Improved Oil Recovery in the Cypress Using an Unconventional Approach

Nathan D. Webb

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Acknowledgments

Project Co-PIs

- Scott Frailey
- Hannes Leetaru

Geology

- Nathan Webb
- Zohreh Askari
- John Grube
- Kalin Howell
- Yaghoob Lasemi

Geocellular modeling and well log analysis

- Nate Grigsby

Reservoir Simulation

- Roland Okwen
- Fang Yang

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Presentation Outline

- Background: Cypress Sandstone and ROZs
- Geologic Characterization
- Well Log Analysis & Preliminary Reservoir Simulation Results
- Summary

Cypress Sandstone

- Cypress Sandstone presents nCO_2-EOR and storage opportunity
  - NE-SW trending fairway of incised valley fill sandstone deposits though the central Illinois Basin

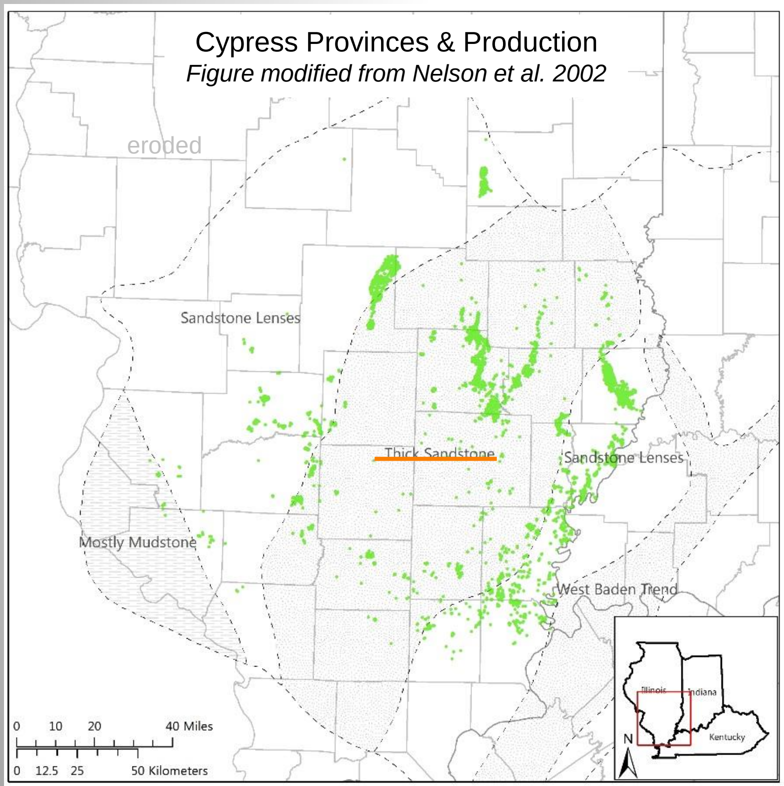

Figure modified from Nelson et al 2002

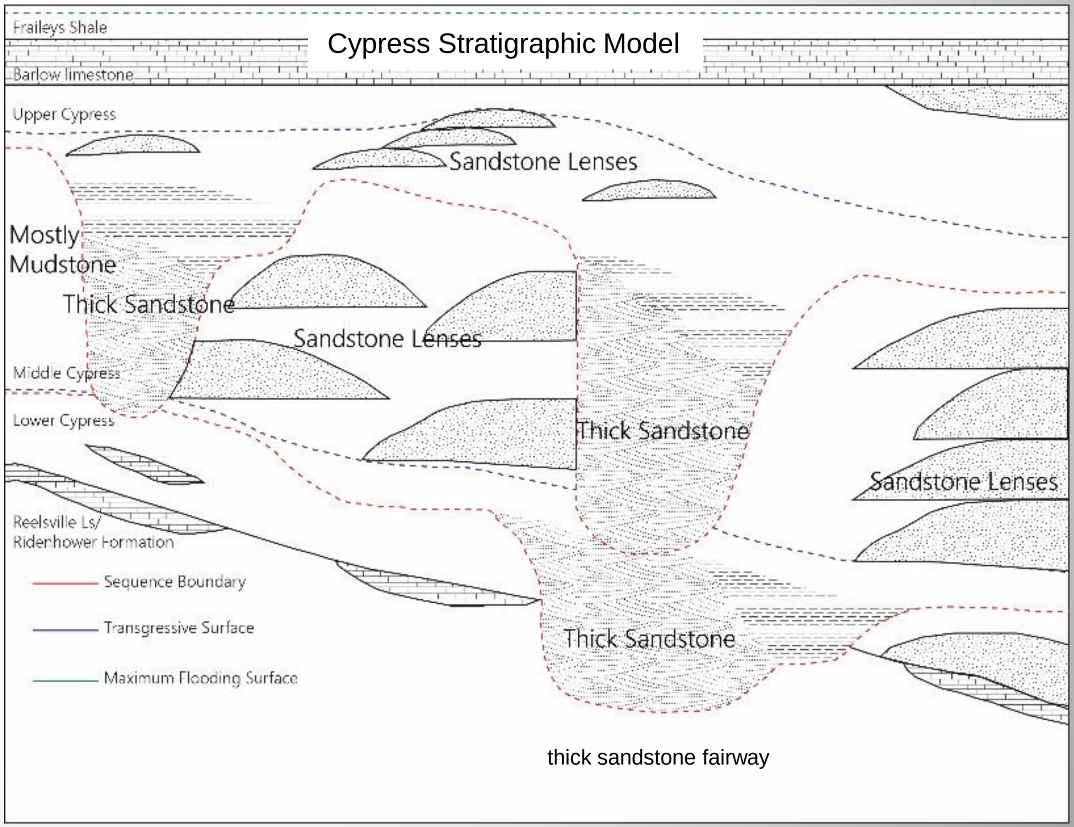

Figure modified from Webb and Grube 2014; no scale implied

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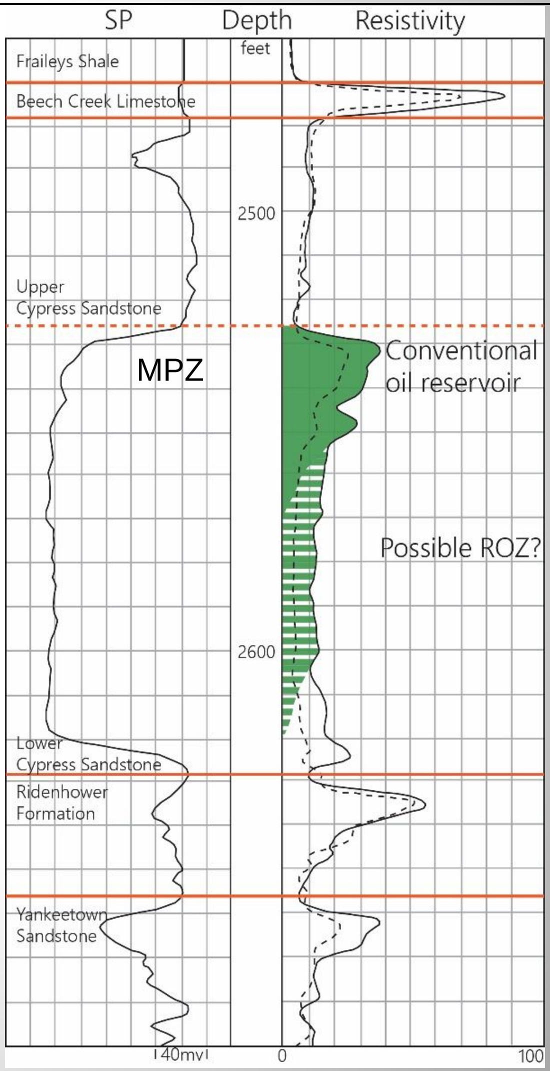
Valley Fill Cypress Ss Reservoirs

- Thin Oil Reservoirs
  - Residual and mobile oil above brine
  - Difficult to produce economically due to water coning and management
- Nonconventional EOR
  - Bypassed oil in the conventional reservoir
  - Potential for underlying Residual Oil Zone (ROZ)



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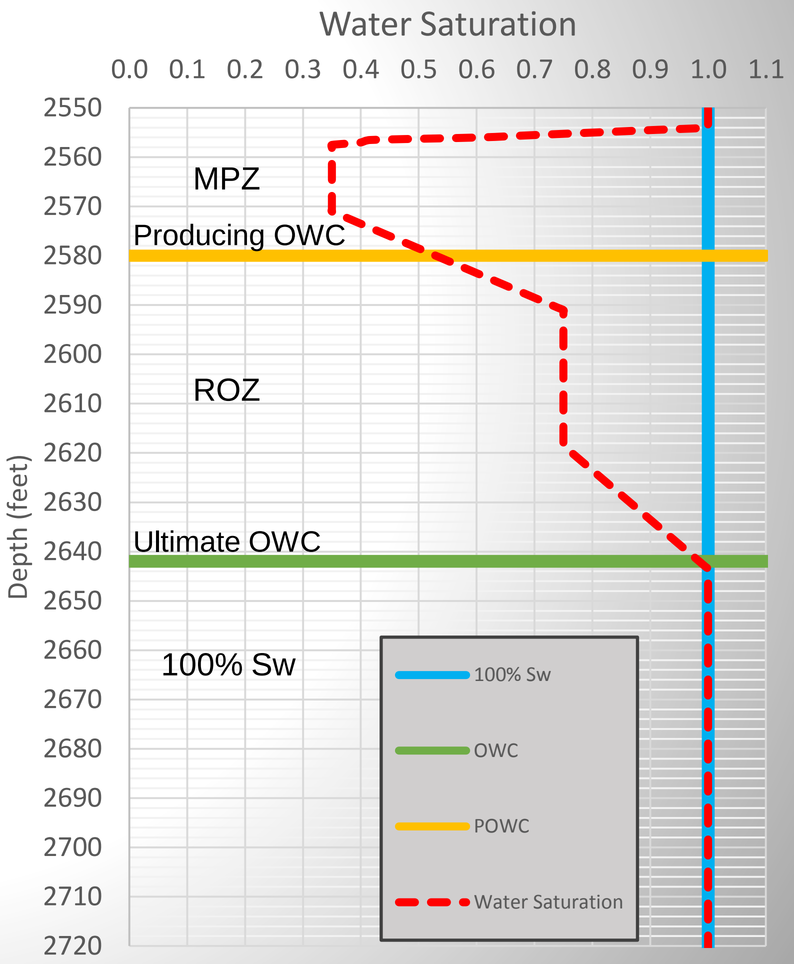
What is an ROZ?

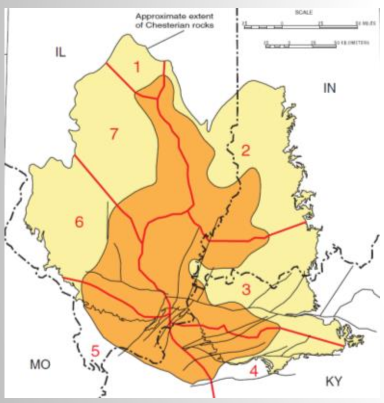
- Result of Mother Nature's Waterflood
  - Brownfield: Has MPZ
  - Greenfield: No MPZ
- Same characteristics as swept portions of a mature waterflood
- Permian Basin examples
  - 15% to 35% S_o
  - 10% to 20% can be recovered by CO_2-EOR
  - Scale and saturations could be quite different in the Illinois Basin

Ideal water saturation profile

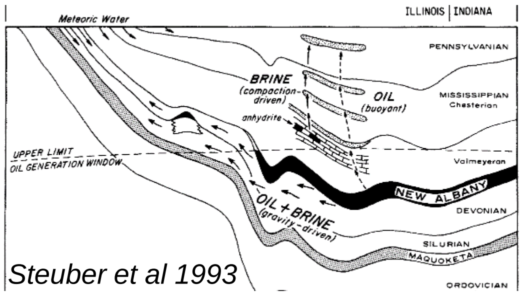


How does an ROZ Form?

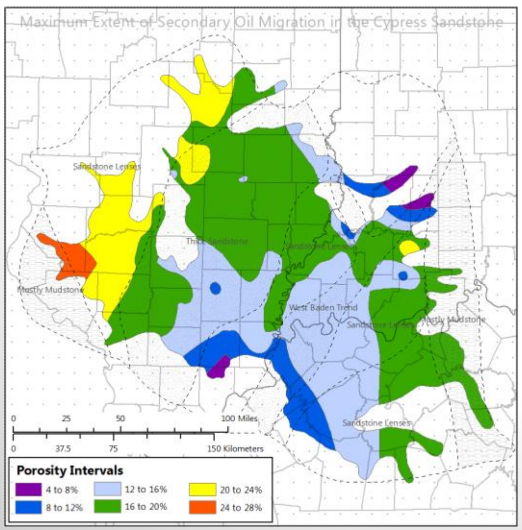
- ROZs form through successive oil migration in the subsurface



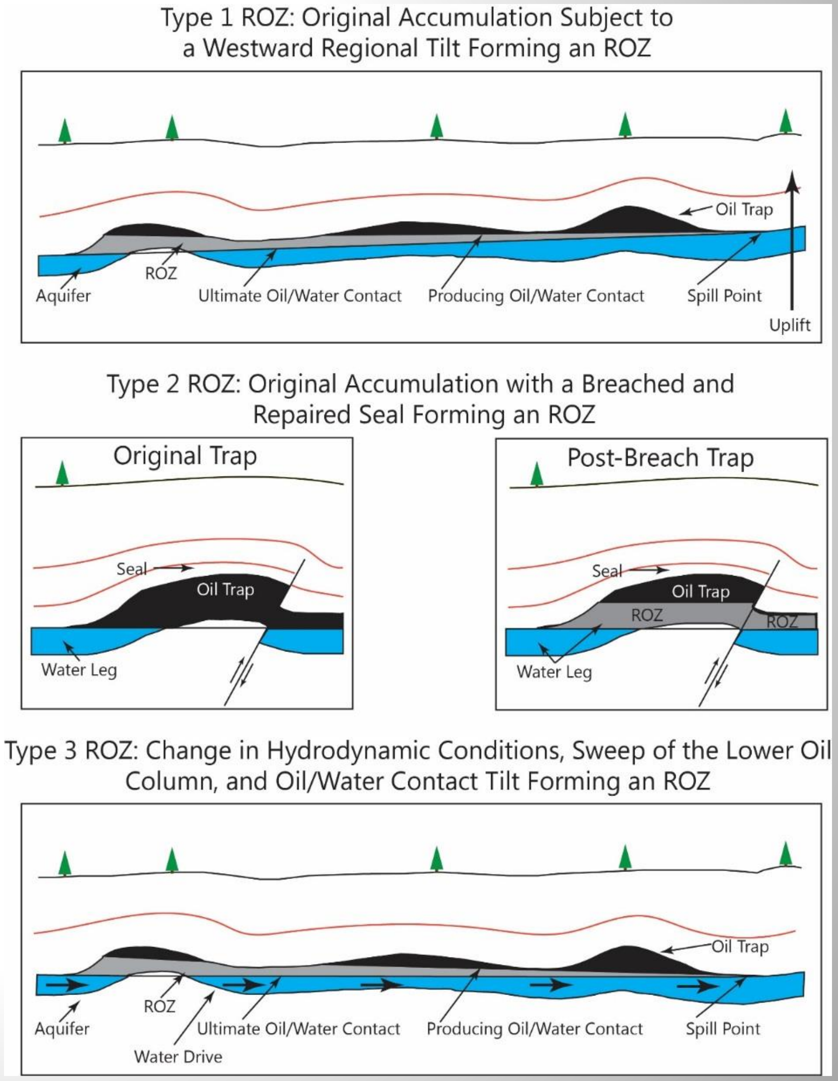
- Secondary migration from mature source
  - driven by buoyancy and hydrodynamic flow
  - followed catchments
  - emplaced in the Cypress Ss over much of the basin



Steuber et al 1993



Modified from Lewan et al. 2002



How do we identify an ROZ?

Geophysical logs
- Well log analysis of existing logs
- New cased hole pulsed neutron logs (*Planned for 2017*)

Cores
- Testing for oil saturation in existing cores
- Evidence of petroleum trapped in mineral cements
- Quantifying oil saturation in fresh core (*Planned for 2017*)

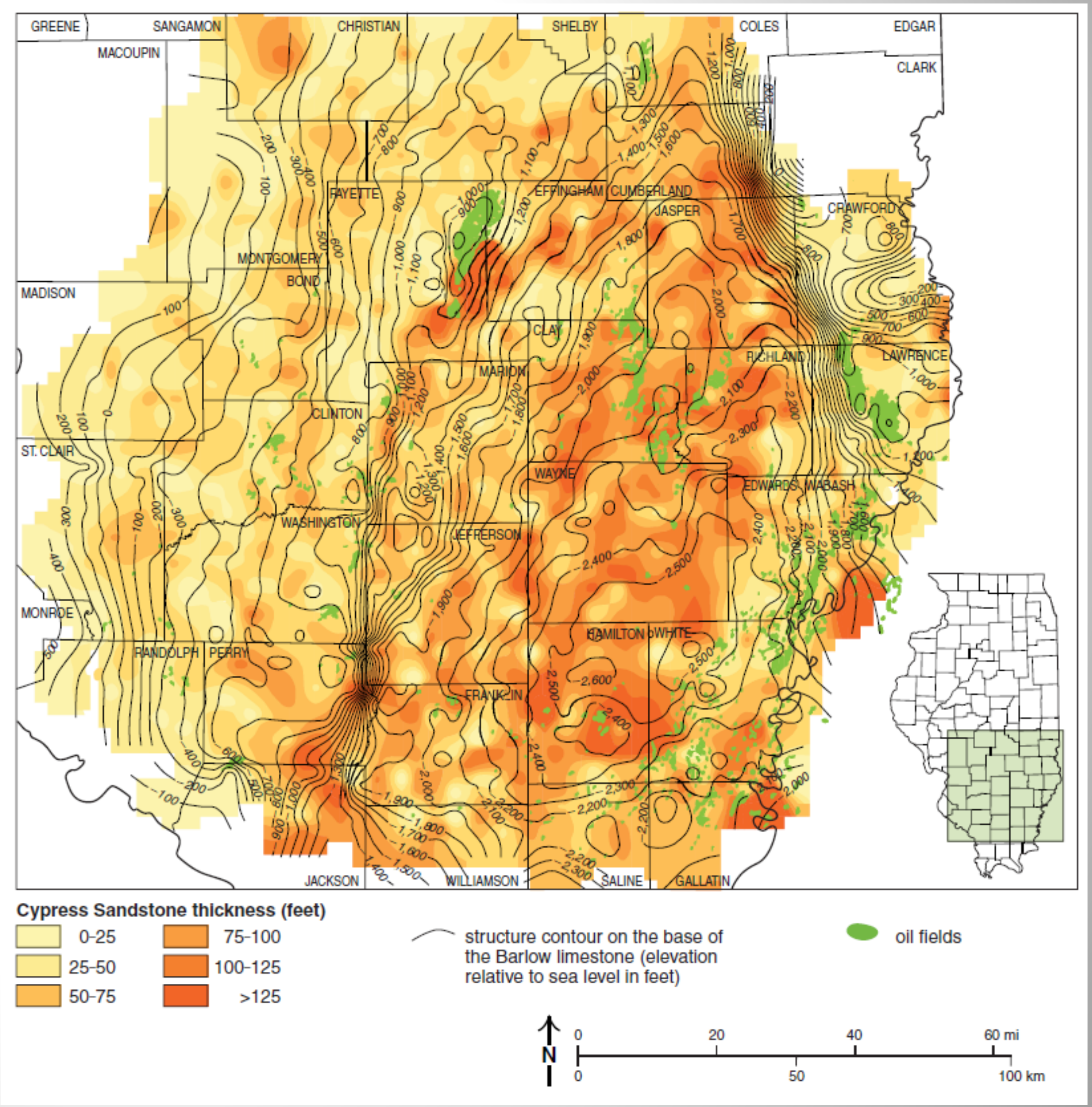
Mapping
- Evidence of tilted oil-water contacts that may reflects tectonic or hydrodynamic changes

