Sedimentology and Reservoir Characterization of the Silurian Carbonates in the Mt. Auburn Trend of the Sangamon Arch, West-Central Illinois

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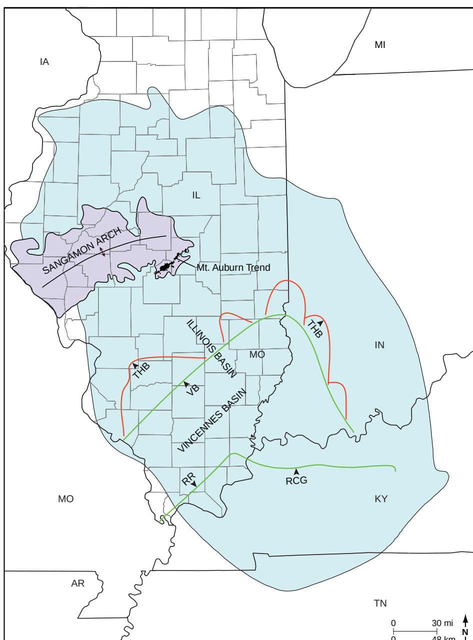

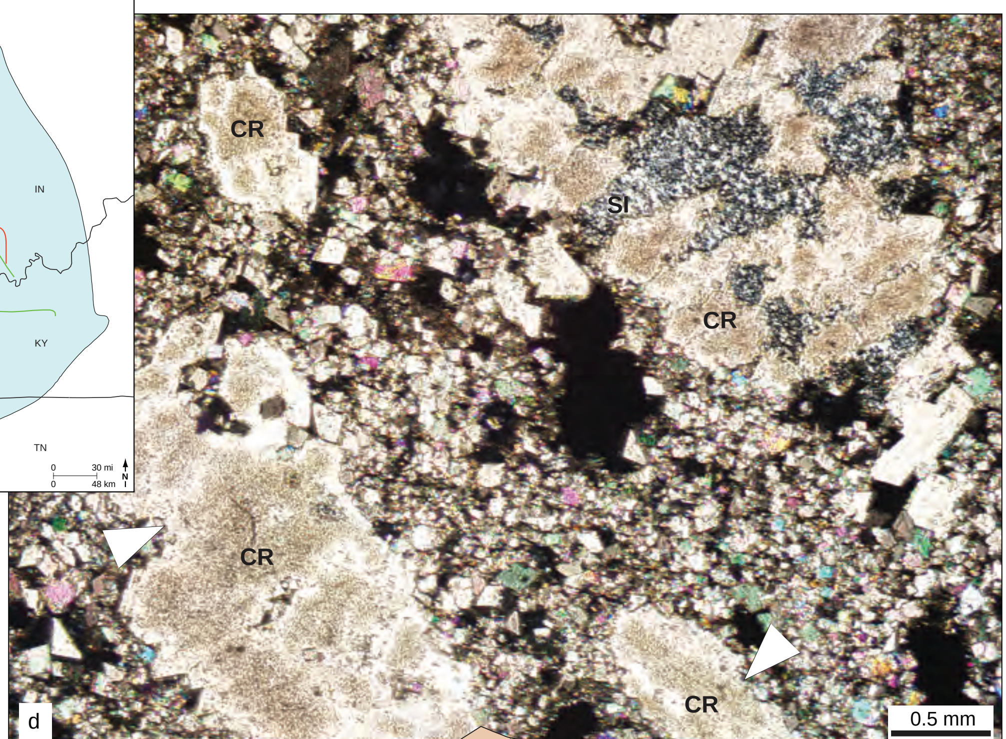

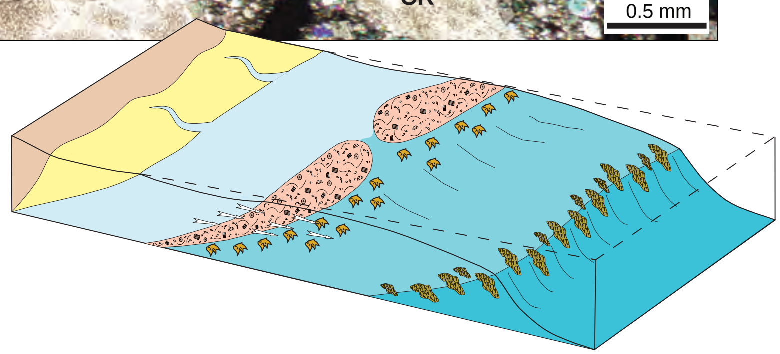

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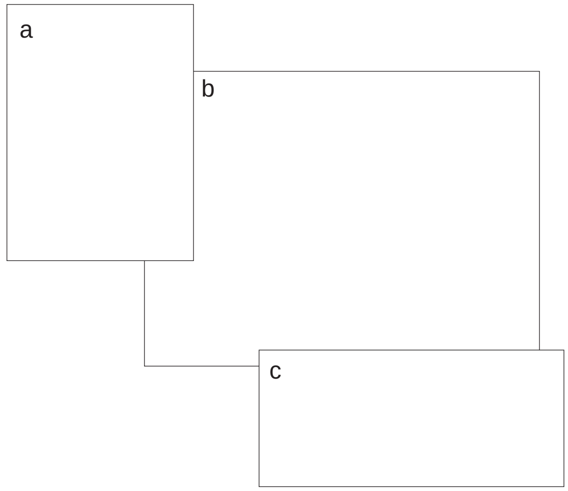
Front Cover: *(a) Location of the Illinois Basin and the Sangamon Arch in west-central Illinois. (b) Photomicrograph of porous dolomitized grainstone facies under polarized light showing an irregular dolomitization front (arrows) on crinoid fragments (CR), dolomite rhombs, and void spaces (black) formed as a result of dolomitization. (c) Generalized depositional model depicting the distally steepened ramp of the Illinois Basin during Niagaran time.*



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CONTENTS

Abstract

The Silurian succession of the Sangamon Arch, a broad southwest-trending structure in west-central Illinois, is composed of hydrocarbon-bearing reservoirs that have produced mainly from dolomitized carbonate units in the upper part of the Niagaran Series. To determine the reservoir facies and to evaluate the occurrence, geometry, distribution, porosity development, and petroleum entrapment mechanism, the present study focuses on the Silurian deposits along the Mt. Auburn trend of the Sangamon Arch. In the Mt. Auburn trend along the southern flank of the arch, the only petroleum reservoir is the uppermost Niagaran Racine Formation (equivalent to the Moccasin Springs Formation of southern Illinois). The Racine Formation is characterized mostly by layers of limestone, dolomite, and silty argillaceous dolomitic limestone/dolomite that vary in thickness and lithology from place to place, making well-to-well correlation difficult. The Racine Formation underlies the Upper Devonian to Lower Mississippian New Albany Shale Group with a distinct unconformity and sharply overlies the lower Niagaran Joliet Formation (equivalent to the St. Clair Formation of southern Illinois). The variable thickness and lithology in the lower part of the Racine Formation are interpreted to be the consequence of sea level fall and differential post-depositional erosion, thus indicating the presence of a prominent erosional unconformity within the Racine Formation. This unconformity subdivides the Racine Formation into two third-order cycles (sequences) that include several producing dolomite reservoirs.

The reservoirs include dolomitized skeletal wackestone-grainstone facies in the upper sequence and coral patch reef/reef rudstone facies in the lower sequence. The reservoirs commonly constitute the upper part of fourth-order shallowing-upward cycles and are characterized by lenticular bodies of limited lateral extent. They normally grade laterally and vertically into laterally extensive impermeable limestone facies, suggesting that fluctuations in sea level and seawater chemistry were the primary controls for early dolomitization of Silurian carbonates in the study area. Petrographic studies indicate that the Racine Formation was deposited within the high-energy depositional environment of the ramp margin (roughly parallel to the Mt. Auburn trend) and in the adjacent deeper subtidal setting. This gently sloping ramp was a part of a distally steepened ramp (the Vincennes Basin) located in the distal deep area of the Illinois Basin. Because the depositional wave energy was not strong enough in the homoclinal ramp setting of the Sangamon Arch, only bioclast grainstone shoal facies and small patch reefs were developed—unlike the large pinnacle reefs that developed along the steeper slope of the deep Illinois Basin margin.

Hydrocarbon production along the Mt. Auburn trend has been chiefly from the non-reef carbonate reservoirs in the uppermost part of the Silurian succession. Most wells drilled thus far have only tested the uppermost part of the Niagaran deposits; only a few wells have tested the lower reservoirs that include the newly recognized patch reefs. The results of this study suggest that there are good possibilities of finding other productive areas with dolomitized patch reefs and non-reef reservoirs in the Mt. Auburn trend of the Sangamon Arch area.

Introduction

The upper part of the Silurian succession (Niagaran Series) in the Sangamon Arch of west-central Illinois contains prolific petroleum reservoirs that have been producing for over 80 years. More than 12 million barrels of oil have been produced from Silurian rocks in the Mt. Auburn trend located along the southern flank of the Sangamon Arch (Figures 1 and 2). The first commercial production from the area was in 1925 from the Decatur Field, but major exploration activity did not begin until 1954 after Sun Oil Company completed the Damery No. 1 well in Macon County in December 1953. That well produced more than 700 barrels of oil per day after fracture treatment of the Silurian reservoir (Whiting 1956).

The Mt. Auburn trend includes a number of oil fields (Figure 2) that have produced chiefly from the dolomitized carbonate reservoirs that occur in the upper part of the Silurian succession. However, there are conflicting views on reservoir development, petroleum entrapment, and their controls. To date there have been no documented studies regarding the reservoir facies types, porosity, occurrence, and petroleum entrapment of these Silurian reservoirs. The objectives of this study are to determine reservoir facies and assess the occurrence, geometry, distribution, porosity development, and petroleum entrapment mechanism in the Niagaran deposits along the Mt. Auburn trend of the Sangamon Arch. The intent is to generate renewed interest in the unexplored areas and encourage secondary recovery of its producing horizons. The depositional model developed in this study should help producers understand reservoir development and predict occurrences of productive Silurian rocks in other areas of the Illinois Basin.

Available subsurface data, including well cuttings, cores, and geophysical logs from more than 950 drill holes, were studied in detail to establish and outline facies distribution and reservoir characteristics of the Silurian deposits in the study area. Maps and stratigraphic cross sections from different areas along the Mt. Auburn trend were constructed using GeoGraphix and Adobe Illustrator software. The reservoir facies are classified on the basis of the textural classification schemes of Dunham (1962) and Embry and Klovan (1971).

Geologic Setting

The intracratonic Illinois Basin (Figure 1) began subsiding during the Late Cambrian Period over the northeast extension of the Late Precambrian to Middle Cambrian Reelfoot Rift system (Kolata and Nelson 1991). This subsidence was associated with the breakup of the Rodinia supercontinent during Late Precambrian to Early Cambrian time (Bond et al. 1984; Piper 2000, 2004; Meert and Torsvik 2003). During the Silurian Period, the rift system formed the axis of a southward plunging trough that opened to the adjacent Iapetus Ocean (Kolata and Nelson 1991). By the Middle to Late Silurian

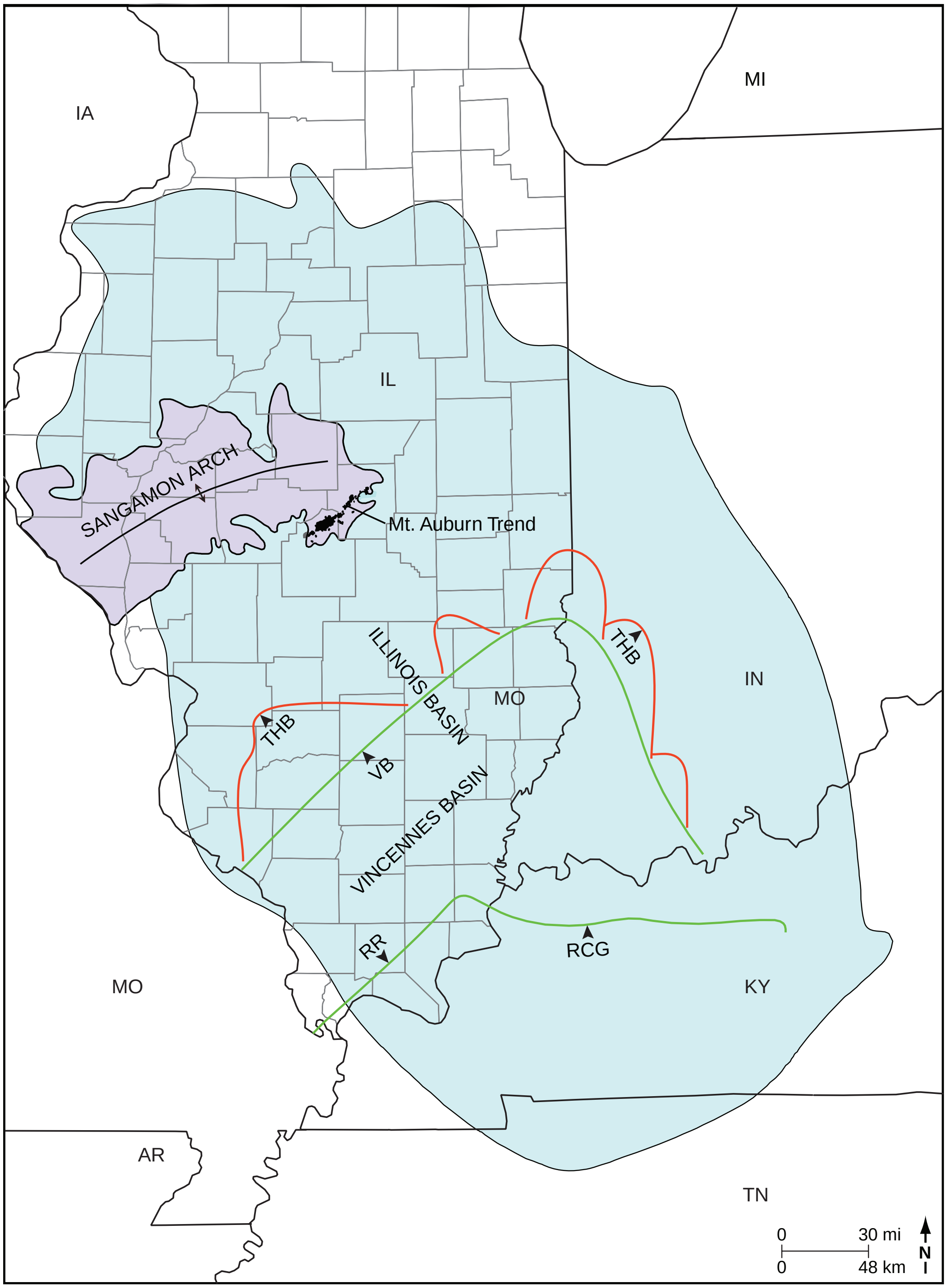

Figure 1 Location of the Illinois Basin (Buschbach and Kolata 1991) and the Sangamon Arch in west-central Illinois. The Sangamon Arch is defined by the zero isopach contour of the Lower to Middle Devonian deposits (Whiting and Stevenson 1965) in the northwestern portion of the Illinois Basin. The Mt. Auburn trend is located along the southeastern flank of the Sangamon Arch and includes several oil fields (Figure 2). Line abbreviations: RR, the northwest limit of the Reelfoot Rift; RCG, the northern limit of the Rough Creek Graben (Kolata and Nelson 1991); VB, the northern limit of the Vincennes Basin; THB, the limit of the known pinnacle reefs in the Terre Haute reef bank (Droste and Shaver 1980, 1987). Both the Vincennes Basin and the Terre Haute reef bank may have marked a slope break in southern Illinois and southwestern Indiana with deeper water to the south.

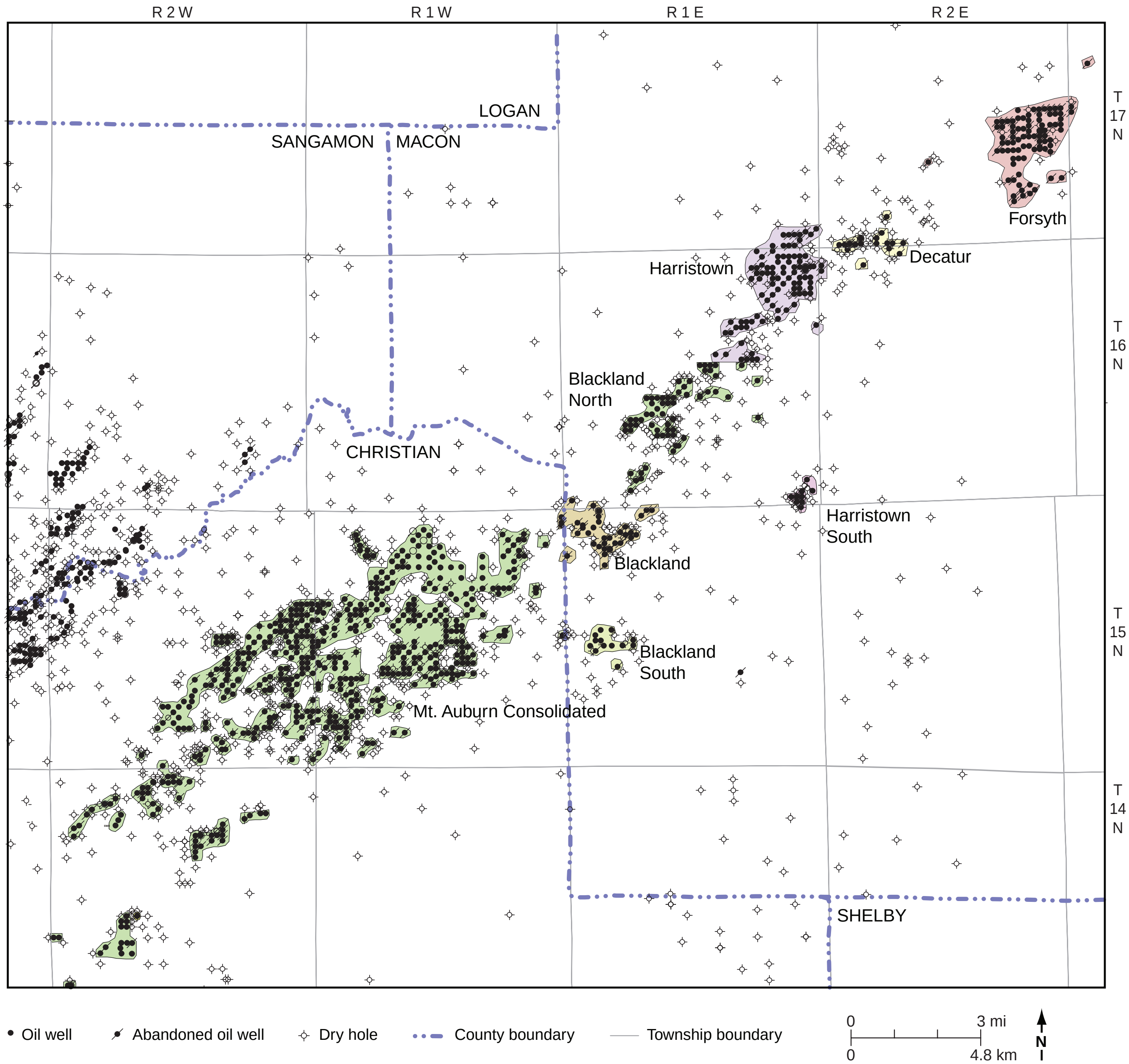

Figure 2 Map of the Mt. Auburn trend of the Sangamon Arch. The trend is delineated by a number of oil fields that have produced from the Silurian reservoirs. Reservoirs are differentiated from one another by color.

