The Backbone Limestone (Lower Devonian), a Potential Reservoir in Southern Indiana

John A. Rupp
Petroleum Section, Indiana Geological Survey
Bloomington, Indiana 47405

Introduction

Evaluation of Lower Devonian rocks (New Harmony Group), which are present only in the subsurface of southwestern Indiana, indicates that conditions exist for the presence of hydrocarbon bearing reservoirs. Moderate depths and multiplicity of possible trap configurations make this group of rocks an economically favorable exploration target. Because the units are present only in the subsurface, limited data are available for use in making paleoenvironmental reconstructions, evaluating sedimentary structures, and interpreting the diagenetic history. Detailed knowledge about the distribution and the composition of these Early Devonian sediments is still lacking, but renewed interest in the group is producing data that will help better define the physical and chemical characteristics of these rocks.

Early in the drilling history of the Illinois Basin, rocks found along the eastern margin of the Illinois Basin below the Middle Devonian carbonate sediments (Muscatatuck Group) were interpreted to be Silurian in age. Following the work of Freeman (11) and Collinson and others (7) a clearer understanding of this wedge of carbonate and siliceous dolomitic sediments emerged. Following the recognition of Lower Devonian faunal assemblages in a core from White County, Illinois, Becker (3) defined and mapped the extent and internal stratigraphy of Lower Devonian rocks in southwestern Indiana. Through the work of Becker (3) and Becker and Droste (5) the regional distribution of the major lithostratigraphic units within the group (Grassy Knob Chert, Backbone Limestone, and Clear Creek Chert) was recognized. The complex lateral and vertical lithofacies relationships between these units are documented by the cross sections and thickness maps in studies by Becker (3), Becker and Droste (5), and Droste and Shaver (10). Readers are referred to the aforementioned publications for details pertaining to the regional stratigraphy and facies distribution.

Backbone Limestone and Silurian Reefs

The Backbone Limestone is a carbonate grainstone that is best developed along the eastern margin of the Lower Devonian rocks within the Illinois Basin. The area in which the thickest accumulation of Backbone lithofacies (type-2 carbonate rocks of Becker and Droste (5)) occurs is the far southwest corner of Indiana. These clean coarse-grained bioclastic carbonate sediments were deposited along the eastern flank of the Paleozoic Vincennes Basin (8) while lateral facies-equivalent rocks, the fine-grained siliceous carbonates of the Grassy Knob and Clear Creek Cherts, were synchronously deposited in the deeper part of the Vincennes Basin (Figure 1). Because of the complex intertonguing relationship between the Backbone lithofacies and time-equivalent cherty carbonate rocks (type-3 carbonate rocks of Becker and Droste (5)), an arbitrary vertical cutoff exists to separate the Backbone Limestone as a formation from lateral-equivalent rocks. The basal carbonate horizon in this sequence is informally termed the "Ozora" limestone in Illinois Basin subsurface terminology. This unit is corelative with the Flat Gap Limestone of Tennessee (20). Thinning of the Backbone sediments to the east is attributed to erosional truncation along the pre-Muscatatuck surface (Figure 2). Although the Backbone is clearly bounded both above and below by unconformities along its eastern extent, this relationship probably does not hold farther west, deeper into the basin because of continuous deposition (Figure 2). Most

