PS The Mississippian Thick Cypress Sandstone: A Nonconventional CO_2-EOR Target in the Illinois Basin*

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Abstract

The Mississippian Cypress Sandstone is the most prolific oil reservoir in the Illinois Basin (ILB). A fairway of thick Cypress Sandstone that can exceed 46 m was deposited in an incised valley system in the ILB. In some places, these thick sandstones contain oil reservoirs in the top with the potential for an underlying residual oil zone (ROZ). These reservoirs typically have low primary recovery due to excessive water coning and are an under produced resource in the ILB. Nonconventional carbon dioxide (CO_2) enhanced oil recovery (EOR) in such reservoirs provides economic incentive to mitigate CO_2 emissions by storing rather than recycling CO_2 compared to conventional CO_2-EOR programs. This research focuses on quantifying the thick Cypress Sandstone CO_2-EOR and storage resource in the ILB. Reservoir characterization using core and analogous outcrop data and analysis of open-hole geophysical logs of varying types and ages to identify the presence of ROZs are underway. If ROZs are present, the mechanism for their emplacement and the geologic characteristics of the formation must be understood so the distribution of ROZs can be predicted. Regional geologic characterization indicates that the thick Cypress Sandstone occurs as multistory fluvial sandstone bodies that become estuarine upward and were deposited in an accommodation limited setting. Marine incursions punctuate the fluvial sandstones with implications for reservoir quality, as marine beds create laterally continuous baffles to vertical fluid flow. Areas with the highest potential for CO_2-EOR and storage occur where multiple sandstone bodies amalgamate and limit the thickness of the intervening marine strata while facilitating enhanced stratigraphic trapping due to differential compaction over the thick sandstones. Open-hole log analyses are being assessed to determine whether ROZs are present with early results showing oil saturation trends within the thick Cypress Sandstone indicative of ROZs. These methods are being refined to provide more confidence of the presence ROZs, with efforts being taken to collect cased-hole pulsed neutron logs and new core to validate open-hole log analyses. Methods developed here could be applied broadly, as analogous thick sandstones with oil reservoirs and potential ROZs are common in other Carboniferous strata in the ILB and likely in similar settings. Such regional resource assessments may provide industry with information needed to initiate CO_2-EOR in the ILB.

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Hurst, A., and P. Nadeau, 1995, Clay microporosity in reservoir sandstones: an application of quantitative electron microscopy in petrophysical evaluation: AAPG Bulletin, 79/4, p. 563–573.

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Motivation

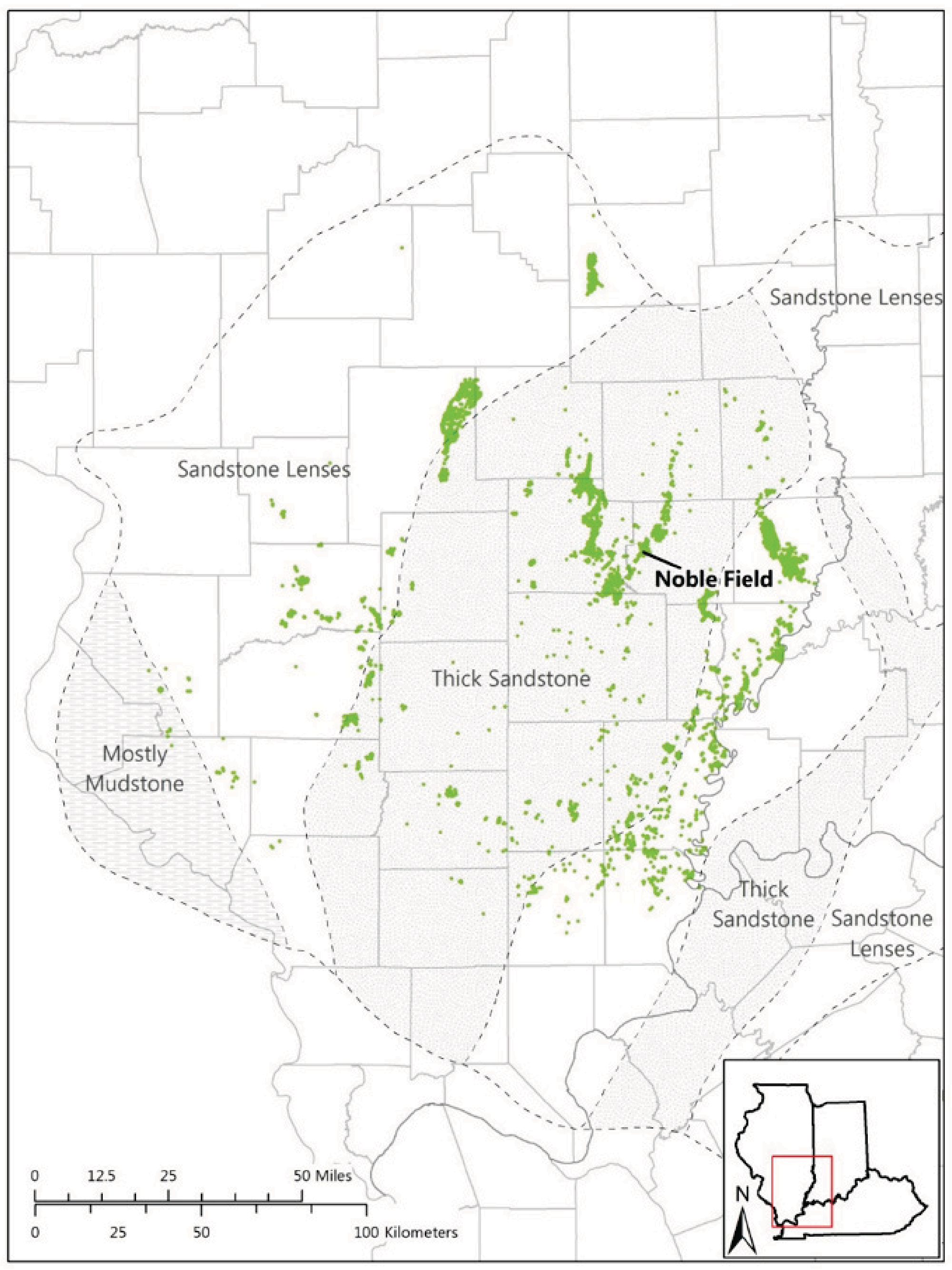
Determine potential for net carbon negative oil (NCNO) production via CO_2-EOR and geologic storage

- Objectives of this four-year study include
  - ◊ Characterizing geology of CO_2-EOR target formation
  - ◊ Identifying ROZs by looking for direct (oil saturation profiles from core or log analysis) and indirect (tilted oil/water contact, relatively fresh water, different oil composition) indicators
  - ◊ Developing a CO_2-EOR/storage strategy for the regional resource based on detailed case studies

