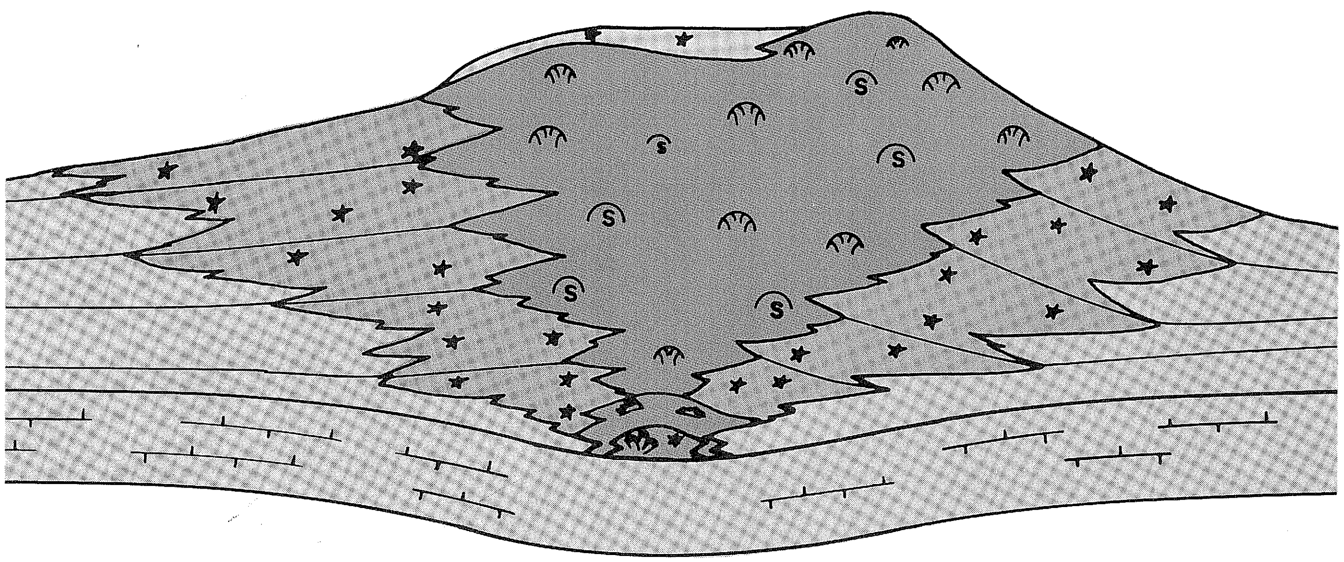
SILURIAN PINNACLE REEF DISTRIBUTION IN ILLINOIS: MODEL FOR HYDROCARBON EXPLORATION

Stephen T. Whitaker



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ILLINOIS STATE GEOLOGICAL SURVEY
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PLATES

ABSTRACT

New interpretations of subsurface data support the hypothesis that pinnacle reefs developed randomly throughout a ramp environment that encompassed most of the Illinois Basin during the Silurian. Given this hypothesis, distribution of reefs would be widespread; thus exploration for hydrocarbons associated with Silurian reefs should not be limited to a commonly perceived "hingeline" trend.

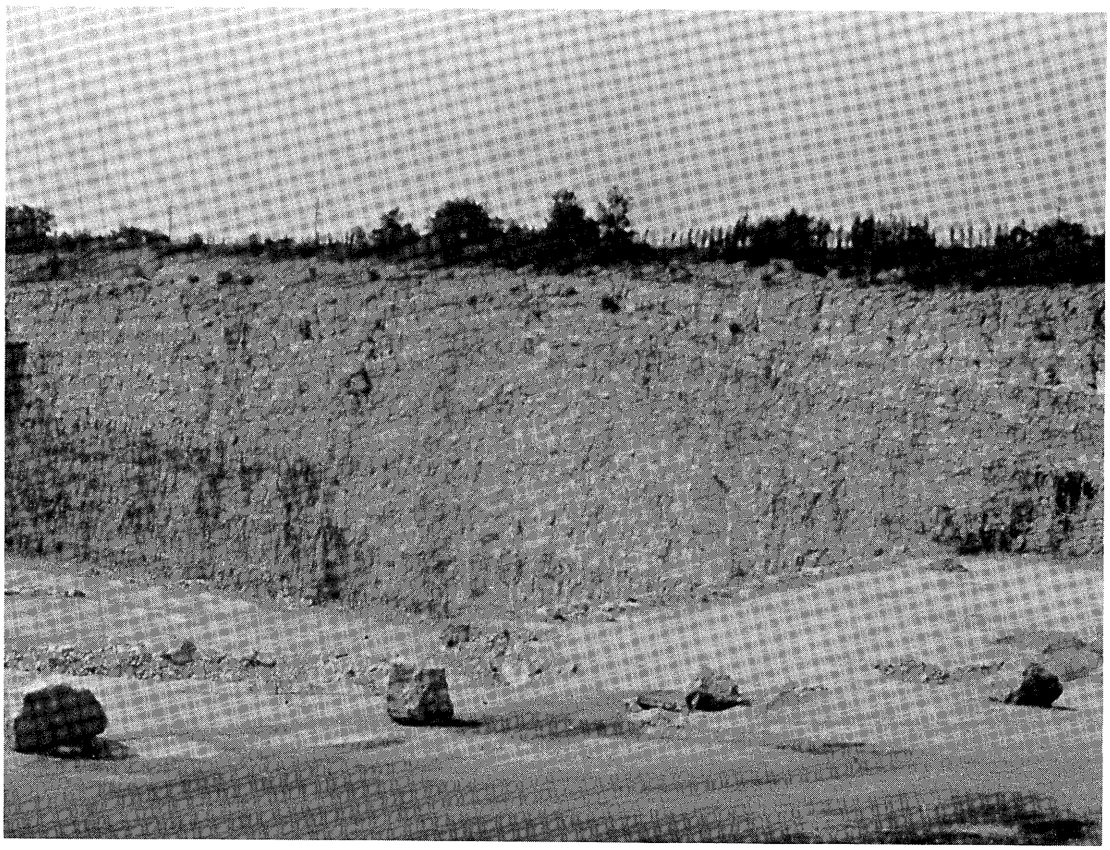
Well log correlations, core analyses, and sample descriptions indicate that Silurian pinnacle reefs first developed in Illinois during earliest Niagaran time. Reef development also began in Indiana at about this time when uplift of the Kankakee and Cincinnati Arches formed the Wabash Platform and altered the depositional setting of the proto-Illinois Basin to a ramp-platform during the early Niagaran. Pinnacle reefs continued to develop throughout the remainder of the Silurian along the middle ramp in Illinois and along the flanks of the Wabash Platform where they formed the Terre Haute and Fort Wayne Banks. Shorter pinnacle reefs and complex coalesced reefs formed along the upper ramp in Illinois and on the shallower portions of the platform in Indiana.

Regressing seas terminated reef development in either late Silurian or early Devonian time. Continued regression during the early Devonian caused erosion of Lower Devonian and Silurian strata on the higher portions of the ramp and platform, particularly on the emerging Sangamon Arch in Illinois and along the Wabash Platform in Indiana. This erosion planed off the tops of pinnacle reefs, and locally, as in west-central Illinois, completely removed topographic expression of the reefs before the middle Devonian transgression. Dolomitization of Silurian strata began where these sediments were subaerially exposed during the Devonian, and hindered subsequent differential compaction of strata around pinnacle reefs.

Erosion patterns have implications for exploration strategies:

- In parts of Illinois where Silurian strata have not been significantly eroded, structures caused by the draping of younger sediments over pinnacle reefs can be detected by using a variety of geological and geophysical methods. The restricted areal extent of pinnacle reefs dictates that investigations incorporate a closely spaced data grid to locate them. Hydrocarbon accumulations in strata draped over Silurian pinnacle reefs probably are confined to these areas.

- Where Silurian strata have been extensively eroded, structural anomalies in beds above pinnacle reefs will be greatly subdued or absent. Exploration methods appropriate for these areas would identify stratigraphic changes indicative of reefs within the Silurian. In particular, seismic data could reveal stratigraphic anomalies, such as porous reef rock. The use of stratigraphic mapping of Silurian strata should result in successful expansion of the pinnacle reef play in the basin.



Reef exposure at the Material Service Corporation's quarry, sec. 10, T38N-R12E, Cook County, Illinois. Note reef flank beds dipping away from the reef core. Because of pre-middle Devonian erosion of Silurian reefs in the northern half of Illinois, together with early dolomitization of Silurian strata, topographic expression of the reefs is less in this area than in southern Illinois.

INTRODUCTION

Buried Silurian reefs have been an important objective for hydrocarbon exploration in Illinois since 1946 when they were first described in the subsurface by Lowenstam and DuBois. Nearly 92 million barrels of oil has been produced in Illinois from what are commonly called "pinnacle" reefs and from younger strata draped over them (fig. 1, table 1).

This report reviews what is known or can be inferred about the genesis, growth, and geologic history of Silurian pinnacle reefs in the Illinois Basin. New interpretations of existing data suggest that oil- and gas-bearing reefs are more widespread in Illinois than previously thought, and that improved application of existing exploration methods can lead to discovery of additional reefs.

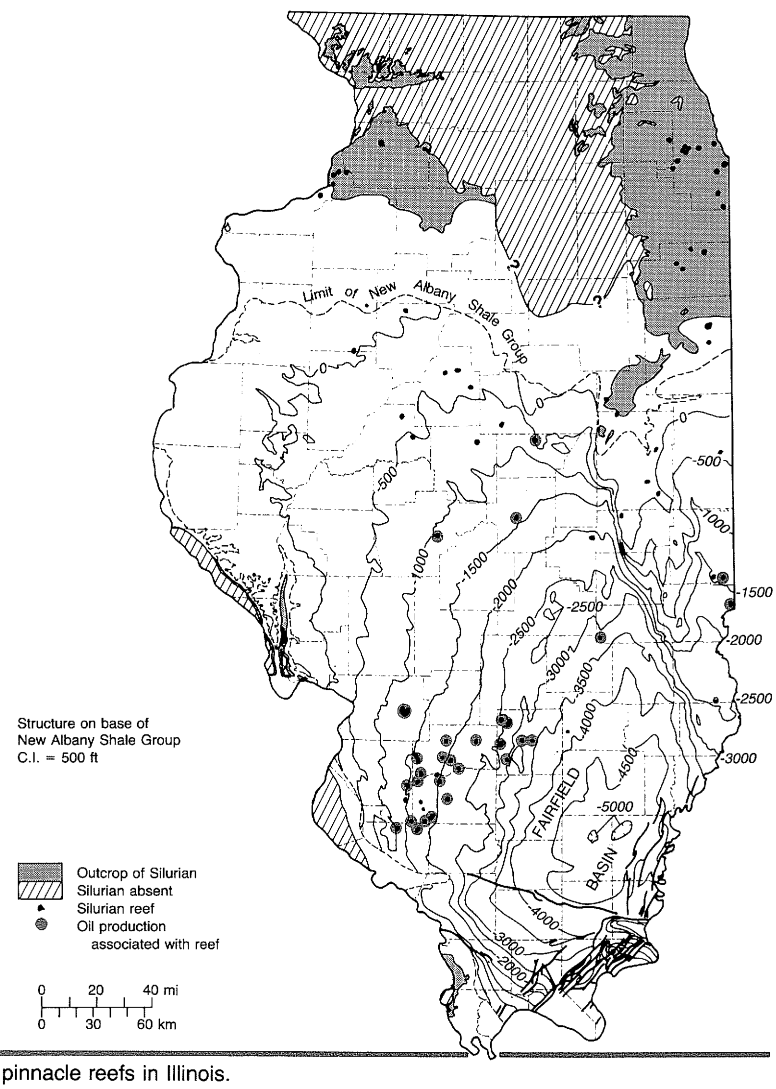


Figure 1
Location of Silurian pinnacle reefs in Illinois.

