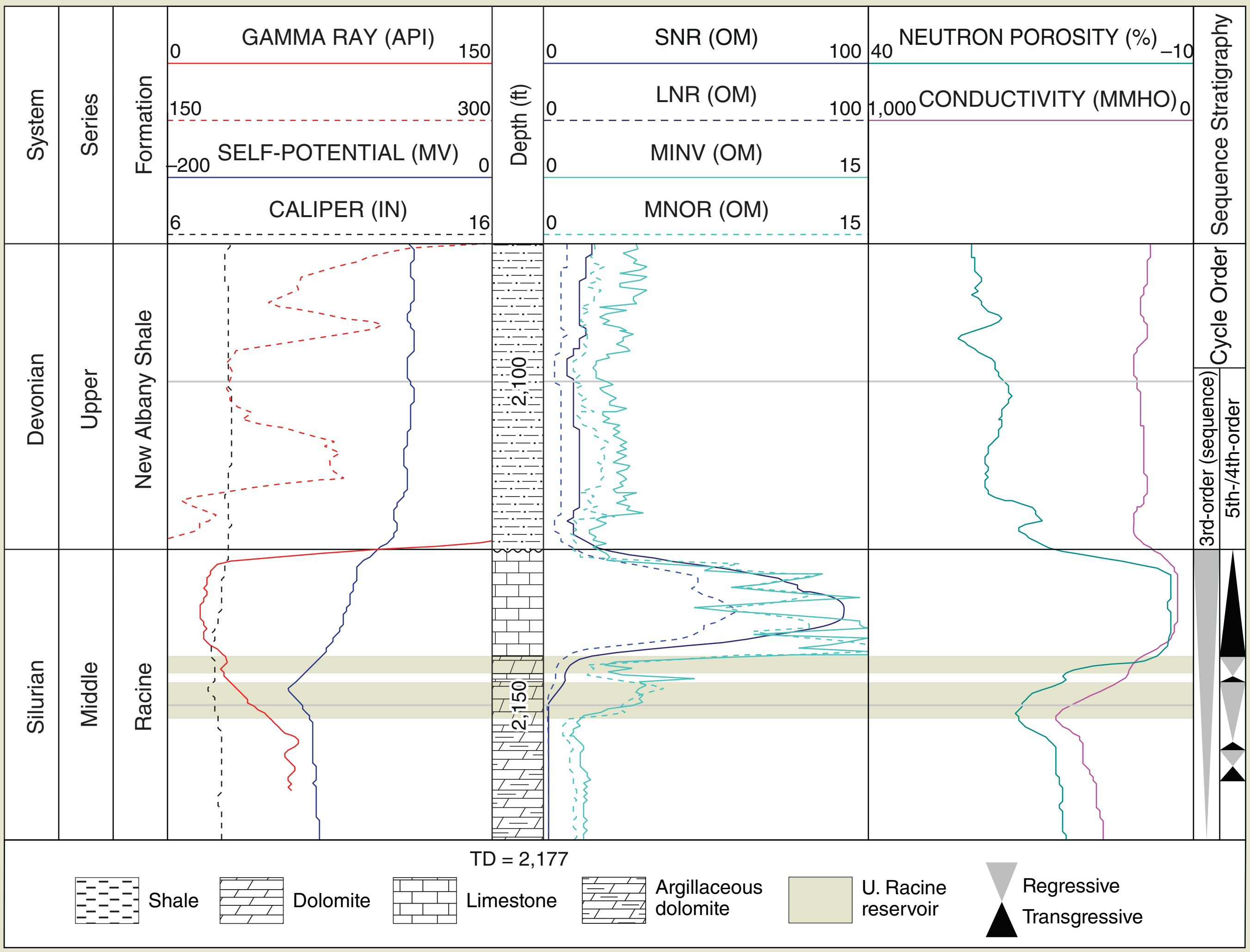
Stratigraphic Architecture and Reservoir Characterization of the Silurian Racine Formation, Forsyth Oil Field, Macon County, Central Illinois

Yaghoob Lasemi

Illinois State Geological Survey, Prairie Research Institute, University of Illinois at Urbana-Champaign, Champaign, Illinois



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Front cover: *Type log in Forsyth Field (Triple G Oil Co. Ltd. Schwarze Trust No. 2, API No. 121152135800) showing the upper Racine dolomite reservoir interval (in tan) in the regressive package of the upper Racine sequence.*

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ILLINOIS STATE GEOLOGICAL SURVEY
Prairie Research Institute
University of Illinois at Urbana-Champaign
615 E. Peabody Drive
Champaign, Illinois 61820-6918
http://www.isgs.illinois.edu

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ABSTRACT

The Silurian Racine Formation (Wenlock-Ludlow) is the major oil-producing unit in a number of oil fields in the Mt. Auburn trend of the Sangamon Arch, central Illinois. This study focuses on geological characterization of the Racine at Forsyth Field to evaluate its potential for future development in the undeveloped areas and through enhanced oil recovery methods. Forsyth Field lies in the extreme northeastern part of the Mt. Auburn trend in the northwest of the Illinois Basin. Discovered in 1963, the field has produced more than 750,000 barrels of oil from a compartmentalized dolomite reservoir in the upper part of the Racine Formation.

The Racine is more than 240 ft (73 m) thick and consists of small- and large-scale interbedding of limestone, dolomite, silty argillaceous dolomite or limestone, and calcareous shale. An unconformity subdivides the formation into two sequences. The reservoir interval at Forsyth occurs in the regressive package of the upper Racine sequence and is a lenticular, commonly compartmentalized, dolomite body reaching a maximum net thickness of nearly 12 ft (3.66 m) with an average porosity of 16%. Each reservoir compartment constitutes the upper part of a small-scale shallowing-upward cycle capped with a transgressive limestone. The reservoir interval, which correlates with reservoirs in the upper part of the Racine in neighboring fields, generally is a nonreef dolomitized fossiliferous grainstone to wackestone. The combination of depositional and diagenetic processes and updip pinch-out of the reservoir against the Sangamon Arch was responsible for petroleum entrapment.

The original oil in place at Forsyth is calculated at more than 9 million barrels, and the field has produced approximately 8% of its original oil in place. Poor reservoir performance and below-average cumulative primary production (nearly 10,000 barrels per well) suggest poor permeability for the dolomite reservoir interval at Forsyth. However, great potential exists for improving petroleum recovery from the field. Several locations are undrilled, and in the developed areas, the reservoir was stimulated with relatively small-volume fracturing. Development of the undrilled areas, infill drilling, and larger volume hydraulic fracturing will undoubtedly improve recovery from the field. The reservoir at Forsyth Field has never been waterflooded; the field is close to a commercial source of carbon dioxide (CO_2) and is a potential candidate for CO_2 enhanced oil recovery, which could result in storage of anthropogenic CO_2 and increased oil production.

INTRODUCTION

The Middle Silurian Racine Formation is a major oil-producing unit in the Mt. Auburn trend of the Sangamon Arch, central Illinois (Figure 1). More than 30 million barrels of oil have been produced from the Racine in Christian, Macon, and Sangamon Counties since commercial oil discovery in 1921. Forsyth Field lies in the extreme northeastern part of the Mt. Auburn trend, in the northwest of the Illinois Basin (Figures 1 and 2), and covers an area of nearly 2,000 acres (809 ha). It is located in north-central Macon County, central Illinois; the main part of the field underlies Secs. 23, 24, 25, and 26, T17N, R2E (Figure 3). The field has produced essentially from a dolomite reservoir in the upper part of the Middle Silurian succession.

Lasemi et al. (2010) carried out regional work on sedimentology, stratigraphy, and reservoir characterization of the Silurian reservoirs along the Mt. Auburn trend, but the oil fields were not the subject of a detailed study. This study focuses on stratigraphic architecture and reservoir characterization of the Racine at Forsyth Field. Geological characterization is vital for evaluating the remaining recoverable oil from the undeveloped areas and by waterflooding or enhanced oil recovery (EOR) methods such as carbon dioxide (CO_2) flooding. A short summary of this work was included in a paper by Damico et al. (2014). Parts of this work were prepared as unpublished reports for Illinois Department of Commerce and Economic Opportunity Grant 13-484001 and for U.S. Department of Energy Grant DE-FE0009612.

For this study, a number of maps and stratigraphic cross sections were prepared. Cores and well cuttings were not available for the entire field. However, a complete suite of both open- and cased-hole geophysical logs were available for most wells. Therefore, geophysical log interpretation and correlation with equivalent intervals in other Mt. Auburn trend fields were the basis for geological characterization. Subsurface maps and cross sections were prepared by using wells with more reliable logs, including density, sidewall neutron, microresistivity (microlog), and induction log.

FIELD DISCOVERY AND DEVELOPMENT

Atkins & Hale discovered Forsyth Field in 1963 when the company reentered an old dry hole, the Schwartz No. 1 (API No. 121150005100) in Sec. 24, T17N, R2E. After a relatively small fracture treatment, Atkins & Hale completed the well in November 1963 with an initial production of 168 barrels (about 42 gal [159 L]) per day from the Silurian Racine reservoir, the top of which was encountered at 2,118 ft (646 m). Initially, M. Mazzarino drilled Schwartz No. 1 in 1956 to a total depth of 2,215 ft (675 m), which was completed as a dry hole.

Subsequent to early development of the field in the 1960s and 1970s, a second phase of development took place in the early 1980s when operators drilled a large number of wells, which resulted in an upsurge in production (Figure 4). In 1981, the production rate peaked at approximately 300 barrels per day from 75 producing wells; however, production declined steeply because of the characteristically poor reservoir permeability. Eighty-nine wells were drilled, of which 82 wells were completed as oil producers. In all completed wells, casing was set through the formation and fractured the porous intervals with low-volume (about 20,000 gal [75,708 L]) water/nitrogen-foam sand hydraulic fracturing. Of the 82 completed oil wells, 42 wells are currently on pump, and the field is producing at a rate of less than 15 barrels per day. Forsyth Field has accumulated more than 750,000 barrels of oil.

GEOLOGICAL SETTING

The Illinois Basin (Figure 1) formed in the Late Cambrian on the northeast extension of the Late Proterozoic to Middle Cambrian Reelfoot Rift–Rough Creek Graben system (Kolata and Nelson 1990). During the Silurian, a reef bank, the Terre