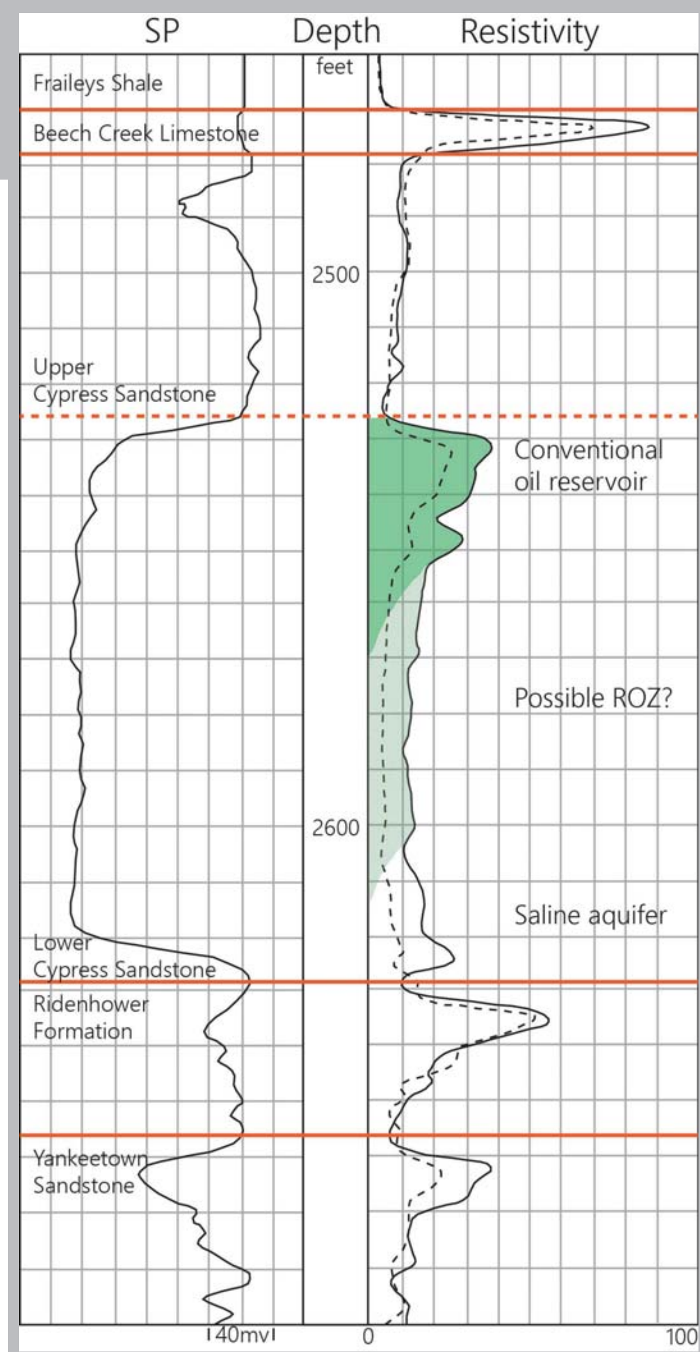
Background and Study Area

Cypress Sandstone

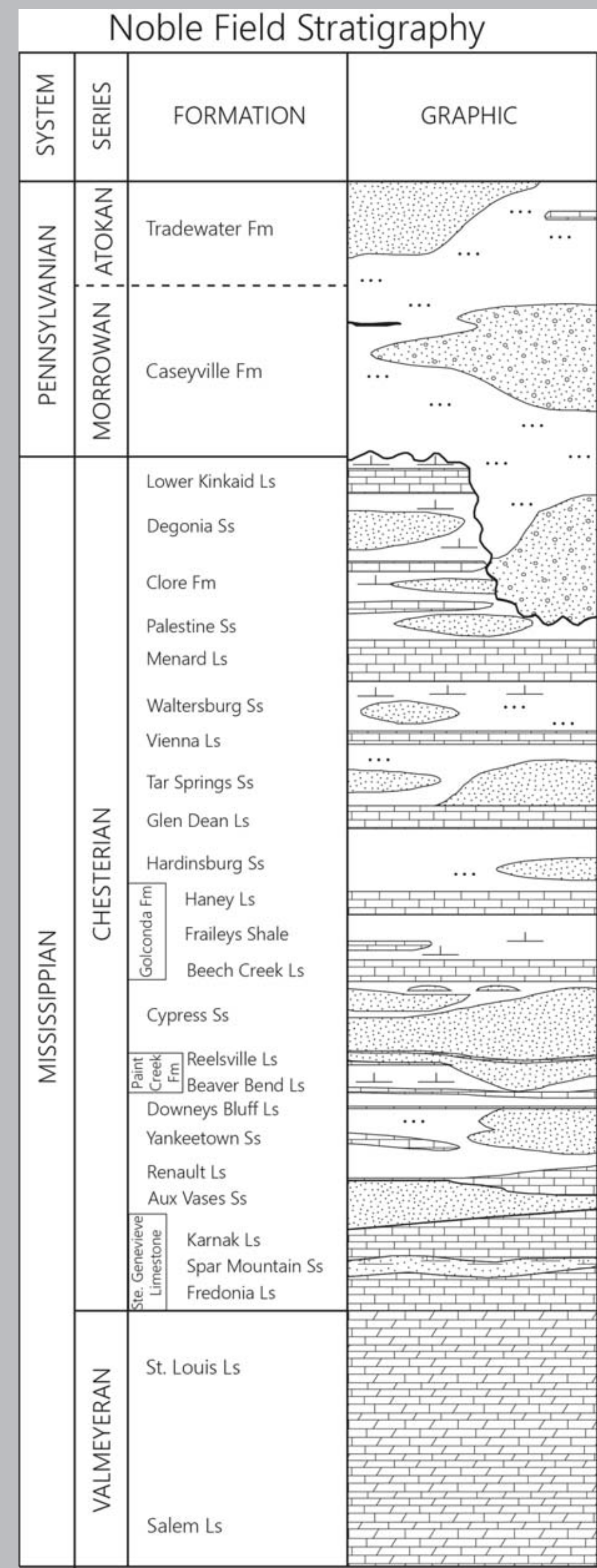
- Multiple facies in the Illinois Basin (Below)
- Production commonly from sandstone lenses



- Thick Cypress Sandstone reservoirs are an under produced resource
  - ◊ Mobile oil above thick (100+ feet) brine aquifers
  - ◊ Water coning issues during production
- Noble Field is the best example of a thick Cypress reservoir in the Basin and provides a good case study for future expansion to regional assessment



- Above - Thin conventional reservoirs with potential residual oil zones (ROZs)
  - ◊ Naturally waterflooded over geologic time
- EOR with high net CO_2 utilization
- Saline storage potential of 3.5 to 40.2 Tcf (0.2 to 2.3 Gt) of CO_2 in the Illinois Basin (DOE/MGSC, 2012)

