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Research Article

Comparison of Hydrocarbon Potentials of New Albany Shale And Maquoketa Group in Indiana, USA

Çağla Akar[1,3], Maria Mastalerz[2*], Arndt Schimmelmann[1], Agnieszka Drobniak[2]

[1]*Department of Geological Sciences, Indiana University, Bloomington, IN 47405-1405, USA*

[2]*Indiana Geological Survey, Indiana University, Bloomington, IN 47405-2208, USA*

[3]*Turkish Petroleum Research and Development Center, Ankara, Turkey*

**Corresponding author: Dr. Maria Mastalerz, Indiana Geological Survey, Indiana University, Bloomington, IN 47405-2208, USA, Tel: 812-855-9416, Email: mmastale@indiana.edu*

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Abstract

Organic petrographic (maceral composition and vitrinite reflectance, R_o) and geochemical methods (Rock-Eval pyrolysis and total organic carbon, TOC) were used to compare hydrocarbon potentials of New Albany Shale (Middle Devonian to Lower Mississippian) and Maquoketa Group (Upper Ordovician) based on 51 samples from 5 drill cores from the Illinois Basin. New Albany Shale is an effective source rock due to its organic matter content and character (Type I and Type II kerogen) and its dominant placement in the oil window. The considerably higher thermal maturity of underlying strata has drawn attention to Maquoketa Shale as a possible source rock. Our results show that although Maquoketa Shale (Rock-Eval T_{max} = 435 to 445 °C) is more mature than New Albany Shale (T_{max} = 427 to 442 °C), the relatively higher organic matter content in New Albany Shale with up to 13.80 wt. % TOC supports a higher hydrocarbon potential than Maquoketa Shale's TOC values between 0.09 to 1.32 wt. %. New Albany Shale's notable differences between directly measured vitrinite reflectance values and calculated R_o values from T_{max} are probably caused by suppression of vitrinite reflectance. Correction for suppression of R_o values would place New Albany Shale more favorably into the oil window.

Introduction

The Middle Devonian to Lower Mississippian New Albany Shale in Illinois, Indiana, and western Kentucky has been known as hydrocarbon source rock in the Illinois Basin due to its organic matter content, organic matter type and thermal maturity [1]. Although New Albany Shale hosts a producing gas play, it is generally believed that it retains little oil [2] even though it is considered to be the source of the majority of oils in the Illinois Basin [3]. Recent oil production in Kentucky and other evidence, however, point to the possibility of the presence of notable amounts of *in-situ* liquid hydrocarbons, which warrants a re-evaluation of New Albany Shale's oil potential. Yet another possible source rock in the Illinois Basin with considerable thermal maturity and thickness is the Upper Ordovician Maquoketa Shale occurring throughout Indiana, Illinois, western Kentucky, and Iowa [4-6], although limited data for its oil potential are available.

Different ages and thermal maturities of New Albany and Maquoketa shales mandate detailed scrutiny to constrain their hydrocarbon potentials for oil and gas. In this study, diagnostic techniques including Rock-Eval pyrolysis, total organic carbon (TOC) content, and organic petrography were used to (i) compare the two shale sequences in terms of organic matter content, type, and maturity, and (ii) to constrain the hydrocarbon potentials at several drill sites where both formations were intersected (Figure 1).

Figure 1. Locations of wells used in this study.

Geological Characteristics of New Albany Shale

New Albany Shale is present in the Illinois Basin in Illinois, Indiana, and western Kentucky (Figure 2) and consists chiefly of organic-rich brownish-black shale, greenish-gray shale, dolomite and siltstone [6,7] with ages from the Middle Devonian to the Early Mississippian, although most sections date to the Late Devonian [8]. The elevation of New Albany Shale ranges from 228 m (748 ft) above sea level to 1370 m (4495 ft) below sea level [9,6]. Its thickness in southern Indiana ranges from almost 30 m (100 ft) to 43 m (140 ft) [10].

In Indiana the New Albany Shale occupies a position between the unconformably underlying Middle Devonian North Vernon Limestone and the overlying, mostly Early Mississippian Rockford Limestone. The occasional absence of the latter causes the New Albany Shale to unconformably underlie the Early Mississippian New Providence Shale [6,11]. The New Albany Shale includes six members: the Blocher Member, the Selmier Member, the Morgan Trail Member, the Camp Run Member, the Clegg Creek Member and the Ellsworth Member (Figure 2) [6,11].

New Albany Shale was deposited in an inland sea spreading across extensive areas of the United States throughout the Late Devonian to Early Mississippian [11]. Previous studies indicate that New Albany Shale was deposited in both shallow and deep-water environments [11]. Laminated, organic-rich black sections of New Albany Shale were deposited under suboxic to anoxic bottom water conditions and contain Type II kerogen that mainly consists of marine amorphous organic matter and alginite and only minor amounts of terrigenous vitrinite and inertinite [1]. In turn, bioturbated organic-poor greenish-gray shales were deposited closer to land under more oxygenated bottom water conditions and contain more Type III kerogen [1].

Vitrinite reflectance (R_o) values of New Albany Shale range from 0.5-0.7% at the basin's margins in Indiana to 1.5% in southern Illinois (Fig. 3) (e.g., [6] and reference therein) and the rocks contain a wide range of organic carbon from approximately 0.1 to 20 wt. % TOC [13].

