal in Oklahoma is the Hartshorne coal in an abandoned coal strip mine exposure south of the Hartshorne coal-split line in northern Latimer County (Hemish, 1999; Wilson, 1970).

The northern limit of the Hartshorne Formation is in northern Muskogee and Okmulgee counties (Fig. 2). Sandstone channels in the Hartshorne Formation occur in the southern part of the Arkoma Basin (Fig. 2; Andrews et al., 1998). The sandstone channels were fluvially dominated with a westerly flow direction. The Lower Hartshorne coal

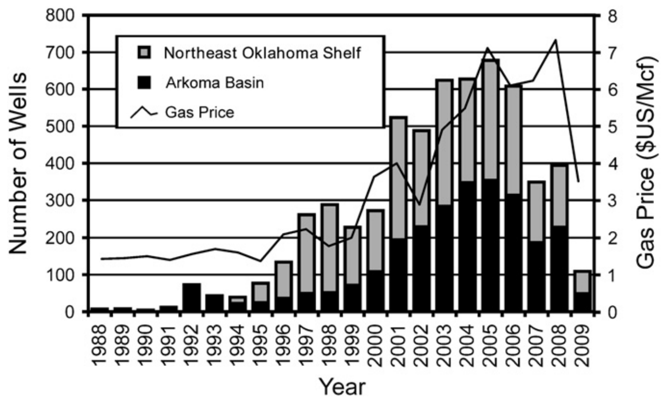

Fig. 5. Histogram showing numbers of Oklahoma coalbed methane well completions, 1988–2009. Oklahoma annual average wellhead natural gas price (not inflation adjusted) is from Soltani, 2010.

is absent where eroded by the upper member incised channels or thin where the lower member sandstone is thickest; the Upper Hartshorne coal is locally missing or thin where the upper member sandstone is thickest (Hemish and Suneson, 1997).

A Hartshorne coal rank map (Fig. 3), based on mean maximum vitrinite reflectance values (Table 1), of the Arkoma Basin was prepared when grab samples from underground coal mines and subsurface well cuttings from CBM drillholes became available for analysis. Mean maximum vitrinite reflectance values range from 0.76% to 2.41% R_{max} based on 100 measurements per sample (ASTM, 2010). Coal-rank boundaries are from Davis (1978): high volatile A bituminous, 0.71% to 1.10% R_{max}; medium volatile bituminous, 1.10% to 1.50% R_{max}; low volatile bituminous, 1.50% to 2.05% R_{max}; semianthracite, 2.05% to 3.00% R_{max} (approximate). In the subsurface, Hartshorne coal rank increases from high volatile bituminous to semianthracite from west to east in the Arkoma Basin in Oklahoma. Sample availability is insufficient to define the rank boundaries where lines are dashed.

The Hartshorne Formation in the Arkoma Basin is highly faulted and folded into broad synclines and tight anticlines that strike east-northeast (Andrews et al., 1998). Overall, the Hartshorne coal rank does not follow present-day depth of burial (Fig. 4). The southern high volatile bituminous/medium volatile bituminous east–west boundary coincides with increasing depth of burial to the north from the outcrop. The semianthracite rank area coincides closely with the Hartshorne Formation 1220 m (4000 ft) present-day overburden contour of Gossling (1994) under Cavanal Mountain in Le Flore County.

5. Time and cause of coalification

Several theories have been proposed to explain the time and cause of coalification in the Arkoma Basin. Possible sources of heat include igneous intrusions, hydrothermal fluids, and maximum depth of burial. The theories must explain the occurrence of bituminous and

