

SOURCE ROCK POTENTIAL OF THE
LOWER PART OF THE
MISSISSIPPIAN ST. LOUIS LIMESTONE IN
SOUTH-CENTRAL INDIANA

U.S. GEOLOGICAL SURVEY BULLETIN 2094-D

Cover. Leached ilmenite grain approximately 60 microns in diameter surrounded by quartz overgrowth in Lower Pennsylvanian sandstone in Indiana. Quartz overgrowths occlude much of the pore space in these rocks. Sample collected by Paula Hansley, U.S. Geological Survey.

Source Rock Potential of the Lower Part of the Mississippian St. Louis Limestone in South-Central Indiana

By J.L. Ridgley *and* V.F. Nuccio

EVOLUTION OF SEDIMENTARY BASINS—ILLINOIS BASIN
J.L. Ridgley, Project Coordinator

U.S. GEOLOGICAL SURVEY BULLETIN 2094—D

*A multidisciplinary approach to research studies of
sedimentary rocks and their constituents and the
evolution of sedimentary basins, both ancient and modern*



UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1995

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

For sale by U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

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Library of Congress Cataloging-in-Publication Data

Ridgley, Jennie L.

Source rock potential of the lower part of the Mississippian St. Louis Limestone in south-central Indiana / by J.L. Ridgley and V.F. Nuccio.

p. cm. — (Evolution of sedimentary basins—Illinois Basin ; D) (U.S. Geological Survey bulletin ; 2094)

Includes bibliographical references.

Supt. of Docs. no.: I 19.3:2094—D

1. Petroleum—Geology—Indiana. 2. Geology, Stratigraphic—Mississippian.
3. Limestone—Indiana. I. Nuccio, Vito F. II. Title. III. Series. IV. Series: U.S. Geological Survey bulletin ; 2094.

TN872.I6R53 1996

557.3 s—dc20

[553.2'8'09772]

95-9486
CIP

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By J.L. Ridgley and V.F. Nuccio

ABSTRACT

The carbonate-evaporite sequence of the lower part of the Mississippian St. Louis Limestone in the Illinois Basin in south-central Indiana can be divided into as many as 19 transgressive-regressive sedimentary cycles. Within each of these cycles, there are organic-rich strata that may be good to excellent hydrocarbon source rocks. The organic-rich strata are laminated or show evidence of compaction; they were deposited either during peak transgression (maximum flooding) or in restricted lagoonal environments when clastic input decreased or anoxic conditions were prevalent. In the two cores examined, the organic-rich strata contain from 0.03 to 15.72 percent total organic carbon types II and III. The organic-rich intervals range from a few centimeters (inches) to as much as a meter (3.3 ft) in thickness; cumulative thickness may be as much as 15–20 percent of the lower part of the St. Louis, or as much as 73 m (250 ft).

The average T_{\max} and production index values both decrease slightly from south to north in the two coreholes examined. On the basis of vitrinite reflectance from the underlying Upper Devonian and Lower Mississippian New Albany Shale and coal-rank data from overlying Pennsylvanian coal measures, the trend in these values falls within the general pattern of thermal maturity in the basin. The organic geochemical and environmental data suggest that the lower part of the St. Louis Limestone warrants further study as a potential source of hydrocarbons in the Illinois Basin, especially in the more thermally mature parts of the basin.

INTRODUCTION

Globally, organic-rich strata are found within interbedded, laminated carbonate and evaporite rock sequences and are major sources of hydrocarbons in the Jurassic of the Arabian Gulf (Murris, 1980; Ayres and others, 1982) and Gulf Coast of the United States (Oehler, 1984), the Pennsylvanian of the Paradox Basin of the United States (Hite and others, 1984), and the Lower Cretaceous of the South Florida Basin of the United States (Palacas and others, 1984). Some of the

organic-rich strata coincide with periods of peak transgression (maximum flooding) when euxinic conditions and reduced clastic input were prevalent. Other organic-rich strata were laid down in restricted marine environments in which the reducing environment associated with evaporite precipitation allowed preservation of the organic matter.

In the Illinois Basin (fig. 1), the source of most of the oil and gas has been attributed to the Upper Devonian and Lower Mississippian New Albany Shale (Hatch and others, 1990), and carbonate rocks generally have been overlooked as potential sources of hydrocarbons. Consequently, their source rock potential, and thus their contribution to the oil resources in the basin, is relatively unknown. An exception is Ordovician carbonate rocks and calcareous shale, sometimes interbedded with anhydrite beds, which are known to have generated oil. If the presence of evaporite rocks in association with carbonate rocks is an important criterion for favorable nonclastic source rocks, then perhaps other formations in the basin might contain favorable source rocks. Most carbonate rock formations, however, contain few, if any, evaporite beds. The one exception is the lower part of the Mississippian (Valmeyeran) St. Louis Limestone, which contains interbedded carbonate-anhydrite/gypsum sequences of variable thickness.

As a part of ongoing studies by the senior author to characterize the depositional environments, sedimentology, and diagenesis of interbedded evaporites and carbonate rocks in the lower part of the Mississippian St. Louis Limestone, we decided to test whether the St. Louis contains suitable source rock beds. In this report we discuss the distribution of organic carbon in two cores from the lower part of the St. Louis on the east side of the Illinois Basin and relate this distribution to depositional facies and thermal history. We show that the most organic rich strata in the St. Louis are associated with both peak transgression (maximum flooding) and restricted lagoons and that the potential for hydrocarbon generation is a function of the change in thermal history of the St. Louis from south to north in the basin. We do not address the source rock potential of other Paleozoic carbonate rock formations in the basin.

METHODOLOGY

Two cores of the St. Louis Limestone in south-central Indiana were interpreted for depositional environments (Ridgley, 1992) and were evaluated for their hydrocarbon source rock potential. The cores are from Survey Drill Hole 16 (SDH-16) (sec. 22, T. 3 N., R. 3 W., Martin County) and

Survey Drill Hole 190 (SDH-190) (sec. 25, T. 4 S., R. 1 E., Crawford County). Locations of the drillholes are shown in figure 1.