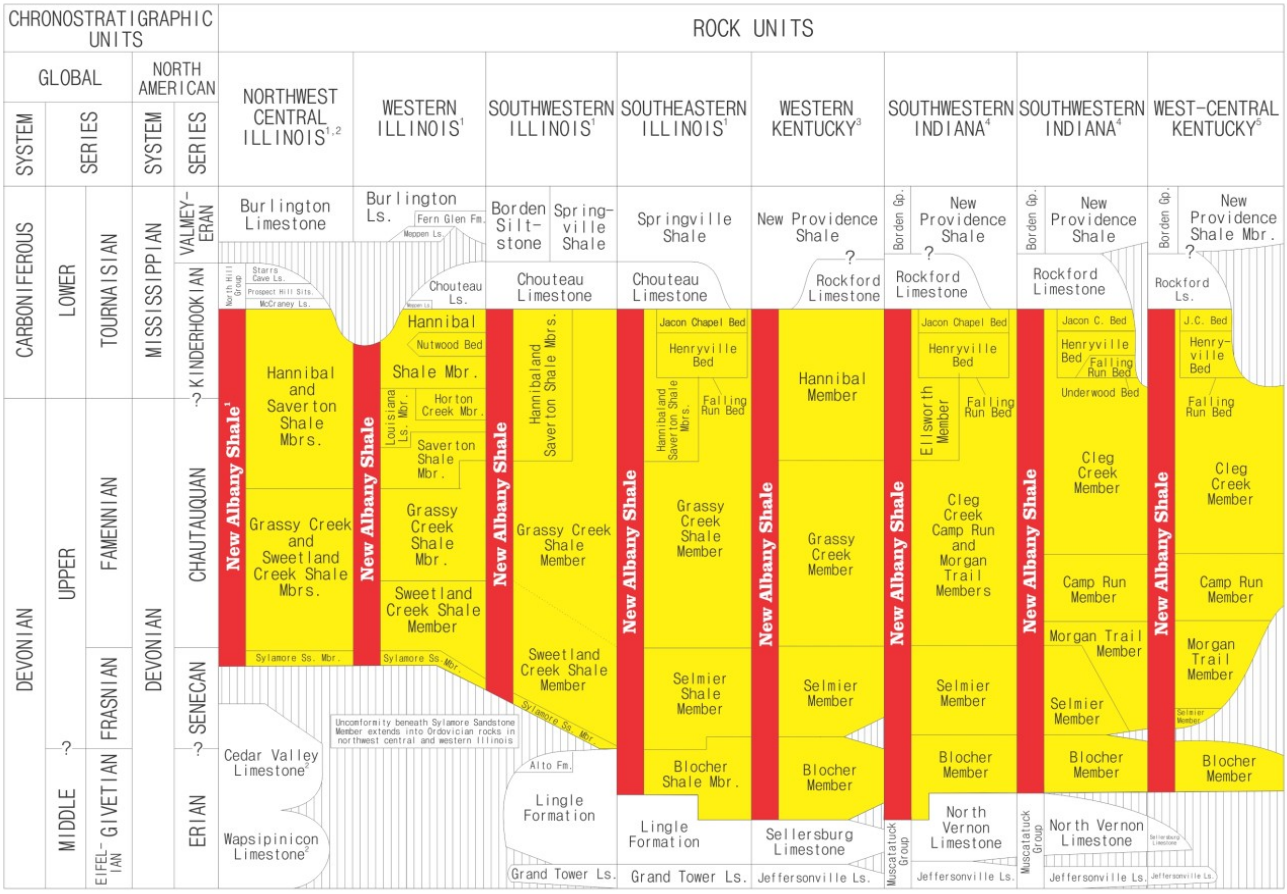

Figure 2. Correlation of New Albany Shale units within the Illinois Basin (modified from [10]).

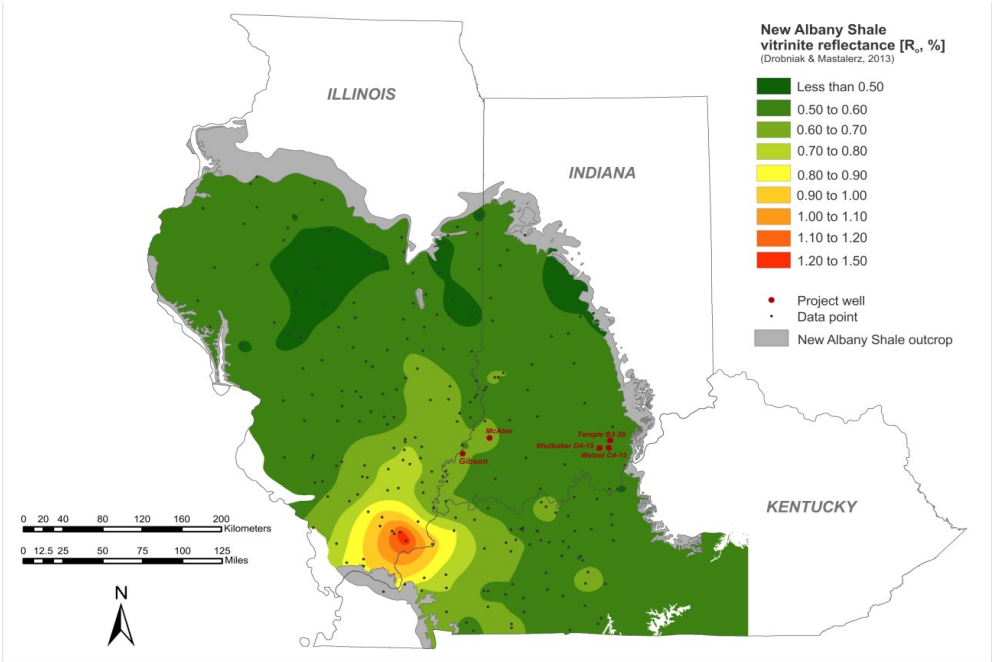

Figure 3. Vitrinite reflectance (R_o) values of New Albany Shale in the Illinois Basin ([12], based on compilation after [9] and our more recent data).

Geological Characteristics of the Maquoketa Group

The Upper Ordovician Maquoketa Shale is present in parts of Indiana, Illinois and Iowa (Fig. 4) [4,5] and contains two lithologically distinct parts. The lower part is composed of calcareous gray shale with a lesser extent of carbonaceous brown shale, whereas the upper part consists chiefly of limestone [14] .

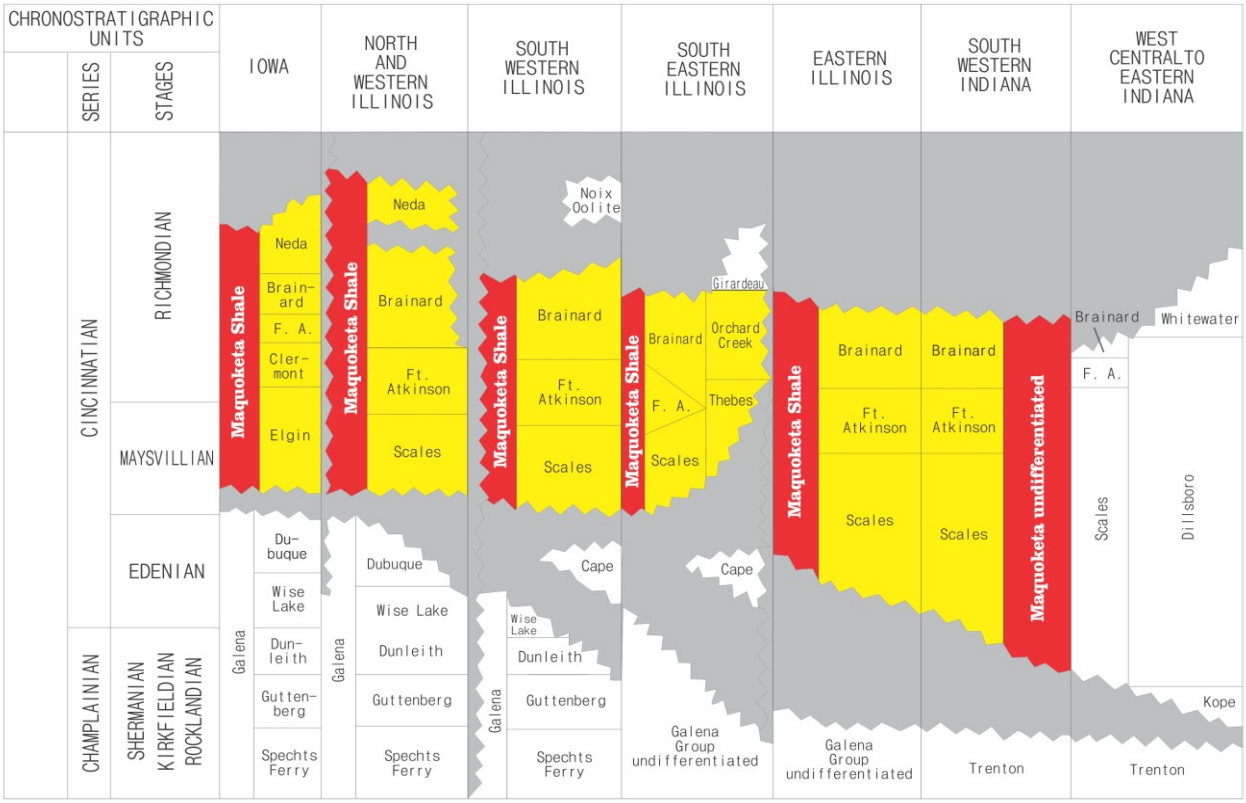

Figure 4. Correlation of Maquoketa Group (Upper Ordovician) throughout Indiana, Illinois and Iowa (modified from [4,5]).

