PS Integrated Reservoir Characterization for Enhanced Oil Recovery, Tar Springs Formation, Illinois Basin*

Timothy Henderson[1], Justin Orr[1], Cliff Johnston[2], Kenneth Ridgway[1], and Bryan Clayton[3]

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[1]Department of Earth, Atmospheric & Planetary Sciences, Purdue University, West Lafayette, Indiana, United States (hende103@purdue.edu)
[2]Department of Agronomy, Purdue University, West Lafayette, Indiana, United States
[3]Pioneer Oil Company, Inc., Vincennes, Indiana, United States

Abstract

The Illinois basin contains many mature Mississippian-aged reservoirs that are potential targets for enhanced oil recovery (EOR). In this study we integrate sedimentology, petrography, quantitative mineralogy (XRD), Fourier transform infrared analysis (FTIR), thermogravimetric analysis/evolved gas analysis (TGA/EGA), and scanning electron microscopy (SEM) to characterize the physical and chemical properties of the Tar Springs Formation in a producing field. Reservoir cores were described, sampled, and analyzed on a foot-by-foot scale using sedimentology and petrography. Five distinct lithofacies serve to categorize the studied reservoir: F1 – fine- to medium-grained, horizontally-stratified sandstone with consistent porosity but large variations in permeability; F2 – very fine- to fine-grained flaser bedded sandstone with consistent porosity and permeability; F3 – very fine-grained wavy bedded sandstone with reduced porosity and permeability; F4 – fine-grained sandstone and mudstone with little porosity and permeability; and F5 – medium-grained sandstone with calcite cement that occludes all porosity and permeability. Lithofacies F1 represents the highest quality reservoir interval but thin-section observations show millimeter-scale heterogeneity as a function of calcite cement and clay-rich horizons. XRD analyses confirm the presence of quartz and calcite but also identify illite, kaolinite, and chlorite as primary constituents in F1. SEM work has revealed pore mineralogy variations that can significantly influence flow distribution as it relates to porosity, permeability, and possible polymer degradation. TGA/EGA and FTIR confirm mineralogy but quantitatively assess residual oil saturations of pre- and post-coreflood studies. Exposures of the Tar Springs Formation along the basin margin as well as available core data from the Indiana Geological Survey and Pioneer Oil Company have also been integrated to provide a geologic framework to better understand the expected variability within producing reservoir core suites. Collectively, all of our data sets are internally consistent with identifying framework grains, cement types, and clay minerals that help define flow parameters such as compartmentalization by permeability barriers and pore space constituents. We will also discuss how these integrated data sets are being used by other members of our research team to determine the optimal surfactant-polymer pairs and reservoir simulation modeling needed for EOR.

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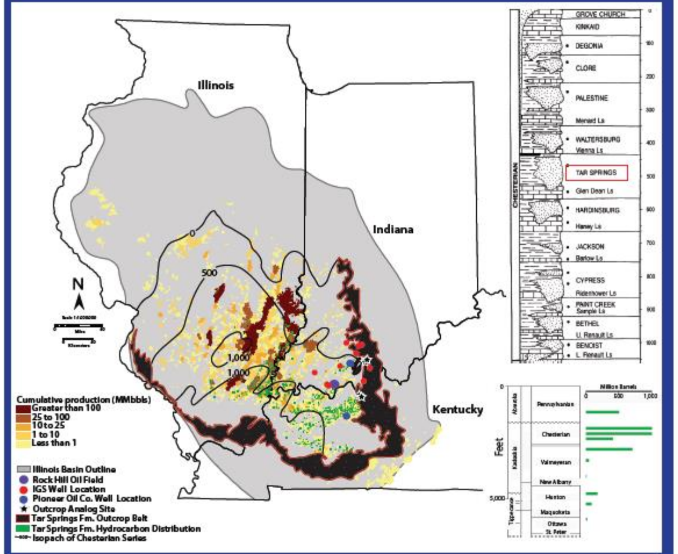
A. Introduction



A) Regional map of the Illinois basin depicting cumulative oil production, locations of the Rock Hill oil field pilot study, Indiana Geological Society / Pioneer Oil Company core locations, and outcrop study sites of the Tar Springs Formation. The regional outcrop belt of the Tar Springs Formation is highlighted. Modified from the Geological Sequestration Consortium. B) Regional stratigraphic column of Middle-Late Mississippian strata outlining the Tar Springs Formation. Modified from Pryor 1990. C) Cumulative Illinois oil production by reservoir horizon up to 1983. Modified from Seyler & Grube 2012.