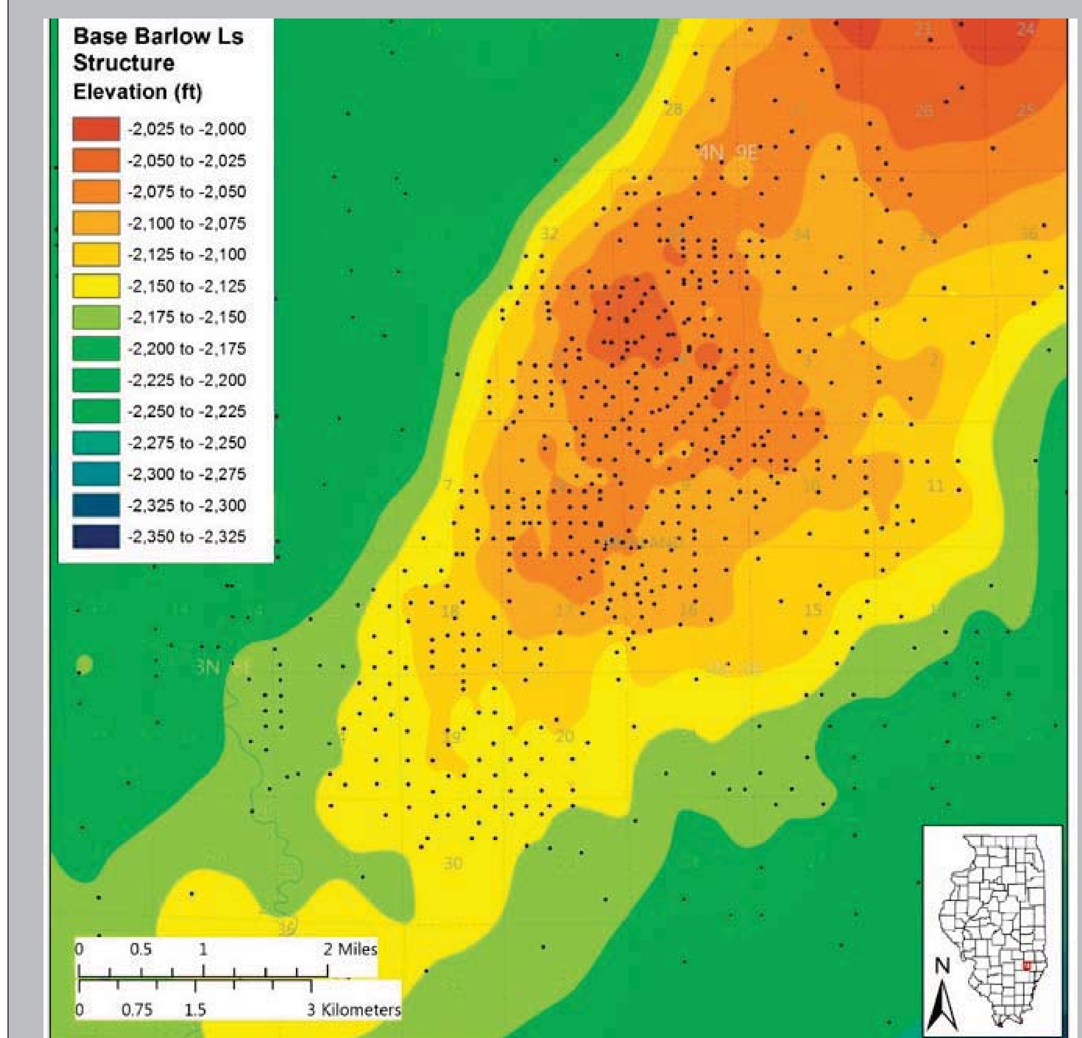


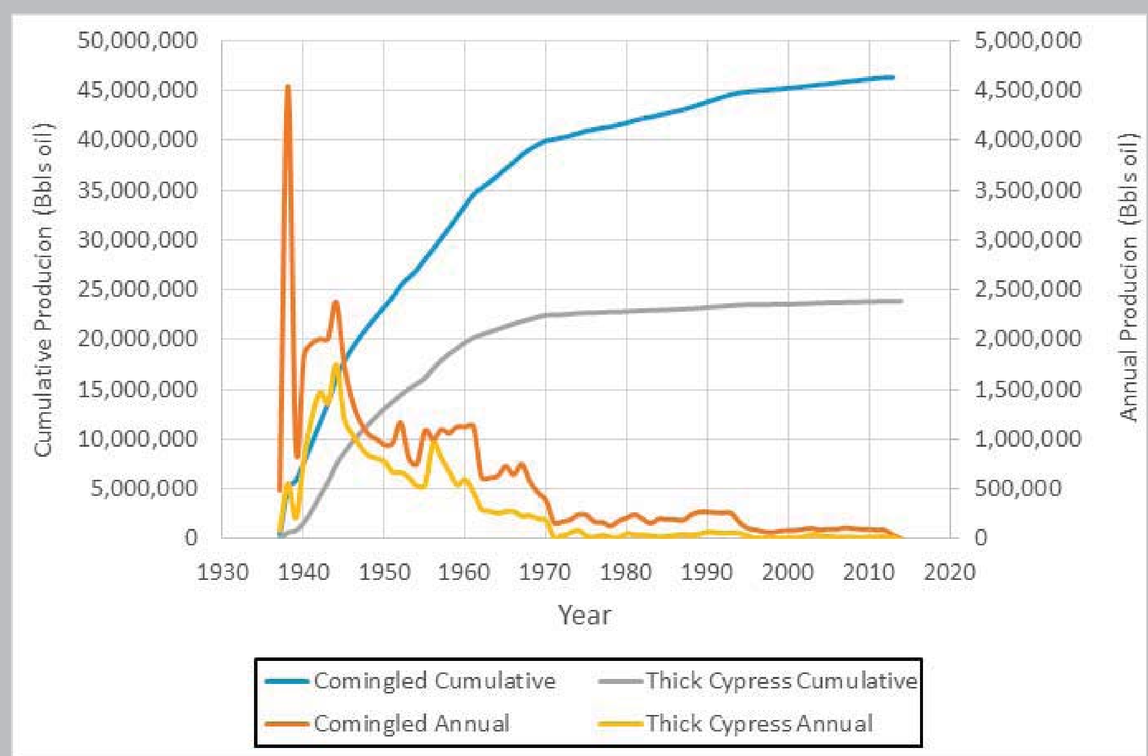
Above - Generalized stratigraphic column of Noble Field showing the Cypress Sandstone

Geologic Setting and History of Noble Field

Noble Field Location

- Discovered in 1937
- Part of Clay City Consolidated Field
- Relatively few areas of the Basin where thick Cypress Sandstone is a prolific producer; Noble Field is the best example





Above is a graph of cumulative (blue line) and annual (orange line) production data for all formations and all leases in Noble Field over the entire history of the field. The Cypress Sandstone accounts for approximately 50% of the total cumulative production. Field has produced >45 MMBO~24 MMBO (~50%) from thick Cypress Sandstone

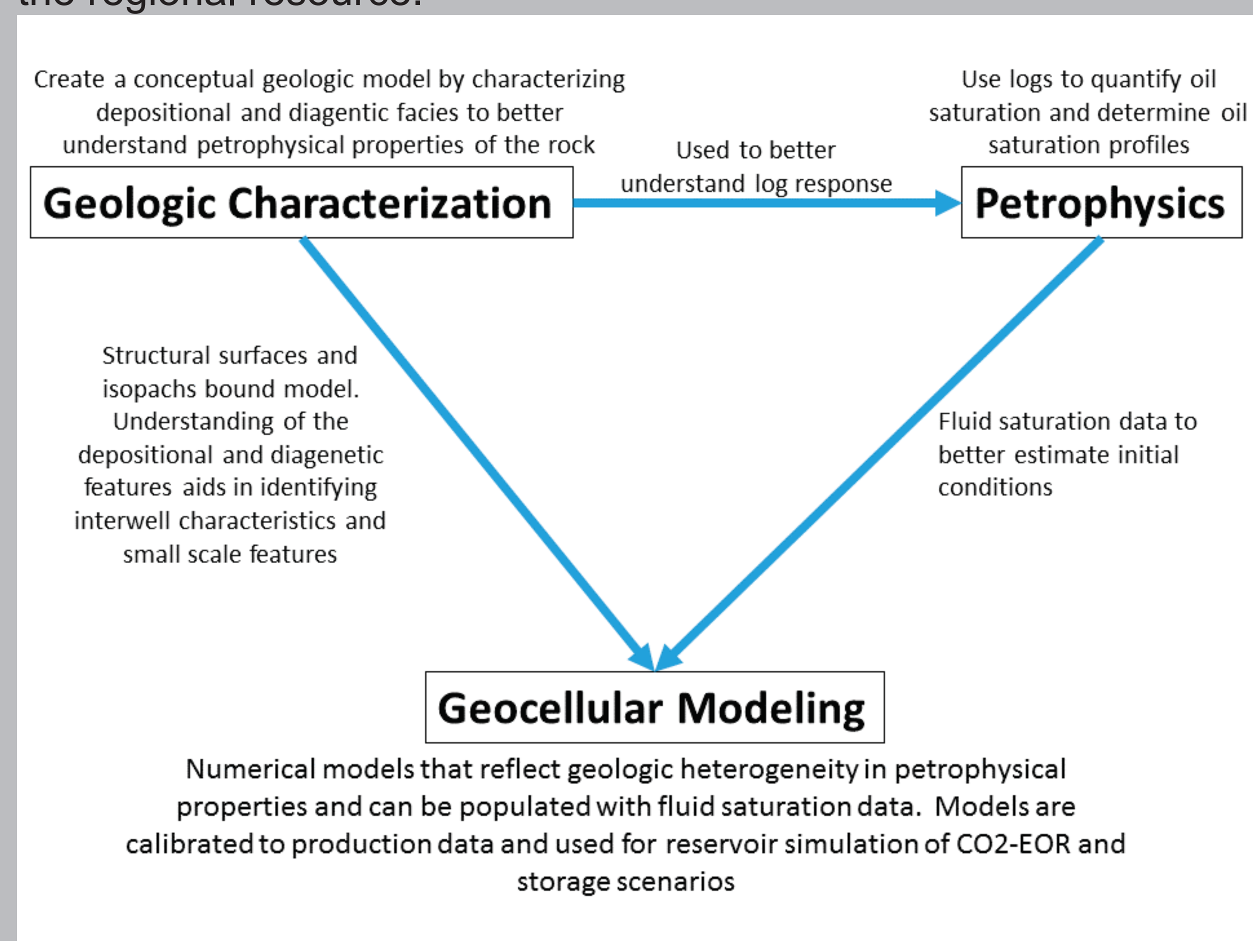
Structure map (Left) contoured on the base of the Barlow Limestone shows the NE-SW trending Clay City anticline on which Noble Field is situated.

Methods

To better understand and assess the regional resource, a detailed case study was conducted concentrating on:

- ◊ Geologic Characterization
- ◊ Petrophysics
- ◊ Geocellular modeling

Leveraging this multidisciplinary approach will allow for a better understanding of the petroleum system and will aid in assessing the regional resource.