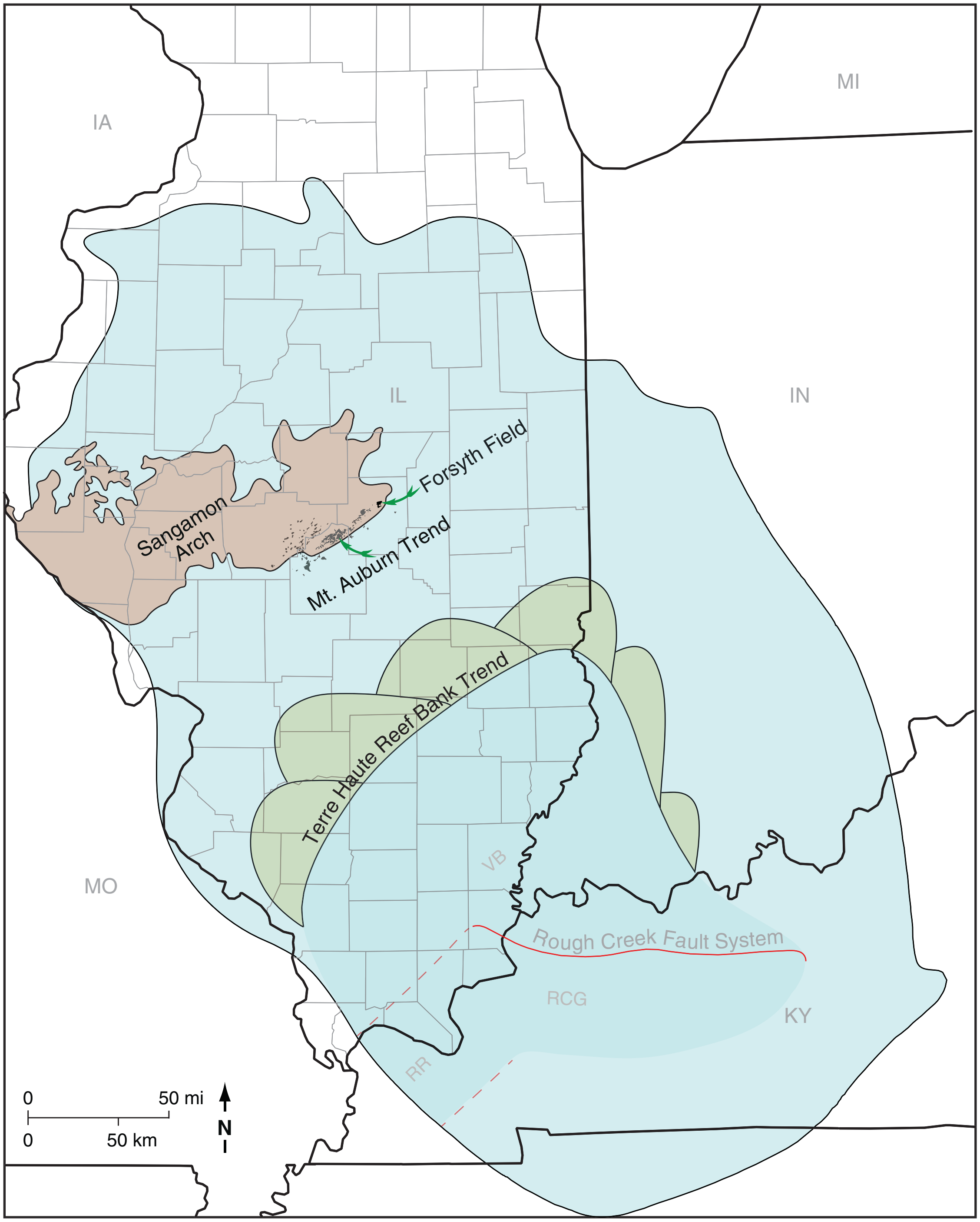

Figure 1 Location of the Illinois Basin in light blue (Buschbach and Kolata 1990) and the Sangamon Arch in west-central Illinois in brown (Whiting and Stevenson 1965) in the northwest area of the Illinois Basin. Forsyth Field is located in the extreme northeast of the Mt. Auburn trend along the southeastern flank of the arch. A slope break in southern Illinois and southwestern Indiana (Droste and Shaver 1980, 1987) separated the gently sloping ramp from the deep Vincennes Basin in the southeastern part of the Illinois Basin during Silurian time (modified from Lasemi et al. 2010). RR, Reelfoot Rift; RCG, Rough Creek Graben; VB, Vincennes Basin.

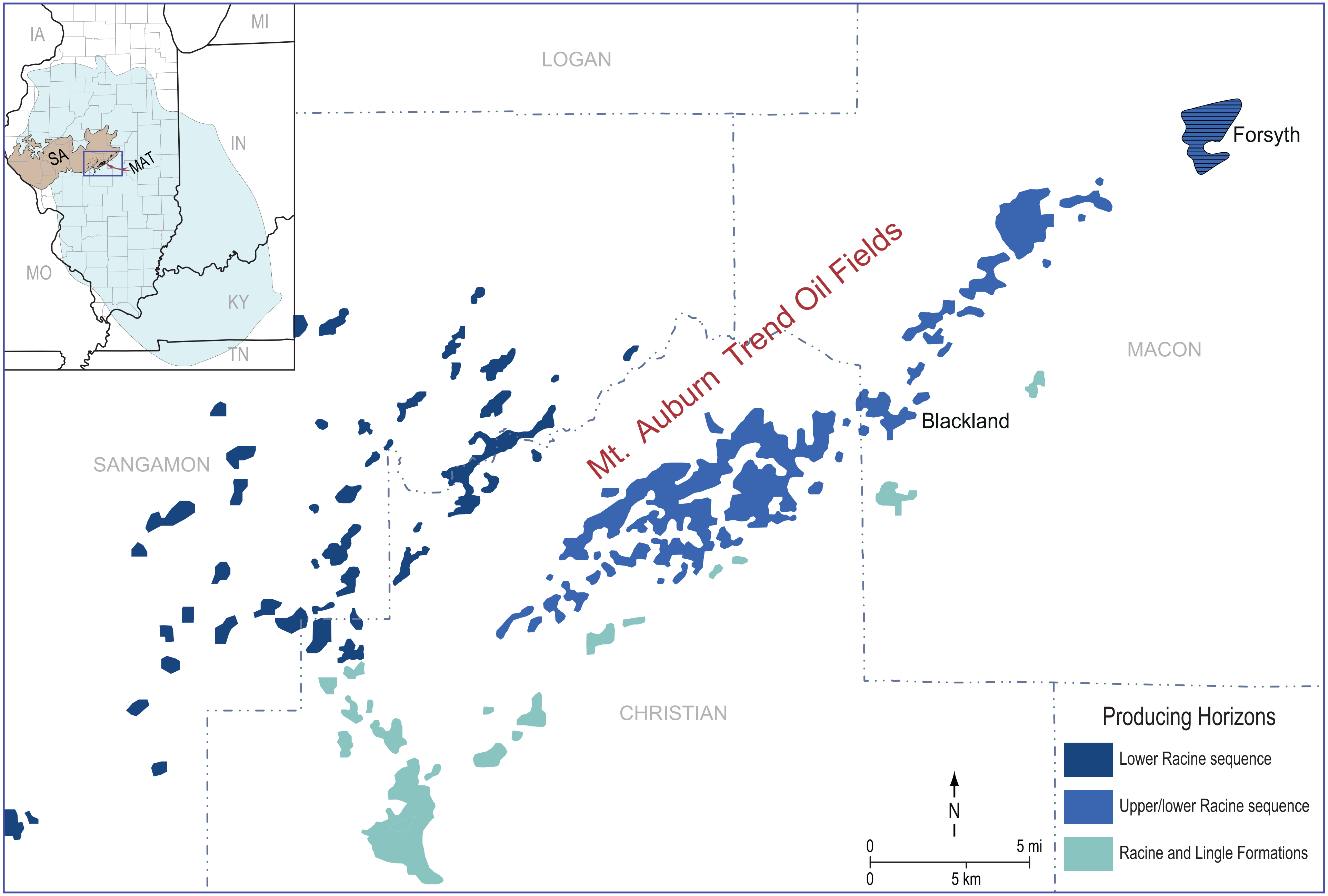

Figure 2 Map of the Mt. Auburn trend showing oil fields and producing horizons. Forsyth Field is located at the northeast end of the trend. SA, Sangamon Arch; MAT, Mt. Auburn trend.

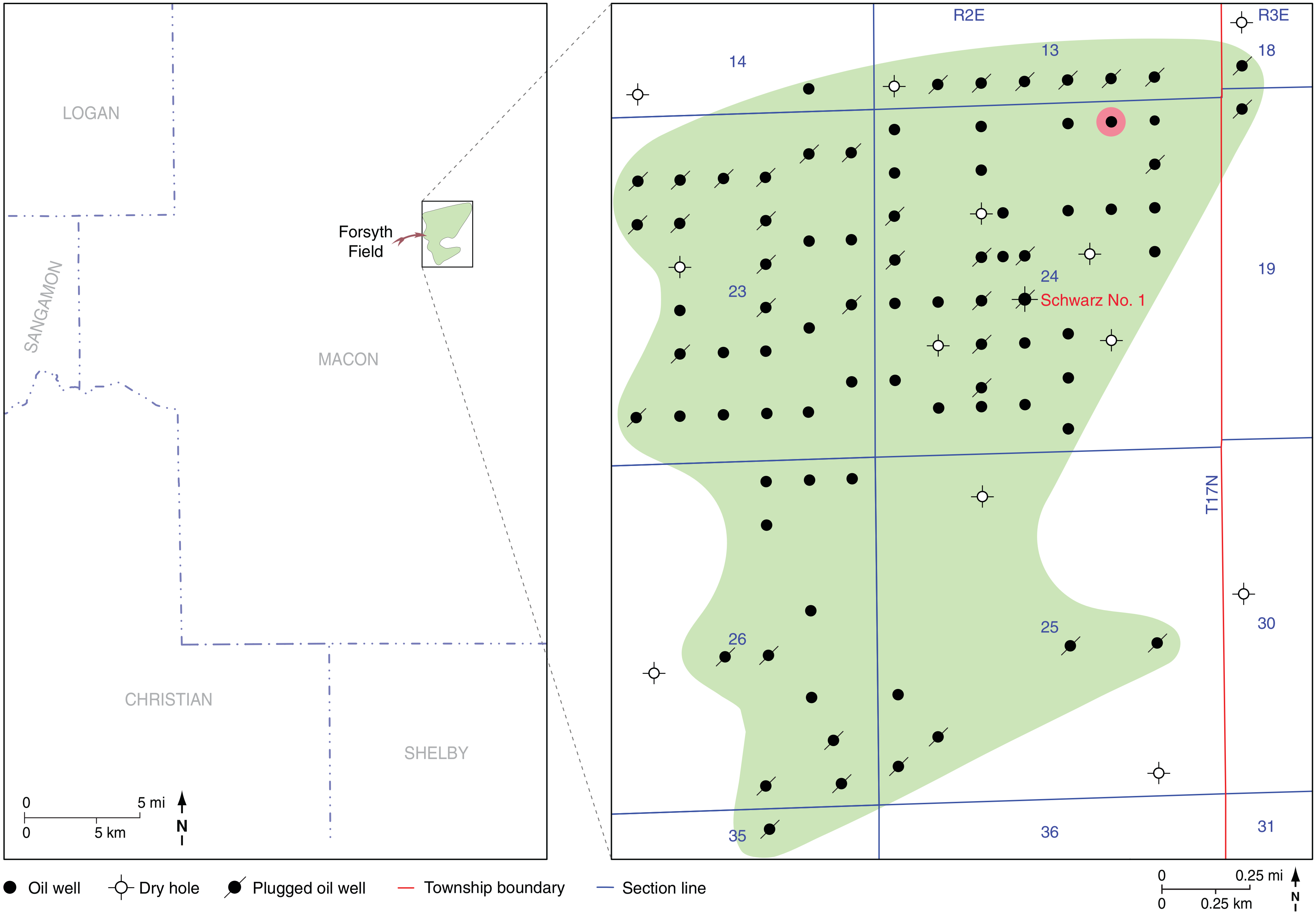

Figure 3 Map showing the location of Forsyth Field and the status of the wells already drilled in the field. The field was discovered when an old dry hole (Schwarz No. 1) was reentered and completed as an oil well in the Racine reservoir. Highlighted in red is the deepest well at Forsyth, which encountered the Upper Ordovician Trenton Limestone. At least 20 undrilled locations are available for future development.

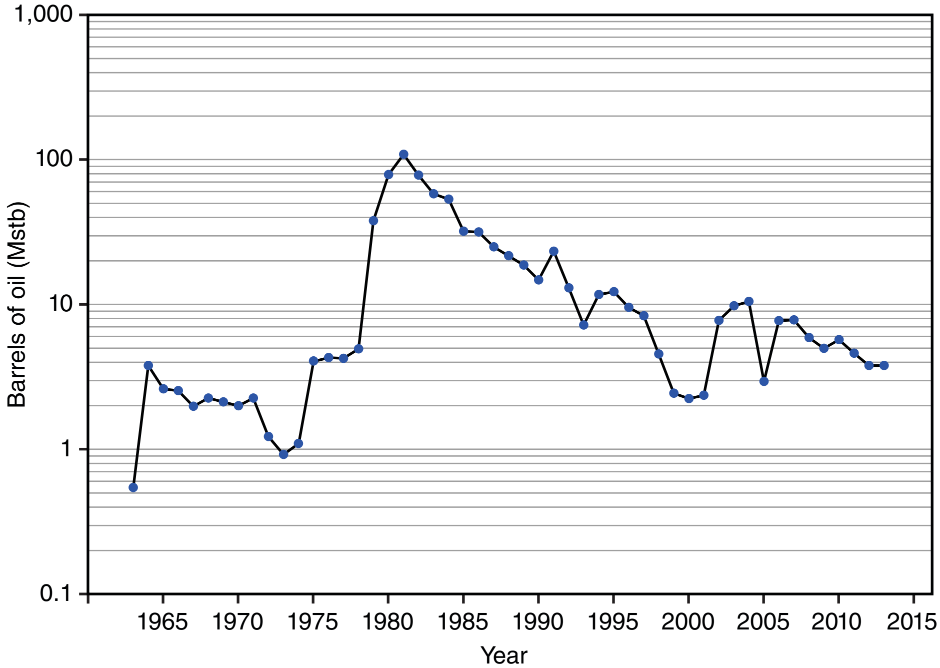

Figure 4 Forsyth Field production decline curve showing stages of field development and production from 1963 through 2013. Mstb, thousand stock tank barrels.