The thickness of the Maquoketa Group is shown in Fig. 5; the Maquoketa Shale alone is almost 900 meters thick in eastern Indiana, but decreases to 200 meters in western Illinois and eastern Iowa [14-17]. Southwestern Indiana features three formations of the Maquoketa Shale, in ascending order the Scales Shale, the Fort Atkinson Limestone, and the Brainard Shale (Figure 4) [4,5]. It is mostly underlain by the Trenton Limestone and overlain by Silurian rocks [14].

Maquoketa Shale was deposited in a shallow epicontinental sea during the Upper Ordovician [15-17]. The two dominant lithologies of the Maquoketa Group are (i) laminated, dark-gray to brown shale (i.e. lower Scales and lower Brainard Shale), and (ii) bioturbated light-gray to gray shale (i.e. upper Brainard, Fort Atkinson and upper Scales formations) [17]. The laminated shale was deposited under low-energy and oxygen-depleted conditions that prevented bioturbation by burrowing organisms and thus facilitated the preservation of organic matter. In contrast, the bioturbated shale was deposited under more oxygenated and higher-energy conditions resulting in diminished preservation of organic matter [17]. The laminated, organic-rich units mainly contain Type I and Type II kerogens [17].

The organic carbon content of Maquoketa Shale typically ranges from 0.92 to 1.62 wt. % TOC [6].

Vitrinite reflectance (R_o) equivalent values in Maquoketa Shale range from 0.60 to 1.40% within the Illinois Basin (Figure 6).

Methods

Organic Petrography

Organic petrographic techniques used in this study include visual maceral examination and measurements of vitrinite reflectance (R_o). A Zeiss Photoscope 3 microscope, a Leica DM 25000 P with TIDAS PMT IV attachment, and oil objectives were used to measure R_o. When vitrinite was absent, reflectances of solid bitumen were measured and recalculated into vitrinite reflectance using [20,21] equations. In addition to reflected white light, fluorescent light was used to identify macerals and their fluorescent intensities to assess relative maturity. Sample preparations and measurements followed standard organic petrography procedures [6,22,23].

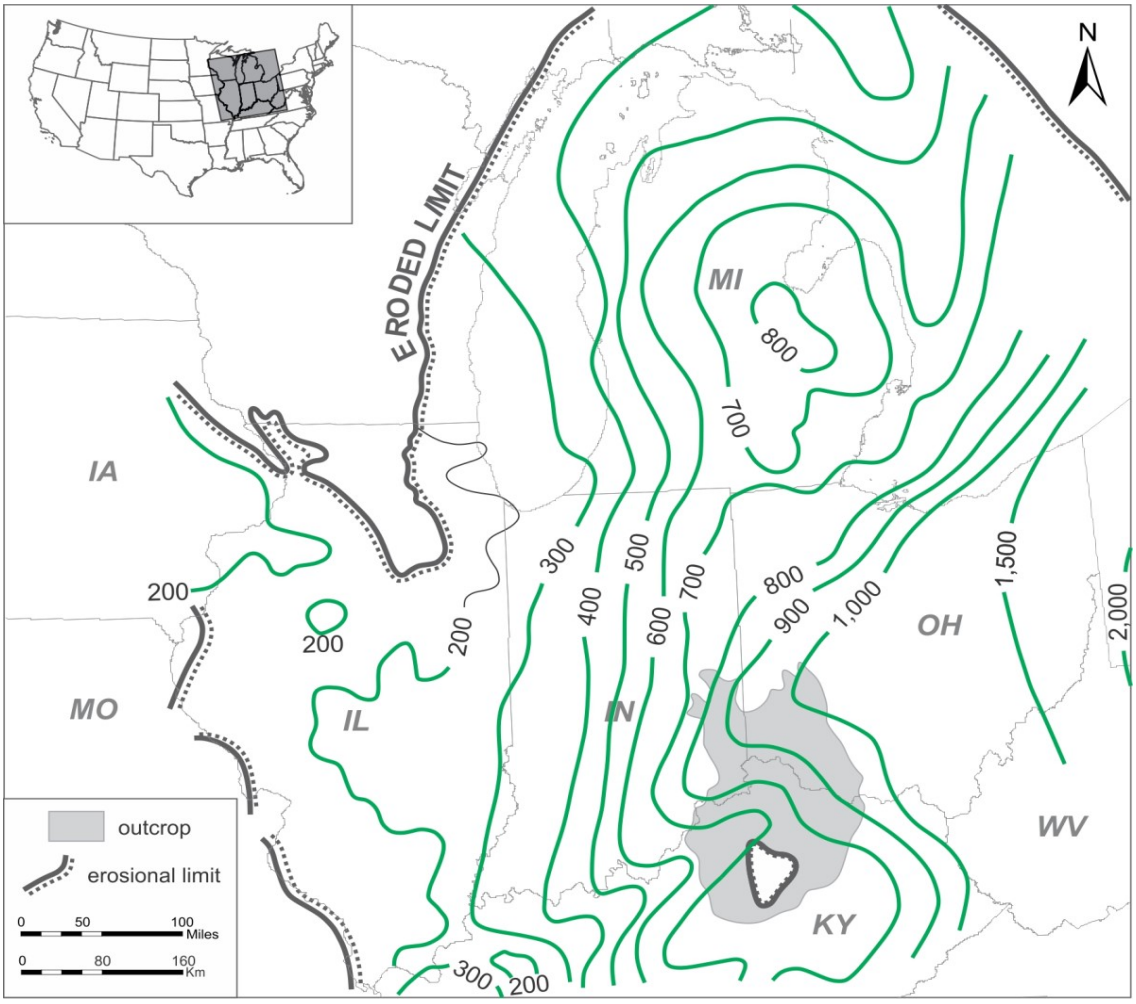

Figure 5. Thickness of the Maquoketa Group and equivalents (contour interval 100 feet and changing to 500 feet where the unit is more than 1,000 meter thick (modified from [18]). There are several penetrations of the Maquoketa Group in western Kentucky to the south of the boundary of this figure (Brandon Nuttall, 2015, personal communication).