Representative chips of medium-gray to black limestone from the cores in the lower part of the St. Louis Limestone were evaluated by Rock-Eval pyrolysis (Espitalie and others, 1977). This technique measures the quantity, quality

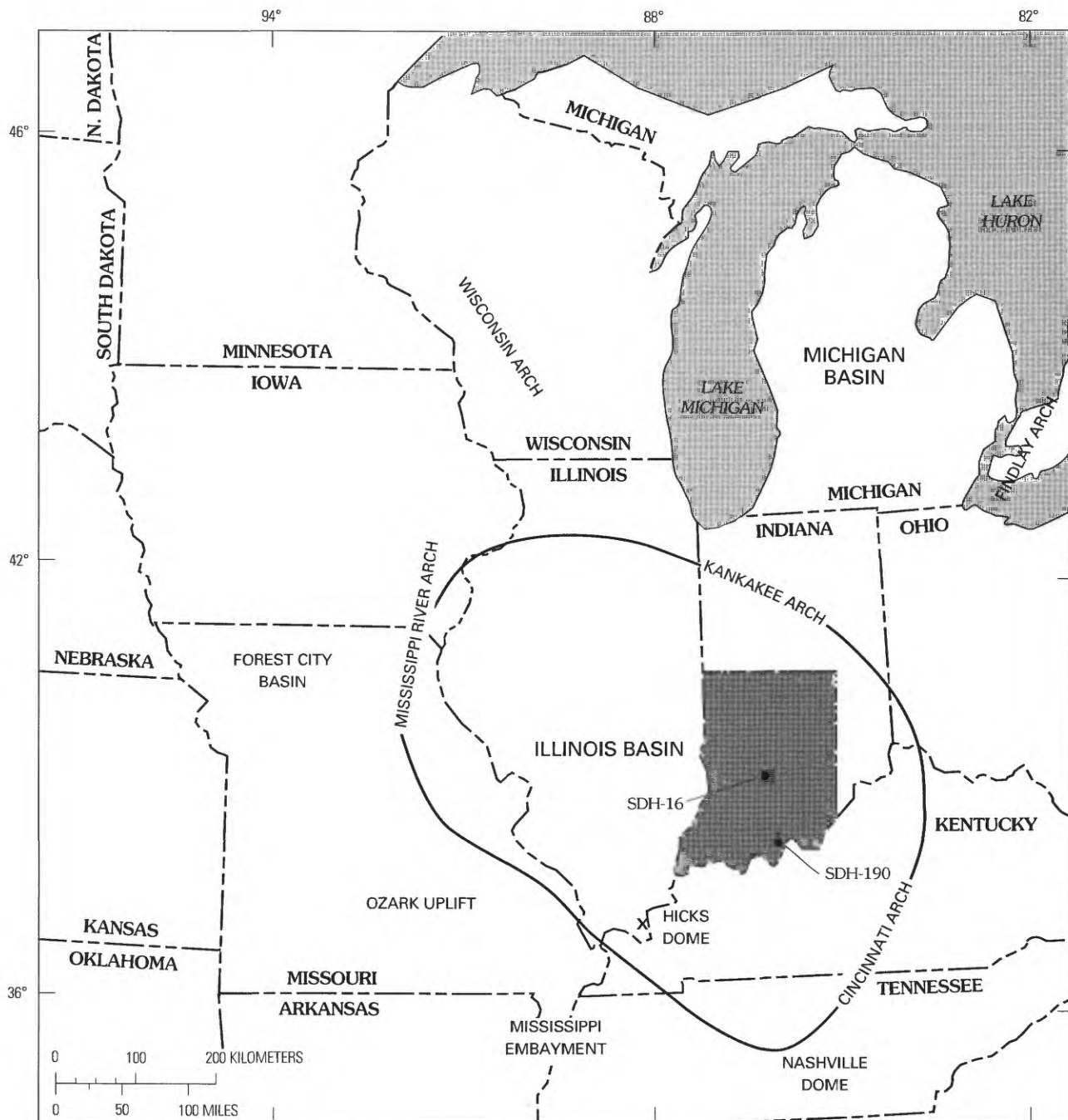


Figure 1. Location of the Illinois Basin, study area (dark shaded), and coreholes Survey Drill Hole 16 (SDH-16) and Survey Drill Hole 190 (SDH-190), north-central United States.

(type), and level of thermal maturation of organic matter contained in a rock. Rock-Eval pyrolysis alone is by no means the only way to evaluate a source rock, but, if used with an understanding of the limitations, it can be very useful as a first screening tool and can yield a general characterization of the organic matter in a rock.

Both organic-rich-appearing (dark-gray to black) and non-organic-rich-appearing (light-gray) rocks were analyzed for total organic carbon (TOC) in drill core from SDH-16. Non-organic-rich-appearing rock was analyzed to provide a measure of background total organic carbon and to assess the effect of facies on the amount of preserved total organic carbon. Several organic-rich-appearing horizons in drill core from SDH-190 were analyzed for total organic carbon. Thin sections of samples from various intervals throughout the two coreholes and from samples analyzed by Rock-Eval pyrolysis were examined to determine depositional facies and rock fabric.

STRATIGRAPHY OF THE ST. LOUIS LIMESTONE

GENERAL GEOLOGY OF THE ST. LOUIS LIMESTONE

The St. Louis Limestone is a small part of a thick package of carbonate rocks that filled the Illinois Basin during the Mississippian (fig. 2). It was deposited over a broad area of the Mid-continent as shallow-shelf carbonates. In the Illinois Basin (fig. 1), the St. Louis is now preserved only in the southern two-thirds of the basin, due to removal below the sub-Pennsylvanian unconformity (Droste and Carpenter, 1990). Outcrops of the St. Louis are confined to small areas on the east, west, and southeast sides of the basin. Maximum thickness of the St. Louis ranges from 136 m (450 ft) (Saxby and Lamar, 1957) to 166 m (550 ft) (Droste and Carpenter, 1990) in the structurally deep part of the Illinois Basin in southeastern Illinois and southwestern Indiana.