Haute reef bank (Figure 1), formed a platform margin in southwestern Indiana and southern Illinois that was facing the deep proto-Illinois Vincennes Basin (Droste and Shaver 1980, 1987). Northward, the Illinois Basin was a southeastward-dipping, gently sloping ramp platform.

A broad northeast–southwest-trending structure, the Sangamon Arch, existed in west-central Illinois (Figure 1) that formed because of upward warping of strata during Middle Silurian through Middle Devonian time (Whiting and Stevenson 1965). It is located on the gently sloping ramp area in the northwest of the Illinois Basin. The southern flank of the Sangamon Arch encompasses a number of oil fields that display a northeast–southwest trend (Figures 1 and 2), namely the Mt. Auburn trend (Lasemi 2009c). A structure contour map of the base of a limestone marker near the top of the Silurian deposits (Figure 5) indicates that the overall direction of regional dip in the study area is toward the southeast.

The petroleum reservoirs in the Mt. Auburn trend area occur in the upper part of Silurian deposits. The encompassing interval, adapting the stratigraphic classification for western Illinois (Willman and Atherton 1975), is classified as the Middle Silurian Racine Formation (Figure 6). Named for quarry exposures at Racine, Wisconsin, the formation is up to 300 ft (91 m) thick and consists of reef and inter-reef silty argillaceous dolomite or limestone facies (Willman and Atherton 1975). Lasemi (2009a, 2009b) recognized an intra-Racine erosional unconformity that subdivides the Racine Formation into two sequences (Figures 6 and 7). The unconformity could be associated with a global eustatic event on top of the Wenlock Series, possibly enhanced by upwarping in the Sangamon Arch. It corresponds to the medium-scale sea level fall (25–75 m) that Haq and Schutter (2008) reported at the Wenlock–Ludlow boundary (Figure 8).

Deposition of the Racine Formation in the study area was coeval with deposition of the lower part of the Moccasin Springs Formation (Figure 8) of southern Illinois (Willman and Atherton 1975; Mikulic 1990; Norby 1990). The Racine overlies, with a conformable contact, the upper Llandovery–lower Wenlock Joliet Formation. Except for the deep part of the basin, where the Silurian–Devonian boundary is conformable, the Silurian succession unconformably underlies the Middle or Upper Devonian deposits with the prominent sub-Kaskaskia erosional unconformity (Willman and Atherton 1975; Droste and Shaver 1987). In the Sangamon Arch area, Lower and Middle Devonian deposits are absent (Whiting and Stevenson 1965; North 1969) and the Silurian rocks unconformably underlie the Upper Devonian–lowermost Mississippian organic-rich New Albany Shale.

STRATIGRAPHY OF THE RACINE FORMATION IN THE STUDY AREA

In the study area, the Racine Formation overlies, with a sharp contact, the Joliet Formation and unconformably underlies the New Albany Shale (Figure 6). The Racine consists of small- and large-scale interbedding of limestone, dolomite, silty argillaceous dolomite or limestone, and calcareous shale (Figure 7). To define key stratigraphic surfaces for correlation and for detailed stratigraphy, the deepest well at Forsyth Field, the Triple G Oil Company Ltd. Schwarze-Pense Community No. 2 in Sec. 24, T17N, R2E, has been selected to serve as a stratigraphic reference section (Figure 7). Several geophysical discontinuities, which represent key stratigraphic surfaces, are present within the Racine Formation. These surfaces are isochronous and correspond to

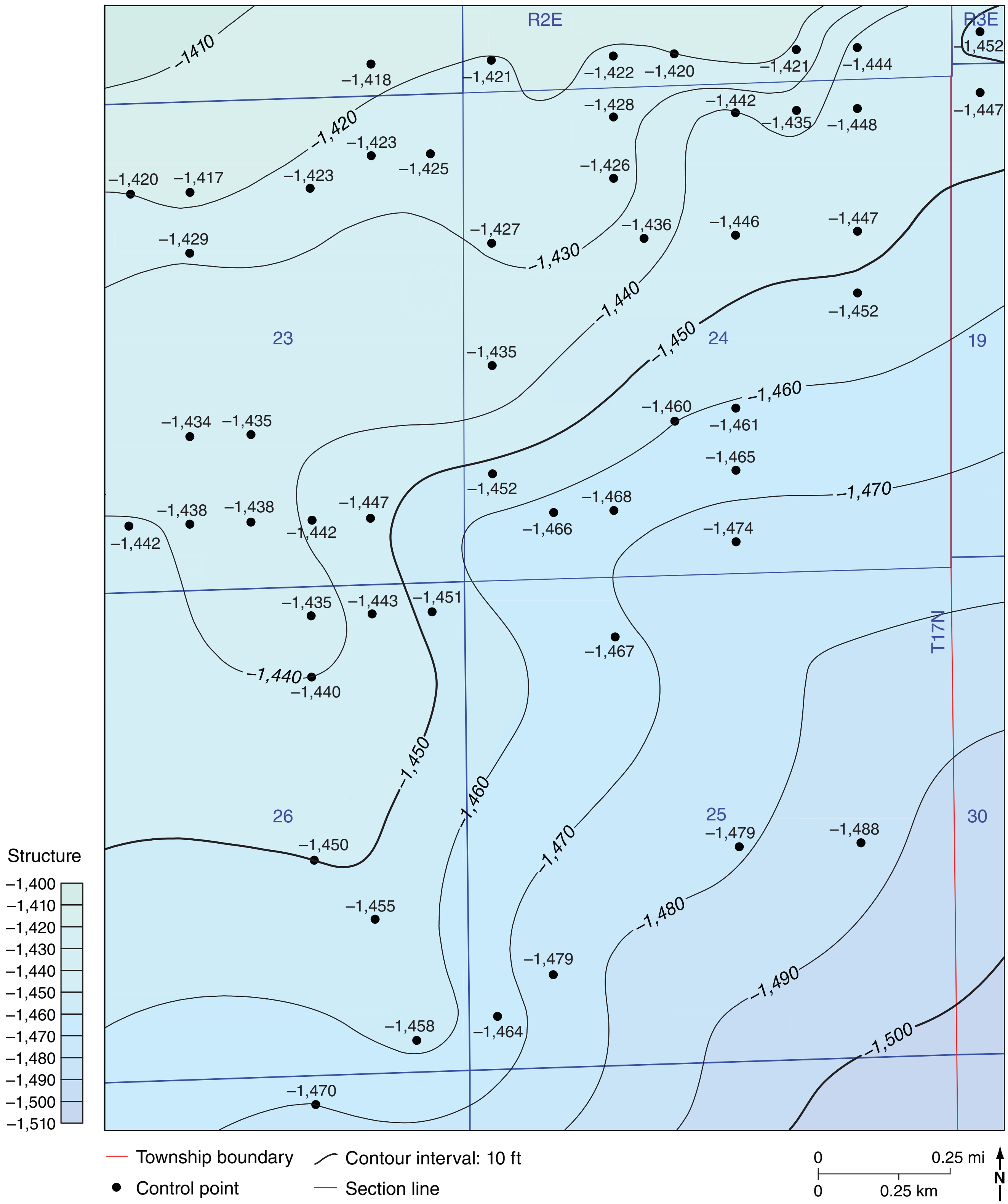

Figure 5 Structure contour map of the top of the reservoir interval at Forsyth showing a regional dip toward the southeast. Note that except for a few southeast-trending noses, no structural closure is present.

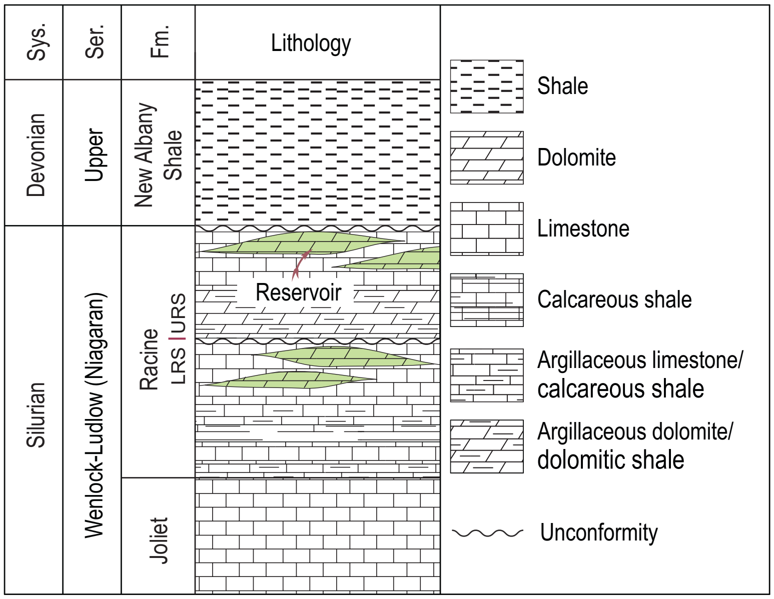

Figure 6 General stratigraphic column in the Mt. Auburn trend showing the reservoirs in the upper part of the Racine sequences. Sys., system; Ser., series; Fm., formation; LRS, lower Racine sequence; URS, upper Racine sequence.

chronostratigraphic events that resulted in major changes in lithology and depositional setting. A few of these surfaces are listed below (Figure 7):

1. The base of the Racine Formation at 2,335 ft (712 m); from this depth, gamma-ray and resistivity logs display a characteristic overall decrease in resistivity and increase in radioactivity upward.
2. The base of a radioactive calcareous shale at 2,270 ft (692 m).
3. The unconformable upper boundary of the lower Racine interval at 2,182 ft (665 m).
4. The base of a transgressive limestone marker that overlies the Racine reservoir near the top of Silurian deposits at 2,114 ft (644 m).
5. The unconformable upper boundary of the upper Racine interval (base of the New Albany Shale at 2,101 ft, 640 m).

The base of the limestone marker serves as a datum for the preparation of maps and cross sections in the study area. It is of variable thickness and is absent in the northwest of the Mt. Auburn trend because of pre-Devonian erosion. Some workers in the oil industry consider this limestone as being of Devonian age and depict the upper contact of the Racine reservoir as a Devonian–Silurian contact. Nevertheless, the Middle Devonian strata pinch out and are absent in the study area of the Sangamon Arch (Whiting and Stevenson 1965; North 1969). In addition, the basal part of Middle Devonian transgressive strata commonly displays a high gamma-ray log signature (Lasemi 2013), which is absent in the Forsyth area. Only in the Triple G Oil Company Ltd. Hockaday No. 7 and Hockaday No. 9 (eastern half of the NW NW of Sec. 23, T17N, R2E) in the extreme northwest of Forsyth Field, a laterally discontinuous uppermost horizon may belong to an erosional remnant of Middle Devonian Lingle Formation (see cross section C–C′ below).

The Racine sequences (third-order cycles) consist of transgressive and regressive (highstand) packages (Figure 7) and are superimposed by smaller scale fifth- to fourth-order shallowing-upward cycles (Figures 9 and 10). The thickness of the Racine Formation varies from place to place because of the lack of deposition or erosion at the sequence boundaries. In the study area, the Racine is more than 240 ft (73 m) thick, but its thickness decreases southwestward. It reaches a thickness of 200 ft (61 m) in Sun Oil Company Damery No. 1, the discovery well of Blackland Field (see cross section A–A′ below).

PETROLEUM RESERVOIRS

Along the Mt. Auburn trend, the Racine Formation generally comprises several permeability pinch-out zones at different horizons. These zones consist of dolomitized limestone intervals that occur in the upper part of the upper Racine and also in the upper part of the lower Racine sequences (Figures 6 and 11). In the northwest margin of the trend, the upper Racine reservoirs are absent because of pre-Devonian erosional unconformity; the oil fields in this area produce from the reservoirs developed in the upper part of the lower Racine sequence (Figure 2).

At Forsyth Field, the main producing interval is a lenticular dolomite reservoir body (Figure 12) that occurs in the regressive package of the upper Racine sequence near the top of the formation (Figures 7 and 9). The reservoir underlies, with a sharp contact, an impermeable limestone (Figure 7), which is persistent throughout the Mt. Auburn trend area (Figures 11 and 13–15). It is a lenticular, commonly compartmentalized dolomite body reaching a maximum net thickness of nearly 12 ft (3.66 m) and is composed of two juxtaposed lenses trending in a northeast–southwest direction (Figure 12), paralleling the trend of the Sangamon Arch. Neither core nor core analysis data are available for the Forsyth Field; however, reservoir porosity is in the range of 8%–27% based on porosity logs. The average porosity of the main reservoir (corrected for dolomite) when using density and sidewall neutron logs is nearly 16%. The porosity types observed in thin sections and core samples of the Racine from the neighboring fields are secondary intercrystalline, vugular, and moldic (dissolved fossil) porosities.