Rock-Eval Pyrolysis and TOC

Rock-Eval pyrolysis data of samples from Pike and Gibson counties were obtained from Weatherford Laboratories in Houston, Texas. A Rock-Eval 2 analyzer was used to characterize the hydrocarbon potential (i.e. T_{max}, hydrogen index HI, oxygen index OI, etc.). TOC concentrations were obtained using a LECO 600 Carbon Analyzer. Additional Rock-Eval data from Temple, Weilbaker, and Wetzel wells from Washington County were provided by GeoMark Research, LTD., Core Laboratories in Houston, Texas.

Results and Discussion

Organic Petrography

New Albany Shale

Petrographic examinations show that organic matter in New Albany Shale is dominated by alginite (mostly *Tasmanites*), amorphous organic matter, liptodetrinite, likely of algal origin, and solid bitumen [24]. Vitrinite, inertinite, and solid bitumen are rare, which is consistent with previous studies (e.g., [6,25]). Measured R_o values for New Albany Shale range from 0.54 to 0.63% in Pike County (Table 1), 0.58 to 0.70% in Gibson County (Table 2), and 0.53 to 0.66% in Washington County (Table 3), and suggest that these sections of New Albany

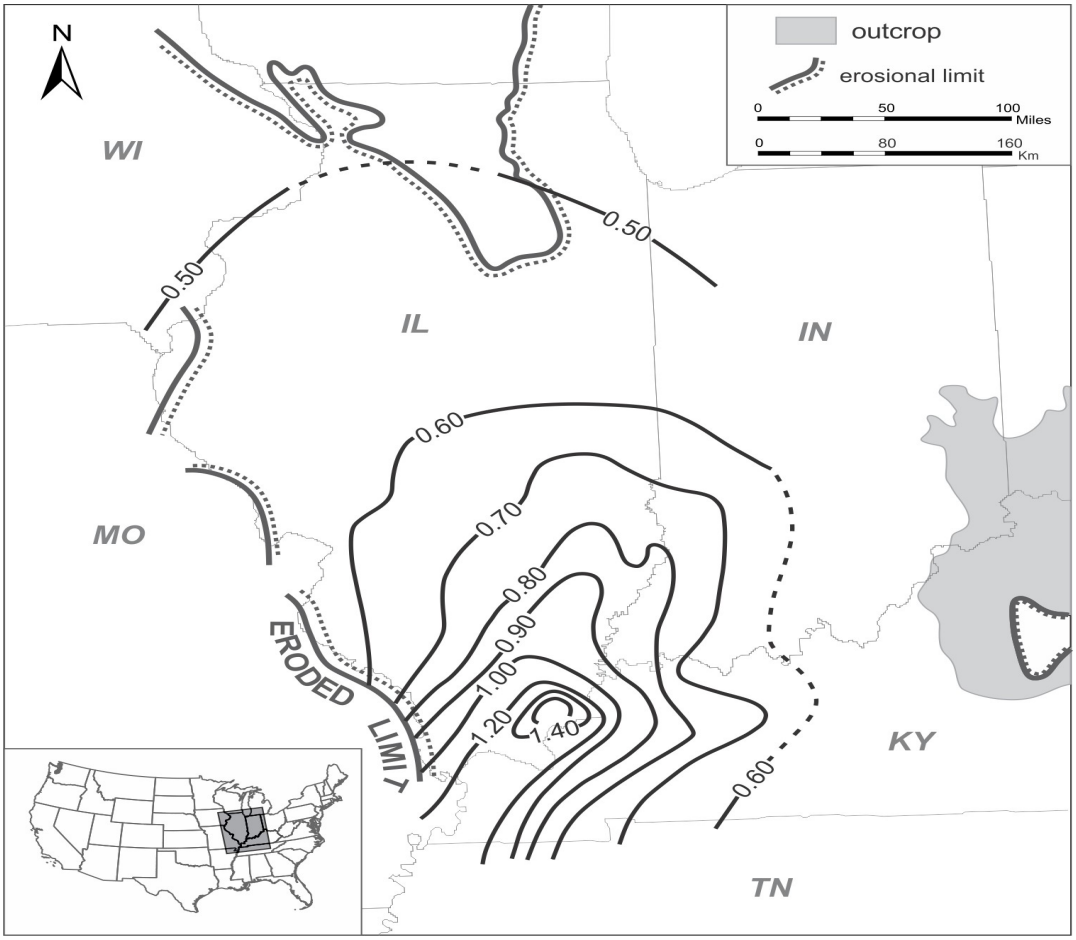

Figure 6. Predicted present-day maturity (R_o, %) at the base of the Maquoketa Group (modified from [18,19])

Shale are mainly within the early oil generation zone. R_o values calculated based on T_{max} from Rock-Eval pyrolysis using the equation of [26] range from 0.53 to 0.78% in Pike County (Table 1), 0.67 to 0.80% in Gibson County (Table 2), and 0.53 to 0.69% in Washington County (Table 3). According to these calculated R_o values, the New Albany Shale in Pike County is positioned within the zone of early to peak oil generation, whereas in Washington County it falls into the zone of early oil generation. Most data from Gibson County place New Albany Shale into the zone of peak oil generation. Comparing measured R_o to the values calculated from T_{max}, almost all measured R_o values are lower than the calculated ones which, together with other geochemical evidence suggests that vitrinite reflectance is likely suppressed [24]. Vitrinite reflectance suppression is a known phenomenon in alginite-rich shales and for the New Albany Shale was suggested earlier by [27].

Maquoketa Shale

Petrographic observations indicate that organic matter in Maquoketa Shale is dominated by liptodetrinite of likely algal origin, amorphous organic matter, and solid bitumen. It also includes sporadic vitrinite-like particles, which are probably reworked or oxidized forms of massive kerogen Type II. Measured R_o values of vitrinite-like particles range from 0.74 to 0.82% in Pike County (Table 1), 0.75 to 0.88% in Gibson County (Table 2), and 0.65 to 0.77% in Washington County (Table 3). In comparison, vitrinite reflectance equivalent values calculated from T_{max} range from 0.67 to 0.85% in Pike County and from 0.71 to 0.80% in Washington County. All measured and calculated R_o values indicate that Maquoketa Shale is mostly positioned within the zone of peak oil generation.

Reflectance of solid bitumen was measured in addition to vitrinite and vitrinite-like macerals and used for calculations of vitrinite reflectance equivalent values according to [20] or [21] equations (Tables 1, 2, 3). Moreover, the fluorescence intensity of liptinite macerals, particularly of *Tasmanites*, was used to constrain relative maturity based on the inverse relationship between maturity and fluorescence intensity as witnessed by the *Tasmanites* color shift from yellow to red [28,1]. With increasing maturity, New Albany Shale and Maquoketa Shale samples from Pike and Gibson counties change their fluorescence color from golden-yellow to light orange, whereas samples from Washington County change from greenish-yellow to orange-yellow [24].

Table 1. Vitrinite reflectance data of New Albany Shale (NAS-1 to NAS-8) and Maquoketa Group (MG-1 to MG-7) from Pike County in Indiana.