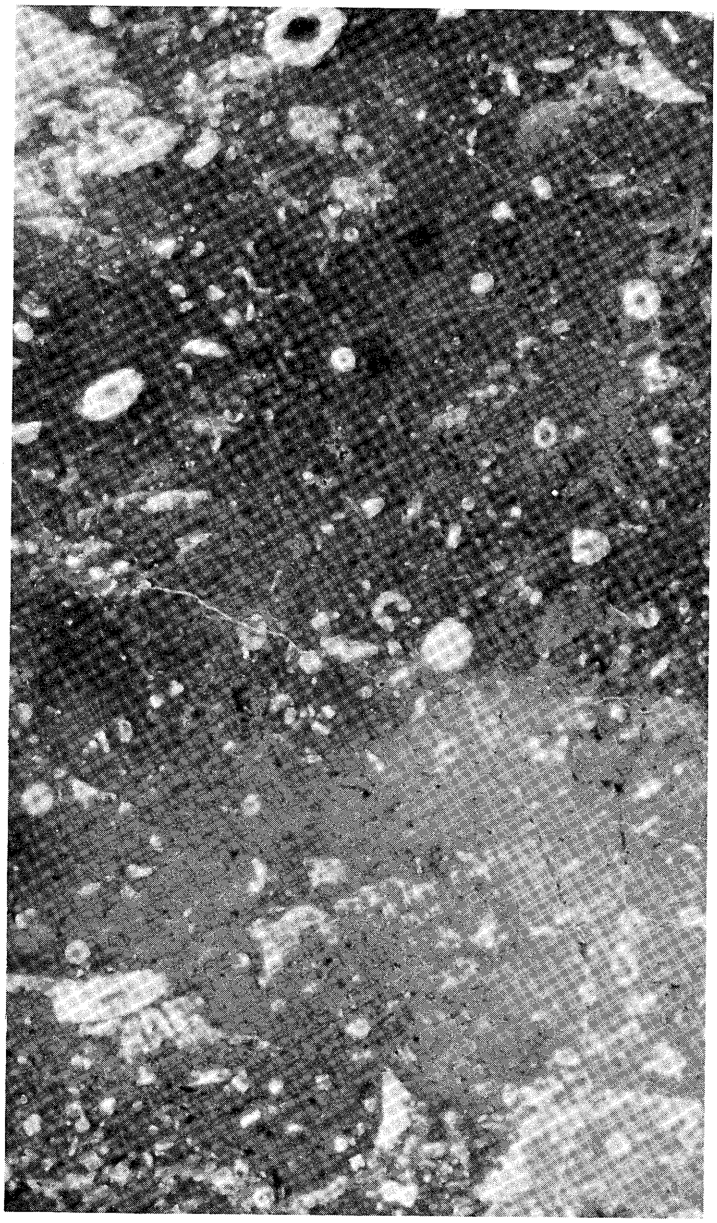
Table 1. Production associated with reefs in Illinois

Field	Year discovered	Approx. prod. area (Acres)	Number wells prod.	Producing strata	Approx. depth of prod. (ft)	1985 prod. (M bbls)	Cum. prod. through 1985 (M bbls)
Baldwin	1954	50	3	Sil. reef	1,535	.175	15
Bartelso	1936	420	76	Cypress	985	22.2	3,300*
	1939	430	41	Sil. reef	2,420	1.3	1,060*
						23.5	4,360
Bartelso East	1950	210	21	Dev. & Sil. reef	2,550	6.5	992
Boulder	1942	500	33	Benoist	1,190	0+	3,620
	1941	470	22	Geneva	2,630		4,470*
	1963	40	1	Sil. reef	2,700		30
						0+	8,120
		+ Field abondoned while making 1400 BOPD due to creation of Carlyle Reservoir					
Coulterville North	1958	50	6	Sil. reef	2,290	0	41.4
Elbridge	1950	10	2	Penn.	760	.4	40*
	1949	430	37	Fredonia	950	4.2	1,509*
	1949	20	2	Devonian+	1,950	0	0
						4.6	1,549
		+ Devonian is used for gas storage					
Frogtown North	1951	60	5	St. Louis	1,200	.5	200*
	1951		5	Devonian	2,220	.5	200*
	1951		27	Sil. reef	2,250	5.4	1,780*
						6.4	2,180
Germantown East	1956	520	35	Sil. reef	2,350	12.6	2,068
Lillyville North	1974	80	3	Spar Mtn.	2,405	?	?
	1974	80	5	McClosky	2,440	?	?
	1974	60	4	Salem	2,840	?	?
	1974	30	3	Geneva	3,825	?	?
						6.2	603
Marine	1943	2470	148	Sil. reef	1,700	62.612	12,444
McKinley	1940	180	17	Benoist	1,050	2	528*
	1948	200	13	Sil. reef	2,240	.3	250*
						2.3	778
Nashville	1973	40	5	Devonian	2,625	23	242*
	1973	480	34	Sil. reef	2,650	100.5	104.5*
						123.5	1,287
New Baden East	1958	290	23	Sil. reef	1,935	3.2	302
New Memphis	1952	940	54	Sil. reef	1,980	30	2,875
New Memphis South ABD	1952 1952, rev 1956, abd 1961	20	2	Sil. reef	2,000	0	0.7
Okawville	1951	50	4	Sil. reef	2,325	0	63.3
Okawville North Consolidated	1955	220	17	Sil. reef	2,200	2.5	200

Field	Year discovered	Approx. prod. area (Acres)	Number wells prod.	Producing strata	Approx. depth of prod. (ft)	1985 prod. (M bbls)	Cum. prod. through 1985 (M bbls)
Patoka East	1941	580	56	Cypress	1,340	?	?
	1941	50	5	Benoist	1,465	?	?
	1953	40	3	McClosky	1,635	?	?
	1952	20	2	Geneva	2,950	?	?
						35.6	6,040
Raccoon Lake	1949	250	18	Cypress	1,625	?	?
	1957	20	2	Benoist	1,715	?	?
	1949	190	1	Ohara	1,885	?	?
	1949	110	11	Spar Mtn.	1,930	?	?
	1949	130	13	McClosky	1,950	?	?
	1951	270	15	Dev.-Sil. reef	330	?	?
						6.6	3,472
Sandoval	1908	20	1	Cypress	1,400	?	?
	1908	480	145	Benoist	1,540	?	?
	1938	260	36	Geneva	2,920	?	3,100
						18	6,439
Springfield East	1952	20	1	Sil. reef	1,600	1.9	278
Tilden	1952	610	35	Sil. reef	2,160	71	4,749
Tilden North	1981	150	9	Devonian	2,010	4.2	186*
	1968	550	34	Sil. reef	2,014	14.5	812*
						18.7	998
Tonti	1939	140	18	Benoist	1,930	?	?
	1939	180	26	Aux Vases	2,005	?	?
	1939	160	16	Spar Mtn	2,125	?	?
	1939	400	75	McClosky	2,130	?	?
	1940	140	7	Devonian	3,500	?	?
						77.1	14,595
Wapella East	1963	30	3	Devonian	1,108	5.3	89*
	1962	350	36	Sil. reef	1,112	46.5	3,300*
						51.8	3,389
Weaver	1953	30	1	Cole	1,565	1	60*
	1949	540	44	Devonian	2,030	11	2,420*
						12	2,480

* estimated production due to co-mingled zones.

Total Silurian	31,350
Total Devonian	12,070
Total Mississippian	48,590
Total Pennsylvanian	40
GRAND TOTAL	92,050



Crinoidal fragments within a pink limestone mud matrix. Specimen was obtained at a depth of 1,938 feet in St. Libory Reef, sec. 25, T1S-R6W, St. Clair County, Illinois. This type of crinoidal wackestone was commonly deposited in a sheltered environment leeward from a reef's crest. Crinoidal wackestones are also found at the bases and on the flanks of reefs.

SILURIAN PINNACLE REEFS IN ILLINOIS BASIN AREA

Shouldice (1955) defined a pinnacle reef as an isolated biohermal structure having a height of more than 250 feet and a maximum diameter of less than two miles. Pinnacle reefs in Illinois originated during deposition of the St. Clair Limestone (Niagaran) and continued to develop during the deposition of Moccasin Springs (Niagaran) and Bailey (Cayugan) Formations (fig. 2). Core analyses and log correlations indicate that reef growth was ultimately terminated by shallowing water during Cayugan or possibly early Devonian time. These reefs, constructed primarily of fossil algae, corals, and stromatoporoids, originally ranged from less than 300 to more than 1,000 feet thick.

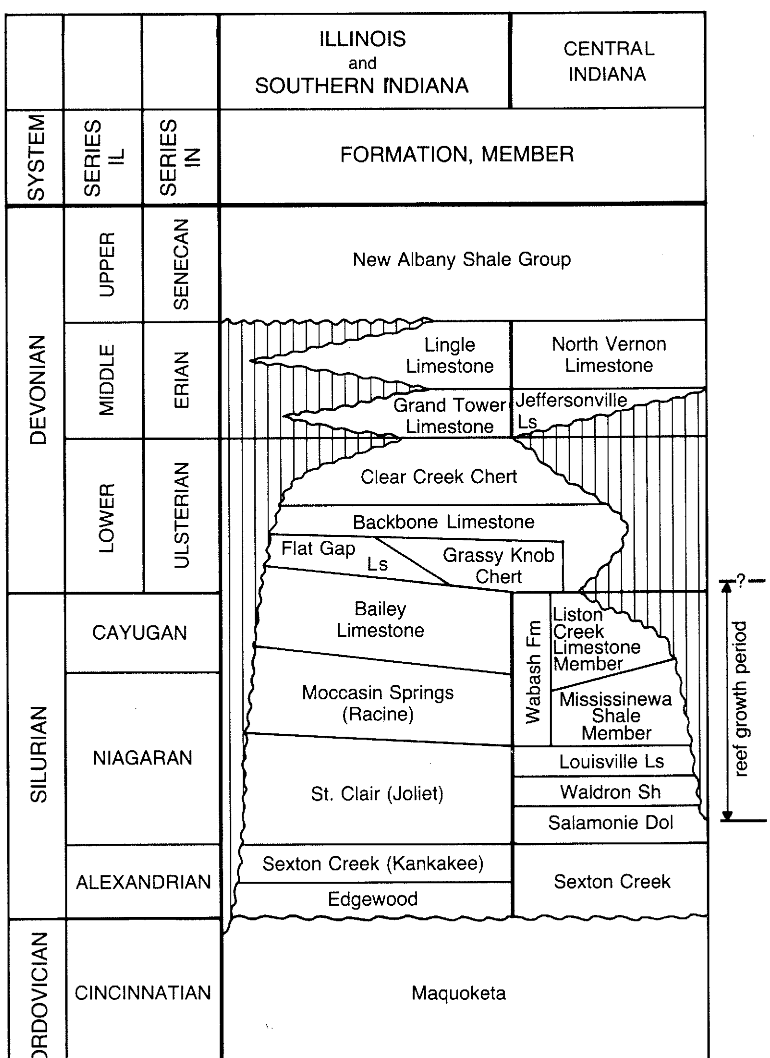


Figure 2
Correlation and nomenclature of the Devonian and Silurian section of the stratigraphic column in the Illinois and Indiana portions of the Illinois Basin. Modified from Droste and Shaver (1987).

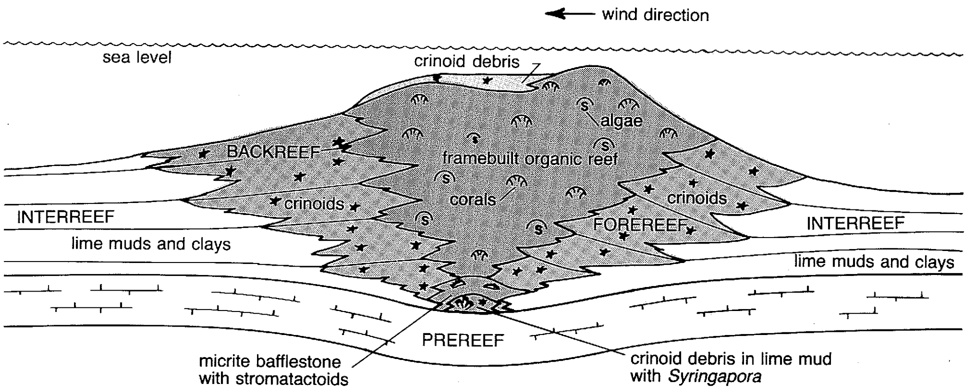


Figure 3
Idealized reef during Middle Silurian showing typical geometry of various facies composing buildup. The relief between reef top and interreef beds was probably less than 100 feet during deposition. Note steeper forereef facies and sag of prereef strata due to compaction under reef.

As a reef developed, the high-energy environment at its top winnowed out silt and clay, resulting in a generally pure, clean, porous carbonate core (fig. 3). Commonly the growing top of a reef extended above wave base where wave action broke off pieces of the reef and deposited them along its flanks. If there had been a prolonged stillstand in sea level, wave action would have caused constant erosion of the growing reef top and thereby encouraged lateral growth of the reef. The fact that Illinois pinnacle reefs exhibit little lateral growth, however, indicates relative sea level kept rising at a rate that encouraged mainly vertical growth.

Low-energy environments predominated between the reefs and characteristically contained carbonate mud and clay deposits; the abundance of fossils and reef-derived carbonate clasts decreased with increasing distance from the reefs. In Illinois, interreef sediments tend to have a relatively high content of silt-size siliciclastics in the southeast and grade to siliciclastic-free deposits in the northwest and north (Lowenstam, 1949). These clastics probably originated from two sources: one southeast of Indiana, perhaps along the Cincinnati Arch, and a second southwest of Illinois, perhaps the Ozark Dome (Droste and Shaver, 1980).

Wilson (1975) postulated that original topographic relief on mature reefs in Illinois was as much as 250 feet; however, recent research suggests that relief on the order of a few tens of feet is more realistic (Droste and Shaver, 1987). The original relief has been modified by subsequent sedimentation that compacted the soft interreef muds and clays of the Moccasin Springs and Bailey Formations. The rigid cores of the reefs retained their original shape, however, and resisted compaction (Lowenstam, 1948; Van Horn, 1956; Ingels, 1963; Ferris, 1972). Through time, differential compaction continued to increase the apparent relief on the reefs—now as much as 200 feet in places. The resultant structural draping of younger strata over buried reefs can be observed in sediments as young as the Pleistocene.