In this report, the St. Louis is informally divided into a lower part and an upper part. The lower part is characterized by cyclic deposition of beds of grainstone, packstone, wackestone, mudstone, dolomite, and evaporite (anhydrite and gypsum), and organic-rich beds are interspersed throughout. Diagenetic chert "nodules" are sparse to absent in the lower part of the St. Louis, and dolomite and evaporite beds are locally common. Deposition of the lower part of the St. Louis took place in open to restricted shallow-water shelf, possibly lagoonal, to supratidal settings. Thickness of the lower part of the St. Louis ranges from zero at its erosional edge to 73 m (250 ft) (Saxby and Lamar, 1957; Droste and Carpenter, 1990) in the deeper part of the basin.

The upper part of the St. Louis contains diagenetic chert "nodules" scattered throughout, few dolomite beds, and no

MISSISSIPPIAN (part)	CHESTERIAN (part)	Paoli Limestone	Downeys Bluff Member
			Yankeetown Member
			Renault Member
			Aux Vases Member
	VALMEYERAN	BLUE RIVER GROUP	Joppa Member
			Karnak Member
			Fredonia Member
		St. Louis Limestone	Upper part
			Lower part
		SANDERS GROUP	Salem Limestone
			Harrodsburg Limestone (part)

Figure 2. Nomenclature for Valmeyeran and Chesterian Mississippian rocks in the Illinois Basin in Indiana. Modified from Droste and Carpenter (1990).

evaporite beds. Grainstone is more abundant than in the lower part. Depositional facies reflect open, shallow-water shelf environments that were more basinward than those of the lower part of the St. Louis.

The St. Louis is overlain by the Ste. Genevieve Limestone and underlain by the Salem Limestone (fig. 2); the contacts have been considered conformable and gradational. Placement of the Salem-St. Louis and St. Louis-Ste. Genevieve contacts (and thus the thickness of the St. Louis) varies with individual interpretation reflecting the complexity of facies relationships between the three formations. Only the

lower part of the St. Louis was evaluated for its organic carbon content, and it is the focus of the remainder of the paper.

DEPOSITIONAL FACIES IN THE LOWER PART OF THE ST. LOUIS LIMESTONE

Detailed examination of core of the lower part of the St. Louis in coreholes SDH-16 and SDH-190 has resulted in identification of as many as 19 full or partial, short-term transgressive-regressive cycles within an overall regression (Ridgley, 1992). Cyclic sedimentation reflecting transgressive and regressive events in the lower part of the St. Louis has also been discussed by Jorgensen and Carr (1972). Figure 3 shows the lithologic, transgressive, and regressive components of an ideal cycle. The cyclic nature of the lower part of the St. Louis is demonstrated in a generalized representation of the major rock types and the relative positions of the transgressive and regressive parts of each cycle in each of the cores (figs. 4, 5). The transgressive and regressive

parts of each cycle vary in thickness depending, in part, on whether a complete cycle is present. In drill core from SDH-16, the regressive part of a cycle is generally thicker than the transgressive part (see fig. 4) in cycle 1 through cycle 8, which marks the end of the lower part of the St. Louis. In the lower part of the upper St. Louis, the reverse relationship is apparent (fig. 4). In drill core from SDH-190, the ratio of the thickness of the transgressive part of a cycle to the thickness of the regressive part of a cycle is more variable (fig. 5).

In the two cores examined, the maximum transgressive part of a cycle is characterized by thinly laminated micrite or fossiliferous limestone that indicates normal-marine salinity. The fossils, which are mostly stenohaline, include frond-type bryozoans, echinoderms, and solitary corals. Compared to limestone beds in the basal part of the transgressive cycle or in the regressive part of a cycle, fossils in the maximum transgressive limestone show a high faunal diversity; tests are robust. The maximum transgressive limestone is underlain and overlain by limestone, dolomite, or anhydrite (gypsum), depending on whether a complete or partial cycle is present (Ridgley, 1992).

Fossiliferous limestone at the base of a transgressive cycle or within the regressive part of a cycle was deposited nearer to the shore than was the maximum transgressive limestone; the contained fossils indicate either normal or restricted marine salinity. The regressive part of a cycle commonly is characterized by limestone that is overlain by silty dolomite and finally by anhydrite (gypsum) (Ridgley, 1992) but, in some cases, may be overlain by anhydrite and dolomite, depending on whether a complete or partial cycle is present. Limestone beds in the regressive part of a cycle show a decrease in diversity and size of fauna when compared to the maximum transgressive limestone beds. Dolomite beds that are associated with anhydrite beds contain either no fossils or only ostracodes. The absence of fossils or the presence of only ostracodes in the dolomite beds indicates much higher salinity conditions during deposition.

The depositional facies interpreted in the cores and as expressed in the transgressive and regressive parts of cycles are indicative of shallow-water open-shelf (or open-lagoon), restricted lagoon, and supratidal environments. The oscillations in depositional environments reflect a change in water depth during short-term fourth-order sea-level rises and falls. Water depths ranged from zero in supratidal environments to just below wave base in the open lagoon or inner shelf during maximum flooding.