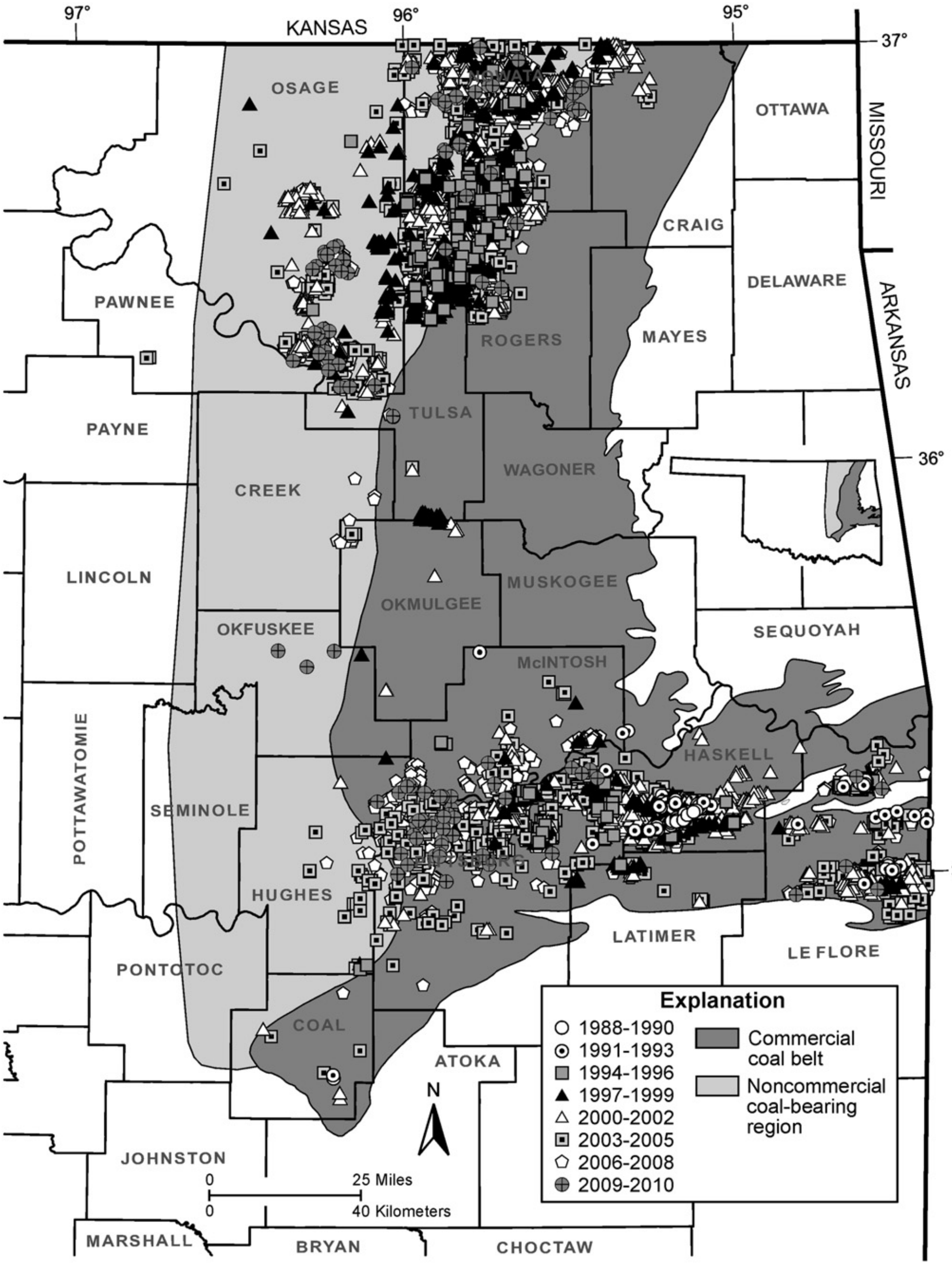

Fig. 6. Map showing 5869 coalbed-methane well completions in Oklahoma by year (1988 to May 2010).

semianthracite rank coals at the surface in Oklahoma and Arkansas, respectively, and the west to east increase in coal rank.

Cretaceous igneous intrusions are present in the Ouachita Mountains, Gulf Coastal Plain, and Mississippi Embayment in Arkansas (Stone and Sterling, 1964). Houseknecht and Matthews (1985) attributed a thermal overprint in the eastern Ouachita Mountains of Arkansas to Mesozoic rifting and intrusive activity in the Mississippi Embayment; the thermal influence from Mesozoic intrusions (>2% random vitrinite reflectance, VR_r) extends 50 km (31 mi) and does not reach outcrops of semianthracite-rank Hartshorne coal west of Russellville, Arkansas. They indicated that, in the western Ouachita Mountains in Oklahoma (and, by extension, the Arkoma Basin), sedimentary and tectonic burial was the main control of thermal maturation of Paleozoic strata. Houseknecht et al. (1992) indicated that thermal maturity decreases east of the semianthracite rank Hartshorne coal in Arkansas toward the Mississippi Embayment. In Arkansas, low volatile bituminous rank coals at the surface between semianthracite rank coals to the north and Mesozoic igneous intrusions to the southeast further discounts an influence of igneous activity on Hartshorne coal rank (Haley, 1982).

