Bring the Realities into Focus: New Integration Process for Geology, Engineering, Petrophysics, and Seismic for a CO_2 Flood*

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Search and Discovery Article #80521 (2016)**
Posted March 14, 2016

*Adapted from oral presentation given at AAPG-SPE Joint Forum, Reality-Based Reservoir Development: New Teams, Techniques, Technologies, Oklahoma City, Oklahoma, September 23, 2015

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Abstract

An extensive multidisciplinary reservoir characterization project was undertaken to construct geologically accurate, 3D reservoir models of the Mississippian at Wellington Field (Sumner County, Kansas) for critical assessment of a pending pilot scale CO2-EOR program. The BEREXCO-operated field, discovered in 1929, has cumulative production of 21 MMBO and is currently being produced using a 5-spot waterflood. As part of the CO2-EOR assessment program, a new multicomponent 3D seismic survey was acquired over the 3.5- × 2.5-mile field and three new wells were drilled and logged near the proposed pilot area. Triple combo, full-wave sonic, nuclear magnetic resonance, elemental, and microresistivity imaging tools were run. New cores were acquired for facies description, stratigraphic analysis, diagenetic studies, routine core measurements, helical CT scanning, and SCAL. Depositional facies identified from core are linked to seven petrophysically distinct rock fabrics having discrete water saturation and relative permeability functions.

Petrophysical analyses, PSDM seismic, borehole data, and observations were integrated into the modeling work flow, which broadly includes the following steps: 1) interpret bounding surfaces, stratal geometries, and faults from seismic; 2) describe the vertical succession of depositional facies; 3) link depositional facies (i.e., rock fabrics) to petrophysical properties and wireline log response, 4) distribute facies and rock fabrics within a predictive chronostratigraphic framework, and; 5) geostatistically collocate petrophysical properties to rock fabrics. Seismic interpretation reveals an approximately 250-ft thick, low-angle (<2˚), dominantly westward prograding ramp system that thickens locally across rotated blocks bound by Chester-age syndepositional faults. High porosity and permeability values (0.045–194 mD; mean: 9.98 mD) are concentrated in 20–60-ft thick spiculite-bearing bioclastic packstones found along the topsets of individual progradational shingles, which form wedges that expand westward and pass downdip into low-permeability (0.001–1.37 mD; mean: 0.096 mD), microporous wackestones. Core-based permeability measurements are consistent with results from a step-rate test, which suggest an average permeability of 17.8 mD for the 60-ft interval above the FWL. The step-rate test also demonstrates that faulting has minimal impact on the effective (i.e.,

interwell-scale) reservoir properties within the pilot area. Modeling and simulation results indicate the optimum flood design for the pilot consists of a crestal CO_2 injector, a ring of producers, and a downdip ring of water injectors for pressure maintenance.

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Bring the Realities into Focus:

New Integration Process
for Geology, Engineering, Petrophysics, and Seismic
for a CO_2 Flood

or….developing a geologically constrained, collaborative 3-D workspace

Jason Rush
Mina FazelAlavi, John Doveton, and Lynn Watney

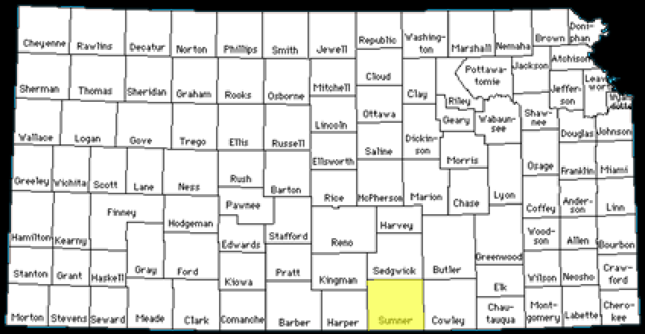
KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

Background

Department of Energy Objectives (some)