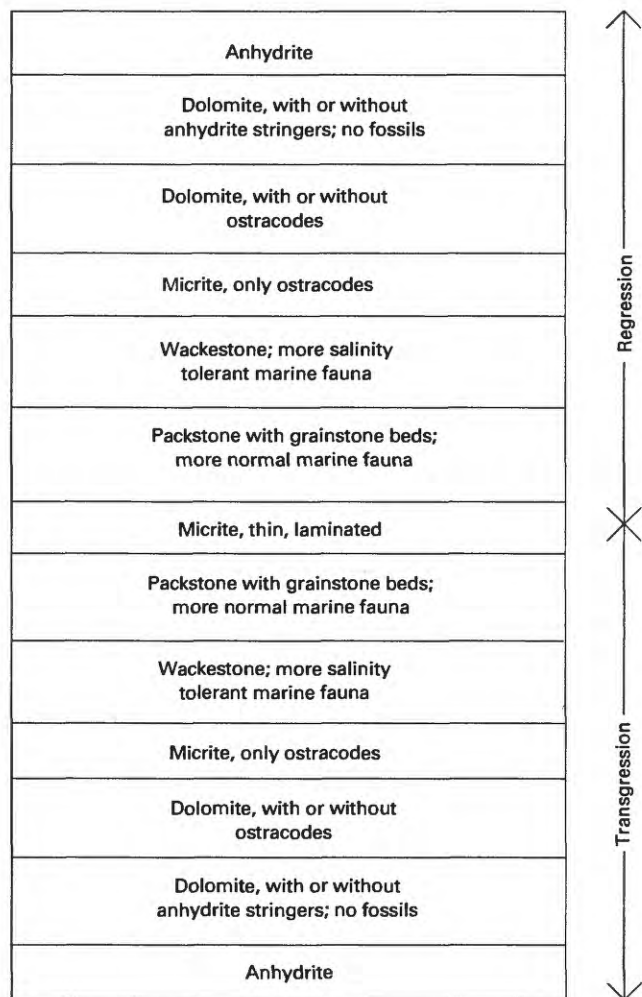
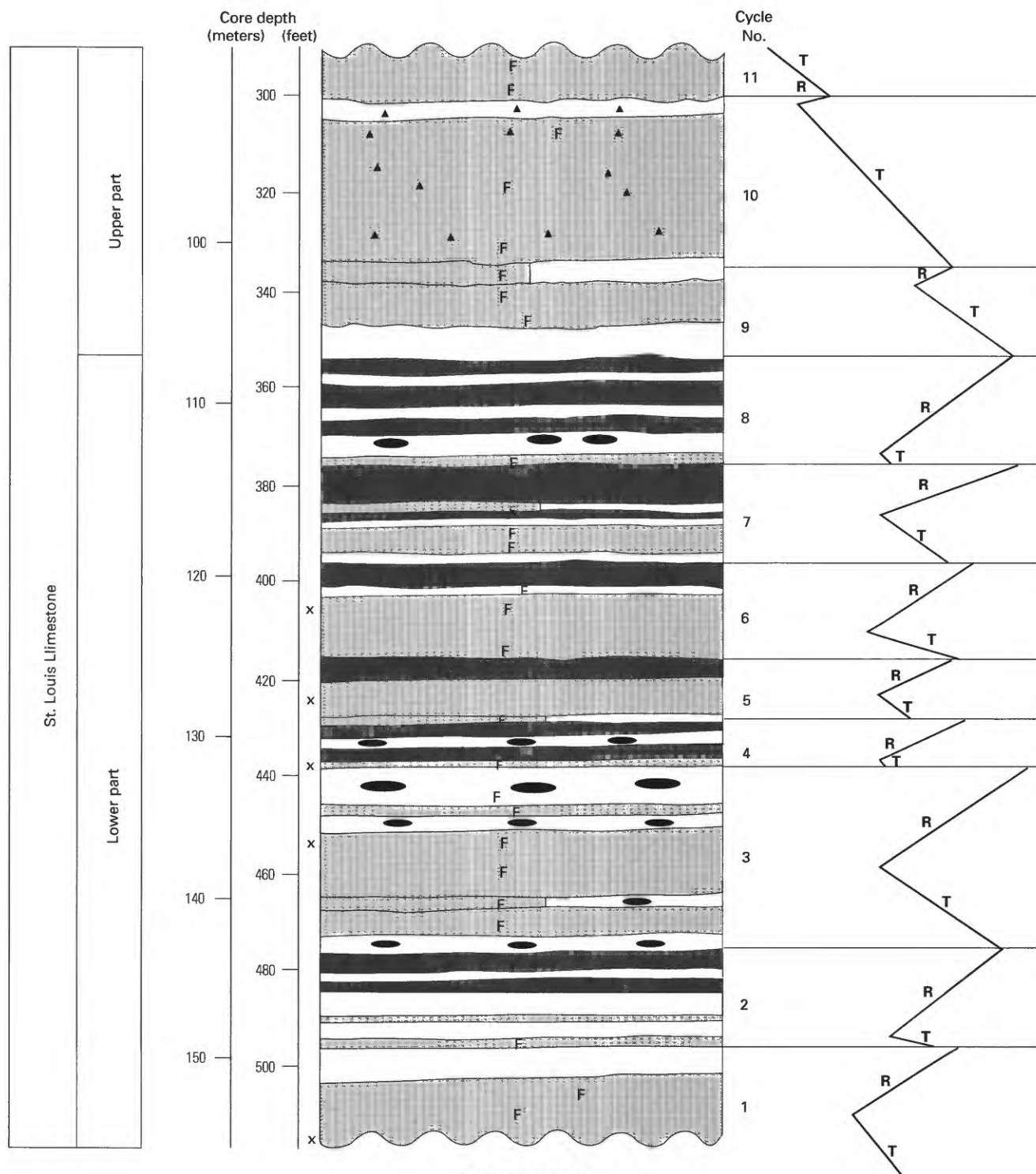


Figure 3. Lithologic components of a complete transgressive-regressive cycle.

Figure 4 (facing page). Generalized stratigraphic section of the St. Louis Limestone in Survey Drill Hole 16, sec. 16, T. 3 N., R. 3 W., Martin County, Indiana, showing principal lithologies, positions of transgressive-regressive cycles, and locations of samples containing 0.50 percent or greater total organic carbon.