Warm fluids emanating from the Ouachita-Arkoma region during the late Paleozoic have been proposed to explain paleo warm spots in Pennsylvanian strata of southeastern Kansas (Barker et al., 1992; Wojcik et al., 1994), Mississippi Valley-type (MVT) lead and zinc deposits of the Ozark Uplift (Appold and Nunn, 2005; Clendenin and Duane, 1990), and metal enrichments in Pennsylvanian black shales in the Midcontinent (Coveney, 1992). Several authors favor hydrothermal fluid migration as the primary source of the anomalously high paleo heat flow in the Arkoma Basin (Houseknecht et al., 1992; Nunn and Lin, 2002; Wojcik et al., 1992). The proposed primary direction of warm fluid flow is north/northwestward from the Ouachita Mountains, Arkoma Basin, and Reelfoot Rift. Filipek (1992) explained the change in deep groundwater flow from northward to westward directions by the erosion of the Ouachita Mountains and formation of the Ozark Uplift in Late Pennsylvanian to Early Permian. Challenging this theory, Lee et al. (1996, p. 25,399) concluded that "present-day thermal data are generally not supportive of theories which invoke topographically driven groundwater flow through the Arkoma Basin in Late Pennsylvanian-Early Permian time (~290 Ma) to explain the genesis of Mississippi Valley-type lead-zinc deposits and regional diagenesis in the North American midcontinent."

Cardott et al. (1986) discounted the effect of burial on Arkoma Basin coalification primarily because the evidence (e.g., overburden) was missing (e.g., eroded). Later studies provided evidence of missing section. Based on apatite fission-track analysis, Arne (1992, p. 392) concluded that "Paleozoic rocks of the Ouachita Mountain fold belt and Arkoma Basin of Arkansas were exposed to maximum paleotemperatures during late Paleozoic burial, prior to the emplacement of Cretaceous plutons in the region." Werner and Griffith (1992) used thermal modeling to estimate maximum burial depths of <3 to >9 km (<10,000 to >30,000 ft) in the Arkoma Basin and Ouachita Mountains. Lee et al. (1996) estimated total erosion of 3 to 7 km (10,000 to 23,000 ft) in the Arkoma Basin based on assumptions pertaining to measured thermal maturity levels. Byrnes and Lawyer (1999) estimated 1.5 to 4.6 km (5000 to 15,000 ft) of section has been removed in the Arkoma Basin. They concluded (p. 23) that, "High thermal maturities, low porosities, and high shale bulk densities of nearsurface stratigraphic units indicate significant surface erosion", and, "Based on burial and thermal history reconstruction, present-day increasing maturation from west to east across the basin is primarily the result of increasing overburden and subsequent surface erosion from west to east," and that "thermal influences other than burial, such as hydrothermal fluid migration up faults, seems to have influenced thermal maturity by less than 20%."