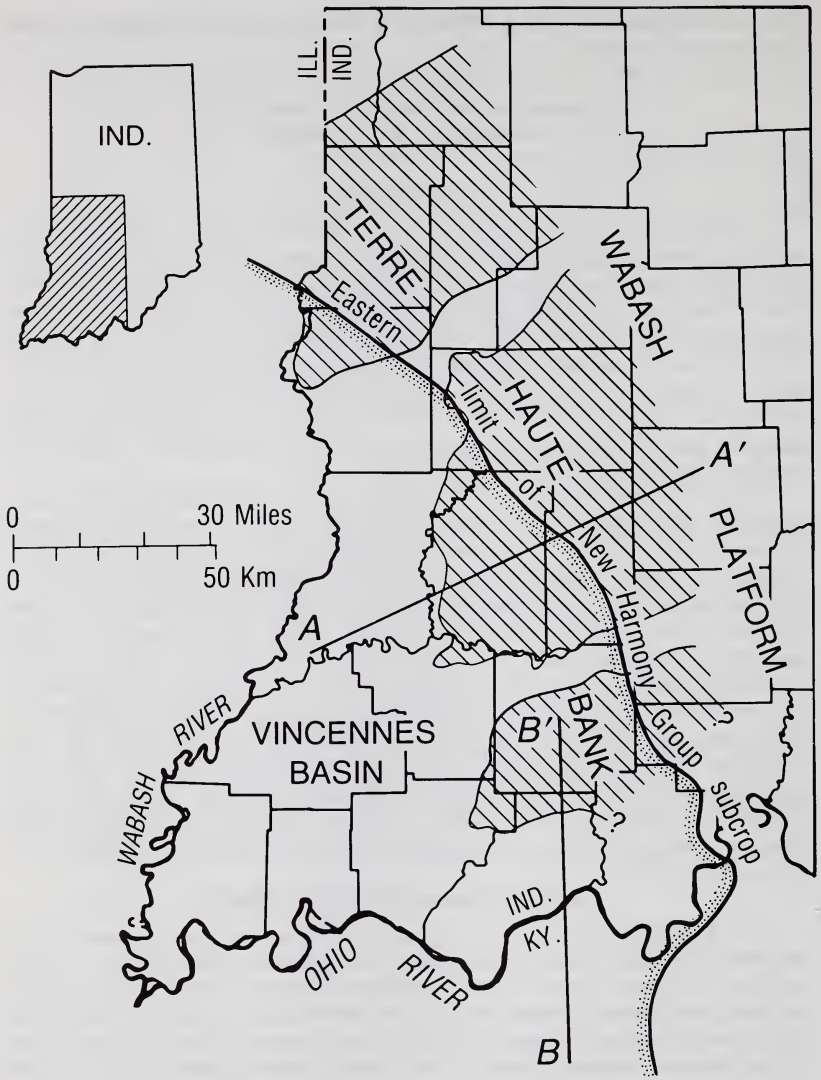

FIGURE 1. Map of southwestern Indiana showing location of Late Silurian depositional areas. Zero line is the eastern limit of the New Harmony Group subcrop. Modified from Droste and Shaver, 1980; in prep.

of the Backbone was probably deposited in a shallowing subtidal to intertidal environment. Cleanliness of the preserved carbonates indicates an energy regime high enough to winnow fine-grained terrigenous siliciclastic and autogenous carbonate muds out of the depositional area, possibly into the deeper parts of the basin as pelagic sediments.

Variations in Backbone thickness, composition, and grain size due to differences within the primary depositional environment are difficult to define due to extensive

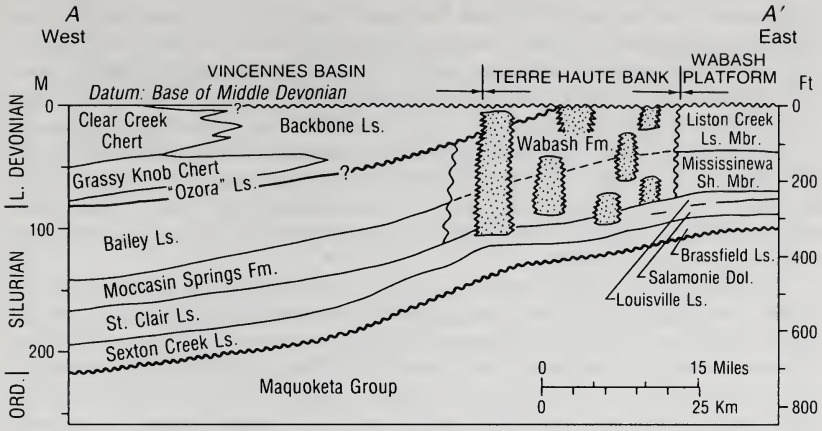

FIGURE 2. East-West stratigraphic cross section across the eastern margin of the Vincennes Basin. Datum is the base of the Middle Devonian Muscatatuck Group. See figure 1 for the location of the cross section A-A′.

diagenetic changes, erosional removal of the original sediments, and lack of detailed subsurface control. A general scheme of cleaner and coarser grained material being concentrated in shallower environments is postulated. In addition to the regional shallowing in an easterly direction toward the basin margin, localized centers of shallower water encouraged higher energy sedimentation to be developed over positive topographic high areas on the Early Devonian sea floor. These positive areas were the result of Silurian carbonate buildups or reefs projecting higher from the sea floor than the surrounding contemporary interreef and basinal sediments (Figure 3).