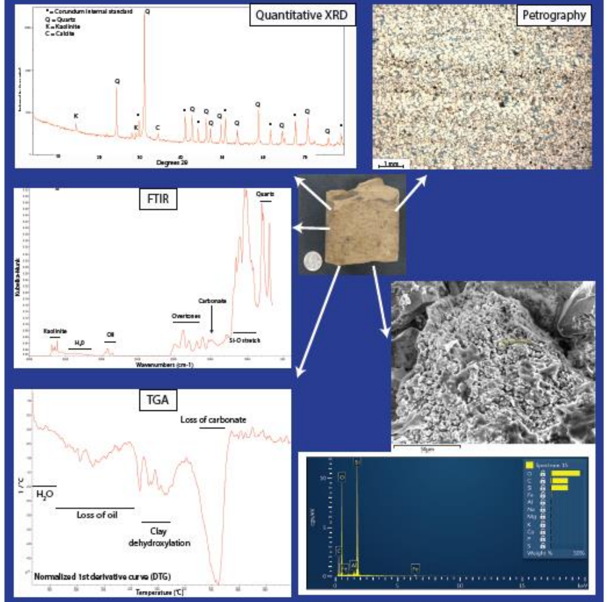
• Since the discovery of oil in the Illinois basin, estimated petroleum production has been over 4,000 MMBO with approximately 7.7 billion barrels remaining in place. The production history of the Illinois basin has largely been dominated by sandstone reservoirs (75%), of which 60% are Mississippian-aged. This research focuses on the Tar Springs Formation, one of many Mississippian siliciclastic-carbonate depositional sequences that serves as a key producing horizon for the region.

• Rock Hill reservoir in southern Indiana is a mature field yet contains abundant residual oil making it an ideal prospect for chemical enhanced oil recovery (CEOR) techniques. By developing an intimate understanding of the reservoir system at both the macro- and micro-scale, our research objective is to construct a regional geologic framework of the Tar Springs Formation that serves as a reservoir model. This framework will then be utilized by chemical engineers to help restore production to many mature oil fields within the Illinois basin and other mature basins.

B. Methods

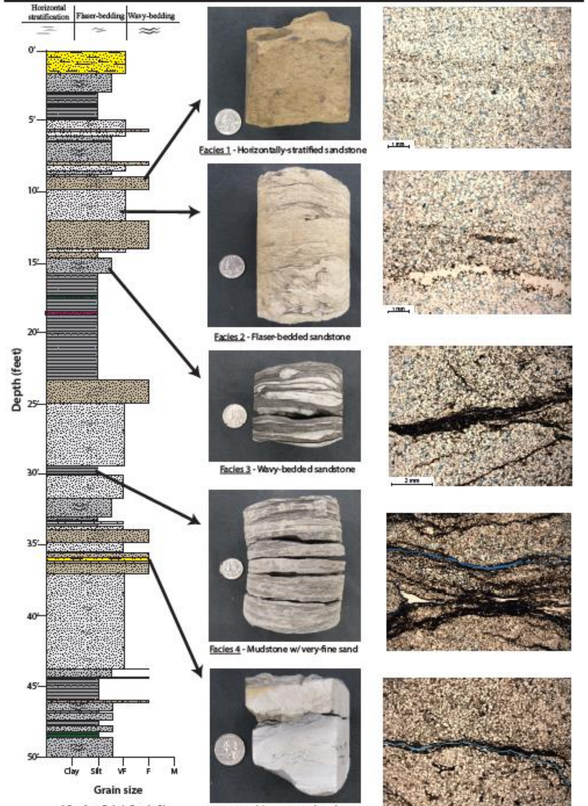
• To develop the Tar Springs Formation geologic framework, multiple sets of data were incorporated that include 1) detailed core assessments, 2) thin section petrography, 3) X-ray diffraction (XRD), 4) scanning electron microscopy (SEM) combined with energy dispersive X-ray spectroscopy (EDX), 5) Fourier transform infrared spectroscopy (FTIR), 6) thermogravimetric analysis/evolved gas analysis (TGA/EGA), and 7) field observations of surface outcrops.

• Cores were provided from both Pioneer Oil Company, Inc. and the Indiana Geological Survey (IGS) core library.



Integrated analytical methods used for reservoir characterization, closewise from top right: A) thin section petrography utilizing epoxy impregnation showing porosity variations as a function of sandstone heterogeneity; B) SEM and EDX data of incipient quartz overgrowth; C) TGA derivative curve showing volatile loss as a function of temperature; D) FTIR spectra showing prominent peaks for mineralogy and residual fluids; E) quantitative XRD spectral peaks identifying major mineral constituents.