EXPLANATION

- Limestone
- Dolomite
- Anhydrite/gypsum

- Authigenic chert
- Dolomite/anhydrite, mixed
- Microfossils

- Transgression
- Regression
- Cycle boundary and number
- Organic carbon sample

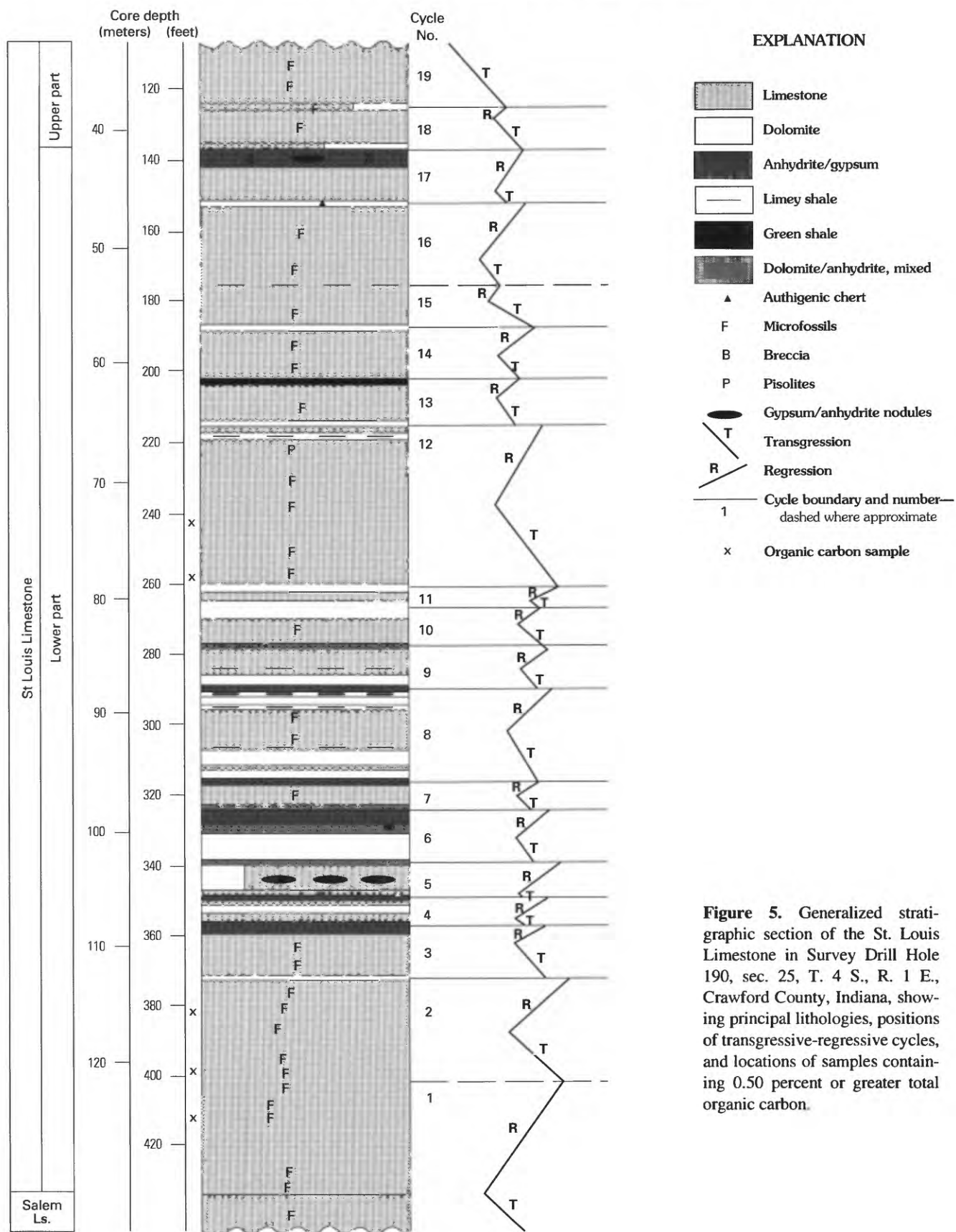


Table 1. Rock-Eval pyrolysis data for selected samples from Survey Drill Hole 16 (SDH-16) and Survey Drill Hole 190 (SDH-190) in the lower part of the Mississippian St. Louis Limestone, Illinois Basin, Indiana.

[Locations of drillholes are shown in figure 1. T_{max} , temperature ($^{\circ}$ C) at which maximum yield of hydrocarbons occurs during pyrolysis of organic matter; TOC, total organic carbon (in weight percent); S_1 , integral of first peak (existing hydrocarbons volatilized at 250° C for 5 minutes) (in milligrams per gram); S_2 , integral of second peak (hydrocarbons produced by pyrolysis of solid organic matter (kerogen) between 250° C and 550° C) (in milligrams per gram); S_3 , integral of third peak (CO_2 produced by pyrolysis of kerogen between 250° C and 390° C) (in milligrams per gram); PI, production index (S_1/S_1+S_2); HI, hydrogen index (S_2/TOC); OI, oxygen index (S_3/TOC). Leaders (---) indicate data not reliable]

Sample No.	Depth		T _{max}	TOC	S ₁	S ₂	S ₃	PI	HI	OI
	(feet)	(meters)								
SDH-16										
1	316.6	96.5	---	0.05	0.03	0.08	0.62	---	---	---
2	337.8	103.0	---	0.26	0.08	0.21	1.01	---	---	---
3	372.6	113.6	---	0.05	0.01	0.04	0.58	---	---	---
4	374.6	114.2	---	0.03	0.01	0.12	0.76	---	---	---
5	405.8	123.7	432	1.05	0.1	0.71	1.23	0.12	67	117
6	424.6	129.5	429	3.55	0.37	4.34	2.38	0.05	206	67
7	439.7	134.0	427	3.42	0.63	8.78	1.74	0.07	256	50
8	439.9	134.1	---	0.31	0.05	0.23	1.88	---	---	---
9	451.0	137.5	426	8.22	1.42	24.59	5.09	0.05	299	61
10	502.2	153.1	---	0.22	0.02	0.07	0.91	---	---	---
11	516.1	157.3	426	2.74	0.67	3.49	2.61	0.16	127	95
SDH-190										
12	244.0	74.4	434	0.92	0.15	0.88	0.57	0.15	95	61
13	258.6	78.8	433	3.53	0.7	6.76	2.91	0.09	191	82
14	381.0	116.2	429	15.72	4.24	40.6	16.06	0.09	258	102
15	399.1	121.7	431	2.03	0.25	2.37	1.59	0.1	116	78
16	413.2	126.0	432	0.71	0.15	0.61	1.2	0.2	85	169

SOURCE ROCK POTENTIAL

ORGANIC MATTER QUANTITY

The quantity of organic matter in samples from the lower part of the St. Louis Limestone is illustrated by the total organic carbon values (TOC) (table 1). Total organic carbon was determined using the Rock-Eval II instrument of Delsi, Inc., and is the sum of the carbon in the pyrolyzate plus the carbon from the residual oxidized organic matter. For this study we assume that a rock must contain a minimum of 0.50 weight percent total organic carbon to be considered a potential hydrocarbon source rock.