Distribution of Pinnacle Reefs

Silurian pinnacle reefs, as with modern reefs, developed best in relatively shallow water where adequate sunlight, normal salinity, abundant nutrient supply, warm temperatures, and a general lack of siliciclastic sediment influx all combined to create favorable conditions for reef-building organisms. The causes for pinnacle-reef development in a specific locality remain obscure, but probably involved subtle features on the shallow sea floor that stimulated reef-building organisms to develop

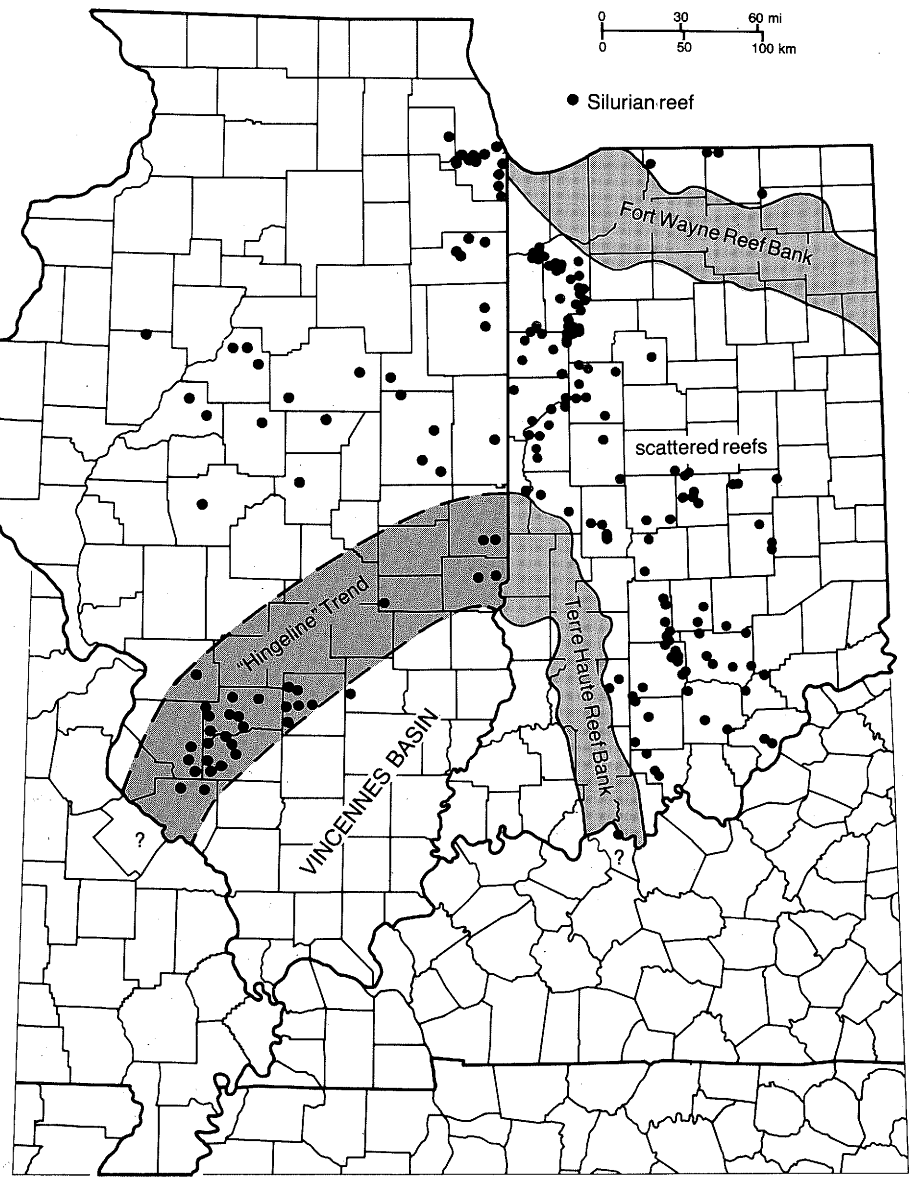


Figure 4
Theoretical connection of Silurian pinnacle reef trend in Illinois to Terre Haute Reef Bank. This arc defines a proposed "hingeline" around the subsiding basin center (Vincennes Basin). Modified from Droste and Shaver (1980).

and grow locally. Regional trends of Silurian reefs in the Illinois Basin area, however, can be determined by studying the paleoenvironments that affected the development of carbonate buildups.

Previous hypotheses The prevailing hypothesis on the evolution of the proto-Illinois Basin during the Silurian is that downwarping at the center of the basin caused a "hingeline" to form a shelf-slope break (fig. 4) in an arc around the subsiding depocenter (Lowenstam, 1953; Rogers, 1972; Droste, Shaver, and Lazor, 1975; Droste and Shaver, 1980; Droste and Shaver, 1987). This hingeline coincides with a reef trend extending northeast from Randolph County in southwestern Illinois to Cumberland and Clark Counties in east-central Illinois, where it joins the Terre Haute Reef Bank which curves back to the south in Indiana. Reefs grew vertically apace with seafloor subsidence along this hingeline, thus maintaining their growing

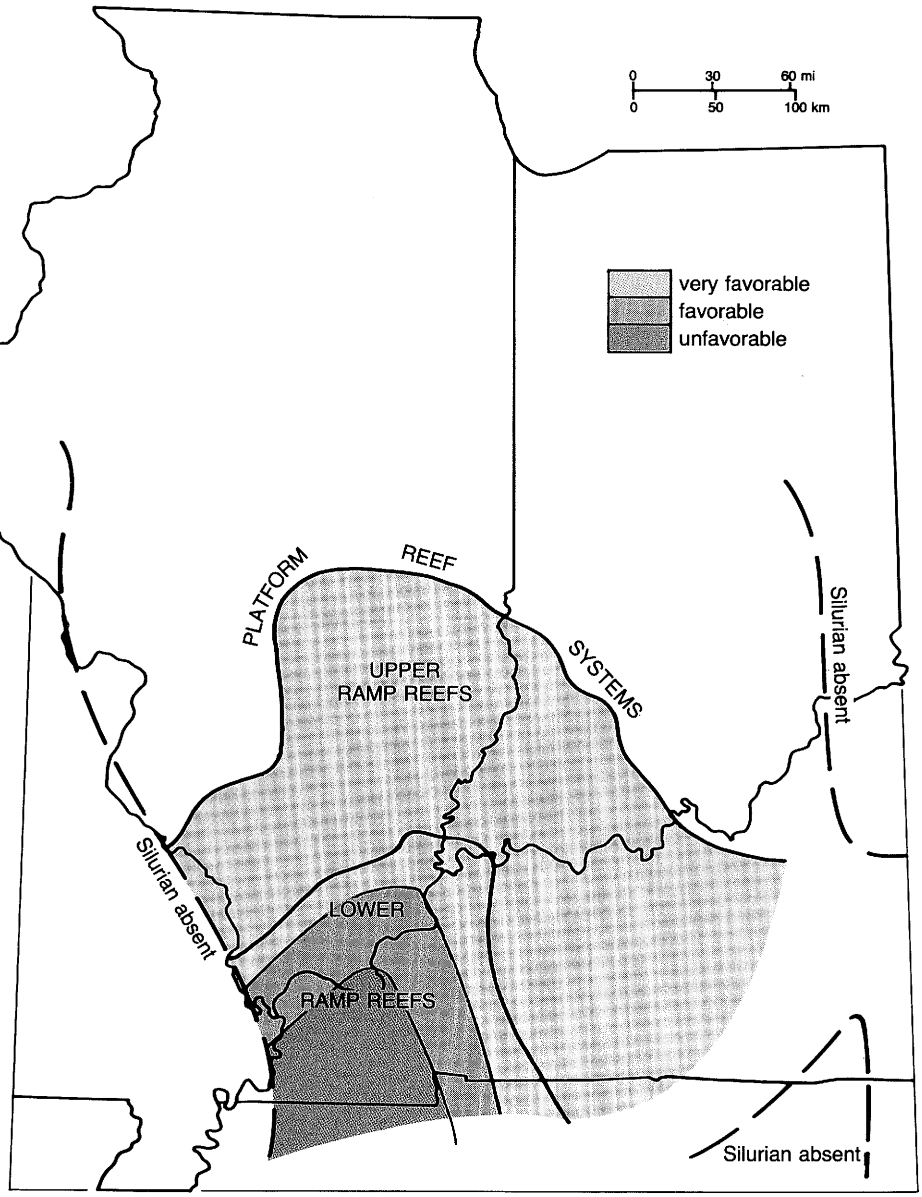


Figure 5.
Exploration potential for Silurian pinnacle reefs in the Illinois Basin based on a ramp model by Coburn (1986).

tops in the shallow-water environment necessary for their survival. Pinnacle-reef development in the Illinois Basin is thought to have been generally restricted to this trend.

A ramp model has recently been proposed (Coburn, 1986) to explain reef distribution in the basin. As defined by Read (1982), a ramp is a gentiy sloping platform that lacks a significant break in slope. The lack of a hingeline in this type of depositional system results in reefs occurring randomly rather than in distinct trends. Coburn concludes that pinnacle reefs developed throughout all of southern Illinois and southwestern Indiana (fig. 5) across his upper and lower ramp environments.

Ramp-platform hypothesis Interpretations presented in this paper modify Coburn's ramp hypothesis for Silurian deposition in the proto-Illinois Basin and suggest that a combination of a ramp and platform environment was responsible for the distribution of pinnacle reefs in the area. Evidence that supports a ramp-platform model begins with the depositional configuration of the Maquoketa Group, which formed the foundation on which Silurian strata were deposited. Lithologic studies of the Maquoketa (Kolata and Graese, 1983) have suggested that (1) deltaic environments of deposition dominated to the east in Pennsylvania and graded to marine environments in Ohio and to the west; and (2) isochronous portions of the marine Maquoketa were deposited in similar water depths throughout the region with the uppermost Maquoketa having been deposited in shallow water.

A regional isopach map of the Maquoketa Group (fig. 6) reveals a relatively uniform thickness of Maquoketa across most of Illinois with steadily thickening values to the east of the state. According to paleobathymetric interpretations by Kolata and Graese, this thickening of the Maquoketa in Indiana and Ohio can best be explained by subsidence of the substrate in those areas due to sediment loading or possibly tectonic influences (fig. 7). A hingeline caused by eastward subsidence

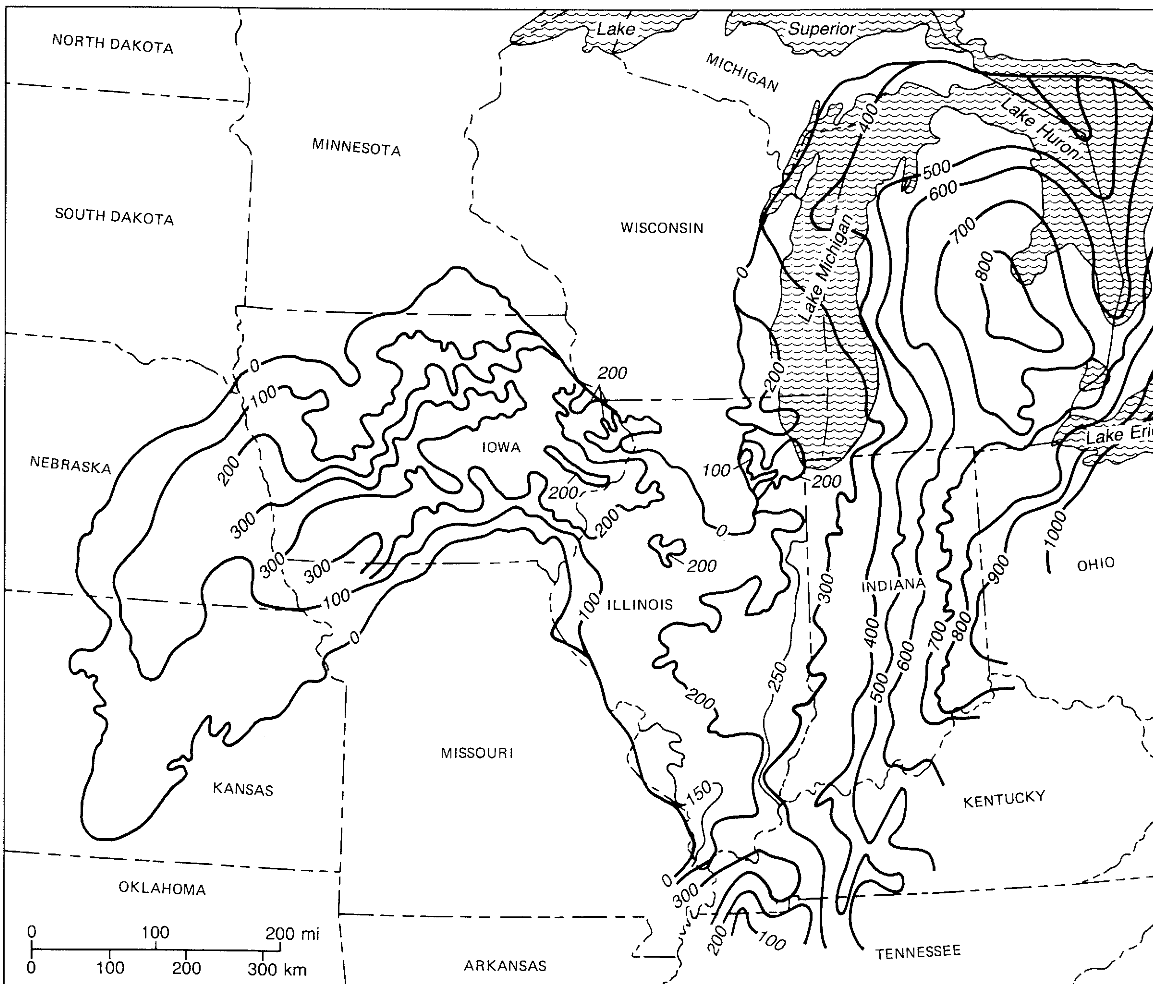


Figure 6
Regional thickness of the Maquoketa and equivalent strata in the Midcontinent. Modified from Kolata and Graese (1983).

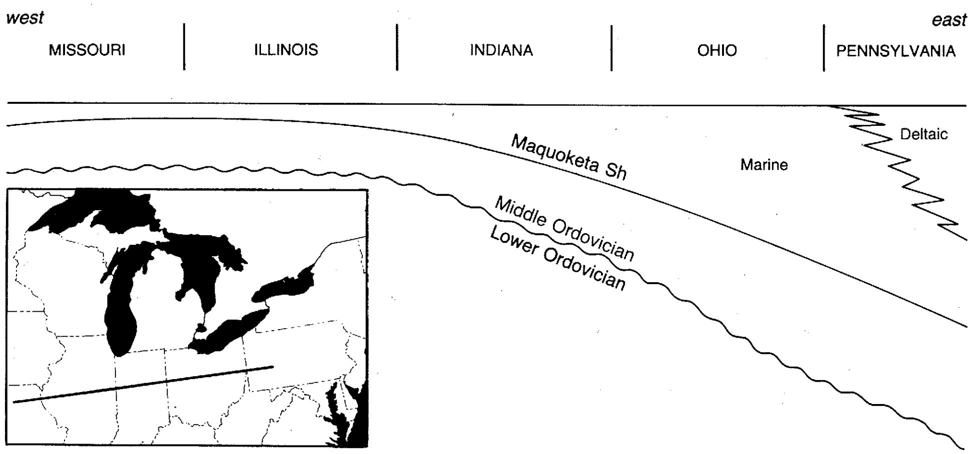


Figure 7
Schematic west-east cross section illustrating subsidence of Ordovician and older strata to the east during Maquoketa deposition. Modified from Dott and Batten (1971).

is indicated by the rapidly thickening isopach values in southeasternmost Illinois trending north-northeast through western Indiana (fig. 6). Consequently this interpretation suggests that Illinois was situated on a broad shelf along the western flank of a large basin, and that no local subsidence unique to a basin in Illinois occurred during late Ordovician time.