C. Common Reservoir Core Lithofacies



Facies 1 - Horizontally-stratified sandstone

Facies 2 - Flaser-bedded sandstone

Facies 3 - Wavy-bedded sandstone

Facies 4 - Mudstone w/ very-fine sand

Facies 5 - Calcite-cemented sandstone

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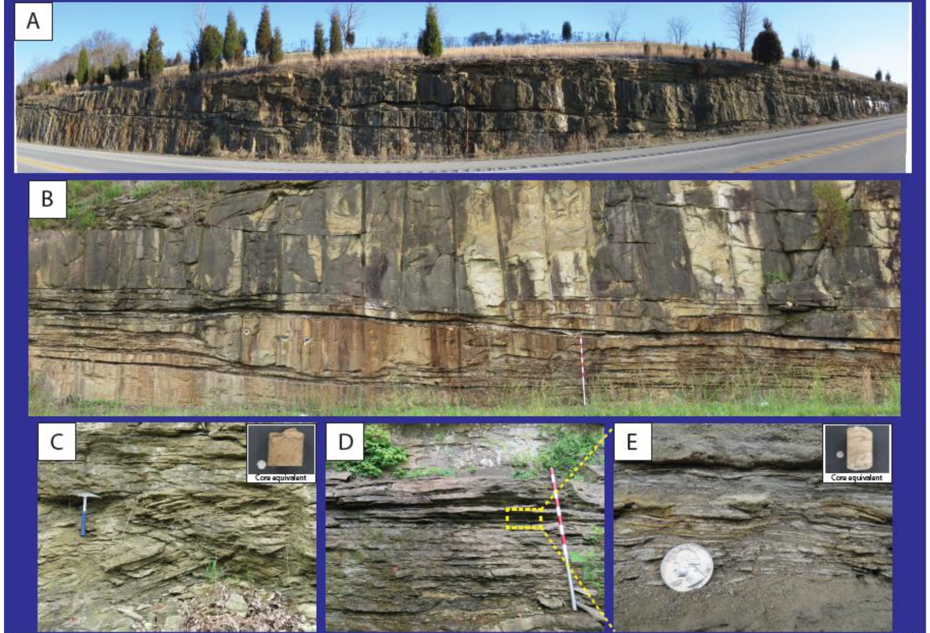
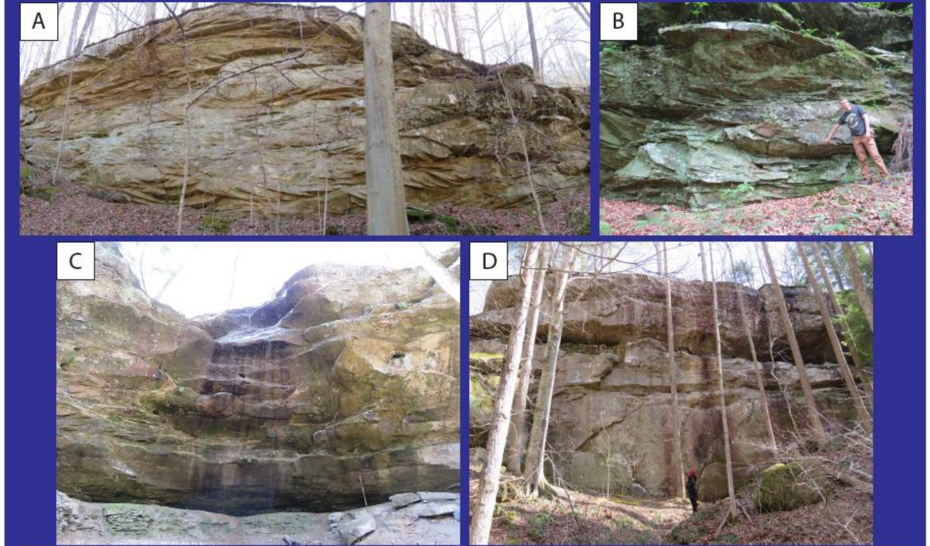
D. Outcrops



