Geological characterization and ROZ potential of the Tar Springs Sandstone

Topical Report

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Stacked Greenfield and Brownfield ROZ Fairways in the Illinois Basin Geo-Laboratory: Co-Optimization of EOR and Associated CO_2 Storage

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Introduction

The upper Mississippian (Chesterian) Tar Springs Sandstone (Figure 1) is a major oil producing unit in Illinois. It is one of several Mississippian sandstone units that together have contributed more than 60% of the cumulative oil production in the Illinois Basin (Howard, 1990). The Tar Springs is present in the southern part of the Illinois Basin; the basin covers southeastern Illinois, western Kentucky, and southwestern Indiana (Figure 2). Like other Mississippian sandstones, the Tar Springs consists of conventional reservoirs and produces from mature oil fields showing declining primary and secondary production trends. Substantial amounts of immobile oil are remaining in the depleted Tar Springs Sandstone reservoirs. Most of the remaining oil could be recovered by the implementation of enhanced oil recovery methods. The average recovery factor for mature reservoirs is estimated to be between 20% to 40% and application of tertiary recovery techniques is effective at mobilizing the remaining oil and increasing the recovery factors up to 50%–70% (Muggeridge et al., 2014).

Conventional oil reservoirs occur in association with residual oil zones (ROZs) that contain naturally occurring immobile oil (Melzer, 2006). The ROZs found below conventional oil reservoirs are named brownfield ROZs that can also extend beyond the boundaries of conventional oil fields (e.g., Sanguinito et al., 2020). ROZs are potential targets for carbon dioxide enhanced oil recovery (CO2-EOR) and for storing large volumes of anthropogenic carbon in the subsurface (Melzer, 2006; Sanguinito et al., 2020).

The Tar Springs Sandstone consists of interbedded shale and sandstone reservoir intervals (Figure 3), which may be oil productive and/or have ROZ potential. It was one of the candidates selected for geologic characterization related to the brownfield lab site in Richland County, Illinois. Here we focus on regional and field scale geological characterization of the Tar Springs in Illinois. We have used well records, including drilling and completion reports, well logs, and core data (core descriptions/core analyses) to analyze and interpret geological variations. In addition, oil saturation indicators (oil shows, oil saturation from core analysis, and drill stem test data) were analyzed to determine the ROZ potential of the Tar Springs Sandstone.

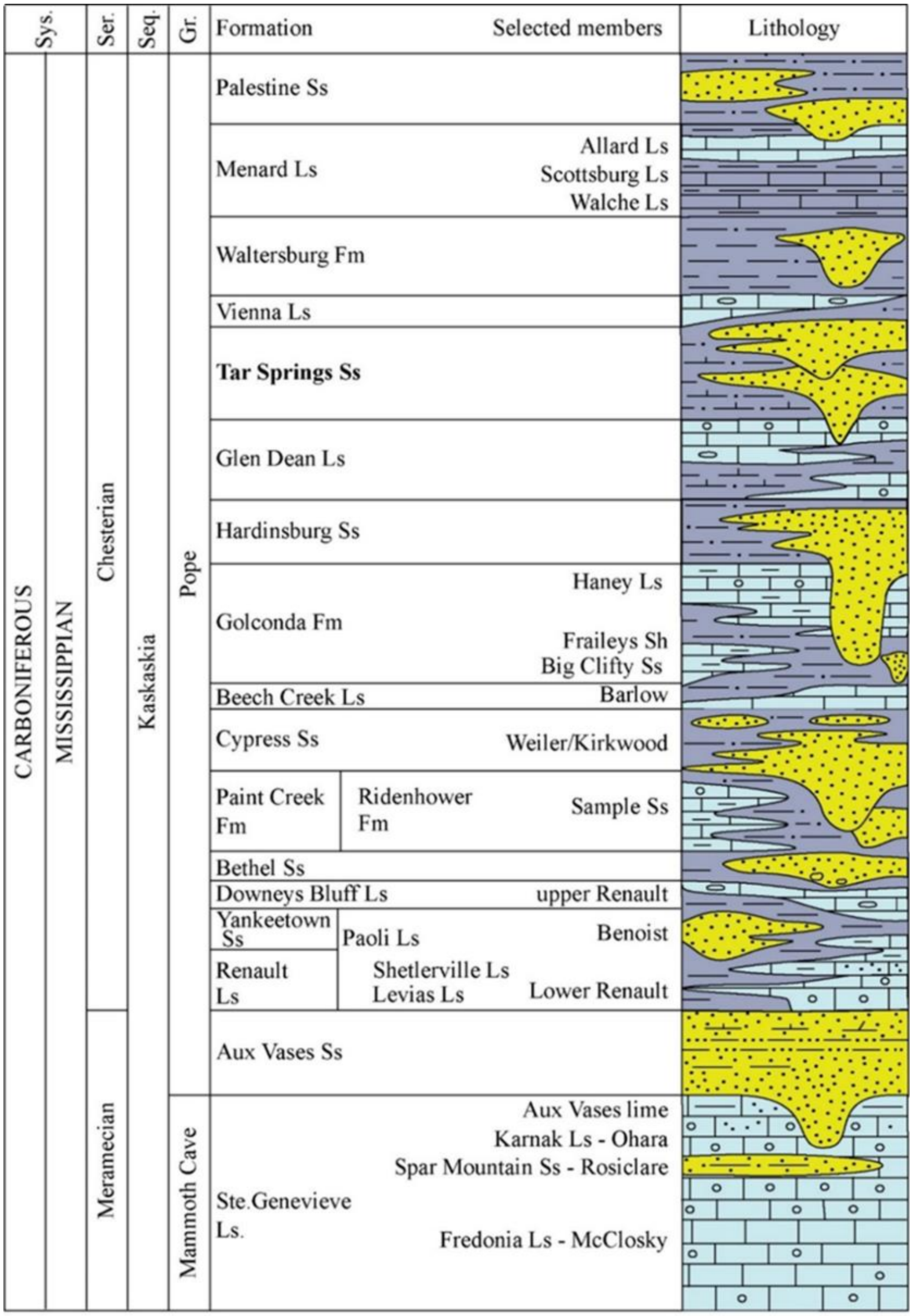

Figure 1. Upper Mississippian stratigraphic column in Illinois (modified from Kolata, 2005). Abbreviations: Dol., dolomite; Fm., formation; Ls., limestone

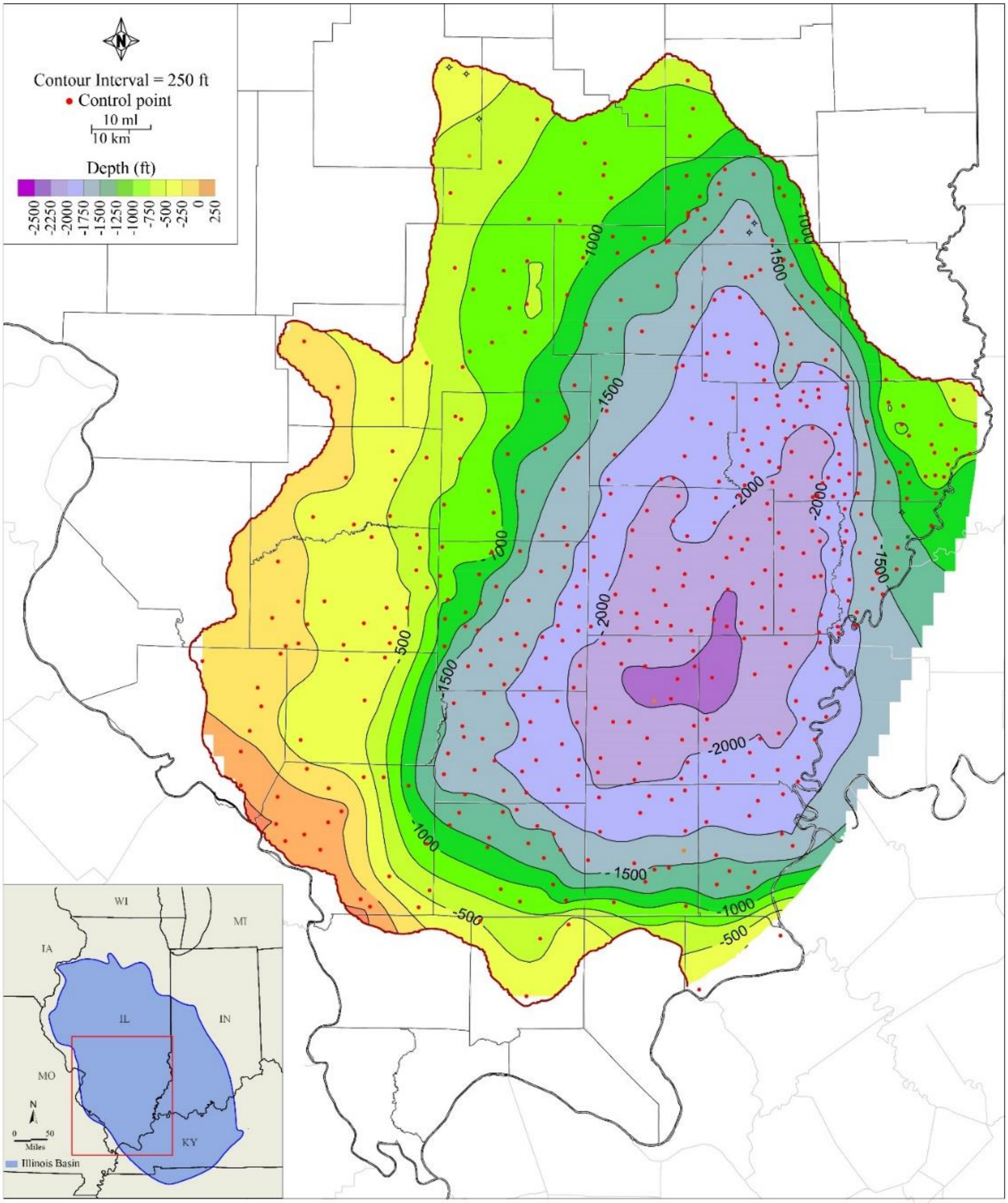

Figure 2. Structure contour map showing the extent of the Illinois Basin in Illinois during deposition of the Tar Springs Sandstone (datum is the base of the upper shale unit of the Tar Springs). The outline of the Illinois Basin (in blue) is shown in the index map.