In drill core from SDH-16, total organic carbon values range from 0.03 to 8.22 percent (table 1). Samples 1, 2, 3, 4, 8, and 10 all have total organic carbon values of less than 0.50 percent and are not considered potential source rocks. These samples are included in this report to provide information on the range of total organic carbon values in the various depositional environments in a vertical succession of the St. Louis. Too often, many reports discussing source rock potential of a formation highlight only the richest samples and fail to provide the reader with information on the vertical and lateral variability within the formation. Table 2 shows the lithology and depositional environment of each of these samples. The low total organic carbon values coincide with limestone of normal marine salinity that has an uncompacted fabric or with dolomite of restricted marine environments.

Samples 5, 6, 7, 9, and 11, however, have high total organic carbon values (1.05, 3.55, 3.42, 8.22, and 2.74 percent, respectively) and on the basis of total organic carbon are considered good to excellent source rocks. Stratigraphic locations of samples having total organic carbon values of 0.50 percent or greater are shown in figure 4. Table 2 lists the lithology and depositional environment of each of these samples. The high total organic carbon values are associated with limestone of restricted lagoon environments that has a compacted rock fabric, with laminated, normal marine limestone indicative of maximum flooding, or with organic-rich dolomite of marine environments.

Samples 12, 13, 14, 15, and 16, from drillhole SDH-190, all have total organic carbon values of greater than 0.50 percent (0.92, 3.53, 15.72, 2.03, and 0.71 percent respectively), indicating they are good to excellent source rocks if only total organic carbon is considered. Their positions within the measured section are shown in figure 5. Table 2 lists the lithology and depositional environment of each sample. Again, the high total organic carbon values are associated with limestone of restricted lagoon environments that has a compacted rock fabric, with laminated, normal marine limestone indicative of maximum flooding, or with organic-rich dolomite of restricted marine environments.

Samples from drillholes SDH-16 and SDH-190 having total organic carbon values of 0.50 weight percent or greater (table 2) have either laminated or compacted rock fabrics. Laminated rock fabrics are primary and reflect deposition of

Table 2. Lithology, depositional environment, and total organic carbon content of samples from Survey Drill Hole 16 (SDH-16) and Survey Drill Hole 190 (SDH-190) in the lower part of the St. Louis Limestone, Illinois Basin, Indiana. [Locations of drill holes are shown in figure 1. Total organic carbon content from Rock-Eval pyrolysis]

Depth (feet)	Depth (meters)	Total organic carbon (wt. percent)	Lithology	Depositional environment
SDH-16				
316.6	96.5	0.05	Limestone, open framework	Open lagoon.
337.8	102.9	0.26	Dolomite, limey, clay-rich	Inner shelf, restricted marine.
372.6	113.6	0.05	Dolomite	Inner shelf, restricted lagoon to supratidal.
374.6	114.2	0.03	Limestone, fossils, open framework	Inner shelf, restricted lagoon.
405.8	123.7	1.05	Limestone, shell debris, flattened, compacted	Inner shelf, restricted lagoon.
424.5	129.5	3.55	Limestone, laminated, dark, fissile	Open marine, maximum flooding.
439.7	134.0	3.42	Limestone, laminated	Inner shelf, restricted lagoon.
439.9	134.1	0.31	Dolomite, limey, few laminae	Inner shelf, restricted lagoon to supratidal.
451.0	137.5	8.22	Dolomite, black, laminated, fissile, minor anhydrite	Inner shelf, restricted lagoon.
502.2	153.1	0.22	Limestone, few laminae	Open lagoon.
516.1	157.3	2.74	Limestone, carbonaceous	Open marine, near maximum flooding.
SDH-190				
244.0	74.4	0.92	Limestone, laminated, fossils, microstylolites	Open marine, near-maximum flooding.
258.6	78.8	3.53	Limestone, flattened shells, black laminae	Inner shelf, restricted lagoon.
381.0	116.2	15.72	Limestone, laminated, microstylolites	Inner shelf, restricted lagoon.
399.1	121.7	2.03	Limestone, laminated, burrowed, secondary dolomite	Inner shelf, restricted lagoon.
413.2	126.0	0.71	Limestone, wavy laminated, shells flattened and broken	Inner shelf, restricted lagoon.

sediment in quiet water. Compacted rock fabrics are secondary and are due to vertical compression. Rocks showing evidence of compaction contain abundant microstylolites (compressed organic matter) and flattened and broken bioclasts (fig. 6). Samples having total organic carbon values of less than 0.50 weight percent (table 2) do not have a laminated fabric, although scattered laminae may be present. They have an open framework fabric and show no evidence of compaction. The correlation of a laminated or compacted rock fabric with high amounts of total organic carbon suggests that other strata, in the lower St. Louis, having these fabrics may potentially be the best source rocks.

ORGANIC MATTER TYPE

Another measure related to the quantity of pyrolyzable organic matter or hydrocarbons is hydrogen index (HI), defined as the S_2 yield (remaining hydrocarbon-generating capacity of the organic matter) normalized by total organic carbon; in other words, it is the fraction of the total organic carbon that is generated as hydrocarbons during pyrolysis. Hydrogen index is also useful in describing the type of organic matter present in a rock and the type of hydrocarbons that will be ultimately generated. Hydrogen index values (in milligrams of hydrocarbons per gram of organic carbon) of 0–150 yield mostly gas, of 150–300 yield gas and oil, and greater than 300 yield mostly oil (Peters, 1986).