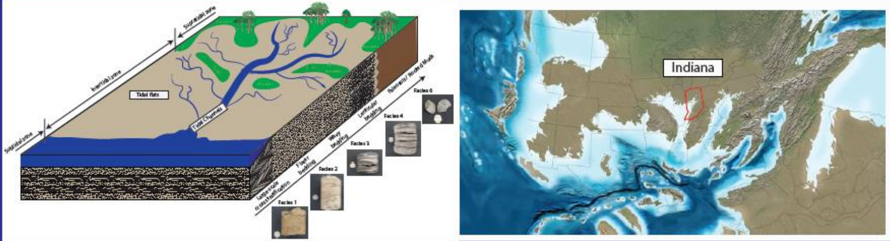
A) Outcrop photograph of the Tar Springs Formation in northern Kentucky comprised of multiple, stacked channel sandstones. Scale bar is approximately 1.5 m. B) Individual channel sandstone that expresses clean, thicker sand intervals that gradually transition into ripple-laminated and flaser-bedded units. C) Stacked, trough cross-bed sets that are capped by ripple-laminated sandstones - inset image shows equivalent reservoir core lithofacies. D) Ripple laminated sandstones with intermingled flaser-bedded sandstone occurrences. E) Close-up view of flaser-bedded sandstone unit - inset image shows equivalent reservoir core lithofacies.

- Tar Springs Formation outcrops provide 3D reservoir geometries with respect to lateral continuity of different lithofacies in addition to sandstone connectivity. Individual channel geometries that comprise the Tar Springs are ~5-10 feet in thickness and extend ~75-100 feet. Stacking of channels can produce sandstone thicknesses >50 feet.

- Outcrops and reservoir cores are comprised of similar lithofacies and both contain sedimentary structures such as large-scale cross-stratification, flaser-bedding, wavy-bedding, mud-rich sandstone intervals, and clay-rich paleosol horizons that are in agreement with a tidally-driven depositional environment such as a tidal flat system. Cross-stratified sandstone exposures that display tidal bundles with lateral foreset thickness variations as well as cores with tidal rhythmite sequences provide additional evidence. Paleogeographic reconstructions of the southern Indiana region are consistent with these interpretations.



A) Outcrop photograph of the Tar Springs Formation in southern Indiana comprised entirely of trough cross-bedded sandstone. Bar for scale is approximately 1.5 m. B) Author pointing to the bottom of a trough cross-bed marking the location of paleoflow measurement. C) Waterfall exposure of the Tar Springs Formation in the Hoosier National Forest, IN. D) Fifty-foot thick, box canyon-forming sandstone outcrop of the Tar Springs in the Hoosier National Forest.



Left) Tidally-influenced depositional model of the Tar Springs Formation. Depositional lithofacies reflect a decrease in overall sand content away from the land-water interface due to a dissapation in tidal current velocities (adopted from Dalrymple 2010). **Right**) Late Mississippian paleogeographic reconstruction of the continental U.S. showing the location of Indiana (image courtesy Ron Blakey 2011).

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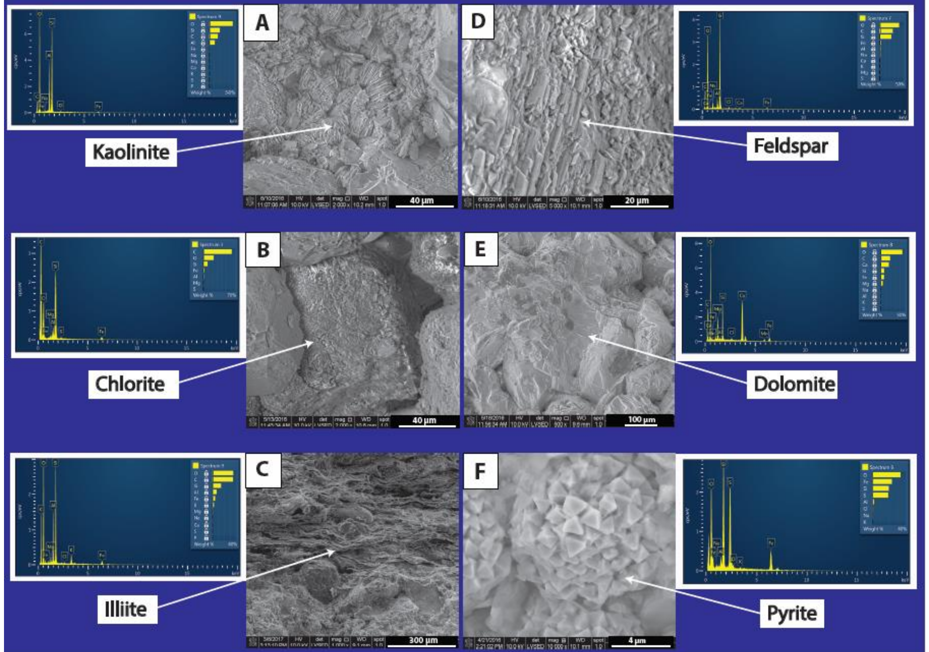
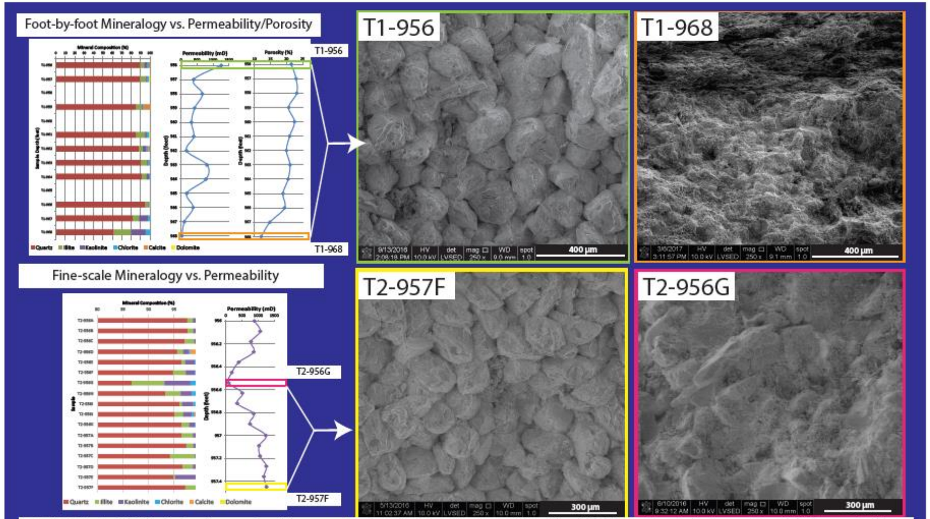
E. Diagenetic Controls of Reservoir Quality