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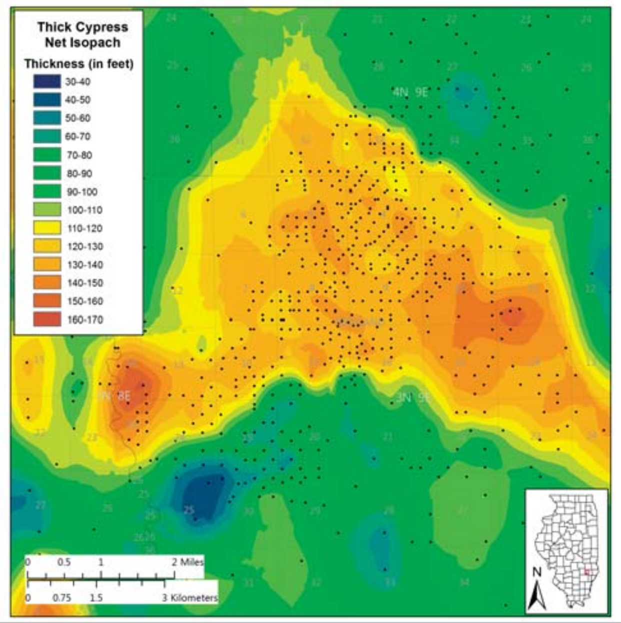
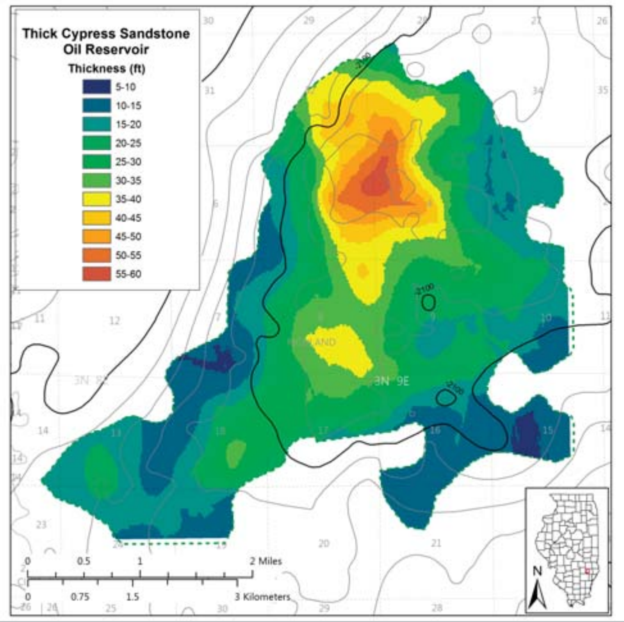
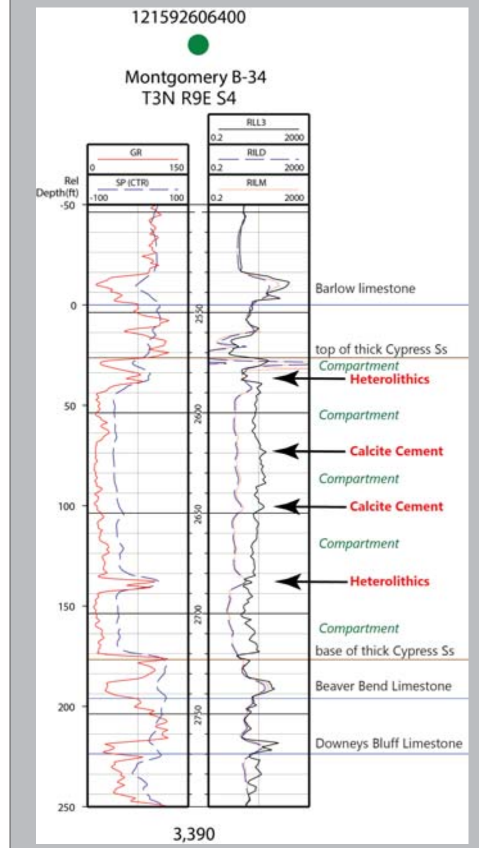
Geologic Characterization - Depositional, Diageneitic, and Reservoir Properties

Geologic Cross Section Correlations and Mapping

- Well defined, blocky appearance on all logs
  - ◊ Laterally continuous — easy correlation of top and bottom
  - ◊ Some internal baffles compartmentalize the reservoir (Below)
    - * Some continuous shale breaks
    - * Persistent calcite- cemented zones
  - ◊ Base of sandstone truncates underlying units
- Isopach shows intersecting NW-SE and NE-SW trending sandstone bodies (Right)







Depositional Environment

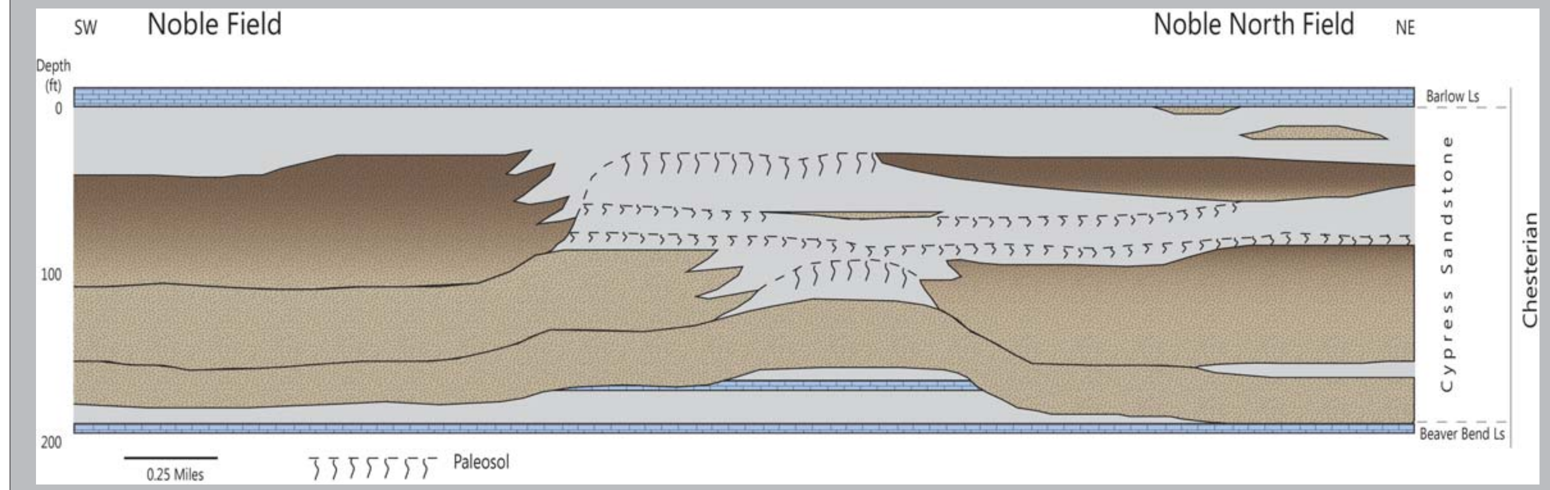
- The Cypress Sandstone at Noble Field is likely part of a lowstand (LST) incised valley fill environment
  - ◊ Multistory sandstone built through parasequence-scale successive fluvial to estuarine depositional episodes
  - ◊ Amalgamated fluvial to estuarine channels are punctuated by marine incursions as indicated by fossil fragments

Oil Water Contact

- Oil/water contact (OWC) tilted to the SW indicates possible ROZ
- Isopach of reservoir above OWC shows down-structure oil (Right)

Geological Model (Below)

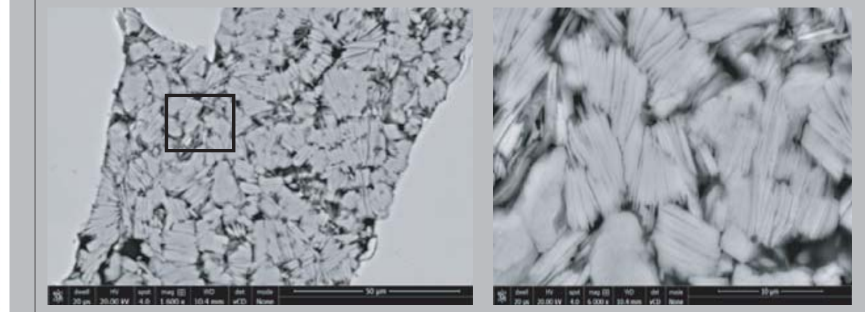
- Basal sandstone blankets entire field and reportedly covers much of the nearby counties; indicates low accommodation
- Middle and upper sandstone stories amalgamate at Noble Field but are less persistent elsewhere
  - ◊ Top of thick Cypress Ss is convex upward where amalgamated
  - ◊ Differential compaction over amalgamated sandstones create stratigraphic oil traps