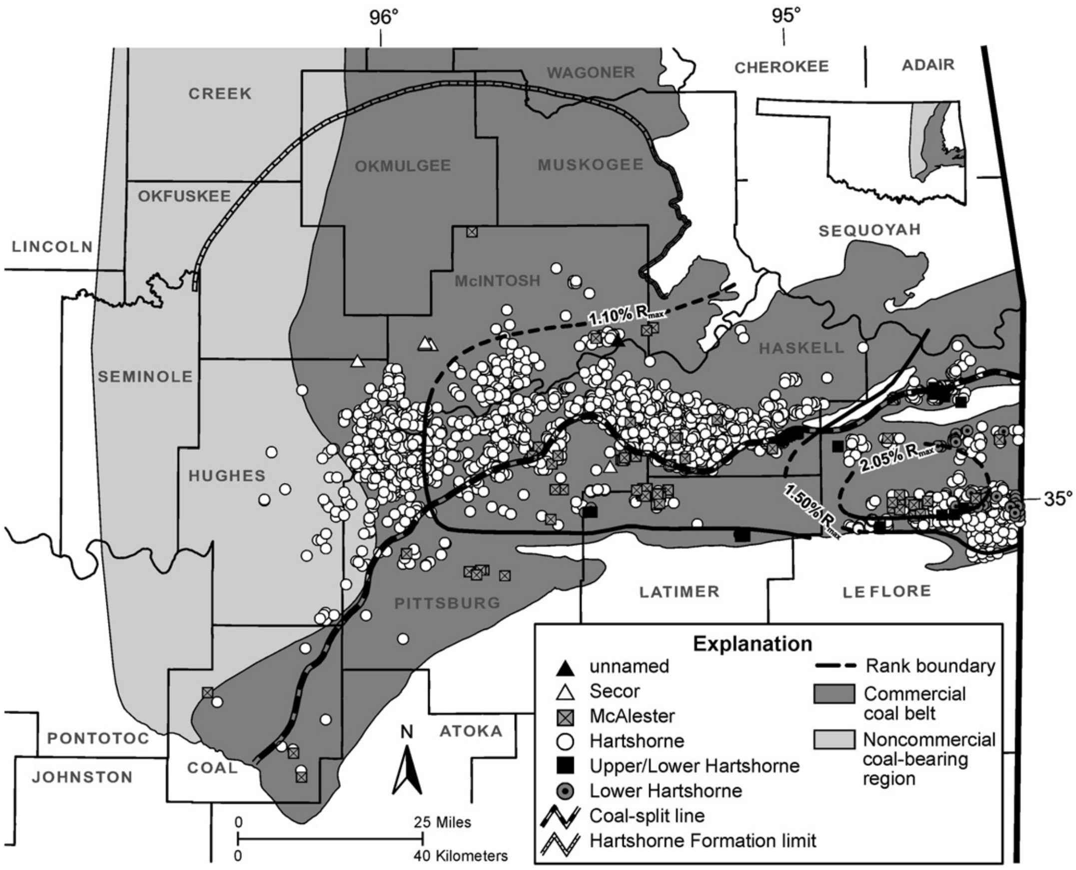

Fig. 7. Arkoma Basin coalbed methane well completions with Hartshorne coal rank.

In summary, heat flow data and metal enrichments indicate that hydrothermal fluids moved out of the Ouachita Mountains, Arkoma Basin, and Reelfoot Rift along faults, fractures, and permeable strata in the late Paleozoic but do not explain cooling east and west of the semianthracite region at the surface in Arkansas because the source of heating was presumed to be to the east. Other lines of evidence discussed above support the influence of burial depth to explain the occurrence and distribution of bituminous and semianthracite rank coals at the surface. Maximum burial depths during the late Paleozoic with subsequent uplift and erosion are deduced herein as the primary source of heat to explain the overall east to west rather than south to north pattern of Hartshorne decreasing coal rank. Whether primarily from maximum burial depths or hydrothermal fluids, the timing of maximum heating was during the late Paleozoic as the result of the Ouachita orogeny.

6. Oklahoma Arkoma Basin coalbed methane activity

The first seven CBM wells in Oklahoma were completed in 1988 in the Hartshorne coal in the Arkoma Basin in Haskell County (Figs. 5 and 6). By the end of 1992, at the deadline for the first phase of the United States Internal Revenue Service Section 29 (IRS §29) tax credit, there were a total of 104 CBM (including Desmoinesian age Hartshorne, Lower Hartshorne, Upper Hartshorne, and McAlester coals) wells in the Arkoma Basin. The first CBM wells completed in the northeast Oklahoma shelf were in 1994. By the 2002 deadline for the second phase of the IRS §29 tax credit (Sanderson and Berggren, 1998) there were a total of 931 CBM wells in the Arkoma Basin. A total of 5869 CBM wells have been completed in the eastern Oklahoma coalfield (including Arkoma Basin and northeast Oklahoma shelf) from 1988 to May 2010. The maximum number of CBM wells in Oklahoma completed in a single year was 353 for the Arkoma Basin and 678 for the entire coalfield in 2005. A dramatic decrease in CBM activity in the Oklahoma coalfield occurred during 2009 (total of 109 new wells) due to a decrease in value of natural gas (Fig. 5).

Fig. 7 shows 2697 CBM well completions in the Arkoma Basin from 1988 through May 2010. Most (2635) wells are in the Hartshorne coals (Hartshorne, Lower Hartshorne, Upper Hartshorne) and occur north of the Hartshorne coal-split line. Hartshorne CBM wells that are south of the coal-split line should be either to the Lower or Upper Hartshorne coal but were not identified as such by most of the operators. In some wells both the Upper and Lower Hartshorne coal beds were perforated (designated as Upper/Lower Hartshorne). Total vertical depths to the top of the coal in the Hartshorne CBM wells range from 87 to 1807 m (284 to 5930 ft; average of 589 m [1931 ft] from 2580 wells reporting coal depth). The shallowest (87 m; 284 ft) Hartshorne CBM well is one of two coal mine methane (CMM) wells in Oklahoma. The shallowest (102 m; 334 ft) vertical CBM (non-CMM) well had an initial potential (IP) gas rate of only 5 thousand cubic feet per day (Mcfd).