Geological and stratigraphic settings

The Illinois Basin was formed in the Cambrian over the northeast extension of the Reelfoot Rift system (Kolata and Nelson 1990, 2010). The basin is bordered by a series of prominent structures and includes southern Illinois, western Kentucky, and southwestern Indiana (Kolata and Nelson, 1990). During the Chesterian (upper Mississippian), the rate of subsidence in the Illinois Basin increased due to compressional stress related to the Ouachita and Alleghenian orogenies (Kolata and Nelson, 1990). As the result, the basin interior was rapidly subsiding and was open to the southwest at the edge of the Ouachita Trough (Nelson, 1995).

The Tar Springs Sandstone constitutes the upper part of the Chesterian Series that is comprised of cyclic alternation of (Figure 1) carbonate and siliciclastic unites (Swann, 1964; Nelson et al., 2002). It was deposited as the result of basinward advance of the Michigan River system (Swann, 1964). The Tar Springs is named for the Tar Springs in western Kentucky and consists of very fine- to fine-grained, friable to well-cemented sandstone (Atherton et al., 1975). It overlies the Glen Dean Limestone and underlies the Vienna Limestone (Figures 1 and 3). A widespread shale interval is present in the uppermost part of the Tar Springs. The upper part of this shale may be carbonaceous and could contain thin coal beds (Morse, 2001; Nelson et al., 2002). According to Atherton et al. (1975) the upper and lower contacts of the Tar Springs are conformable. However, Swann (1963) and Morse (2001) reported local erosion along the lower boundary and removal of up to 40 feet (12 m) of the upper part of the Glen Dean Limestone. Morse (2001) recognized channelized sandstone bodies directly above the Glen Dean Limestone and suggested a widespread minor disconformity at the base of the Tar Springs. The isopach contour map (Figure 4) shows the areal extent and lateral thickness variation of the Tar Springs sandstone in Illinois. The thickness of the Tar Springs ranges from zero to more than 140 feet (0 to 43 m).

Lithofacies and depositional setting

The Tar Springs Sandstone consists of massive and stacked lenticular sandstone bodies interbedded with shale/siltstone (Figures 5 and 6). The lower part of the Tar Springs commonly consists of massive fluvial channel sandstone bodies that overlie directly on the Glen Dean Limestone or on a shale/siltstone interval in the basal part of the Tar Springs (Fig. 3, 5, and 6). The massive sandstone is generally widespread, but its thickness is very variable ranging from zero to over 100 feet. It may locally consist of stacked channel deposits separated by thin shale or shale partings. The upper part of the Tar Springs is comprised of shale and lenticular sandstone intervals; the lower massive sandstone interval may also change laterally to compartmentalized lenticular sand bodies with shale interbeds (Figures 3 and 6).

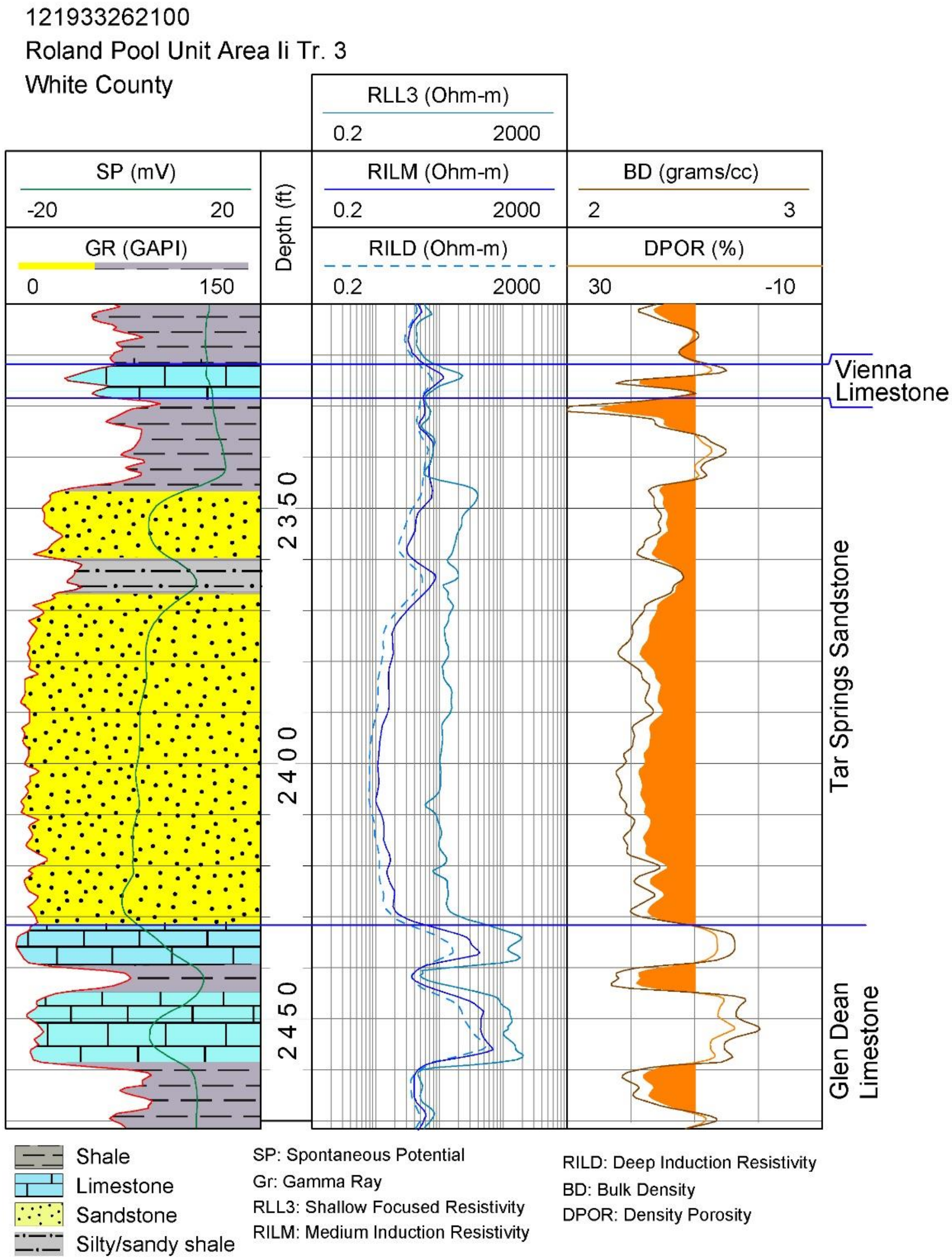

Figure 3. Type log and lithologic column in white County, Illinois (well API 121933262100) showing the stratigraphic relationship of the Tar Springs Sandstone with the underlying and overlying carbonate formations. Gamma ray log signature indicates blocky, coarsening, and finning upward motifs. massive sandstone and thin lenticular sandstone that occur in the lower and upper part of the Tar Springs, respectively.

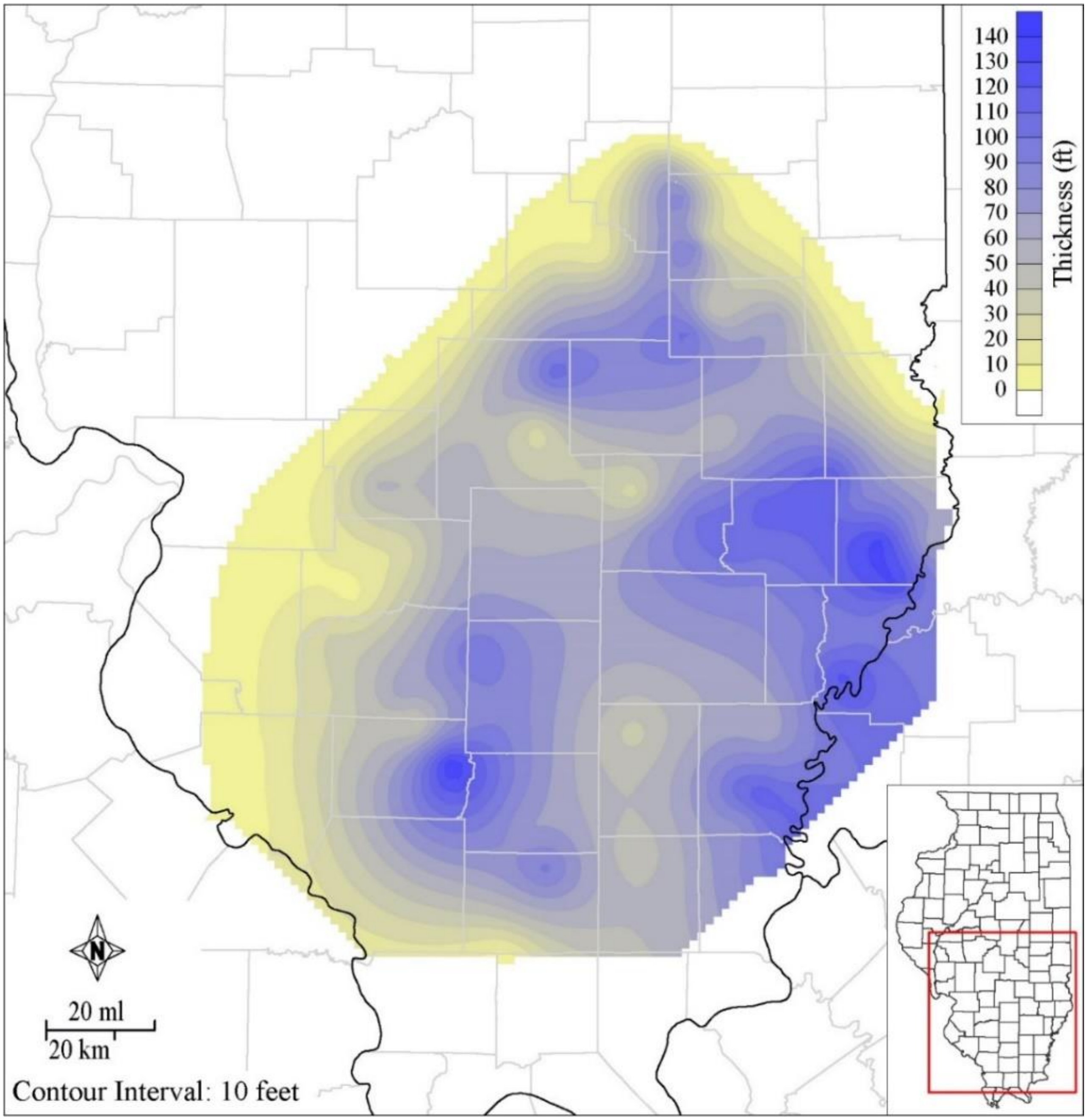

Figure 4. Isopach contour map showing the Tar Springs Sandstone thickness and its areal extent in Illinois. Note that the Tar Springs depocenters in Illinois display an overall north-south/northeast-southwest trend.