Period, a platform margin (the Terre Haute reef bank) marked a slope break in southern Illinois and southwestern Indiana that faced the deep proto-Illinois (Vincennes) Basin (Droste and Shaver 1980, 1987).

The Sangamon Arch is a broad northeast-southwest–trending structure in west-central Illinois (Figure 1) that was formed as a result of upward warping during Silurian and Devonian times (Whiting and Stevenson 1965). The Sangamon Arch formed a ramp area on the northwestern part of the Illinois Basin, where the general direction of the regional dip is toward the southeast. The Mt. Auburn trend is located along the southern flank of the arch (Figure 1) and encompasses a number of oil fields in parts of Macon and Christian Counties in west-central Illinois (Figure 2).

Subsidence coincident with the long-term Silurian global (eustatic) sea level rise that culminated during the Middle Silurian (Golonka and Kiessling 2002, Haq and Schutter 2008) resulted in deposition of over 400 feet (120 m) of mainly shallow marine carbonates in the Sangamon Arch area. Carbonate deposition was terminated as a result of the worldwide pre-Middle Devonian sea level fall (Sloss 1963, Vail et al. 1977, Haq and Schutter 2008) and upwarping of the arch during Late Silurian through Middle Devonian times. In the deep basinal area to the south, however, deposition was continuous across the Silurian-Devonian boundary (Droste and Shaver 1987, Mikulic 1991).

Stratigraphic Setting

The Silurian succession of the Illinois Basin is a part of the Silurian-Middle Devonian Hunton Megagroup (Swann and Willman 1961), which constitutes the upper part of the Tippecanoe sequence of Sloss (1963) and overlies the Upper Ordovician (Cincinnatian) deposits with the distinct unconformity below the Tippecanoe II subsequence (Figure 3). In the platform areas (inner to mid ramp) of the Illinois Basin, the Silurian rocks unconformably underlie the Middle Devonian deposits with the pronounced sub-Kaskaskia erosional unconformity, but, in the deep part of the Basin, the Silurian-Devonian boundary is conformable (Willman and Atherton 1975, Droste and Shaver 1987, Mikulic 1991). In the Sangamon Arch area, Lower and Middle Devonian deposits are absent (Whiting and Stevenson 1965), and Silurian carbonates are overlain by the Upper Devonian to lowermost Mississippian New Albany Shale Group (Figure 4). In the Sangamon Arch area, the Silurian encompasses the Alexandrian and Niagaran Series (Willman and Atherton 1975), which consist mainly of limestone and dolomite. The Alexandrian-Niagaran boundary is marked by an unconformity (Willman and Atherton 1975, Mikulic 1991, Kluessendorf and Mikulic 1996). The unconformity corresponds with the major phase of the Caledonian Orogeny during the Early Silurian through Late Devonian (Golonka and Kiessling 2002).

The Silurian System of the Illinois Basin has been the subject of several lithostratigraphic classifications (Willman and Atherton 1975, Droste and Shaver 1987). In the present study, the stratigraphic nomenclature scheme of Willman and Atherton (1975) for western Illinois (Figure 4) has been adopted to identify the Silurian deposits of the Sangamon Arch area. Based on this classification, the Silurian deposits of the Mt. Auburn trend comprise, from base to top, the Alexandrian Edgewood and Kankakee Formations and the Niagaran Joliet and Racine Formations. In the Mt. Auburn trend, the uppermost Niagaran Racine Formation includes several hydrocarbon-producing dolomite horizons. The Racine Formation (Hall 1861 in Willman and Atherton 1975) takes its name from the quarry exposures at Racine, Wisconsin. It is up to 300 feet (90 m) thick and consists of pure limestone and/or dolomite reef facies and silty argillaceous dolomite or limestone inter-reef facies (Willman and Atherton 1975). The Racine Formation is equivalent to the Moccasin Springs Formation of southern Illinois that displays a characteristic “two-kick, three-kick” interval (resistive signatures best recognized on old electric logs) in its lower part, just above the Niagaran St. Clair Formation (equivalent to the Joliet Formation) (Willman and Atherton 1975).

Stratigraphy of the Racine Formation

In the study area, the Racine Formation underlies the Upper Devonian through the lowermost Mississippian New Albany Shale Group with an interregional unconformity (Figure 4). It overlies, with a sharp contact, the thick-bedded fossiliferous limestone of the Joliet Formation (equivalent to the St. Clair Limestone of southern Illinois) (Figure 5). A prominent unconformity subdivides the Racine Formation into two sequences (Y. Lasemi 2009a, 2009b).

A subsurface reference section, the Equitable Resources Exploration IL-3032 well (southwest of the Mt. Auburn Consolidated Field) in Christian County, has been chosen to illustrate significant and laterally continuous geophysical markers in the area (Figure 5). The reference section surfaces are designated in ascending order, from base to top, by letters a to g, which correspond to important chronostratigraphic events and may coincide with the boundaries of lithostratigraphic units. The surfaces represent (a) the top of the Joliet Formation, (b) the base of a thin radioactive shale, (c) the top of a radioactive calcareous shale or argillaceous limestone that may reach a thickness of 30 feet (9 m) above marker b, (d) the top of the lower Racine sequence, (e) the base of a resistive cherty limestone marker near the Silurian-Devonian boundary, (f) the top of the upper Racine sequence, and (g) the top of the New Albany Shale Group.

The lower part of the Racine Formation displays characteristic and widely traceable geophysical log signatures, which commonly represent alternating gray fossiliferous limestone, silty argillaceous dolomitic limestone/dolomite, and calcareous shale (Figure 5). The log signatures exhibit an overall upward decrease in resistivity and an upward increase in radioactivity in the lower part of the formation (e.g., depths 2,100 to 2,030 feet in Figure 5). This interval is similar to the lower part of the Moccasin Springs Formation in southern Illinois, but the characteristic “two-kick, three-kick” resistivity signatures (Willman and Atherton 1975) are not fully discernible in the Mt. Auburn trend area.

The thickness of the Racine Formation on the Sangamon Arch is variable due to post-depositional erosion, as is discussed more fully in the following section. Deposition of the Racine Formation on the Sangamon Arch was coeval with the deposition of the Moccasin Springs Formation of southern Illinois and the lower part of the Wabash Formation of Indiana (Willman and Atherton 1975, Droste and Shaver 1987, Mikulic 1991).

Unconformable Boundaries and Lateral Distribution

Examination of the geophysical log signatures and stratigraphic correlation in the study area (Figures 6 through 10) indicates fairly uniform thickness and lithology for the lower Niagaran Joliet Formation (equivalent to the St. Clair Formation of southern Illinois) and the underlying Alexandrian Edgewood-Kankakee Formations (Figure 7), which

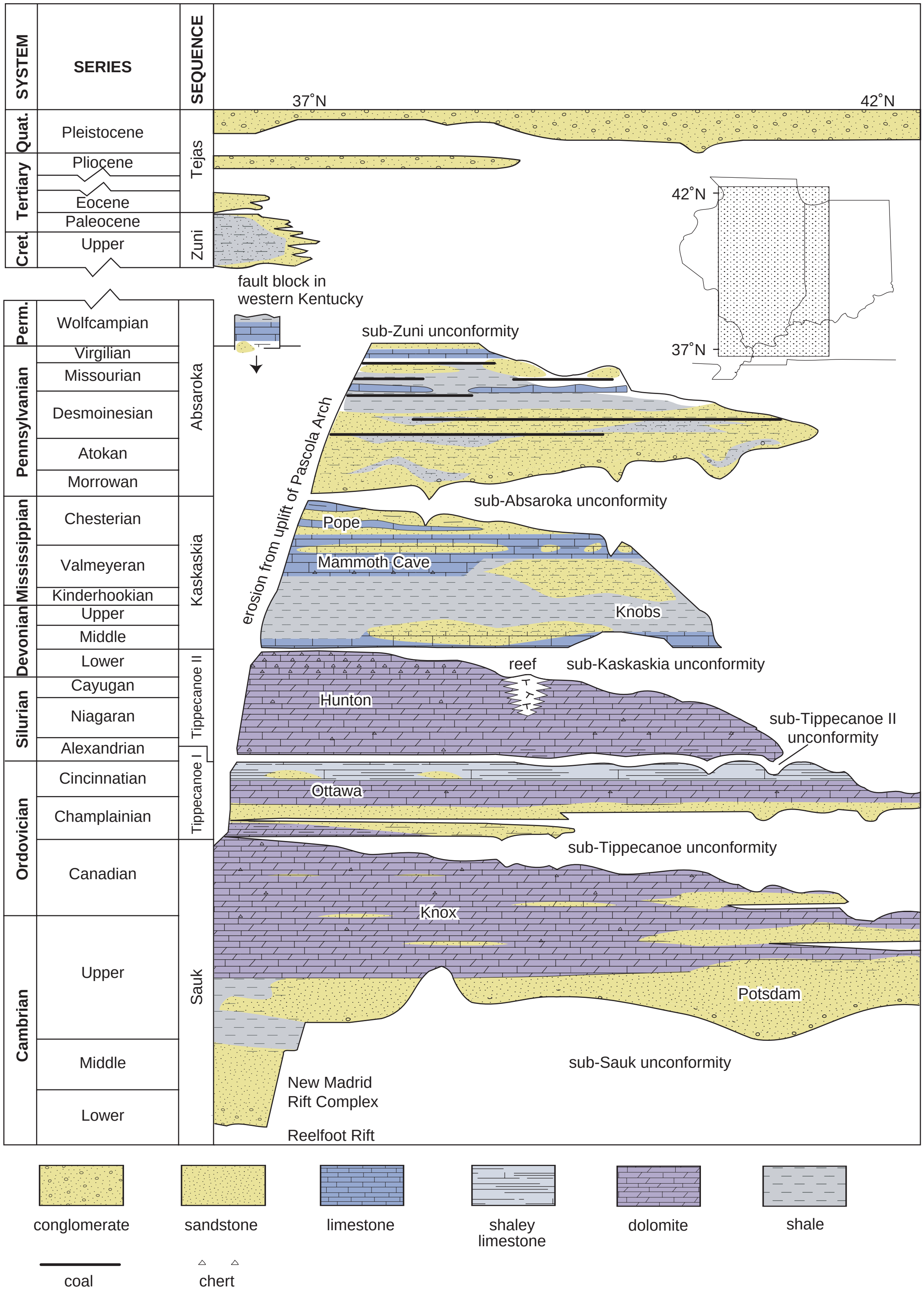

Figure 3 General stratigraphic column, sequences, and megagroups of the Illinois Basin (Swann and Willman 1961, Sloss 1963, Buschbach and Kolata 1991, Kolata 2005). Abbreviations: Cret., Cretaceous; Perm., Permian; Quat., Quaternary.

suggests no differential erosion prior to the deposition of the upper Niagaran Racine Formation. The Racine Formation, however, is characterized by variable thickness and lithology of strata, making well-to-well correlation difficult (Figures 7 through 10).

The variable thickness and lithologies in the lower part of the Racine Formation (see Figures 7 through 10) are interpreted to be the consequence of global sea level fall and differential post-depositional erosion, thus indicating the presence of an erosional unconformity within the Racine Formation (Y. Lasemi 2009a, 2009b). The presence of an unconformity within the Niagaran deposits was first suggested by Whiting and Oros (1957) in the vicinity of the study area. The differential erosion along this unconformity is as much as 70 feet (21 m) in parts of the study area (e.g., compare the Texas Co. Dipper No. 1 with Pawnee Oil & Gas, Inc. Beatty 5 in Figure 8). The intra-Racine unconformity records a major tectono-eustatic sea level fall during Middle Silurian time and divides the Racine Formation into two depositional sequences (Y. Lasemi 2009a, 2009b).

The interregional unconformity at the top of the Racine Formation is the consequence of a major global sea level fall at the Silurian-Devonian boundary (Sloss 1963, Vail et al. 1977, Haq and Schutter 2008) and could be partly the result of Late Silurian through Middle Devonian upwarping of the Sangamon Arch (Y. Lasemi 2009a, 2009b). Prolonged exposure of the Sangamon Arch resulted in partial erosion of the Silurian deposits and formation of an uneven topography that was later buried by the Upper Devonian to lowermost Mississippian New Albany Shale. The uneven topography is well displayed on the isopach map of the New Albany Shale Group (Figure 11) and the structural contour map on the top of the Silurian succession (Figure 12), which shows several noses and a few minor closures. The irregular erosional topography is also illustrated by the stratigraphic cross sections that are hung on the base or top of marker horizons within the Silurian deposits (Figures 7 through 10). The New Albany Shale Group generally becomes thin-

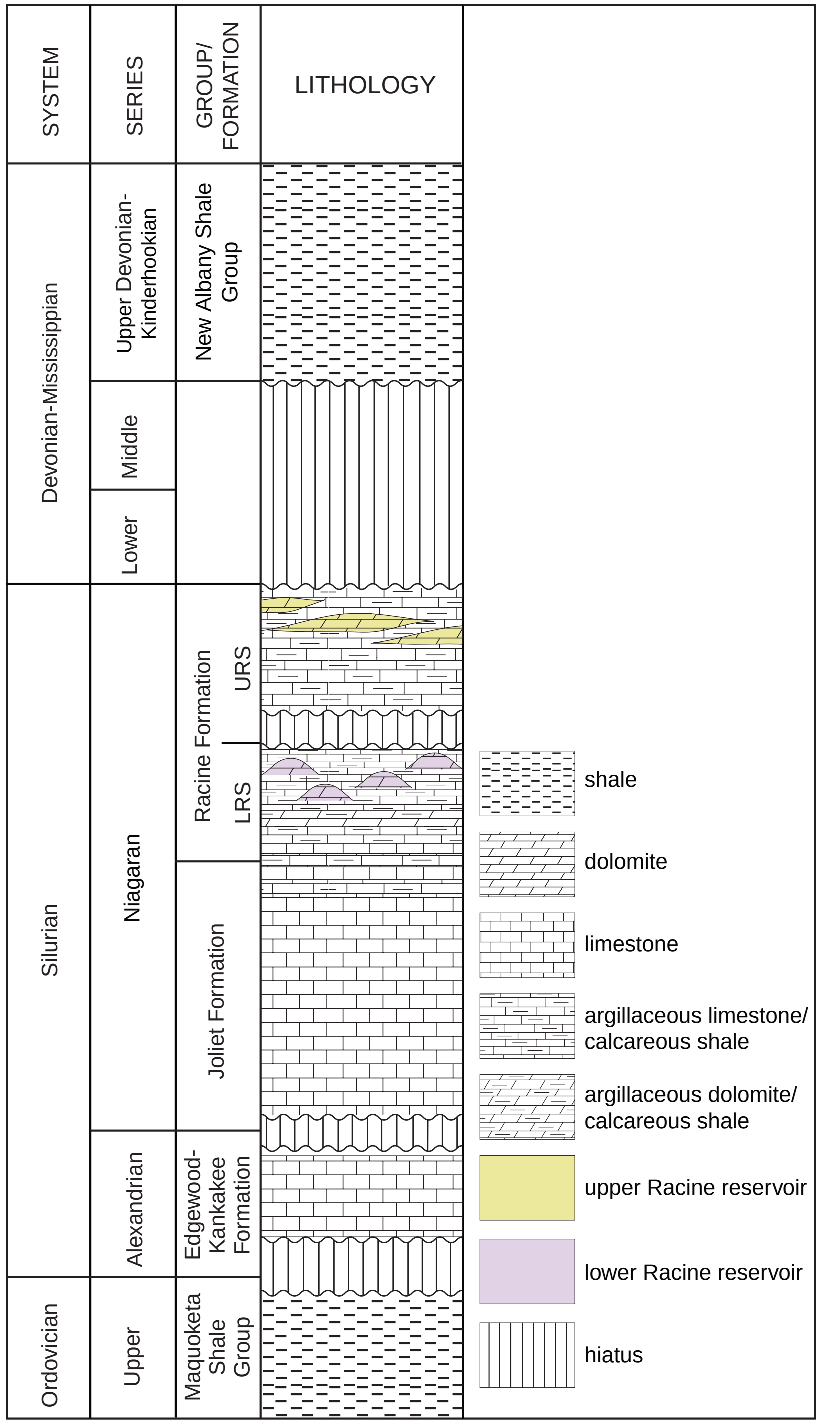

Figure 4 General stratigraphic column of the Upper Ordovician to lowermost Mississippian strata in the Sangamon Arch area. Note that the Lower and Middle Devonian deposits are absent in the Sangamon Arch area because of the pronounced sub-Kaskaskia unconformity and that the New Albany Shale Group rests on the Silurian strata. An unconformity subdivides the Racine Formation into lower and upper sequences. Note that non-reef reservoirs occur in the upper part of the upper sequence, but coral patch reefs exist in the upper part of the lower sequence. Abbreviations: LRS, lower Racine sequence; URS, upper Racine sequence.