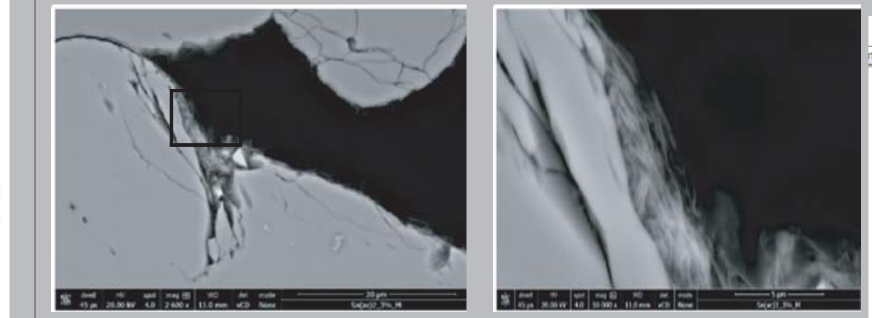
Quantifying Clay Microporosity using Scanning Electron Microscopy

- Microporosity is the part of pore space with characteristic dimension less than 1 µm
- Identify clay texture with petrographic microscope; Image area with SEM
- Sample Preparation: Epoxy impregnated, polished, carbon coated, attached with carbon tape and silver paint
- Contrast in back-scattered electron images is determined by the atomic number (Z) of the phase
- Silicates with high Z elements (Si, Al, O) appear LIGHT; Epoxy (C, H, etc) appear DARK

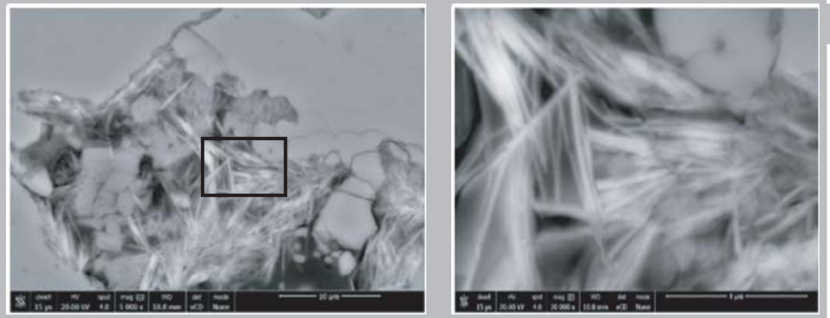
Pore-filling kaolinite booklets



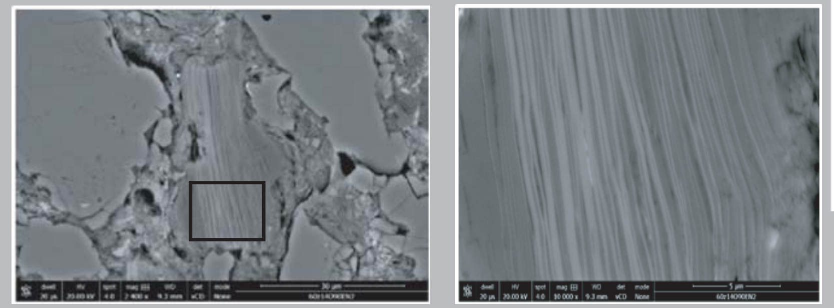
Grain-coating chlorite rosettes



Pore-filling and pore-bridging hairy illite



Densely packed detrital shale clast

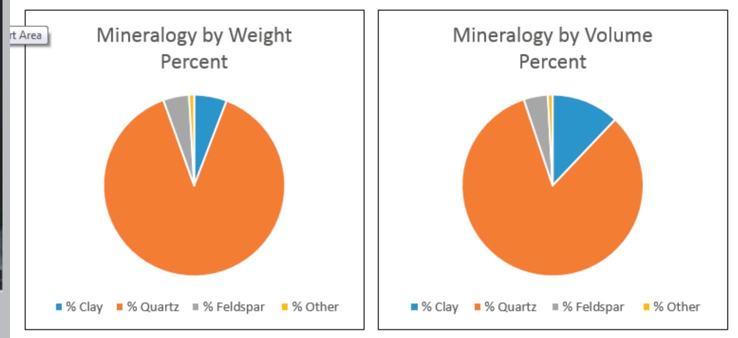


Clay Microporosity Determinations from BSE Images

Clay	φ_m(%)	$\bar{x}$ (%)	σ (%)	Number of Observations
Blocky Kaolinite	35 – 47	43	5.5	10
Vermicular Kaolinite	18 – 50	37	14	3
Chlorite	39 – 65	55	10	4
Illite	62 – 80	65	6.5	7
Illite-Smectite	65	65	0	1

*φ_m = microporosity, $\bar{x}$ = mean, σ = standard deviation

Comparison of Weight Percent and Volume Percent from a Sandstone Interval in the thick Cypress Sandstone



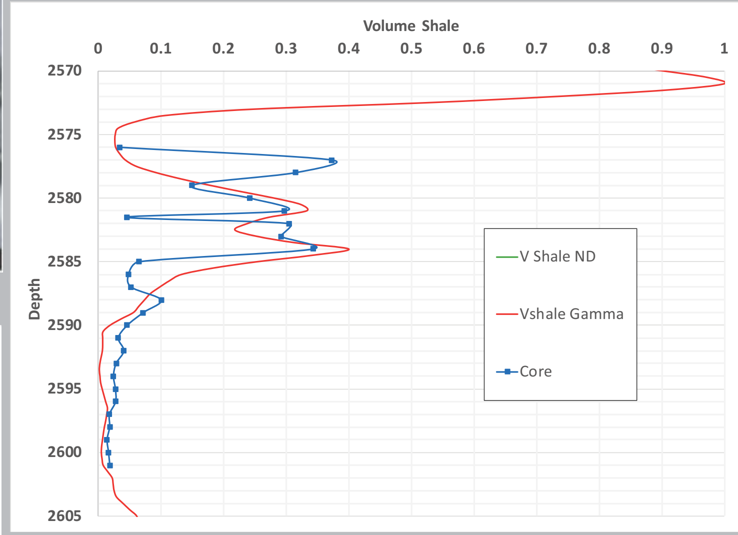


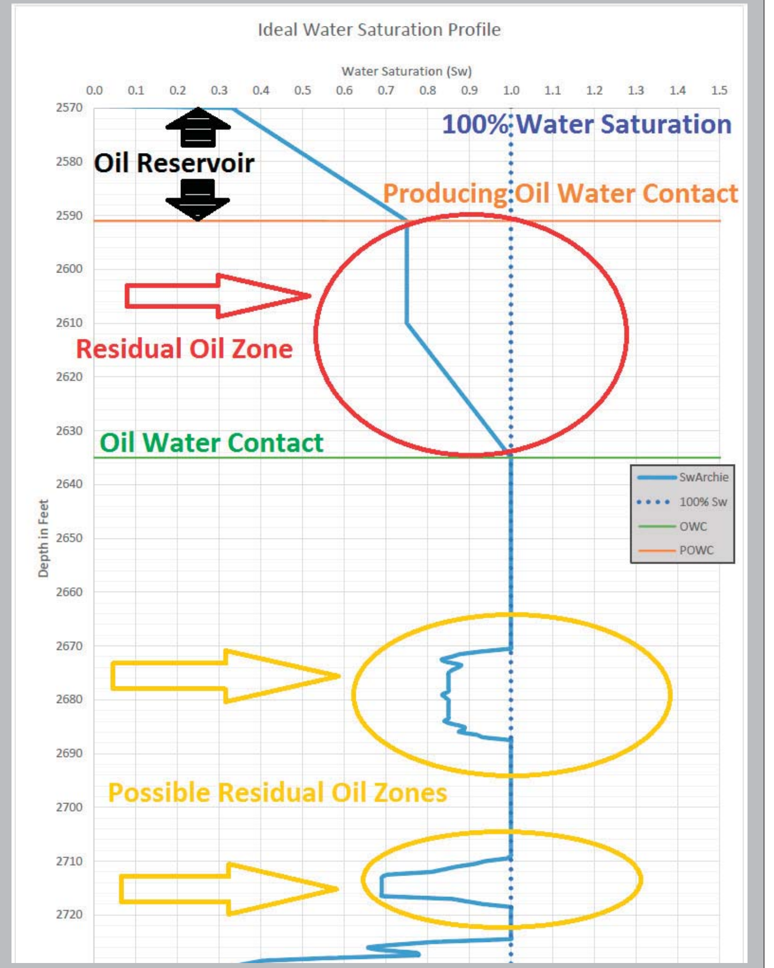
Chart showing results of Ve calculations from microporosity data versus Vshale calculations from wireline logs through an interval of the IVF. The lower section is clean sand and the upper portion is more heterolithic.