Pike County							
Sample name	Depth (m)	R_o from T_{max} (%)	Measured V R_o (%)	Measured V-like R_o (%)	SB R_o (%)	VRE[1]	VRE[2]
NAS-1	835	0.76	0.63	nd.	0.43	0.67	0.77
NAS-2	839	0.78	0.62	nd.	0.37	0.63	0.72
NAS-3	842	0.63	0.62	nd.	0.35	0.62	0.70
NAS-4	844	0.65	0.54	nd.	0.37	0.63	0.72
NAS-5	848	0.53	0.60	nd.	0.38	0.63	0.72
NAS-6	850	0.69	0.55	nd.	0.35	0.62	0.70
NAS-7	852	0.74	0.60	nd.	0.36	0.62	0.71
NAS-8	858	0.60	0.62	nd.	0.38	0.63	0.72
MG-1	1317	0.83	nd.	0.78	0.52	0.72	0.85
MG-2	1321	0.81	nd.	nd.	0.51	0.72	0.84
MG-3	1322	0.80	nd.	nd.	0.50	0.71	0.83
MG-4	1324	0.80	nd.	0.81	0.51	0.72	0.84
MG-5	1329.5	0.74	nd.	nd.	0.55	0.74	0.88
MG-6	1330	0.85	n.d.	0.74	0.51	0.72	0.84
MG-7	1333.5	0.67	nd.	0.82	0.51	0.72	0.84

V R_o - vitrinite reflectance; V-like - vitrinite-like; SB - solid bitumen; VRE - vitrinite reflectance equivalent; [1] - based on [20] equation; [2] - based on [21] equation; nd. - not determined. [26] equation was used to calculate vitrinite reflectance from T_{max}.

Table 2. Vitrinite reflectance data of New Albany Shale (NAS-9 to NAS-14) and Maquoketa Shale (MG-8 to MG-13) from Gibson County in Indiana.

Gibson County							
Sample name	Depth (m)	R_o R_o calculated from T_{max} (%)	Measured V R_o (%)	Measured V-like R_o (%)	SB R_o (%)	VRE[1]	VRE[2]
NAS-9	1200	0.74	0.70	nd.	0.41	0.65	0.75
NAS-10	1204	0.72	0.65	nd.	0.43	0.67	0.77
NAS-11	1205	0.67	0.60	nd.	0.44	0.67	0.78
NAS-12	1209	0.78	0.58	nd.	0.42	0.66	0.76
NAS-13	1214	0.76	0.59	nd.	0.45	0.68	0.79
NAS-14	1218	0.80	0.68	nd.	0.43	0.67	0.77
MG-8	1636	nd.	nd.	0.88	0.65	0.80	0.97
MG-9	1637	nd.	nd.	0.75	0.57	0.75	0.90
MG-10	1637	nd.	nd.	0.87	0.50	0.71	0.83
MG-11	1641	nd.	nd.	nd.	0.52	0.72	0.85
MG-12	1642	nd.	nd.	0.82	0.59	0.76	0.92
MS-13	1644	nd.	nd.	0.75	0.50	0.71	0.83

V R_o - vitrinite reflectance; V-like - vitrinite-like; SB - solid bitumen; VRE - vitrinite reflectance equivalent; [1]- based on [20] equation; [2]- based on [21] equation; nd. - not determined. [26] equation was used to calculate vitrinite reflectance from $T_{max.}$

Table 3. Vitrinite reflectance data of New Albany Shale (NAS) and Maquoketa Shale (MG) from Temple, Weilbaker and Wetzel wells of Washington County in Indiana.

Washington County							
Sample name	Depth (m)	R_o R_o calculated from T_{max} (%)	Measured V R_o (%)	Measured V-like R_o (%)	SB R_o (%)	VRE[1]	VRE[2]
Temple well							
NAS-15	192	0.56	0.56	nd.	0.42	0.66	0.76
NAS-16	207	0.60	0.56	nd.	0.41	0.65	0.75
NAS-17	213	0.62	0.54	nd.	0.40	0.65	0.74
NAS-18	216	0.65	nd.	nd.	0.39	0.64	0.73
NAS-19	223	0.60	0.57	nd.	0.39	0.64	0.73
MG-14	320	0.72	nd.	0.70	0.58	0.76	0.91
MG-15	323	0.76	nd.	0.77	0.51	0.72	0.84
MG-16	329	0.74	nd.	0.65	0.50	0.71	0.83
Weilbaker well							
NAS-20	247	0.53	0.61	nd.	0.38	0.63	0.72
NAS-21	253	0.67	0.63	nd.	0.40	0.65	0.74
NAS-22	256	0.60	0.64	nd.	0.37	0.63	0.72
NAS-23	265	0.56	0.66	nd.	0.35	0.62	0.70
NAS-24	268	0.69	0.62	nd.	0.40	0.65	0.74
MG-17	375	nd.	nd.	0.77	0.52	0.72	0.85
MG-18	378	0.71	nd.	0.67	0.54	0.73	0.87
MG-19	384	nd.	nd.	nd.	0.57	0.75	0.90
Wetzel well							
NAS-25	244	0.53	0.53	nd.	0.37	0.63	0.72
NAS-26	253	0.62	0.56	nd.	0.37	0.63	0.72
NAS-27	259	0.63	0.55	nd.	0.40	0.65	0.74
NAS-28	268	0.67	0.58	nd.	0.35	0.62	0.70
MG-20	372	0.71	nd.	nd.	0.51	0.72	0.84
MG-21	375	0.76	nd.	nd.	0.55	0.74	0.88
MG-22	381	0.80	nd.	nd.	0.52	0.72	0.85
MG-23	387	0.72	nd.	nd.	0.52	0.72	0.85

V R_o - vitrinite reflectance; V-like - vitrinite-like; SB - solid bitumen; VRE - vitrinite reflectance equivalent; [1] - based on [20] equation; [2] - based on [21] equation; nd. - not determined. [26] equation was used to calculate vitrinite reflectance from T_{max}.

It can be concluded that New Albany Shale and Maquoketa Shale samples from Pike and Gibson counties are generally more mature than those from Washington County. The same trends are observed for measured and calculated vitrinite reflectance values.

Rock-Eval Pyrolysis and TOC

New Albany Shale

Most samples from New Albany Shale contain kerogen Type I (very oil prone) and Type II (oil prone; Figs. 7, 8) and these kerogen types indicate lacustrine and marine depositional environments [29].

samples from Washington County have HI and S2/S3 values larger than 300 and 5, respectively (Table 5). These results indicate that New Albany Shale in general has the potential togenerate oil (Table 4), although samples NAS-1, NAS-23, and NAS-26 from Pike and Washington counties exhibit lower hydrogen indices and S2/S3 values and are positioned within the gas and/or oil windows.

The generative hydrocarbon potential places New Albany Shale in the 'very good' category (Table 4) based on (i) 6 out of 8 samples from Pike County (TOC ranging from 4.86 to 8.81 wt. %), (ii) 6 samples from Gibson County

Table 4. Geochemical and petrographic parameters to evaluate amount, type and thermal maturity of organic matter (modified from [30]; additional data from [31]).