DOE Contracts:
DE-FE0002056
DE-FE0006821

Wellington Field, Kansas



- multidisciplinary reservoir characterization of the Mississippian Lime reservoir
- implement CO_2-EOR pilot (inject 30,000 tonnes Mississippian; 40,000 Arbuckle)
- test the feasibility for CO_2-EOR in mid-continent reservoirs (immediate goal)
- sequester and manage CO_2 within the Arbuckle saline aquifer (long-term goal)

Demonstrate

Petrophysical results from magnetic resonance imaging

Syndepositional faulting impacts various Mississippian shelf-to-basin motif

Lower Mississippian has “expected” stratal geometries

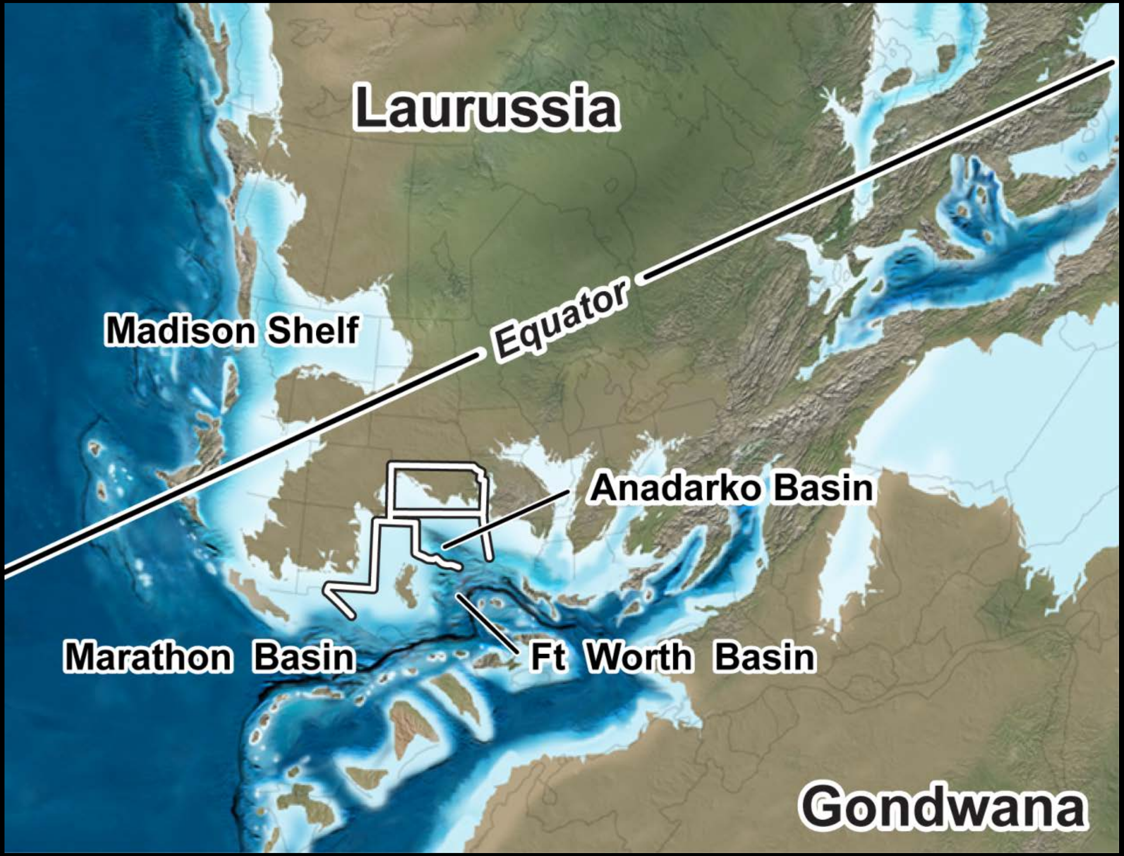
Upper Mississippian stratal geometries complex near faults

Quachita orogeny impacts Mississippian structure and stratigraphy

PSDM-seismic provides best constraint for reservoir architecture

Integrative workflow for multi-disciplinary teams especially for those working
Mid-continent Mississippian