Geophysical log motifs, including gamma ray, spontaneous potential (SP), and resistivity log signatures of the Tar Springs sandstone bodies display barrel/blocky, bell (fining upward) or funnel (coarsening upward) log signatures with shale interbeds (Figures 3, 5, and 6). The log motifs of sand bodies and interbedding with shale are interpreted as fluvio-deltaic depositional system (e.g., Coleman and Prior 1982). The depocenters of the sandstone bodies as indicated by net sandstone isopach map (Figure 7), log motifs, and facies analysis (Wescott, 1982; Morse, 2001; Henderson et al., 2020) indicate a heterogeneous unit recording a general northeast-southwest transition and depositional change from mainly coastal fluvial systems to tidally influenced deltaic and shallow-marine environments.

The stacked lenticular sandstones showing coarsening upward and barrel shape log motifs (for examples see wells API# 121592628300 and 121592354600 in Figure 5 and well API# 121933213700 in figure 6) represent deltaic distributary mouth bars and distributary channel facies, respectively. The shale intervals correspond to interdistributary bay and deeper marine prodelta settings. Massive sandstone showing barrel or fining upward log signatures (for examples see wells API#121592608400 and 121590025000in Figure 5 and wells API#121933213100 and 121933217900 in Figure 6) that locally cut into the lower shale interval of the basal Tar Springs represent narrow southwest trending fluvial channel belts. The fluvial channel deposits commonly constitute the lower part of the Tar Springs and change laterally and vertically to coastal and mainly delta front and delta plain facies.

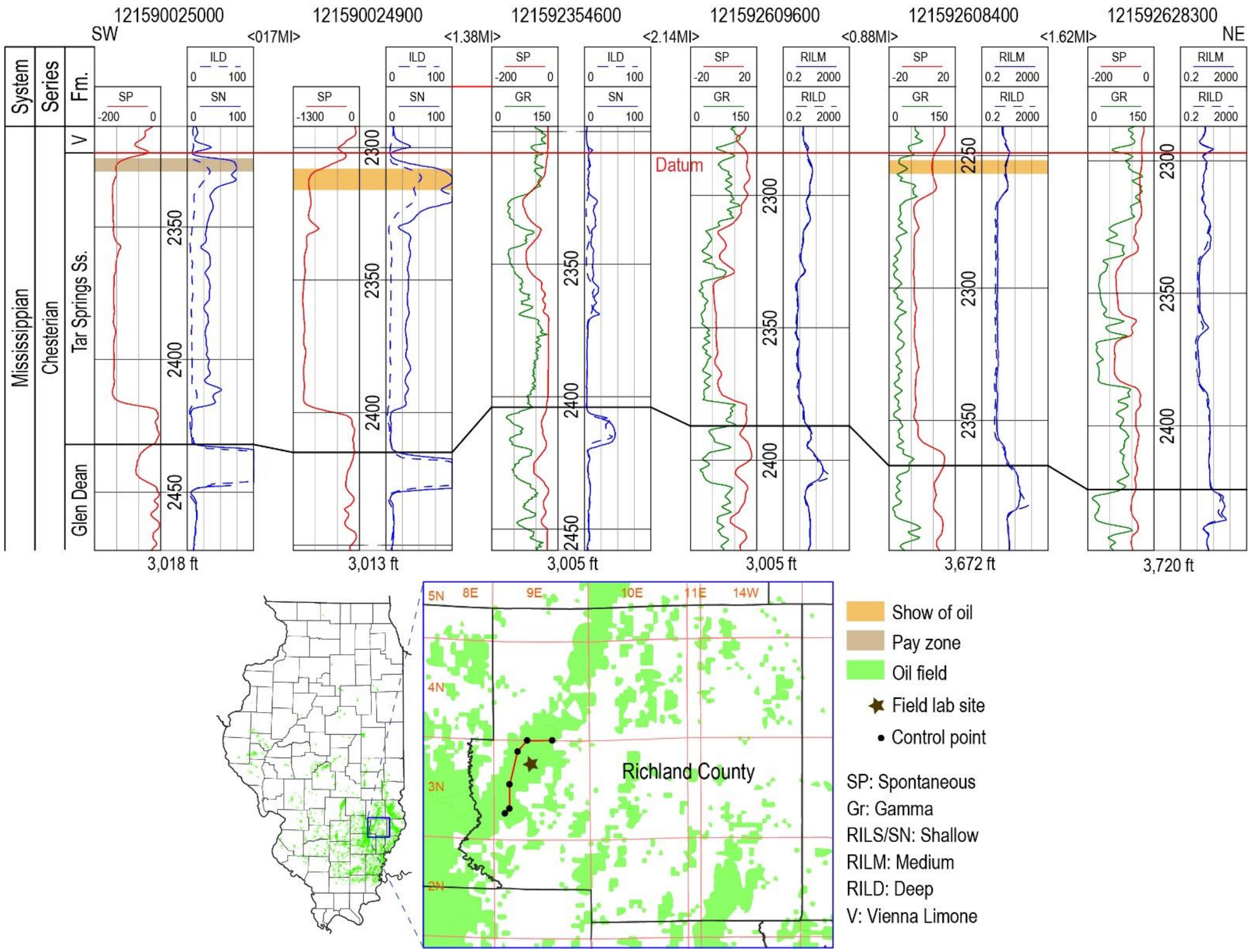

Figure 5. SW-NE stratigraphic cross section along the Clay City Consolidated oil field, Richland County showing lateral and vertical variations of the massive and lenticular sandstone intervals in the Tar Springs Sandstone. Note gamma ray log signatures showing blocky, coarsening, and finning upward profiles. Note also lateral change of massive sandstone to lenticular sandstone (datum base of the Vienna Limestone).

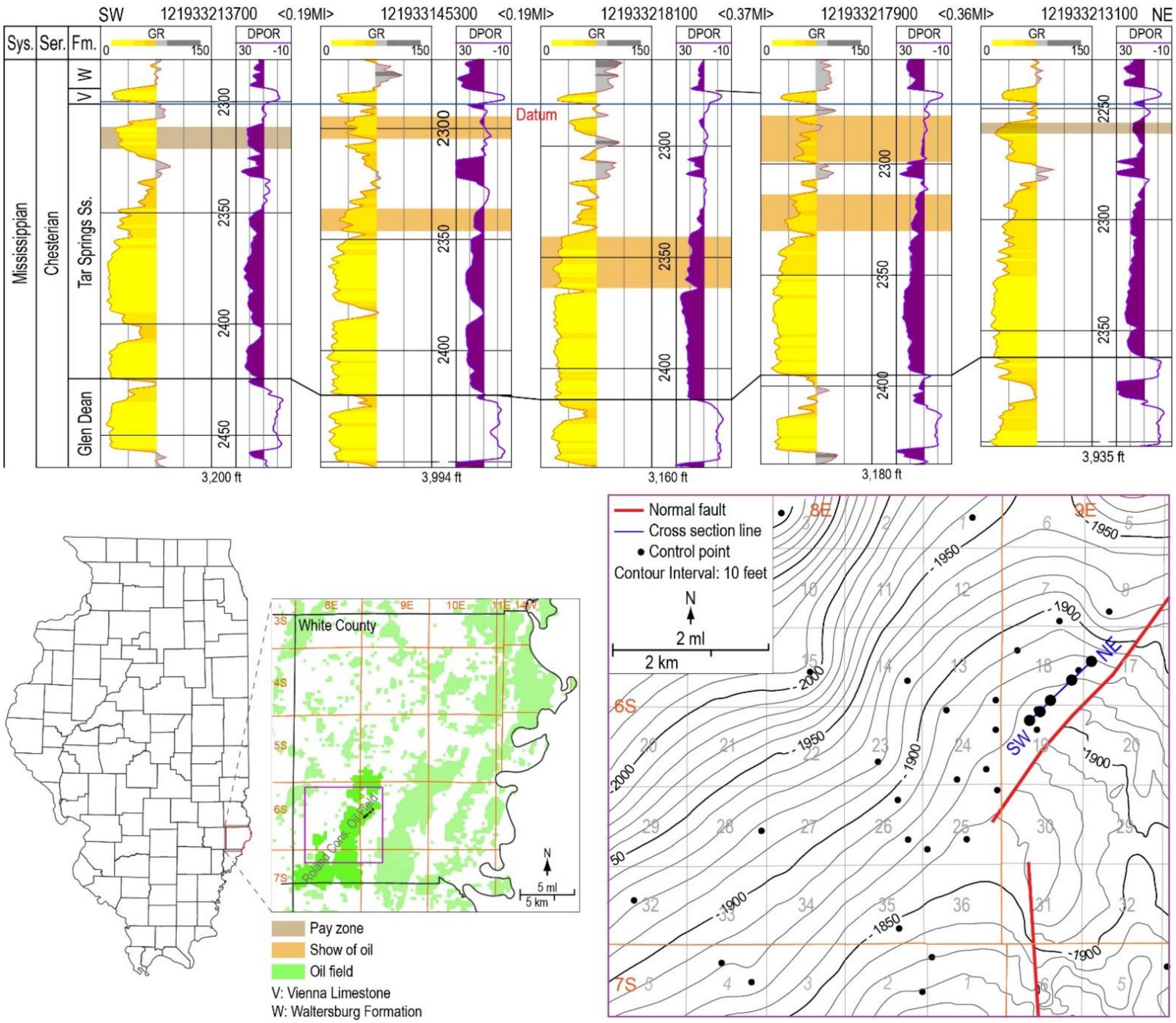

Figure 6. Stratigraphic geophysical log cross section showing lateral continuity and vertical lithologic variation of the massive and stacked lenticular sand bodies of the Tar Springs Sandstone in the northeast of the Roland Field, White County. Note the oil shows and oil productive intervals (Datum is the base of the Vienna Limestone). Note also that the wells with show of oil (database record) should be productive because the subsea elevation of these wells are nearly the same as in the productive wells (Datum is the base of the Vienna Limestone).