In addition to eastward subsidence, thickening of the Maquoketa over the buried rift zone in western Kentucky indicates that the rift zone was subsiding slightly during late Ordovician. The trends on the Maquoketa isopach map in Illinois and Indiana exhibit little deflection suggestive of a rift-related hingeline; however, the rift may have influenced the entire region by forming an elongated subsidence center that caused areas north of the rift to dip southward in a relatively uniform, gentle slope lacking a hingeline. In such a setting, the rift would have provided an excellent mechanism for the formation of a ramp environment in Illinois and Indiana.

The Maquoketa isopach map (fig. 6) shows that at the close of the Ordovician only three paleofeatures were significant enough to affect Silurian reef development trends in the Illinois Basin area:

- Rapidly thickening Maquoketa to the east of Illinois in Indiana and Ohio indicates an eastward paleobathymetric drop, providing that minor eastward subsidence continued for some time following Maquoketa deposition.
- Thickening of the Maquoketa over the buried rift also suggests a relatively abrupt, local paleobathymetric drop.
- A subtle but significant structural high in southwestern Illinois can be inferred from anomalously thin Maquoketa there.

With the exception of these areas, the proto-Illinois Basin was apparently a featureless ramp dipping gently eastward, probably with a southward-dipping component.

Transgression by the Silurian sea deposited Alexandrian strata over Maquoketa Shale throughout the area now encompassed by the Illinois Basin. Although Alexandrian rocks are as much as 150 feet thick where they fill paleovalleys in the Maquoketa in northern Illinois, they are distributed relatively uniformly across most of the region. Not until deposition of the lower part of the St. Clair Limestone (early Niagaran) did the first reef-like assemblages and carbonate banks begin to form in the proto-Illinois Basin area (Lowenstam, 1949; Pryor and Ross, 1962; Droste and Shaver, 1987; Meents, personal communication, 1986). Where these banks developed, the Silurian strata are thicker because they are typically more fossiliferous and hence more resistant to subsequent compaction than neighboring areas lacking carbonate buildups. Silurian strata are thinner in areas that were either too shallow or too deep for these banks to develop.

An isopach map of Alexandrian and Niagaran Silurian strata (pl. 1) supports the paleobathymetric interpretation inferred from the Maquoketa isopach map (fig. 6). Silurian sediments thin over an area interpreted as structurally high in southwestern Illinois, and also over an area interpreted as structurally low in southeastern Illinois. A correlation between the Maquoketa and Silurian isopach maps concerning the ramp environment of the proto-Illinois Basin would suggest that the rest of Illinois should have provided relatively uniform potential for random reef development.

Some researchers have concluded that thick Silurian strata trending northeast-southwest and centered in Clinton County, Illinois (pl. 1), correspond to a "hingeline" to which pinnacle-reef development was predominantly restricted. This thickness trend is misleading, however. Silurian strata were eroded extensively north and northwest of the limit of the Bailey Formation (Cayugan) as shown in Plate 1 and in cross sections A-A′, B-B′, and C-C′ (figs. 8a, 9a, and 10a). Had this erosion not occurred, the Silurian isopach map would show a greater distribution of thick carbonate banks in central Illinois with reefs scattered among them (figs. 8b, 9b, and 10b). Consequently, the thick trend is most probably a remnant of a formerly extensive area of thick Silurian strata, which is now preserved only on the downdip side of the erosional limit of Cayugan strata.

Eroded remnants of pinnacle reefs have been identified north of the hingeline trend in outcrop and in subsurface cores (fig. 1). At least three reef remnants produce oil: one at Springfield East Field (sec. 21, T15N-R4W, Sangamon County), the second at Wapella East Field (sec. 20, 21, 28, 29, T21N-R3E, De Witt County), and the third at Decatur Field (sec. 32, T17N-R2E, Macon County). Reefs north of the hingeline are additional evidence that pinnacle-reef distribution is more widespread in Illinois than has been generally thought.

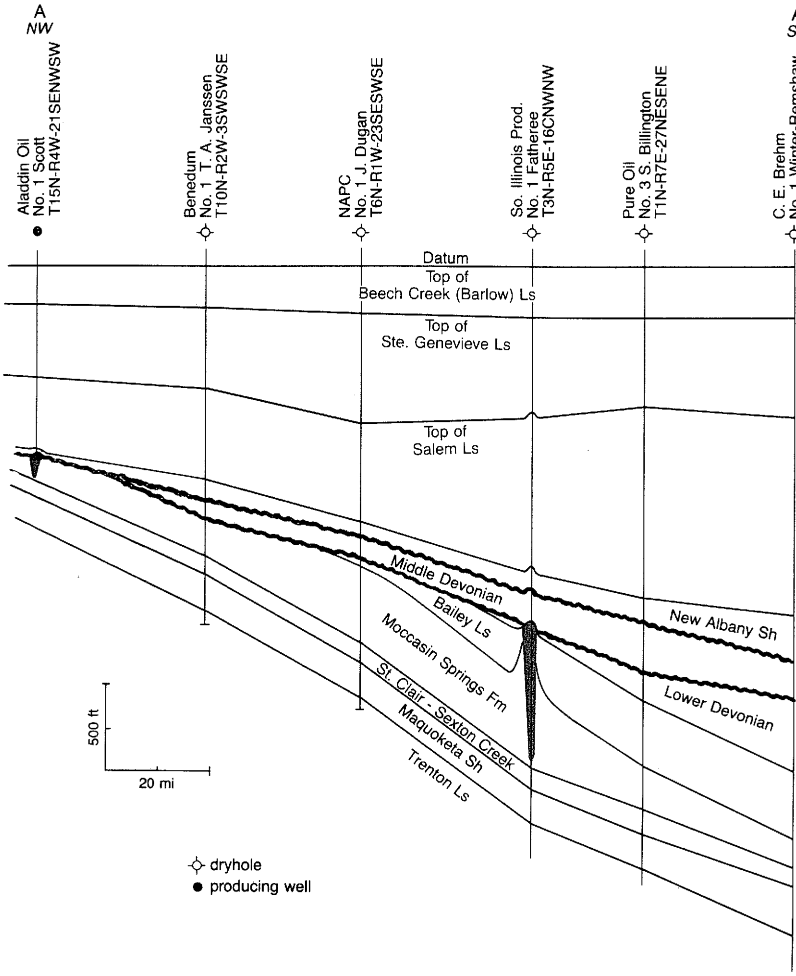


Figure 8a

Cross section A-A' (reference map plate 1) restored to Beech Creek (Barlow) datum illustrates the effects of pre-Middle Devonian erosion on Silurian strata. Uplift of the Sangamon Arch during early Devonian time accelerated erosion, which removed structural expressions of reefs.

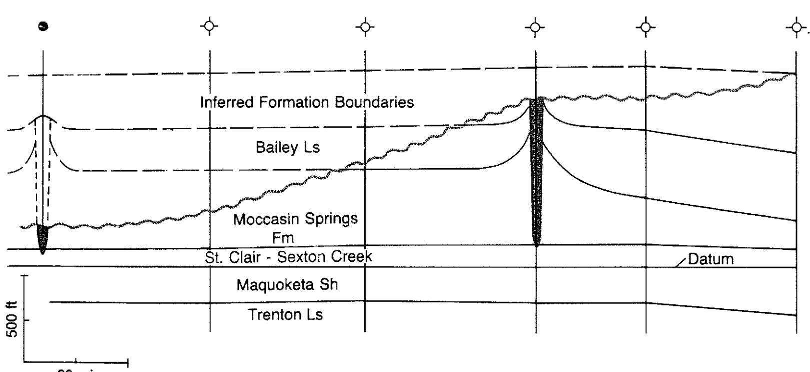


Figure 8b

Cross section A-A' restored to Maquoketa datum assumes that Maquoketa strata were relatively flat-lying across Illinois (see Maquoketa isopach map). The geometry of the strata indicates that there was no subsiding basin center during upper Ordovician to lower Devonian time. A ramp model explains the occurrence of remnant reefs that are significantly removed from the proposed reef trend centered in Clinton County (for example, the #1 Scott well in this section).

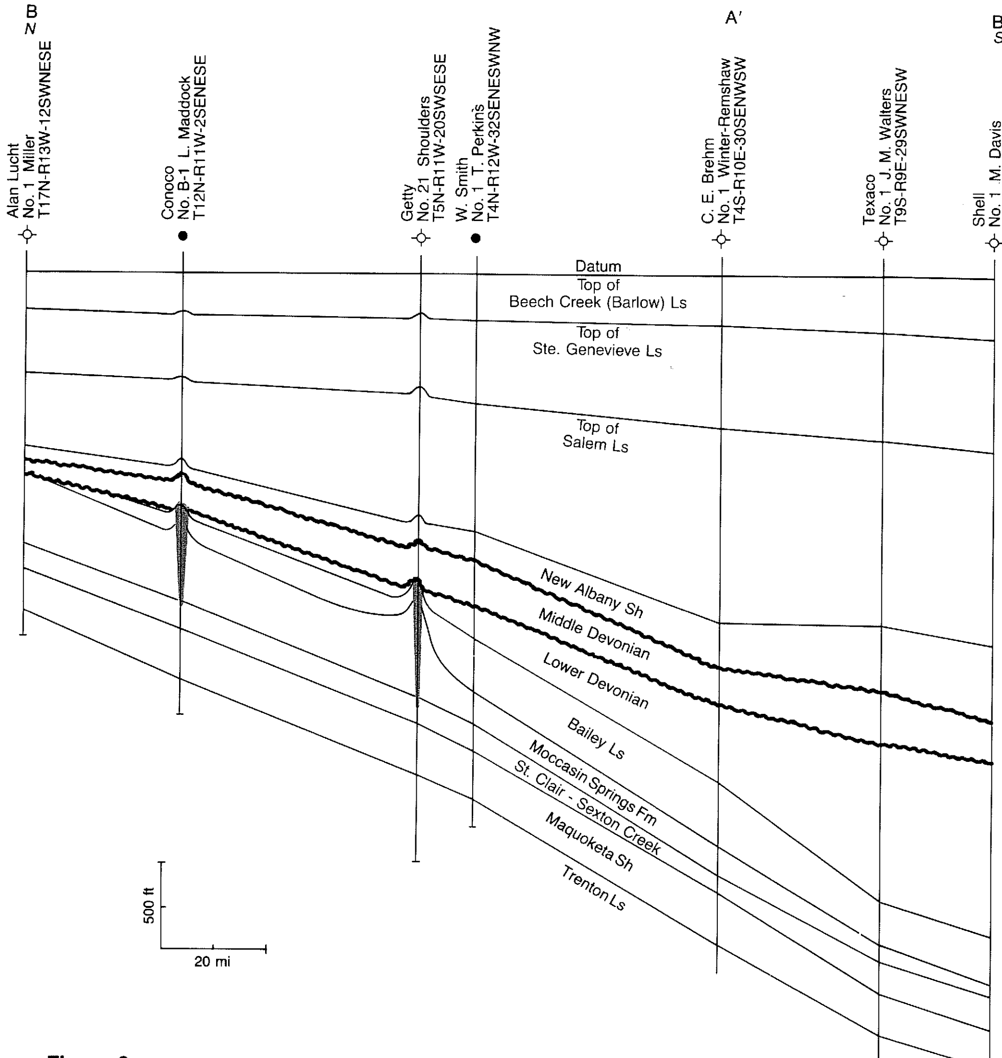


Figure 9a

Cross section B-B' restored to Beech Creek (Barlow) datum illustrates the effects of structural deformation of Lower Devonian, Silurian, and older strata caused by both continued uplift of the Kankakee Arch during Devonian time and by periodic uplift of the La Salle Anticline during Mississippian time. Erosion of Silurian strata prior to deposition of Middle Devonian sediments was most pronounced along the upper ramp environments and across the emerging arches.

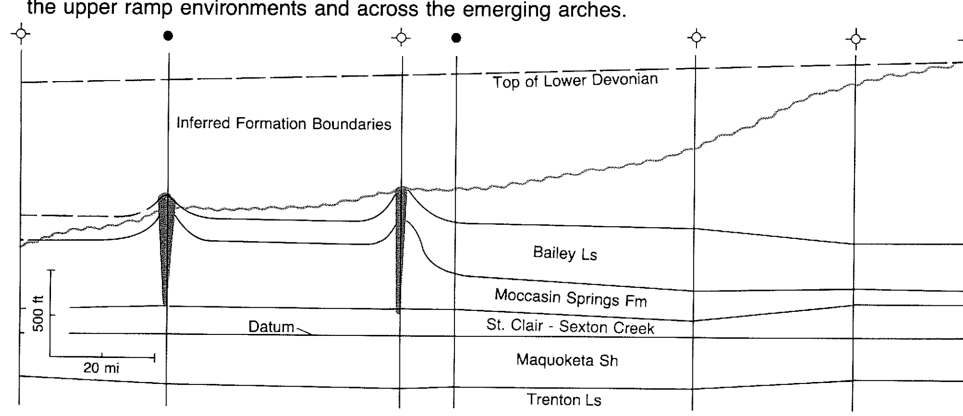


Figure 9b

Cross section B-B′ restored to Maquoketa datum indicates that there was no shelf-basin hingeline that would have caused changes in thickness in all strata. Reef growth occurred in the middle ramp environment and extended into the shallow upper ramp environment. To the south the lower ramp environment was too deep to favor carbonate bank and reef development and resulted in a thin Moccasin Springs interval.