Source Rock Generative Hydrocarbon Potential			
Quantity	TOC (wt. %)	S1	S2
Poor	0-0.5	0-0.5	0-2.5
Fair	0.5-1	0.5-1	2.5-5
Good	1-2	1-2	5-10
Very good	>2	>2	>10
Type of Hydrocarbons Generated			
Type	HI (mg HC/g C_{org})*	S2/S3*	
Gas	0-150	0-3	
Gas and oil	150-300	3-5	
Oil	>300	>5	
Level of Thermal Maturity			
Maturity	PI (S1/(S1+S2))	T_{max} (°C)	R_o (%)†
Beginning of oil window	~0.1	~435-445+	~0.5
End of oil window	~0.4	~470	~1.35

TOC - Total Organic Carbon (wt. %); S1 - volatile hydrocarbon (HC) content (mg HC/g rock); S2 - remaining HC generative potential (mg HC/g rock); S3 - carbon dioxide content (mg CO_2/g rock); HI - Hydrogen Index = S2x100/TOC (mg HC/g TOC); PI - Production Index = S1/(S1+S2); R_o - vitrinite reflectance (%).

* Assumes thermal maturity equivalent to R_o = 0.6%.

† Values are for Type I and Type II kerogens.

+ Many maturation parameters (particularly T_{max}) depend on the type of organic matter.

Table 4 reviews geochemical criteria to evaluate the potential of hydrocarbon generation, the type of generated hydrocarbons, and the level of thermal maturity.

In the case of New Albany Shale, 7 out of 8 samples from Pike County, all 6 samples from Gibson County, and 12 out of 14 (TOC from 4.63 to 7.92 wt. %), and (iii) 8 out of 14 samples from Washington County (TOC from 3.47 to 6.83 wt. %) (Table 5). Outliers are the 3 samples NAS-15, NAS-20 and NAS-25 from Washington County with higher potentials, as well as a few samples with lower potentials from Pike County (NAS-1, NAS-2) and Washington County (NAS-21 and NAS-23 from Weilbaker well; NAS-26 from Wetzel well).

Table 5. Rock-Eval pyrolysis data for (A) samples of New Albany Shale and (B) samples of Maquoketa Group from Indiana.

Sample name	Depth (m)	TOC	S1	S2	S3	T_{max} (°C)	HI	OI	S2/S3	S1/TOC *100	PI
Pike County, McAtee well											
NAS-1	835	0.38	0.24	0.18	0.55	440**	47	144	0.3	63	0.57
NAS-2	839	1.31	0.39	4.63	0.35	441	352	27	13.2	29	0.08
NAS-3	842	6.45	3.59	36.57	1.33	433	567	21	27.5	56	0.09
NAS-4	844	4.86	2.99	27.47	0.92	434	565	19	29.9	61	0.10
NAS-5	848	8.81	4.99	42.44	0.88	427	482	10	48.2	57	0.11
NAS-6	850	5.85	3.69	30.72	0.77	436	526	13	39.9	63	0.11
NAS-7	852	5.86	4.06	35.53	0.74	439	606	13	48.0	69	0.10
NAS-8	858	6.34	4.33	31.21	1.56	431	493	25	20.0	68	0.12
Gibson County											
NAS-9	1200	7.92	5.54	39.72	0.47	439	502	6	84.5	70	0.12
NAS-10	1204	6.90	4.67	36.28	0.44	438	526	6	82.5	68	0.11
NAS-11	1205	7.38	5.15	35.89	0.82	435	486	11	43.8	70	0.13
NAS-12	1209	4.63	3.27	24.45	0.50	441	529	11	48.9	71	0.12
NAS-13	1214	5.89	4.55	28.50	0.54	440	484	9	52.8	77	0.14
NAS-14	1218	4.94	4.77	29.21	0.48	442	591	10	60.9	96	0.14
Washington County, Temple well											
NAS-15	192	11.30	3.04	84.98	0.99	429	752	9	86.0	27	0.03
NAS-16	207	3.47	1.15	23.88	0.35	431	688	10	68.0	33	0.05
NAS-17	213	5.41	2.25	45.68	0.44	432	844	8	104.0	42	0.05
NAS-18	216	4.18	1.72	33.19	0.39	434	794	9	85.0	41	0.05
NAS-19	223	5.42	3.00	43.78	0.42	431	808	8	104.0	55	0.06
Washington County, Weilbaker well											
NAS-20	247	13.10	6.62	101.76	0.98	427	777	7	104.0	51	0.06
NAS-21	253	1.27	0.54	7.01	0.22	435	552	17	32.0	43	0.07
NAS-22	256	6.83	4.19	53.35	0.44	431	781	6	121.0	61	0.07
NAS-23	265	0.25	0.08	0.49	0.10	429	197	40	5.0	32	0.14
NAS-24	268	6.21	3.43	53.56	0.44	436	862	7	122.0	55	0.06
Washington County, Wetzel well											
NAS-25	244	13.80	6.42	104.69	1.02	427	759	7	103.0	47	0.06
NAS-26	253	0.41	0.08	0.83	0.12	432	203	29	7.0	20	0.09
NAS-27	259	5.12	2.32	38.97	0.42	433	761	8	93.0	45	0.06
NAS-28	268	5.95	3.75	50.17	0.32	435	843	5	157.0	63	0.07

B. Maquoketa Group

Sample name	Depth (m)	TOC	S1	S2	S3	T_{max} (°C)	HI	OI	S2/S3	S1/TOCPI *100	PI
Pike County, McAtee well											
MG-1	1317	0.92	1.16	1.96	0.77	444	214	84	2.5	127	0.37
MG-2	1321	1.12	1.21	2.73	0.59	443	244	53	4.6	108	0.31
MG-3	1322	0.94	1.01	2.28	0.95	442	243	101	2.4	107	0.31
MG-4	1324	1.08	1.03	2.48	0.63	442	230	58	3.9	95	0.29
MG-5	1329.5	1.28	1.19	2.86	1.77	439	223	138	1.6	93	0.29
MG-6	1330	1.32	1.11	2.84	1.03	445	215	78	2.8	84	0.28
MG-7	1333.5	1.16	1.16	2.70	1.42	435	232	122	1.9	100	0.30
Gibson County											
MG-8	1636	0.42	0.19	0.44	0.45	439**	105	108	1.0	45	0.30
MG-9	1637	0.34	0.13	0.30	1.01	428**	87	294	0.3	39	0.31
MG-10	1637	0.30	0.06	0.21	0.78	376**	71	264	0.3	21	0.23
MG-11	1641	0.35	0.10	0.27	0.37	393**	78	107	0.7	28	0.27
MG-12	1642	0.36	0.11	0.26	0.31	372**	72	86	0.8	29	0.29
MG-13	1644	0.36	0.12	0.38	0.25	386**	107	70	1.5	34	0.24
Washington County, Temple well											
MG-14	320	0.71	0.13	0.62	0.18	438	87	25	3.0	18	0.17
MG-15	323	0.24	0.04	0.22	0.11	440	92	46	2.0	17	0.15
MG-16	329	0.37	0.04	0.27	0.12	439	72	32	2.0	11	0.13
Washington County, Weilbaker well											
MG-17	375	0.09	0.03	0.14	0.12	0	152	130	1.0	33	0.18
MG-18	378	0.25	0.03	0.20	0.15	437	79	59	1.0	12	0.13
MG-19	384	0.11	0.01	0.06	0.13	0	55	119	0.0	9	0.14
Washington County, Wetzel well											
MG-20	372	0.23	0.04	0.17	0.12	437	74	52	1.0	17	0.19
MG-21	375	0.41	0.07	0.31	0.11	440	75	27	3.0	17	0.18
MG-22	381	0.18	0.04	0.12	0.12	442	66	66	1.0	22	0.25
MG-23	387	0.26	0.02	0.15	0.09	438	59	35	2.0	8	0.12