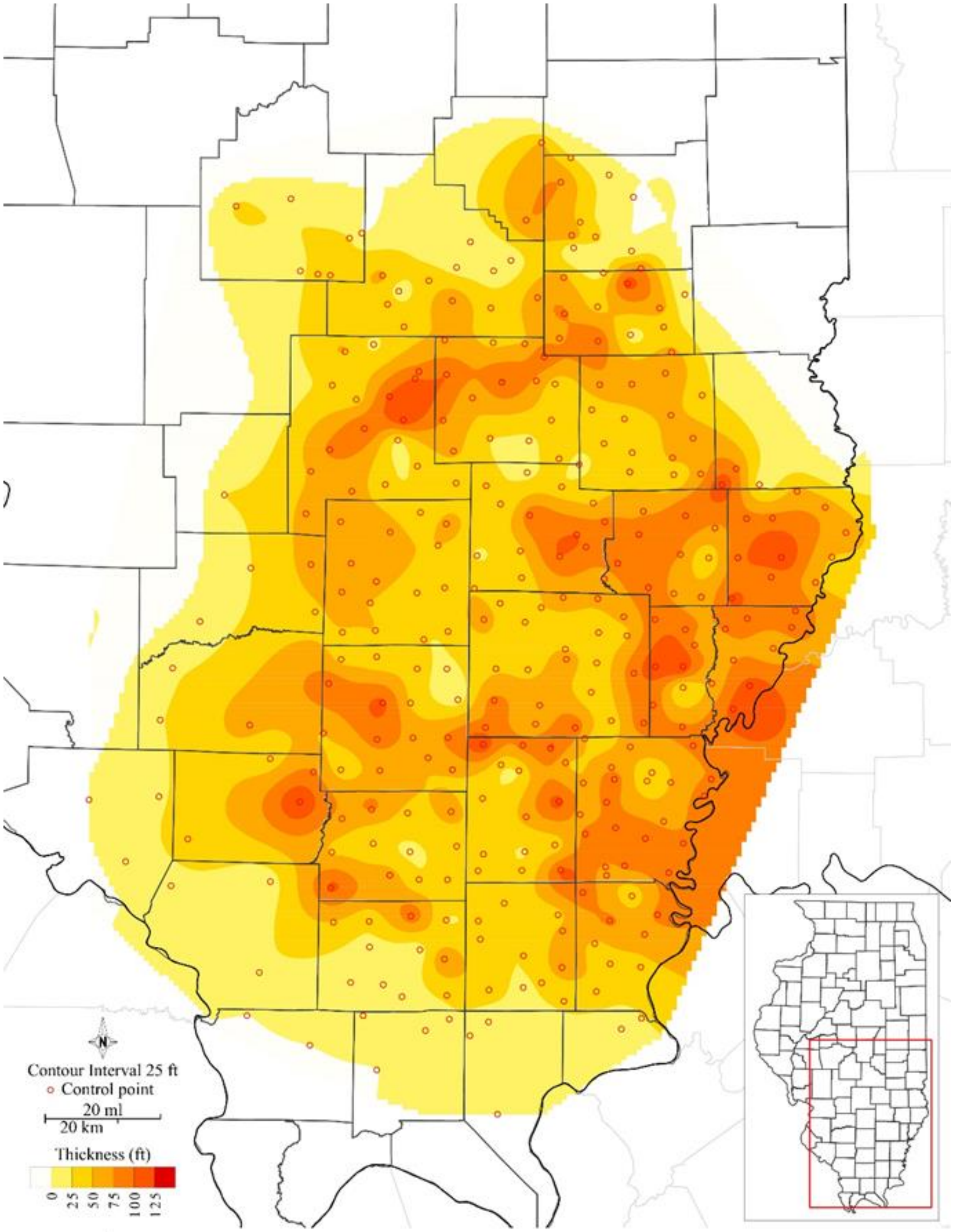

Figure 7. Net sand isopach map of the Tar Springs in Illinois showing. The overall paleo-shoreline perpendicular northeast-southwest/north-south trend.

Reservoir facies and trap mechanism

The Tar Springs Sandstone consists of quartzose sandstone bodies with siltstone and gray shale interbeds. Morse (2001) and Henderson et al. (2020) described the Tar Springs reservoirs as well-sorted, fine- to medium-grained quartz arenites with less than 5% feldspar and chert containing abundant cross bedding, ripple cross-lamination and planar bedding. Digenetic quartz overgrowth and clay mineral cement (mainly kaolinite and chlorite) partially occlude pore throats impacting porosity and permeability (Morse, 2001; Henderson et al., 2020).

The impact of post-depositional diagenesis on reservoir porosity and permeability of the Tar Springs varies in various parts of the basin. In the Roland consolidated, Inman east consolidated, and Rock Hill oil fields (Figure 8) for example, measured porosity ranges from 14 to 23% and permeability varies in the range of zero to 740 millidarcies (md). In the Roland consolidated field, White County (see below) core analysis report of 15 wells indicated porosity ranges from 6% to 25% and permeability from zero to 740 md with average measured core porosity and permeability of 17% and 76 md, respectively. In the Inman east consolidated oil field, Gallatin County, Morse (2001) measured porosity and permeability values in cores of 31 wells and measured reservoir porosity that ranged from 16% to 19% and permeability from 60 to 700 md with average permeability of 107 md and average core porosity of 17%. In the Rock Hill field, southwest Indiana, Henderson et al. (2020) used core plugs from three wells and measured average porosity and permeability of 20.5% and 644.3 md, respectively.

The Tar Springs reservoirs in Illinois have been productive in several oil fields with more than 1,290 producing wells. Entrapment and accumulations of oil in the Tar Springs was controlled by structural, stratigraphic (sandstone body lateral pinch out), or structural-stratigraphic combination traps. Structural control is the main trap mechanism in most oil fields. Along the Clay City Anticline near the brownfield lab site in Richland County, Illinois few wells produce from the Tar Springs Sandstone (Figure 5). Most of the Tar Springs oil production in southeastern Illinois is from oil fields along the Wabash River (Figure 9). Here, production is mainly from fault controlled anticlinal structures in Gallatin and White Counties.

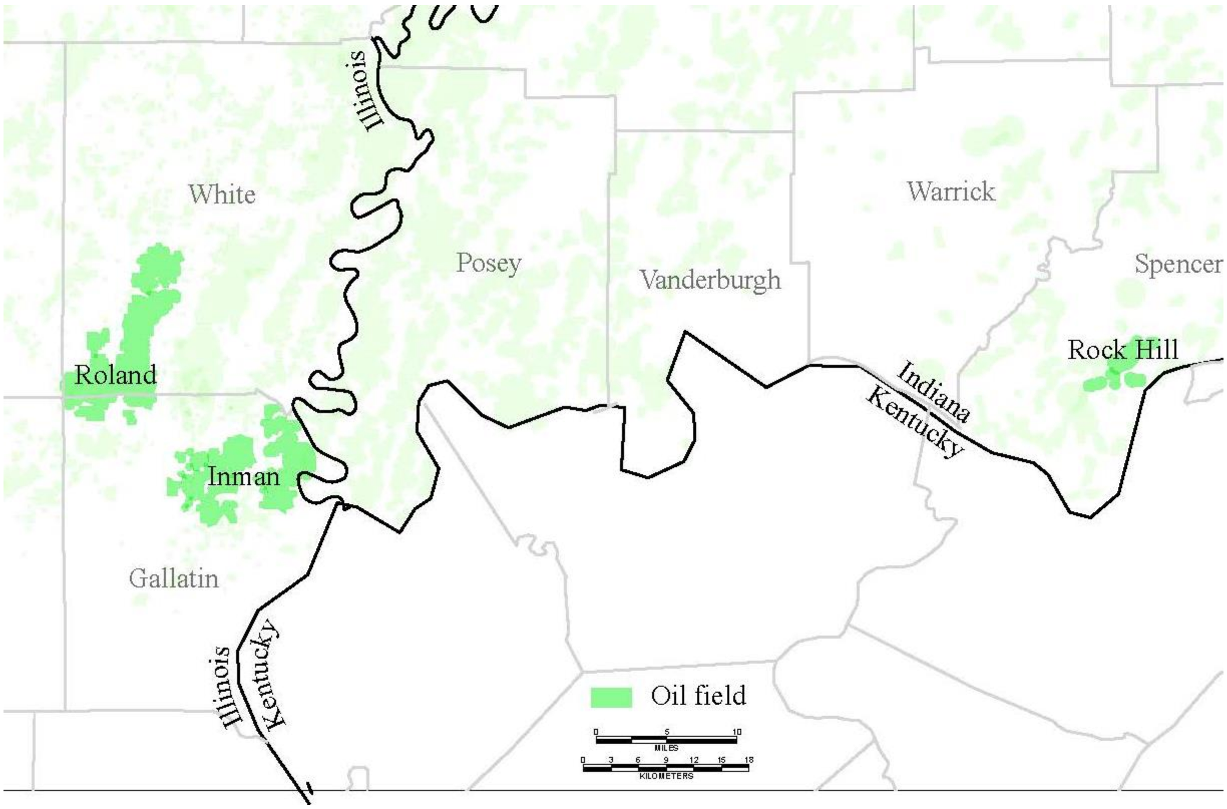

Figure 8. Index map showing Roland Consolidated, Inman East Consolidated, and Rock Hill fields in the southwestern part of the Illinois Basin.