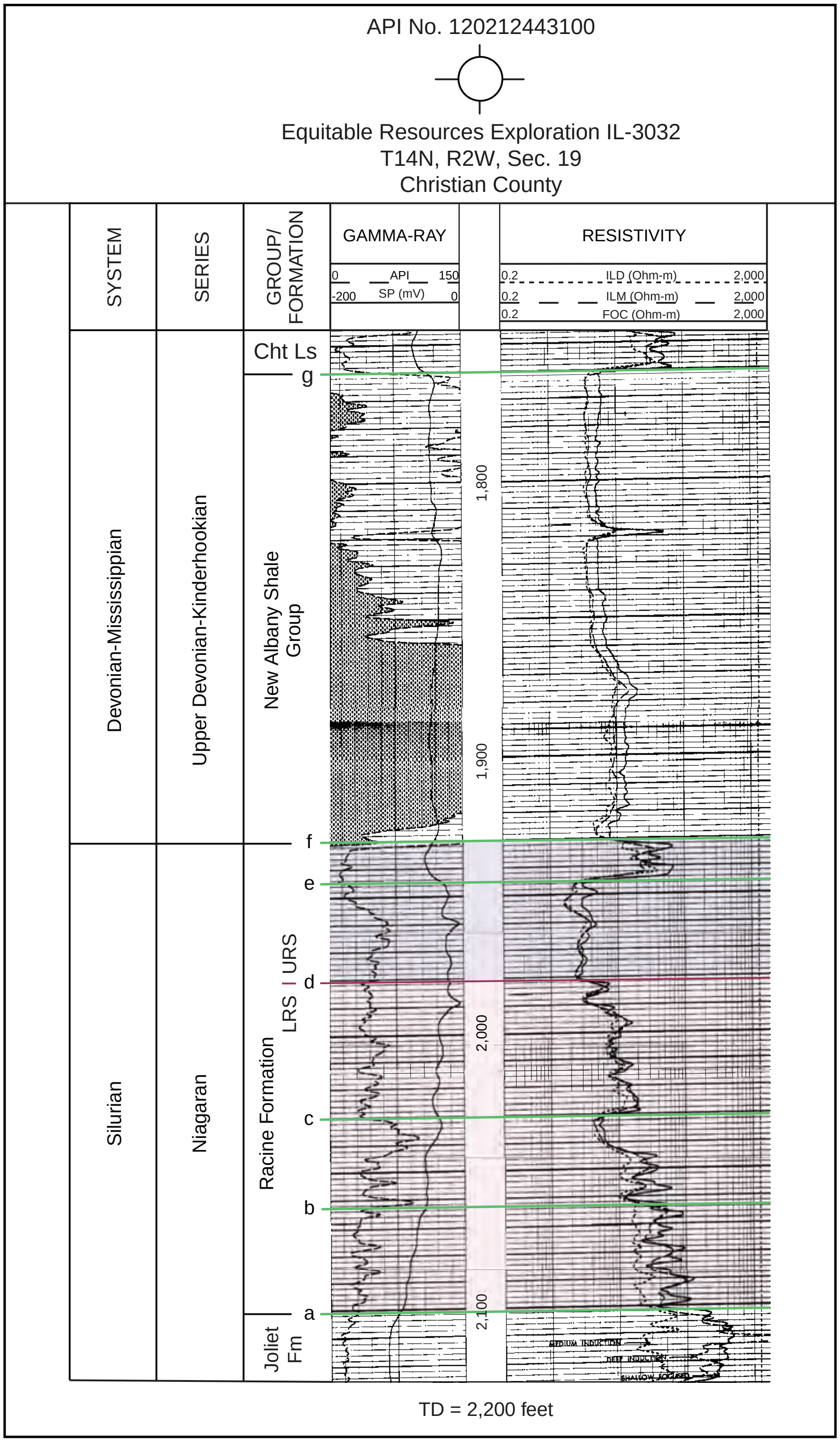

Figure 5 Subsurface gamma-ray and electric log stratigraphic reference section for the Mt. Auburn trend. Significant and laterally continuous geophysical horizons are designated with letters a through g. Abbreviations: Cht Ls, Chouteau Limestone; Fm, Formation; FOC, focused; ILD, induction log deep; ILM, induction log medium; LRS, lower Racine sequence; SP, self-potential; TD, total depth; URS, upper Racine sequence.

ner toward the east and southeast on the Mt. Auburn trend, a positive Silurian remnant, but thickens toward the west and northwest along the crest of the arch, where the Silurian rocks are deeply eroded (Figures 10 and 11). The thickening of the New Albany could be explained by differential compaction of the shale over the Silurian erosional remnant and by increased accommodation space for shale deposition, probably as a consequence of the downwarping of the Sangamon Arch area during Late Devonian time.

The thickness of the Racine Formation is fairly uniform along the Mt. Auburn trend (cross section C–C′ in Figure 9). However, the thickness of the Racine Formation generally decreases toward the west and northwest and increases toward the northeast and east of the study area (Figures 7, 9, and 10). The Racine Formation reaches a maximum thickness of 235 feet (70.5 m) in the Forsyth Field (Triple G Oil Co. Schwarze-Pense Community No. 2 well in Figure 9) in Macon County. About 50 miles (80 km) to the east of the study area in Douglas County (Villa Grove Quadrangle, T16N, R9E, Sec. 30), Mikulic and Kluessendorf (2001) assigned over 400 feet (120 m) of the upper part of the Silurian succession to the Moccasin Springs Formation (equivalent to the Racine Formation of the Sangamon Arch). In Grafton Quarry (Jersey County) in western Illinois, about 75 miles (120 km) to the southwest of the study area, the uppermost Silurian interval of about 45 feet (14 m) that overlies the Joliet Formation was assigned to the Racine Formation by Willman and Atherton (1975). This youngest Silurian interval was recently correlated with the Sugar Run Formation, a lithostratigraphic unit underlying the Racine Formation in northeastern Illinois (Mikulic and Kluessendorf 2000).

Cyclostratigraphy

The erosional unconformity within the Racine Formation divides the Racine Formation into two third-order cycles (Y. Lasemi 2009a, 2009b) or depositional sequences (in the sense of Vail et al. 1977 and Van Wagoner et al. 1988). Theses cycles are designated as lower

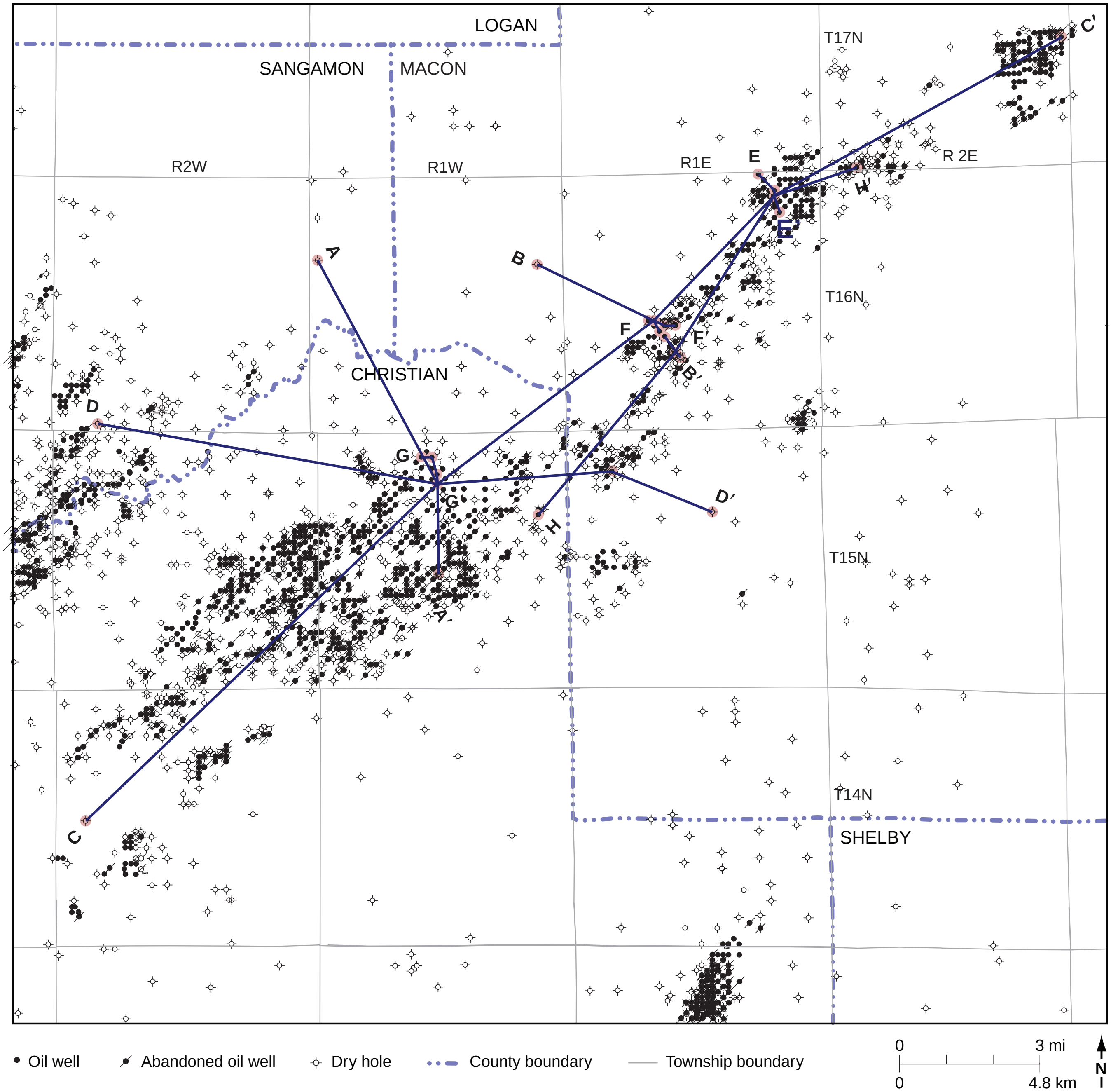

Figure 6 Map of the Mt. Auburn trend area showing the lines of stratigraphic cross sections A–A′ through H–H′.

Racine sequence and upper Racine sequence to facilitate descriptions of the petroleum reservoirs of the Mt. Auburn trend.

Each third-order cycle consists of smaller-scale fourth-order cycles (Figure 13). In the third-order transgressive tract, radioactivity increases upward and attains a maximum value at the maximum flooding surface (e.g., depths 1,962 feet and 1,884 feet in Figure 13). In the third-order regressive tract, however, radioactivity generally decreases upward (Figures 13). The regressive tracts are incomplete due to post-depositional erosion.

Smaller-scale high-frequency fifth- to sixth-order cycles are also distinguishable (see Figure 13). The petroleum reservoirs in the Racine Formation commonly constitute the upper part of high-frequency fourth-order transgressive-regressive cycles (Figures 13 through 15).

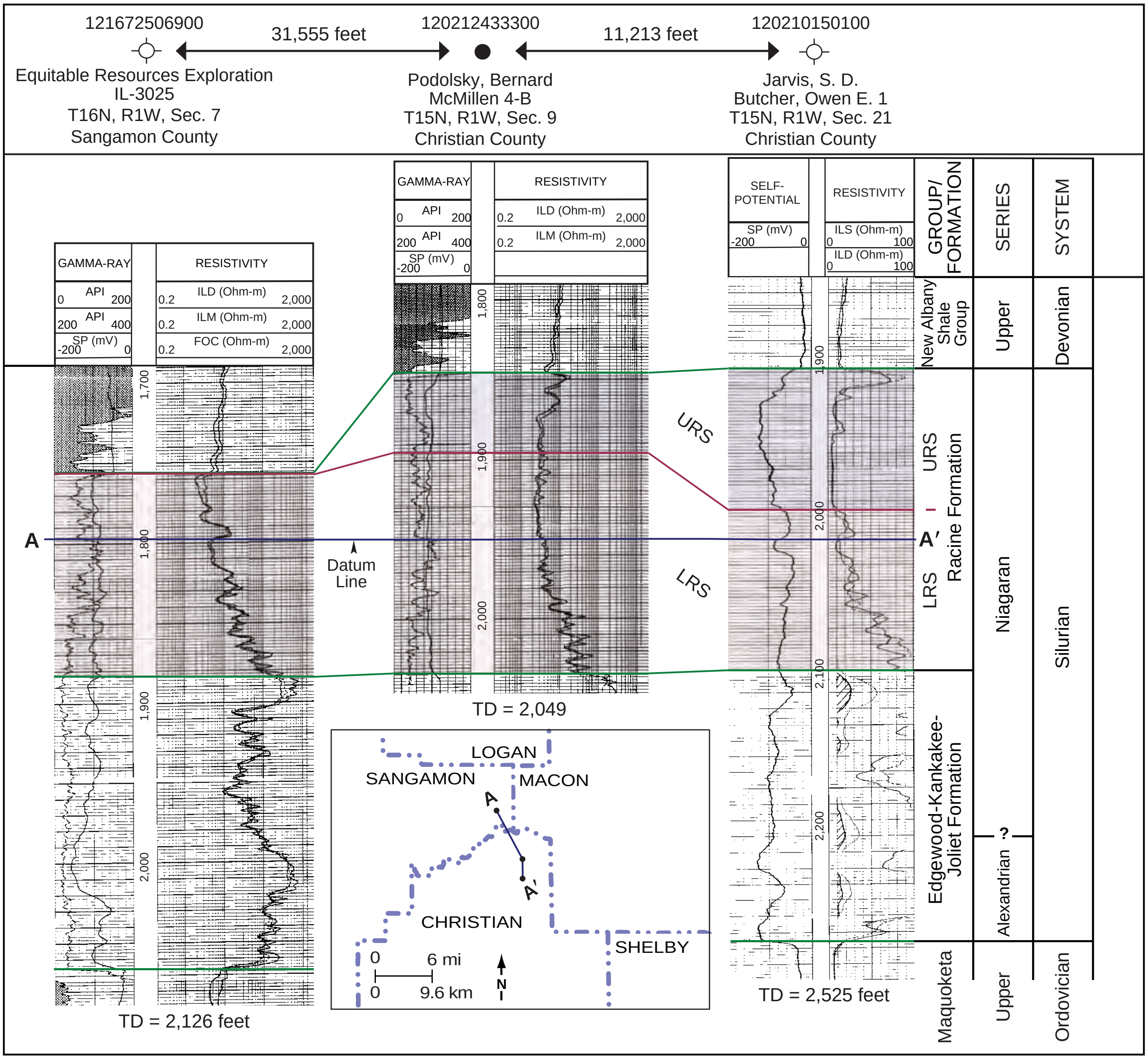

Figure 7 Northwest-southeast stratigraphic cross section A–A′ across the Mt. Auburn trend showing the Racine Formation sequences and the lateral variations in their thickness and lithology as a result of post-depositional erosion. Note that the Silurian rocks underlying the Racine Formation (mainly resistive limestone) display fairly uniform thickness. Datum (labeled A–A′) is horizon c (see Figure 5) within the lower sequence. Abbreviations: FOC, focused; ILD, induction log deep; ILM, induction log medium; ILS, induction log shallow; LRS, lower Racine sequence; Ls, Limestone; SP, self-potential; TD, total depth; URS, upper Racine sequence.

Petroleum Reservoirs and Seals

The Racine Formation along the Mt. Auburn trend comprises several permeability pinch-out zones (herein referred to as reservoir units) at different horizons. These zones generally include dolomitized wackestone to grainstone facies in the upper Racine sequence and dolomitized coral patch reef/reef rudstone facies in the lower Racine sequence (Figure 4). The zones are interlayered with laterally extensive impermeable units that have formed flow barriers dividing the Racine Formation into stratigraphic cycles of impervious and porous horizons (Figures 13, 14, and 15). The reservoir units are light yellowish brown, due to oil staining, instead of the light gray

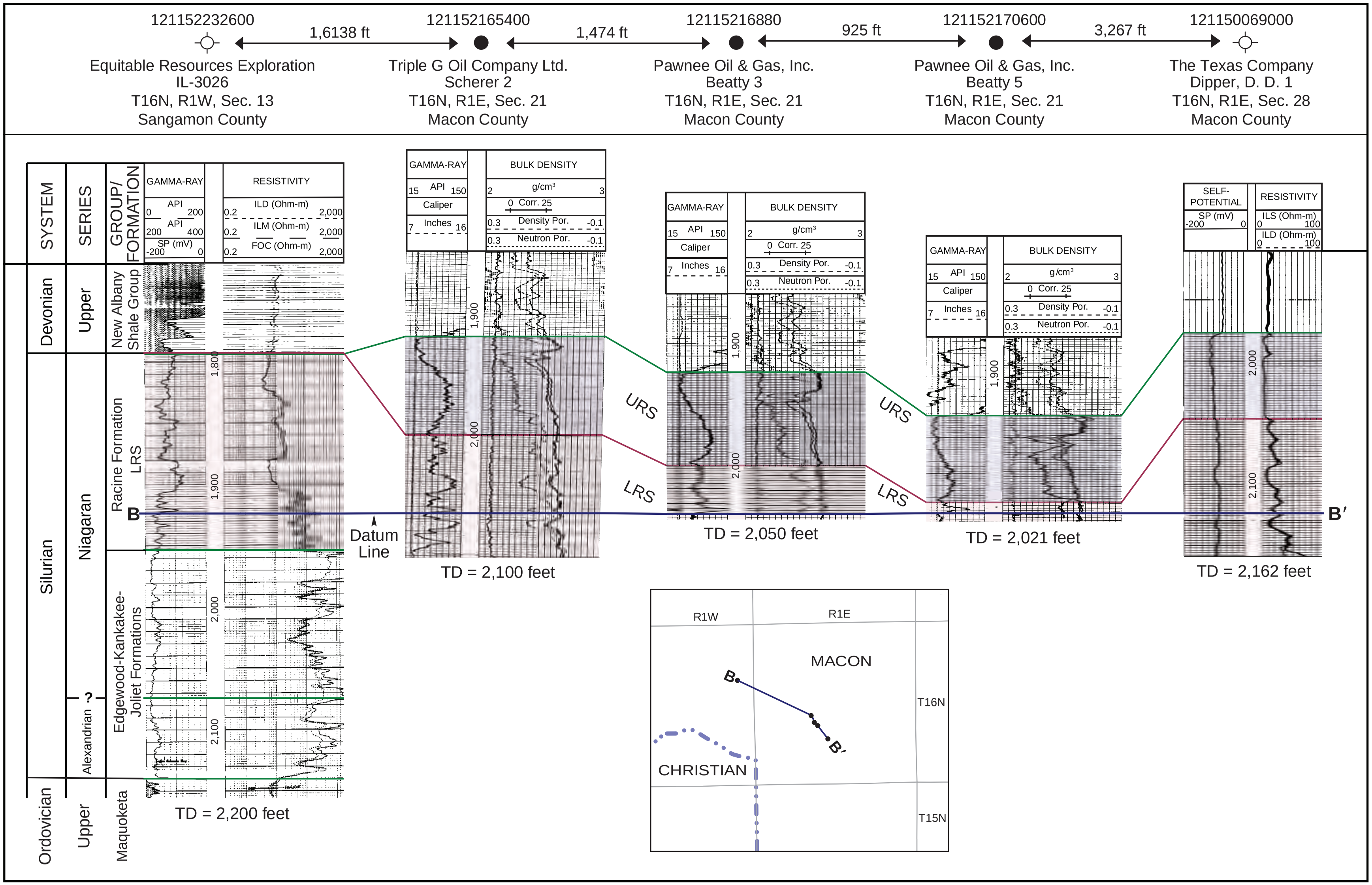

Figure 8 Stratigraphic cross section B–B′ across the Mt. Auburn trend showing the lateral distribution of the Racine Formation. Note the erosional truncation and uneven topography in the upper boundary of the lower and upper Racine sequences. Note also that the lower Racine sequence thickens and the upper sequence pinches out toward the northwest. Datum horizon (labeled B–B′) is below the thin radioactive layer shown as horizon b in Figure 5. Abbreviations: Corr., correction; FOC, focused; ILD, induction log deep; ILM, induction log medium; ILS induction log shallow; LRS, lower Racine sequence; Por., porosity; SP, self-potential; TD, total depth; URS, upper Racine sequence.