Geochemistry
- Evidence of biodegraded oils (*Planned for 2017*)
  - Decrease in API Gravity and n-alkanes
  - Sterane and hopane biomarkers absent

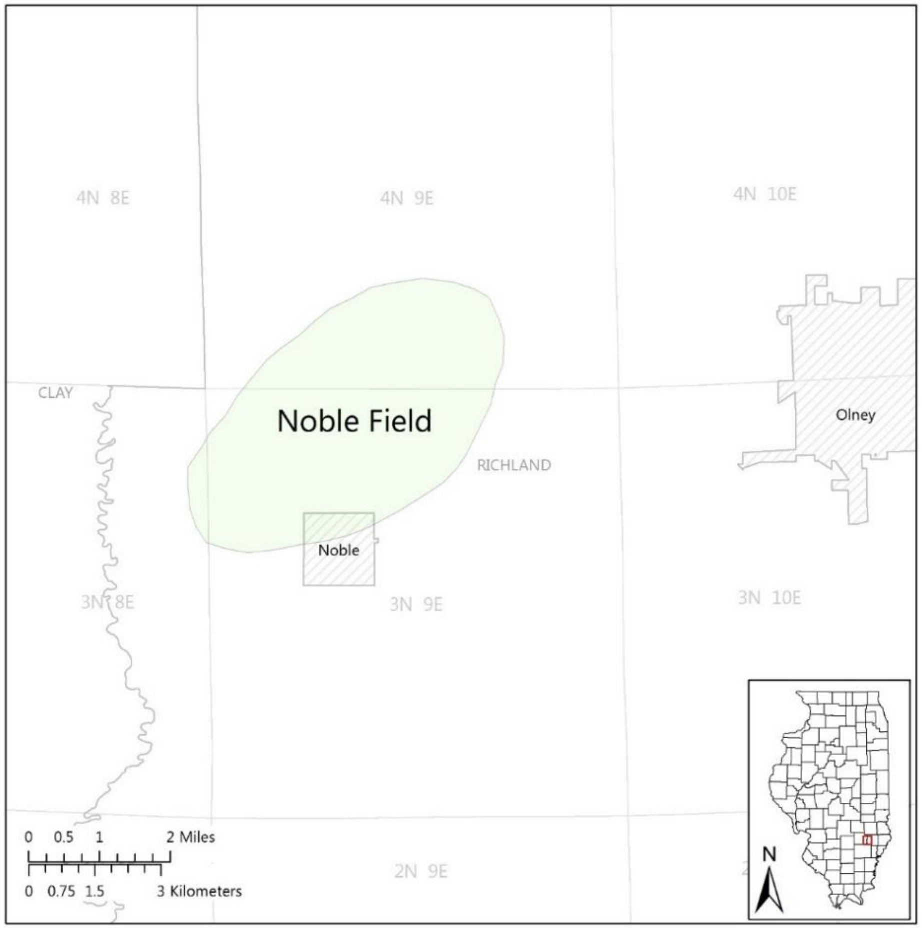
Geologic Characterization

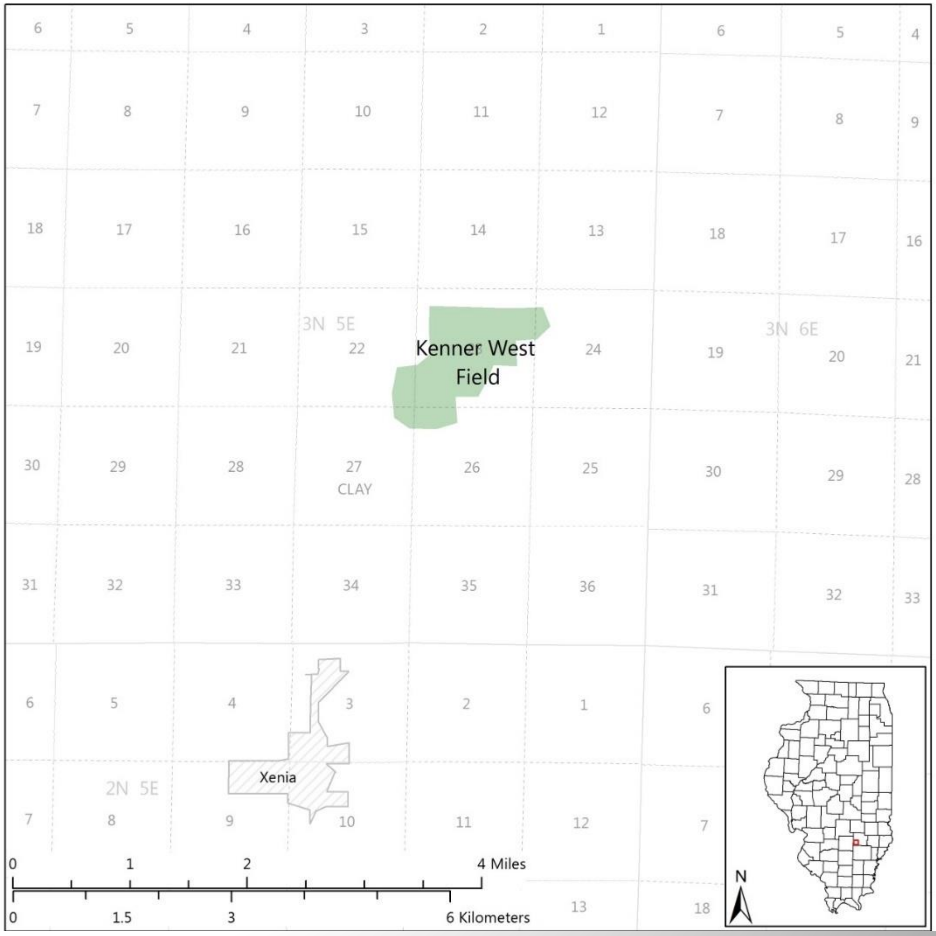
Geologic Characterization

- Oil field studies
  - **Noble Field**
  - **Kenner West Field**
  - Loudon Field
  - Dale Field
- Regional studies
  - Core
  - Outcrop



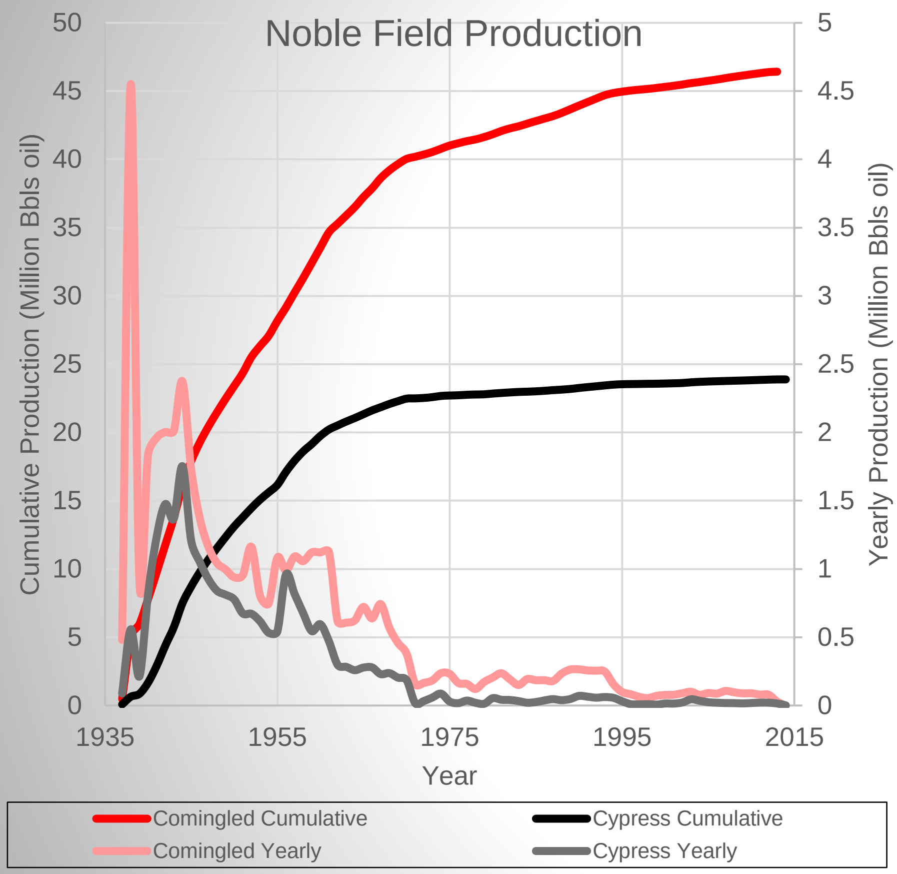
Case Studies: Noble and Kenner West Fields

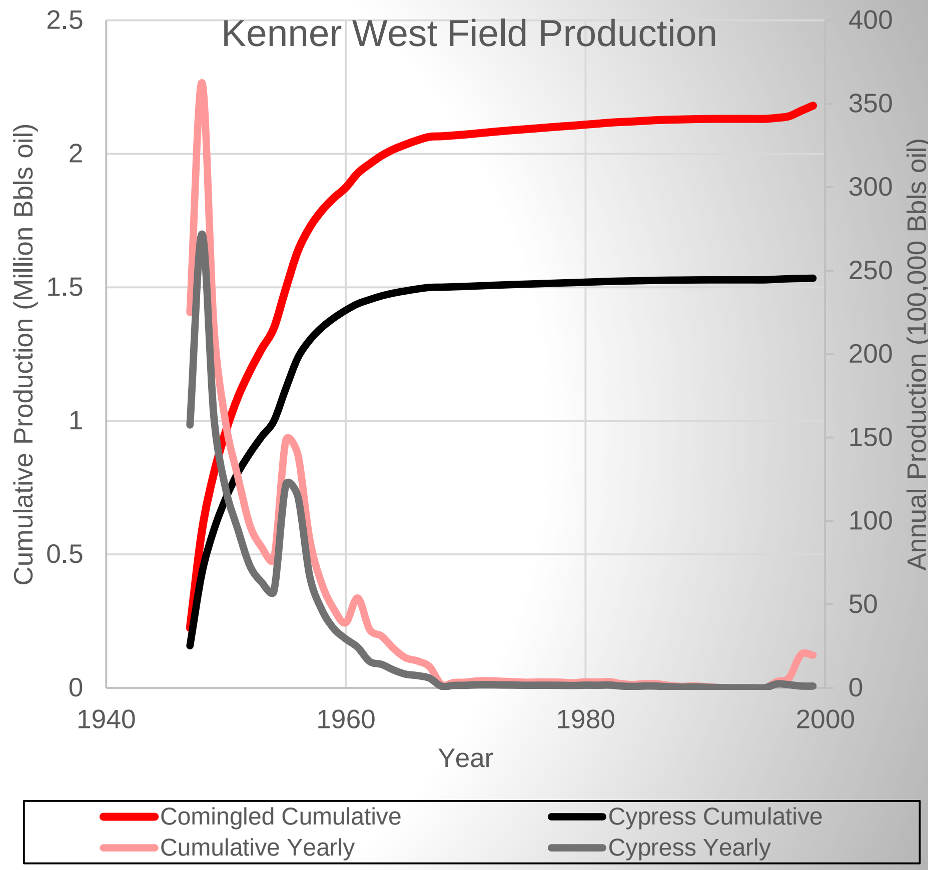




- Oil fields with documented production from the thick Cypress Sandstone
- Abundant core and log data available for detailed characterization

Case Studies: Noble and Kenner West Fields





- Cypress Production = 24 MMBO
- OOIP = 95 to 110 MMBO
- Recovery Efficiency = ~25%

- Cypress Production = 1.3 MMBO
- OOIP = 7.8 to 10 MMBO
- Recovery Efficiency = ~15%

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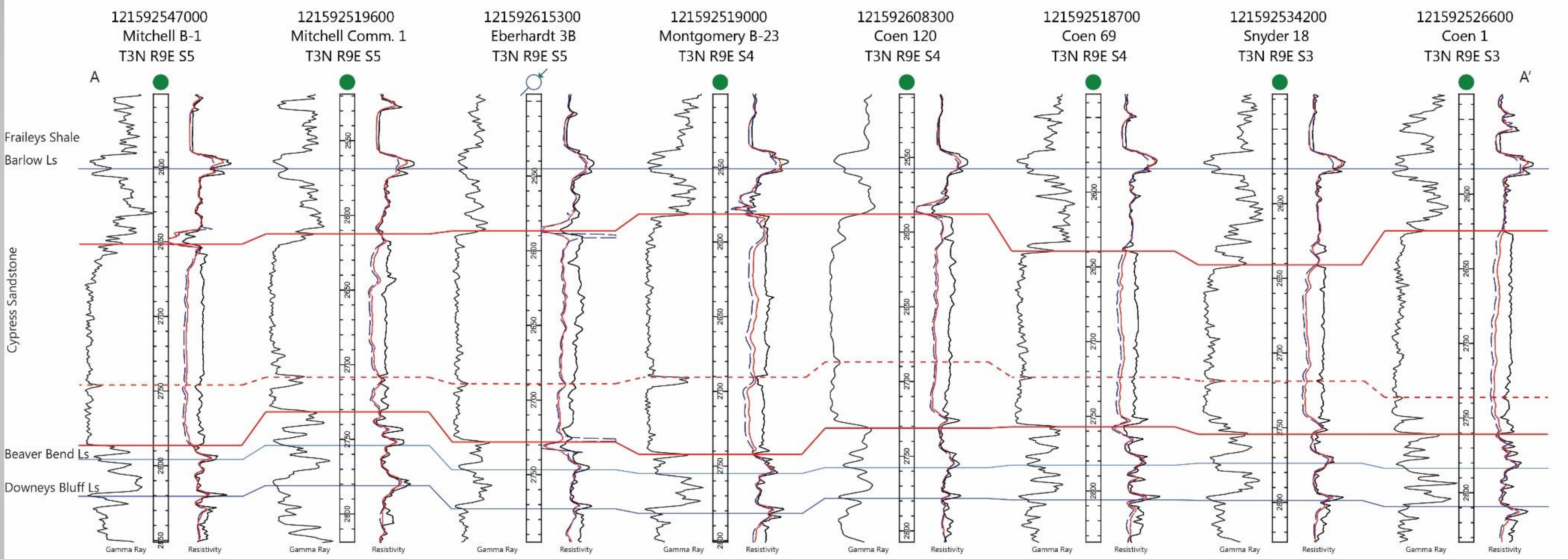
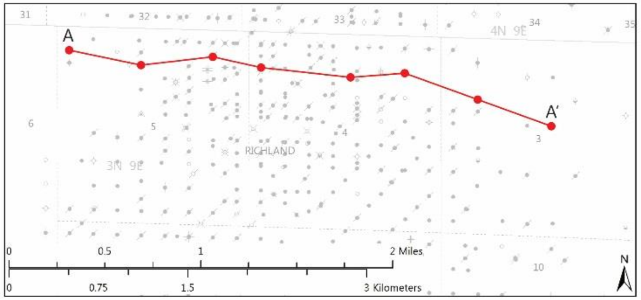
Noble Correlations

Example Noble Field Cross Section





- Correlated nearly 1,000 logs to map geometry of thick Cypress Sandstone
- Stacked sandstone bodies
  - Lower "sheet" sandstone extends out of field
  - Upper sandstone bodies change facies laterally

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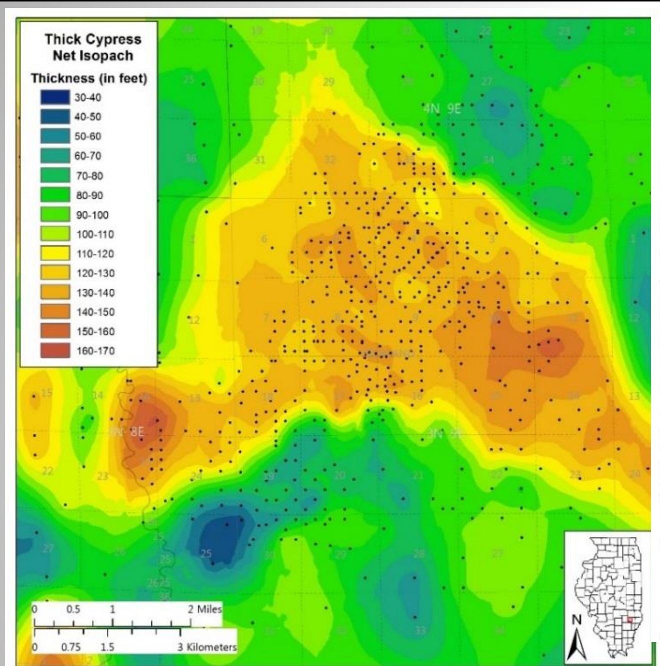
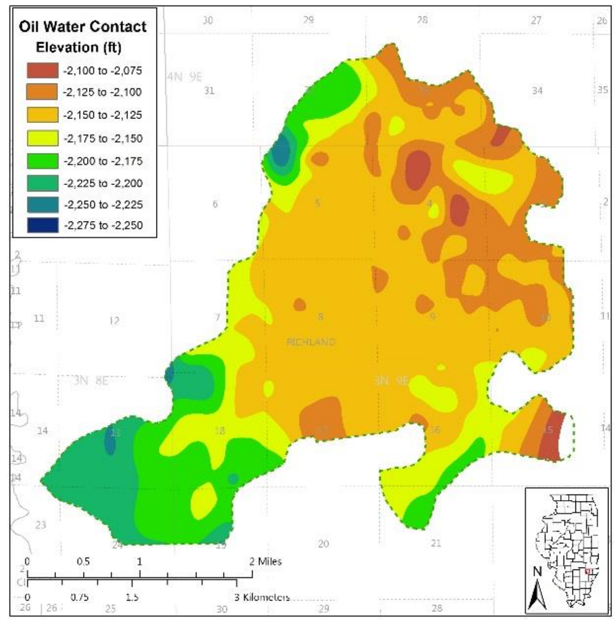
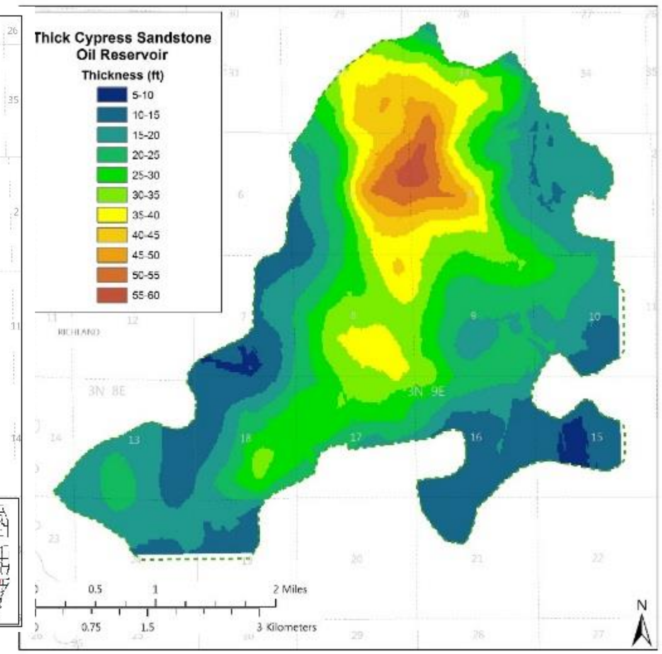
Noble Maps