The large arcuate archipelago of reefs that range in size from small free-standing digitate pinnacle reefs to larger lower relief reef masses and atolls rings the eastern margin of the Vincennes Basin and is collectively termed the Terre Haute Bank (fig. 1) (4,5,6,8,9,10). The Terre Haute Bank forms the basinward edge of a large regional

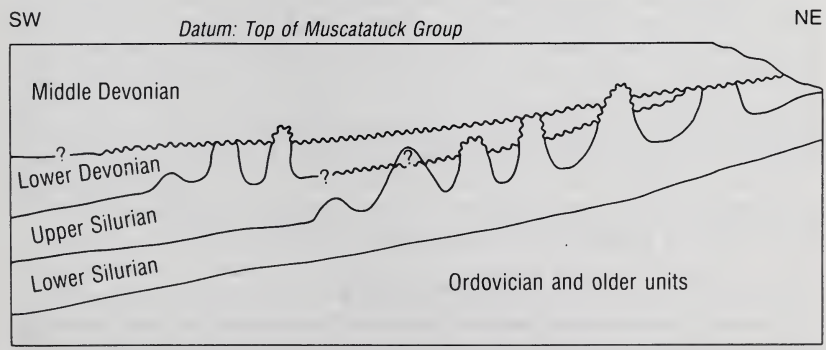

FIGURE 3. Diagramatic northeast-southwest cross section showing possible configurations of Silurian reefs in the Terre Haute Bank in relation to the overlying sediments of the Lower and Middle Devonian sequence. Datum is the base of the Upper Devonian New Albany Shale.

shallow-water shelf termed the Wabash Platform (Figure 1) (8). Although the pre-New Harmony unconformity probably removed and modified much of the Late Silurian paleotopography, as evidenced by the easterly regional thinning of the Silurian units (1,6), the erosional influence decreased rapidly basinward to the west. Most all of what is now defined as the main part of the Terre Haute Bank was affected to some degree by pre-Backbone erosion, but in the deeper more basinward setting isolated pinnacle reefs may not have been unaffected by erosion. There is probably a wide variety in the degree of preservation of the Late Silurian reefal buildups. Figure 3 illustrates some of the many types of configuration of preservation that can be observed and postulated for Silurian reefs.

In addition to pre-New Harmony (Lower Devonian) erosion, a pre-Muscatatuck (Middle Devonian) erosional event also modified topographically high Silurian sediments and New Harmony units (fig. 3). This event may have removed much of the Backbone carbonate section that was located over upward-projecting Silurian reefs, as evidenced in the Iva East Reef of northeastern Pike County, where Middle Devonian rocks lie directly over Silurian reef rocks. This reef is west of the regional pinchout in an area where Backbone sediments were deposited.

Structural Configuration

Structural doming on many of the Paleozoic horizons that overlie Silurian reefs may be the result of numerous factors that include: (A) differential compaction due to contrasting initial compositions and diagenetic histories of reef and nonreef sediments (9), (B) buoyancy effect of the porous reef framework relative to the more dense surrounding sediments, (C) drape of subsequent sediments over a topographically high and rigid reefal substrate (14), and (D) possibly tectonic movements (21) that were localized at reef sites. Whatever the causes for the structural relief, it is clearly documented throughout the Illinois Basin, in many places propagating upward through large regional unconformities (e.g. Mississippian-Pennsylvanian systemic boundary) over more basinward digitate or pinnacle reefs. Higher relief and more pronounced structures may be produced over basinward digitate or pinnacle reefs, and at the same time the significance of the pre-Muscatatuck unconformity, which becomes increasingly influential in an easterly direction toward the basin margin, may be important in dampening the structural effect on the overlying sediments.

Presently the Terre Haute Bank as defined on the basis of subsurface samples, geophysical logs, and structural analysis stretches from Vigo County on the northern flank of the Vincennes Basin to southern Dubois County on the eastern margin of the basin (Figure 1). The bank does not retain its shallow-water, platform characteristics as it is projected farther to the south. A complex interfingering of basinal facies (Bailey Limestone and Moccasin Springs Formation) and interreef platform facies (Liston Creek and Mississinawa Shale Members of the Wabash Formation) is equivalent to the coalesced reef bodies that make up the well-defined bank father to the north (Figure 4). Regional investigations south of the Ohio River show very limited platform lithologies and a predominance of basinal rocks within the Silurian section (11,19,20).