The Hartshorne coal-rank boundaries in Fig. 7 indicate that the coal rank in most Hartshorne CBM wells is medium volatile bituminous. Medium volatile bituminous rank corresponds to peak thermogenic methane generation (Boyer, 1989) and the cross-over point where gas generation generally exceeds storage capacity (e.g., Rice, 1993; Scott et al., 1995). Based on this work, in theory high volatile bituminous rank coals can store as much gas in the adsorbed state as the coal can generate, while expulsion of free gas is likely for low volatile bituminous and semianthracite rank coals. Therefore, it is assumed that some thermogenic methane generated from low volatile bituminous and semianthracite rank Hartshorne coals migrated into the adjacent sandstone thereby reducing the amount of gas in the coal to the maximum storage capacity. Iannacchione et al. (1983, p. 17) speculated that, "So much methane was generated in the

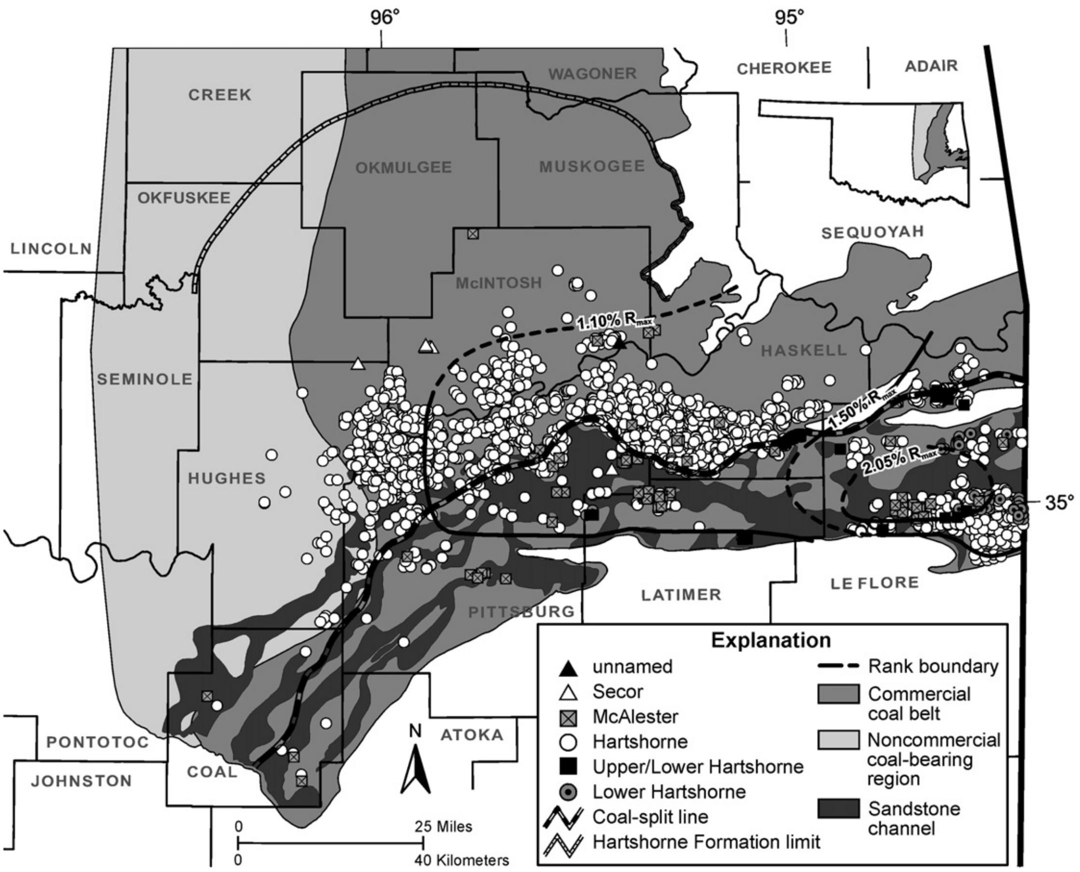

Fig. 8. Arkoma Basin coalbed methane well completions with Hartshorne sandstone channels (modified from Andrews et al., 1998).