Cypress net sandstone isopach map



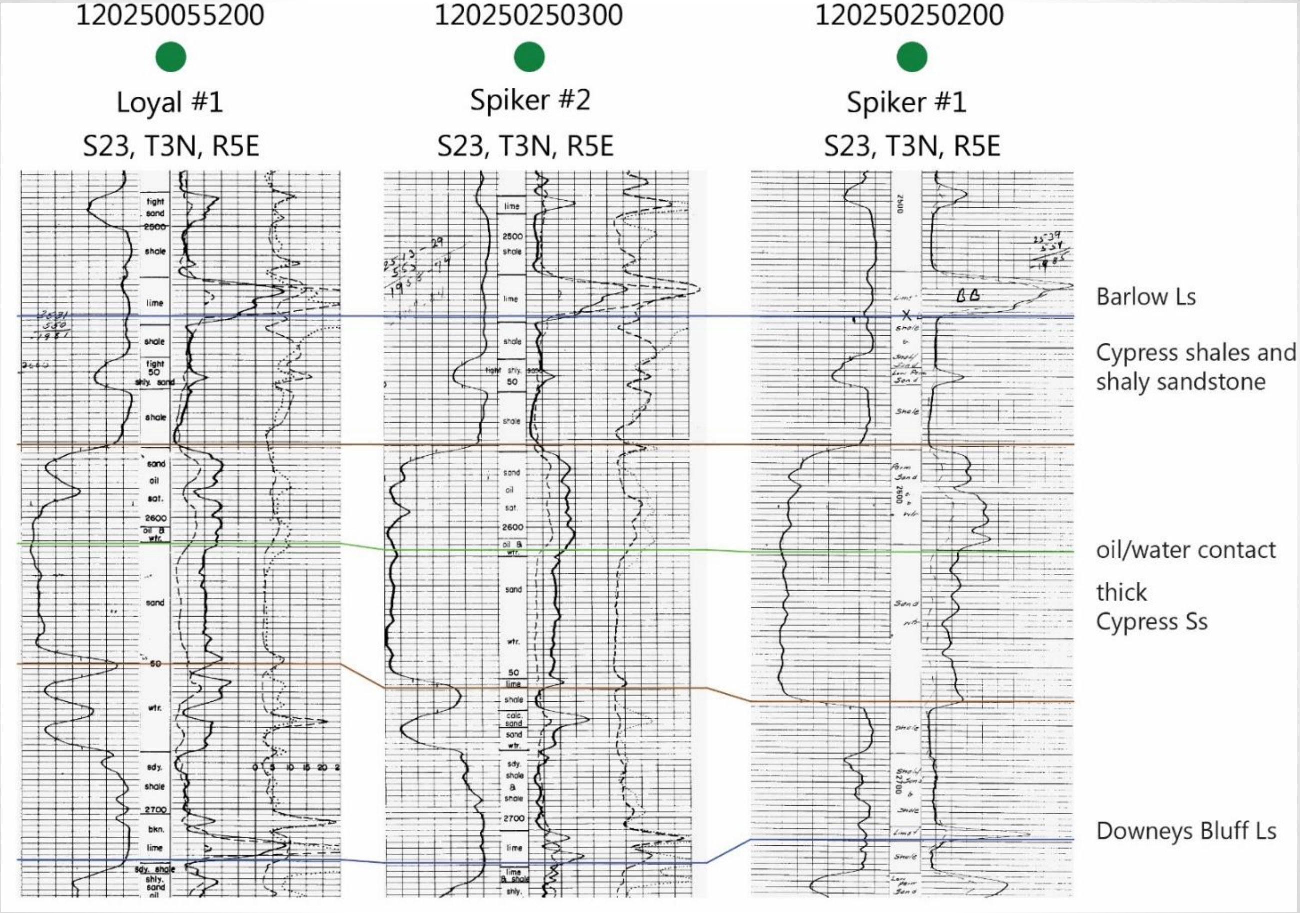
OWC structure map



Oil reservoir isopach map

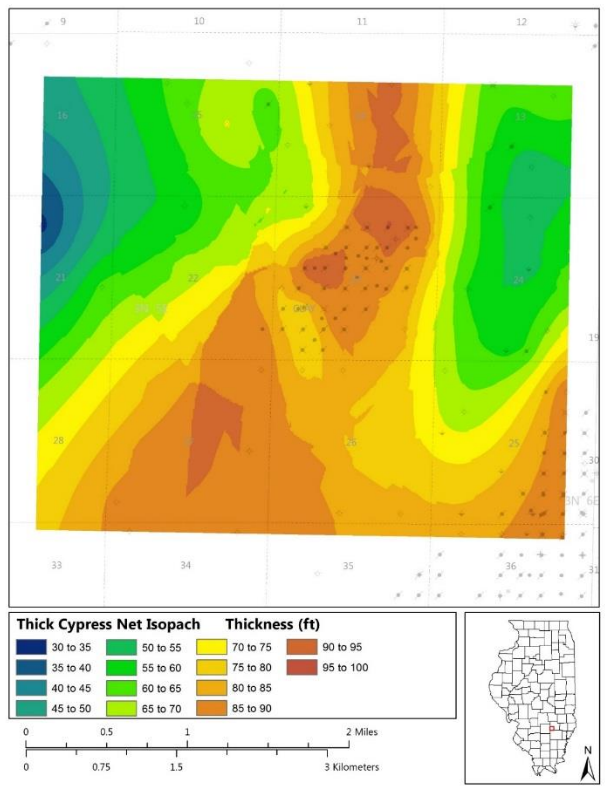
- Up to 170 ft thick sandstone intersects Clay City Anticline
- Tilted OWC with down dip oil saturation to the SW; Paleo-OWC related calcite cement?
- MPZ up to 55 ft thick; 110 ft closure

Kenner West Correlations

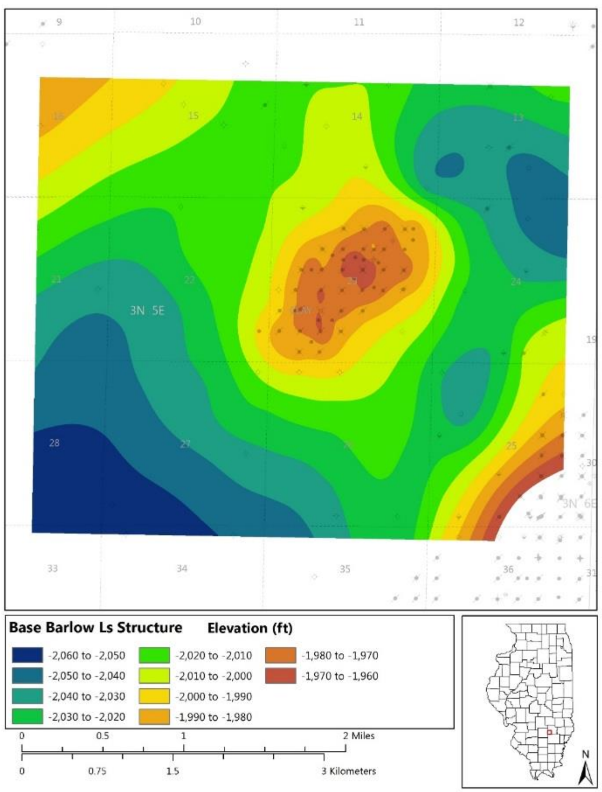


- Similar to Noble Field, but better developed "upper" Cypress Ss lenses

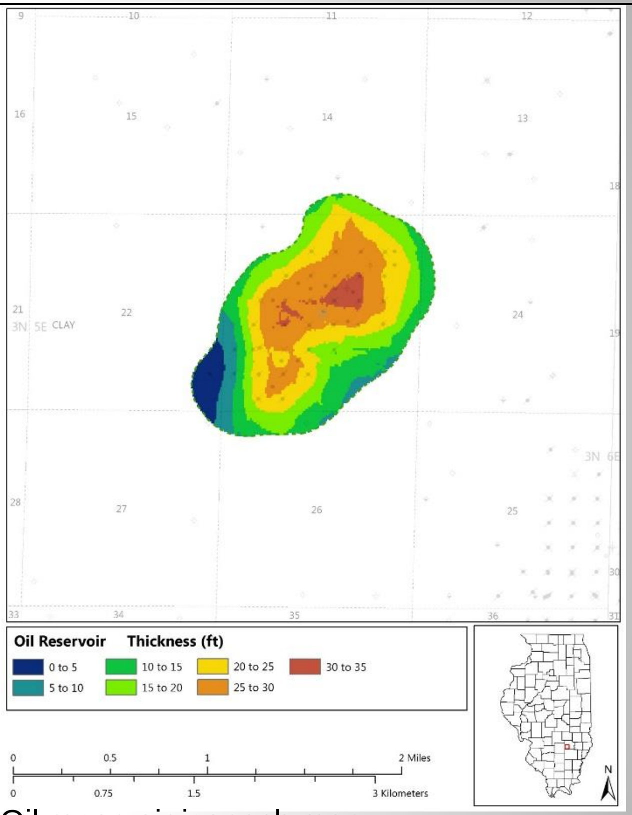
Kenner West Maps



Cypress net sandstone isopach map



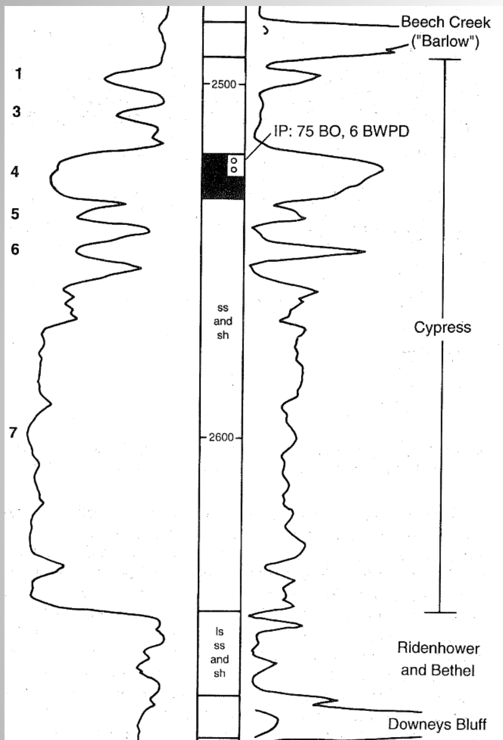
Base of Barlow Ls structure map



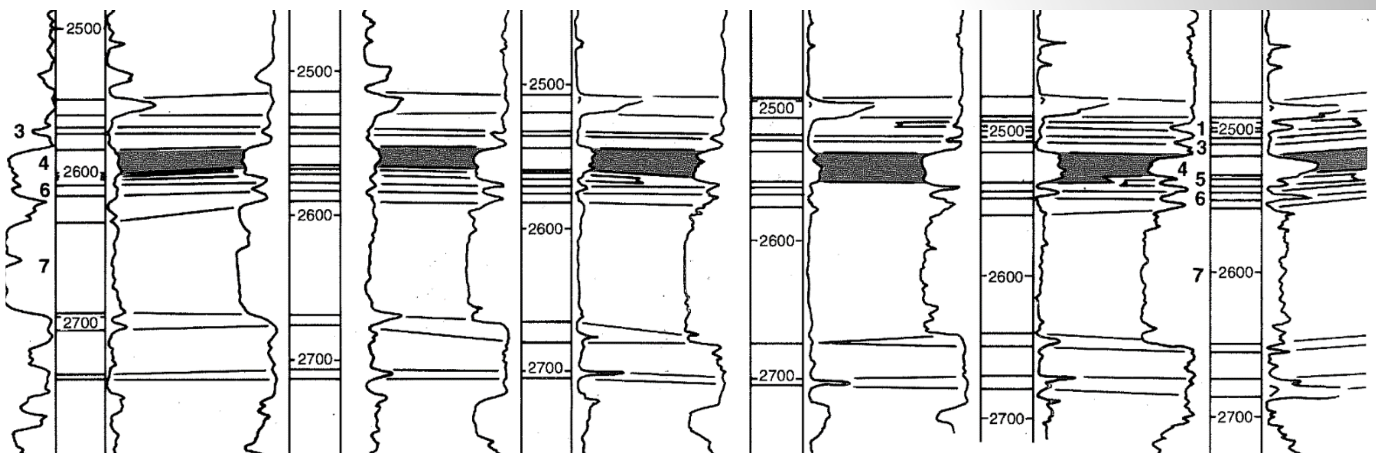
Oil reservoir isopach map

- 1 mile-wide N-S sandstone trend intersects small dome forming structural-stratigraphic trap
- Sandstone up to 100 ft thick; MPZ up to 35 ft thick; 40 ft closure
- OWC tilts slightly to the southeast

Comparison with Xenia East Field



- No thick Cypress Ss oil production from Xenia East, 4 mi south of KW



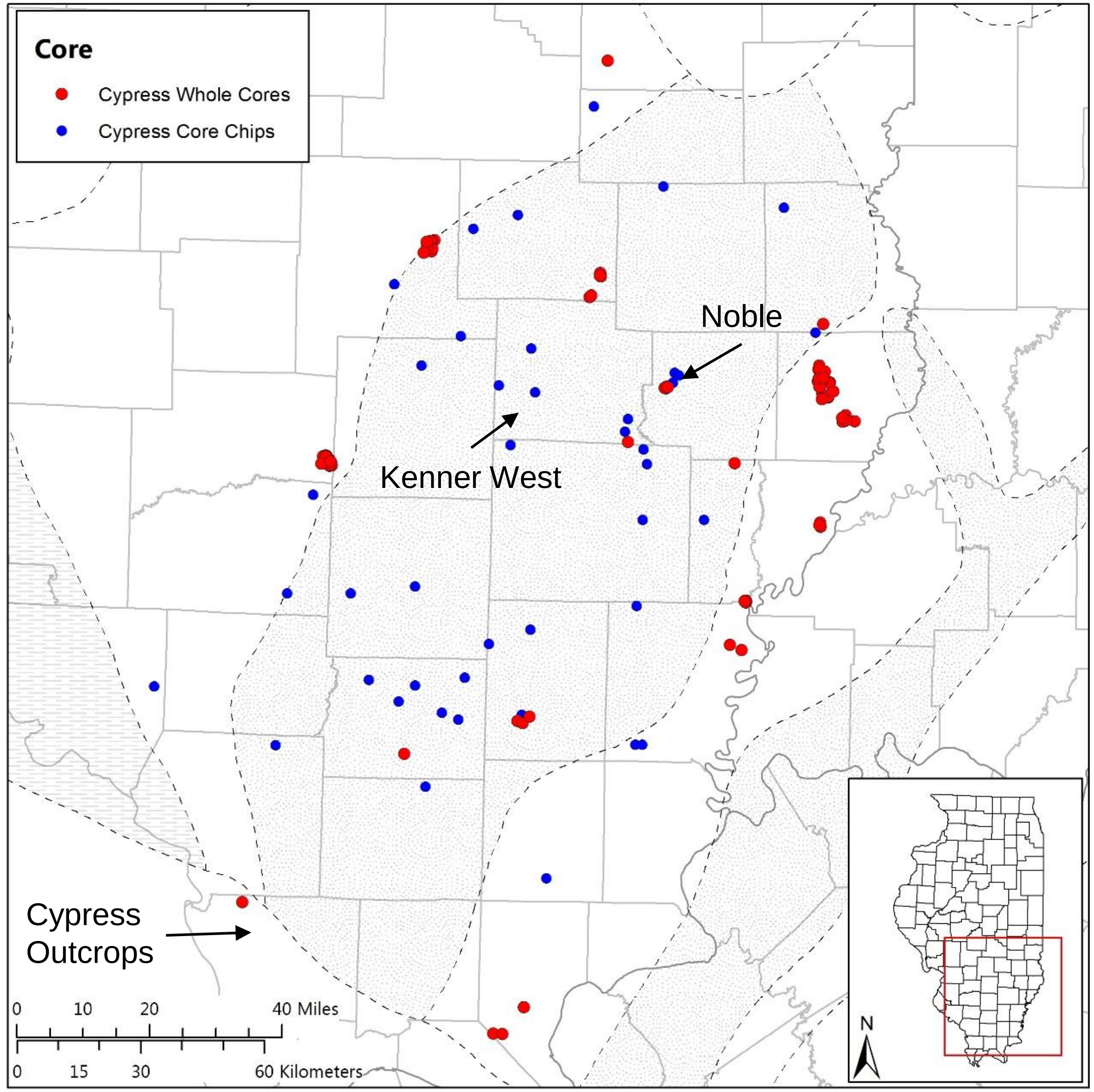
Xu and Huff 1995

- Structural closure plays a role in oil emplacement, but so does geology of the Cypress
  - Are there areas where thick Cypress Ss is oil productive when there are "upper" Cypress Ss lenses?
  - Cypress shales are leaky seals?

Core Study

How do we interpret the geology and understand the geologic controls on reservoir properties? Rocks!