A thin limestone bed that is commonly recognizable in microresistivity logs (up to 2 ft, 0.61 m) divides the reservoir into two compartments (Figure 9). This intervening limestone may locally reach a thickness of up to 6 ft (1.83 m) in parts of the Mt. Auburn trend (see the Rothwell No. 1 well, API No. 121152155700 in Figure 10 for an example). The reservoir

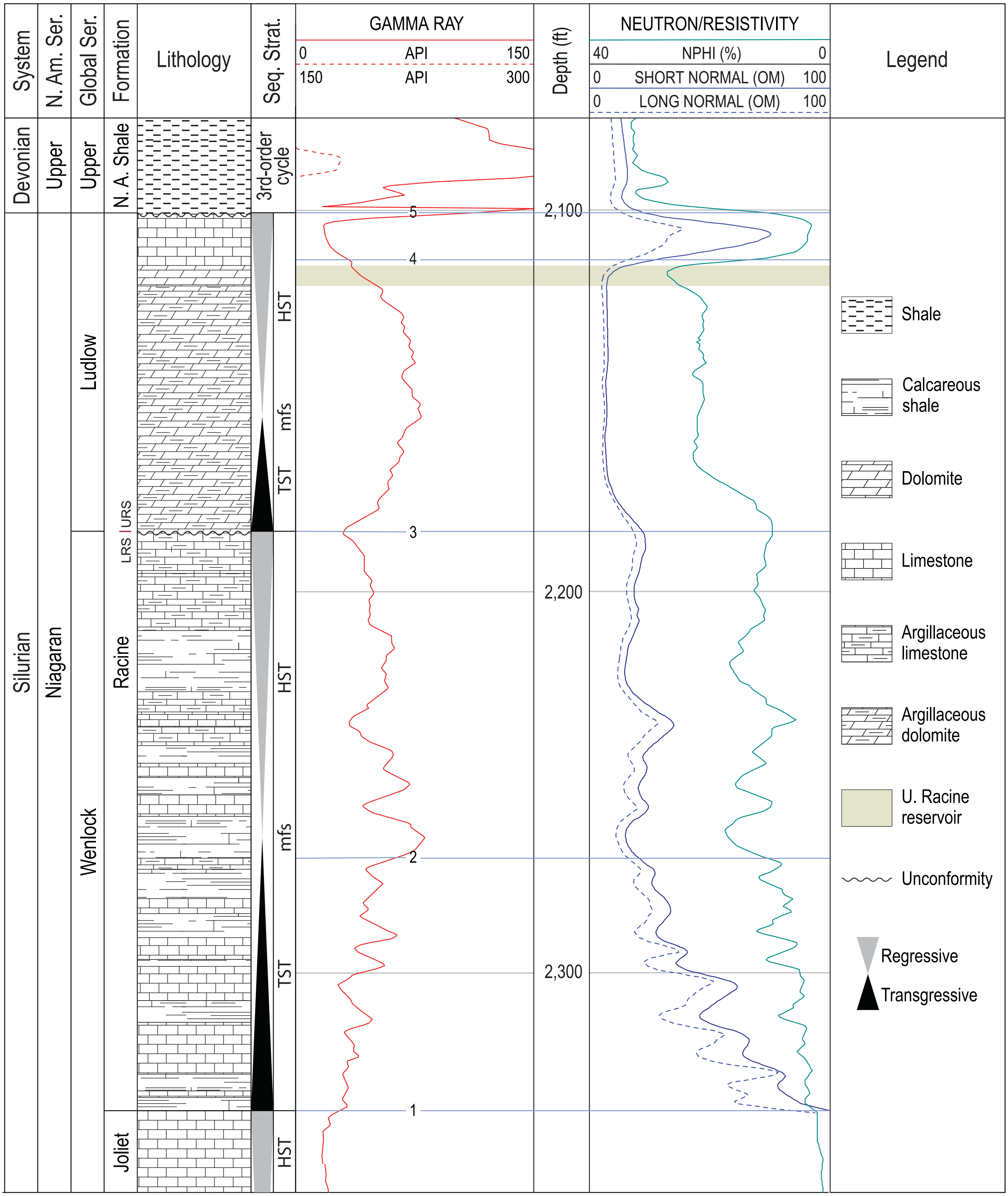

Figure 7 Stratigraphic reference section in Forsyth Field (Triple G Oil Co. Ltd. Schwarze No. 2, API No. 121152144400) showing geophysical logs, a lithologic column, and sequences of the Racine Formation. Note that the neutron porosity displays limestone porosity and that the reservoir (in tan) underlies a dense limestone marker in the upper Racine sequence. N. Am. Ser., North American series; Global Ser., global series; N. A. Shale, New Albany Shale; Seq. Strat., sequence stratigraphy; API, American Petroleum Institute units; NPHI, neutron porosity; OM, ohmmeter; LRS, lower Racine sequence; URS, upper Racine sequence; TST, transgressive systems tract; mfs, maximum flooding surface; HST, highstand systems tract; U. Racine reservoir, upper Racine reservoir.

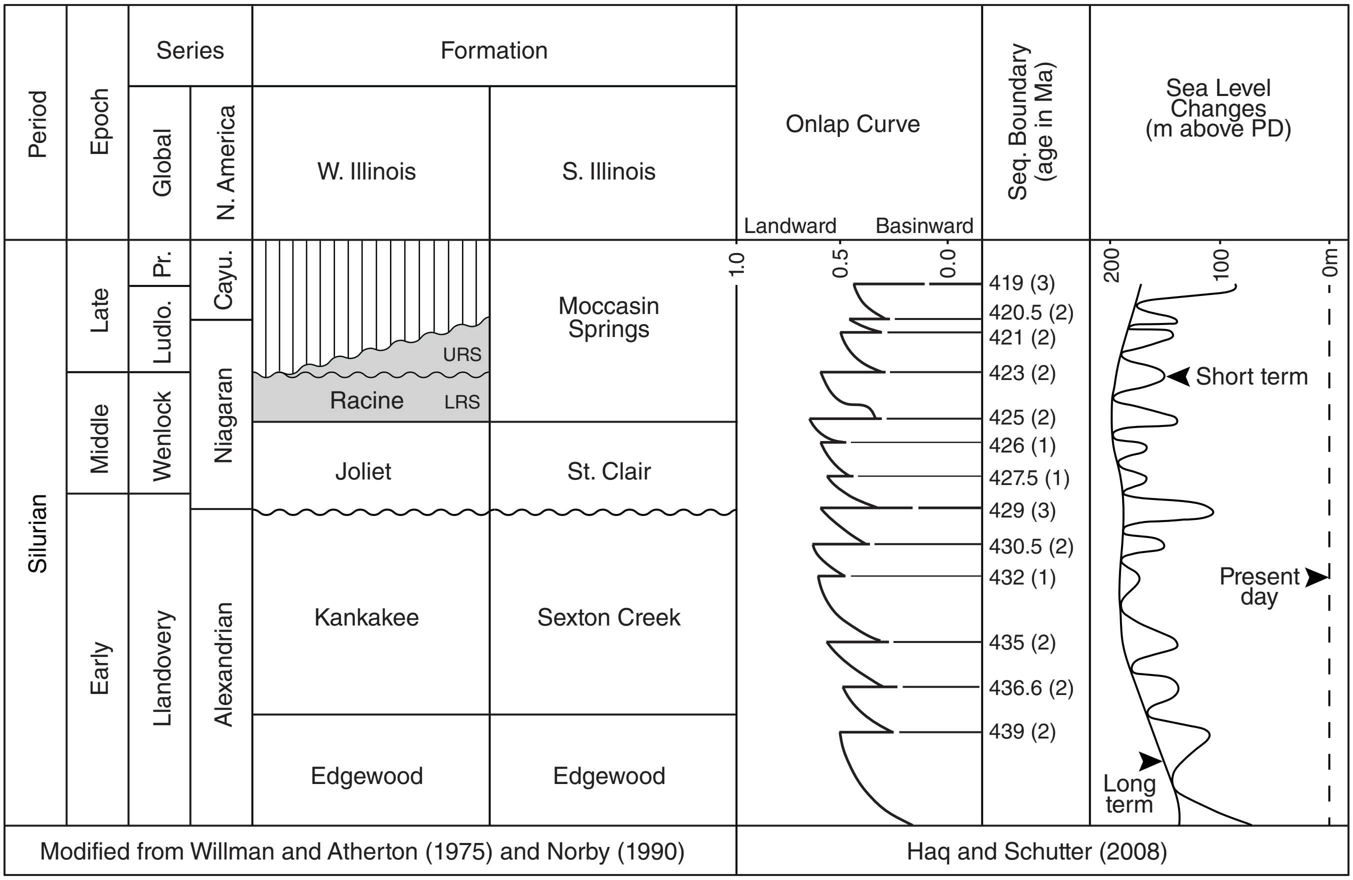

Figure 8 Stratigraphic nomenclature of the Silurian System in Illinois and Silurian sea level changes. Stratigraphic column modified from Willman and Atherton (1975) and Norby (1990); Racine subdivision based on Lasemi (2009a, 2009b). N. America, North America; W. Illinois, western Illinois; S. Illinois, southern Illinois; Seq. boundary, sequence boundary; m above PD, meters above present day; Ludlo., Ludlow; Pr., Pridolian; Cayu., Cayugan; URS, upper Racine sequence; LRS, lower Racine sequence.

constitutes the upper part of small-scale, fifth- to fourth-order shallowing-upward cycles, which are capped, with a sharp contact, by a transgressive limestone facies (Figures 9 and 10). The reservoir interval is coeval with the combined reservoir units B and C of Lasemi et al. (2010), in which the intervening limestone between the reservoir units was beyond the resolution of the geophysical log.

In the extreme northwest of Forsyth Field, two laterally discontinuous younger horizons produced in the Triple G Oil Company Ltd. Hockaday No. 7 (Figure 13) and Hockaday No. 9 in the eastern half of the NW NW of Sec. 23, T17N, R2E. In these wells, the uppermost reservoir may be an erosional remnant belonging to the Middle Devonian Lingle Formation, although its affinity to the Upper Devonian Hardin (Sylamore) Sandstone, which locally occurs at the base of the New Albany Shale, cannot be ruled out.

A report by IBEX Geological Consultants Inc. (1992) indicated a Silurian reservoir thickness of more than 15 ft (4.6 m) in parts of Forsyth Field (Figure 16). However, the validity of the thickness map in this report is questionable. The report shows an abnormally high reservoir thickness for parts of the field because it considers the three pay horizons in the northwest of the field mentioned above (Figure 16) as a single reservoir. In addition, wells with a conventional electric log/cased-hole gamma-ray log, which are not very reliable for the recognition of contacts, were included in preparing the thickness map. IBEX Geological Consultants Inc. (1992) envisioned four separate lenticular reservoir pinch-outs within the field (Figure 16). Well-to-well correlation and the isopach map of the main producing interval (Figure 12), however, indicate a lenticular body composed of two juxtaposed lenses, which do not appear to show any intervening porosity barrier.