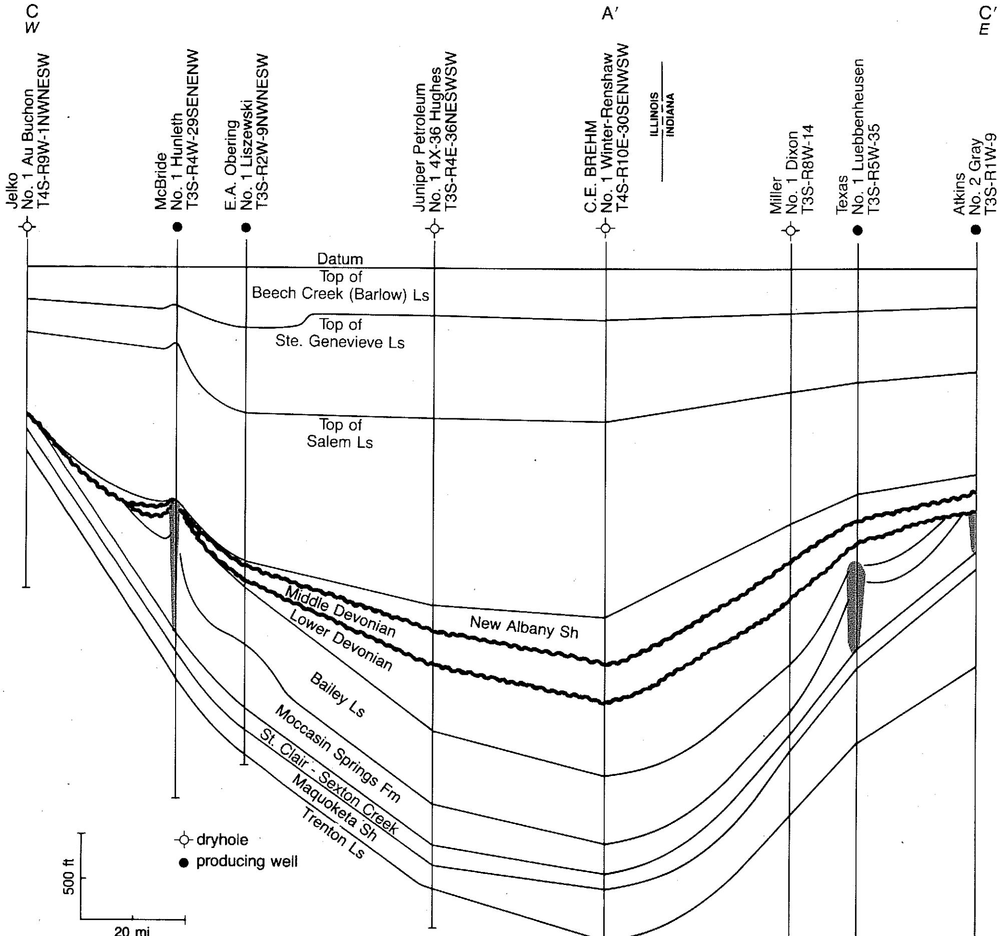


Figure 10a
Cross section C-C' restored to Beech Creek (Barlow) datum illustrates that structural deformation of strata occurred in southwestern Illinois due to uplift of the Sparta shelf during late Middle Devonian. Erosion bevelled Lower Devonian and Silurian strata prior to deposition of Middle Devonian sediments, which in turn were subjected to periods of erosion.

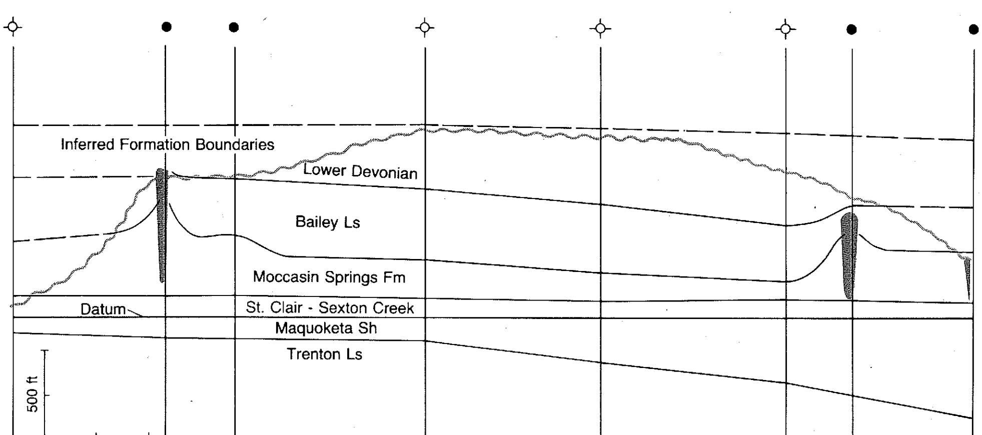


Figure 10b
Cross section C-C' restored to Maquoketa datum. The thinning of the St. Clair and Sexton Creek Formations as well as the thinning of the Moccasin Springs Formation toward the east from Illinois suggests the Maquoketa surface may have dipped relatively uniformly and gently to the east. The uplift of the Wabash Platform in early Niagaran time enabled reefs to develop along its flanks. Contemporaneously, reef development occurred along the middle and upper ramp environments in Illinois. No hingelines due to basin subsidence in Illinois are indicated.

Isopach maps, reef distribution, and lithologic studies indicate that a local basin (Vincennes Basin) may not have developed in Illinois during the Silurian; hence, the hingeline trend may not be a viable hypothesis. According to the ramp-platform hypothesis, reefs began to form on a stable ramp across most of the proto-Illinois Basin area during St. Clair deposition. Gentle uplift of the Cincinnati and Kankakee Arches eastward across Indiana during the early Silurian formed a broad platform, known as the Wabash Platform, with relatively steep slopes along its flanks (fig. 11a). This uplift altered the environment of Indiana, which became shallow enough for reef growth during St. Clair and Moccasin Springs deposition and changed the geometry of the ramp to a combination ramp-platform.

Pinnacle reefs continued to grow in southern and central Illinois and along the flanks of the platform in Indiana, as relative sea level rose during the remainder of Silurian time (Vail et al., 1977). Although reefs would have developed randomly on the ramp across most of Illinois, distinct reef trends would have developed along the flanks of the Wabash Platform: the "Fort Wayne Bank" along the north and the "Terre Haute Bank" along the south (fig. 11b). The higher portions of the Wabash Platform remained too shallow for the development of large pinnacle reefs, but were favorable for shorter, pinnacle reefs and broader, complex coalesced reefs (Droste and Shaver, 1980). Similarly, complex coalesced reefs and small pinnacle reefs formed in northern Illinois along the shallow upper ramp environment.

The thick carbonate deposits of the Terre Haute Bank extend northwestward into the northeastern portion of Illinois (pl. 1). This bank is well defined in easternmost Illinois, where it is separated from other thick carbonate bank deposits by relatively thin interreef strata, particularly in western Crawford, Clark, and Edgar Counties. Northwest of this area the Terre Haute Bank trend becomes more diffuse and probably joins the thick carbonate bank deposits that occupied much of northern Illinois during the Silurian.

Uplift of the Cincinnati and Kankakee Arches, as opposed to downwarping in the area of the proposed Vincennes Basin, is a logical explanation for concurrent reef development in Illinois and Indiana. Illinois was apparently situated on a shallow ramp during early Silurian, whereas prior to uplift, Indiana occupied a position in a slightly deeper shelf or ramp environment that was unfavorable for reef development due to continued subsidence to the east toward Ohio. Uplift of the arches also explains the depositional and erosional patterns of Silurian strata, as well as the creation of restricted, hypersaline conditions in the Michigan Basin to the north (fig. 11c). This hypothesis, however, also suggests that pinnacle reefs would not have developed in the deeper waters of southeastern Illinois or extreme southwestern Indiana (pl. 2) since the environment there would never have been conducive to reef development.

In other studies of Silurian reefs, Freeman (1951), Lowenstam (1953), and Droste and Shaver (1980) speculated that pinnacle-reef growth terminated during Cayugan (late Silurian) time due to sediment influx and/or deepening water; however, there is no evidence of any relatively deep-water sediments conformably overlying reefs in the Illinois Basin. On the contrary, Lower Devonian carbonate sediments conformably overlying Silurian strata indicate a gradually shallowing sea characteristic of regression, which could have terminated reef growth during the late Silurian or early Devonian as shallowing water progressively exposed the reef tops. This interpretation is supported by relative sea-level curves that indicate global lowering of sea level during the early Devonian (Vail et al., 1977). Although sedimentation would have continued in the deeper interreef areas during early Devonian time,

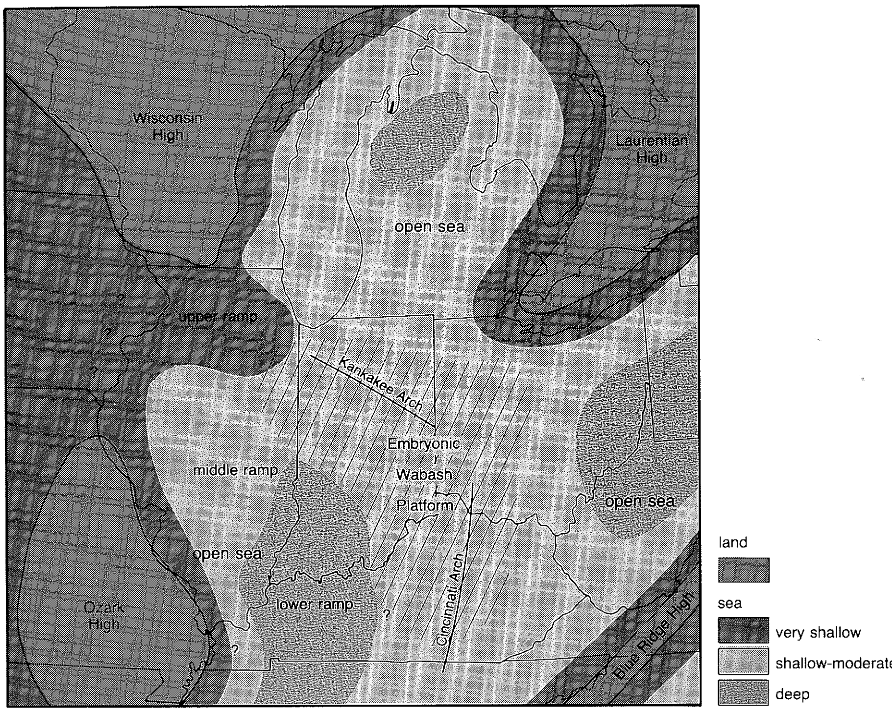


Figure 11a

Early Silurian (Alexandrian): formation of Kankakee and Cincinnati Arches slowly uplifts the embryonic Wabash Platform from its former position along deeper shelf. Illinois occupies a position on a stable shallow shelf.

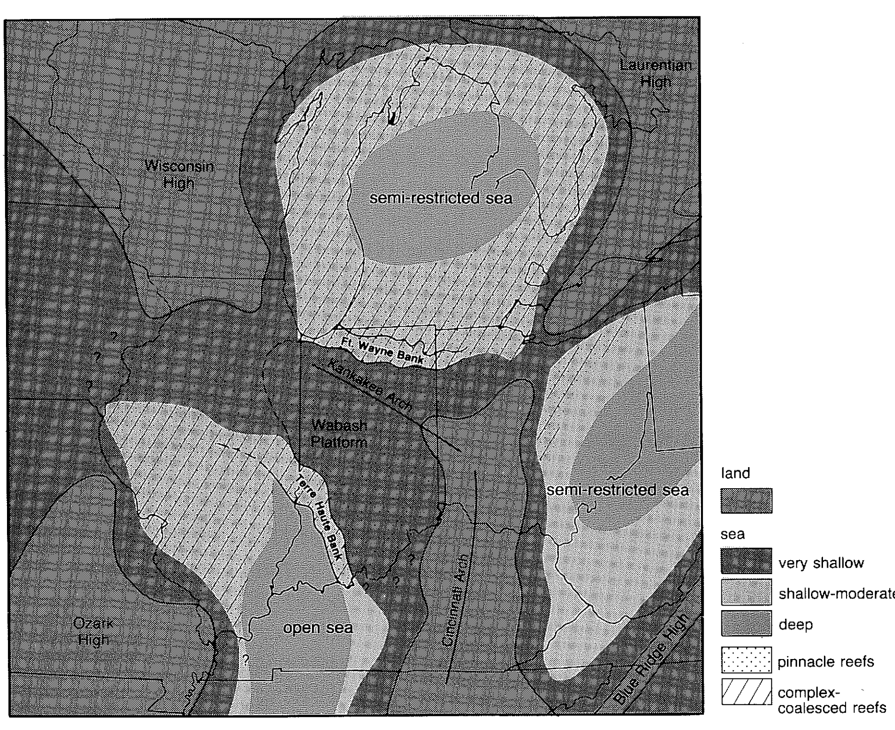


Figure 11b

Middle Silurian (Niagaran): the proto-Illinois Basin evolves to on embayment with pinnacle reefs developing randomly across Illinois on a broad, gently sloping ramp. Shorter pinnacle reefs and complex coalesced reefs form along the upper ramp environment in northern Illinois. The uplifted Wabash Platform is in sufficiently shallow water to enable the development of relatively large pinnacle reefs along its flanks and shorter pinnacle reefs and complex coalesced reefs on the shallower portions of the platform itself. Reef bank trends along the platform flanks merge with carbonate bank deposits and scattered reefs in Illinois.