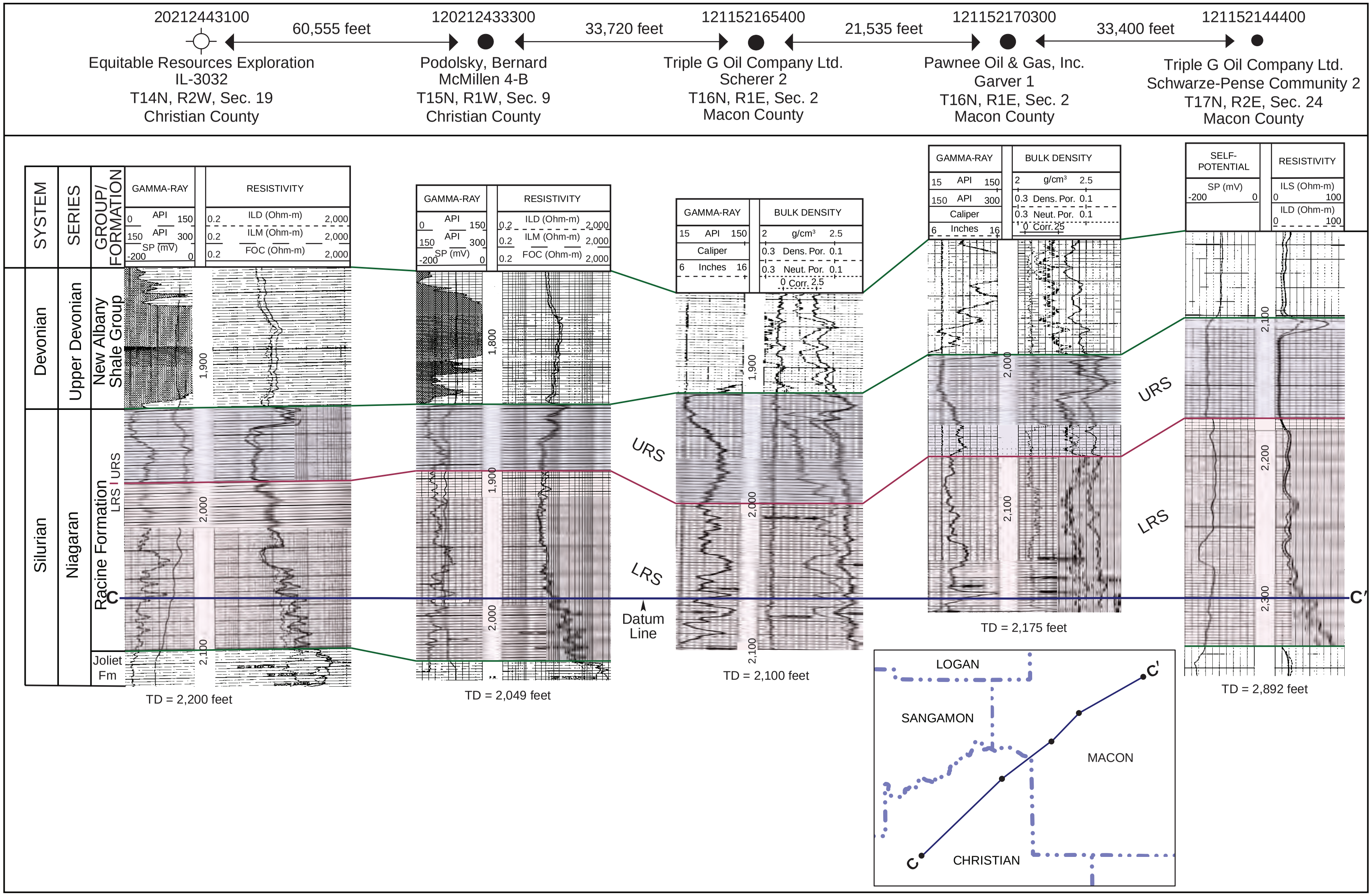

Figure 9 Stratigraphic cross section C–C′ along the Mt. Auburn trend showing rather uniform thickness and lithology for the Racine sequences. Datum horizon (labeled C–C′) is below the thin radioactive layer within the lower sequence shown as horizon b in Figure 5. Abbreviations: Dens., density; FOC, focused; Fm, Formation; ILD, induction log deep; ILM, induction log medium; IRS, induction log shallow; LRS, lower Racine sequence; Neut., neutron; Por., porosity; SP, self-potential; TD, total depth; URS, upper Racine sequence.

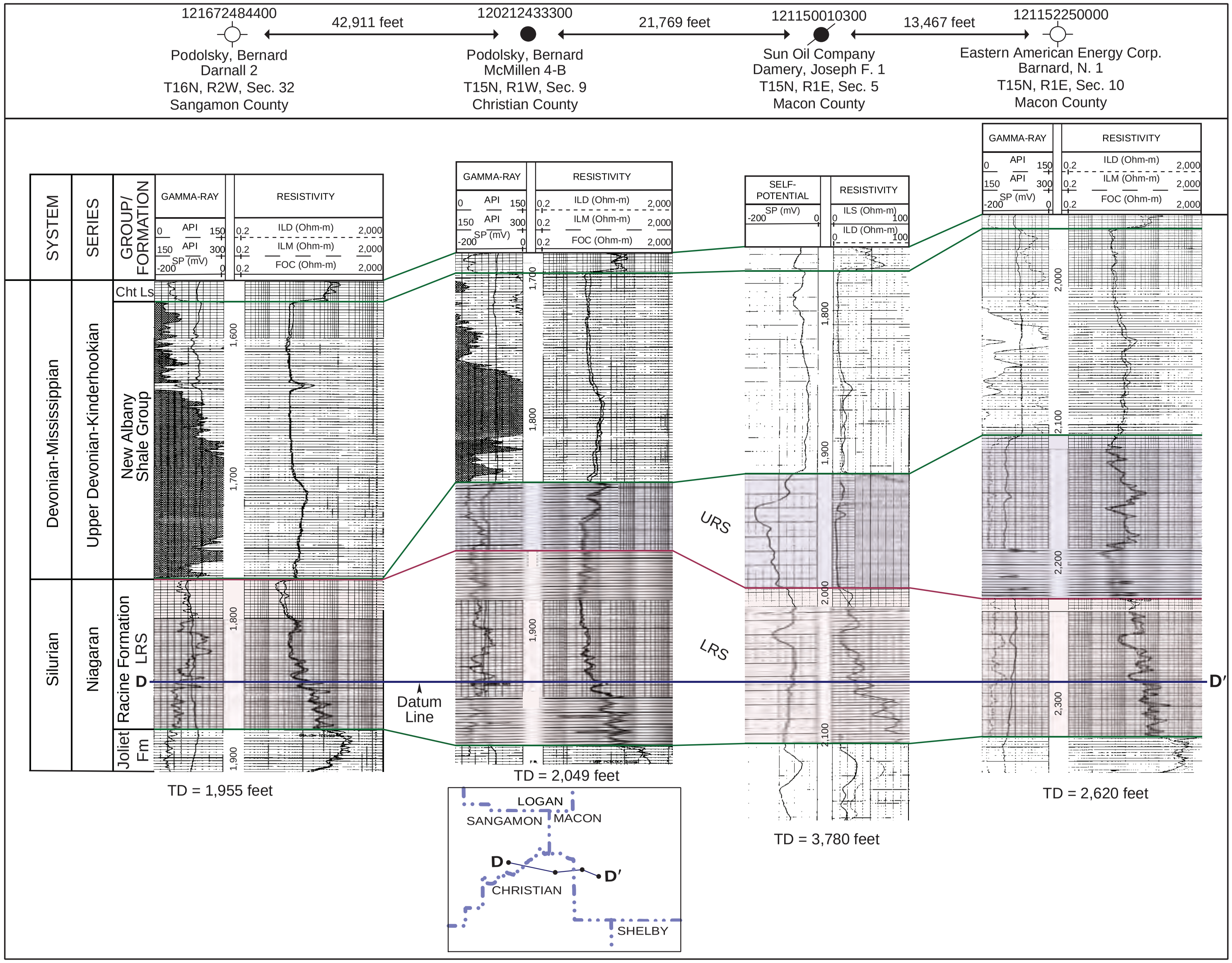

Figure 10 Cross section D–D′ across the Mt. Auburn trend showing erosional truncation and uneven topography in the upper boundary of the lower and upper Racine sequences. Note that the New Albany Shale Group thickens, but the Racine Formation becomes thinner toward the west. Datum (labeled D–D′) is the same as datum for Figure 9 (shown as horizon b in Figure 5). Abbreviations: Cht Ls, Chouteau Limestone; Fm, Formation; FOC, focused; ILD, induction log deep; ILM, induction log medium; ILS, induction log shallow; LRS, lower Racine sequence; URS, upper Racine sequence; SP, self-potential; TD, total depth.

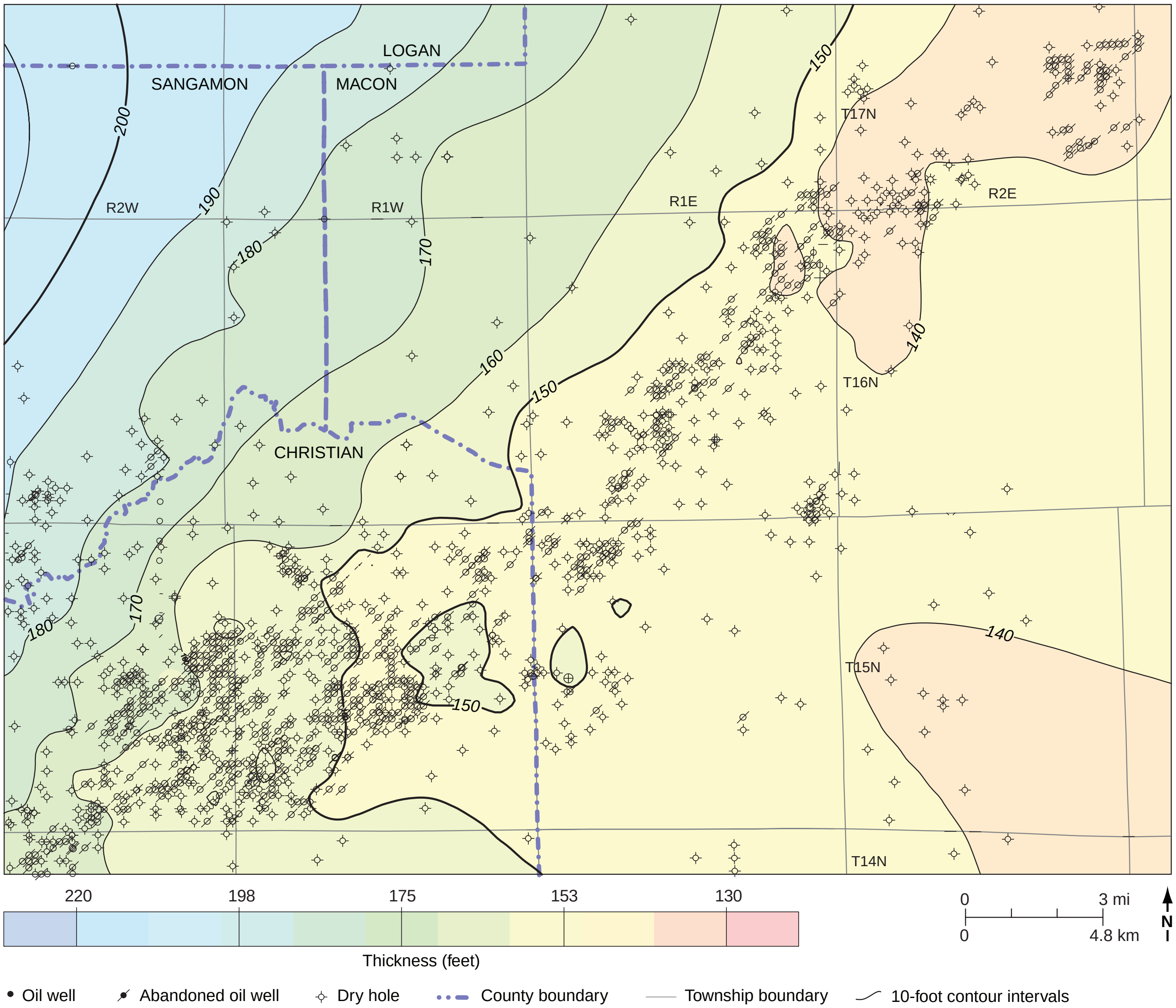

Figure 11 Thickness map of the New Albany Shale Group from the top of the Silurian to the base of the Chouteau Limestone. The New Albany Shale Group thickens toward the northwest, away from the Mt. Auburn trend and toward the center of the Sangamon Arch (see Figure 1 for the location of the Sangamon Arch), suggesting that the arch area was subsiding at the onset of the Upper Devonian deposition. The closures in the Mt. Auburn trend area are due to pre-Devonian differential erosion.

that is typical of non-reservoir facies. The reservoir units are defined here on the basis of facies and their stratigraphic position and are designated, from top to base, as non-reef reservoir units A, B, and C and patch reef/reef rudstone reservoir unit D. Individual reservoirs may show internal vertical porosity variations (e.g., the high-frequency fifth-order cycles and core photographs from the Bernard Podolsky McMillen 4-B well in Figure 13).

No structural closures are present in the study area, and minor closures in some areas of the Sangamon Arch are the consequence of post-depositional erosion and the formation of uneven topography at the sequence boundaries (Y. Lasemi 2009c). A combination of depositional and diagenetic stratigraphic traps controlled petroleum entrapment in the Mt. Auburn trend, and the reservoirs are normally sealed by lime mudstones to packstones that were deposited in quiet water environments following the flooding stages of high-frequency sea level cycles (Y. Lasemi 2009c).

Non-reef Reservoir Units A, B, and C

Non-reef reservoir units A, B, and C occur in the upper part of the upper sequence of the Racine Formation (Figure 4). They are characterized by

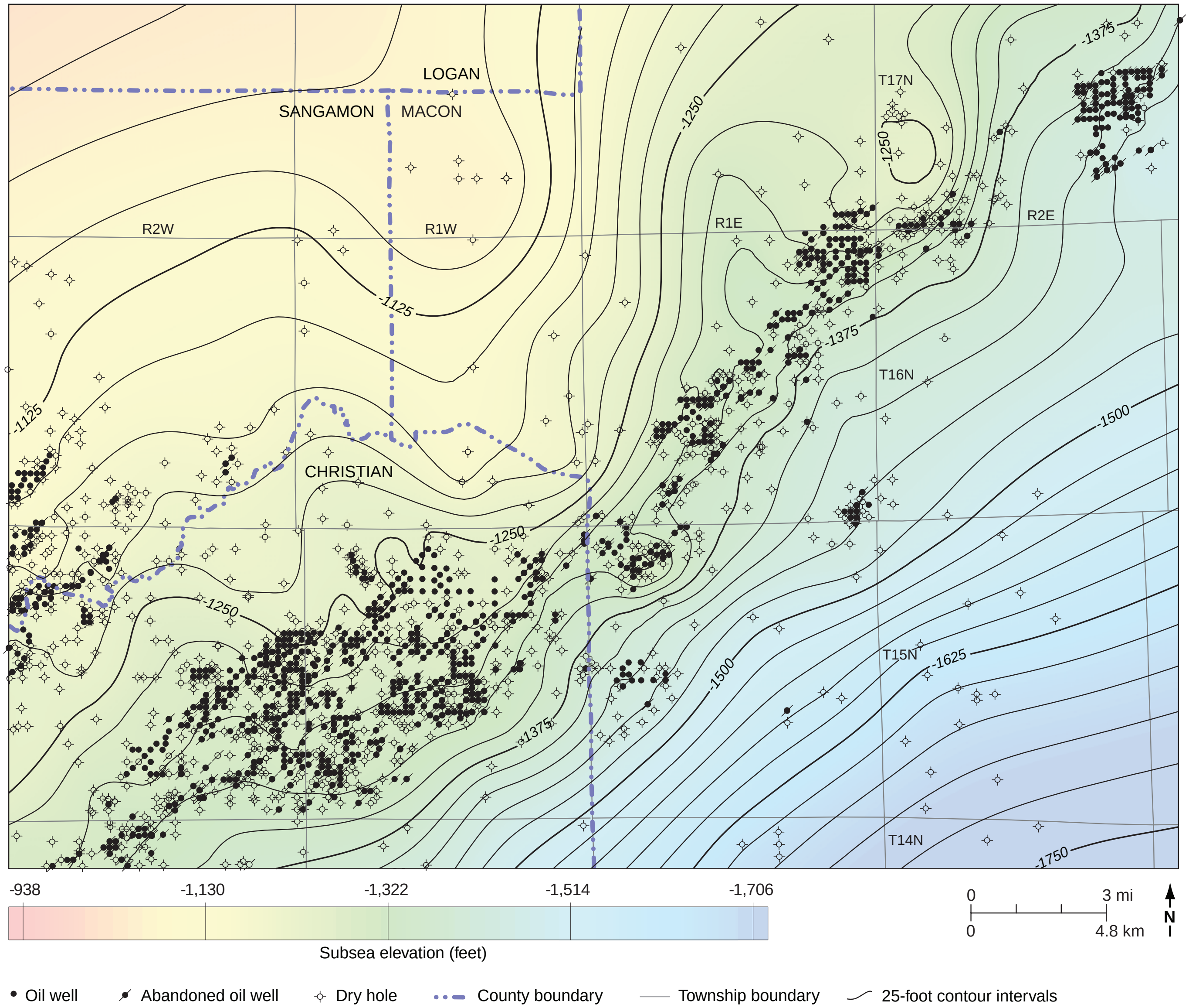

Figure 12 Structure contour map of the base of the New Albany Shale Group showing the direction of the regional dip toward the southeast. Note minor closures and noses that are due to uneven pre-New Albany Shale Group topography.

porous dolomitized wackestone to grainstone (Figures 13; 16c, d; and 17a, b). The reservoirs contain partially dolomitized echinoderm fragments (Figures 16d and 17b) and molds of bioclasts that include crinoids, brachiopods, corals, and non-recognizable grains (Figure 17b). In some areas or in some horizons within a reservoir, only dolomite crystals are recognized, but they contain a very faint relict shadowing that could represent the organic residue of the original bioclasts that they replaced (Figure 17a). The reservoirs are lenticular (Figures 18, 19, and 20) and are encased within impermeable host limestone strata (Figure 16a, b) displaying cyclic patterns of non-reservoir to reservoir packages (Figures 4, 13, 14, 15, 21, 22, and 23). Porosity of the reservoir rocks exceeds 20% in some horizons. The highest reported initial production was 1,360 barrels of oil per day in the Comanche Oil Co. No. 3 Tomlin well, T15N, R2W, Sec. 7, Mt. Auburn Consolidated Field, in Christian County. Examination of the numerous wells in the Mt. Auburn trend indicates that most of the wells drilled thus far have only tested the upper part of the upper sequence of the Racine Formation.