- Noble Field
  - Whole core of upper 30-40 ft in two wells
  - Chips/partial core from a handful of old wells
- Kenner West Field
  - No cores, but lots of core analysis data



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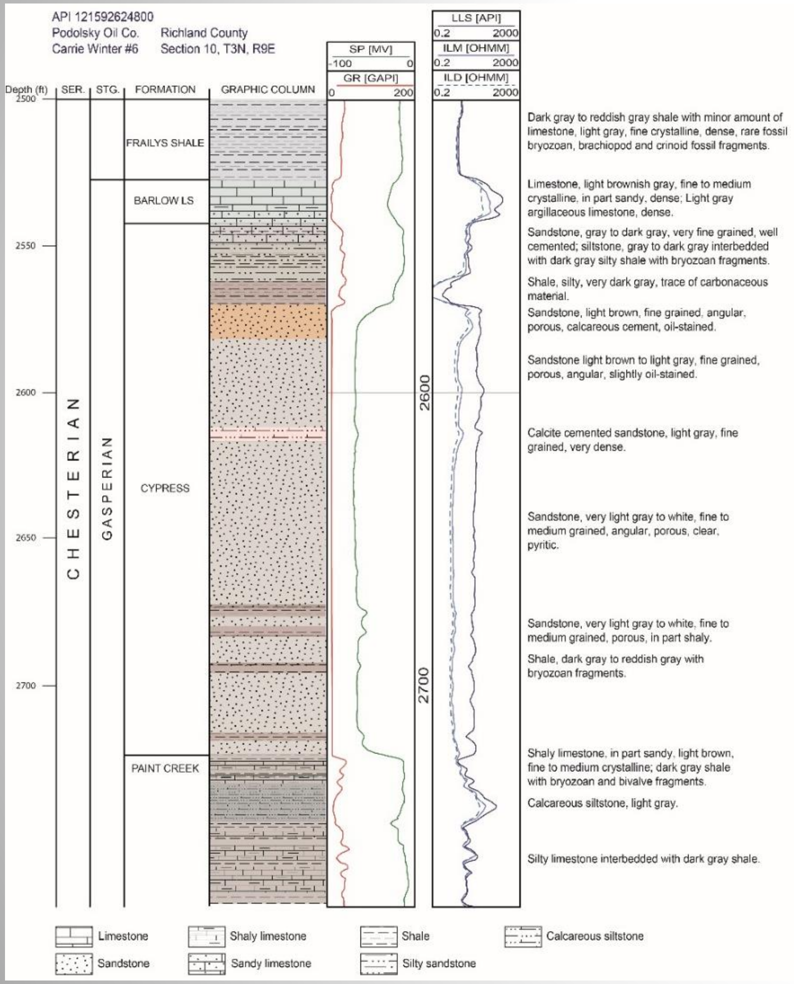
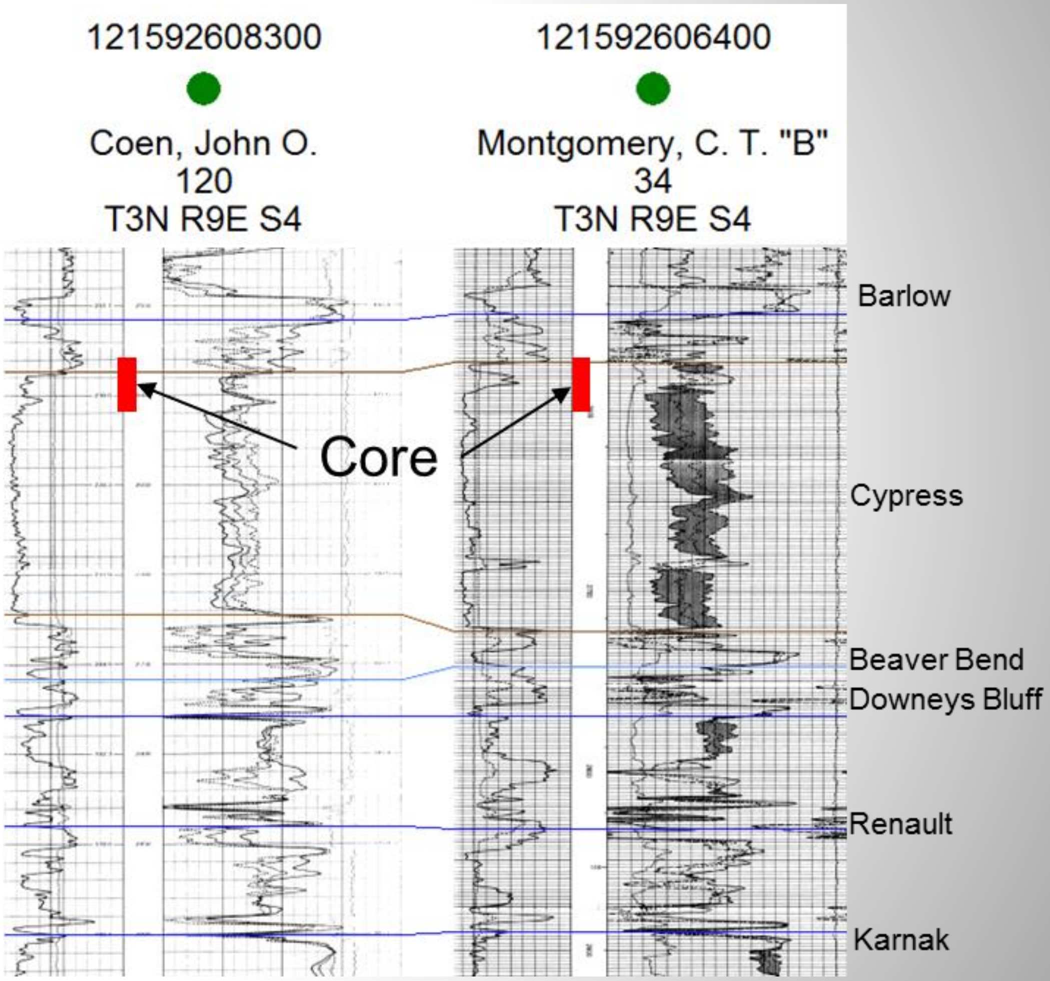
Samples and Core

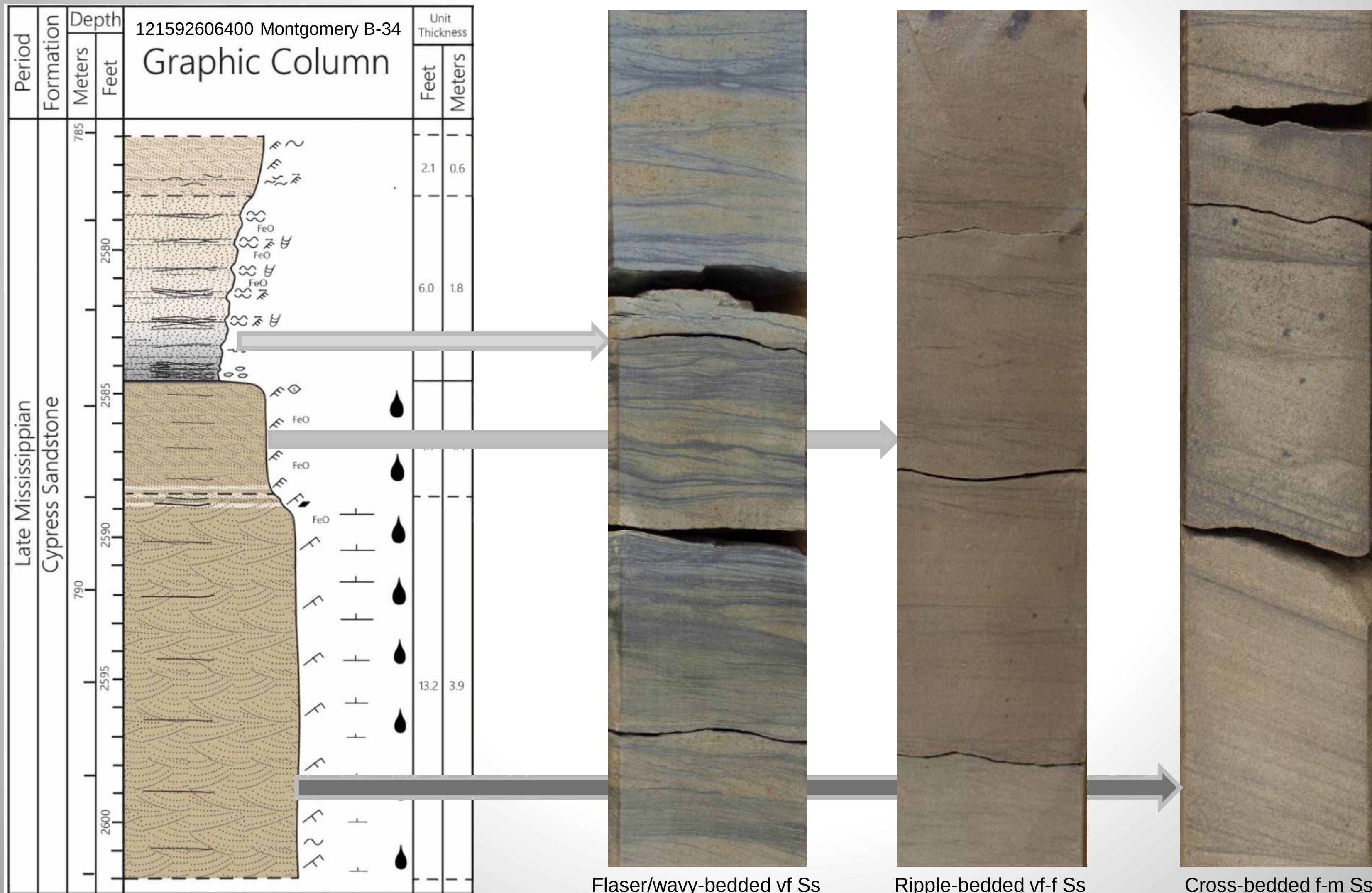




Samples can reveal general lithology and texture and provide material to test for oil saturation

Cores allow detailed sedimentological study but are usually limited to the MPZ

Sedimentology



Decreasing depositional energy

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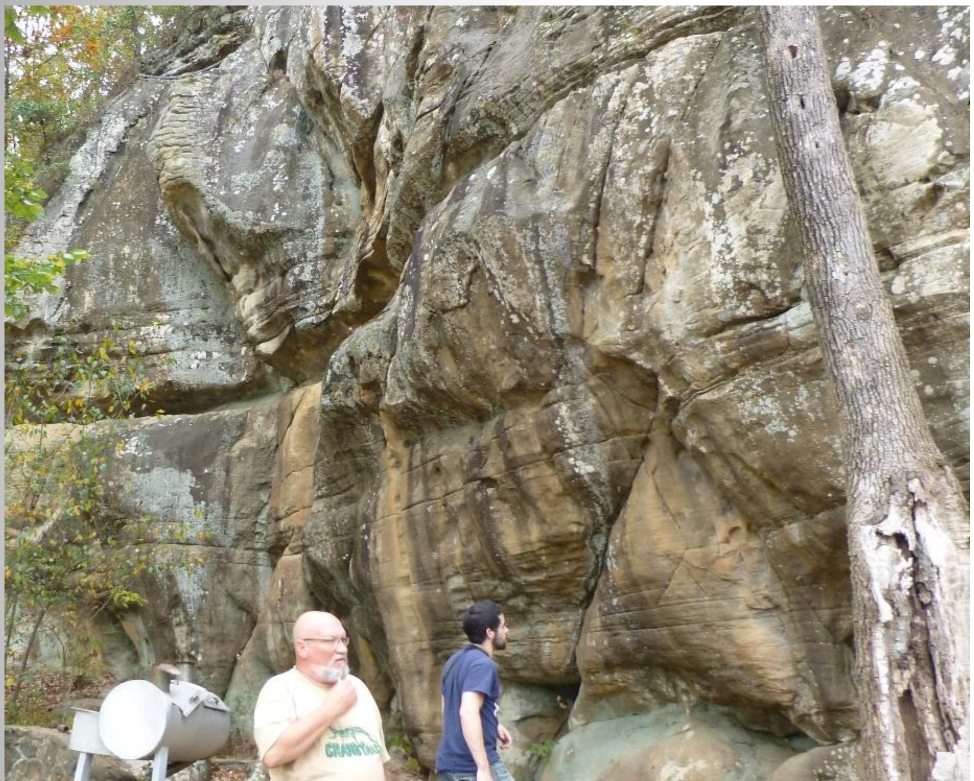
Integrating Core/Outcrop Studies



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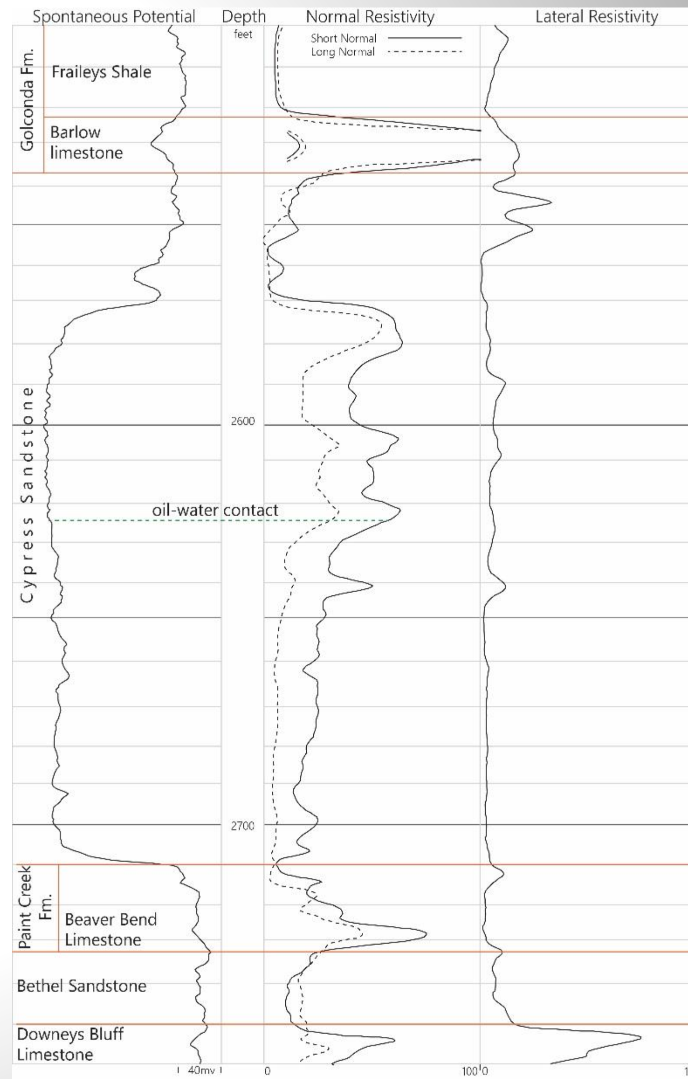
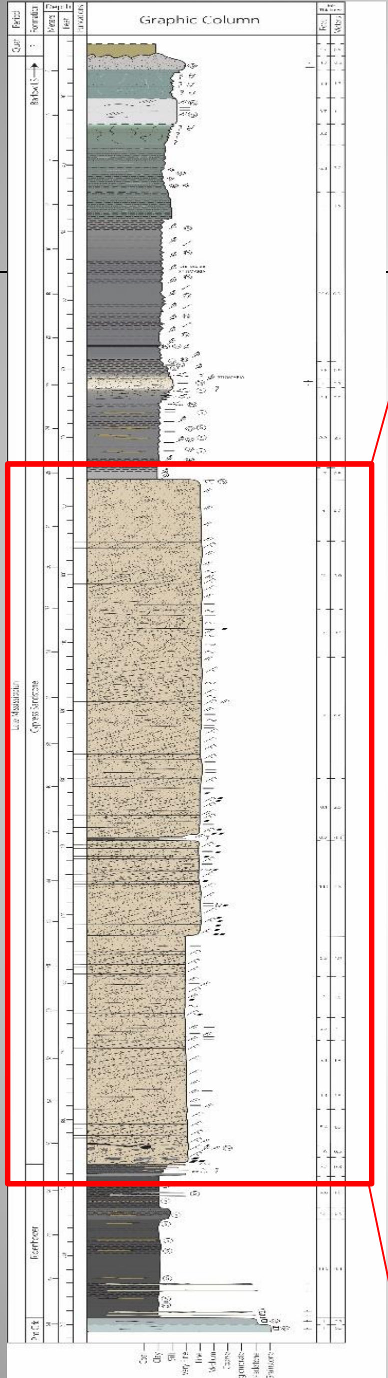


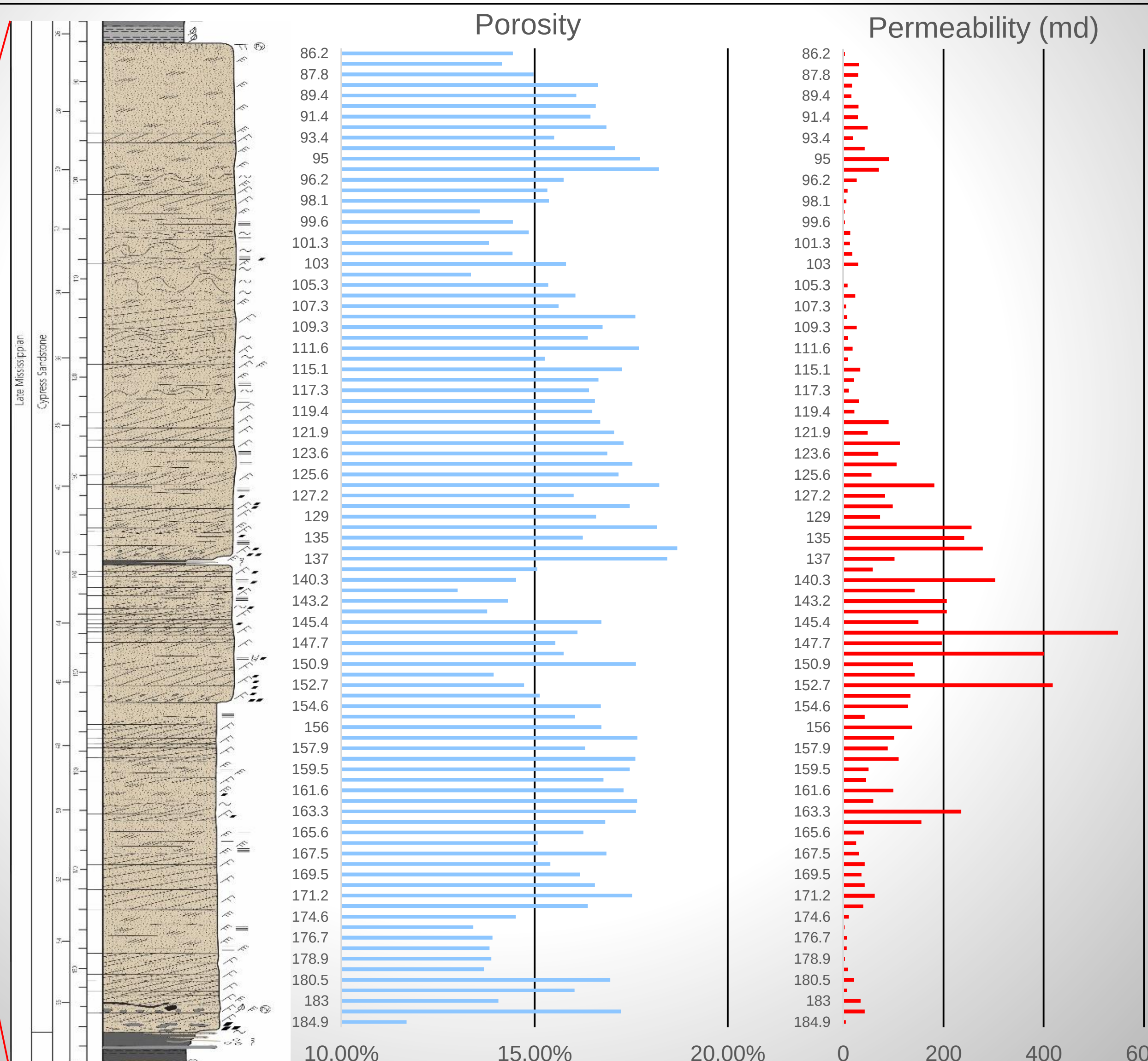
- Can we build on core studies by leveraging outcrops to better understand internal reservoir architecture of the Cypress?