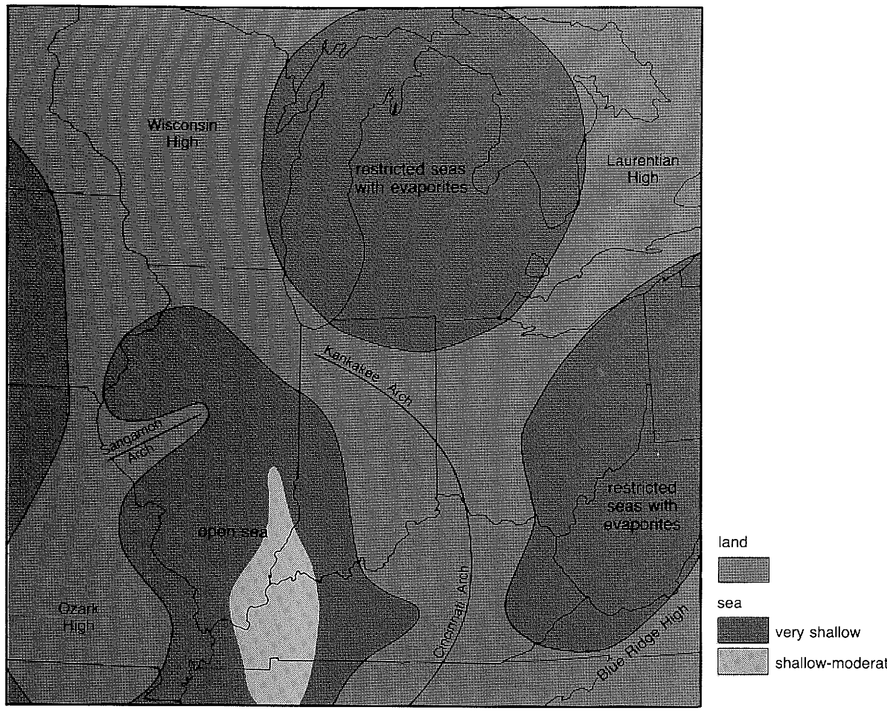


Figure 11c
Early Devonian: reef growth was terminated due to regressing seas. Continued emergence of the Kankakee and Cincinnati arches isolated the Michigan Basin, but left the future Illinois Basin open to the south and still in an embayment configuration. Structurally positive areas become exposed and allowed erosion to remove portions of Lower Devonian and Silurian strata prior to the Middle Devonian.

the reef tops would have been subaerially exposed and subjected to desiccation and erosion. This explanation would partly account for the fact that Lower Devonian sediments have never been observed to overlie Silurian reef cores.

Regressing seas exposed Lower Devonian strata to erosion in the shallower areas of the ramp and platform. Before and during middle Devonian time, erosion removed significant portions of Lower Devonian and Silurian strata from the exposed areas of the ramp-platform, such as on the Kankakee and Cincinnati Arches and the emerging Sangamon Arch in west-central Illinois (fig. 11c). For this reason, pinnacle reefs located in these structurally positive areas during the Devonian were either more eroded, and thus smaller than reefs lower on the ramp-platform, or completely removed by erosion.

Rugose corals within a tight, fossiliferous, grayish tan limestone matrix at a depth of 2,256 feet in McKinley Reef, sec. 29, T3S-R4W, Washington County, Illinois. This coral assemblage is from the central core of the reef, approximately 40 feet below its top. Note porosity associated with the corals.

HYDROCARBON ENTRAPMENT

Preliminary results from geochemical studies at the Illinois State Geological Survey indicate that hydrocarbons in Silurian sediments of Illinois could have at least two sources: organic-rich shales from a yet-to-be defined middle Ordovician zone and the Devonian New Albany Shale. Hydrocarbons sourced from the New Albany were apparently generated in southern Illinois in the present Fairfield Basin; oil migrated from that area into reservoirs throughout the state (Bethke et al., in press). No studies have yet defined migration of oil from middle Ordovician source rocks.

Although oil and gas are commonly encountered in younger strata draped over Silurian pinnacle reefs, hydrocarbon entrapment in reefs largely depends on three factors: (1) the preservation of original porosity; (2) the presence of an impermeable caprock; and (3) secondary porosity development in Silurian strata.

Original porosity development was generally restricted to reef cores, proximal reef flank beds, and shoals within carbonate banks. Subsequent cementation usually infilled most voids but ordinarily was insufficient to totally destroy porosity.

Although attenuation of localized porosity in reefs provides effective seals to lateral migration, a vertical seal is also necessary to trap hydrocarbons. Such a vertical seal is provided by impermeable caprock, usually New Albany Shale, which forms a structural closure that encompasses a portion of the reef (fig. 12). Lack of caprock closure is a common cause for failure of a reef to trap oil or gas.

Widespread dolomitization of Silurian strata in the northern half of Illinois has further affected the distribution of traps. Dissolution, leaching, and replacement has resulted in moldic, vuggy porosity in highly fossiliferous Silurian strata, such as reef cores, reef wash, and carbonate banks. The abundance of blue-gray, vuggy dolomite in northern Illinois, particularly along the areas containing complex coalesced reefs, precludes isolated porosity development and results in fewer traps. Therefore traps in reef rock will most likely be found in those portions of Illinois that contain isolated pinnacle reefs (pl. 2).

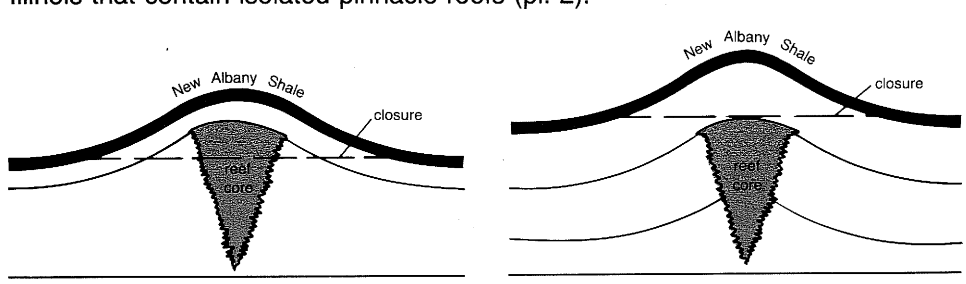
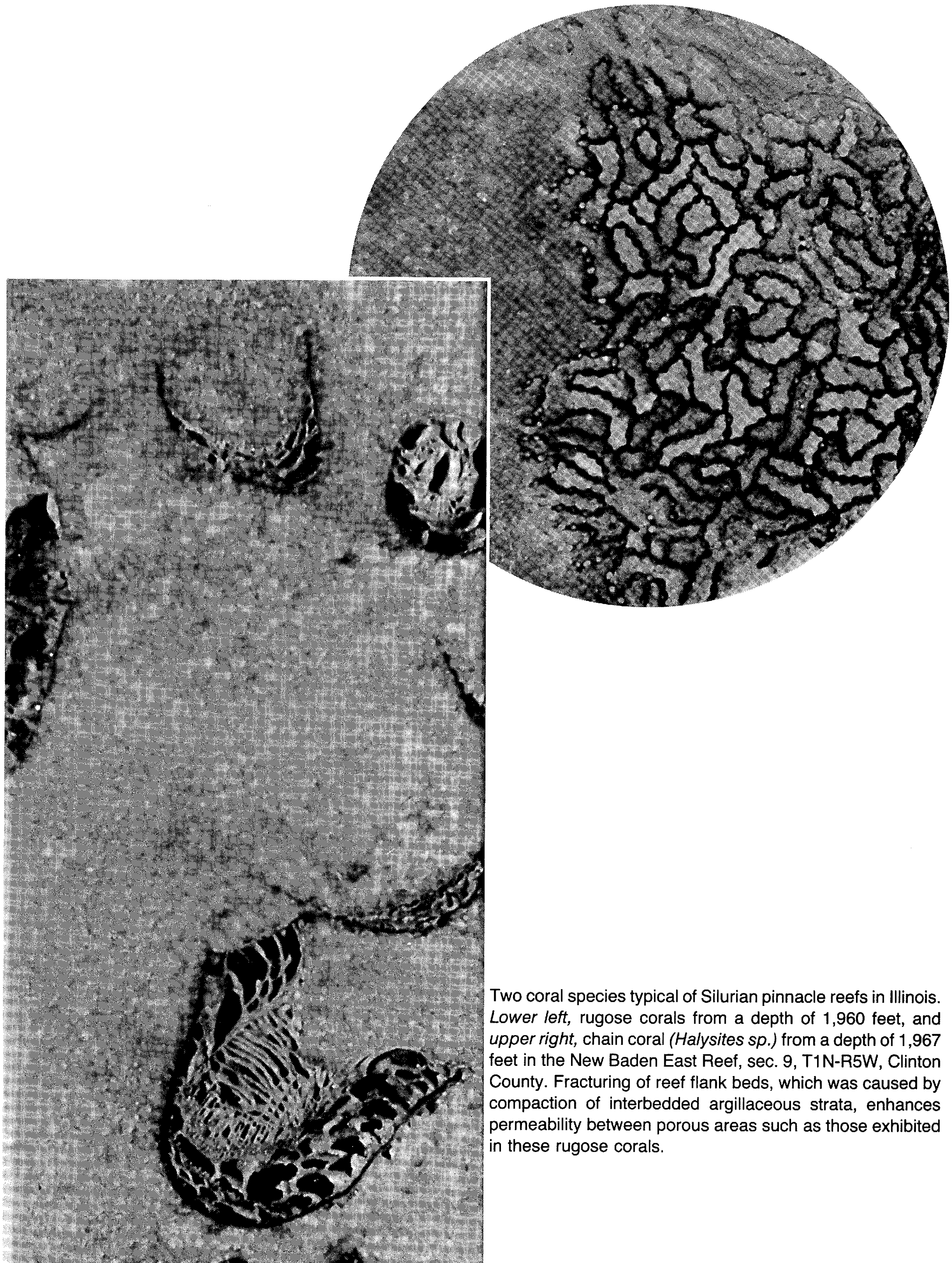


Figure 12
Diagrammatic cross section of vertical seals and their relationship to hydrocarbon entrapment in Silurian pinnacle reefs: a) Structural closure on impermeable strata (New Albany Shale) draped over a reef encompasses a portion of the reef. Ductility of shale resists fracturing due to drape and therefore remains an effective seal. b) Structural closure on New Albany Shale does not encompass underlying reef. Permeable beds directly above reef, probably enhanced by fracturing caused by drape, allow hydrocarbons to migrate out of porous reef rock.



Two coral species typical of Silurian pinnacle reefs in Illinois. *Lower left,* rugose corals from a depth of 1,960 feet, and *upper right,* chain coral *(Halysites sp.)* from a depth of 1,967 feet in the New Baden East Reef, sec. 9, T1N-R5W, Clinton County. Fracturing of reef flank beds, which was caused by compaction of interbedded argillaceous strata, enhances permeability between porous areas such as those exhibited in these rugose corals.

HYDROCARBON EXPLORATION

Structure Mapping

Subsurface mapping The draping effect caused by differential compaction of sediments around Silurian reefs may create pronounced structural closures in younger strata. Structural mapping of Pennsylvanian coals, for example, led to the discoveries of several Silurian reefs including those at Baldwin, Bartelso, and Patoka Fields (Bristol, 1974).

Surface mapping Geomorphic mapping has also been useful for locating buried reefs, such as New Baden East Field (fig. 13) where stream drainage was deflected by a topographic high over a buried reef. Factors other than buried pinnacle reefs, however, can cause these shallow structures and alter drainage patterns.

Seismic structure mapping Structures created by Silurian reefs have also been mapped using seismic data. The strong seismic reflector at the New Albany Shale interval, has been used extensively for structural mapping. An example of a seismic anomaly over a buried pinnacle reef is shown in the section over Sandoval Reef (fig. 14). Many reefs such as those at Boulder, Germantown East, Marine, Lillyville North, and Okawville Fields have been found using this method. A relatively dense grid of seismic data is needed to detect pinnacle reefs, which are typically less than one mile in diameter. Consequently, seismic surveys along section-line roads commonly will not be able to locate reefs within the interior of sections.

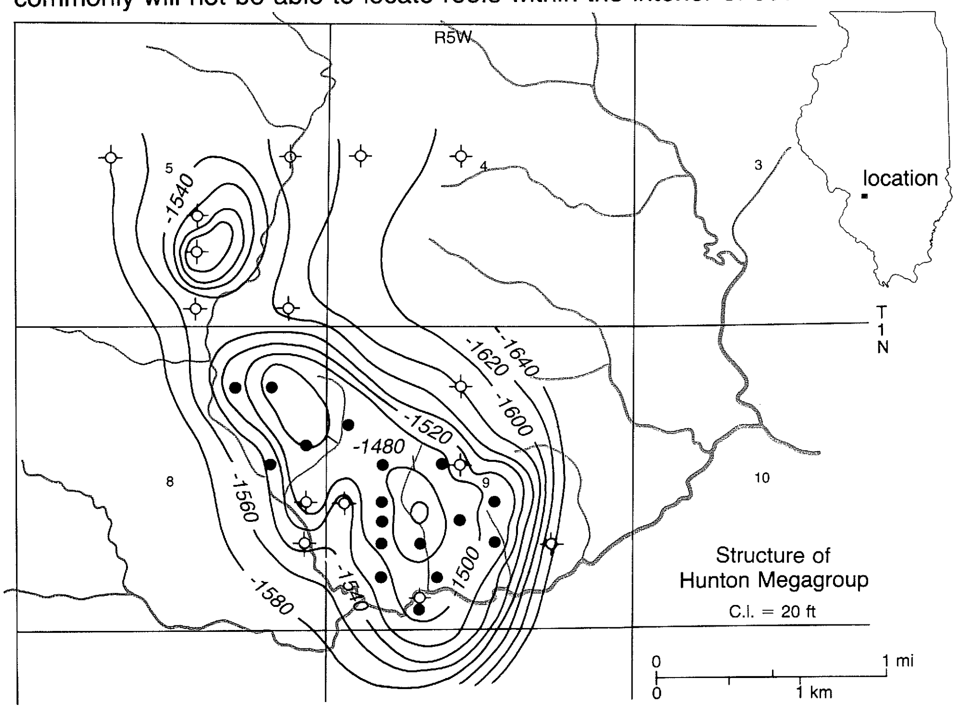


Figure 13
Deflected drainage and radial drainage pattern at New Baden East Field illustrate that surface expressions of buried pinnacle reefs can be a useful method for exploration where reef structures are preserved.