Reservoir Unit A Unit A is a lenticular dolomite reservoir of limited lateral extent (Figure 18) that is recognized in the uppermost part of the upper Racine sequence (Figures 14, 15, 21, 22, and 23). Reservoir unit A is up to 14 feet (4 m) thick and is separated from unit B or C by up to 10 feet (3 m)

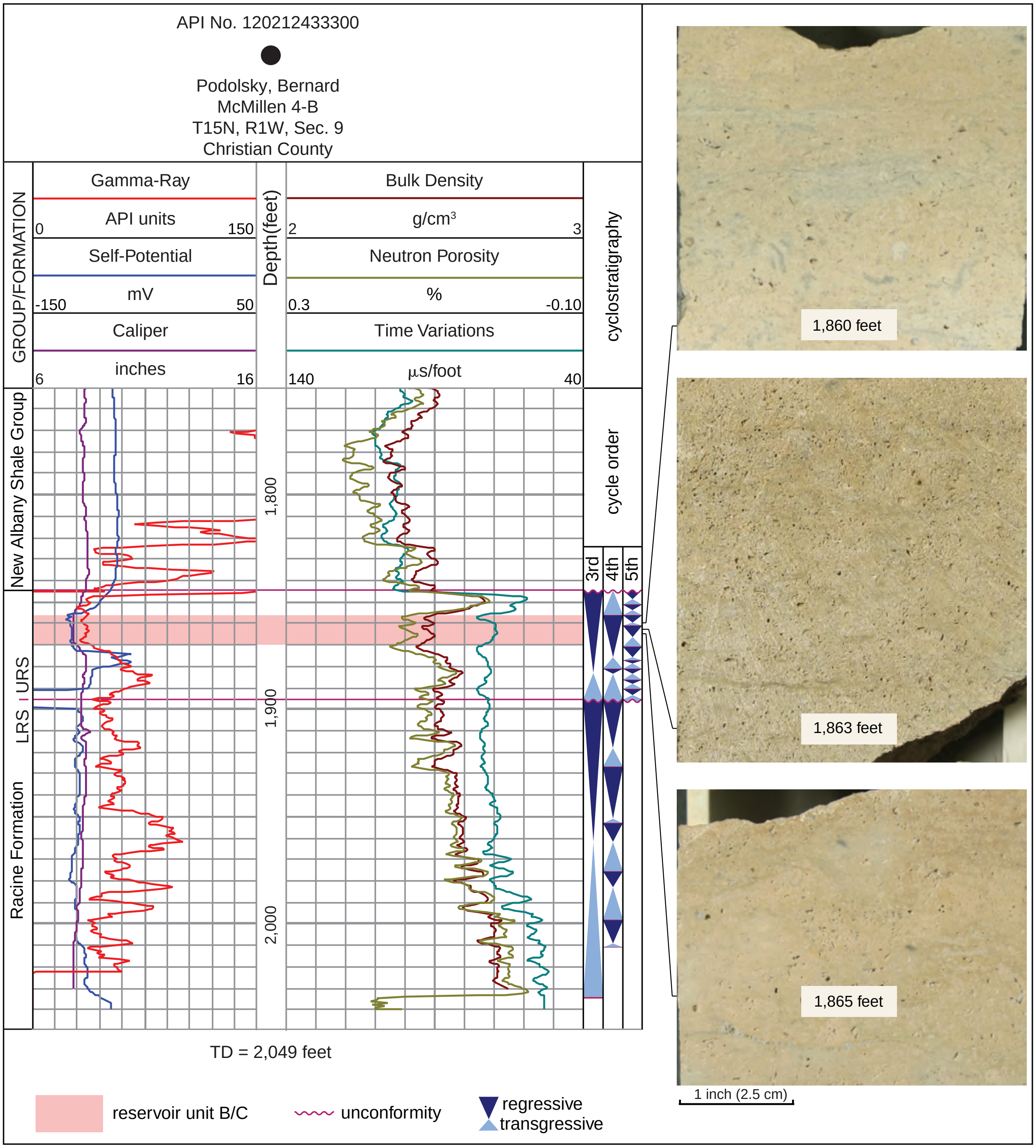

Figure 13 Digitized log and core photographs of the reservoir interval (reservoir unit B/C) in the Bernard Podolsky McMillen 4-B well in the Mt. Auburn Consolidated Field in Christian County. Vertical facies variations and cyclostratigraphy of the Racine Formation are shown. Note the reservoir development in the upper part of a fourth-order cycle within the regressive (highstand) deposits of the upper Racine sequence. Note also vertical porosity variations in the reservoir shown in the core photographs and fifth-order cycles. Grain size is larger, and porosity is higher, in the regressive portion of the cycles (rock at 1,863 feet is more porous than at 1,860 feet and 1,865 feet). See Figure 16d, e, and f for the petrographic detail of depth 1,863 feet). Abbreviations: LRS, lower Racine sequence; TD, total depth; URS, upper Racine sequence.

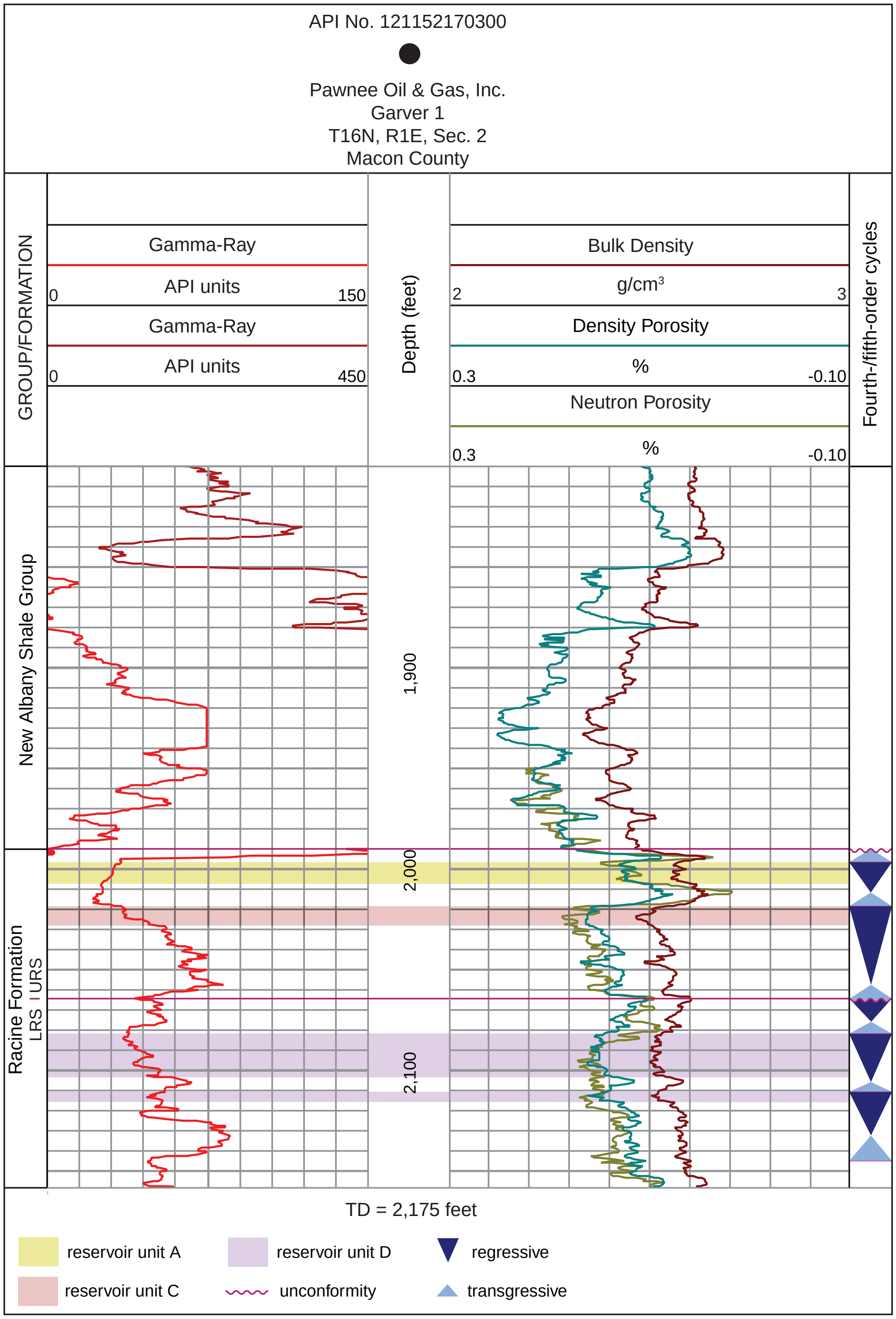

Figure 14 Digitized log of the Pawnee Oil and Gas Inc. Garver No. 1 well in the Harristown Field, Macon County, showing cyclicity and reservoir development in the Racine Formation sequences. Note the development of reservoir units A and C in the upper sequence and reservoir unit D in the lower sequence (no cores/samples are available for this well, and the differentiation of reef and non-reef reservoirs is based on stratigraphic correlation). Note also that the reservoirs occur in the upper part of fourth-order cycles within the shallowing-upward portion (highstand tract) of the third-order cycles. Abbreviations: LRS, lower Racine sequence; TD, total depth; URS, upper Racine sequence.

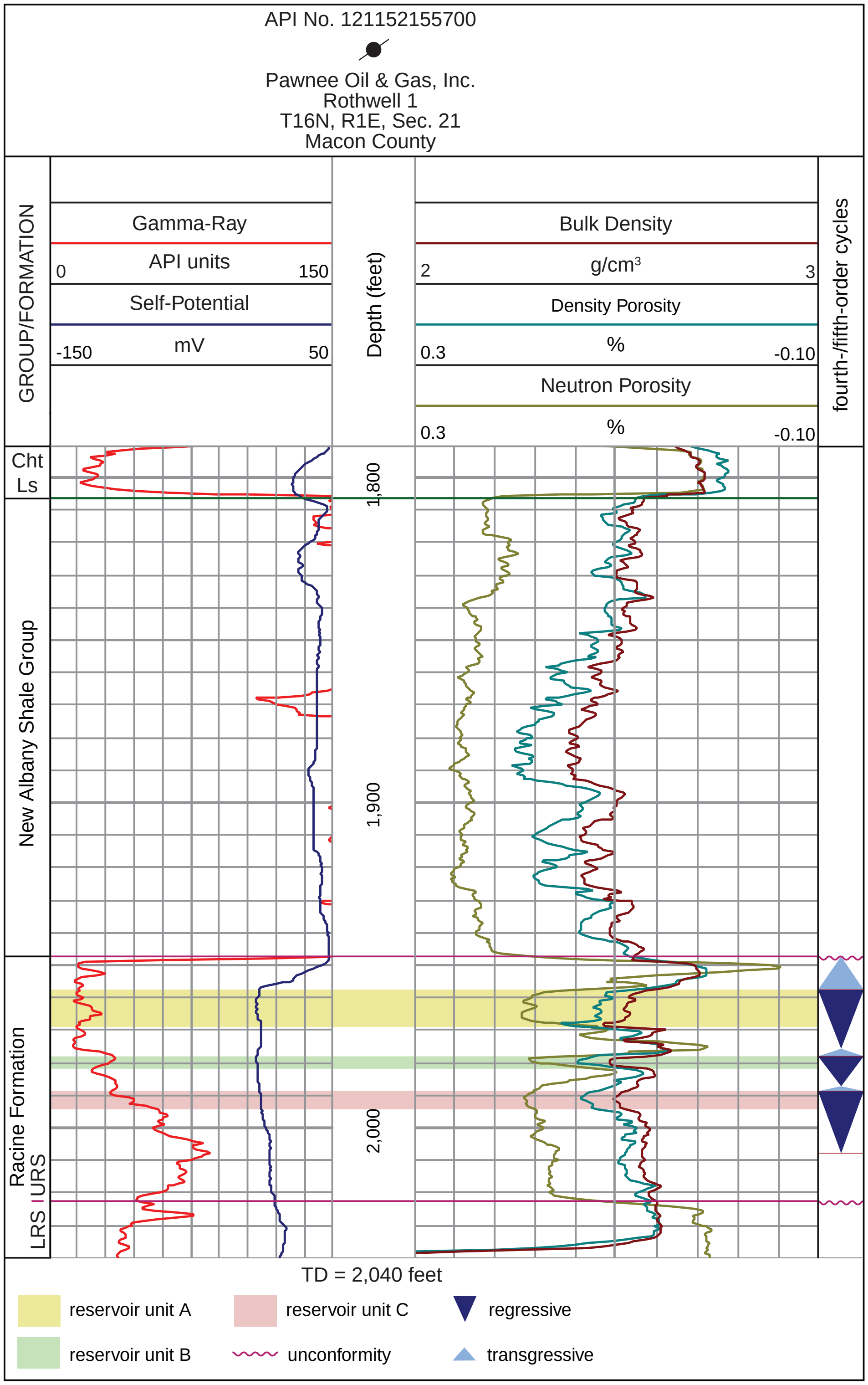

Figure 15 Digitized log of the Pawnee Oil and Gas Inc. Rothwell No. 1 well in the Blackland North Field in Macon County showing the development of non-reef reservoir units A, B, and C in the upper part of the upper Racine sequence. Note the occurrence of the reservoirs in the regressive portion of fourth-order depositional cycles. Abbreviations: Cht Ls, Chouteau Limestone; LRS, lower Racine sequence; TD, total depth; URS, upper Racine sequence.

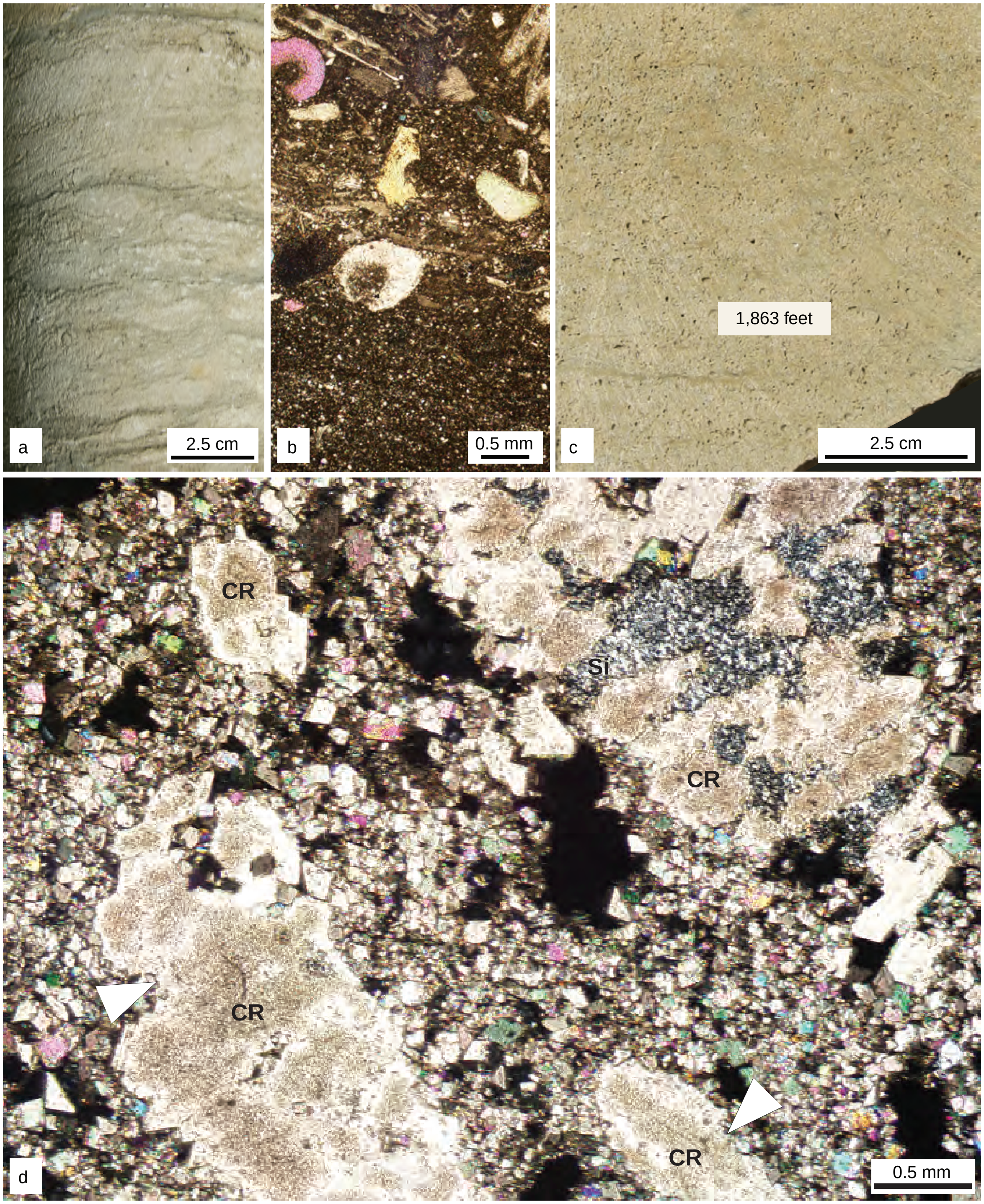

Figure 16 (a) Core photograph of a bioturbated lime mudstone to wackestone facies in the Pawnee Oil Corp. Elder No. 1 well, T15N, R1W, Sec. 12, in the Mt. Auburn Consolidated Field in Christian County that caps a dolomitized patch reef reservoir. (b) Photomicrograph of a coarsening-upward lime mudstone to bryozoan crinoid wackestone facies from an impermeable capping limestone. The groundmass is partially replaced by very finely crystalline dolomite. (c) Polished core slab photograph of a porous dolomitized grainstone facies (also shown in Figure 13). (d) Photomicrograph of a part of c under polarized light showing an irregular dolomitization front (arrows) on crinoid fragments (CR), dolomite rhombs, and void spaces (black) formed as a result of dolomitization. Note that the crinoid fragment in the upper right is partially silicified (SI).

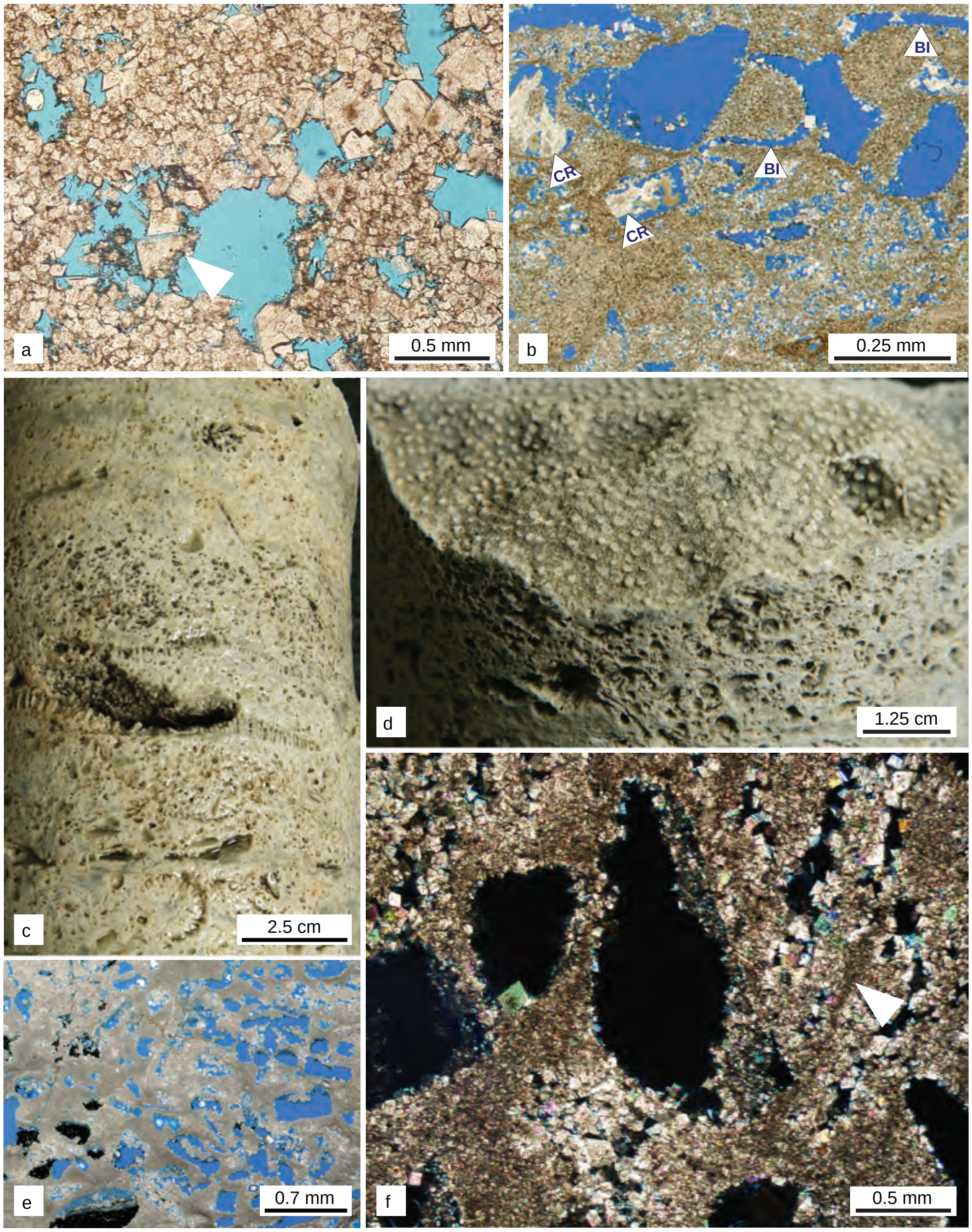

Figure 17 Photomicrographs a and b are from reservoir unit C in Bernard Podolsky McMillen 4-B well (depth 1,859, see Figure 13), T15N, R1W, Sec. 9, in the Mt. Auburn Consolidated Field in Christian County. (a) Porous dolomitized non-reef reservoir under plane light in which the original texture has been destroyed by pervasive dolomitization. Note the partial dissolution of the dolomite rhombs and enlargement of the pore spaces (arrow). (b) Photomicrograph of a non-reef wackestone reservoir showing partially preserved crinoids (CR) and molds of bivalves (BI) and other unrecognizable grains in a finely crystalline dolomite groundmass. Core photographs c, d, e, and f are of a patch reef reservoir unit D in the Pawnee Oil Corp. Elder No. 1 well (depth 2,005 feet, see Figure 24), T15N, R1W, Sec. 12, in the Mt. Auburn Consolidated Field in Christian County. (c, d) Dolomitized reef facies composed mainly of coral skeletons. (e) Photomicrograph of a thin section of d showing vuggy porosity as a result of dissolution of the skeletons, which are hardly recognizable in thin section. (f) Photomicrograph of an enlarged portion of e. Note the organic residue of the original skeletons and the dissolution of dolomite rhombs (white arrow) to form larger pore spaces.