The most widely used graphical tool for defining the type of organic matter contained in a source rock is the



Figure 6. Limestone representing restricted lagoonal facies in the lower part of the St. Louis Limestone at 115.45 m (381.0–381.25 ft) depth in Survey Drill Hole 190. Note the compacted nature of the rock; dark microstylolites are compacted organic matter. Anhydrite nodules (light areas) are early diagenetic and formed from pore fluids supersaturated with respect to calcium sulfate. Length of core is 7.62 cm (3 in.). Total organic carbon value for this interval is 15.72 percent.

modified van Krevelen diagram. This diagram is a plot of the hydrogen index and the oxygen index (OI) (S_2 and S_3 normalized by total organic carbon respectively), and gives an indication of the type of organic matter (types I, II, III, and IV) and the degree of thermal evolution. Type I organic matter is hydrogen rich (sapropelic or lipid rich), is present primarily in marine and lacustrine rocks, and generates mainly oil during catagenesis. Type II organic matter is generally present in marine rocks and generates oil and gas during catagenesis. Type III kerogen is oxygen rich and hydrogen poor (huminitic and vitrinitic), is present mainly in terrestrial, marginal-lacustrine, or marginal-marine rocks, and generates mostly gas during catagenesis. Type IV organic matter is inert, contains very little hydrogen, and has no hydrocarbon-generating capability. Its path is not shown in figure 7 but would plot below that of type III.

Figure 7 illustrates the types of organic matter in the St. Louis Limestone samples using a modified van Krevelen diagram. Only samples that have total organic carbon values greater than 0.50 weight percent were plotted. Samples from drill cores SDH-16 and SDH-190 plot in the type II-III area, indicating that they are potentially source rocks for both oil and gas. A mixture of type II and III organic matter is expected for the depositional setting of the lower part of the St. Louis, in which semirestricted, nearshore environments acted as a sink for accumulation and preservation of both terrestrial and marine organic matter.

There is no apparent correlation between environment of deposition of St. Louis samples and the type of organic matter as represented by the position of the samples on the modified van Krevelen diagram (compare table 2 and figure 7). One might expect that samples from the more restricted lagoonal facies would contain more terrestrial organic matter than samples from the maximum normal marine facies; however, this correlation is probably absent because the lateral shift in the depositional environments within the inner shelf in the study area is nominal.

THERMAL MATURITY

The level of thermal maturity of samples of the St. Louis Limestone that have total organic carbon values greater than 0.50 weight percent was estimated three ways. The first method used the relative position of the points plotted on the modified van Krevelen diagram. In general, plotted samples should migrate toward the origin of the diagram ($HI=0$, $OI=0$) with increasing maturity. The fact that the St. Louis Limestone samples fall well away from the origin suggests that they are relatively immature (fig. 7).

A second thermal maturity indicator used was T_{max} , the temperature at which maximum yield of hydrocarbons occurs during pyrolysis or, in other words, the temperature at which the S_2 peak occurs. The onset of oil generation (tran-

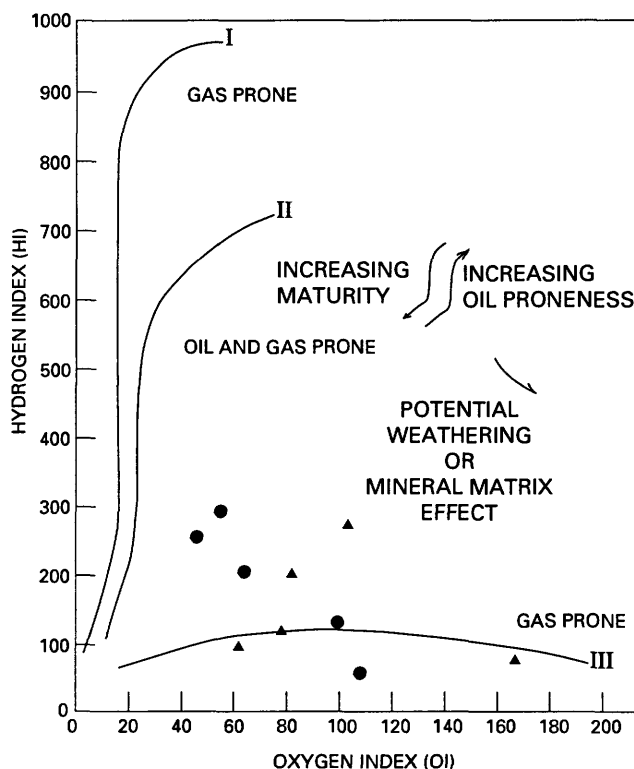


Figure 7. Modified van Krevelen diagram of hydrogen and oxygen indexes determined by pyrolysis for samples in Survey Drill Hole 16 (solid circles) and Survey Drill Hole 190 (triangles) for samples containing 0.50 percent or greater total organic carbon.

sition from immature to mature) is considered to occur at a T_{max} of 430°C (Humble Laboratory, 1993, based on written communication from J. Espitalie, 1982) or 435°C (Tissot and Welte, 1984), and the upper limit of oil generation occurs at about 460°C (Tissot and Welte, 1984). Peters (1986) suggested that the analytical error of a measured T_{max} is commonly from 1° to 3° C. All of the St. Louis Limestone samples have T_{max} values of less than 435°C, although a few have values only 1°–2° C lower (table 1). Most samples from drill core SDH-190 have T_{max} values between 430°C and 435°C, and these samples could be within the oil-generation window, depending the classification of thermal maturity used and on analytical error. Samples containing less than 0.50 percent total organic carbon have spurious T_{max} values due to low S_1 and S_2 values; thus, T_{max} values for these samples are not shown in table 1.

Several variables (such as clay content, type of organic matter, and ratio of organic matter to mineral matrix) affect the temperature of onset of hydrocarbon generation, and therefore that temperature should vary from sample to sample (Peters, 1986). Thus, use of a rigid temperature value of 435°C to depict the onset of hydrocarbon generation may have less validity than would a range of temperatures. Regardless of the classification used, T_{max} values in the St.

Table 3. Pyrolysis parameters used to define source rock generative potential.

[Parameters are defined in table 1]

Quantity	TOC (wt. percent) ¹	S ₁ (mg/g) ¹	S ₂ (mg/g) ¹	S ₂ (mg/g) ²	S ₁ +S ₂ (mg/g) ³
Poor	0–0.5	0–0.5	0–2.5	0–2.2	<2
Fair	0.5–1	0.5–1	2.5–5	2.2–5.5	2–6
Good	1–2	1–2	5–10	>5.5	>6
Excellent	2+	2+	10+	>5.5	>6

¹Peters (1986).²Humble Laboratory (J. Espitalie, written commun., 1982).³Tissot and Welte (1984).