Tripp #1 Core

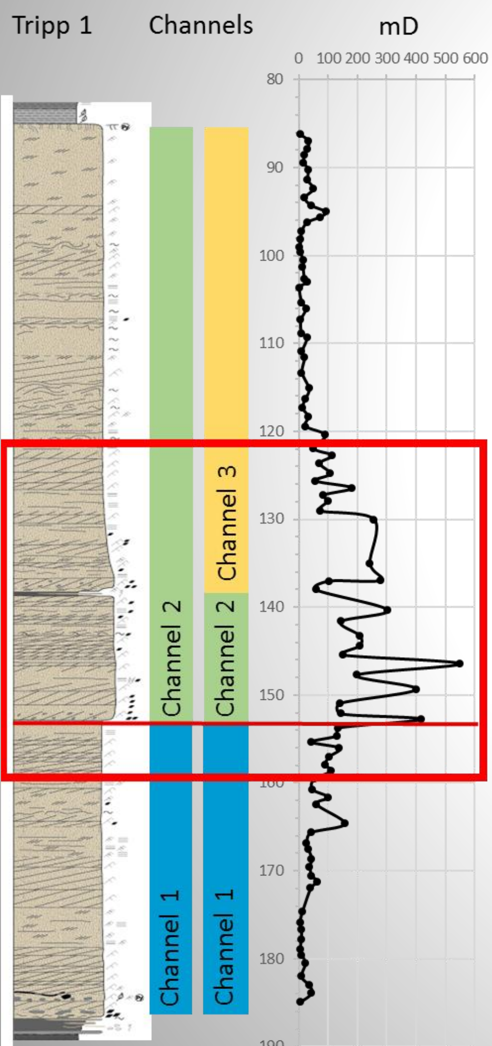
- Drilled Sept 2016 in Union Co., IL
- Southern end of valley fill Cypress fairway
- 259 ft TD
  - 160 ft Cypress Fm
    - 100 ft thick Ss
- Near I-57 roadcut and Cypress Creek outcrops

Tripp #1 Properties

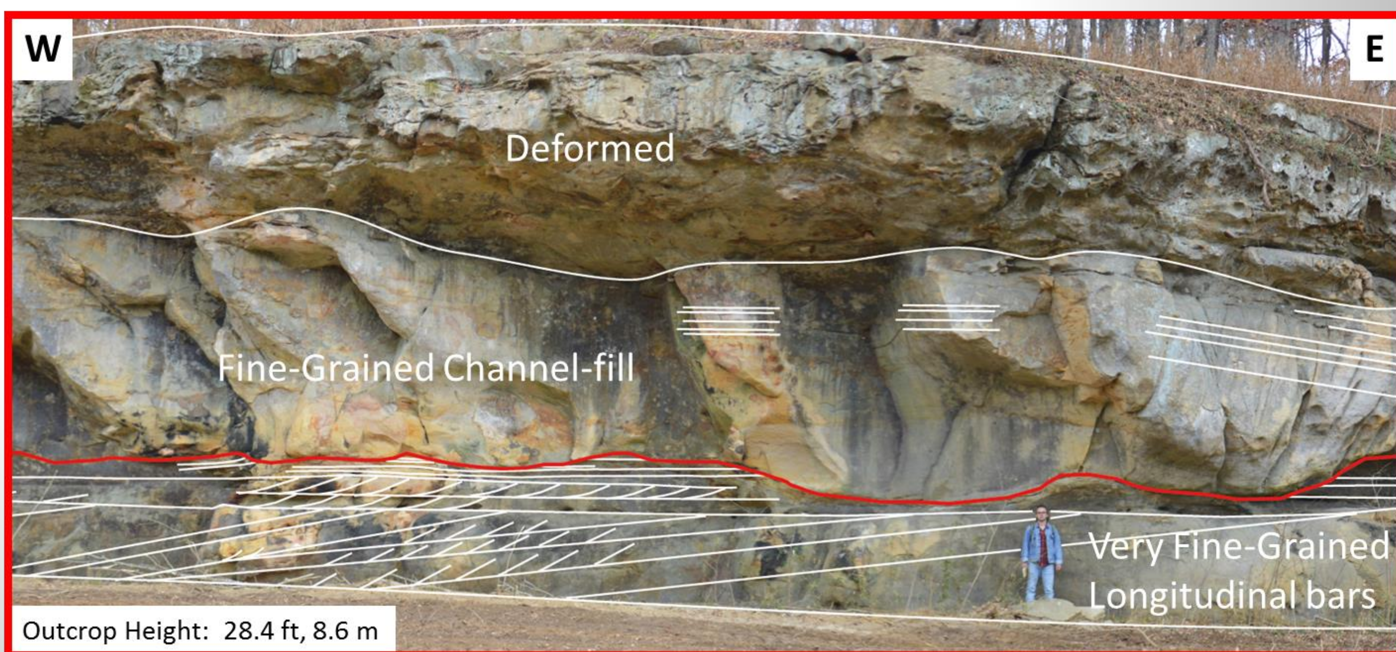




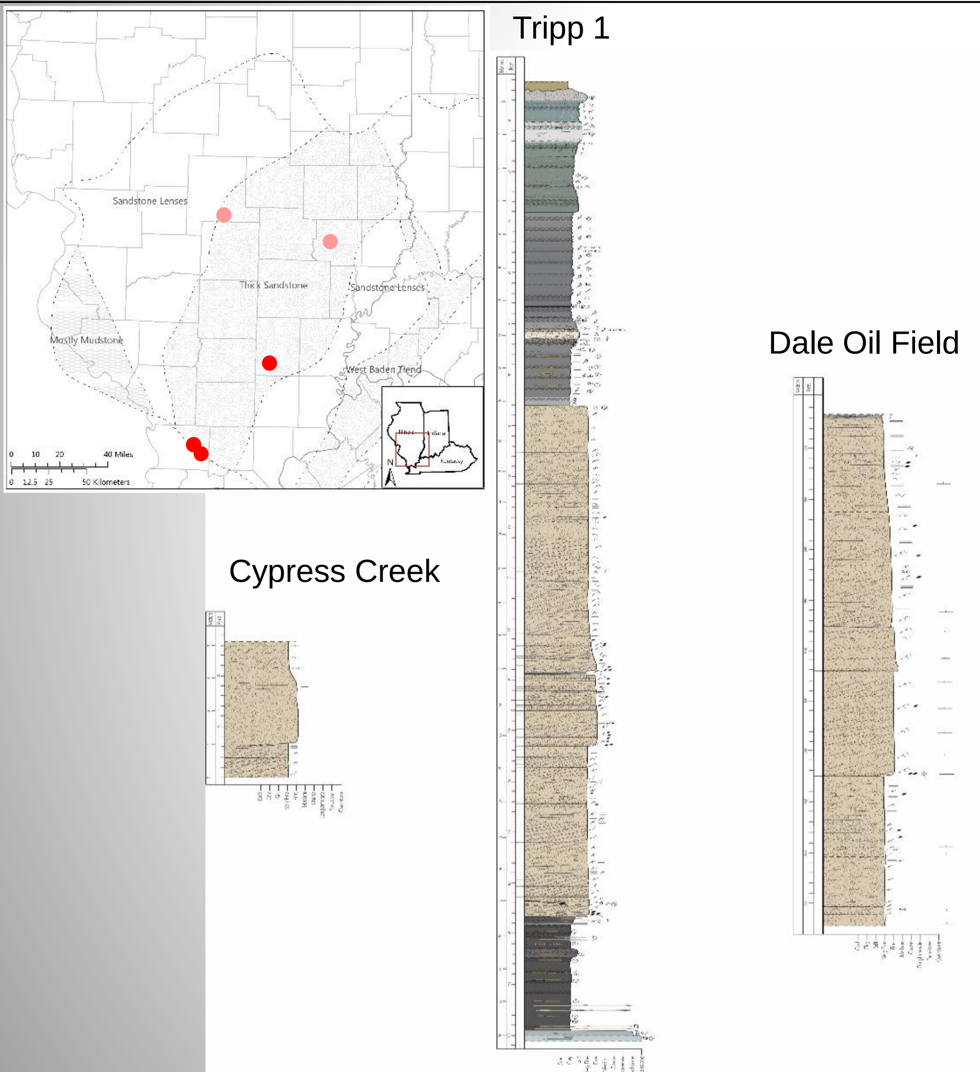
Relating Core to Outcrop



- Multistory fluvial channels
  - Channels likely form flow units within a reservoir
- Stacked sandstone channels are not a continuous genetic body
  - Grain size increase, basal lags, and juxtaposing lithofacies



Parallels to Basin Interior



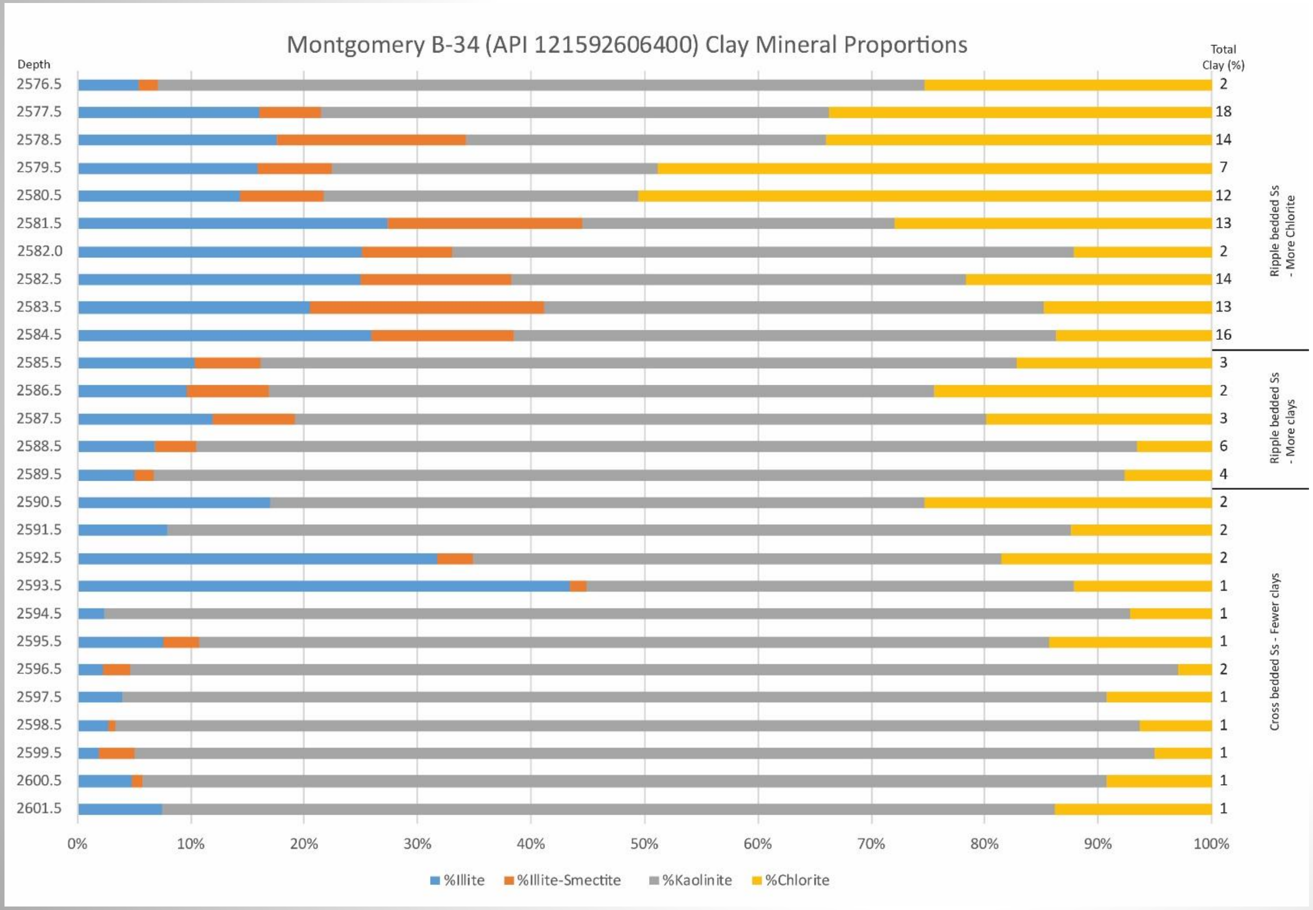
- Similar sedimentology to oilfield cores
  - Dominantly vf-f cross bedded and ripple bedded sandstone with coarser sand in channel bases
- Channel bases hard or impossible to identify on well logs, but permeability is likely a better proxy
- Next: Correlation with existing core in Loudon Field and an upcoming core from Noble Field

Controls on Porosity/Permeability

- Depositional environment and diagenetic history control reservoir properties
  - Porosity and permeability vary amongst fields in the Illinois Basin
    - Minor variations in depositional environment?
    - Different diagenetic histories in different areas of the basin?

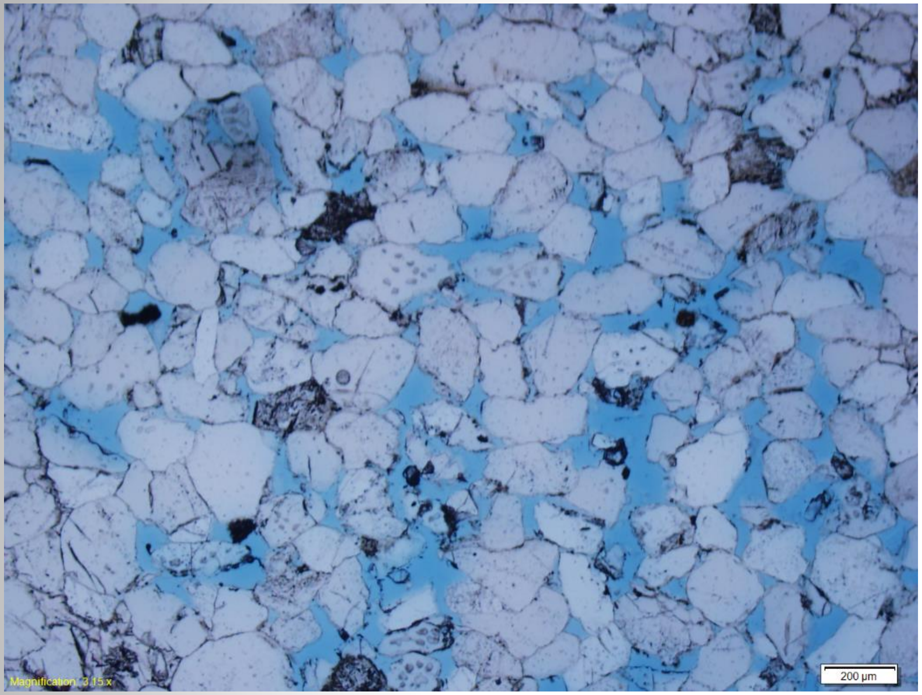
Field	Location	Depth to Cypress, ft (m)	Typical porosity, %	Typical permeability, mD (μm^2)
Loudon	Eastern Fayette County	1,600 (487.7)	19.2	80.9 (0.080)
Noble	Western Richland County	2,600 (792.5)	18.0	482.0 (0.476)
Kenner West	Southwestern Clay County	2,600 (792.5)	18.0	106.0 (0.105)
Dale	Southern Hamilton County	2,900 (883.9)	13.5	62.5 (0.062)

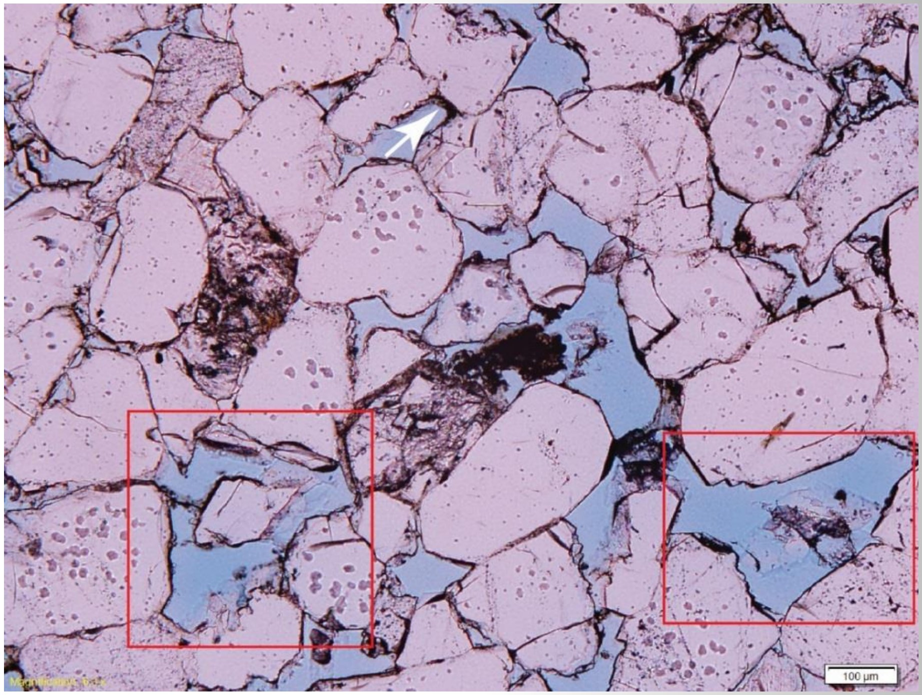
Controls on Porosity/Permeability



- Analyzed XRD results for bulk and clay mineralogy
- Related mineralogical composition to facies and porosity / permeability