TOC - Total Organic Carbon (wt. %); S1 - volatile hydrocarbon (HC) content (mg HC/g rock); S2 - remaining HC generative potential (mg HC/g rock); S3 - carbon dioxide content (mg CO2/g rock); HI - Hydrogen Index = S2x100/TOC (mg HC/g TOC); OI - Oxygen Index = S3x100/TOC (mg CO2/g TOC); PI - Production Index = S1/(S1+S2); ** - low S2 and unreliable T_{max}. All data from Weatherford Laboratories in Houston, Texas.

Production indices and T_{max} values of 7 out of 8 New Albany Shale samples from Pike County range from 0.08 to 0.12, and from 427 to 441 °C, respectively (Table 5). This places New Albany Shale into a very good category in terms of generative potential of a source rock in the early oil window (Table 4).

All 6 samples from Gibson County have PI and T_{max} values from 0.11 to 0.14, and from 435 to 442 °C (Table 5), respectively, placing them into the early to peak oil window. In Washington County, however, production indices for 13 out of 14 samples range from 0.03 to 0.09 and T_{max} values of these samples are between 427 and 436 °C. These values characterize New Albany Shale as immature to early mature. Not all values fit the pattern. Especially NAS-1 from Pike County and NAS-23 from Washington County exhibit anomalously high production indices (Table 5). Deviations from expected values in these two samples as well as in NAS-2, NAS-21 and NAS-26 can be observed for almost all parameters.

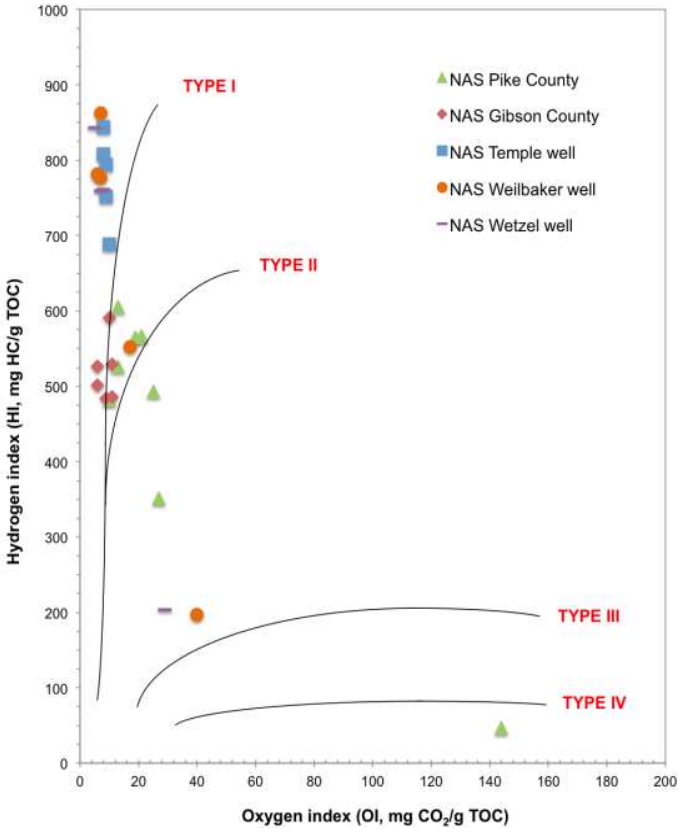

Figure 7. Kerogen types of New Albany Shale (NAS) samples from the wells studied. These data are comparable to those reported in previous New Albany Shale studies [32,33]. (Curved lines characterize expected trends for different types of kerogen according to a modified van Krevelen diagram ([29], Demaison et al., 1983).

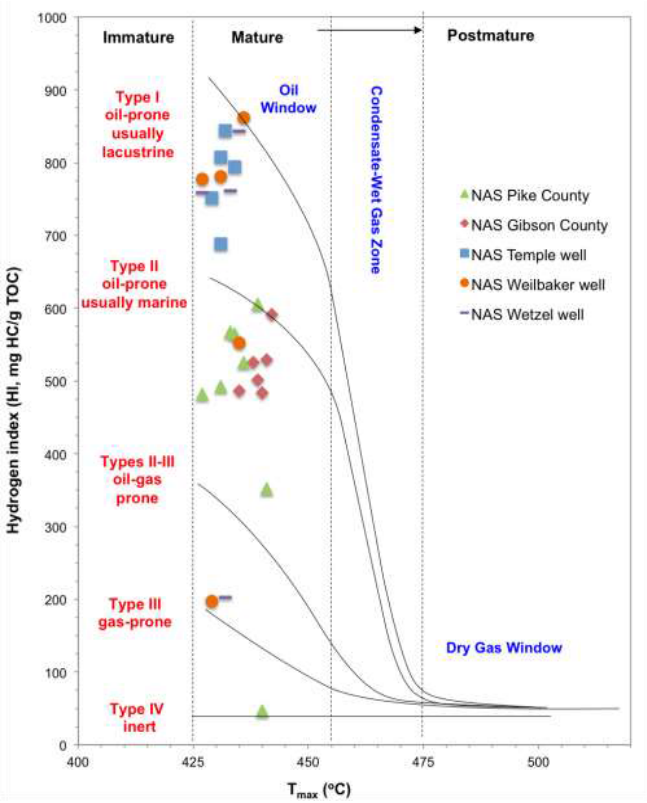

Figure 8. Plots of Hydrogen index (HI) vs. T_{max} for New Albany Shale (NAS) samples. Curved lines characterize expected trends for different types of kerogen according to a modified van Krevelen diagram ([29], Demaison et al., 1983). Vertical dashed lines separate zones of different maturity from immature to postmature based on T_{max} (425 to 475 °C).

Maquoketa Group

Based on Rock-Eval pyrolysis data, the organic matter in Maquoketa Shale is placed either in the field of kerogen Type III (gas prone) or Type IV (inert; Fig. 9) consistent with a traditional characterization as terrestrial organic matter [29]. These are, however, pre-Devonian rocks and terrestrial origin of the organic matter is unlikely. As this type of diagram is based on chemistry, and specifically on HI and OI, the shift towards lower HI and higher OI is related to reworking/oxidation of organic matter (causing higher oxygen content) and maturity (resulting in lower hydrogen content) of the original kerogen Type I and Type II, rather than any terrestrial input. Caution has been frequently suggested in the literature when using Rock-Eval pyrolysis data for organic matter source interpretation (e.g., [34,35]). With regard to hydrocarbon generation, the samples are placed in the oil window (Fig. 10).