Mississippian Paleogeography

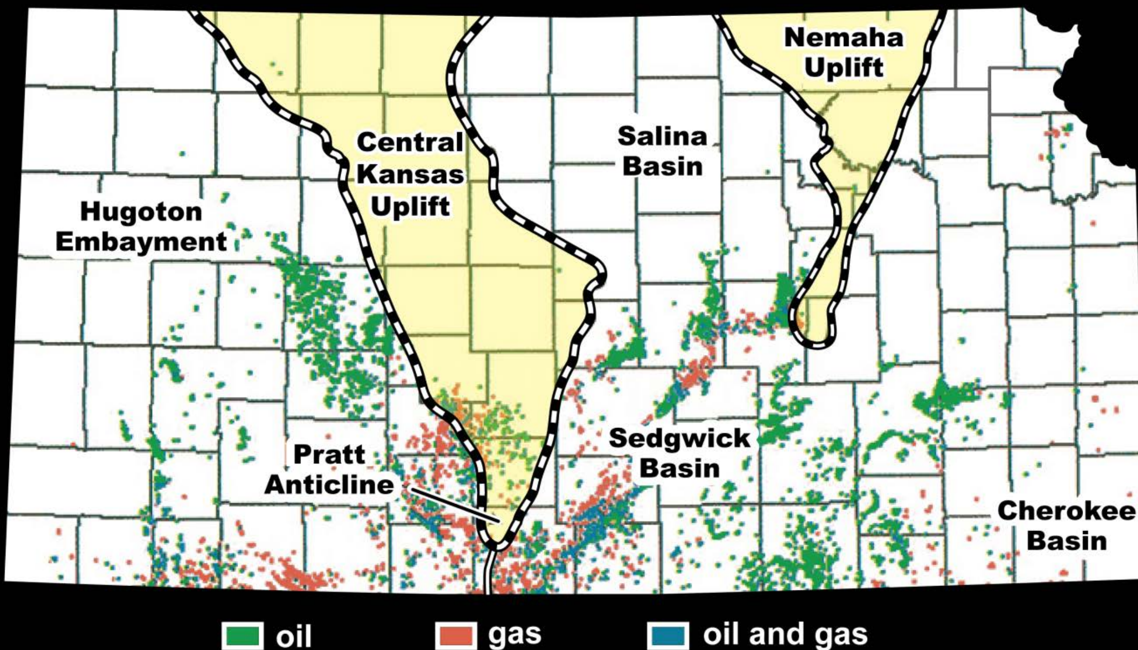


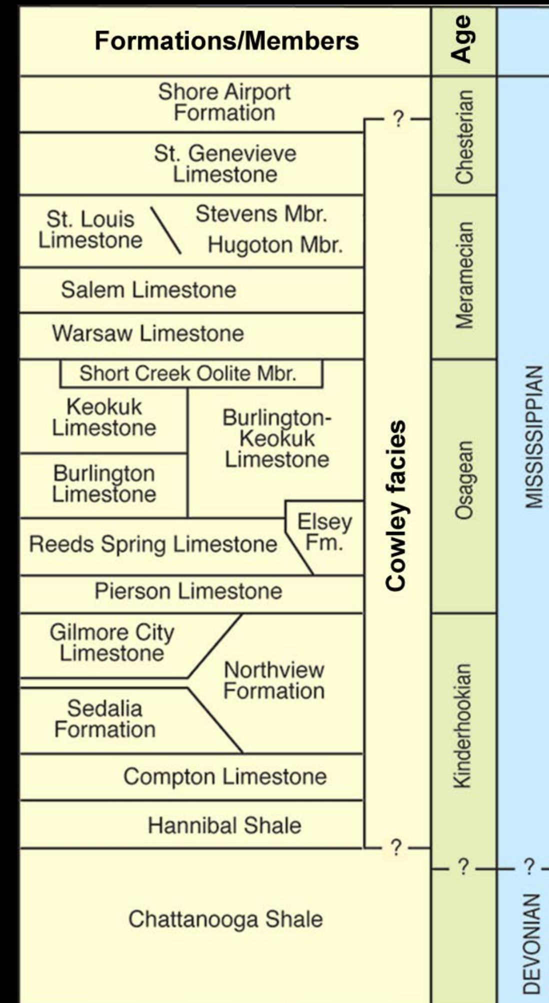
modified from Blakey, 2010