Controls on Porosity/Permeability

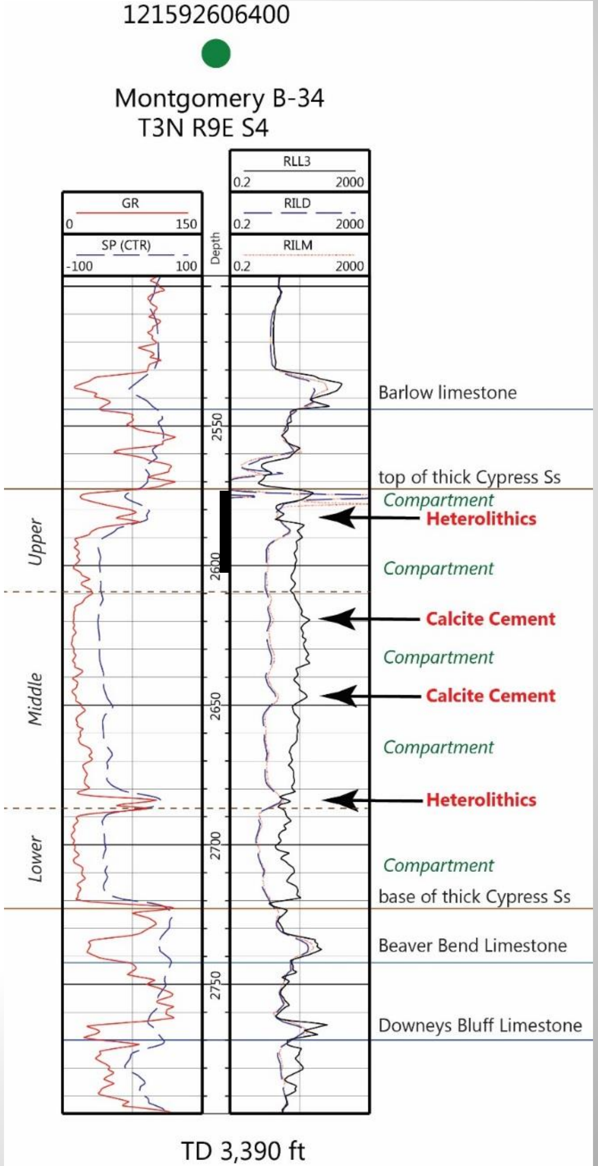




- Hybrid pore system of primary intergranular and secondary porosity from dissolution of grains and cements
- Long, well-connected pores contribute to the exceedingly high permeability observed in Noble Field

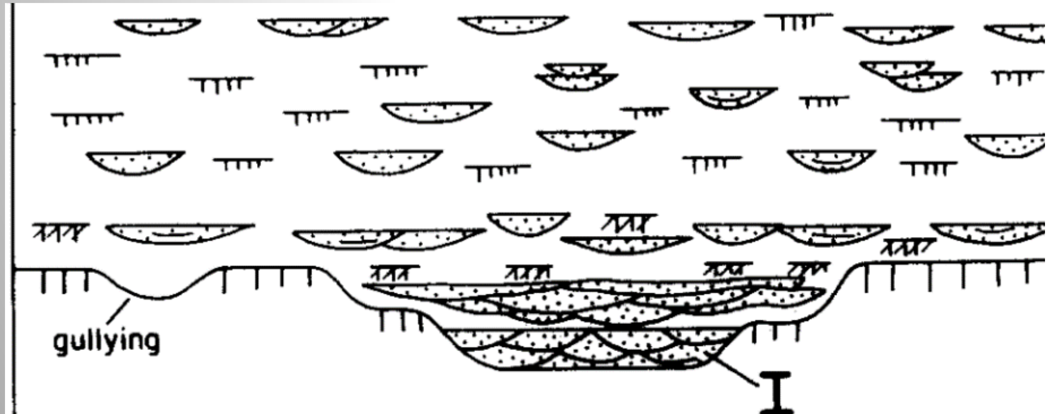
Reservoir Architecture

- Compartmentalization despite being relatively homogeneous
  - Grain size variation relating to channel stacking
  - Minor thin shale interbeds and heterolithic intervals within the sandstone body
    - Some can be laterally extensive
  - Calcite cements
    - Some concurrent with and others unrelated to OWC

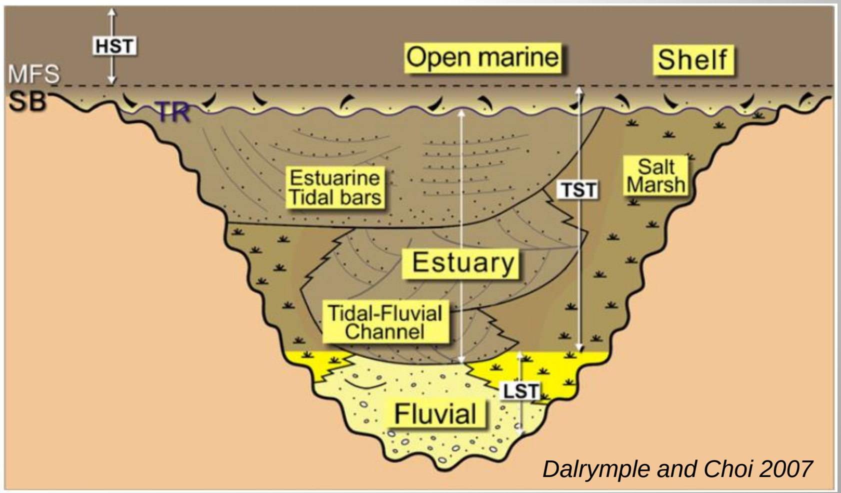


Depositional Environments

- Interpreted the Cypress Sandstone at Noble Field as part of an incised valley fill system (LST-TST)
  - Erosional base, multistory sandstone, overall fining upward (f-vf)
  - Becomes estuarine at the top (lower energy, more clays, lower reservoir quality)
  - Distinct environment from Cypress Ss tidal shoals

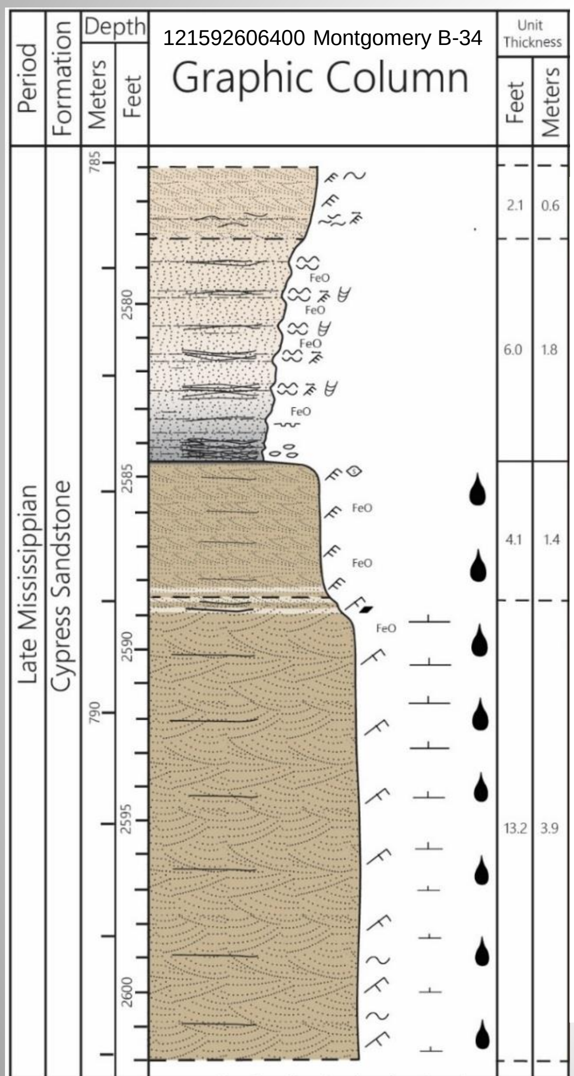


Wright and Marriott 1993

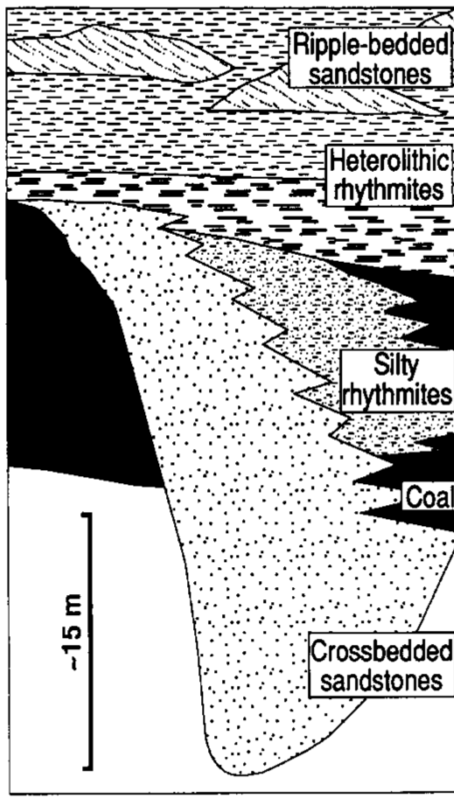


Dalrymple and Choi 2007

Depositional Environments



Summary of major facies and attributes for Carboniferous valley-fill sequence



Facies	Physical attributes	Biological attributes
Ripple-bedded sandstones	Flaggy, internally ripple bedded, 5 to 50-cm thick, discontinuous clay drapes,current and wave ripples, planated ripples, runzel marks	Fragmentary, abraded stems and wood, *Scolicia, Lockeia, Rhizocorallium, Rusophycus, Cruziana, Eione*
Heterolithic rhythmites	Planar laminae to lenticular, wavy, and flaser bedding, well-developed clay drapes, tidal periodicities, current and wave ripples	Upright trees (2-m tall), well preserved foliage, lowest part nonbioturbated, overlain by vertical-*Lockeia*, overlain by horizontal-*Lockeia* assemblage, upper part bioturb. by *Asterosoma, Teichichnus, Conostichus*
Silty rhythmites	Vertically accreted laminae to thin beds (10 cm) of silt, thin clay drapes, CRL, tidal periodicities, exposure features (raindrops, rills, drain features), current ripples only	Upright lycopods, calamites, pteridosperms (3-m tall), well preserved foliage, cones, *Plangtichnus, Treptichnus, Haplotichnus, Kouphichnium*, fish-fin drag marks, tetrapod trackways
Coal	During drier intervals, restricted to paleo-valley, during wetter intervals, laterally wide-spread, splits common in paleovalley, low-sulfur (1.5%) under rhythmites, high-sulfur (>5%) under bioturbated marine roof	Upright trees only in areas of rhythmite roof, upright ferns project into roof facies in areas of silty-rhythmite roof, carbonate diagenetic features, such as coal balls, only in areas of bioturbated marine roof
Crossbedded sandstones	Medium grained, basal conglomerates, shoestring geometry, 30-m thick, trough crossbedding at base, tabular-planar cross-bedded at top, clay-draped bedforms at top	Logs in basal conglomerates, fragmented plants and leaf-litter on foresets, nonbioturbated, rare *Cochlichnus, Planolites*

Archer et al 1994

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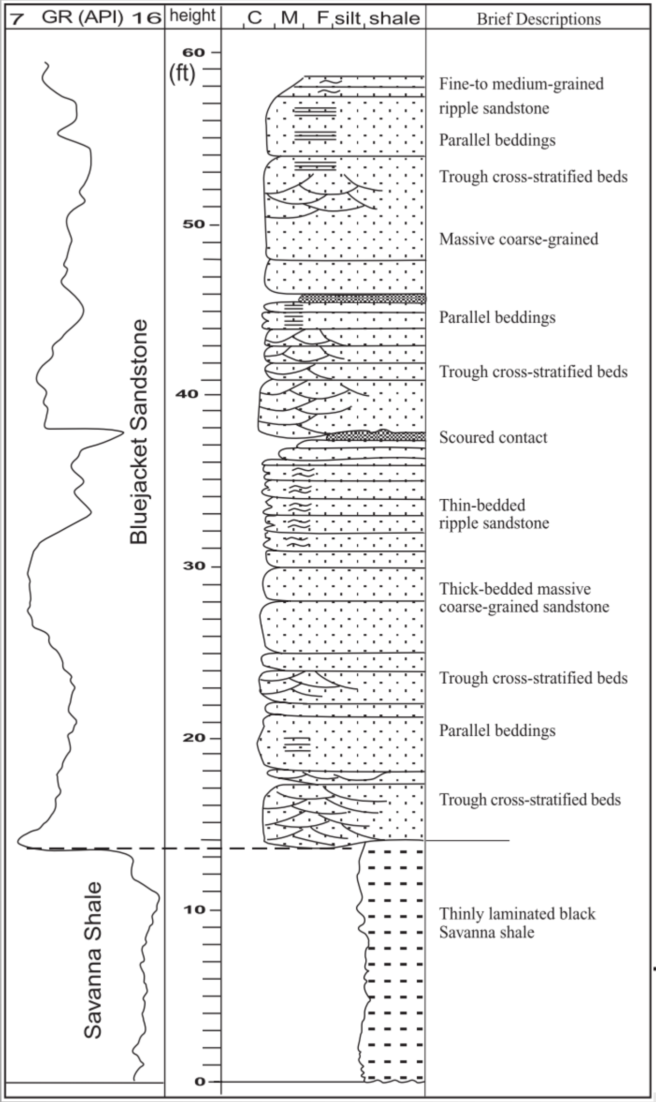
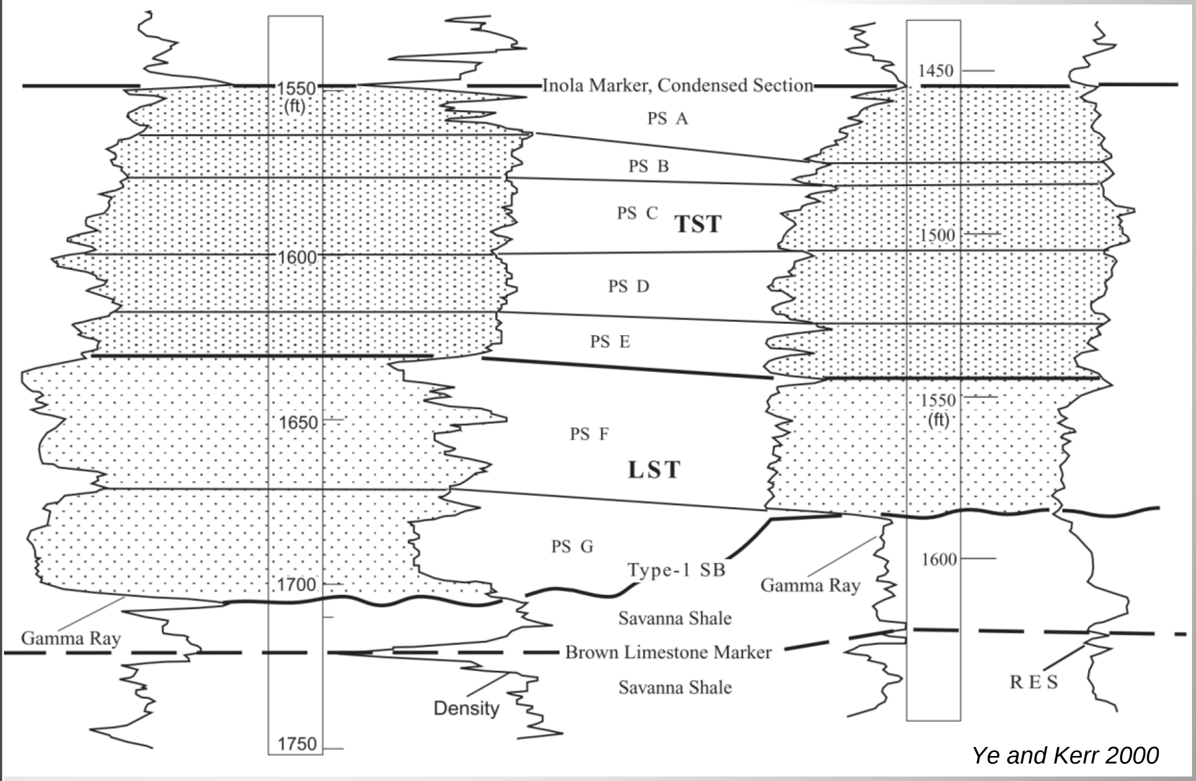
Analogue: Bartlesville Ss



- Braided fluvial lower "sheet" sandstone
- Meandering fluvial middle sandstone
- Tidal-estuarine upper facies



Ye and Kerr 2000

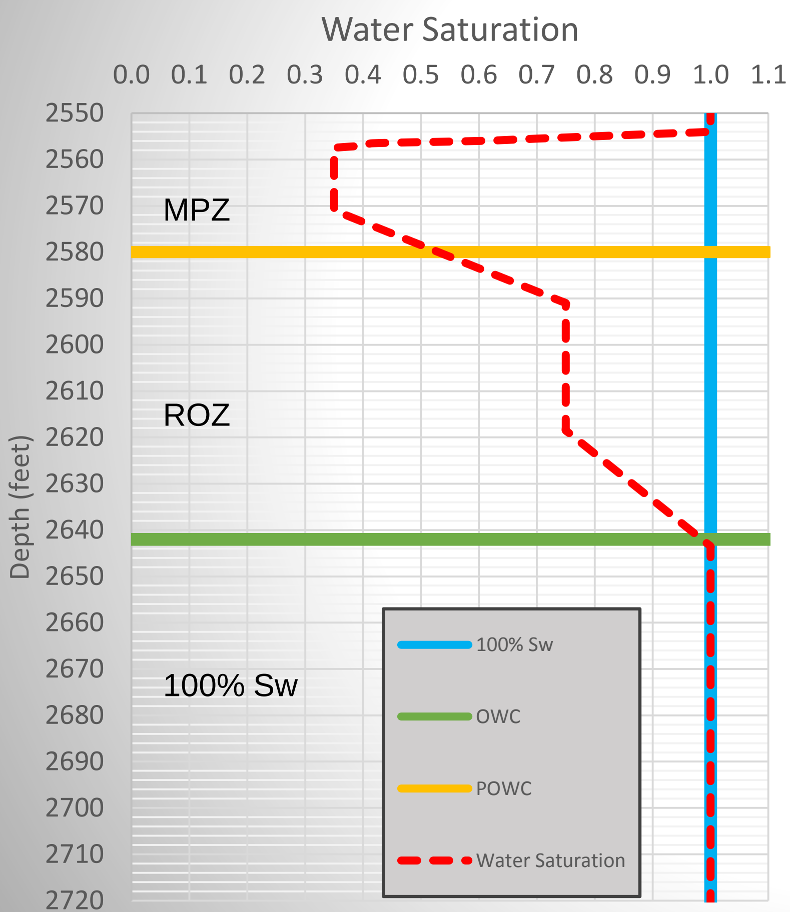
Summary of Characterization

- Multistory valley fill Cypress Sandstone dominated by high energy deposits with good reservoir properties
- Depositional and diagenetic controls on porosity and permeability
  - Sandstone texture and sedimentary structures very similar across the basin
  - Diagenetic factors may be responsible for regional variation in porosity and permeability
- Combination of structural and stratigraphic controls on oil trapping; tilted OWCs a clue for ROZs
- Through DOE investment in ROZ and CO_2-EOR and research, we learn a lot about geology and reservoir properties of the Cypress Sandstone