Diagenetic Model

It is within the interface between the known Terre Haute Bank and the deeper water portions of the Vincennes Basin that the occurrence of isolated distal pinnacle reefs may have been influential in creating conditions favorable for the development of reservoir-quality rocks in the overlying Backbone Limestone. Where the Terre Haute Bank extends beyond the eastern limit of the Lower Devonian subcrop, porosity is commonly developed in the Middle Devonian limestones and dolomites, which directly

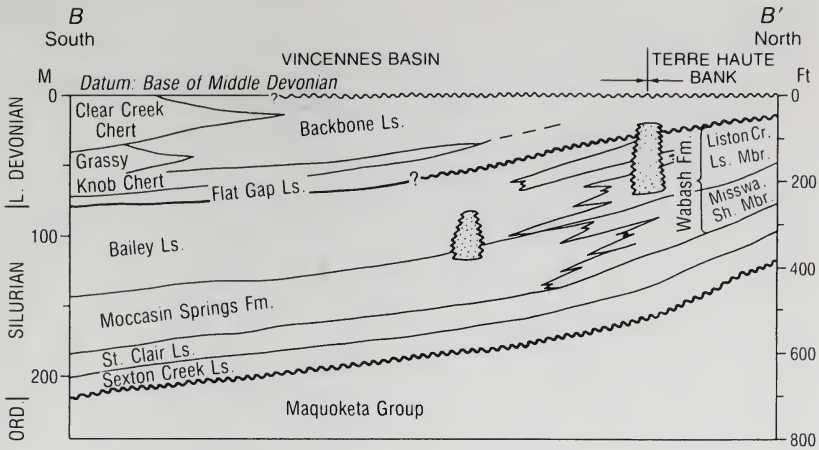

FIGURE 4. North-South stratigraphic cross section along the southeastern margin of the Vincennes Basin. Datum is the base of the Middle Devonian Muscatatuck Group. See figure 1 for the location of the cross section B-B′.

overlie the Silurian reefs. An examination of the structural drape-induced fields of the Terre Haute Bank demonstrates that the Middle Devonian carbonate section is almost exclusively the reservoir facies north and east of the regional subcrop limit of the Lower Devonian rocks (Vigo, Clay, Greene, and southern Sullivan Counties). South and west of this subcrop oil and gas fields produce from younger Mississippian reservoirs (Daviess, Dubois, and Pike Counties) (Figure 1). Undiscovered reserves basinward of the subcrop limit await testing in the porous Backbone carbonate rocks, which would directly overlie the Silurian reefs.

A proposed diagenetic model for the formation of reservoir-quality porosity over reefs in the Backbone Limestone consists of four stages.

(A) Localized topographic relief formed on reef masses in Late Silurian to Early Devonian time. The extremely porous and rigid framework cores were cemented and preserved as the siliceous and argillaceous reef flank and basinal sediments dewatered and compacted. Water expelled by the surrounding flank and basinal sediments may have carried sufficient magnesium concentrations to dolomitize the reef cores (13,15) (Figure 5). An influx of meteoric water for Dorag or schizohaline dolomitization appears unlikely for these more distal reefs as no known evidence for subaerial exposure currently exists this far into the basin. Similarly, dolomitization schemes that require subaerial concentration of brines by evaporation (sabbka) or evaporative pumping appear inappropriate.

(B) Following the initiation of Lower Devonian deposition, coarse-grained carbonate sediments of the Backbone Limestone were deposited along the margin of the Vincennes Basin. Deposition was influenced by the topography of the basin margin. Areas in which higher energy regimes operated, including reef induced topographically higher localities, favored clean carbonate production, while fine-grained carbonate muds and siliceous sediments were deposited in the lower energy, deeper waters. Sedimentation of Backbone carbonates aided the continuation of burial diagenetic events in the underlying Silurian sediments. Continued brine expulsion by the flank sediments and brittle deformation (fracturing) within the reef cores occurred, which facilitated further dolomitization and additional development of structural relief (Figure 6).