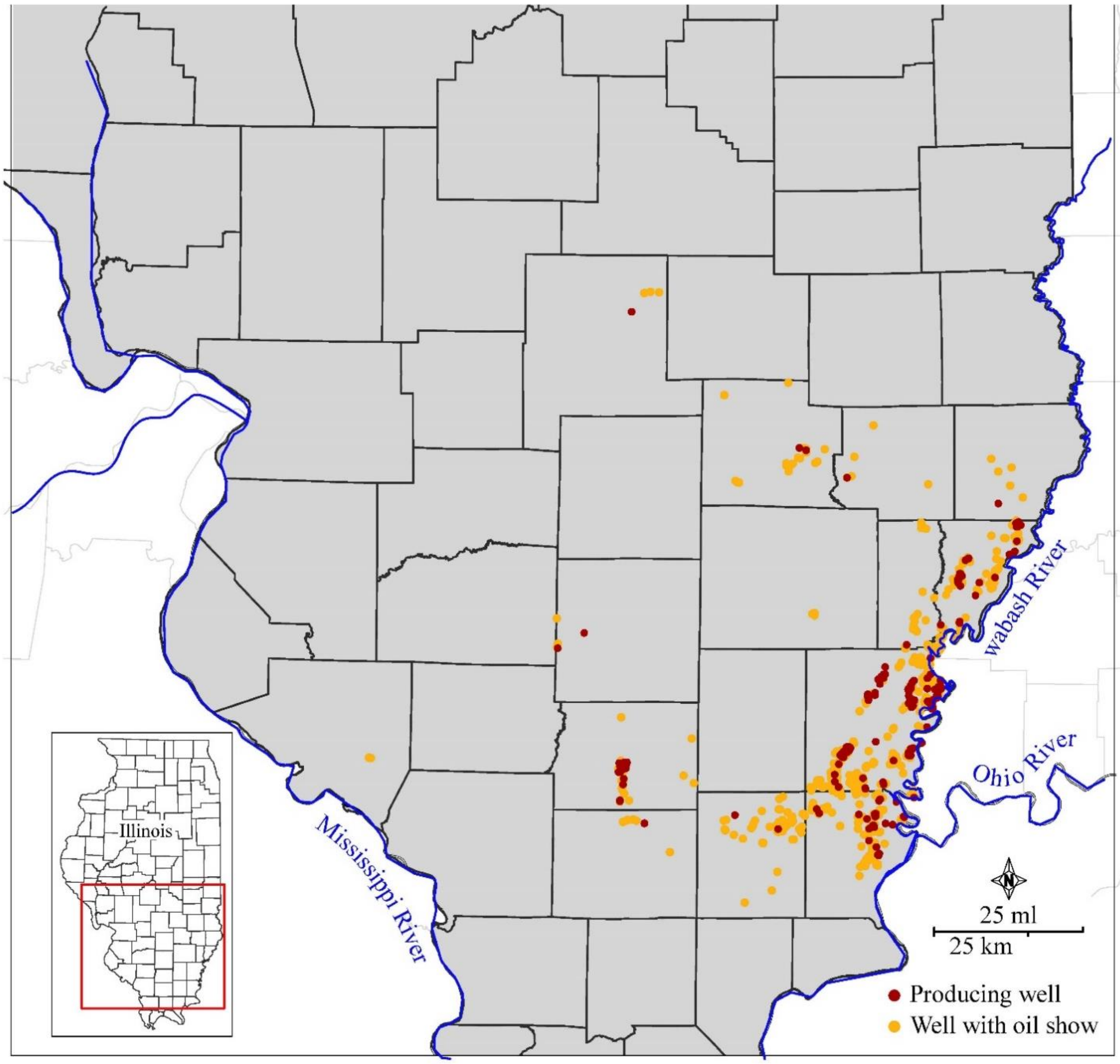

Figure 9. Distribution of wells (not all wells are shown) and oil indicators in the Tar Springs Sandstone. Note that some of the wells with oil show could have produced. Wells along the crest of the anticlines encounter more than one reservoir but the normal practice is production from the deeper reservoir during early life of a well. Operators do not report any future workover on producing wells.

Oil field characterization

The Roland Consolidated Field along the Albion-Ridgway Fault Zone (Figure 10), southeastern Illinois was selected for field scale geological characterization and ROZ evaluation of the Tar Springs Sandstone. The rationale for this selection was that the field has produced from compartmentalized lenticular sandstones and the upper part of the massive sandstones both of which have Roz potential. The oil fields in southeast Illinois, including the Roland consolidated field were developed along the fault zones in the Wabash Valley fault system. The fault system consists of a series of high-angle normal faults (Nelson 1995).

Roland Consolidated Field

The Roland Field is developed along the Albion-Ridgway Fault Zone, a north-northeast trending high angle normal fault in southeastern Illinois (Figure 10). The producing wells and those with show of oil indicators in the Tar Springs occur mostly along the eastern margin of the field (Figure 10), where a dragged fold anticlinal structure (Figure 11) was developed in the upthrown side of the Albion-Ridgway Fault Zone. The field was discovered in 1940 and is primarily located in southwestern White County, Illinois (Figures 8 and 10). More than 1500 wells were drilled in the field and nearly 70 million barrels of oil have been produced from various Chesterian carbonate and siliciclastic units including the Tar Springs. A structural-stratigraphic combination trap mechanism was generally responsible for oil entrapment. The shale in the uppermost part of the Tar Springs Sandstone, the Vienna limestone, and the underlying shale of the sandstone of the Waltersburg Formation provide caprock/seal for the Tar Springs reservoirs (Figure 12).

In the Roland Field, like other areas of the basin, the Tar Springs consists of massive and stacked lenticular sandstone bodies the upper part of which may be oil saturated and productive of oil (Figures 6 and 13 through 15). Blocky, bell, and funnel geophysical log motifs (Figures 6, 14 and 15) indicate a general northeast-southwest trend of the sand bodies suggesting fluvial and coastal deltaic and tidal flat depositional setting. Based on core analysis data of the upper and lower sandstone intervals from 15 wells in the Roland Field, reservoir porosity ranges from 6% to 25% and permeability from zero to 740 md with average measured core porosity and permeability of 17% and 76 md, respectively (Figure 16).

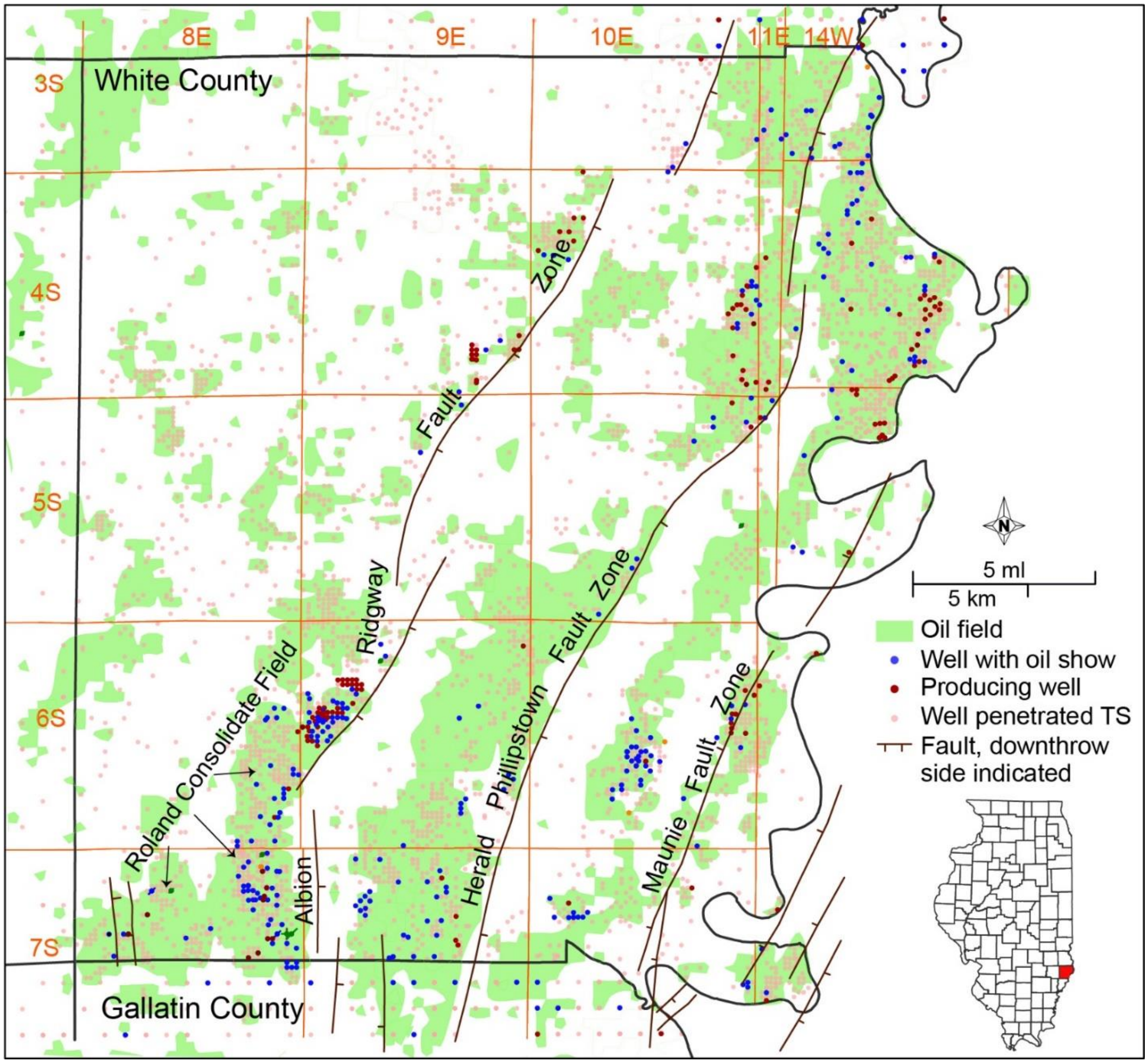

Figure 10. Map showing the fault zones along the Wabash Valley fault system in White County, Illinois (from Nelson, 1995). Note the wells that penetrated the Tar Springs Sandstone and the producing wells, and wells with show of oil in the Tar Springs.