Louis Limestone suggest that the formation is immature to marginally mature where sampled.

The third thermal maturity indicator is the production index (PI) or transformation ratio. Production index is defined as the ratio of volatile hydrocarbon yield to total hydrocarbon yield $S_1/(S_1 + S_2)$. The transition from immature to mature, or beginning of the oil window, is about $PI=0.10$, and the end of the oil window is about $PI=0.50$ (Tissot and Welte, 1984). According to production index values, most of the samples are immature; however, samples 5, 11, 12, 15, and 16 have values slightly greater than 0.10, indicating that they are marginally mature (table 1). Samples 13 and 14 have a $PI=0.09$, placing them just below the oil-generation window. Production index values for samples containing less than 0.50 percent total organic carbon and having low S_1 and S_2 values are not reliable and thus are not shown in table 1.

The three maturity indicators used are internally consistent and indicate that the St. Louis Limestone samples are immature to marginally mature. T_{max} data for the samples containing greater than 0.50 percent total organic carbon show a slight regional cooling from SDH-190 (average value 432°C) to SDH-16 (average value 428°C), consistent with the overall reduction of the paleothermal history from south to north in the basin. The production indices show a slight decrease from SDH-190 to SDH-16, which is also consistent with the overall reduction of the paleothermal gradient from south to north in the basin.

These trends are within the general pattern of thermal maturity in the basin determined on the basis of vitrinite reflectance data for the underlying Upper Devonian and Lower Mississippian New Albany Shale and coal-rank data for overlying Pennsylvanian coal measures. In the areas of the SDH-16 and SDH-190, vitrinite reflectance of the New Albany Shale is approximately 0.60 percent (Barrows and others, 1979; Barrows and Cluff, 1984). It should be noted that vitrinite reflectance values of the New Albany may be suppressed and that the corrected values could be as high as 0.70–0.80 percent. If we extrapolate coal-rank trends of the

Herrin No. 6 coal bed in Illinois (Damberger, 1971) into western Indiana, vitrinite reflectance values in the area of the SDH-16 and SDH-190 would be in the 0.60–0.70 percent range. Thus, the St. Louis Limestone samples have an equivalent vitrinite reflectance (based on T_{max} and production index values) of approximately 0.60–0.65 percent, values consistent with the vertical vitrinite reflectance profile or gradient in that part of the Illinois Basin.

PETROLEUM POTENTIAL

Several pyrolysis parameters are commonly used to define source rock favorability. These include S_1 , S_2 , and S_1+S_2 , which is the genetic potential of Tissot and Welte (1984). The categories of source rock favorability for these parameters are shown in table 3. If only the S_1 peak is considered, then samples 7, 9, and 11 from drill core SDH-16 and samples 13 and 14 from drill core SDH-190 are fair to excellent source rocks (tables 1, 3). If only the S_2 peak is considered, samples 6, 7, 9, and 11 from drill core SDH-16 and samples 13, 14, and 15 from drill core SDH-190 are fair to excellent source rocks (tables 1, 3). If only genetic potential (S_1+S_2) is considered, samples 6, 7, 9, and 11 from SDH-16 and samples 13, 14, and 15 from SDH-190 are fair to excellent source rocks.

To date, no oils have been reported as sourced from Mississippian rocks in the Illinois Basin. Because biomarker information on organic matter in the St. Louis Limestone is not available, it is not known whether oil has actually been generated from the St. Louis and its signature masked by commingling with oils generated from the New Albany Shale. On the basis of the limited Rock-Eval pyrolysis data presented herein, the St. Louis Limestone could be considered a fair to excellent potential source rock for both oil and gas in the Illinois Basin. Our suite of data is fairly limited, so we cannot say for a certainty that the St. Louis Limestone has similar source rock potential in other parts of the basin; however, paleoreconstructions in progress by the senior author

indicate that favorable facies may be present in the deeper part of the basin. The distribution of organic-rich beds should coincide with the occurrence of evaporite beds or rocks of restricted marine origin because organic matter has the greatest potential for preservation in these depositional environments.

The samples analyzed are immature to marginally mature because the St. Louis on the eastern side of the Illinois Basin was never buried under significantly more overburden (303 m [1,000 ft] or less) (Cluff and Byrnes, 1990) than it is today. It is likely that, in the deeper parts of the basin, with additional depth of burial, or in areas with a higher paleothermal gradient, the St. Louis Limestone will be more thermally mature and hence further into the hydrocarbon-generation window.

Organic-rich strata are present in beds that range in thickness from a few centimeters to as much as a meter. These strata are thinner where they coincide with the maximum flooding surface and thickest in restricted lagoonal environments. Although individual beds are not unusually thick, the combined thickness of organic-rich strata in all the cycles represents a few percent to as much as 15–20 percent of the lower part of the St. Louis. Thus, the cumulative thickness of favorable source rock beds suggests that further study of the source rock potential of the St. Louis is warranted.

SUMMARY

The data presented herein suggest that the lower part of the Mississippian St. Louis Limestone could be a source of hydrocarbons in the Illinois Basin; however, additional studies of the source rock potential are needed. Such studies would include characterization of the organic matter in the St. Louis and the application of sequence stratigraphic concepts to paleoreconstruction of the lower part of the St. Louis to delineate favorable source rock facies. Source rock facies containing high amounts of preserved total organic carbon should have a laminated or compacted rock fabric; they should coincide either with maximum flooding during peak transgression or with restricted marine environments that are associated with evaporites. Potential for actual hydrocarbon generation from these rocks is greatest in the thermally mature parts of the Illinois Basin such as the deeper parts of the structural basin or the area around Hicks dome, which is an area of probable high heat flow in the southern part of the basin (fig. 1). Local oil-bearing reservoirs in the St. Louis and overlying Ste. Genevieve Limestones in proximity to organic-rich facies in the lower part of the St. Louis should be evaluated to see if the oils were sourced (at least in part) from the St. Louis. Evaporites in the St. Louis, although not very thick, could have served as local seals.

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Published in the Central Region, Denver, Colorado
Manuscript approved for publication April 27, 1995
Edited by Judith Stoeser
Graphics and photocomposition by Joan Nadeau