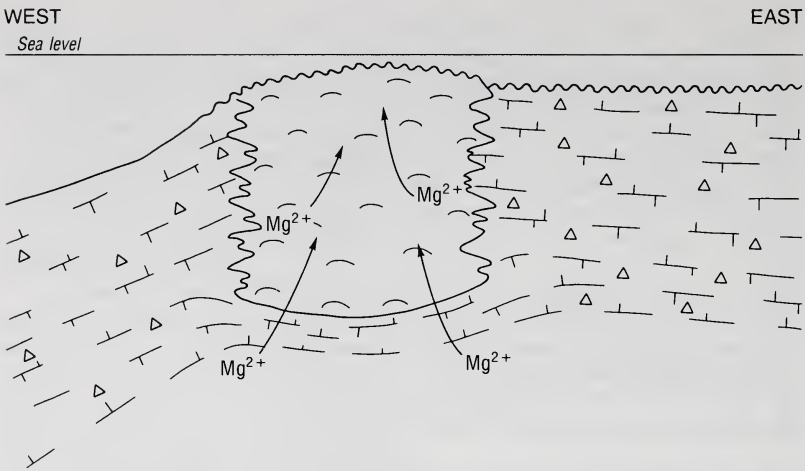

FIGURE 5. Diagramatic cross section showing Silurian reef deposition and initial diagenesis of reef core sediments.

(C) As Lower Devonian sedimentation came to a close, the pre-Muscatatuck erosion moved westward toward the basin center, and Early Devonian sediments were exposed and eroded. Backbone sediments over reefs were possibly subaerially exposed as these topographically higher areas became emergent. Bioclastic, coarse-grained sediments with high primary porosity and permeability acted as aquifers, a condition that allowed the influx of meteoric water (Figure 7). The mixing of ocean-derived brines and fresh ground water is proposed for dolomitization in a manner similar to the Dorag model for dolomitization in a manner similar to the Dorag model for dolomitization proposed for Middle Ordovician carbonates exposed in Wisconsin (2). Dolomitization of Backbone sediments along the shallower eastern margin of the basin may be restricted to positive, emergent areas, some of which coincide with reef-induced structures.

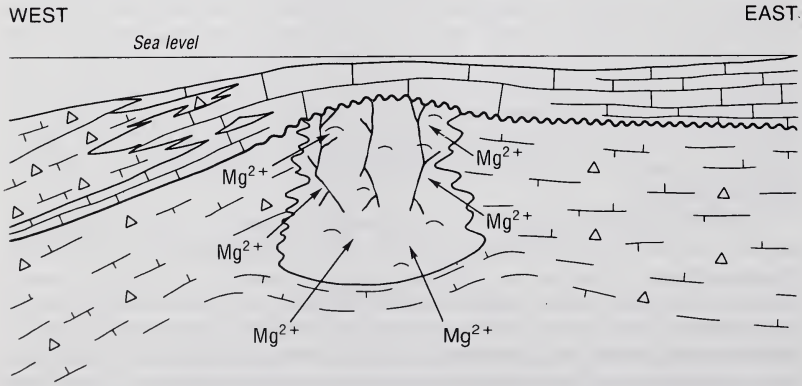

FIGURE 6. Diagramatic cross section showing Lower Devonian deposition and continued diagenesis of Silurian reef cores.

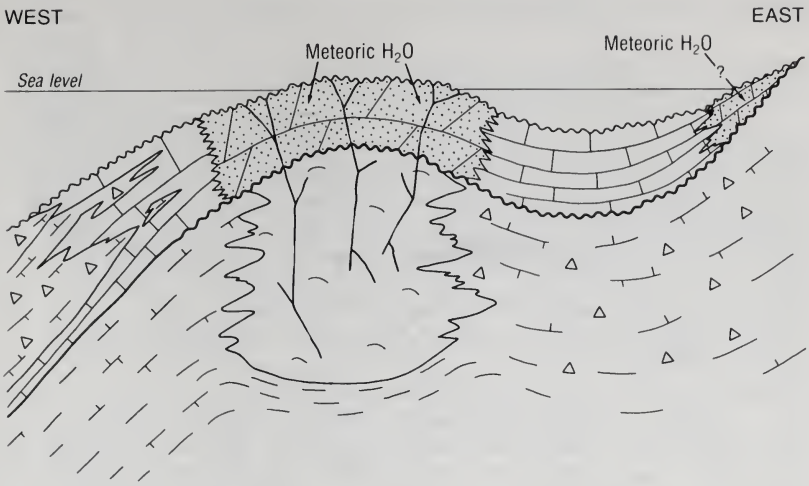

FIGURE 7. Diagramatic cross section showing Pre-Middle Devonian unconformity and diagenesis of Lower Devonian sediments.