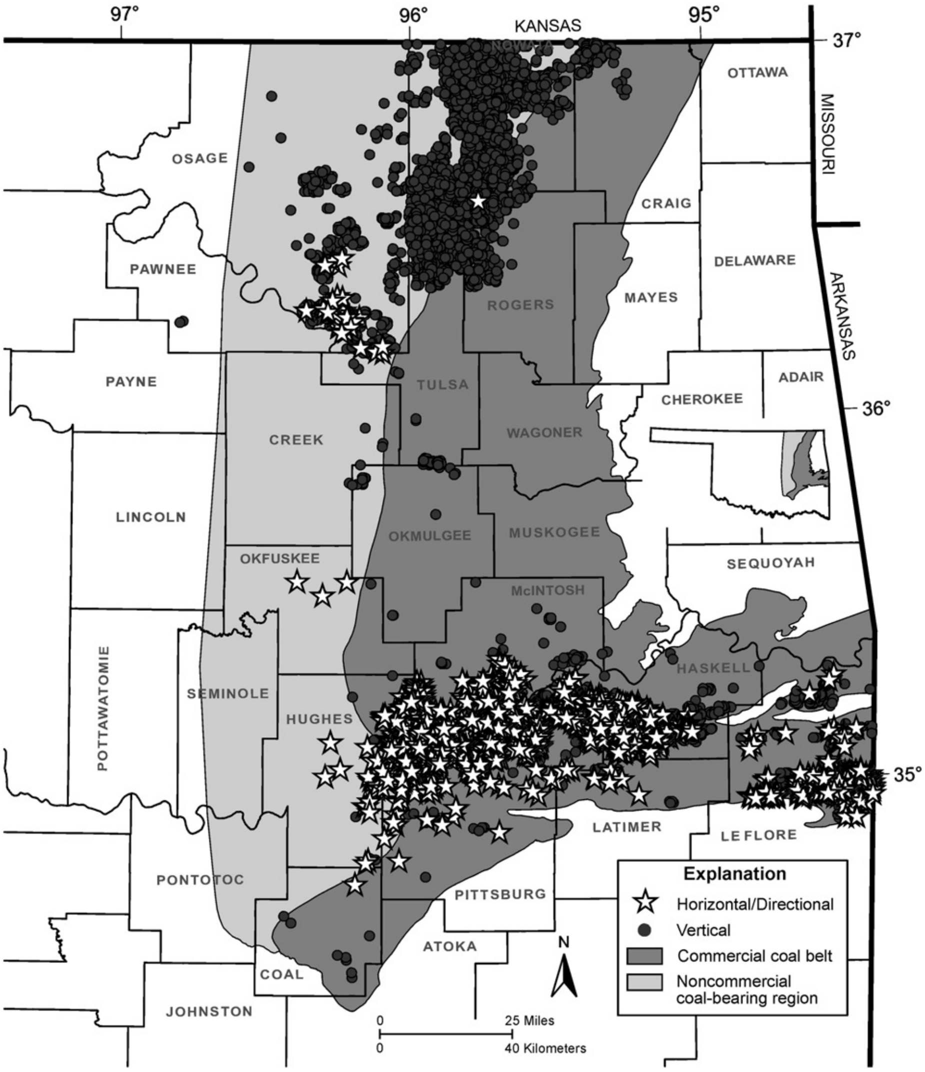

Fig. 9. Horizontal/directional and vertical coalbed methane wells in Oklahoma (1988–2010).

advance stages of coalification (medium- to low-volatile bituminous coal ranks) that gas migrated from the [Hartshorne] coalbed into the surrounding sandstones." Based on gas geochemistry, Rice (1996) indicated that most of the gas in the Hartshorne sandstone probably was generated in the adjacent coal beds. Few Hartshorne CBM wells have been completed in areas with Hartshorne sandstone channels (Fig. 8). Areas of sandstone channels, often with thin coal of low gas content, are better prospects for conventional sandstone completions than for a CBM completion.

Most (1610) Hartshorne CBM wells are horizontal wells with vertical depths of 127 to 1807 m (417 to 5930 ft; average of 682 m [2238 ft] based on 1561 horizontal Hartshorne CBM wells reporting vertical depths; Fig. 9). Hartshorne horizontal CBM well lateral lengths range from 4 to 1498 m (14 to 4914 ft; average of 669 m [2195 ft] based on 1555 wells). The earliest Hartshorne horizontal CBM wells in 1998 had drilling problems staying in thin coal beds (<1.5 m; <5 ft). Advances in measurement-while-drilling horizontal wells in the year 1999 shifted new drilling from vertical to horizontal wells. By 2005, 333 (94%) of 353 new CBM wells in the Arkoma Basin were horizontal wells. Gas rates in CBM wells are the highest from days to months into production due to desorption following a drop in hydrostatic pressure (Schraufnagel, 1993). However, IP gas rates are readily available whereas estimated ultimate recovery and peak month data are difficult to obtain. A comparison of IP gas rates for horizontal and vertical CBM wells in the Arkoma Basin shows that horizontal wells have higher rates (Fig. 10). IP gas rates of horizontal CBM wells range from 0 to 65.6 thousand cubic meters per day, Mcmd (0 to 2316 thousand cubic feet per day, Mcfd) (average of 8.6 Mcmd, 302 Mcfd) at vertical depths of 127 to 1340 m (417 to 4397 ft) from 1513 wells compared to IP gas rates of vertical CBM wells which range from 0 to 14.5 Mcmd (0 to 512 Mcfd) (average of 1.4 Mcmd, 50 Mcfd)