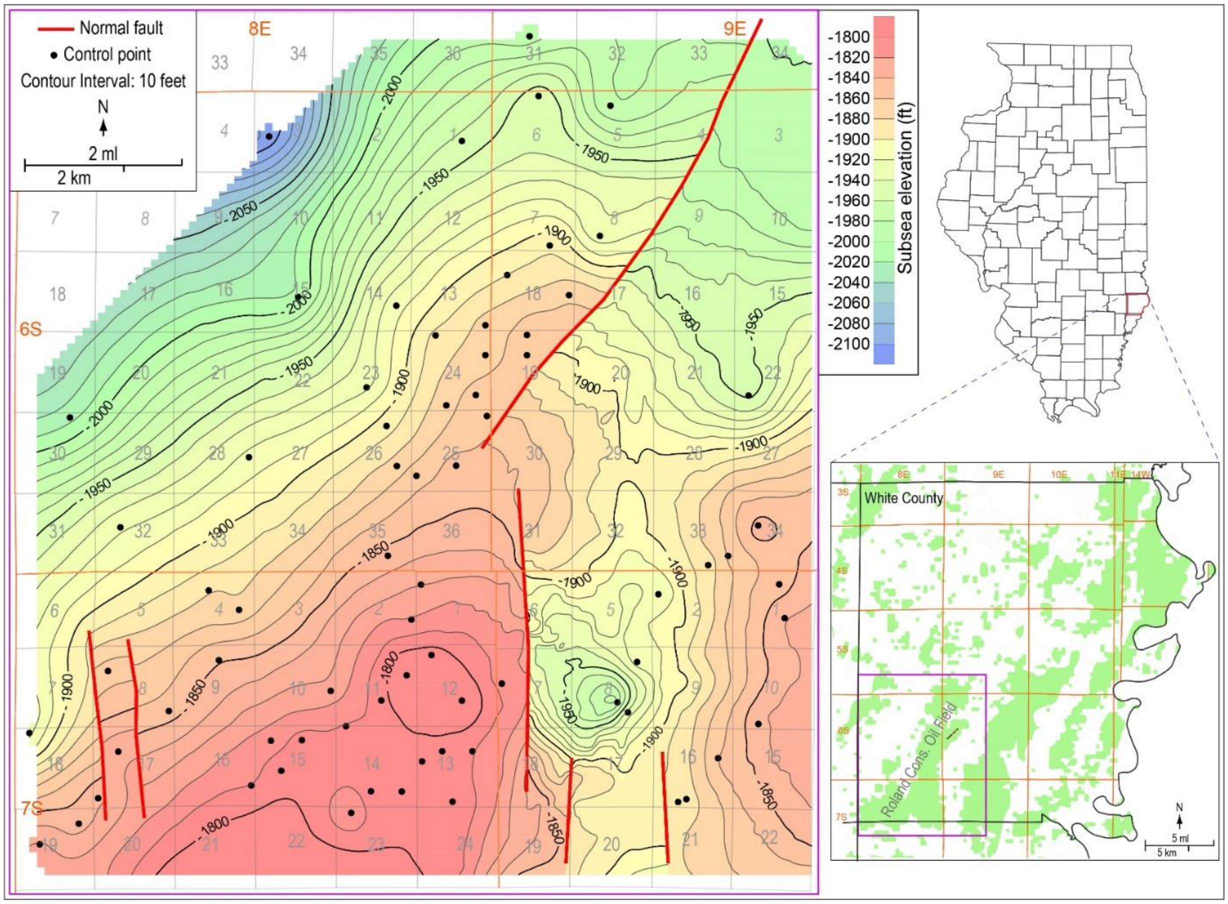

Figure. 11. Structural contour map of the Roland Consolidated Field area showing the dragged fold structures developed along the Wabash valley fault zones.

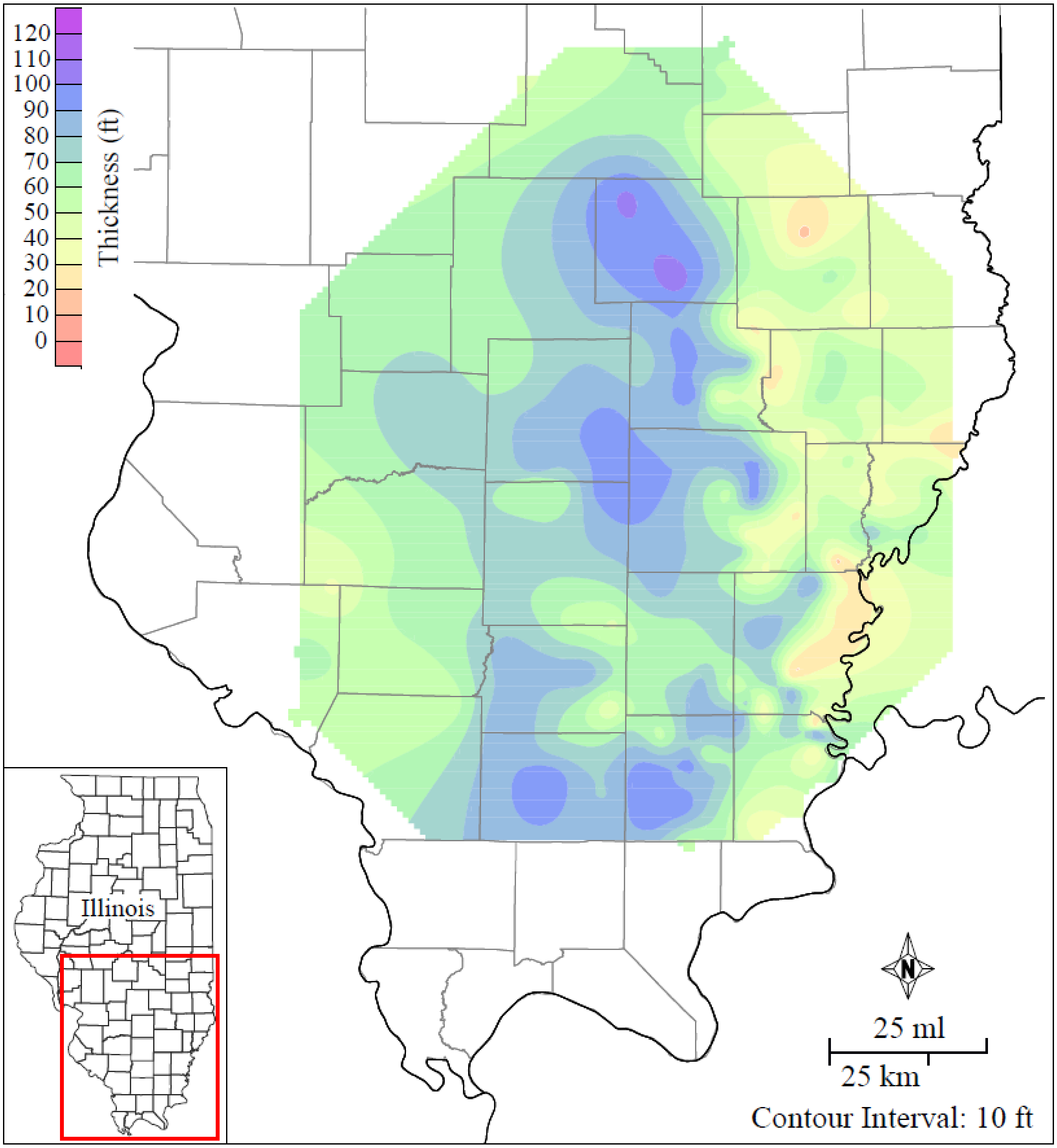

Figure 12. Isopach map of the seal for the Tar Springs sandstone reservoirs. The map is prepared using the combined thickness of the shale in the uppermost part of the Tar Springs Sandstone, the Vienna limestone, and the shale interval underlying the sandstone unit of the Waltersburg Formation.

Production has been from the upper lenticular sandstone and the upper part of the massive sandstone. The wells with show of oil in the Tar Springs reservoirs could have in fact been oil productive because: (1) they are located near the crest of the fold (Figures 14 and 15), (2) geophysical log signatures show porous intervals with high true resistivity (Figures 13 through 15), (3) drill stem tests (For example well API#121930682800 in figure 14 and Wells API#121930192600 and 121930195500 in figure 15) recorded several to hundreds of feet of oil, and (4) core analysis reports (for examples see figure 13) indicate oil saturation. In the Roland Field, several formations are oil productive. The common practice is production from the deeper reservoirs followed by perforating the shallower reservoirs after depletion of the deeper pays. Operators generally do not report any future workover; thus, the database underrepresents the number of wells producing from the Tar Springs.

This study revealed that substantial amounts of immobile residual oil remain in the depleted Tar Springs Sandstone reservoirs and those that extend beyond the boundaries of conventional oil fields in which their ROZ potential has been established through the available subsurface records in the subsurface. Well completion reports, oil shows/oil saturation from core analysis and drill stem test data suggest that the Tar Springs Sandstone has an excellent potential for CO2-EOR and storage of anthropogenic carbon dioxide. CO2-EOR is effective at mobilizing the residual oil from the ROZs and would also store anthropogenic carbon in the subsurface (e.g., Sanguinito et al., 2020).