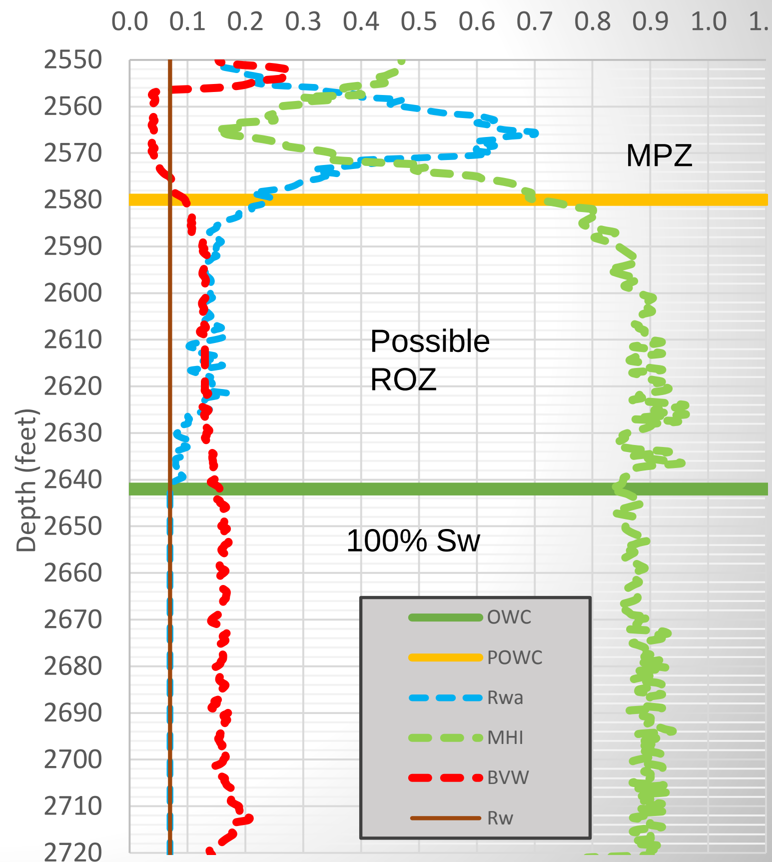
Well Log Analysis & Preliminary Reservoir Simulation Results

Well Log Analysis

Ideal ROZ saturation curve



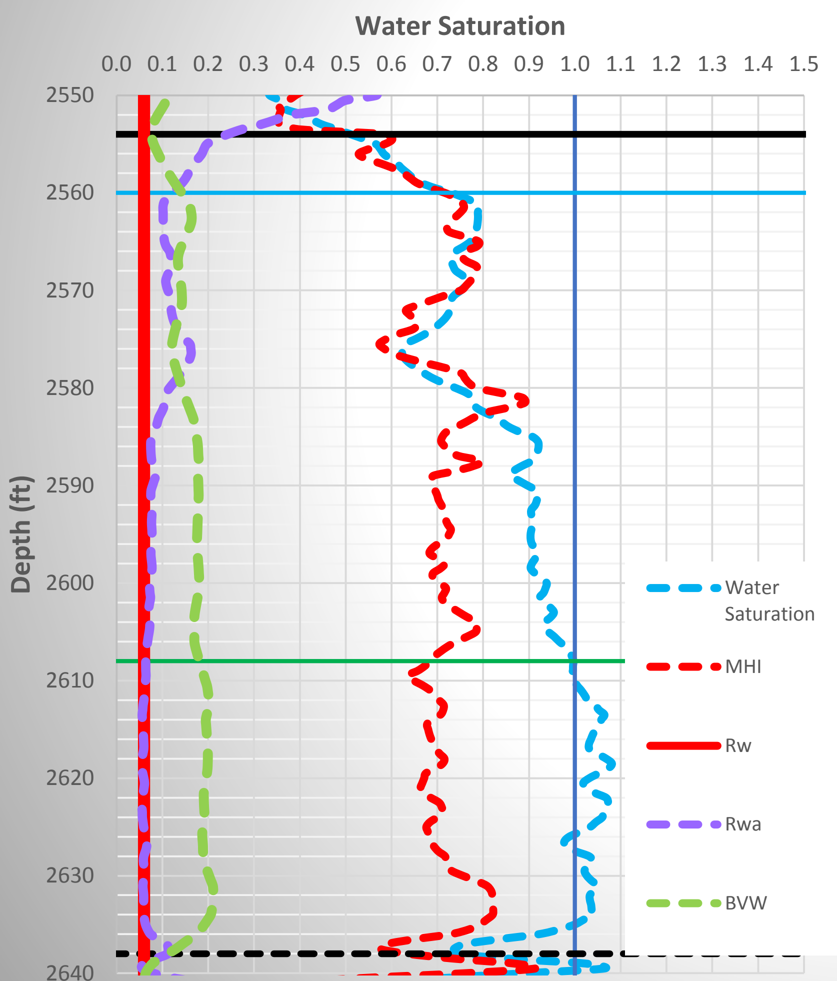
Analyses applied to detect ROZ



Movable Hydrocarbon Index, Bulk Volume Water, Water Resistivity

Example from Kenner West Field

Curves



Quantity

- Main Pay Zone (MPZ)
  - 6 ft thick
  - ≈ 40% oil saturation
  - 0.5 feet of oil
    - $\sum(1 - S_w)\phi$
- Residual Oil Zone (ROZ)
  - 48 Feet
  - ≈10 – 25% oil saturation
  - 1.8 feet of oil
    - $\sum(1 - S_w)\phi$

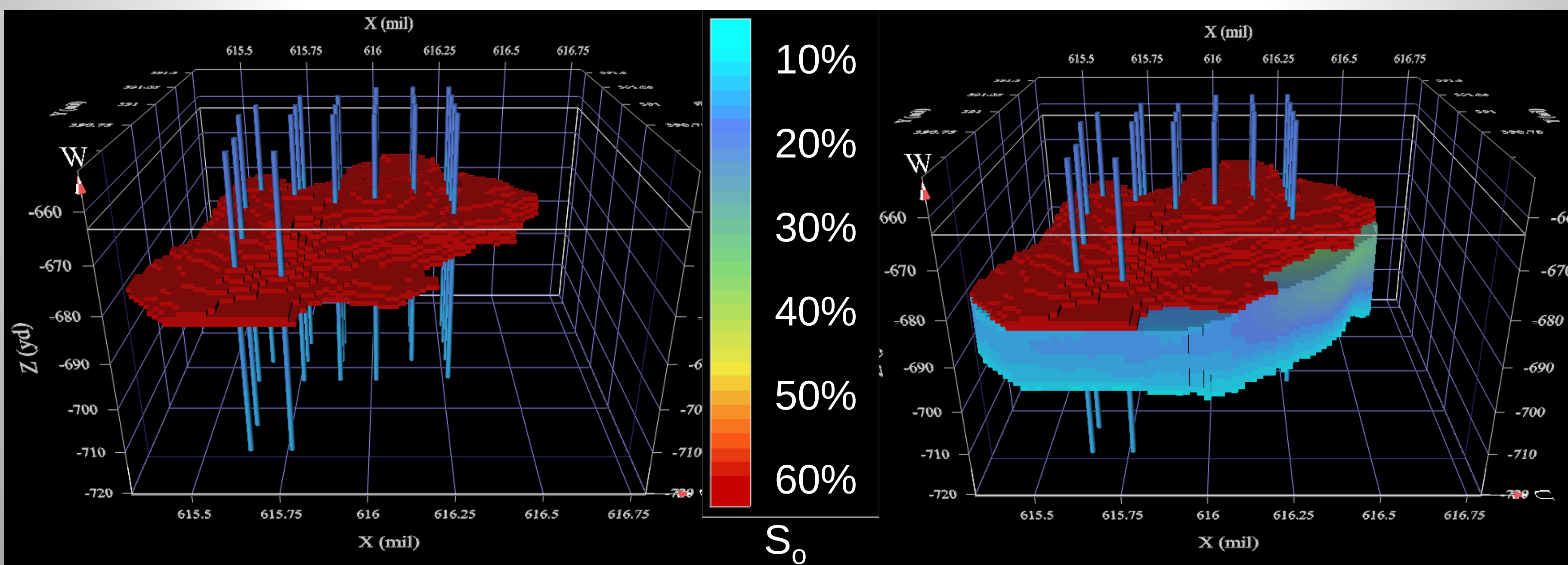
Kenner West saturation model

MPZ

- Thin MPZ at the top of the Cypress Ss
- OOIP ≈ 7.8 MMBO

MPZ + ROZ

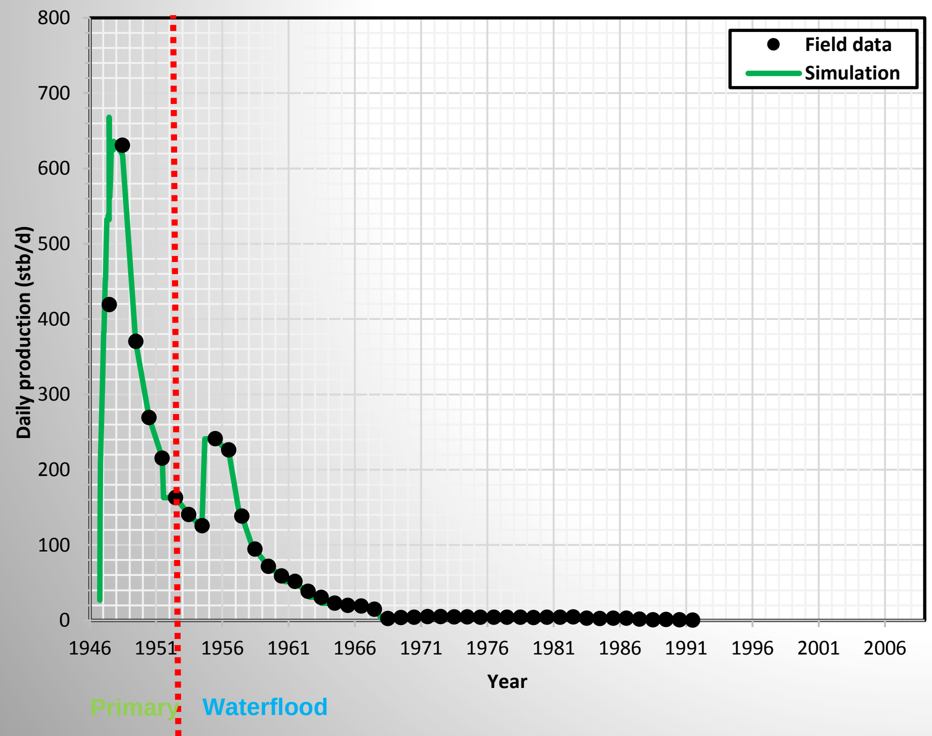
- Much thicker underlying ROZ
- OOIP ≈ 19.7 MMBO



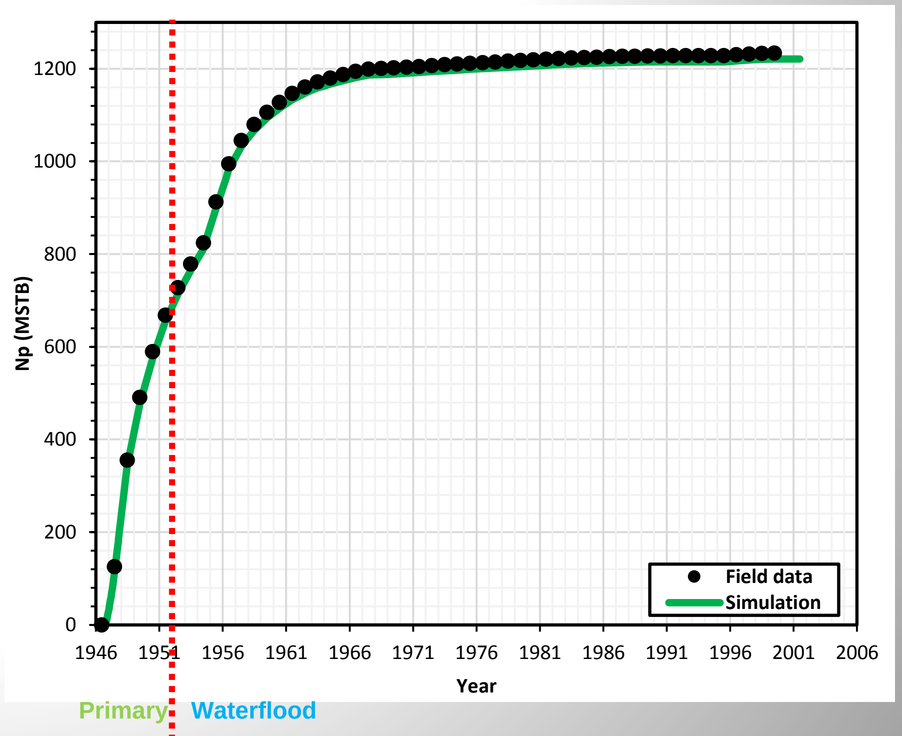
Kenner West Reservoir Simulations: History Match

- Compare simulation results to historical production
- Increase confidence in geologic and geocellular models and distribution of oil and water within the formation