of impermeable cherty fossiliferous limestone. This tight limestone is just above marker horizon e (Figure 5) and is a laterally persistent horizon in the Mt. Auburn trend (Figures 7, 8, 9, 10, 21, 22, 23, and 24). Reservoir unit A is capped by impermeable limestone of variable thickness (Figures 14, 15, 21, 22, and 23), but, where it is removed by erosion, the New Albany Shale Group becomes the capping facies for petroleum entrapment (Bernard Podolsky Vail 3-A, Figure 23). In some areas of the Mt. Auburn trend, however, the absence of reservoir unit A may be the result of post-Silurian erosion, which is well illustrated in cross section G–G′ (Figure 23). In some areas of the Mt. Auburn trend, deep erosion has removed the interval that could otherwise include reservoir unit A (Figures 21, 22, and 23). In some areas of the Mt. Auburn trend, reservoir unit A is subdivided into two horizons separated by

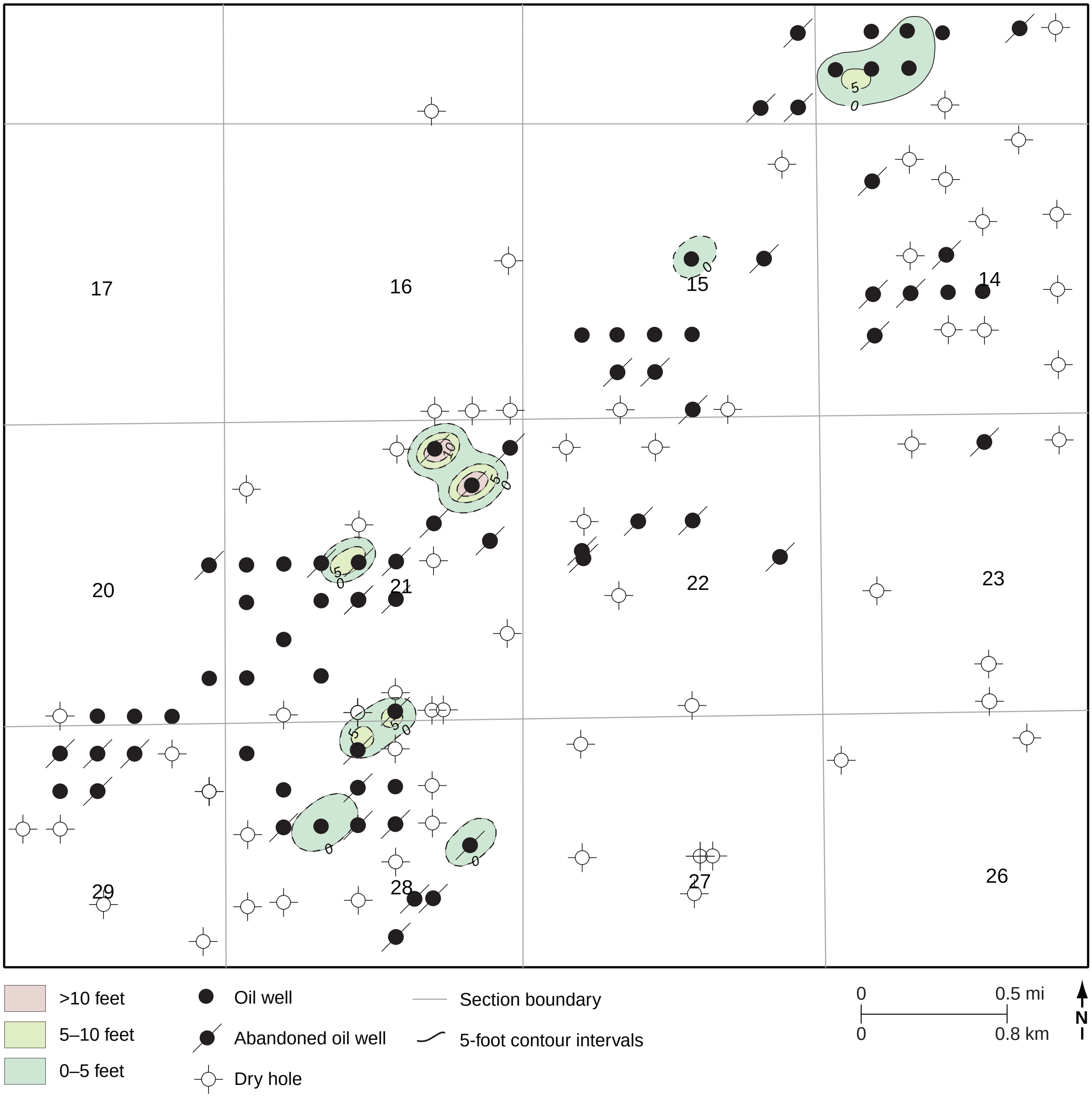

Figure 18 Thickness map of the dolomite reservoir unit A in the Blackland North Field showing a very limited lateral extent of the reservoir due to lateral facies changes and post-Silurian erosion.

a tight impermeable limestone (e.g., Bernard Podolsky McMillen 3-A, Figure 23).

Reservoir Unit B Reservoir unit B is another lenticular dolomitic horizon along the Mt. Auburn trend of the Sangamon Arch, and it is best developed in the Blackland North Field (Figures 2 and 19). Reservoir unit B is up to 5 feet (1.5 m) thick and occurs just below the impermeable and persistent limestone marker below geophysical marker e (Figures 15 and 22). A tight limestone up to 6 feet (2 m) thick separates reservoir unit B from the underlying reservoir unit C. In other fields of the Mt. Auburn trend, either reservoir unit B pinches out, leaving reservoir unit C below the tight limestone as the only reservoir there, or the tight underlying limestone thins out, forming a single combined reservoir of units B and C (Figures 21 and 23).

Reservoir Unit C Reservoir unit C can attain a thickness of over 20 feet

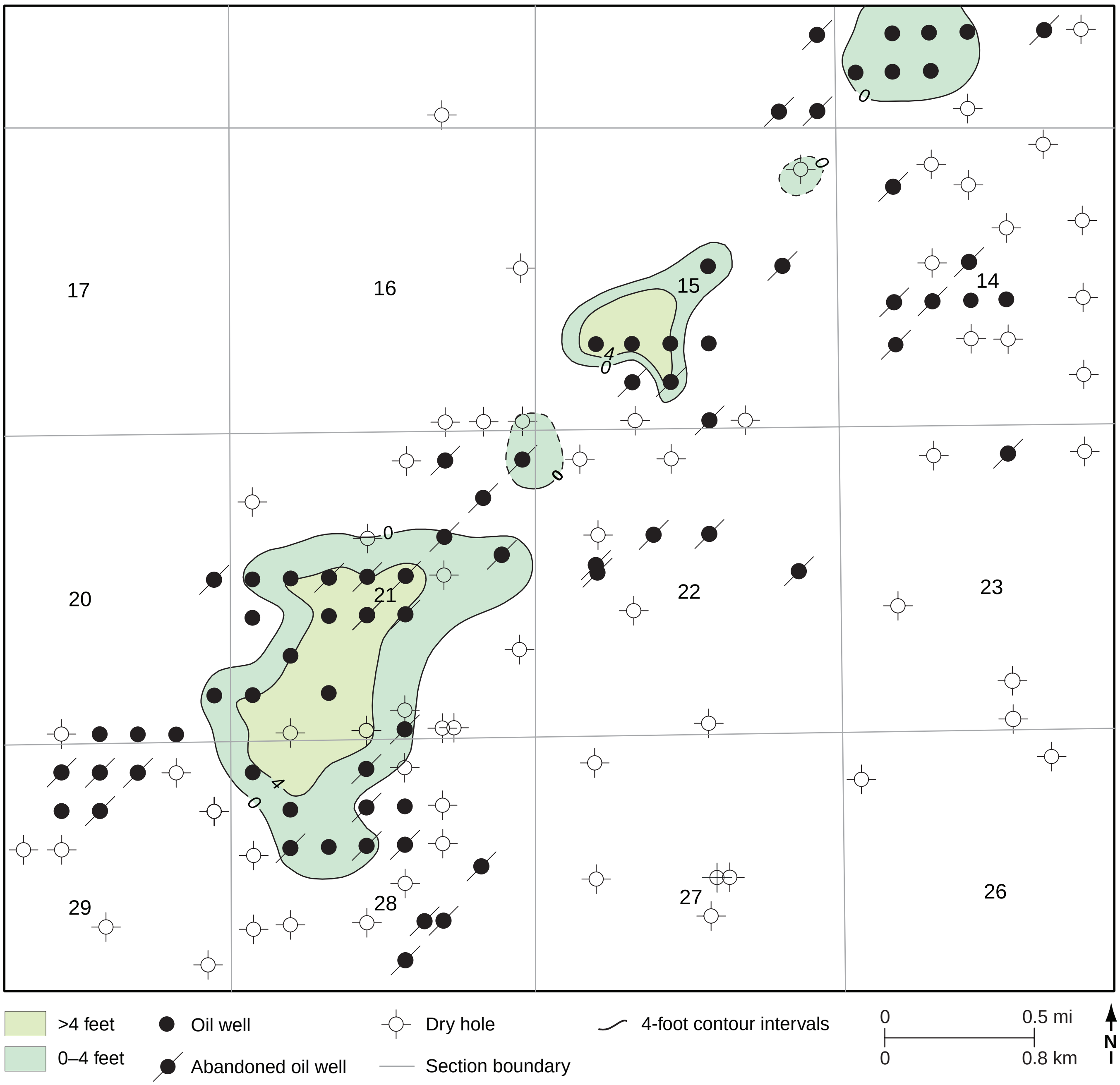

Figure 19 Thickness map of the dolomite reservoir unit B in the Blackland North Field showing the lenticular nature of the reservoir. Note that the reservoir lenses are aligned in a northeast-southwest direction lying roughly parallel to the Mt. Auburn trend.

(6 m) of dolomite in parts of the Mt. Auburn trend and is more extensive than the other reservoirs (Figure 20). It is overlain by up to 6 feet (2 m) of impermeable limestone in Blackland North Field (Figures 15 and 22). This tight limestone thins out laterally beyond the resolution of the geophysical logs (Figures 21 and 23). Due to lateral thinning of this tight limestone, reservoir units B and C may coalesce, forming a single unit C reservoir underlying the widespread impermeable cherty limestone marker just below geophysical marker e (Figures 13, 21, and 23). Reservoir unit C is also lenticular (Figure 20) and pinches out laterally into impermeable facies (e.g.,

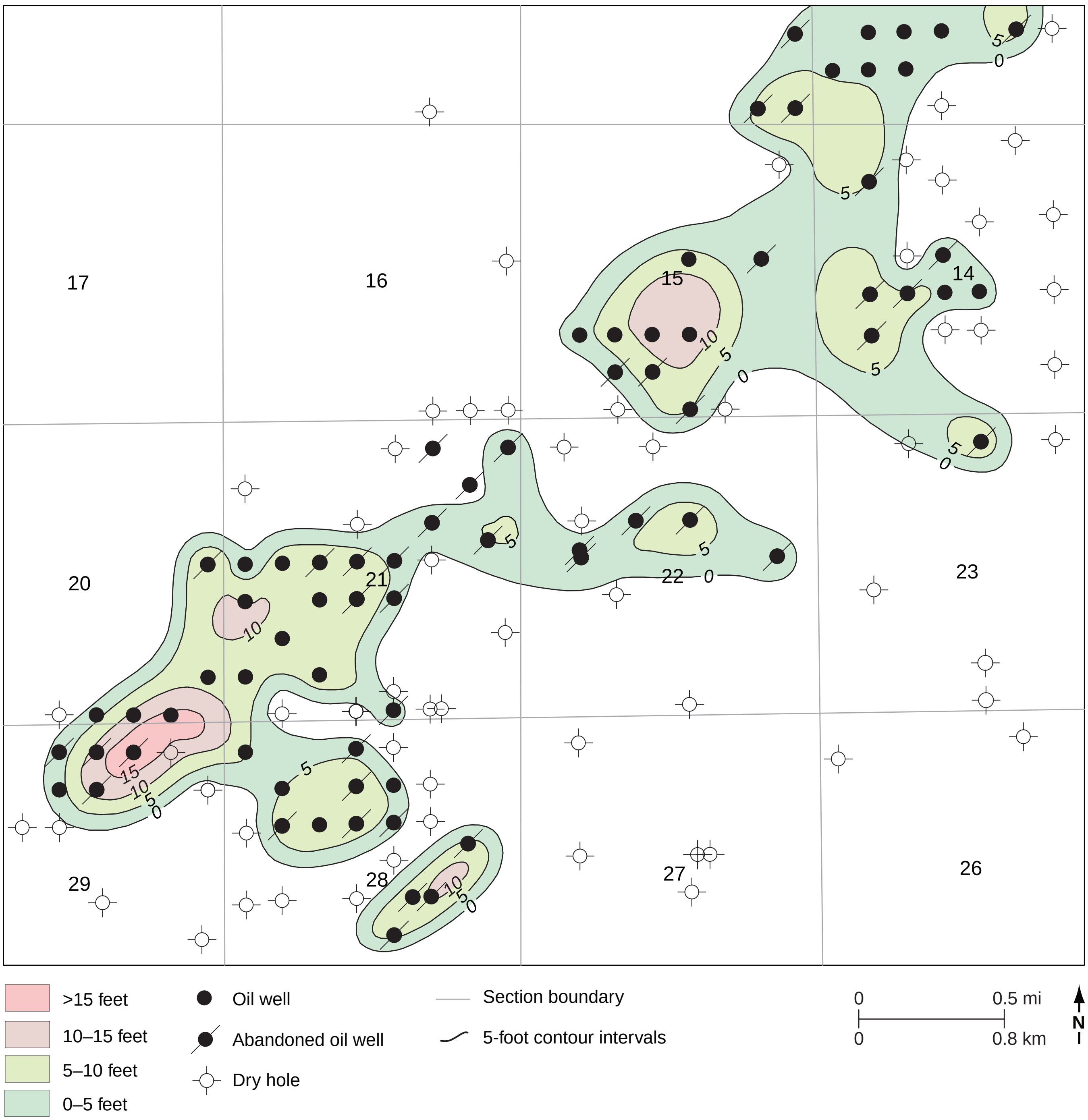

Figure 20 Thickness map showing the lateral distribution of the dolomite reservoir unit C along the Mt. Auburn trend. This lenticular dolomite unit is more extensive than reservoir units A and B and is present in all of the oil fields along the Mt. Auburn trend.

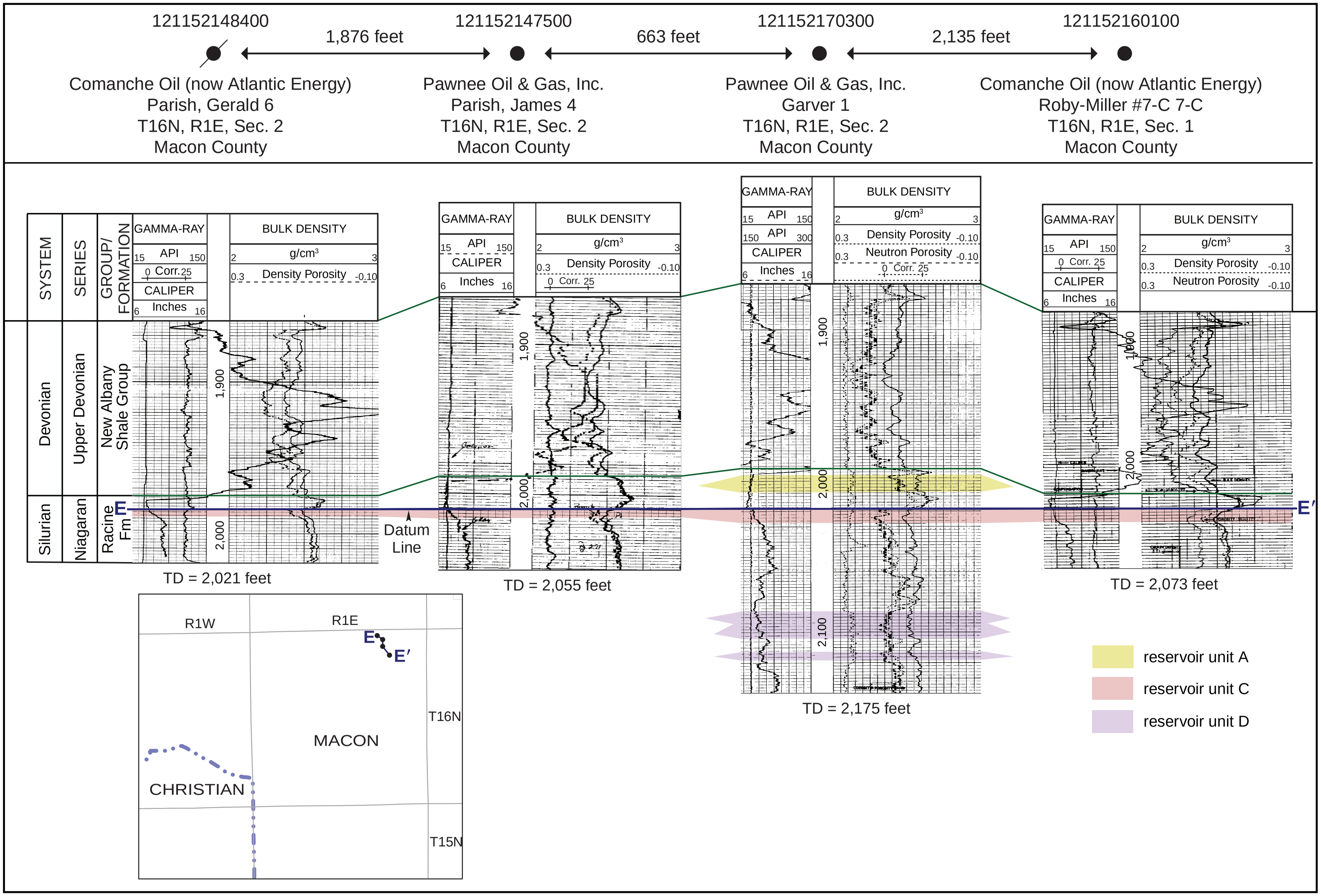

Figure 21 Northwest-southeast cross section E–E′ across the Mt. Auburn trend in the Harristown Field showing the lenticular nature of the porosity pinch-outs within the Silurian impermeable carbonates (lenticular reservoir unit C is most continuous reservoir in the study area). Note that the Pawnee Oil and Gas Inc. Garver No. 1 well encountered the reef/rudstone reservoir unit D, but the neighboring wells are not deep enough to test the lower sequence. Note also the uneven topography of the Silurian upper contact below the New Albany Shale Group. Datum horizon E–E′ is the base of the tight limestone just above reservoir unit C. Abbreviations: Corr., correction; Fm, Formation; TD, total depth.