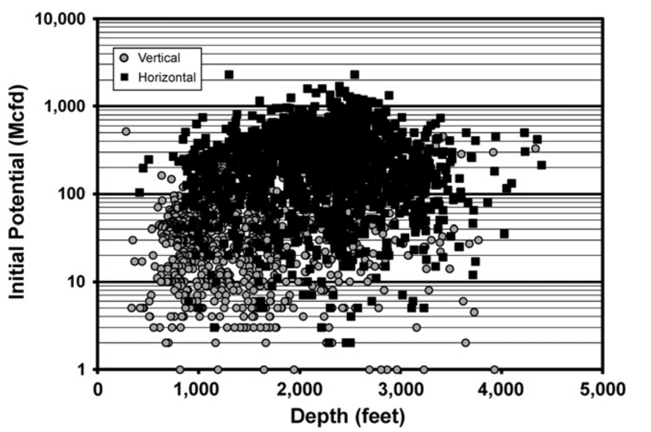

Fig. 10. Scatter plot of initial potential gas rate (Mcfd) vs. depth (feet) for Arkoma Basin coalbed methane wells (1988–2010).

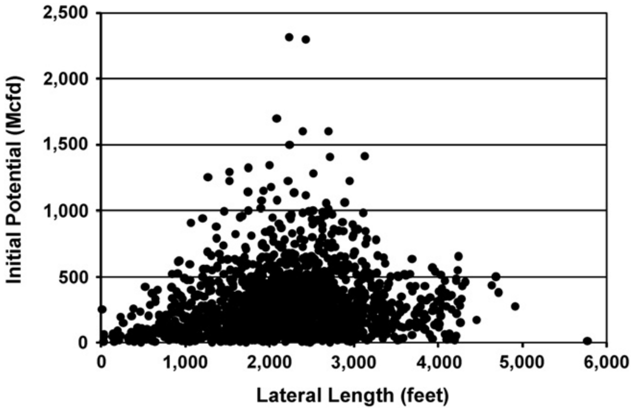

Fig. 11. Scatter plot of initial potential gas rate (Mcfd) vs. lateral length for Arkoma Basin coalbed methane horizontal wells (1998–2010).

at depths of 87 to 1322 m (284 to 4337 ft) from 906 wells. The highest IP gas rates (>28.3 Mcmd, >1 million cubic feet per day, MMcfd) were not from the deepest wells. The highest IP gas rate for a vertical CBM well (14.5 Mcmd, 512 Mcfd) was from a coal-mine-methane well (Cohort Energy 1–32 Greenwood well in sealed-off portion of GCI Pollyanna No. 8 active underground coal mine) at a depth of 87 m (284 ft). The gas composition was diluted by air contamination from a leak in the seal to the active mine.

Fig. 11 compares IP gas rate with lateral length of Arkoma Basin horizontal CBM wells. The highest IP gas rates (>28.3 Mcmd, >1 MMcfd) correspond to lateral lengths of about 305 to 915 m (1000 to 3000 ft) instead of to the longest lateral lengths. Many horizontal CBM wells have a perforated liner that reduces problems from hole collapse. Even with this precaution, problems are encountered in horizontal CBM wells with long laterals, primarily from drilling through faults.

Fig. 12 illustrates the IP gas rate of horizontal and vertical Hartshorne-only CBM wells on the coal-rank map. IP gas rates >28.3 Mcmd (>1 MMcfd) are in CBM wells of high volatile bituminous and medium volatile bituminous rank. All Hartshorne CBM wells of low volatile bituminous and semianthracite rank had IP gas rates <28.3 Mcmd (<1 MMcfd). Gas rate may be affected by the stimulation and completion method (e.g., vertical vs. horizontal well; lateral length; use of perforated liner). However, the lack of IP gas rates >28.3 Mcmd (>1 MMcfd) in Hartshorne CBM wells of low volatile bituminous and semianthracite rank in Le Flore County could be due to complications in drilling high rank coals with close (<1 cm) cleat spacing (Law, 1993; e.g., creation of coal fines that plug permeability), stimulation differences, or to lower gas contents in areas adjacent to Hartshorne sandstone channels.