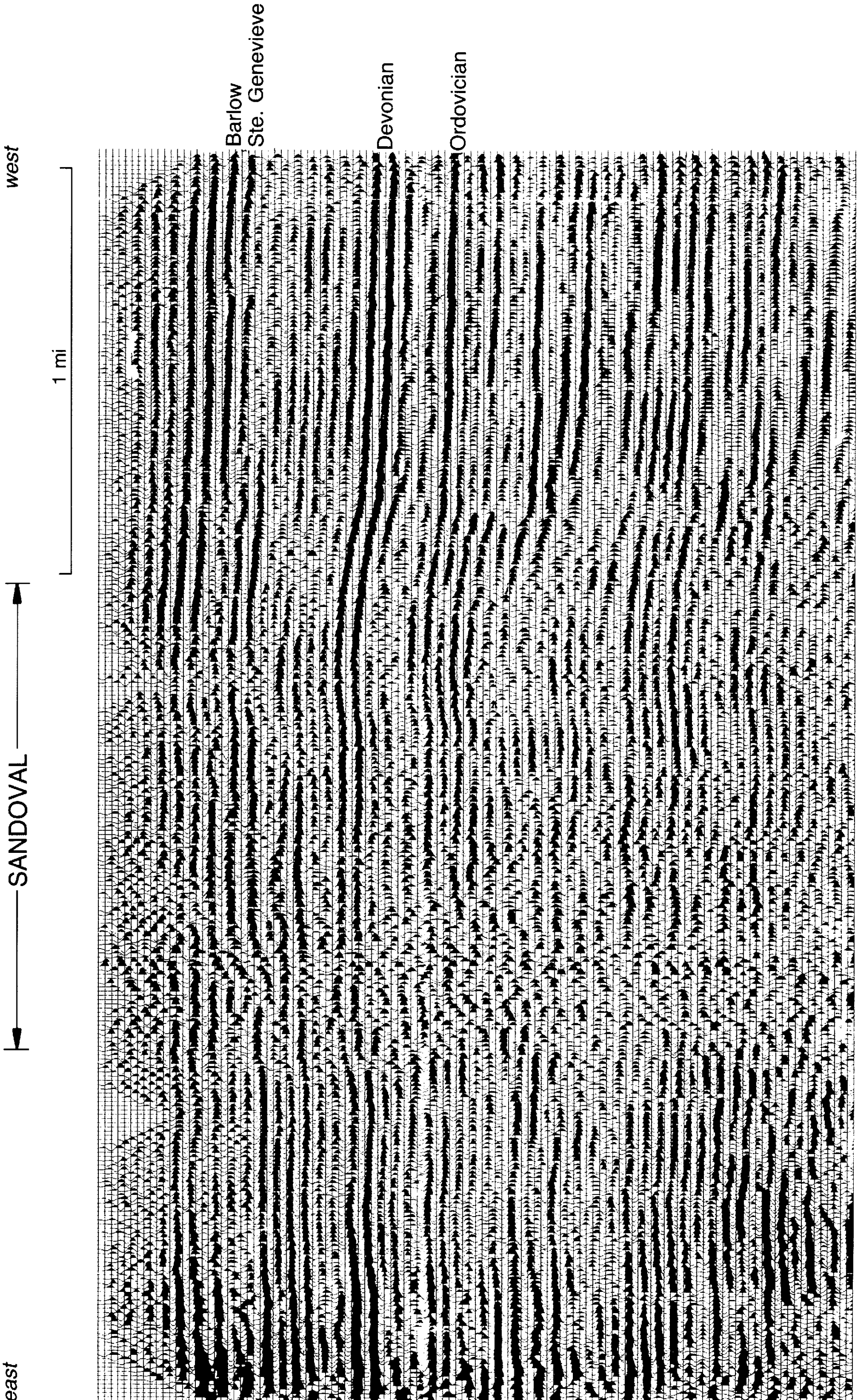


Figure 14

Seismic line over Sandoval Reef. Structural reflectors above the reef at Sandoval show typical structural expression of pinnacle reef and draping effect of younger strata over reef core. This line was acquired and processed in the early 1970s for structural mapping and does not have the high resolution needed to detect stratigraphic anomalies associated with reef rock.

Structural mapping of closures created by the draping effect over pinnacle reefs is not as effective for exploring in areas where erosion has removed significant portions of Silurian strata. Intervals of erosion during the Devonian beveled structural features on the Silurian surface, including reefs, and left a much subdued topography. In addition, subaerial exposure of the Moccasin Springs Formation during the Devonian probably initiated dolomitization of these deposits and prevented subsequent compaction of interreef strata. Without significant compaction of interreef strata, structural relief of the pinnacle reefs would not be sufficiently exaggerated to allow detection by structural mapping alone.

Stratigraphic Mapping

Stratigraphic mapping has been used in many basins to locate hydrocarbon reservoirs that are not detectable by other means. Stratigraphic studies of Silurian rocks in Illinois may be required to locate buried pinnacle reefs that have no structural expression.

One example that illustrates the need to develop and use stratigraphic studies to determine the locations of buried reefs is offered by the Aladdin Oil #1 Scott well (SENWSW sec. 21, T15N-R4W, Sangamon County). By chance this well penetrated a remnant of a reef core from which as much as 500 feet may have been removed by erosion. No mappable structural anomaly shows over this reef remnant in sediments younger than Devonian (cross section A-A', figure 8a), yet a study that would have identified lithologic changes in Silurian rock may have enabled the prediction of the porous reef. This well has produced approximately 278,000 barrels of oil to date from the reef-remnant. Discoveries such as this indicate not only that additional hydrocarbon reserves exist in other such remnant reefs in Illinois, but also that stratigraphic studies are needed so that future reef discoveries will not need to rely on an accidental encounter.

Lithologic studies The locations of pinnacle reefs can be predicted in both eroded and non-eroded areas of Illinois from lithologic analyses of Silurian strata obtained from cores. Paleoenvironments such as reef, reef flank, proximal interreef, or distal interreef can be determined from these analyses. Several excellent papers (Lowenstam, 1949; Droste and Shaver, 1980; Droste and Shaver, 1987) describe in detail the lithologies of reef, reef wash, and interreef sediments. This information, especially with dip indicators, can be used to predict a borehole's proximity to and direction from a reef. A reef in Decatur Field (sec. 32, T17N-R2E, Macon County) was found using this method (C. Watters, personal communication).

Seismic stratigraphy Successful exploration for pinnacle reefs is largely dependent upon using a database with dense coverage. The lack of drilling in many portions of Illinois, and the lack of deep drilling in particular, precludes using well data alone as an effective tool for reef exploration in many areas. Detailed seismic mapping is the most consistently accurate method for locating prospective subsurface anomalies in an area that lacks adequate well data.

Seismic data have been used for a number of years to locate pinnacle reefs. Historically, however, most seismic data in Illinois have been processed for structural plays only, with little or no attention paid to the stratigraphic information that can be obtained. A seismic section over Lillyville North Field (T9N-R7E, Cumberland County) shows the potential for successful stratigraphic mapping from seismic data (fig. 15). Although this line was not shot or processed for stratigraphic quality

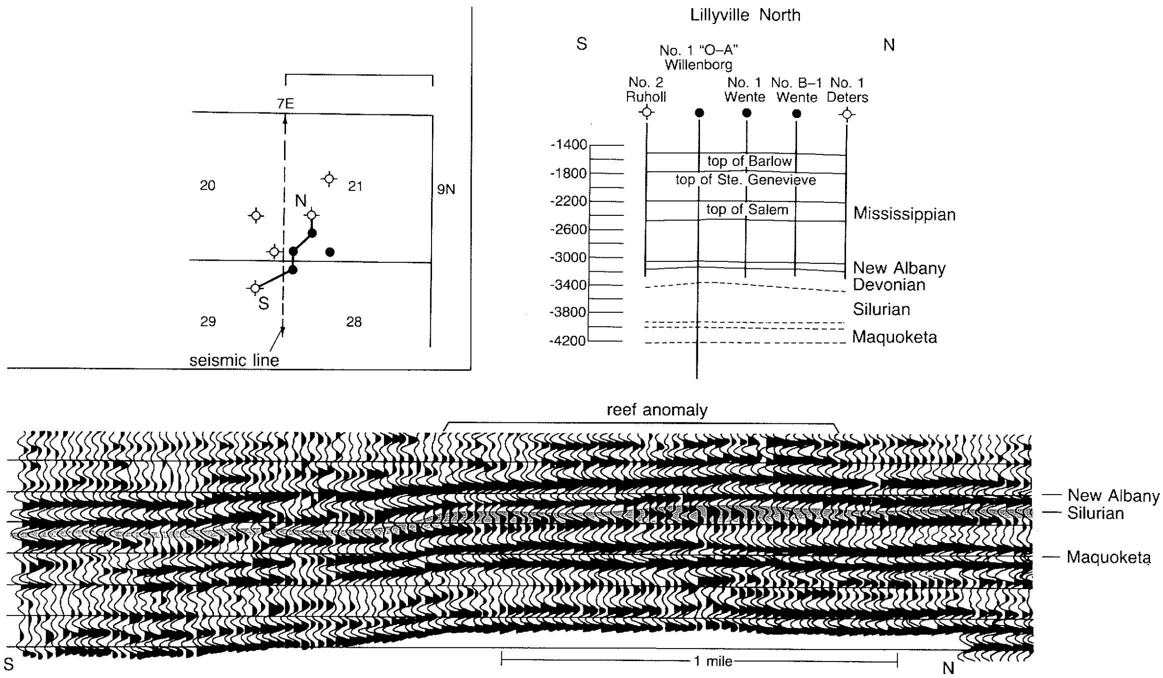


Figure 15
A seismic line over the reef at Lillyville North Field shows character anomaly associated with the reef. Geologic cross section is placed at projected position on seismic line and is to scale.

data, it shows a character anomaly at the Silurian horizon unique to the reef facies, and apparently defines the horizontal limits of the reef. The structural relief on the reef at Lillyville North, although obvious, is not as pronounced as in most known reefs in Illinois.

Preliminary studies on seismic responses to reef lithologies in Michigan (Loveland, 1986) indicate that in certain cases seismic data can differentiate reef core facies from interreef facies. Detailed seismic modeling is needed to define optimum shooting and processing parameters for detecting lithologic changes in strata such as the Silurian in Illinois. Once these parameters are established, seismic data should be an accurate tool for locating eroded pinnacle reefs.

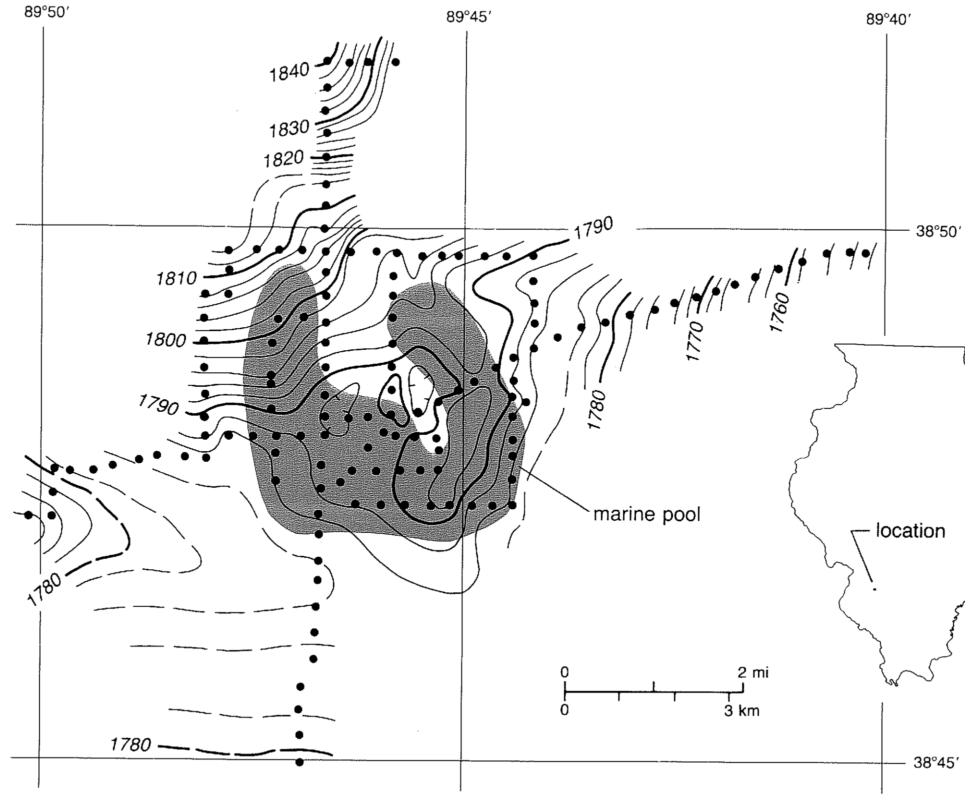
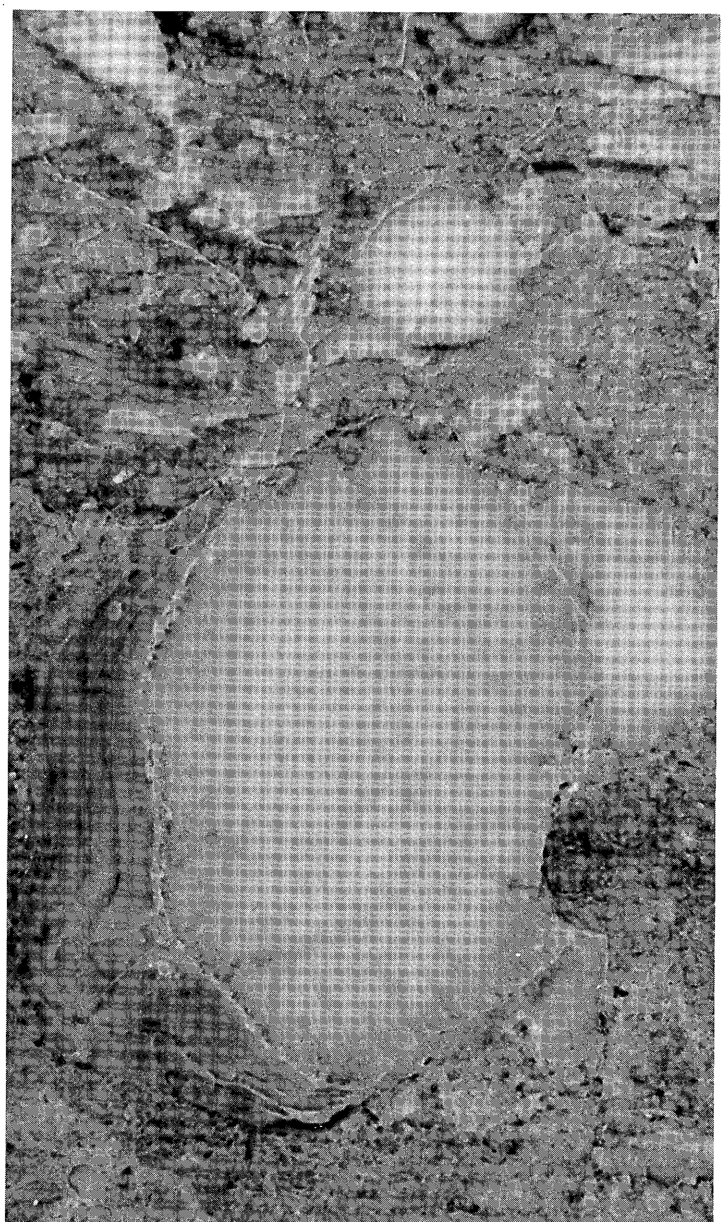