FACIES AND DEPOSITIONAL SETTING

Cores and well samples are missing for the entire area of Forsyth Field. According to the Scout Check report cards and notes written on a few old electric logs, reservoir intervals were cored in a number of wells, but the cores were not saved. Geophysical log cross sections indicate that the Silurian reservoir interval at Forsyth correlates with the reservoirs in the upper part of the Racine Formation in the neighboring fields of the Mt. Auburn

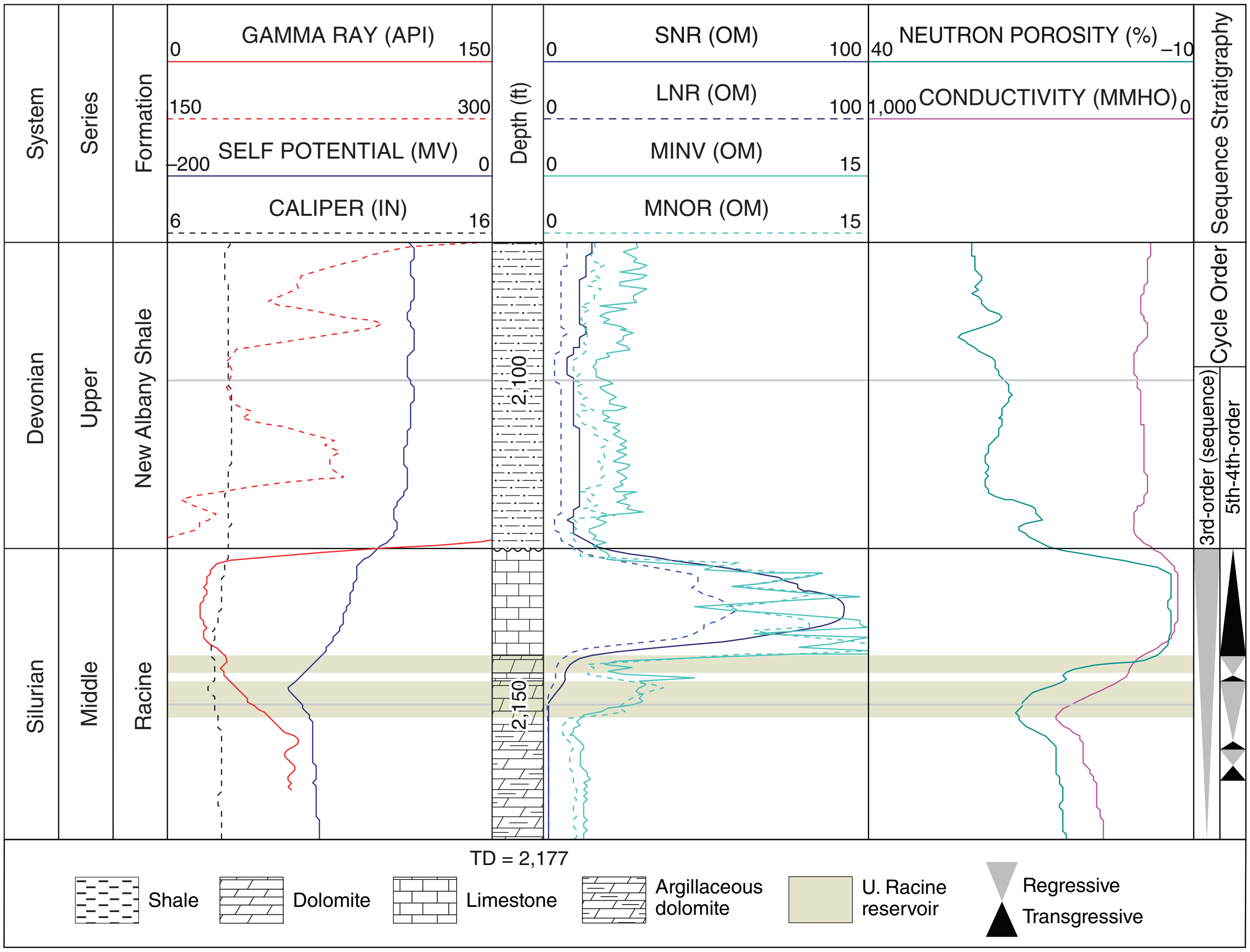

Figure 9 Type log in Forsyth Field (Triple G Oil Co. Ltd. Schwarze Trust No. 2, API No. 121152135800) showing the upper Racine dolomite reservoir interval (in tan) in the regressive package of the upper Racine sequence. Note that a thin dolomitic limestone horizon (<1 ft, <0.3 m) divides the reservoir interval into two compartments. Note also the sharp contact between the reservoir and the overlying transgressive limestone. This well penetrated the highstand (regressive) part of the sequence; for the complete upper Racine sequence stratigraphy, see Figures 7 and 10. API, American Petroleum Institute units; MV, millivolts; IN, inches; SNR, short normal resistivity; LNR, long normal resistivity, MINV, microinverse; MNOR, micronormal; OM, ohmmeter; MMHO, milli-mohs; TD, total depth; U. Racine reservoir, upper Racine reservoir.

area. In these fields, the reservoir facies is commonly a nonreef dolomitized fossiliferous grainstone to wackestone (Figure 17a–d) capped, with a sharp contact, by a dense limestone facies (Figures 7 and 10). This facies is generally a bioturbated fossiliferous lime mudstone to packstone (Figure 17e,f) interpreted as a transgressive horizon.

The depositional model of the Racine Formation is a gently sloping ramp (ramp platform of Ahr 1973, 1998) that existed during deposition in the Sangamon Arch area (Figure 18). Because the depositional wave energy was not strong in the homoclinal ramp setting on the arch, only bioclast grainstone shoal facies and small patch reefs were developed (Lasemi 2009c; Lasemi et al. 2010), as opposed to the large pinnacle reefs that developed along the steeper slope of the deep Illinois Basin margin (Bristol 1974; Droste and Shaver 1987). These facies graded to lime wackestone and mudstone basinward (Lasemi 2009c, 2014; Lasemi et al. 2010), similar to numerous modern and ancient examples (Wilson 1975; Tucker and Wright 1990; Flügel 2010). Dolomite reservoirs formed because slightly saltier magnesium-rich seawater percolated through the previously deposited lime sediment (Figure 18) during the regressive phase of a small-scale shallowing-upward cycle and was capped by deeper water-impermeable limestone beds following transgression (Lasemi 2010, 2012, 2014; Lasemi et al. 2010). During burial diagenesis, undolomitized limestone was compacted but the dolomite resisted compaction, thus retaining its porosity.

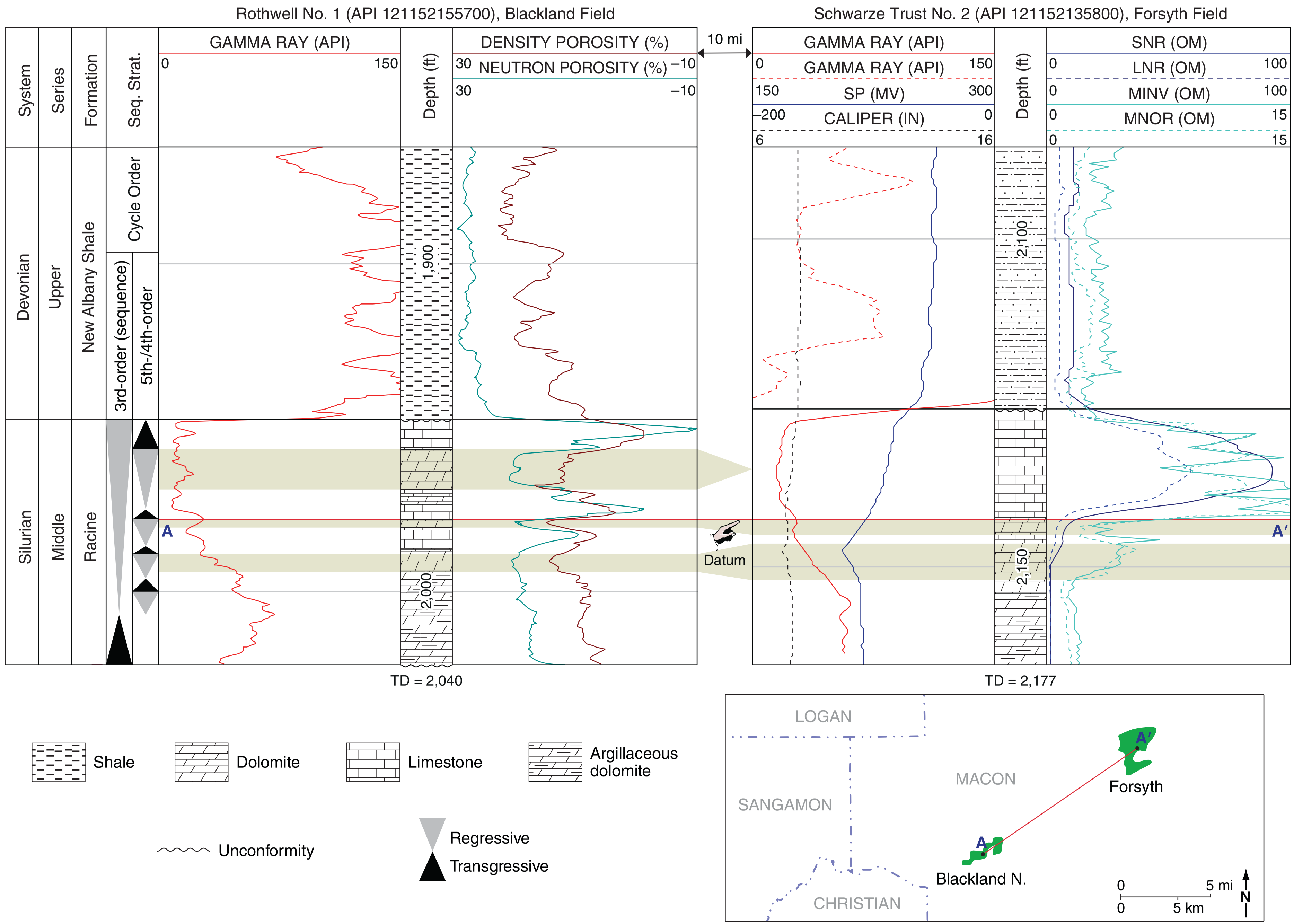

Figure 10 Cross section A–A′ showing lateral and vertical variability of the upper Racine reservoir compartments in the Mt. Auburn trend from Blackland North Field to Forsyth Field. Note that the reservoir horizons (in tan) constitute the upper part of small-scale shallowing-upward cycles in the regressive package of the upper Racine sequence. Note also the sharp contact between dense transgressive limestone and the underlying reservoir units. Seq. Strat., sequence stratigraphy; API, American Petroleum Institute units; SP, self-potential; MV, millivolts; IN, inches; SNR, short normal resistivity; LNR, long normal resistivity, MINV, microinverse; MNOR, micronormal; OM, ohmmeter; TD, total depth.