7. Conclusions

Mean maximum vitrinite reflectance values of 0.76% to 2.41% R_{max} were measured from 70 surface and subsurface Hartshorne coal (Middle Pennsylvanian) samples from vertical depths of 0 (surface) to 1327 m (4355 ft). The resultant coal-rank map shows rank increasing from high volatile bituminous to semianthracite from west to east in the Arkoma Basin in Oklahoma. Rank boundaries are limited by the availability of coal samples from recent CBM development wells.

It is concluded that Hartshorne coal rank was primarily established from maximum burial depth during the late Paleozoic followed by uplift and erosion of up to 4.6 km (15,000 ft) of overburden to the present. Less of an influence is attributed to hydrothermal fluid flow away from the Ouachita orogenic belt during the late Paleozoic.

A total of 2635 Hartshorne (Hartshorne, Lower Hartshorne, and Upper Hartshorne) coalbed methane (CBM) wells have been completed in Oklahoma from 1988 to May 2010. The coal rank in most of the Hartshorne CBM wells is medium volatile bituminous. The Hartshorne coal is semianthracite rank in about 160 CBM wells in Le

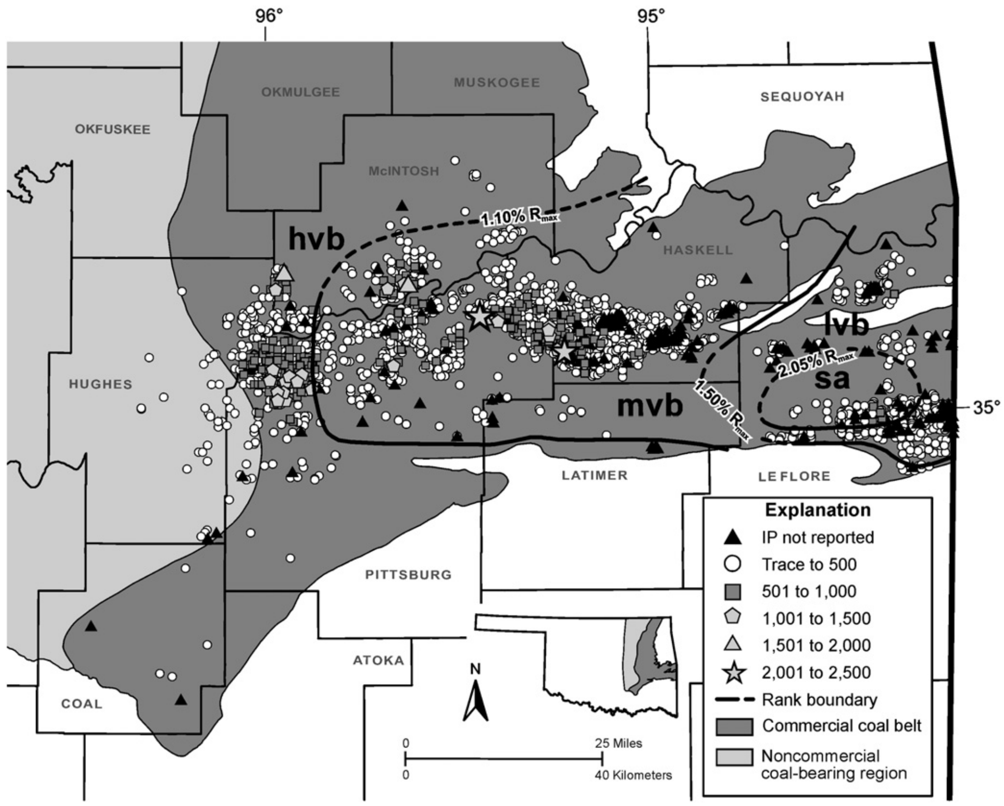

Fig. 12. Initial potential gas rate (Mcfd) of Hartshorne-only coalbed methane wells (1988–2010).

Flore County. Initial potential (IP) gas rates >28.3 thousand cubic meters per day, Mcmd (>1 million cubic feet per day, MMcfd) are from CBM wells with coals of high volatile bituminous and medium volatile bituminous rank. IP gas rates <28.3 Mcmd (<1 MMcfd) from CBM wells with coals of low volatile bituminous or semianthracite rank may be low due to the creation of coal fines while drilling high-rank coals with close (<1 cm) cleat spacing, to differences in stimulation practice, or to lower gas contents in areas adjacent to Hartshorne sandstone channels.

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