N–S oriented cool-water carbonate ramp

Thrusting impacts late Mississippian structure

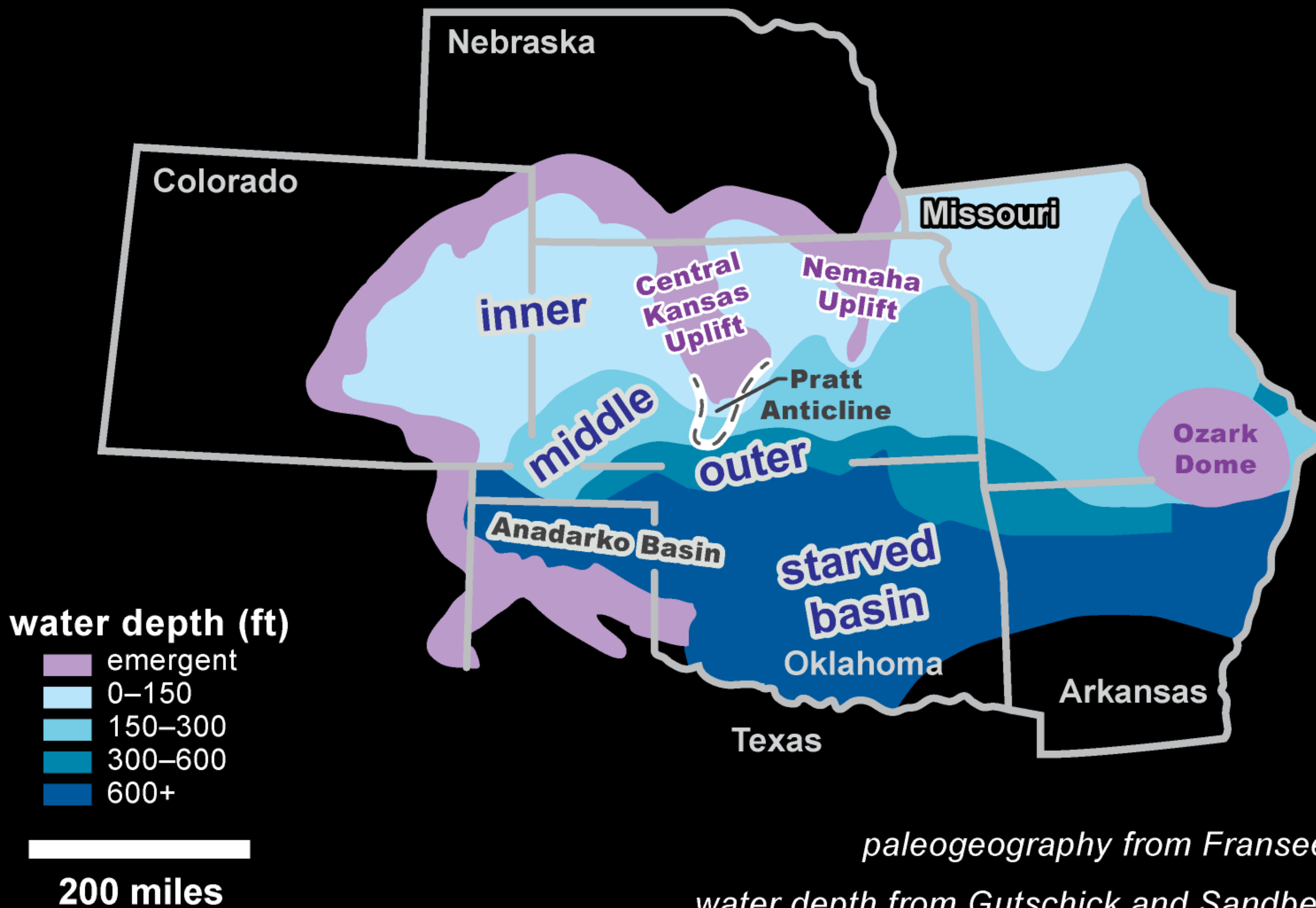
Mississippian Production