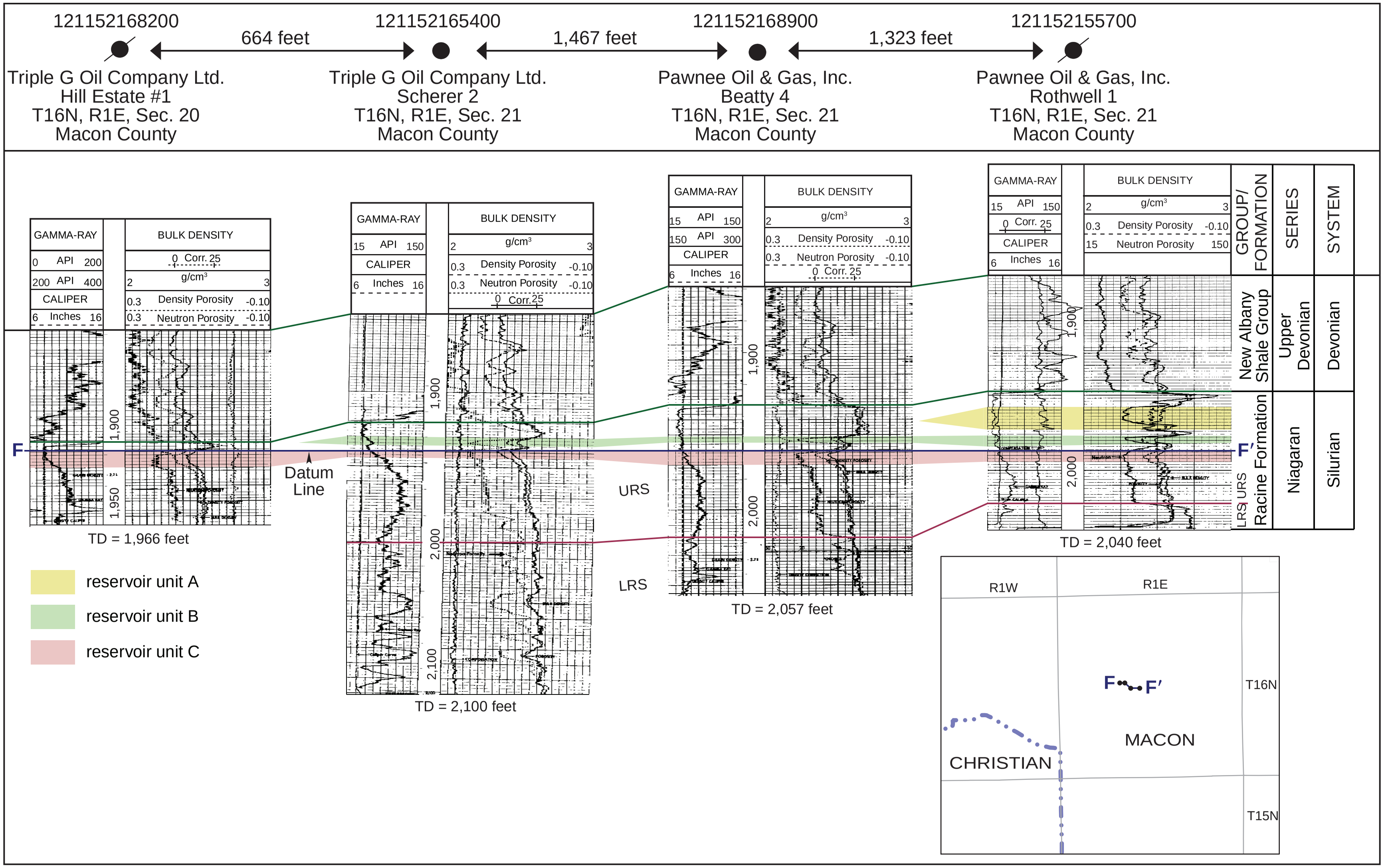

Figure 22 West-east cross section F–F′ across the Mt. Auburn trend showing the development of reservoir units A, B, and C. Note the persistence of reservoir unit C and the westward pinch-out of reservoir unit A into a dense impermeable limestone. Note also that the upper part of the upper sequence of the Racine Formation includes reservoir units A and B and the dense impermeable carbonates (cherty limestone interbeds) that thin toward the west, in Triple G Oil Company Ltd. Hill Estate No. 1 well, as a result of pre-Devonian erosion. Datum horizon F–F′ is the base of the tight limestone just below reservoir B. Abbreviations: Corr., correction; LRS, lower Racine sequence; TD, total depth; URS, upper Racine sequence.

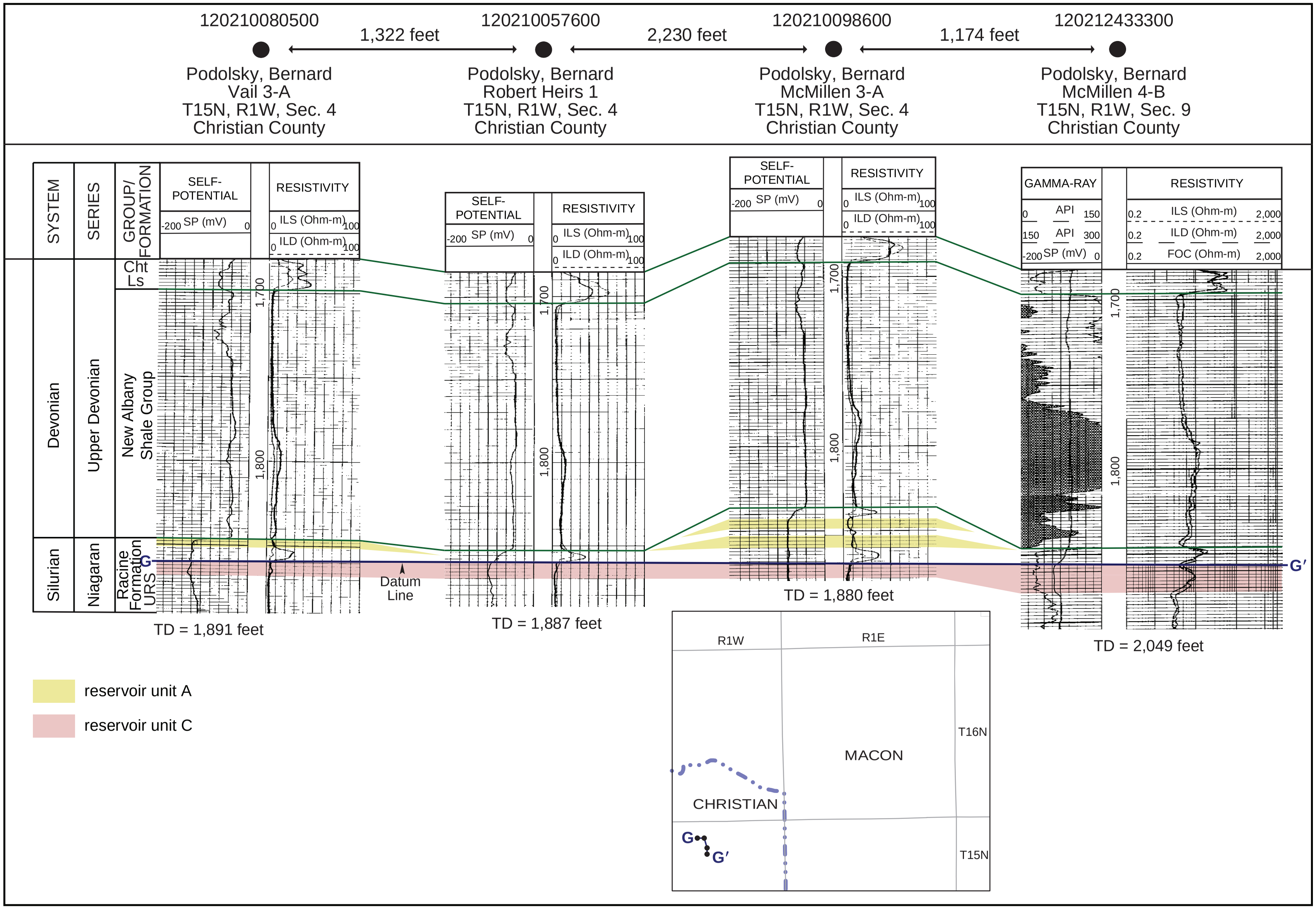

Figure 23 Northwest-southeast cross section G–G′ across the Mt. Auburn trend in the Mt. Auburn Consolidated Field showing the development of reservoir units A and C. Note the irregular topography of the upper contact of the Racine Formation and the lateral pinch-out of reservoir unit A into the overlying New Albany Shale as a result of post-Silurian erosion. Note also that in the Bernard Podolsky Vail 3-A well, the New Albany Shale Group caps the reservoir as a result of erosion and removal of the dense cherty limestone that normally overlies reservoir unit A. Datum line G–G′ is the base of the impermeable limestone, horizon (Figure 5), just above reservoir C. Abbreviations: Cht Ls, Chouteau Limestone; FOC, focused; ILD, induction log deep; ILS, induction log shallow; SP, self-potential; TD, total depth; URS, upper Racine sequence.

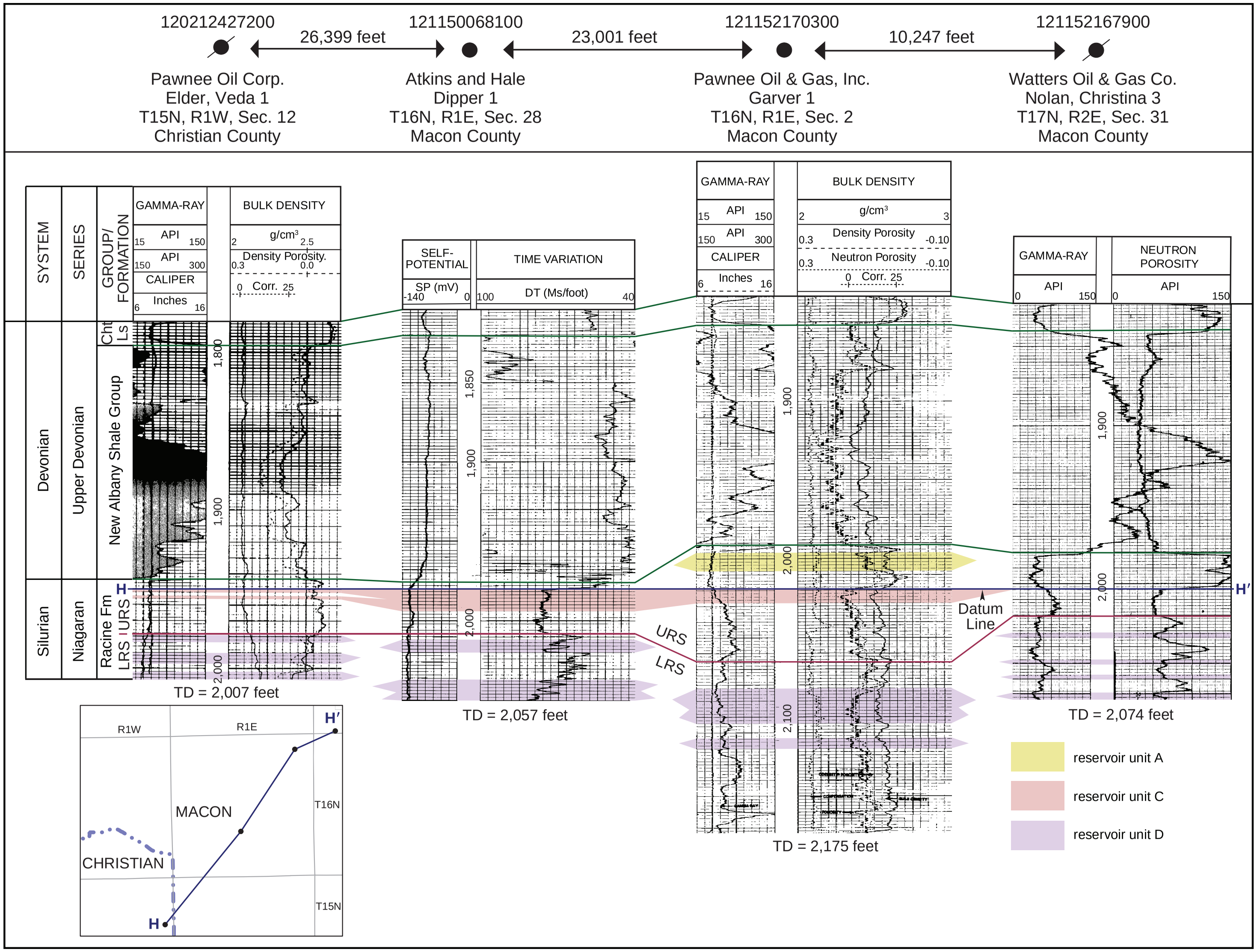

Figure 24 Cross section H–H′ parallel to the Mt. Auburn trend showing the development of reef and non-reef reservoirs in the upper part of the sequences of the Racine Formation in Christian and Macon Counties. Note the lenticular nature of the reservoirs that change laterally and vertically to impermeable carbonate facies; reservoir unit C thins out into dense limestone in the Pawnee Oil Corp. Elder 1 well, but changes to shale facies in the Watters Oil and Gas Co. Nolan 3 well. Note also the irregular surface of erosion at the upper contact of both the lower and upper sequences of the Racine Formation. Datum horizon H–H′ is the base of the impermeable limestone in the upper part of the upper sequence, horizon e (see Figure 5), just above reservoir C. Abbreviations: Cht Ls, Chouteau Limestone; Corr., correction; DT, sonic time variation; LRS, lower Racine sequence; SP, self-potential; URS, upper Racine sequence.

Watters Oil and Gas Company Nolan No. 3 in Figure 24).

Patch Reef Reservoir Unit D

Based on detailed inspection of well cuttings and cores and correlation of geophysical logs from a few wells that have penetrated the lower part of the Niagaran Series, a patch reef and associated rudstone facies are identified in the upper part of the lower sequence of the Racine Formation (Y. Lasemi 2009c). The patch reefs (Figures 14 and 17c, d, e, f) are recognized in the following wells along the Mt. Auburn trend (Figures 24, 25, and 26):

- Atkins and Hale Dipper No. 1, T16N, R1E, Sec. 28, in the Blackland North Field in Macon County (Figure 25, depths 2,012–2,020 feet and 2,037–2,050 feet).
- Pawnee Oil Corp. Garver No. 1, T16N, R1E, Sec. 2, in the Harristown Field in Macon County (Figure 25, depths 2,082–2,103 feet and 2,112–2,118 feet).
- Watters Oil and Gas Co. Graves No. 1, T16N, R2E, Sec. 6; Dalton No. 4 and 5, T17N, R2E, Sec. 32; Nolan No. 1, T17N, R2E, Sec. 31; and Nolan No. 3, T17N, R2E, Sec. 31, all in the Decatur field in Macon County (see Figure 25, depths 2,030–2,035 feet, 2,048–2,051 feet, and 2,069–2,074 feet for the Nolan No. 3 well).
- Pawnee Oil Corp. Elder No. 1, T15N, R1W, Sec. 12, in the Mt. Auburn Consolidated Field in Christian County (Figure 25, depths 1,988–1994 feet, 2,000–2,007 feet and 2,012–2,017 feet).

The patch reef facies is characterized by porous dolomitized coral reef/reef rudstone facies (Figure 17c, d, e, f) and is the lowermost productive horizon recognized in the Racine Formation (Figures 14, 24, and 25). The patch reef facies consists of coarsely crystalline dolomite containing remnants and molds of reef-building organisms (mainly corals). The reef-building skeletons are recognizable in cores and hand samples (Figure 17c, d), but the detail of their structure is lost due to pervasive dolomitization. In thin sections, only very faint relicts of the organic material of the original skeleton are visible (Figure 17e, f). Intercrystalline and moldic porosities can reach more than 25%; the highest initial production reported was 3,120 barrels of oil per day in the Atkins and Hale Dipper No. 1, T16N, R1E, Sec. 28, in Macon County.

The majority of wells in the study area have not tested the lower part of the Niagaran deposits that include the newly recognized patch reefs, and these potentially prolific lower horizons have been mostly overlooked. The highest initial production (over 3,000 barrels per day) is associated with this type of reservoir; therefore, more productive Niagaran patch reefs are likely to be found along the Sangamon Arch.

Discussion

Depositional Environment and Carbonate Platform

The Racine Formation is composed mostly of various skeletal components that include fragments of echinoderms, bryozoans, brachiopods, and corals, suggesting deposition in an open marine setting. Coral fragments were probably derived by storm events from the reefs that had existed farther offshore in the deeper part of the basin. The Racine Formation consists of high-energy bioclast grainstone to packstone (Figure 16c, d), coral patch reef/reef rudstone facies (Figure 17c, d), and low-energy, below wave base, bioclastic mudstone to wackestone (Figure 16a, b), silty argillaceous dolomitic lime mudstone/dolomite, and calcareous shale. These facies were deposited in a gently sloping ramp with a ramp margin that was roughly parallel to the Mt. Auburn trend and graded basinward (southeast) into muddy carbonates (Figure 27) similar to the numerous modern and ancient examples (Wilson 1975, Tucker and Wright 1990, Flügel 2010). During deposition of the Racine Formation, long-term third-order sea level fluctuations resulted in the development of two third-order cycles consisting of short-term fourth- to fifth-order cycles as a result of short-term sea level variation (Figures 13 through 15).