Accurate identification of sandstone reservoir clay minerals and cementing agents holds important implications for determining reservoir quality as a control on porosity and permeability distributions. Combined research methods have identified various authigenic, pore-filling minerals based on morphology and composition.

- A) Euhedral kaolinite booklets and more commonly vermicular growths that are either pore-lining or pore-filling in nature
- B) Euhedral, Fe-rich chlorite platelets that coat detrital quartz grains but can potentially develop into rosette clusters that partially obstruct pore geometries
- C) Illite sheets comprised of irregular flakes
- D) Na-rich plagioclase grains that express partial dissolution features
- E) Diagenetic, partially dissolved calcite and dolomite cement
- F) Trace abundances of framboidal pyrite comprised of octahedral crystals that are indicative of reducing reservoir conditions





Top) Foot-by-foot analysis of a Tar Springs Formation reservoir core that compare modal mineralogy to both porosity and permeability variations. SEM photos show the contrast between sandstones with differing amounts of clay minerals that can inhibit flow parameters. Bottom) Fine-scale analysis of a two-foot section of Tar Springs reservoir material that compares modal mineralogy versus permeability variations of high-quality reservoir facies 1 (horizontally-stratified sandstones). SEM photos of two particular samples showing how clay mineral abundances drastically influence reservoir quality.

F. Mineralogical Implications for EOR

- Clay minerals and diagenetic calcite cement present within sandstone of the Tar Springs Formation are important controls to reservoir quality and have significant effects on porosity, permeability, and reactivity to various enhanced oil recovery techniques. Each of the clay minerals present in Tar Springs Formation sandstones possess unique surface areas and charges that can interact differently with EOR fluids and influence oil extraction.
- Pore size and geometry are modified by clay minerals that either act as pore-filling or pore-lining. Grain-coating chlorite platelets are beneficial to porosity and permeability due to their ability to inhibit the formation of quartz overgrowths (where present) and prevent pressure dissolution. Kaolinite acts as a pore-filling clay but also has been observed to line pore spaces in conjunction with chlorite. Together, both chlorite and kaolinite can have an adverse effect on permeability as pore throats become more constricted or occluded. Samples containing mud drapes show an increased abundance of illite clay sheets that can both partially coat sand grains as well as line pore throats. Calcite cement dissolution has the potential to lead to secondary porosity in sandstones; however, diagenetic calcite is observed to occlude all porosity and permeability in some Tar Springs Formation samples, effectively becoming permeability barriers.
- The geologic framework and rock-fluid data from this study are currently being incorporated into reservoir coreflood analyses in addition to reservoir models to maximize the effectiveness of surfactant-polymer combinations.

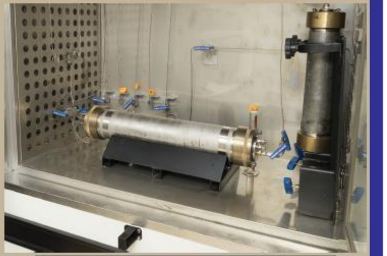


Photo of EOR coreflood apparatus at Purdue University