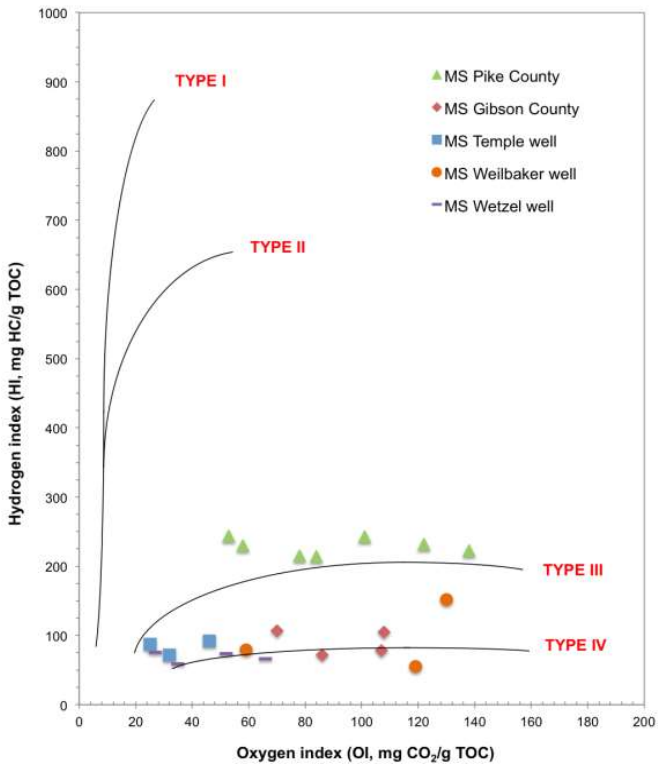

Figure 9. Kerogen types of Maquoketa Shale (MG) samples from counties in Indiana. Curved lines characterize expected trends for different types of kerogen according to a modified van Krevelen diagram ([29], Demaison et al., 1983).

The data in Table 5B show that hydrogen indices of Maquoketa Shale samples from Pike County range from 214 to 244 mg HC/g TOC and thus indicate gas and oil generation. In contrast, all 16 samples from Gibson and Washington counties with hydrogen indices from 55 to 152 mg HC/g TOC indicate gas generation.

Maquoketa Shale's source rock potential is judged 'fair to good' based on 7 samples from Pike County (TOC from 0.92 to 1.32 wt. %) and sample MG-14 from Washington County (TOC 0.71 wt. %), whereas all 6 samples from Gibson County (TOC from 0.30 to 0.42 wt. %) and 9 out of 10 samples from Washington County (TOC from 0.09 to 0.41 wt. %, Table 5) rank the generative hydrocarbon potential as 'poor' (Table 4).

With regard to the thermal maturity of Maquoketa Shale, the production indices of all 7 samples in Pike County ranging from 0.28 to 0.37 and T_{max} ranging from 435 to 445 °C (Table 5) place Maquoketa Shale within the peak oil window. Also, production indices of Maquoketa Shale from Gibson County range from 0.23 to 0.31, which indicates peak oil window. T_{max} values are unreliable because of underlying low S2 values. Washington County samples' production indices from 0.12 to 0.25 and T_{max} values from 437 to 442 °C along with respective data from most other Maquoketa Shale samples indicate a position in the early to peak oil window except for samples MG-17 and MG-19 with T_{max} values equal to zero.

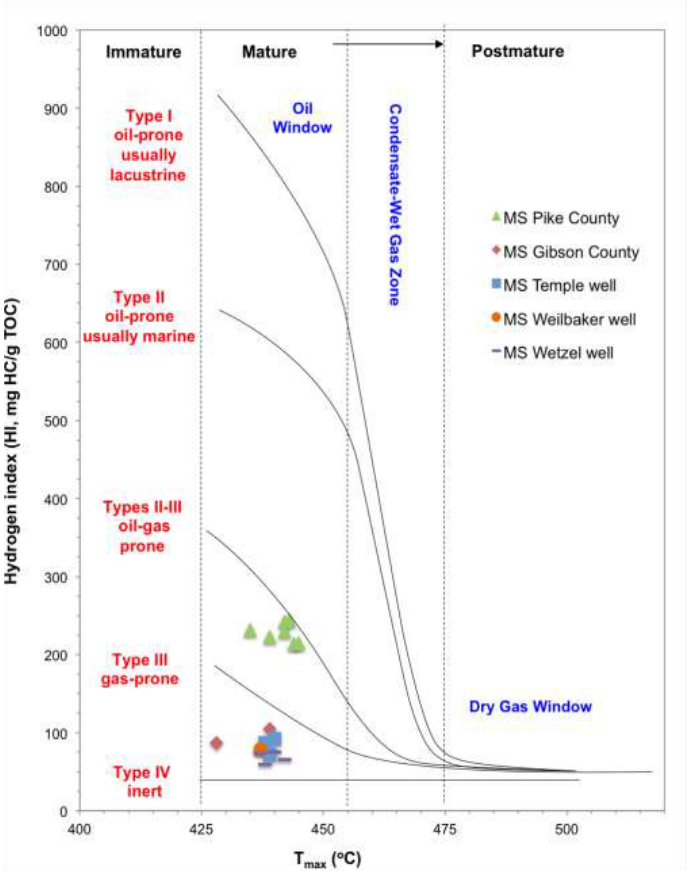

Figure 10. Plots of hydrogen index (HI) vs. T_{max} for Maquoketa Shale (MG) samples. Curved lines characterize expected trends for different types of kerogen according to a modified van Krevelen diagram ([29] Demaison et al., 1983). Vertical dashed lines separate zones of different maturity from immature to postmature based on T_{max} (425 to 475 °C).

Conclusions

▪ New Albany Shale and Maquoketa Shale were investigated as potential source rocks in the Illinois Basin to compare their hydrocarbon potentials

▪ Petrographic and geochemical studies show that amorphous organic matter and alginite are predominant components of organic matter in New Albany Shale representing mainly kerogen of Type I and Type II as indicated by Rock-Eval pyrolysis. In contrast, organic matter in Maquoketa Shale is composed of small, often reworked or oxidized liptinite macerals. Rock-Eval pyrolysis based on HI and OI characterizes this organic matter as mostly kerogen Type III and Type IV. We interpret this shift towards lower HI and higher OI values as combined influence of higher maturity and reworking of the original Type I and

Type II kerogen.

- The organic matter content of New Albany Shale ranges from 0.25 to 13.80 wt. % total organic carbon (TOC) and of Maquoketa Shale ranges from 0.09 to 1.32 wt. % TOC. The higher organic matter content in New Albany Shale compared to Maquoketa Shale can be explained by (i) elevated marine productivity in the photic zone supplying a larger flux of detrital organic matter to the seafloor, and (ii) a depositional environment and resulting organic facies favoring improved preservation and burial of organic matter.

- Our results suggest that the thermal maturity of (i) New Albany Shale is mainly early mature to mid-mature, (ii) of Maquoketa Shale is mid-mature, and (iii) that both shales are positioned within the oil window. Discrepancy between measured R_o and that calculated from T_{max} and solid bitumen reflectance in some samples for Gibson and Pike counties may be related to vitrinite reflectance suppression.

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