Incorporating Microporosity

- Microporosity in clay minerals creates a continuously conducting path of water-filled pores
- Extra source of conductance can cause a low resistivity log response, resulting in an overestimation of water saturation; underestimation of oil saturation
- Core based volume of shale will be used to calibrate log based estimates to improve petrophysical analysis
- Effective porosity (φ_e) is the pore space that contributes to fluid flow
- Water in clay microporosity is immobile (does not flow) during production
- This can lead to significant overestimations of porosity, and therefore recoverable oil
- For accurate resource assessment, microporosity (φ_m) must be excluded from total porosity (φ_t)

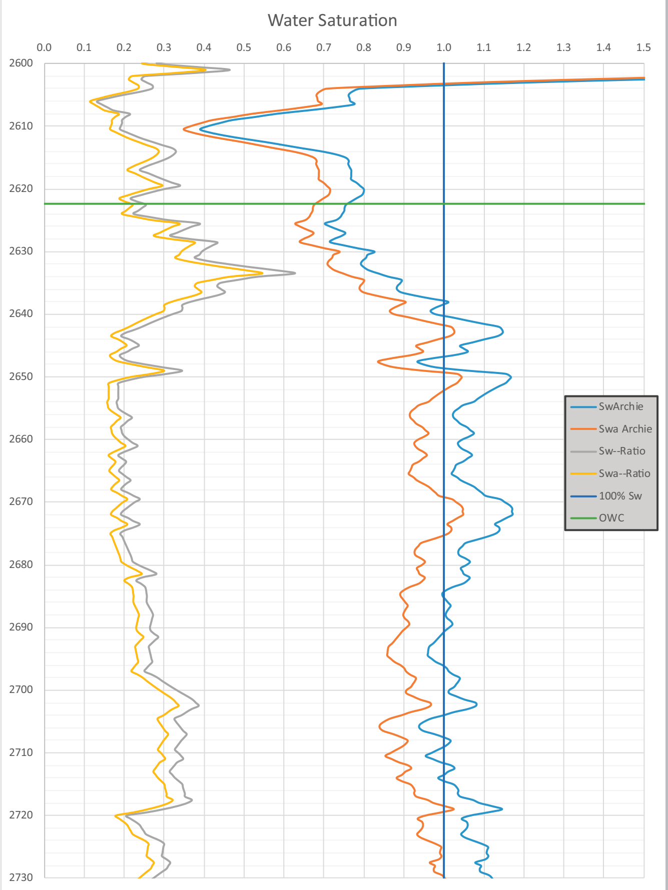
Petrophysical Analysis

- Need to develop quick-look method to find ROZs
- Geophysical logs can be used to calculate water saturation (S_w)
  - ◊ Gradual transition in S_w between oil reservoir and brine aquifer may indicate ROZs (Example Log, Right)
- Petrophysical analysis can provide indirect indication of ROZs
  - ◊ Need core and cased hole logs for validation

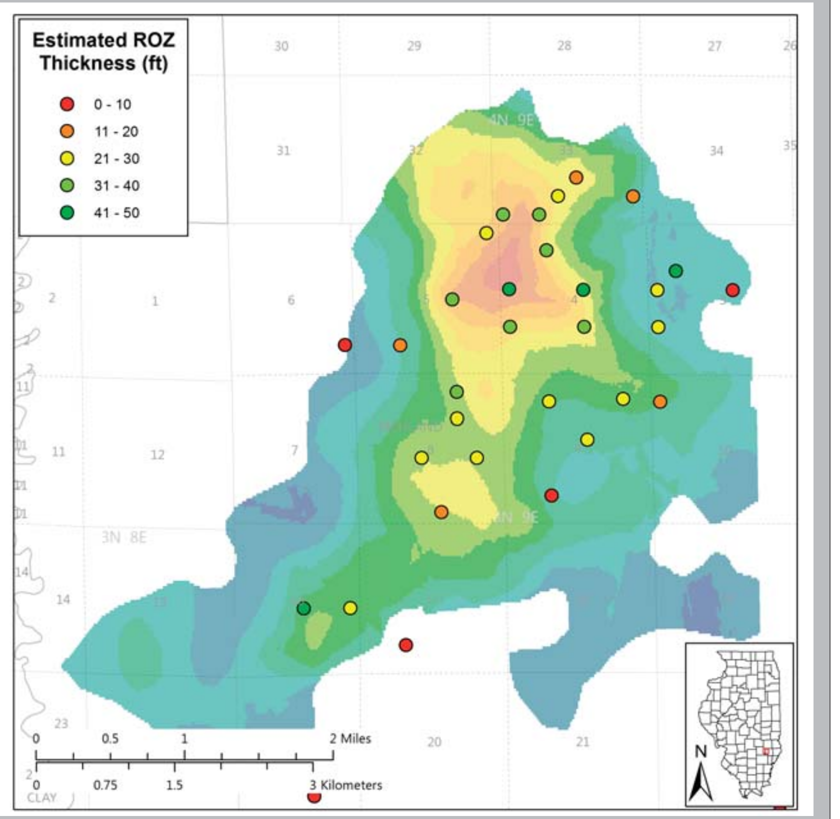


Methods

- S_w profiles calculated from logs in Noble Field using two methods that leverage different log types:
  - ◊ Archie (Resistivity + Porosity logs)
  - ◊ Ratio (Resistivity logs only)
- Both methods rely on the resistivity of formation water (R_w) which is not directly measured
- R_w is estimated from SP logs; $R_{w(a)}$ is estimated from resistivity and porosity logs



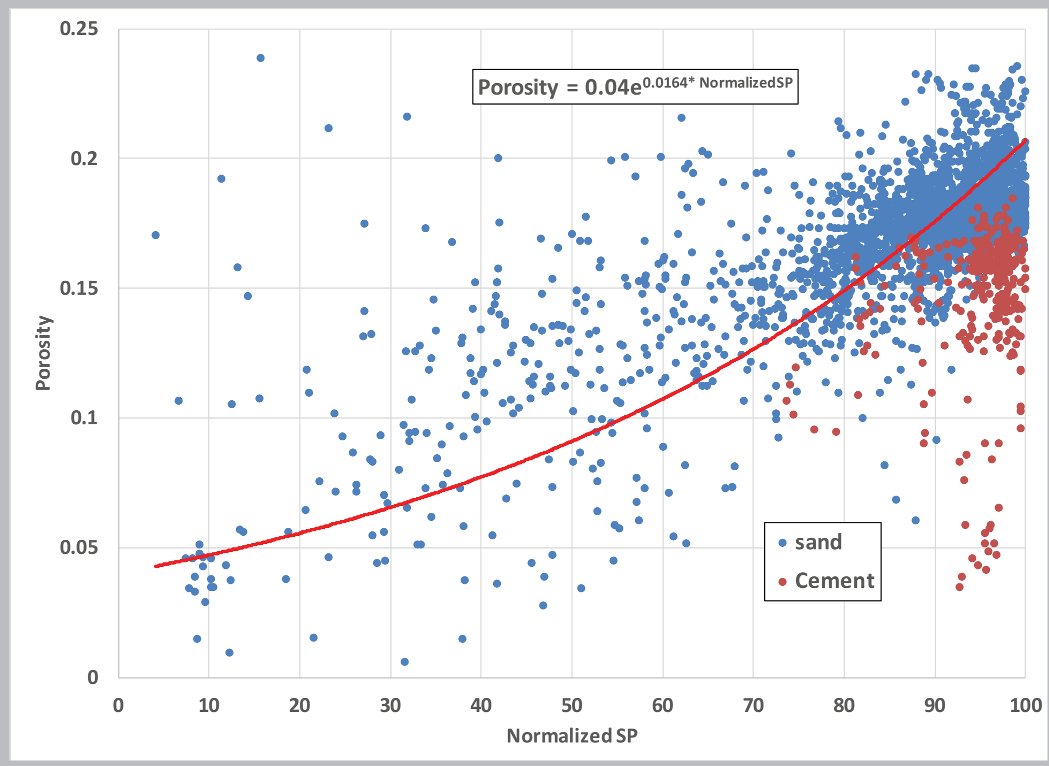
- Above - Saturation curves show potential ROZ below the producing OWC
- Similar trends are produced between Archie and Ratio methods, but the Ratio method generally had a suppressed S_w curve
  - ◊ Consistently lower S_w than the Archie Method
- Several wells had Sw values >100%
- A few possible explanations
  - ◊ Microporosity caused by diagenetic clay minerals
  - ◊ Negative electrical charges within detrital shaly interbeds