(D) After the erosion and selective dolomitization of the Backbone limestones, continued sedimentation and subsidence of post-New Harmony rocks caused accentuated draping and fracturing of sediments over rigid reef cores and steeper dips along the basin margin. As the reef flank and basinal source rocks (Bailey Limestone, Moccasion Springs Formation and, Clear Creek and Grassy Knob Cherts) became more deeply buried, favorable conditions for hydrocarbon maturation developed. A suitable combination of adequate elevated temperature and time allowed for the generation of liquid hydrocarbons. As compaction continued, primary migration of oil from source rocks into fractures and porous sediments of the Lower Devonian aquifer occurred. Flow probably followed a general hydrologic gradient out of the deep basin and entered into radial flow patterns when nearing reefs. Secondary migration and final filling of reservoirs also probably occurred under radial flow conditions (15). Dense carbonates sediments of the lower Middle Devonian section formed the seal over the reservoir.

In addition to reef-induced structures, two types of potential stratigraphic traps may exist: (a) within facies boundaries between the dense, impermeable part of the basinal New Harmony rocks and the more porous, shallower water facies and (b) along the eastern limit of the New Harmony Group (Figure 8), where a regional truncation of predominantly coarse-grained, possibly dolomitized Backbone sediments becomes a porosity pinchout because of the angular unconformable erosional relationship with the overlying sediments (Figure 8).

Summary

Although the petroleum-producing potential of the Backbone Limestone has yet to be fully evaluated in the eastern Illinois Basin, recent data indicate that the unit could be commercially productive.

There are numerous examples of Devonian carbonate rocks being highly productive reservoirs in similar geologic settings. An analogous situation exists on the Eastern Shelf of the Midland Basin in west Texas where a regional pinchout of Silurian-Devonian dolomitized carbonates rocks has recently developed into a significant productive play

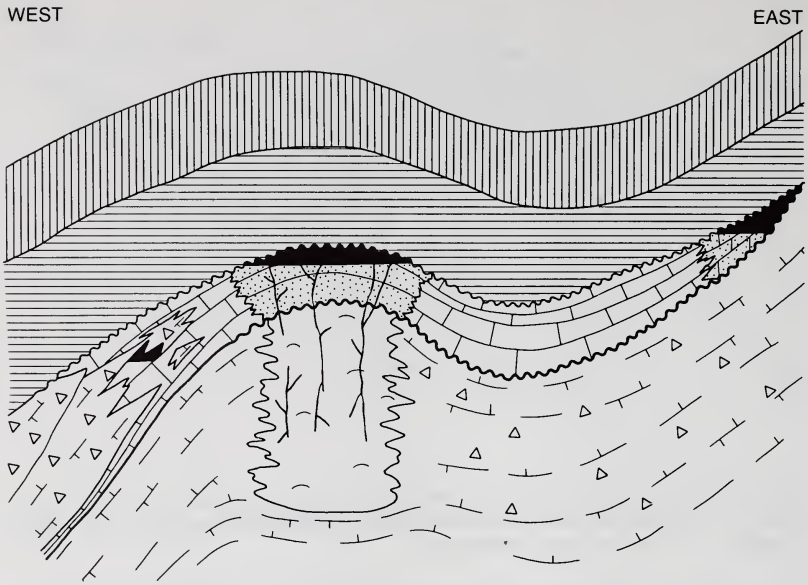

FIGURE 8. Diagramatic cross section showing hydrocarbon filled Lower Devonian reef-induced reservoir. Two types of stratagraphic accumulations as described in the text, (a) and (b) respectively, are also shown.

(12,18). The Bois d'Arc Limestone (Devonian) is a prolific reservoir on the eastern flank of the Anadarko Basin of central Oklahoma (17) where the section is erosionally juxtaposed against Pennsylvanian sediments over structural highs. In south-central Kentucky, regional truncation of the Lower Devonian section has created numerous strateigraphic traps (16).