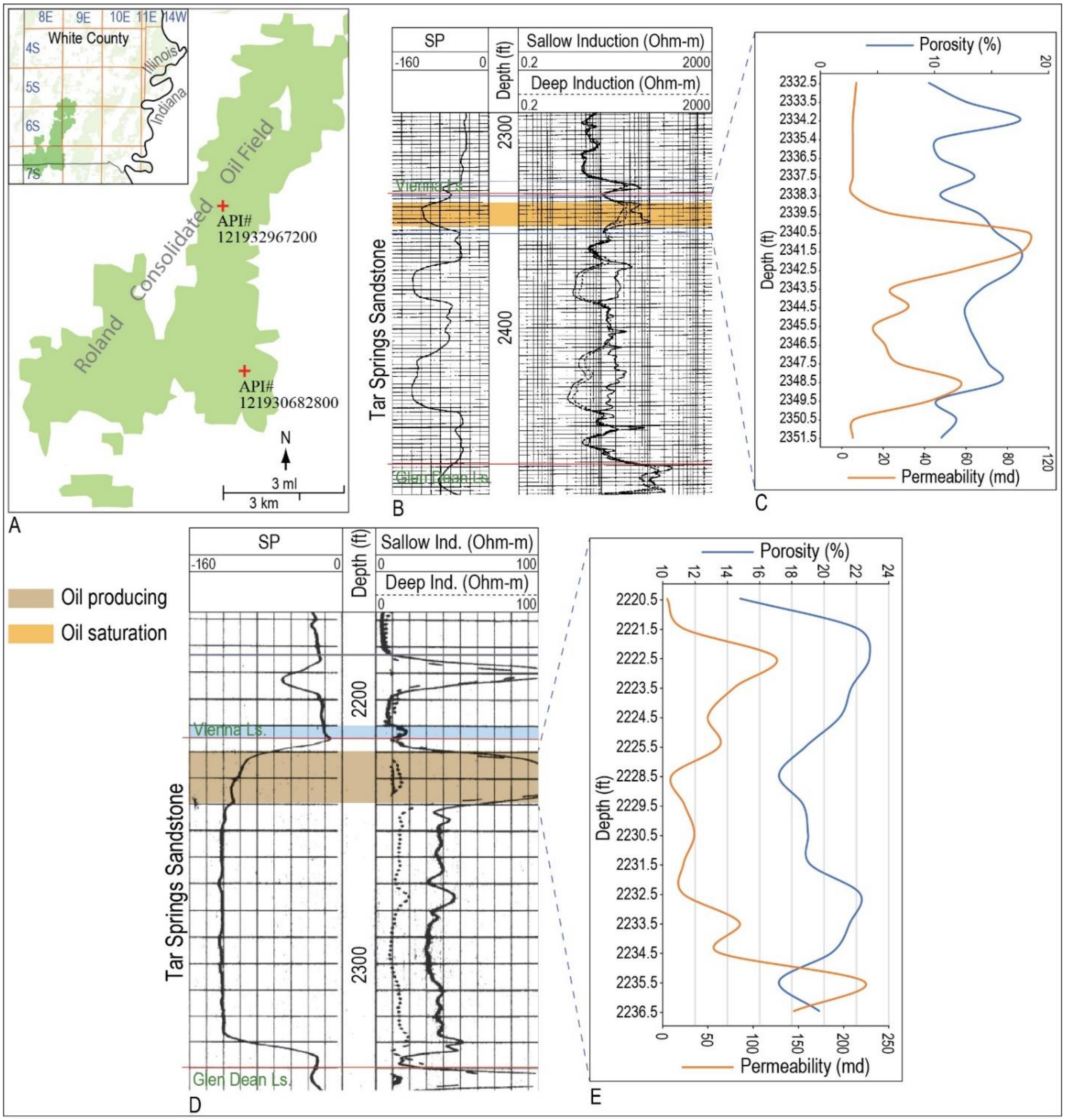

Figure. 13. Core analyses of two wells in the Roland Consolidated Field, White County, Illinois. (A) Location map. (B) Electric log of well API#121932967200. (C) Plot of porosity versus permeability from core analysis report of the upper Tar Springs oil saturated lenticular sandstone reservoir. (D) Electric log of well API#21930682800. (E) Plot of porosity versus permeability from core analysis report of the upper part of the massive Tar Springs sandstone reservoir.

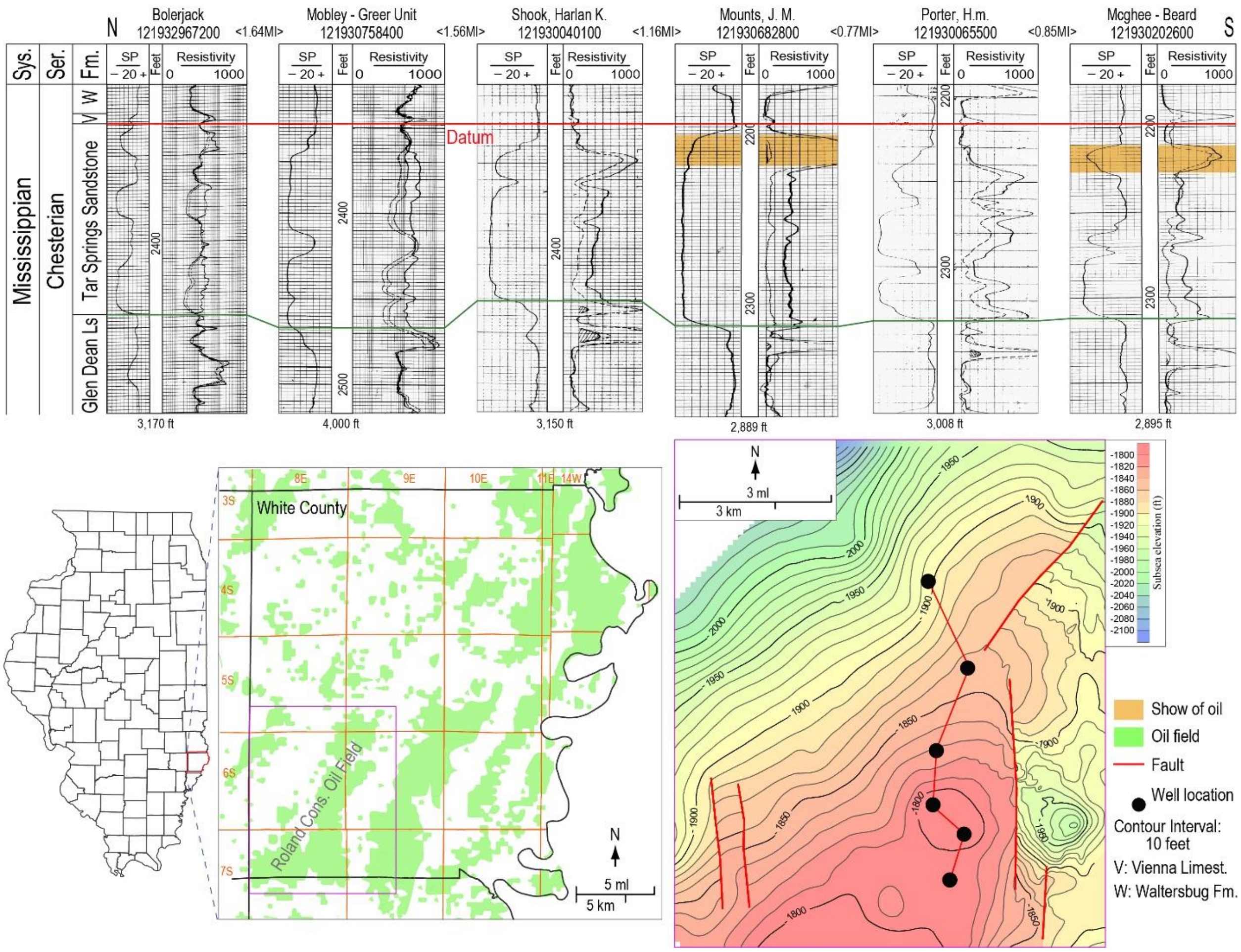

Figure 14. N-S stratigraphic electric log cross section in the Roland anticlinal structure, eastern margin of Roland Field. Note lateral and vertical variations of the Tar Springs Sandstone in which massive sandstone change laterally to lenticular non-massive reservoir bodies. Core analysis report and electrical resistivity of the sandstones indicate that all the lenticular sandstones in the upper part of the Tar Spring are oil saturated (datum base of the Vienna Limestone).