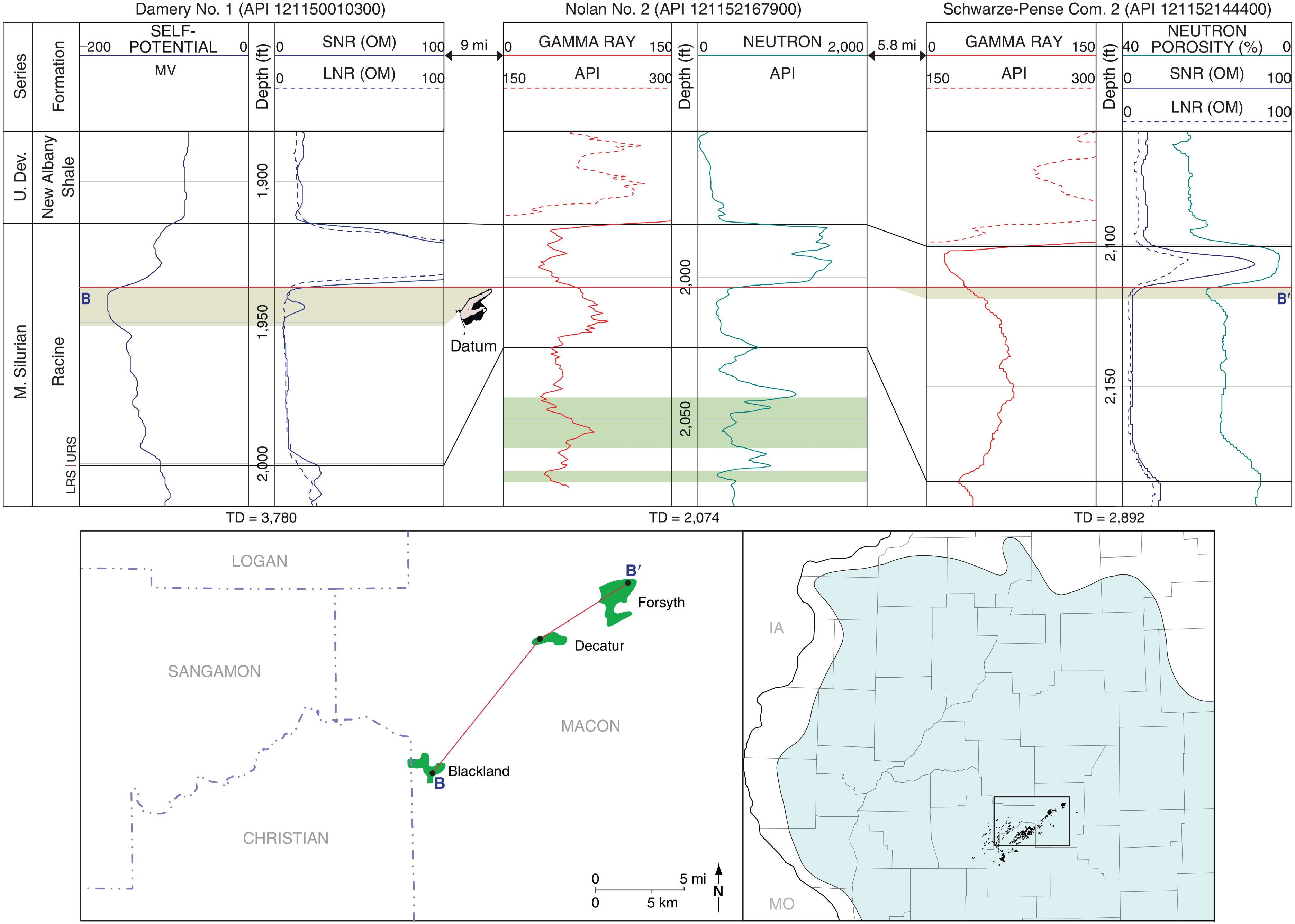

Figure 11 Southwest–northeast cross section B–B′ along the Mt. Auburn trend from Blackland Field to Forsyth Field that shows the reservoirs (in tan) in the upper and lower Racine sequences. Note that the reservoir at Forsyth and Blackland Fields occurs in the upper sequence. The reservoir in the lower sequence at Decatur Field correlates with a patch reef reservoir further to the southwest. Note the sharp contact between the base of the datum (limestone marker) and the uppermost Racine reservoir in this figure. API, American Petroleum Institute units; MV, millivolts; SNR, short normal resistivity; LNR, long normal resistivity; OM, ohmmeter; U. Dev., Upper Devonian; M. Silurian, Middle Silurian; LRS, lower Racine sequence; URS, upper Racine sequence; TD, total depth.

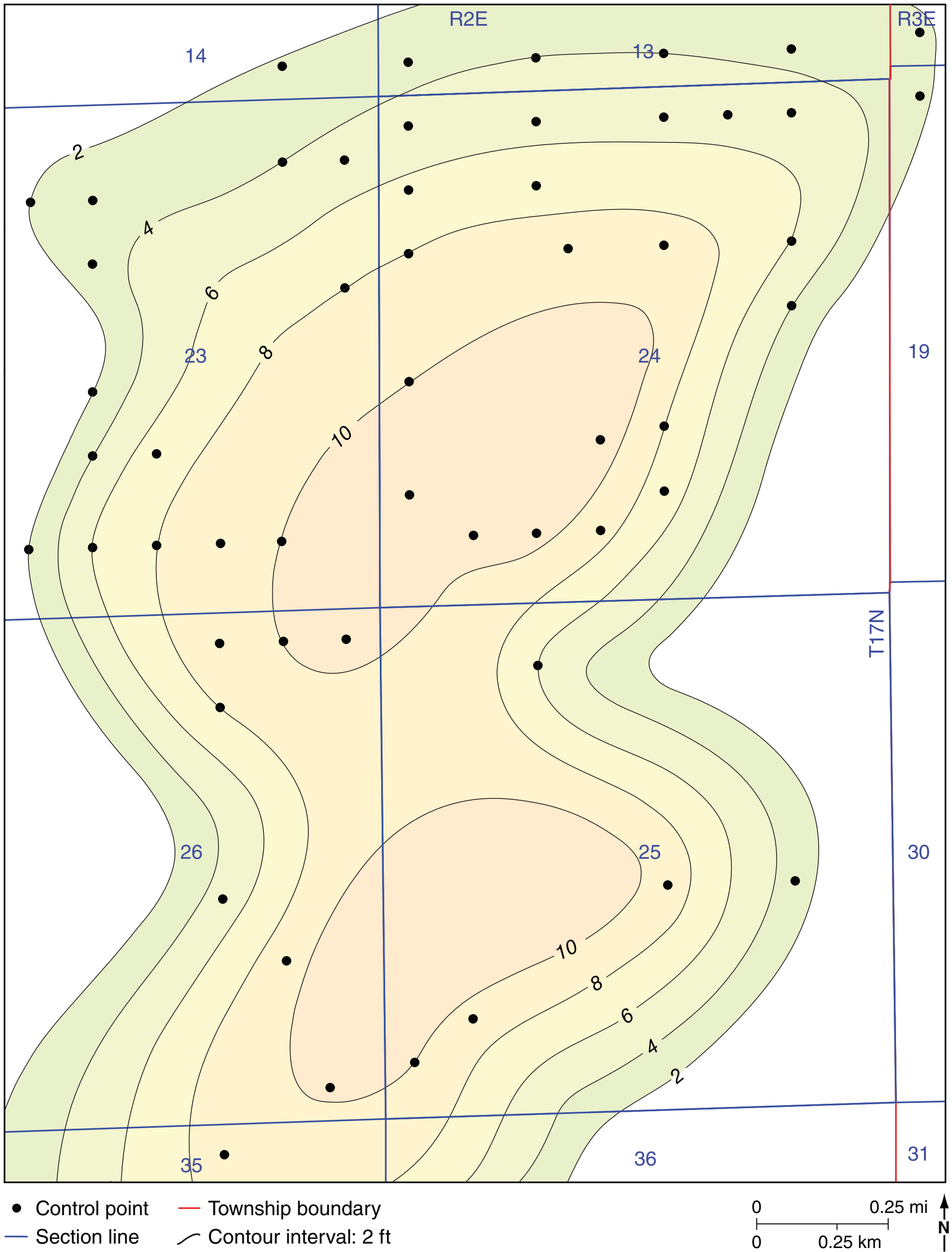

Figure 12 Isopach map of the main reservoir interval at Forsyth Field showing two northeast–southwest-trending juxtaposed bodies that formed as ramp margin facies parallel to the shoreline during deposition.

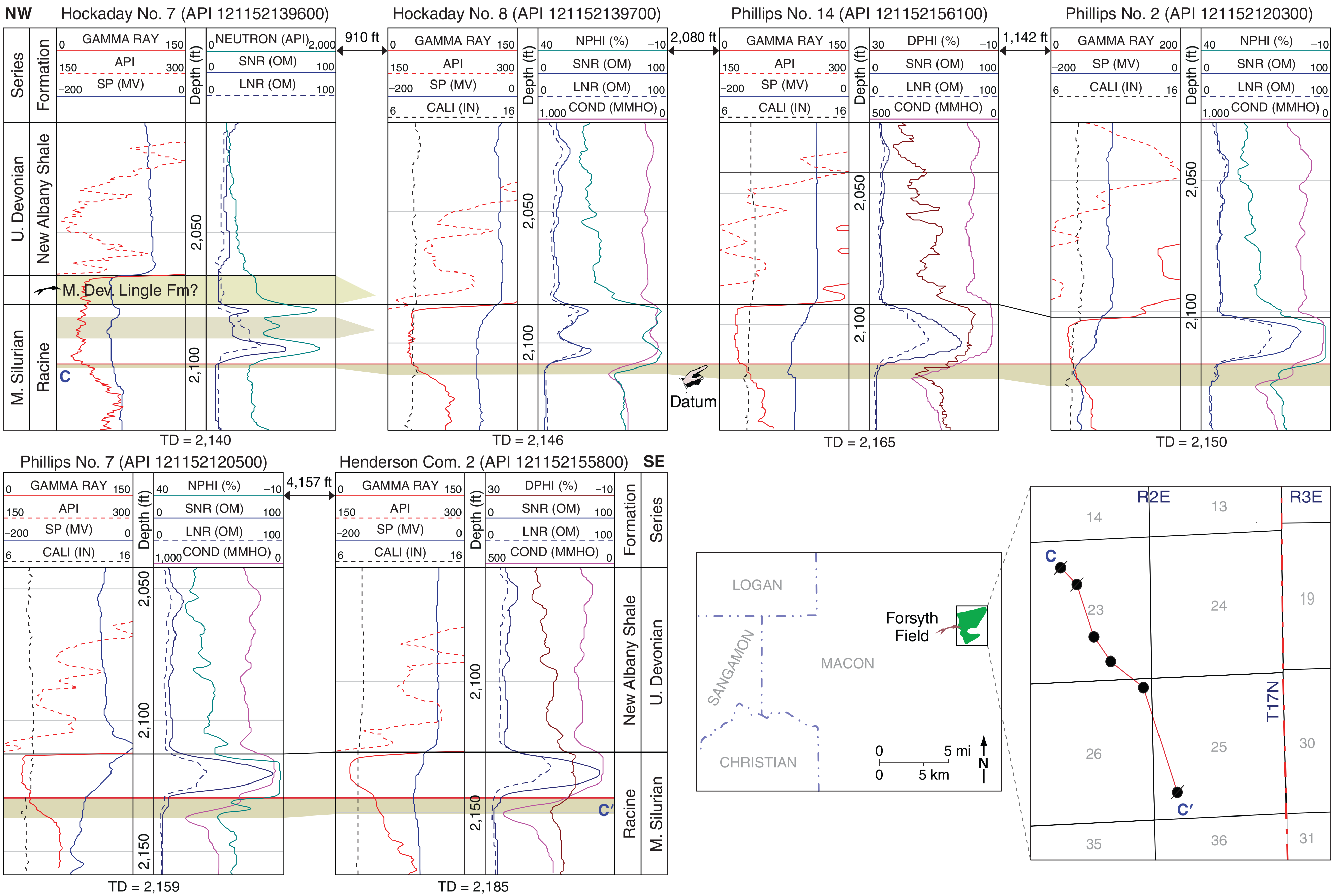

Figure 13 Northwest–southeast correlation C–C′ showing the lateral variation of the Racine reservoirs shown in tan at Forsyth (log porosity based on the limestone matrix). The variation in thickness of the limestone marker is due to dolomitization and pre-Devonian erosion. Note the presence of two reservoirs above the main reservoir in Hockaday No. 7 that pinch out in only one location to the southeast. API, American Petroleum Institute units; SP, self-potential; MV, millivolts; SNR, short normal resistivity; LNR, long normal resistivity; OM, ohm-meter; CALI, caliper; IN, inches; NPHI, neutron porosity; COND, conductivity; MMHO, milli-mohs; DPHI, density porosity; U. Devonian, Upper Devonian; M. Dev. Lingle Fm., Middle Devonian Lingle Formation; M. Silurian, Middle Silurian; TD, total depth.