Figure 16
Bouguer anomaly gravity map shows anomaly at Marine Reef (T4N-R6W). Bouguer anomaly maps and derivative maps of gravity data can be effective methods for reef exploration in certain cases. Gravity data provided by Tidelands Oil Co.

Gravity Mapping

Gravity mapping may show an anomaly that coincides with a reef, providing the reef formed over a substantial enough basement high, or has a strong density contrast with neighboring interreef sediments. An example of a simple gravity anomaly over the reef at Marine Field (T4N-R6W, Madison County) is shown in figure 16. Such an anomaly was partly responsible for the discovery of the reef at New Memphis Field (Bristol, 1974). Gravity data may also prove to be useful in locating eroded remnants of reefs. Not all reefs display gravity anomalies, however; nor does every gravity anomaly indicate the presence of a reef.



Stromatoporoid encrusting coral *(Heliolites sp.)*. Specimen represents a depth of 2,597 feet in Bartelso Reef, sec. 5, T1N-R3W, Clinton County, Illinois. Stromatoporoids, a major constituent of Silurian reefs, may locally exhibit good porosity. Evidence of algal contributions to reef buildups is sometimes difficult to recognize because of dolomitized reef facies and the small size of drill cuttings.

CONCLUSION

The data support the hypothesis that pinnacle reefs developed randomly across most of the southern half of Illinois along a middle ramp environment. In Indiana, uplift of the Cincinnati and Kankakee Arches during the early Silurian had formed the Wabash Platform and enabled banks of pinnacle reefs to develop along its flanks. Shorter pinnacle reefs or complex coalesced reefs tended to develop along the upper ramp environment of northern Illinois and along the upper portions of the platform in Indiana.

A combination of uplift, particularly along the Sangamon Arch, and regression during early Devonian time caused extensive erosion of Silurian strata. This erosion planed off the tops of pinnacle reefs and locally eliminated topographic expression of the reefs before the middle Devonian transgression. Dolomitization of Silurian strata in the structurally higher portions of the basin during the Devonian hindered subsequent differential compaction around pinnacle reefs.

Where Silurian strata were extensively eroded and/or dolomitized, structural anomalies in beds above remnant pinnacle reefs are greatly subdued or absent. Exploration methods in these areas will have to stress stratigraphic changes within Silurian strata to identify the locations of buried pinnacle reef remnants. Data from lithologic and/or geophysical studies should prove to be effective exploration tools in these areas.

Acknowledgments

I would like to thank Dick Howard of the ISGS, Wayne Meents, retired geologist with the ISGS, and Bob Shaver of the Indiana Geological Survey, for their comments and assistance with this manuscript.

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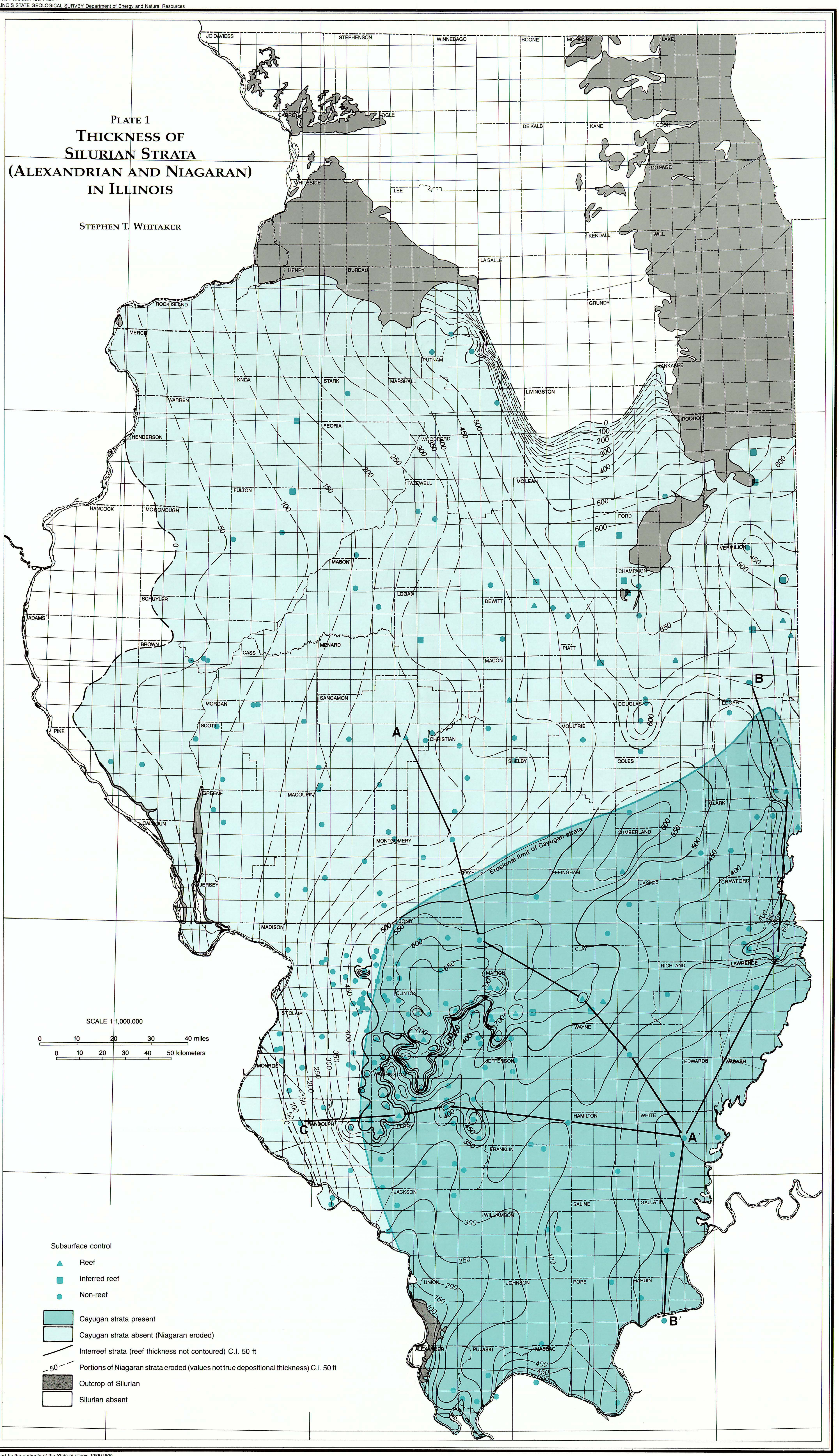

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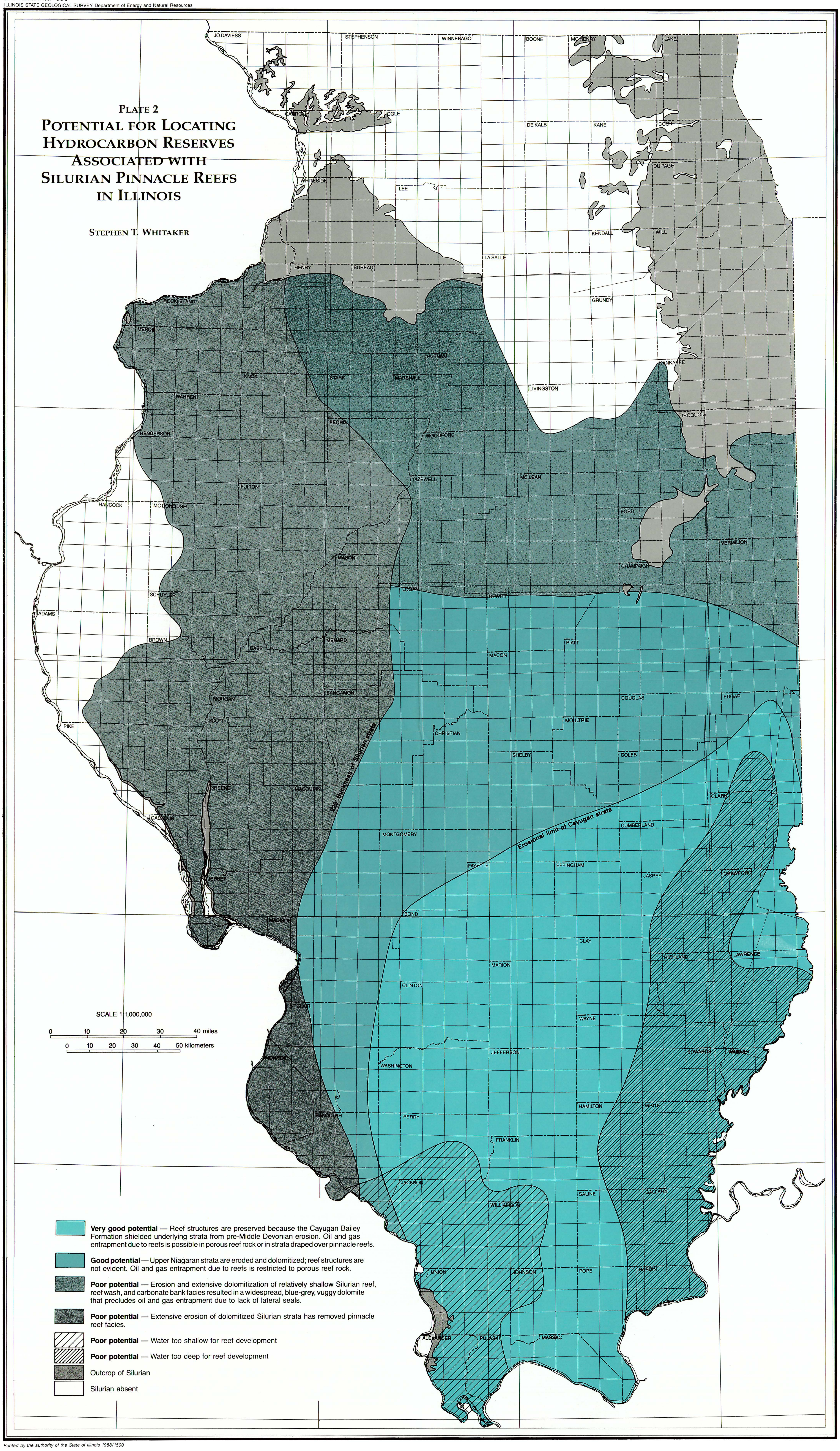
Illinois Petroleum 130, Plate 2
ILLINOIS STATE GEOLOGICAL SURVEY Department of Energy and Natural Resources

Plate 2
Potential for Locating Hydrocarbon Reserves Associated with Silurian Pinnacle Reefs in Illinois

Stephen T. Whitaker



Very good potential — Reef structures are preserved because the Cayugan Bailey Formation shielded underlying strata from pre-Middle Devonian erosion. Oil and gas entrapment due to reefs is possible in porous reef rock or in strata draped over pinnacle reefs.

Good potential — Upper Niagaran strata are eroded and dolomitized; reef structures are not evident. Oil and gas entrapment due to reefs is restricted to porous reef rock.

Poor potential — Erosion and extensive dolomitization of relatively shallow Silurian reef, reef wash, and carbonate bank facies resulted in a widespread, blue-grey, vuggy dolomite that precludes oil and gas entrapment due to lack of lateral seals.

Poor potential — Extensive erosion of dolomitized Silurian strata has removed pinnacle reef facies.

Poor potential — Water too shallow for reef development

Poor potential — Water too deep for reef development

Outcrop of Silurian

Silurian absent

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