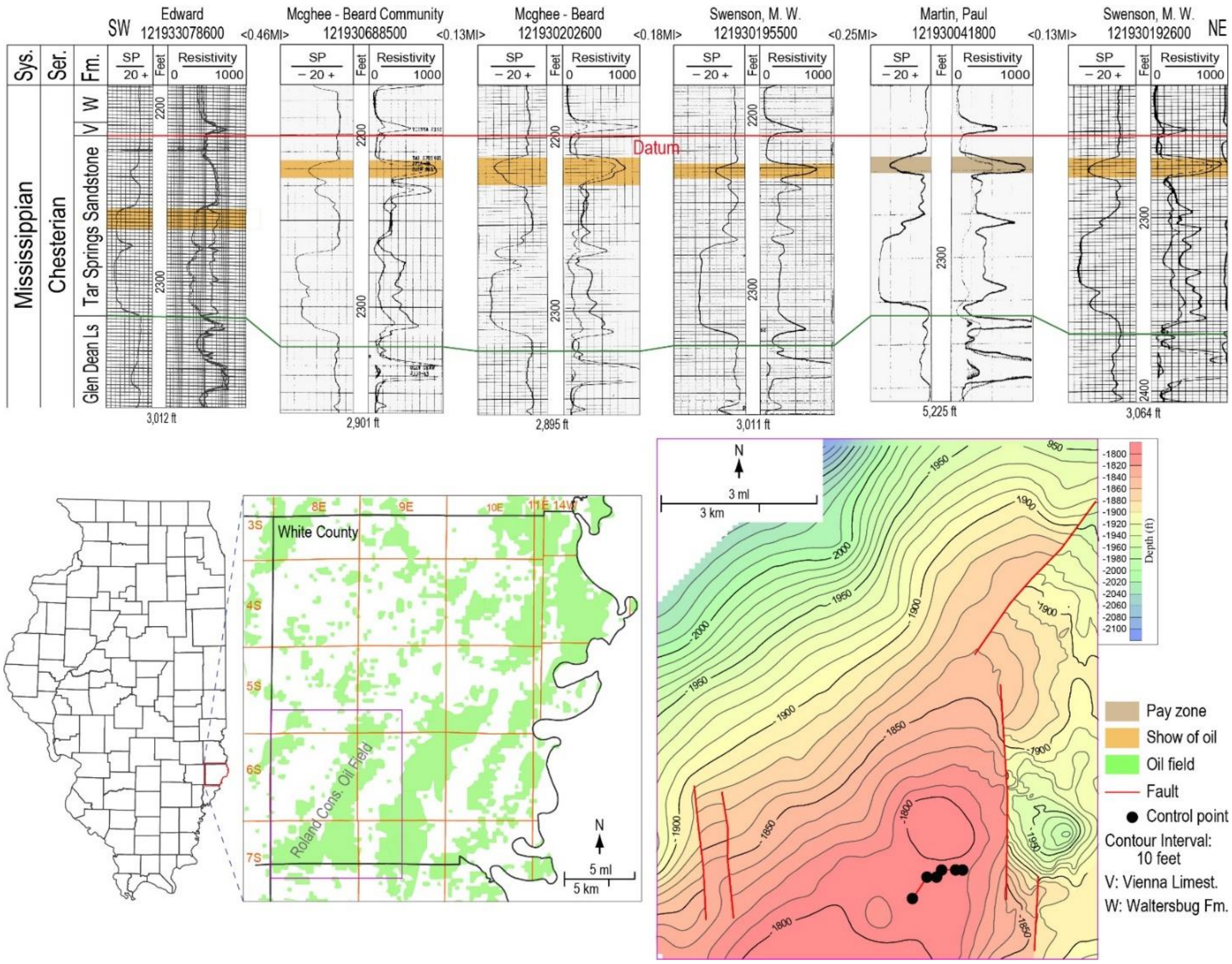

Figure 15. SW-NE stratigraphic electric log cross section in the Roland anticlinal structure, south eastern corner of Roland Field. Note lateral and vertical variations of the Tar Springs Sandstone in which massive sandstone in the lower part change to lenticular non-massive reservoir bodies (datum base of the Vienna Limestone).

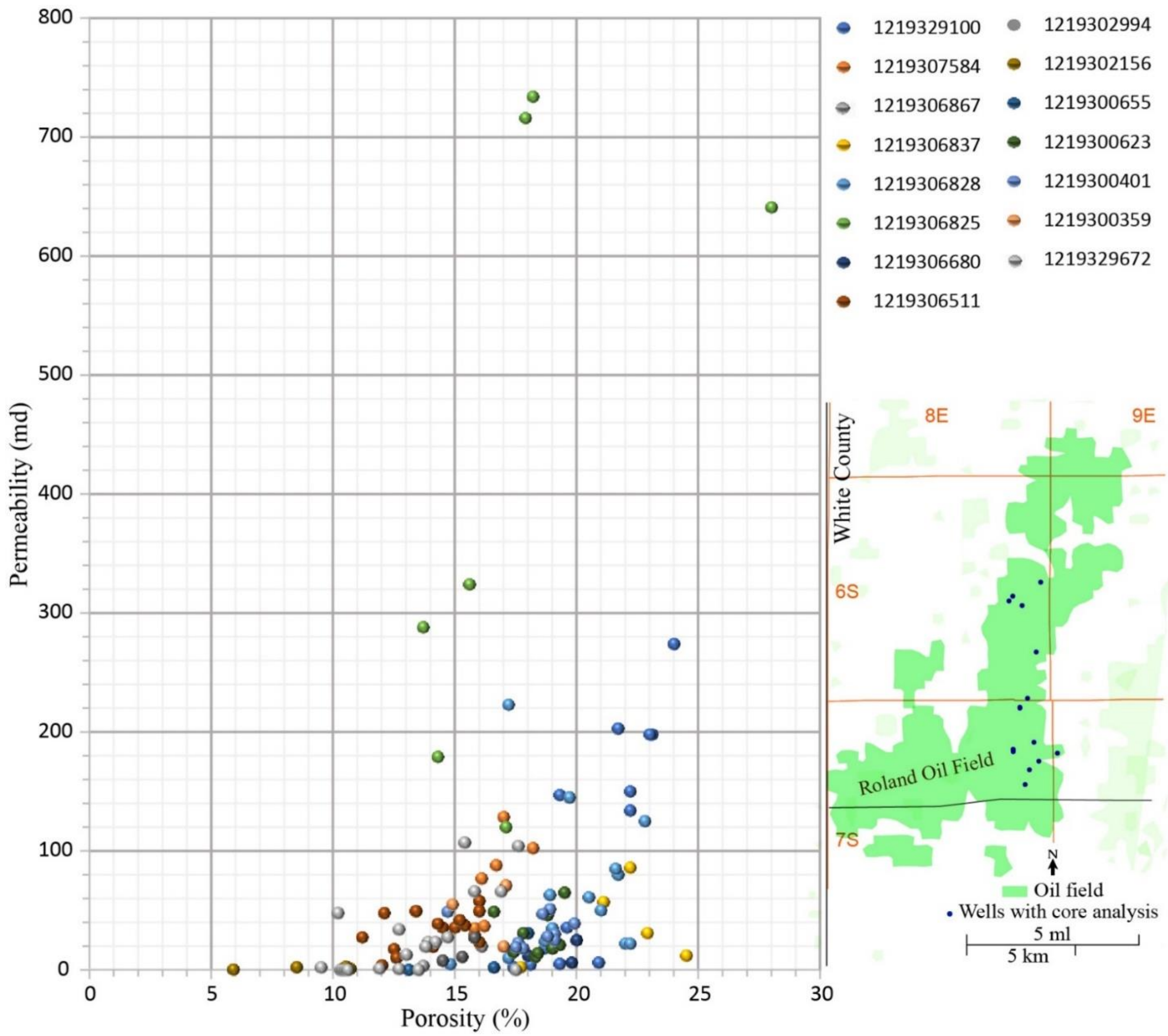

Figure 16. Permeability vs Porosity Xplot of 15 wells in the Roland Field based on core analysis report.

References

Atherton, E., C. Collinson, and J. A. Lineback, 1975. Mississippian System. Handbook of Illinois Stratigraphy: Illinois State Geological Survey Bulletin 95, pp. 104-163.

Coleman, J. M., and D. B. Prior, 1981, Deltaic environments of deposition, in P. A. Scholle and D. Spearing, (eds.), Sandstone depositional environments: AAPG Memoir 31, p. 139-178.

Henderson, T.C., Ridgway, K.D., Johnston, C.T., and Everett, T.A., Integrated reservoir characterization of enhanced oil recovery targets in mature basins: An example from the Tar Springs Formation, Rock Hill field, Illinois Basin, United States. AAPG Bulletin; 104 (10): 2077–2098.

Howard, R. H., 1990. Hydrocarbon Reservoir Distribution in the Illinois Basin: Chapter 21: Part I. Illinois Basin: Oil and Gas Systems. AAPG Memoir 51, pp. 299-327.

Kolata, D. R., 2005. Bedrock geology of Illinois. Illinois State Geological Survey, Illinois Map 14, 2 sheets, scale 1: 500,000.

Kolata, D. R. and Nelson, W. J., 2010. Tectonic history. In: Kolata and C. K. Nimz (eds.) Geology of Illinois. Illinois State Geological Survey, p. 77-89.

Kolata, D. R. and Nelson, W. J., 1990. Tectonic history of the Illinois Basin. In: Leighton, M.W., Kolata, D. R., Oltz, D. F., Eidel, J. J. (eds.), Interior Cratonic Basins. AAPG Memoir 51, p. 263-285.

Melzer, S., 2006. Stranded oil in the residual oil zone. A report prepared for Advanced Resources International and U.S. Department of Energy Office of Fossil Energy - Office of Oil and Natural Gas. 91 p.

Morse, D. G., 2001, Sedimentology, Diagenesis and Trapping Style, Mississippian Tar Springs Sandstone, Inman East Consolidated Field, Gallatin County, Illinois: Urbana, IL, Illinois State Geological Survey, Illinois Petroleum 157, 67 p.

Muggeridge, A., Cockin, A., Webb, K., Frampton, H., Collins, I., Moulds, T., and Salino, P., 2014. Recovery rates, enhanced oil recovery and technological limits. Phil. Trans. R. Soc. A 372: 20120320.

Nelson, W. J., 1995, Structural features in Illinois: Illinois State Geological Survey Bulletin 100, 144 p.

Nelson, W. J., Smith, L. B., Treworgy, J. D., 2002. Sequence Stratigraphy of the Lower Chesterian (Mississippian) Strata of the Illinois Basin. Illinois State Geological Survey Bulletin 107, 70 p.

Sanguinitoa, S. et al., 2020. Methodology for estimating the prospective CO2 storage resource of residual oil zones at the national and regional scale. International Journal of Greenhouse Gas Control 96, p. 1-8.

Swann, D.H., 1963, Classification of Genevievian and Chesterian (Late Mississippian) rocks in Illinois: Illinois State Geologic Survey, Report of Investigations 216, 91 p.

Swann, D.H., 1964, Late Mississippian rhythmic sedimentation of the Mississippi Valley: American Association of Petroleum Geologists Bulletin, v. 79, p. 24 71-2483.

Thompson T. A., K. H. Sowder, and M. R. Johnson, 2016. Generalized stratigraphic column of Indiana bedrock. Indiana Geological Survey, Bloomington, Indiana.