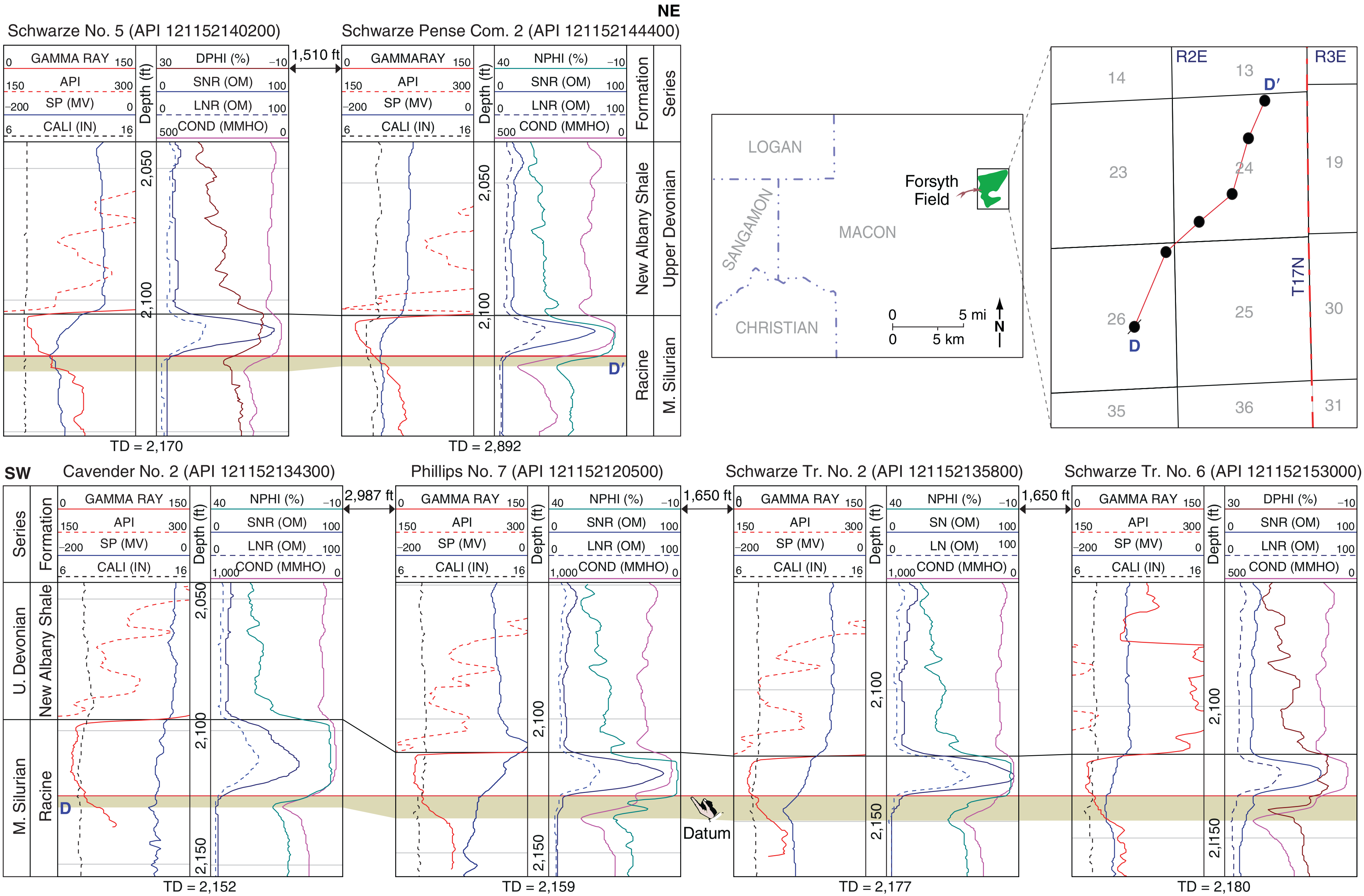

Figure 14 Southwest–northeast correlation D–D′ showing the lateral variation in the Racine reservoirs at Forsyth (log porosity based on the limestone matrix). The variation in thickness of the limestone marker is due to pre-Devonian erosion. API, American Petroleum Institute units; SP, self-potential; MV, millivolts; CALI, caliper; IN, inches; DPHI, density porosity; SNR, short normal resistivity; LNR, long normal resistivity; OM, ohmmeter; COND, conductivity; MMHO, milli-mohs; NPHI, neutron porosity; M. Silurian, Middle Silurian; U. Devonian, Upper Devonian; TD, total depth.

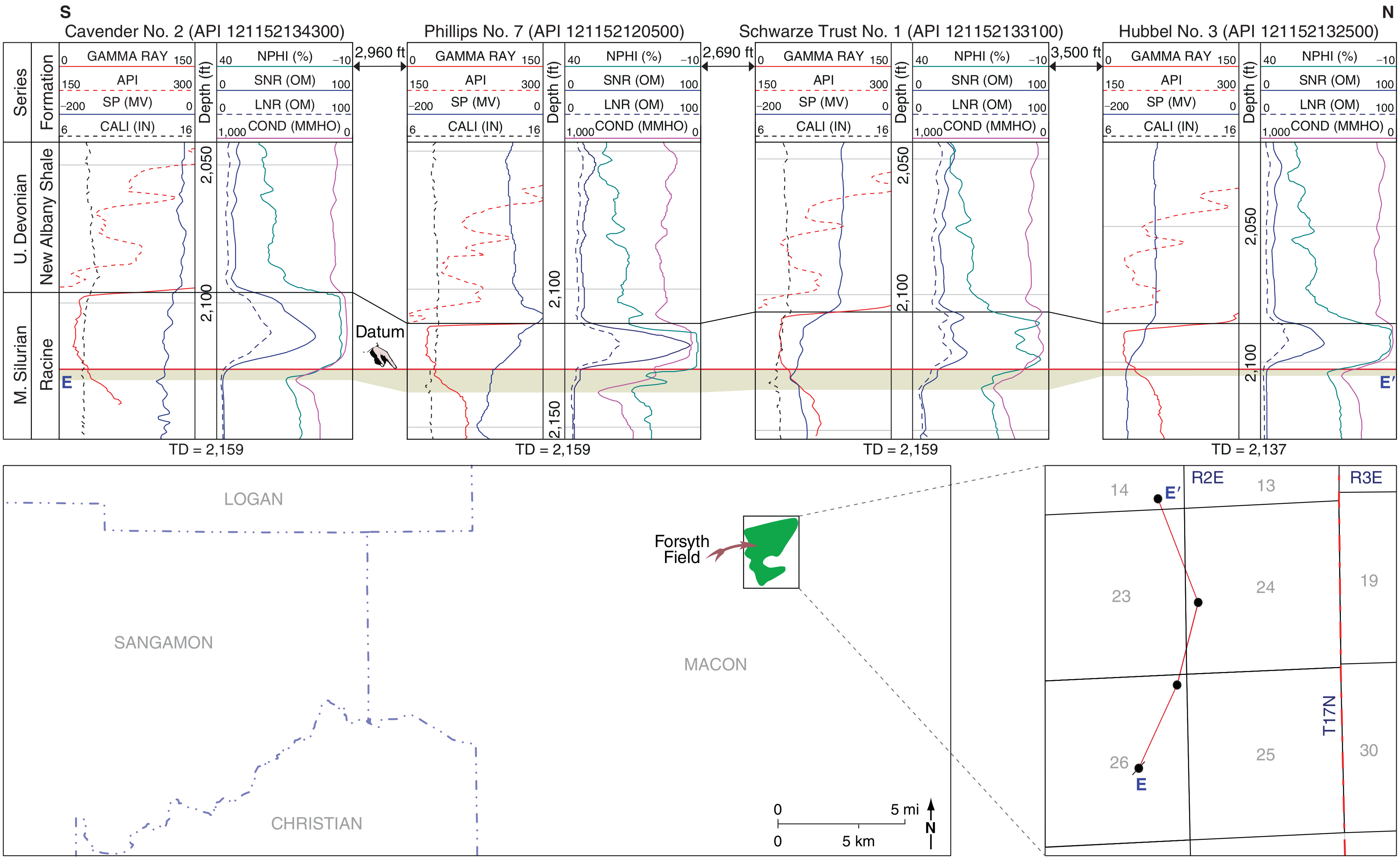

Figure 15 South–north correlation E–E′ showing lateral variation in the Racine reservoir shown in tan (log porosity based on the limestone matrix). The variation in thickness of the limestone marker is due to pre-Devonian erosion. API, American Petroleum Institute units; SP, self-potential; MV, millivolts; CALI, caliper; IN, inches; NPHI, neutron porosity; SNR, short normal resistivity; LNR, long normal resistivity; OM, ohmmeter; COND, conductivity; MMHO, milli-mohs; M. Silurian, Middle Silurian; U. Devonian, Upper Devonian; TD, total depth.

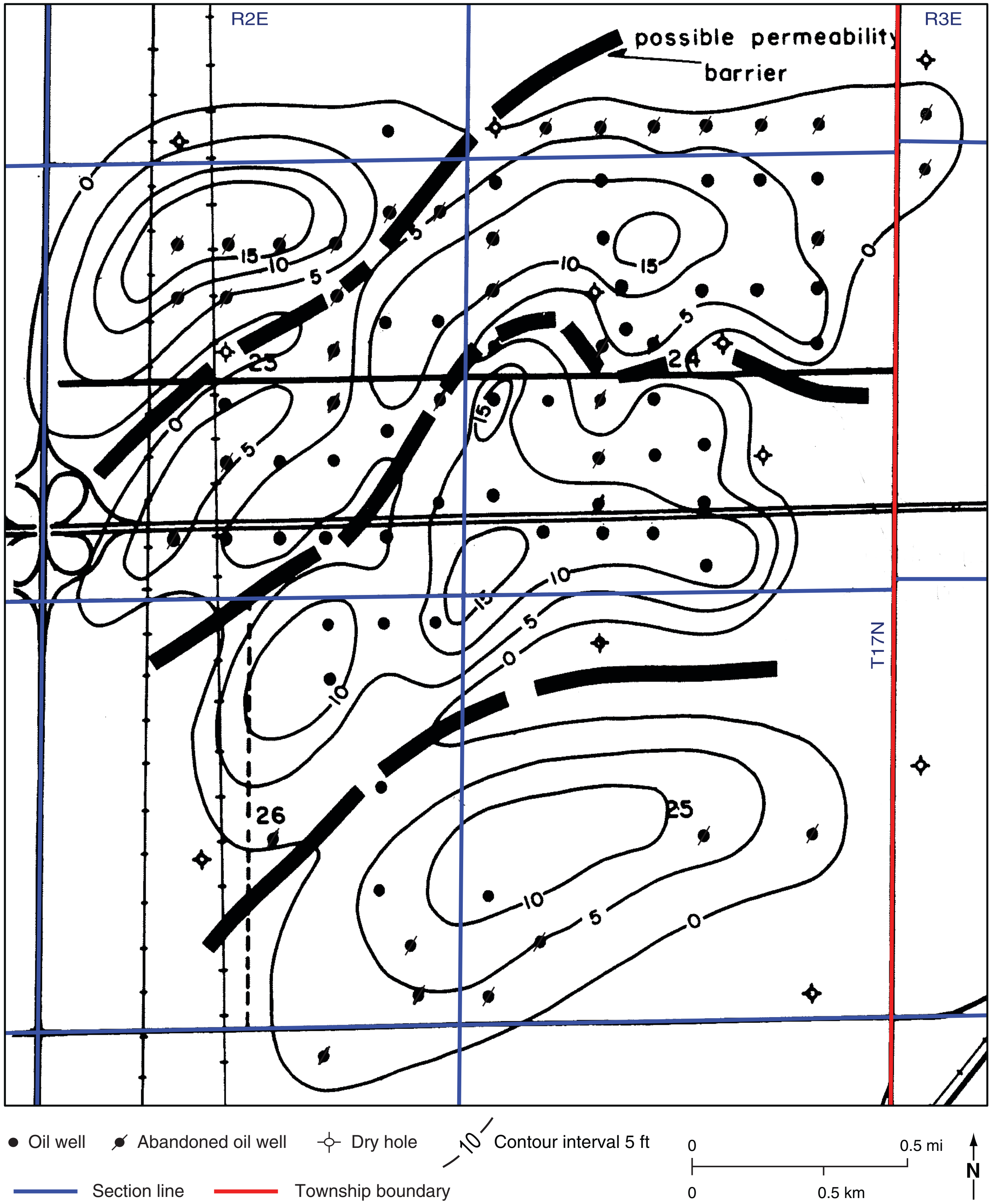

Figure 16 Isopach map of the Racine reservoir modified from the map by IBEX Geological Consultants Inc. (1992). In Sec. 23 (northwest of the map), the thicknesses of the main reservoir and two younger reservoir units are combined, giving rise to an abnormally large thickness (cf. Figures 12 and 13).