The depositional model of the Racine Formation in the Sangamon Arch is that of a homoclinal ramp portion (ramp margin and its adjacent seaward margin) of a distally steepened ramp, just landward of the deep Vincennes Basin (Figure 27). According to Droste and Shaver (1980, 1987), during the Middle to Late Silurian Period, a platform margin (Terre Haute reef bank) marked a slope break in southern Illinois and southwestern Indiana that was facing the deep Vincennes Basin (Figures 1 and 27). Coburn (1986) and Whitaker (1988) envisioned a gently sloping ramp for the entire Illinois Basin that deepened toward the south and east during Silurian time. Restricted lagoonal and tidal flat facies of the inner ramp were presumably deposited landward of the Mt. Auburn trend, toward the Mississippi River Arch, but are absent due to post-depositional erosion.

Although the carbonate ramp model (Ahr 1973, 1998; Read 1985; Burchette and Wright 1992) is appropriate for the Illinois Basin, reactivation of old normal faults along the northeastward extension of the Reelfoot Rift system during the Silurian Period possibly resulted in the formation of a distally steepened ramp (Read 1985) and the Vincennes Basin (Figures 1 and 27). This interpretation is supported by the thick Lower Devonian basinal deposits that thin to zero toward the platform area and by the steeper slope along the reef trend than in the platform and basinal settings (Droste and Shaver 1980, 1987). In addition, the southeast margin of the Vincennes Basin aligns with the trend of the Reelfoot Rift, and the platform margin parallels the trend of a northeastward extension of the rift (Figure 1), suggesting that footwall subsidence along the rift-related normal faults probably formed the relatively deep Vincennes Basin in southern Illinois. Lower Devonian through Mississippian deep marine deposits (including turbidites) are recognized in the general area of southern Illinois (Lineback 1966, 1981; Banaee 1981; Cluff et al. 1981; Lineback and Cluff 1985; Z. Lasemi et al. 1998, 2003). These deposits, which conformably overlie the Silurian succession (Norby 1991, Mikulic 1991, Droste and Shaver

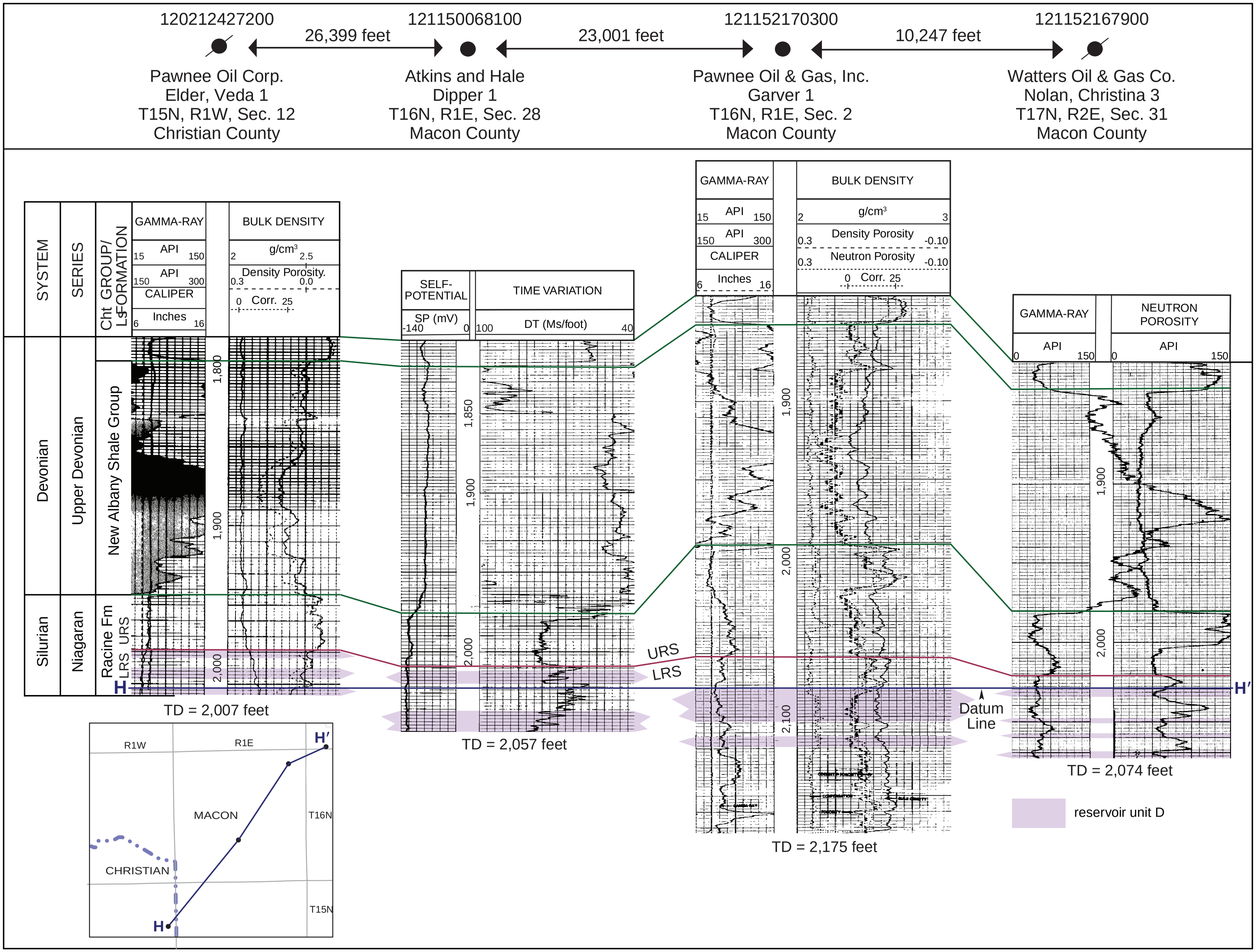

Figure 25 Cross section H–H′ (same as Figure 24) showing the occurrence of patch reef reservoirs within the upper part of the lower sequence of the Racine Formation. Datum has been changed to the top of a fourth-order transgressive-regressive cycle at the base of a dense facies within the upper sequence. Note the irregular surface of erosion at the upper contacts of both sequences. Abbreviations: Cht Ls, Chouteau Limestone; Corr., correction; DT, sonic time variation; LRS, lower Racine sequence; SP, self-potential; URS, upper Racine sequence.

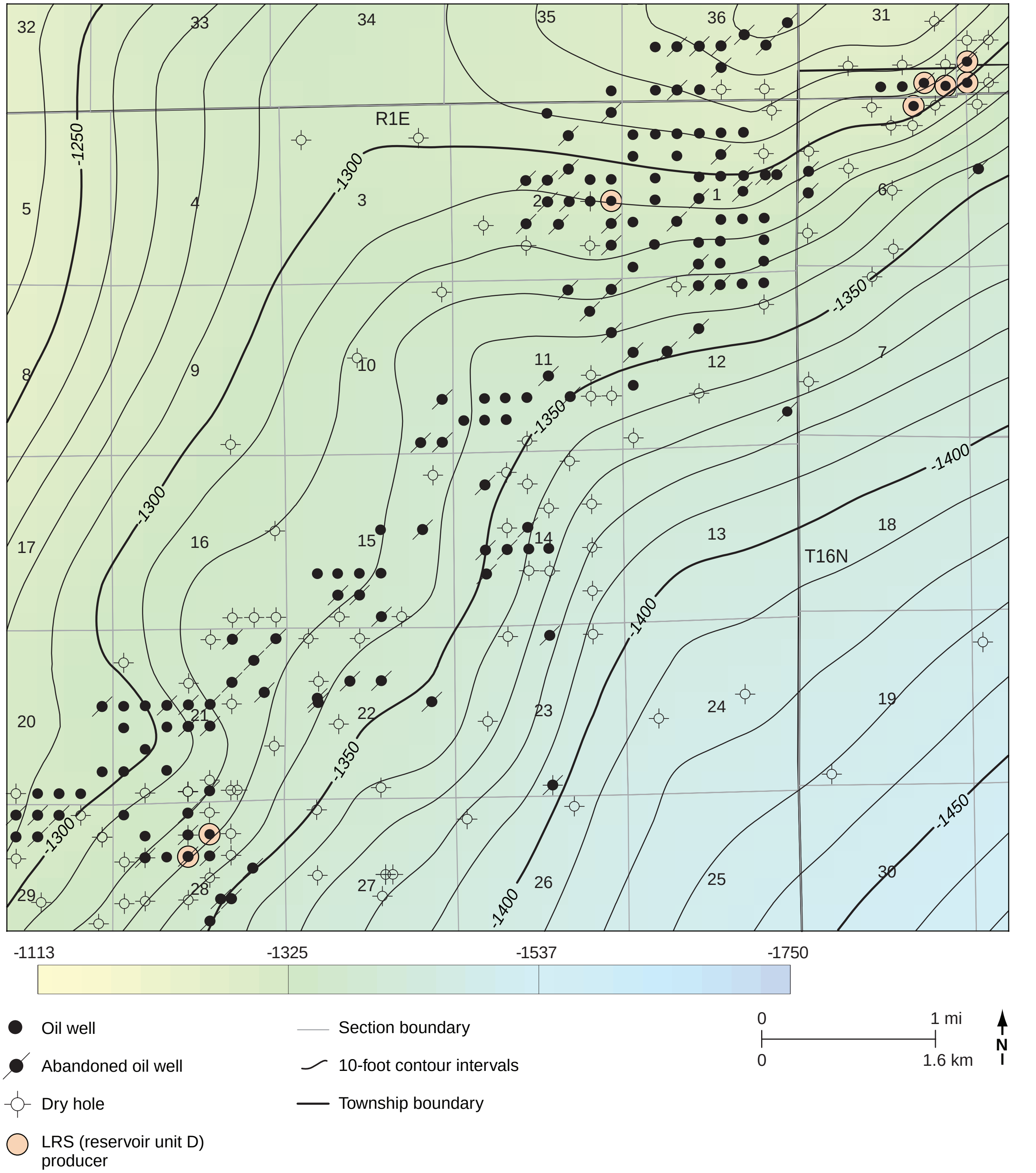

Figure 26 Enlarged portion of part of the regional structural contour map shown in Figure 12. The map portion shows the location of wells that have produced from the upper and lower Racine reservoirs. Encircled wells have produced from the lower Racine reef reservoir unit D. Abbreviation: LRS, lower Racine sequence.

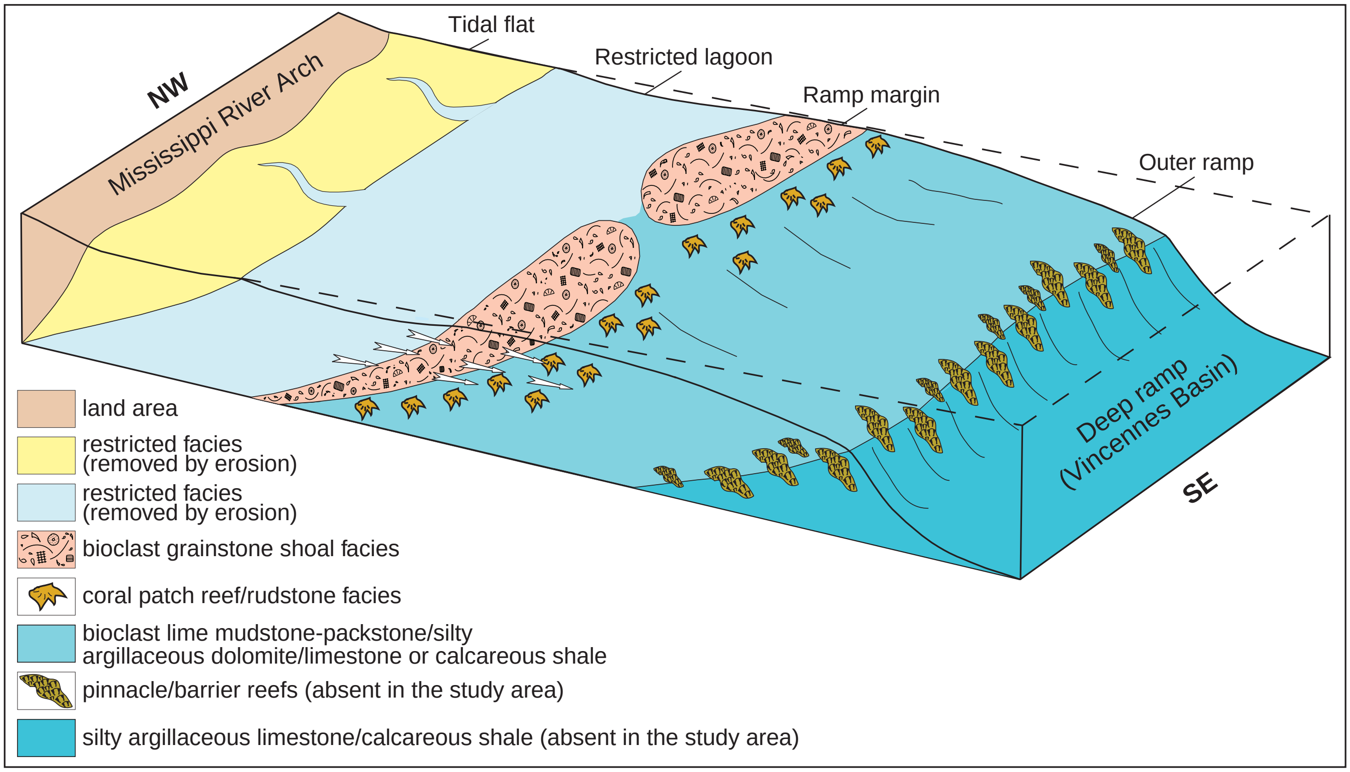

Figure 27 Generalized depositional model depicting the distally steepened ramp of the Illinois Basin during Niagaran time. The depositional facies of the inner ramp (restricted lagoon and tidal flat facies) are absent due to subsequent erosion at the upper contact of the Niagaran sequences and the complete removal of the Silurian deposits toward the northwest in the Mississippi River Arch area. Small coral patch reefs developed seaward of the bioclastic ramp margin, and the large pinnacle reefs were mainly restricted to the distally steepened outer ramp margin. Seaward percolation of the denser dolomitizing fluids from the restricted lagoon, in the direction of arrows, could have been responsible for early dolomitization of the precursor limestone deposits.

1987), further suggest that a distally steepened ramp could have existed in the southern part of the Illinois Basin during the deposition of the Niagaran Series.

Patch Reef Versus Pinnacle Reef

The known productive reefs in Illinois are pinnacle reefs up to 700 feet (210 m) thick (Lowenstam 1949, Bristol 1974) that developed almost entirely during the Middle to Late Silurian Period along the northeast-southwest–trending platform margin (possibly along a distally steepened ramp margin) (Figure 27) facing the deep Vincennes Basin (Shaver et al. 1978, Droste and Shaver 1980, 1987). The presence of patch reef reservoirs in the Niagaran rocks of the Sangamon Arch has recently been documented (Y. Lasemi 2009c). These patch reefs are of limited lateral and vertical extent in the upper part of the lower sequence of the Racine Formation (Figures 4, 14, 21, 24, and 25). They may occur in one to four horizons with a total thickness of up to 30 feet (9 m), and they constitute the upper parts of fourth- to fifth-order shallowing-upward cycles (Figures 14 and 25).

Patch reefs of the Sangamon Arch developed on the very gently sloping homoclinal ramp platform (ramp platform of Ahr 1973), similar to that in the present-day Persian Gulf (Purser 1973). Reef-building metazoans typically build laterally and vertically along the platform margin, where nutrient supply is abundant and depositional energy is very high (Wilson 1975, James 1983). Because the depositional wave and current energy were not strong enough to cause the reef builders to construct large buildups in the homoclinal ramp setting of the Sangamon Arch, only bioclast grainstone shoal facies and small patch reefs were developed—in contrast to the large pinnacle reefs (Lowenstam 1949, Bristol 1974) that developed along the southern Illinois platform margin (Shaver et al. 1978; Droste and Shaver 1980, 1987). Whitaker (1988) suggested that pinnacle reefs had existed in the shelf areas of the Illinois Basin, including the Sangamon Arch, but that much of their thickness had been reduced by pre-Devonian erosion. The present study, however, does not support the development of pinnacle reefs along the Sangamon Arch (see Y. Lasemi 2009c for further discussion).

Dolomitization and Reservoir Development

Detailed subsurface studies of the Silurian succession along the Mt. Auburn trend have revealed the presence of several lenticular dolomitized reservoirs (permeability pinch-outs) that are interlayered with laterally extensive impermeable limestone intervals. The reservoirs generally constitute the upper parts of fourth-order transgressive-regressive cycles within the Racine Formation (Figures 13, 14, and 15). The laterally discontinuous reservoirs are cyclic and are commonly surrounded by impermeable pure limestone or finely crystalline silty argillaceous dolomitic limestone/dolomite (Figures 13, 14, 15, 21, 22, 23, and 24), suggesting that sea level fluctuations and seawater chemistry were the primary controls for early dolomitization of the compartmentalized Silurian reservoirs.

Based on comparisons with their modern counterparts, the initially impermeable mud-rich precursors had an initial porosity of around 70% (Enos and Sawatsky 1981, Z. Lasemi et al. 1990), which was reduced to less than 5% during burial diagenesis. Dolomitization was probably caused by reflux of slightly evaporated seawater (Sun 1995) in the inner ramp setting; the initial grainstone facies of the ramp margin and the adjacent open marine bioclastic packstone-wackestone acted as a conduit for the dolomitizing sea water. As shown by the depositional model (Figure 27), the slightly evaporated, denser water in the back barrier inner ramp lagoon, which had higher magnesium-to-calcium ratio than normal seawater, could have percolated through the sediments deposited during the previous sea level cycles, leading to early dolomitization and formation of laterally discontinuous dolomite lenses. The dolomitizing fluid apparently could not reach the distal portion and the lower part of the previously deposited limestone cycle, leading to lenticular dolomite bodies. This interpretation is supported by these findings:

- The lenticular dolomitized reservoirs show gradational contacts with the underlying limestone, and their skeletal remains are identical to those of the associated limestone; they change to dolomitic limestone and lose their porosity in both landward and basinward directions.
- Dolomite layers are resistant to chemical compaction and the resulting cementation (Brown 1997, Lucia 2004, Ehrenberg et al. 2006), thus preserving their original porosity. Laterally continuous interlayered lime mudstone to packstone facies, however, compact and lose their initial high porosity during burial diagenesis.

It appears that dolomitization initially affected the carbonate lime mud matrix of the groundmass (Figures 16b and 17b) and the more susceptible fossil fragments; crinoids were the last grains to be dolomitized (Figures 16d and 17b). Later reservoir porosity enhancement likely occurred during prolonged subaerial exposure, resulting in partial dissolution of the dolomite crystals along the pore walls by fluids undersaturated with respect to dolomite (Figure 17a).

Conclusions

The Racine Formation was deposited in a gently sloping ramp with a ramp margin roughly parallel to and southeast of the trend of the Sangamon Arch. The Racine Formation is subdivided into two depositional sequences that, in the Mt. Auburn trend, contain multiple dolomitized reservoirs.

The reservoirs are compartmentalized and are commonly surrounded by impermeable limestone, suggesting fluctuations in sea level and seawater chemistry as the primary controls for early dolomitization of the Silurian reservoirs. The interlayered undolomitized limestone was compacted during burial diagenesis, but the dolomite resisted compaction, thus retaining its porosity.

Examination of numerous wells indicates that most of those drilled thus far have tested the uppermost part of the Niagaran succession; only a few wells have tested the lower reservoirs that include the newly recognized patch reefs, so the potentially prolific lower horizons have been mostly overlooked.

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