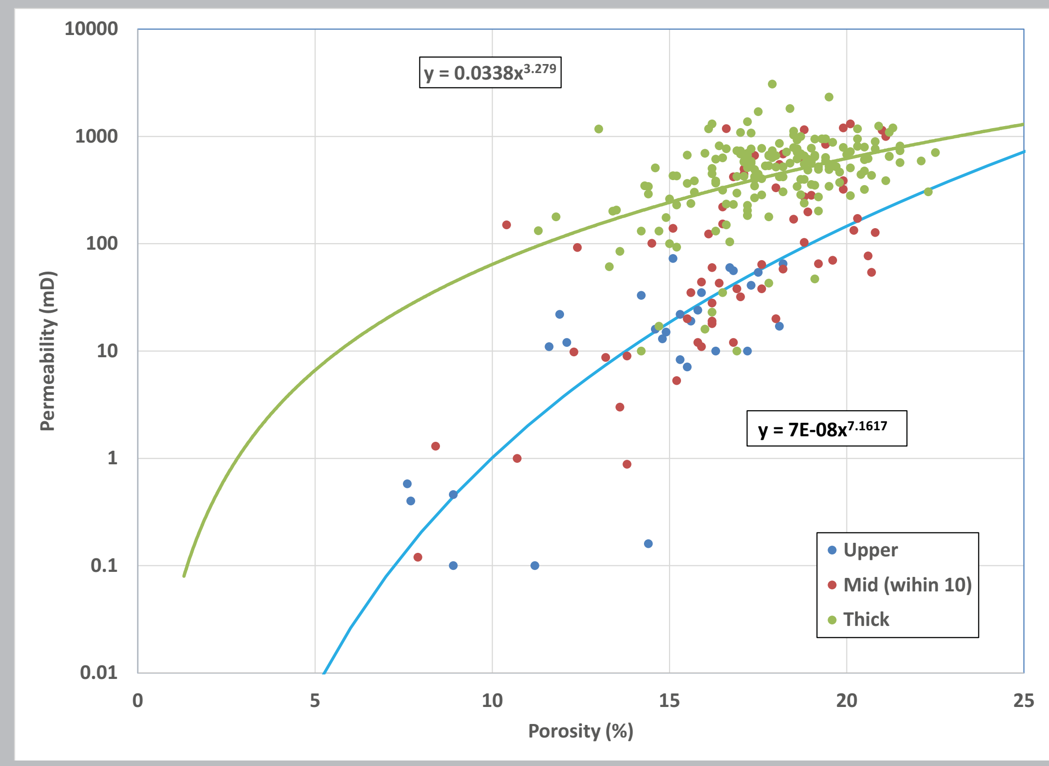
Preliminary map showing thickness of potential ROZ in wells in Noble Field based on petrophysical analysis overlain on an isopach of reservoir thickness. The ROZ, like the reservoir, is thickest at the crest of the structure.

Geocellular Model

- The geocellular model is designed to reflect the internal architecture of the reservoir
- Geostatistical analysis of core-calibrated geophysical log data allows interpolation of porosity and permeability between wells
- 385 Normalized SP (NSP) logs
  - ◊ Dense coverage, lower resolution/quality
  - ◊ Sandstone/shale ratio
  - ◊ Lithofacies model
- 126 Porosity Logs
  - ◊ Less coverage, higher resolution/ quality
  - ◊ Detects porosity variations within sandstone
  - ◊ Diagenetic model



- Left: NSP cross plotted and regressed against neutron density porosity
  - ◊ Cemented zones omited from regression
  - ◊ Equation defining the curve used to transform NSP into porosity
- Right: Core porosity cross plotted and regressed against core permeability
  - ◊ Data was grouped by facies
  - ◊ Equation for green curve was used to transform porosity to permeability



SP Log Model Results

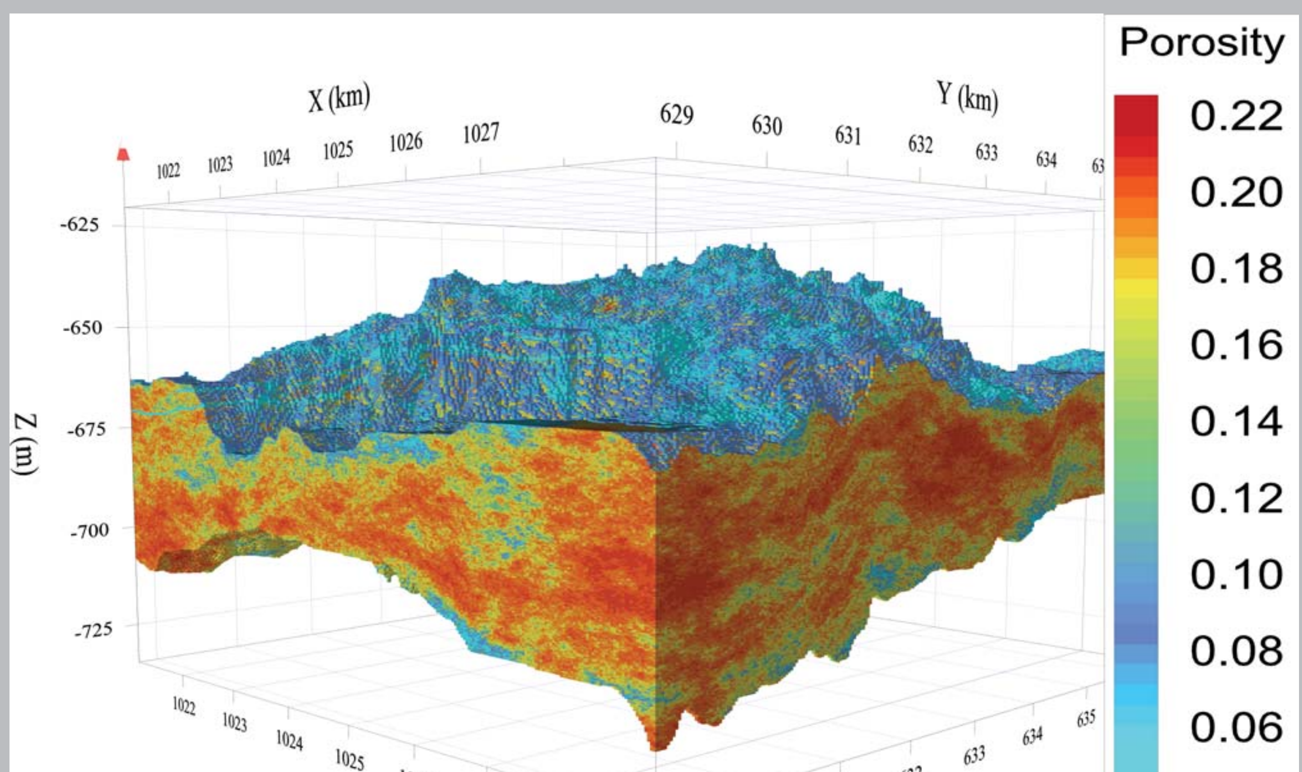
- Each cell is assigned a NSP value
- Data supports results of geologic conceptual model
  - ◊ Consistent sand throughout middle with more shale in the top and base
- SP cannot detect the calcite cemented zones found in core