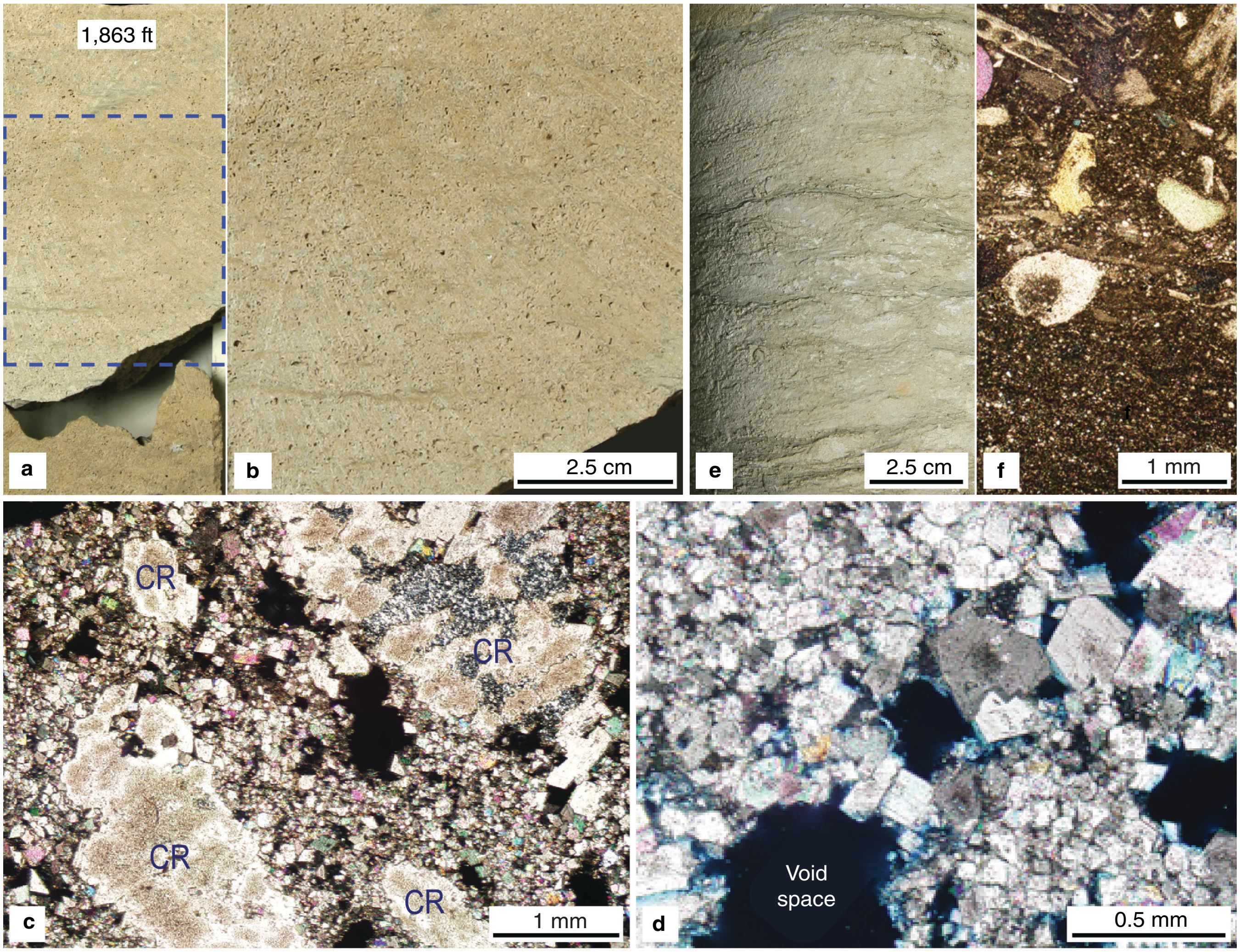

Figure 17 (a, b) Core samples and (c, d) photomicrographs of the reservoir showing porous, partially dolomitized crinoid fragments (CR) and (d) medium to coarsely crystalline dolomite. Note the intercrystalline and vugular secondary porosities in panels c and d. (e, f) Core sample and photomicrograph of bioturbated dense caprock facies. Samples are from a core in Podolsky Oil Company McMillen B-4, Mt. Auburn Consolidated Field.

STRUCTURE AND PETROLEUM TRAP

Because of pre-Upper Devonian unconformity and the formation of an erosional remnant on the Silurian deposits, a structure map prepared on this diachronous surface may not represent the true structural attributes of the Racine reservoir. Therefore, the structure contour map (Figure 5) was prepared by using the base of a limestone marker that directly overlies the Racine reservoir near the top of the Silurian deposits. This transgressive limestone marker rests on the reservoir with a sharp contact (Figures 10 and 11), reflecting a synchronous, relatively rapid sea level rise event. According to the reservoir isopach map (Figure 12), the reservoir at Forsyth is lenticular, appears to pinch out laterally, and has an overall northeast–southwest trend. It lies along the southeastern flank of the Sangamon Arch (Figure 2) on a regional dip that slopes to the southeast (Figure 5). Except for southeast-plunging noses (the prominent one being the nose at the southwest of the map), no structural closure exists. Therefore, the main control on petroleum entrapment is stratigraphic. Combined depositional and diagenetic processes and an updip pinch-out of the reservoir against the Sangamon Arch were responsible for petroleum entrapment (Lasemi 2010, 2014; Lasemi et al. 2010).

POTENTIAL FOR IMPROVING RECOVERY

At Forsyth Field, initial oil production was relatively low and mainly less than 100 barrels of oil. The average cumulative primary production per well is less than 10,000 barrels, which is below average for the Mt. Auburn trend area. Solution gas drive was the primary recovery mechanism. A drill stem test report from a couple of wells in the Forsyth Field area indicated low shut-in pressure (less than

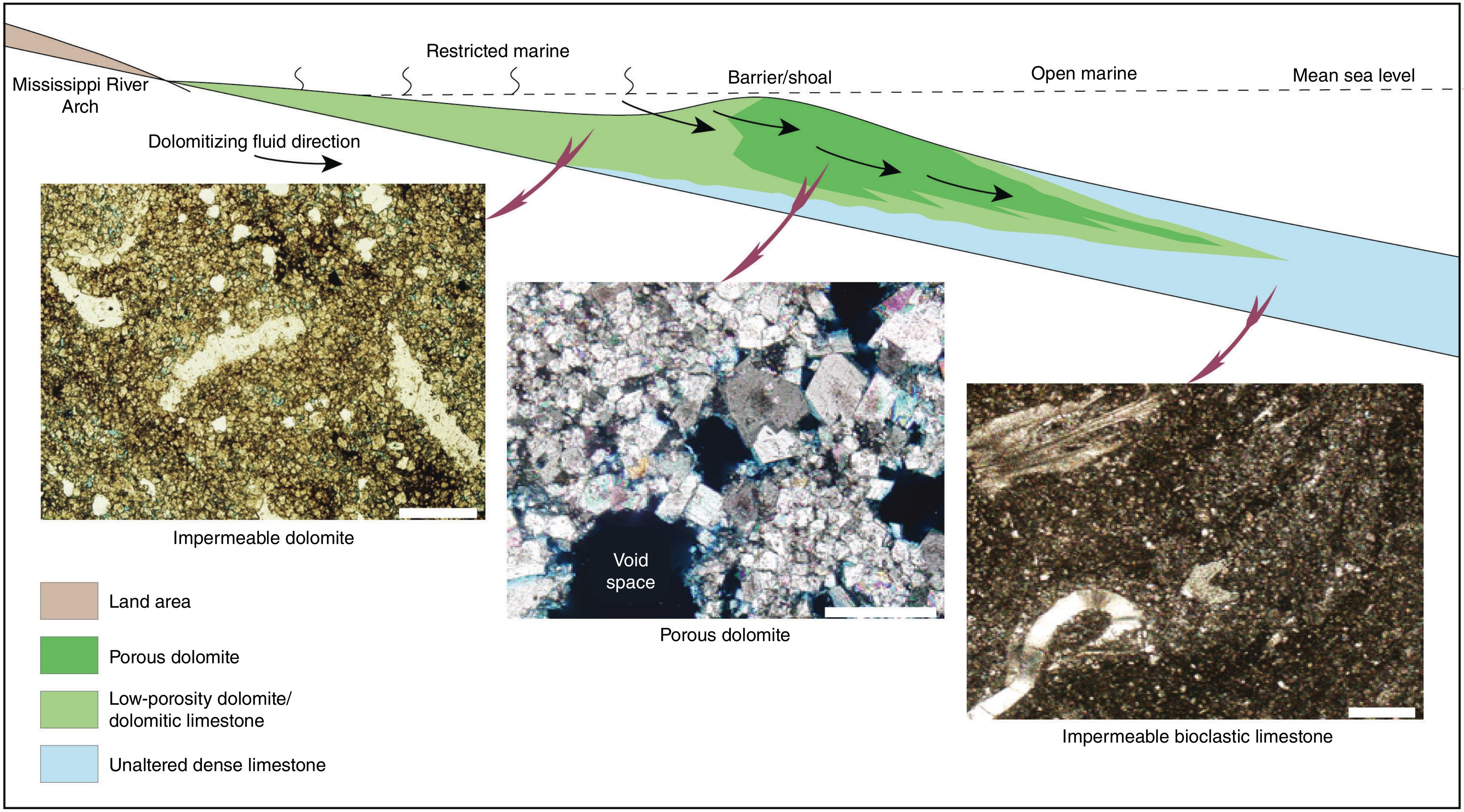

Figure 18 Depositional and diagenetic model for the development of a Silurian dolomite reservoir in the Mt. Auburn trend area of the Sangamon Arch (Lasemi 2013). Seaward percolation of the denser dolomitizing fluids from a restricted environment (black arrows) could have resulted in early dolomitization of the previously deposited lime sediment. Dolomitizing fluid did not reach the deeper open marine facies, but the shallower proximal facies was dolomitized. In the proximal inner platform setting, an impermeable facies formed because of the finer dolomite crystal size and small intercrystalline pore spaces and because of infilling of bioclast molds. During sea level highstand, dense fossiliferous limestone was deposited, forming the widespread caprock facies. Scale bar is 0.5 mm.

100 psi) and minimal fluid recovery (for an example, see the Scout Check report in Mazzarino Schwartz No. 1, API No. 121150005100). Low reservoir pressure and insignificant fluid recovery, low initial oil production, and below-average cumulative primary production per well suggest poor permeability of the dolomite reservoir interval at Forsyth. Therefore, large-volume hydraulic fracturing may be necessary (e.g., Cluff 2015) in any future development and for EOR.

Great potential exists for improving petroleum recovery in the Forsyth Field. A large portion of the field is not completely developed, and several locations in the field are undrilled (Figure 3). Development of the undrilled areas, infill drilling, and large-volume hydraulic fracturing will undoubtedly improve recovery in the field. Horizontal drilling and high-volume multistage fracturing is another possibility for improved recovery. The wells drilled previously are all vertical holes, and the reservoir was stimulated with relatively small-volume (about 20,000 gal, [75,708 L]) hydraulic fracturing. The application of a horizontal drilling technique in the porous and poorly permeable Racine reservoir at Forsyth could result in better communication between the undrained isolated pore spaces and laterally discontinuous compartments that may exist, leading to a significant increase in oil production from the field.

Forsyth Field has never been waterflooded and has great potential for CO_2-EOR, which could result in both increased oil production and storage of CO_2 produced by anthropogenic activity. The calculated original oil in place (OOIP) of the reservoir, based on the acre-feet of the reservoir region (about 14,000), a porosity of 16%, a formation volume factor of 1.05, and oil saturation of 50%, is more than 9 million barrels. The Racine at Forsyth has produced approximately 8% of its OOIP. Preliminary assessment of the field (Damico et al. 2014) indicated significant quantities of recoverable oil through CO_2-EOR. Reservoir simulation results of CO_2-EOR indicated an estimated oil recovery of 26% and 42% of OOIP for near-miscible and miscible conditions, respectively (Damico et al. 2014). Assuming a repressurized reservoir and full deployment of the field (with several new producing and injection wells drilled), more than 3,000,000 barrels of oil could be recovered through CO_2-EOR. The field is approximately 3 mi (4.8 km) from Archer Daniels Midland Company, which could serve as a source for commercial CO_2.

CONCLUSIONS

This study focused on geological characterization of the Racine Formation at Forsyth Field, which is vital in evaluating the remaining recoverable oil through primary and EOR methods. The main results relevant to geological characterization of the Racine Formation are as follows:

1. The Silurian reservoir interval at Forsyth consists of porous, low-permeability, heterogeneous, and compartmentalized lenticular dolomite bodies in the regressive part of the upper Racine sequence. Deposited in the nearshore areas of a carbonate ramp margin, these bodies display a northeast–southwest trend paralleling the Silurian paleoshoreline.
2. The main reservoir constitutes the upper part of small-scale, shallowing-upward cycles capped, with a sharp contact, by a transgressive limestone facies; it reaches a net thickness of nearly 12 ft (3.66 m) and has an average porosity of 16%. Low recorded shut-in pressure and minimal fluid recovery in drill stem tests, insignificant initial oil production, and below-average cumulative primary production per well suggest poor permeability of the reservoir interval at Forsyth.
3. The wells previously drilled at Forsyth Field are vertical and were stimulated with low-volume hydraulic fracturing. Infill drilling and development of the undrilled areas, horizontal drilling, and large-volume hydraulic fracturing will significantly improve recovery from the field.
4. The reservoir has produced less than 8% of its OOIP of more than 9 million barrels and has never been water-flooded; therefore, it has great potential for retrieval of its recoverable residual oil through EOR methods.
5. The proximity of the field to a commercial source of CO_2 makes the Racine reservoir a potential target for CO_2-EOR, which could result in storage of CO_2 produced by anthropogenic activity and significant oil recovery.

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