A more thorough understanding of the primary depositional environments and the subsequent diagenetic changes within the Lower Devonian section will facilitate better and more successful exploration programs for these carbonate reservoirs.

Literature Cited

1. Ault, C. H. and others. 1976. Map of Indiana showing thickness of Silurian rocks and location of reefs and reef-induced structures. Indiana Geological Survey Miscellaneous Map 22.
2. Badiozamani, K. 1973. The Dorag dolomitization model—application to the Middle Ordovician of Wisconsin. Journal Sedimentary Petrology 43:965-985.
3. Becker, L. E. 1974. Silurian and Devonian rocks in Indiana southwest of the Cincinnati Arch. Indiana Geological Survey Bulletin 50. 83 pp.
4. Becker, L. E. and Droste, J. B. 1976. General sedimentological history of the Late Silurian and Early Devonian events in southwestern Indiana (abs). American Association Petroleum Geologists Bulletin 60:1618.
5. Becker, L. E. and Droste, J. B. 1978. Late Silurian and Early Devonian sedimentological history of southwestern Indiana. Indiana Geological Survey Occasional Paper 24. 14 pp.
6. Becker, L. E. and Keller, S. J. 1976. Silurian reefs in southwestern Indiana and

their relation to petroleum accumulation. Indiana Geological Survey Occasional Paper 19. 11 pp.

7. Collinson, C. H. and others. 1967. Devonian of the north-central region, United States. In Alberta Society Petroleum Geologists, International Symposium on the Devonian System 1:933-971.
8. Droste, J. B. and Shaver, R. H. 1975. Jeffersonville Limestone (Middle Devonian) of Indiana: stratigraphy, sedimentation, and relation to Silurian reef-bearing rocks. American Association Petroleum Geologists Bulletin 59:393-413.
9. Droste, J. B. and Shaver, R. H. 1980. Recognition of buried Silurian reefs in southwestern Indiana: application to the Terre Haute Bank. Journal Geology 88:567-587.
10. Droste, J. B. and Shaver, R. H. in prep. Upper Silurian and Lower Devonian stratigraphy of the central Illinois Basin. Indiana Geological Survey Special Report ____. ____ pp.
11. Freeman, L. B. 1951. Regional aspects of Silurian and Devonian stratigraphy in Kentucky. Kentucky Geological Survey Series 9, Bulletin 6. 565 pp.
12. Hanson, B. M. 1985. Truncated Devonian and Fusselman fields and their relationship to Permian Basin reserves (abs). American Association Petroleum Geologists Bulletin 69:144.
13. Illing, L. V. 1959. Deposition and diagenesis of some upper Paleozoic carbonate sediments in western Canada. in 5th World Petroleum Congress, Proceedings, Sec. 1, New York, N.Y.:23-52.
14. Indiana University Paleontology Seminar. 1976. Constitution, growth, and significance of the Silurian reef complex at Rockford, Ohio. American Association Petroleum Geologists Bulletin 60:428-451.
15. Jodry, R. L. 1969. Growth and dolomitization of Silurian reefs, St. Clair County, Michigan. American Association Petroleum Geologists Bulletin 53:957-981.
16. McGrain, Preston and Sutton, G. S. 1973. Economic geology of Warren County, Kentucky. Kentucky Geological Survey Series 10 County Report 6. 28 pp.
17. McGee, D. A. and Jenkins, H. D. 1946. West Edmond oil field, central Oklahoma. American Association Petroleum Geologists Bulletin 30:1797-1829.
18. Munn, J. K. 1971. Breedlove Field, Martin County, Texas. American Association Petroleum Geologists Bulletin 55:403-412.
19. Schwalb, H. R. 1975. Oil and gas in Butler County, Kentucky. Kentucky Geological Survey Series 10 Report of Investigations 16. 65 pp.
20. Seale, G. L. 1985. Relationship of possible Silurian reef trend to Middle Paleozoic stratigraphy and structure of the southern Illinois Basin of western Kentucky. Kentucky Geological Survey Series 11 Thesis Series 3. 63 pp.
21. Stevenson, D. L. 1973. The effect of buried Niagaran reefs on overlying strata in southwestern Illinois. Illinois Geological Survey Circular 482. 22 pp.