Porosity Log Model Results

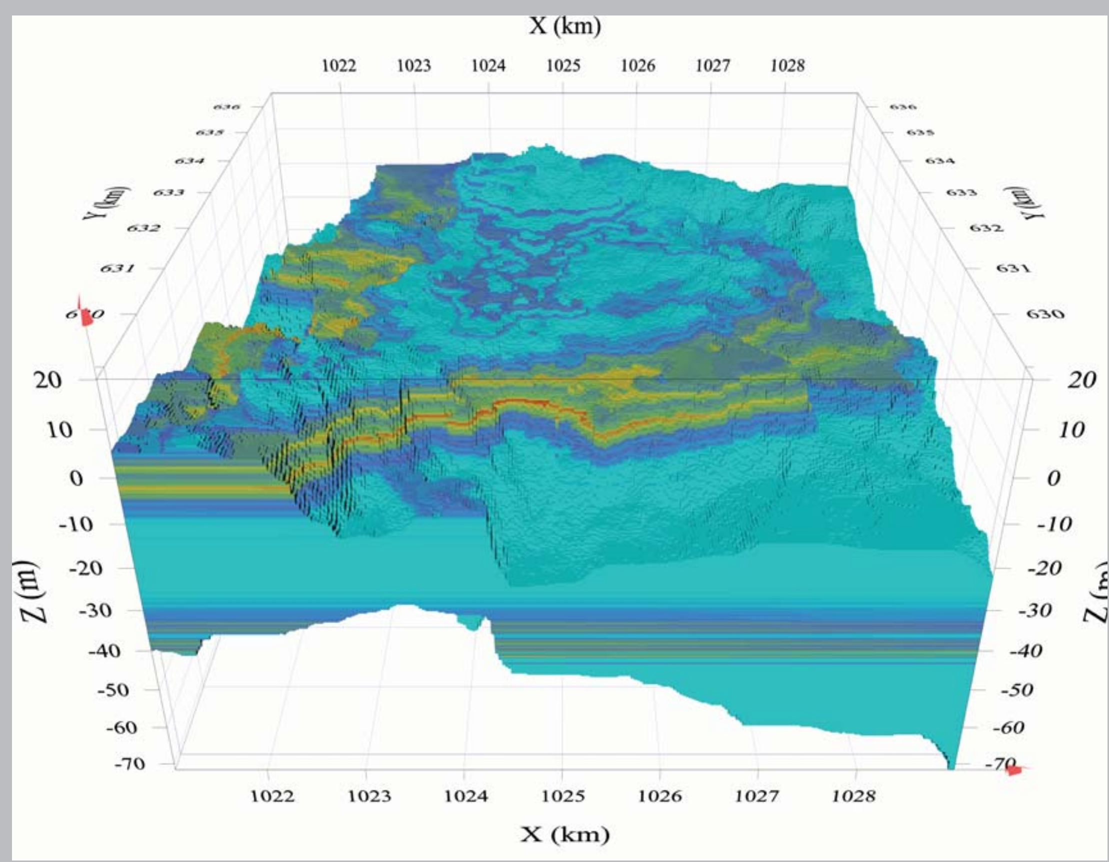
- Two parallel layers of calcite cement
  - ◊ One at the oil/water contact and one below it (paleo oil-water contact?)
- Model shows the odds of encountering cement
  - ◊ Two parallel bands that disappear to the NE

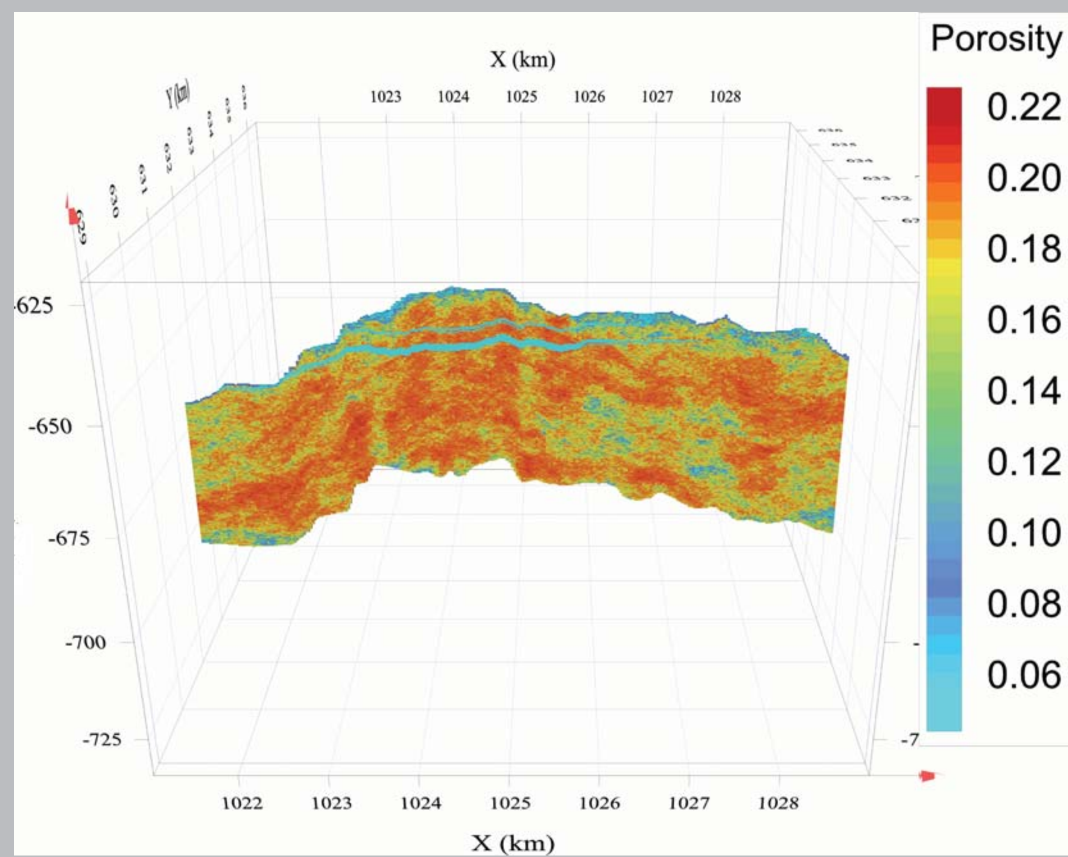
Geocellular Model

- SP and neutron-density log based models were combined to incorporate depositional and diagenetic facies
  - ◊ Shaly, estuarine facies at the top of the model
  - ◊ Thin shale interbeds
  - ◊ Low porosity calcite-cemented sandstone zones



Geocellular porosity model at Noble Field. Created from SP and ND logs. Roughly 0.5 × 0.5 mi., 50× vertical exaggeration.





Findings and Implications

- Noble Field is a microcosm of the regional nonconventional CO_2-EOR resource of the thick Cypress Sandstone
  - ◊ Abundant oil production and sound geologic interpretation provide confidence in modeling results and information for better understanding the regional resource
- Noble Field has thickest known oil column and <25% recovery efficiency, highlighting the potential for CO_2-EOR
- Indications of an ROZ has implications for the regional nonconventional CO_2-EOR target
  - ◊ Oil/water contact is tilted towards the south
  - ◊ Petrophysical analysis indicates possible ROZ
  - ◊ Calcite cement below oil/water contact may represent paleo-oil/water contact
- Integrating geologic characterization, petrophysics, and geocellular modeling leads to a better overall interpretation

Future Work

- Fingerprint oil to its source to understand migration into the reservoir
  - ◊ Understanding the mechanism for ROZ formation to predict where they occur
- Investigate calcite cemented zones and relationship to oil/water contact
  - ◊ Indications of paleo-oil/water contact? Evidence for ROZ?
- Coring and cased hole logging to validate petrophysical results
- Simulate production history to determine the most effective CO_2-EOR and storage method
  - ◊ Scenarios weighted towards oil production and storage
  - ◊ Potential to produce net carbon negative oil (NCNO)
- Map thick Cypress Sandstone at regional scale
  - ◊ Identify locations with oil reservoirs and possible ROZs analogous to Noble Field
- Estimate regional resource using results from Noble Field case study and reservoir simulation
  - ◊ Better understanding of the geology of the thick Cypress Sandstone
- Refine algorithm for identifying ROZs

References

- Hurst, A., & Nadeau, P. (1995). Clay microporosity in reservoir sandstones: an application of quantitative electron microscopy in petrophysical evaluation. AAPG Bulletin, 79(4), 563–573.
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Contributors

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- Petrophysical Analysis – Josh Arneson and Scott Frailey
- Clay Microporosity and Mineralogy – Leo Giannetta and Shane Butler
- Sedimentary Descriptions – Kalin Howell and Zohreh Askari
- Petrography – Jaclyn Daum and Jared Freiburg
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- For project information, including reports and presentations, please visit: http://www.isgs.illinois.edu/research/oil-gas/doe