Daily oil production rates



Cumulative oil production



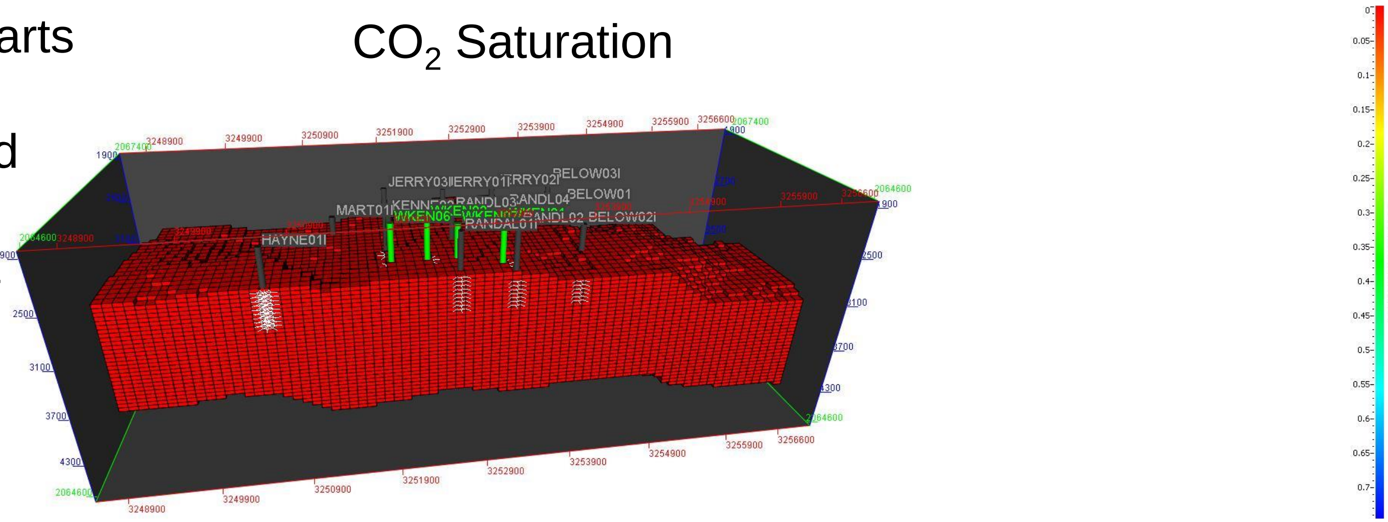
Kenner West Reservoir Simulations

Time 1: Before EOR Starts

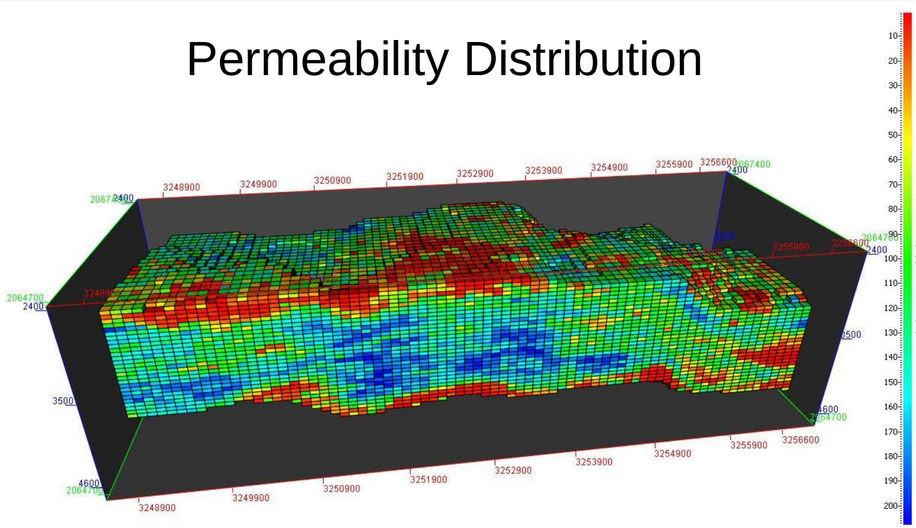
After Primary/waterflood

Water coning/inefficient recovery of MPZ

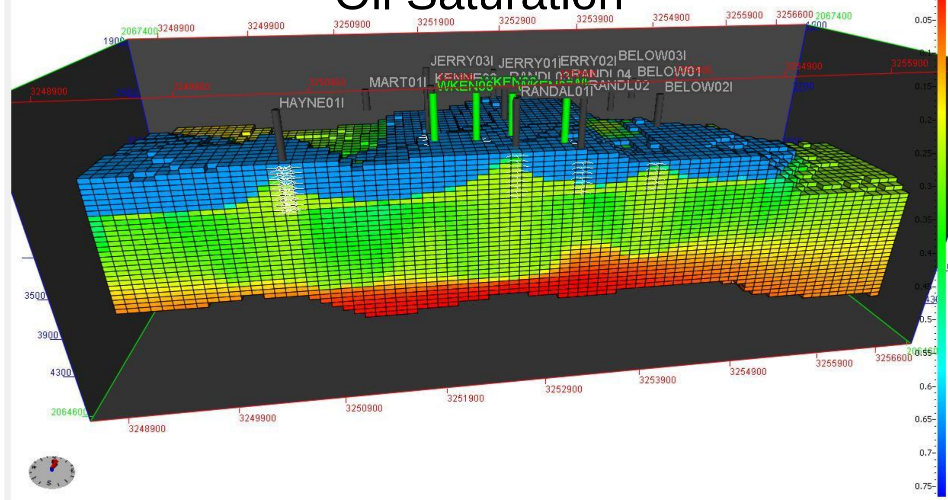
CO_2 Saturation



Permeability Distribution



Oil Saturation

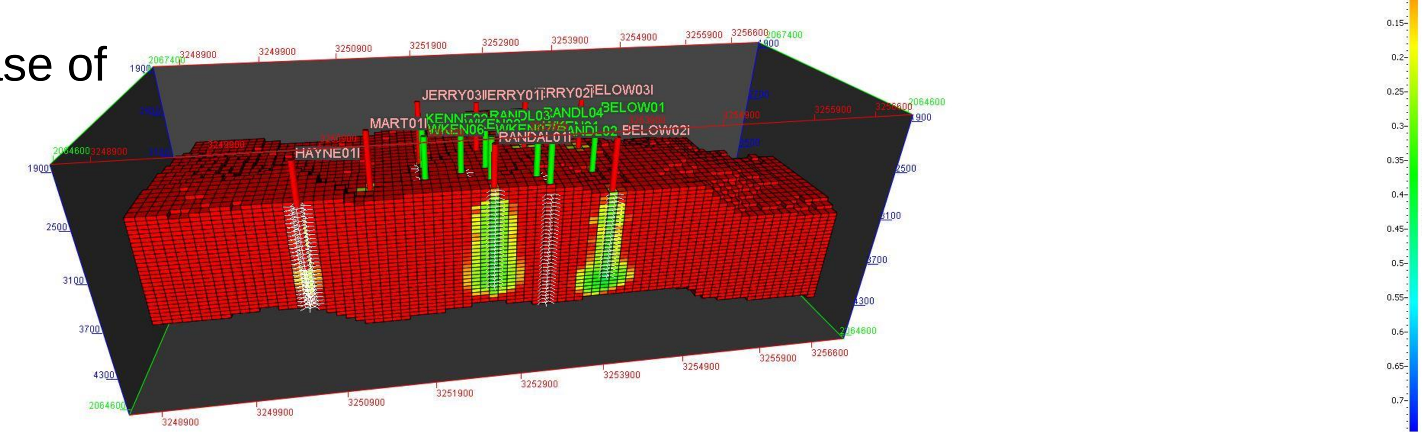


Kenner West Reservoir Simulations

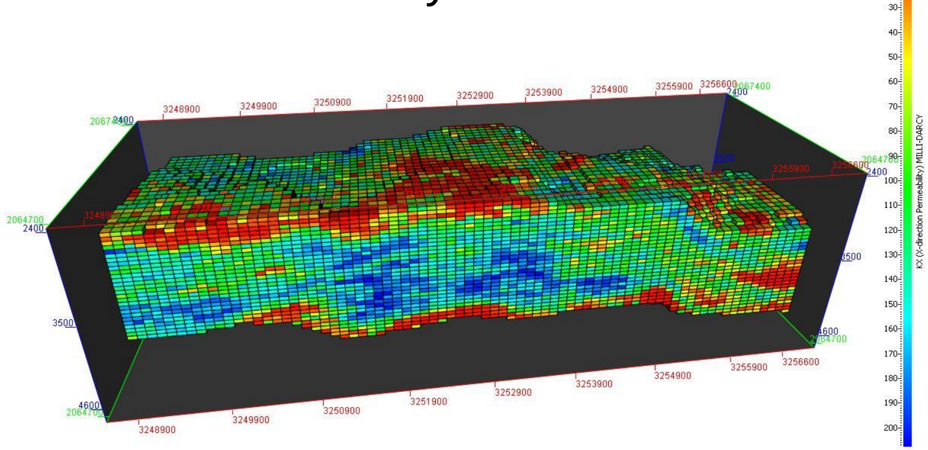
Time 2: EOR Starts

Perforations: From base of ROZ to top of MPZ

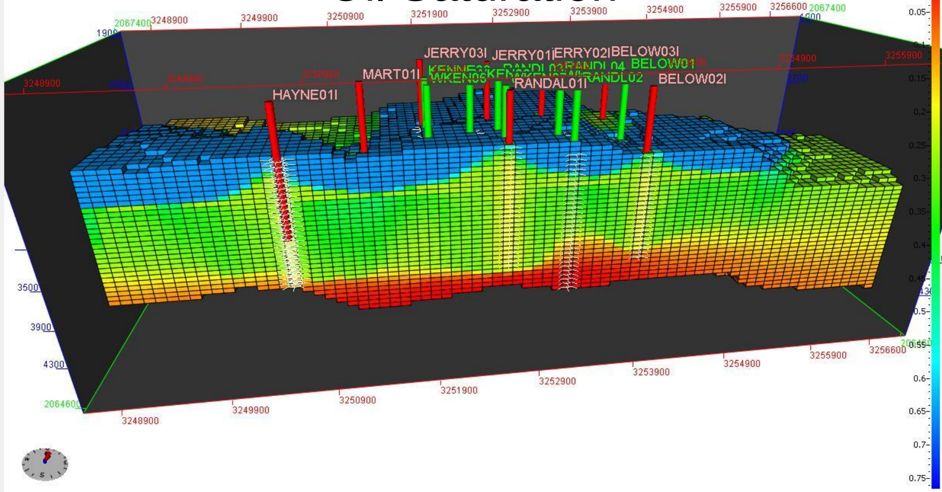
CO_2 Saturation



Permeability Distribution



Oil Saturation

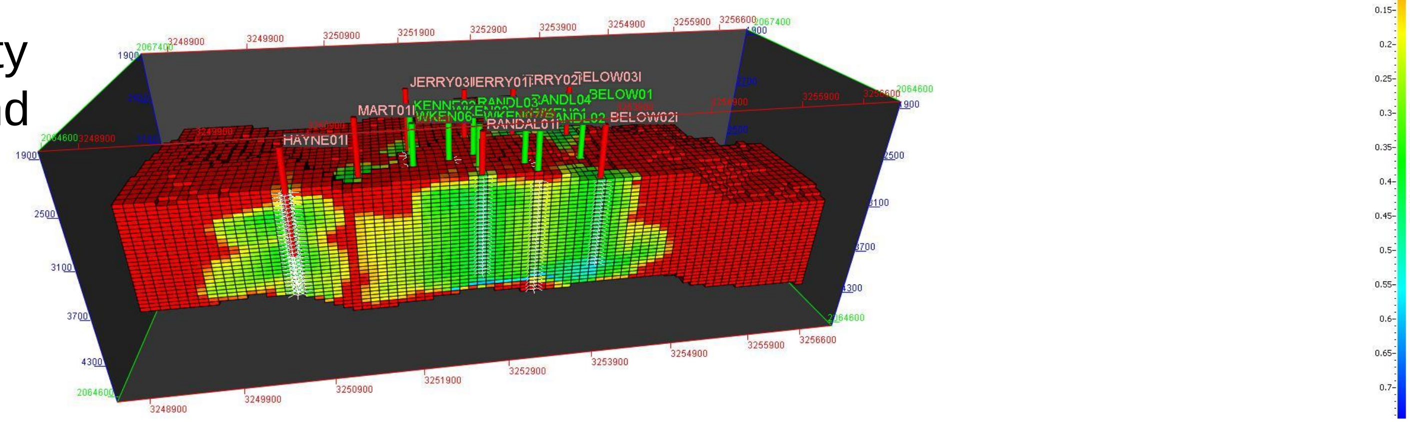


Kenner West Reservoir Simulations

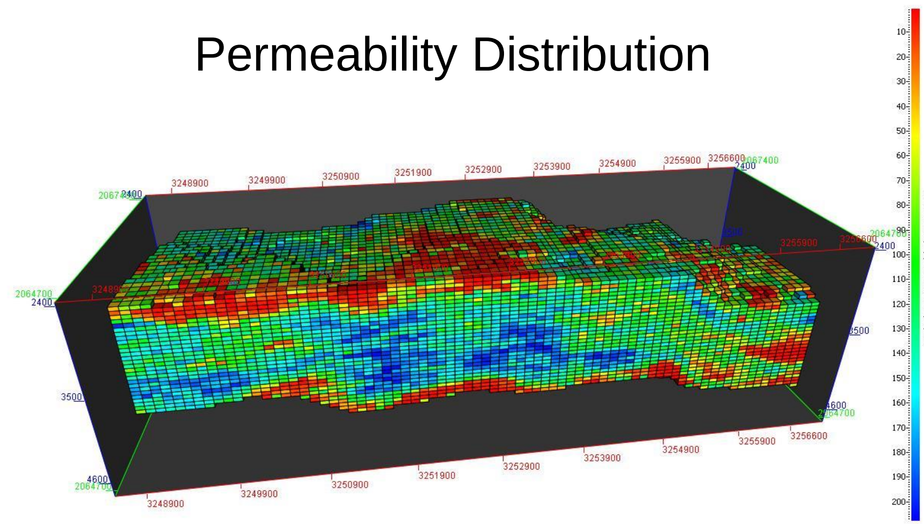
Time 1: Before EOR Starts

Buoyancy and solubility of CO_2 sweep ROZ and MPZ

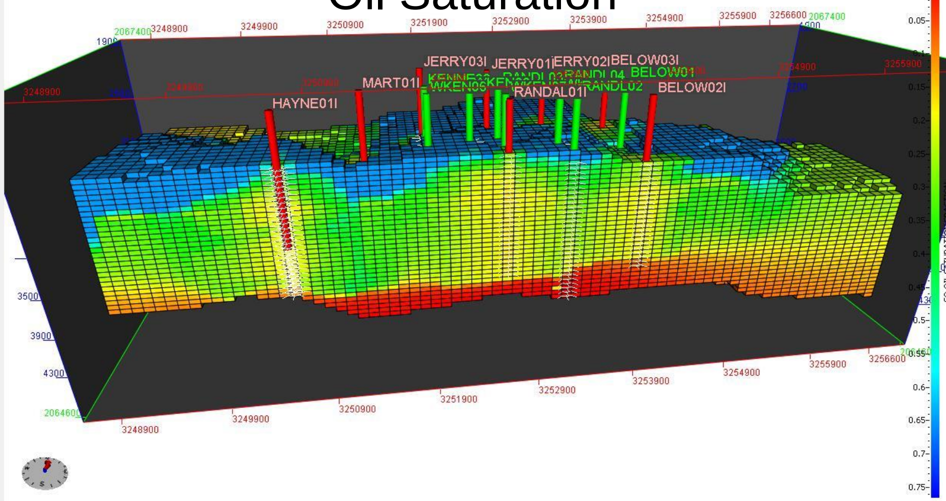
CO_2 Saturation



Permeability Distribution



Oil Saturation



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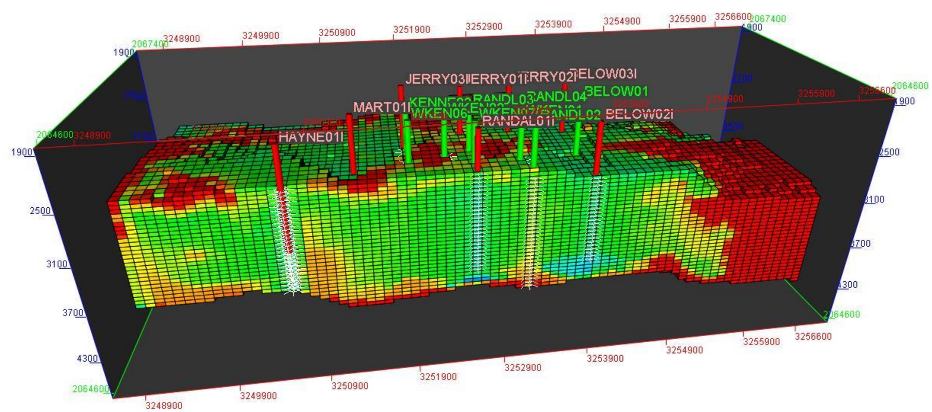
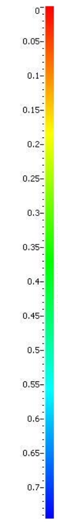
Kenner West Reservoir Simulations

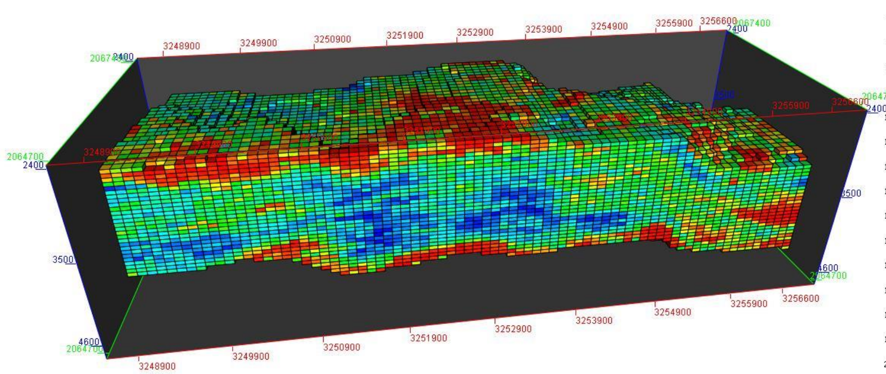
Time 4: 8 Years of EOR

CO_2 Saturation

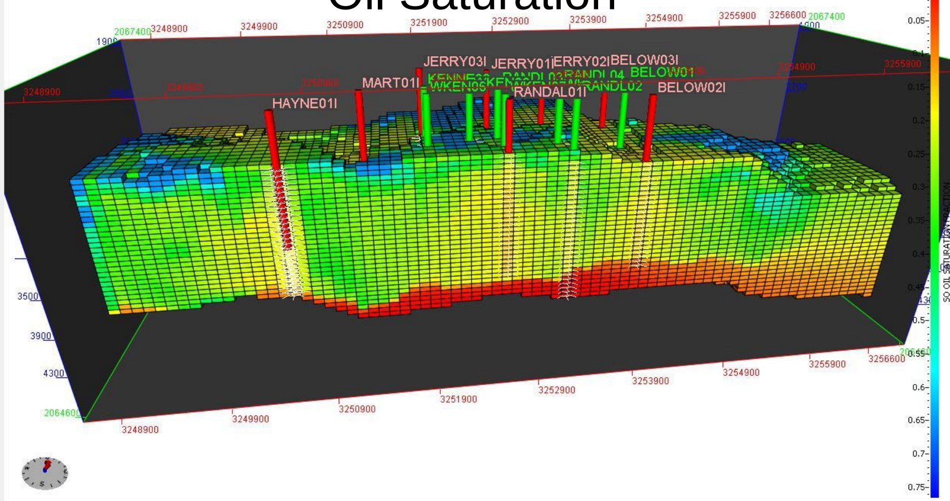




Permeability Distribution

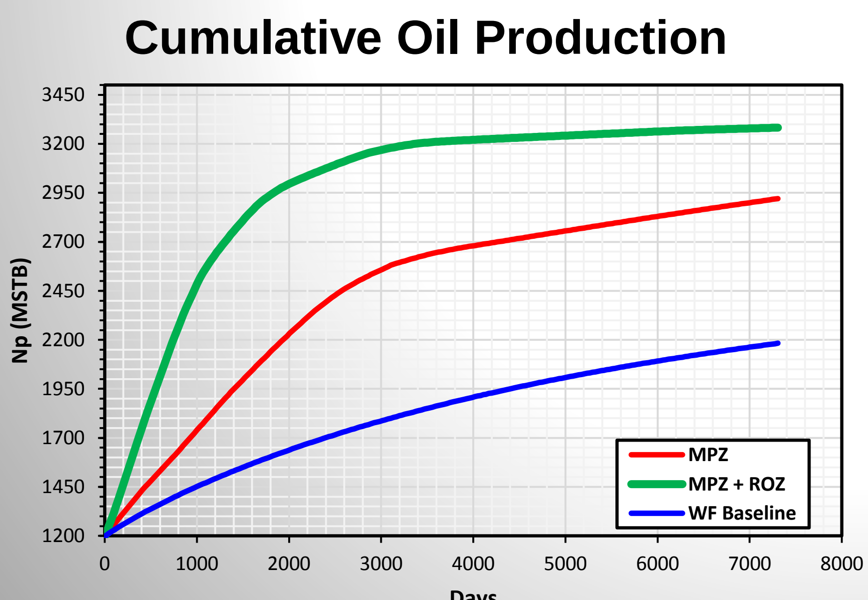


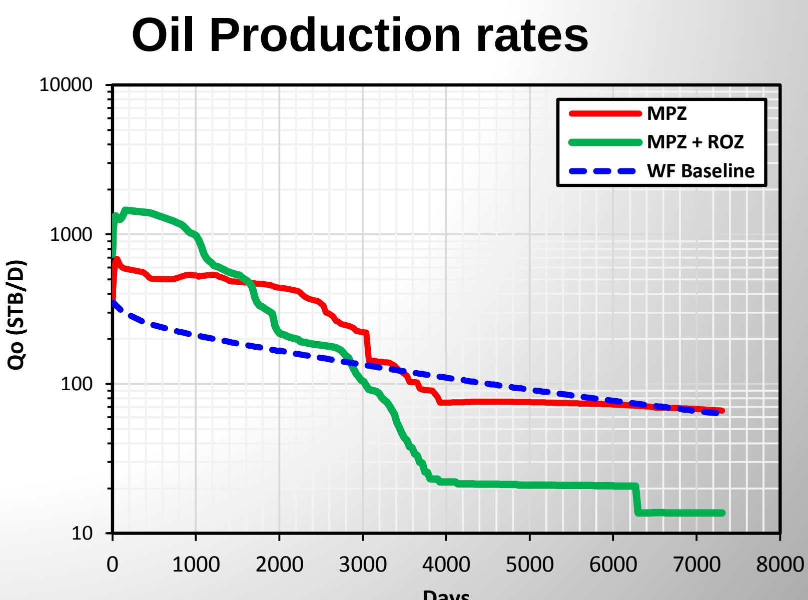
Oil Saturation



Kenner West Reservoir Simulations: Future Projections

- Testing various injection scenarios
- EOR produces additional oil over waterflood in the MPZ and MPZ+ROZ
  - 9.8% of MPZ OOIP produced via EOR
  - 5.6% of MPZ+ROZ OOIP produced via EOR





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Summary of Log Analysis and Simulation

- Log analyses also indicate possible ROZs below MPZ
- Still need physical evidence of ROZ resource
  - Planned core through entire thickness of the Cypress in Noble Field
  - Planned cased hole logs through entire thickness of the Cypress in Noble Field
- Reservoir simulations show potential for increasing oil production from the MPZ and new production from the ROZ

Project Outcomes

- Quantification of the potential ROZ resource within the Cypress Sandstone
- Better understanding of how to develop valley fill Cypress Sandstone reservoirs
- DOE investment may yield identification of ROZ resource and has allowed us to advance our geological understanding of the Cypress Ss
  - New outcrop studies and cores (one near outcrop, one in Noble Field)
  - Sampling/testing of numerous shale units for TOC content and biomarkers
  - Sampling/testing of oils from the Cypress Ss for biomarkers and linking to source rock

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Nathan D. Webb
ASSISTANT PETROLEUM GEOLOGIST
ndwebb2@illinois.edu
615 E. Peabody Dr. – Champaign, IL 61820-6918
+1 217 244 2426

http://isgs.illinois.edu/research/ERD/NCO2EOR