modified from Evans and Newell, 2013

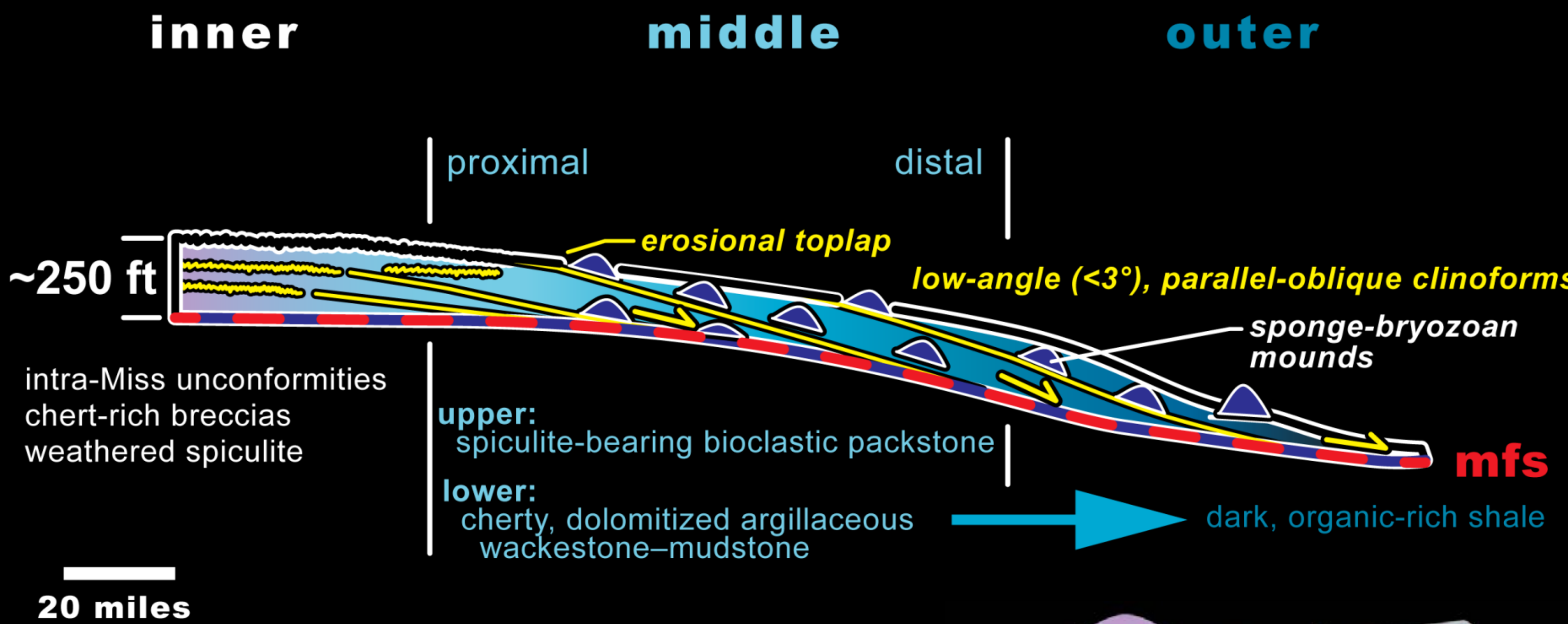
Mid-Continent Mississippian Cool-Water Ramp



paleogeography from Franseen, 2006

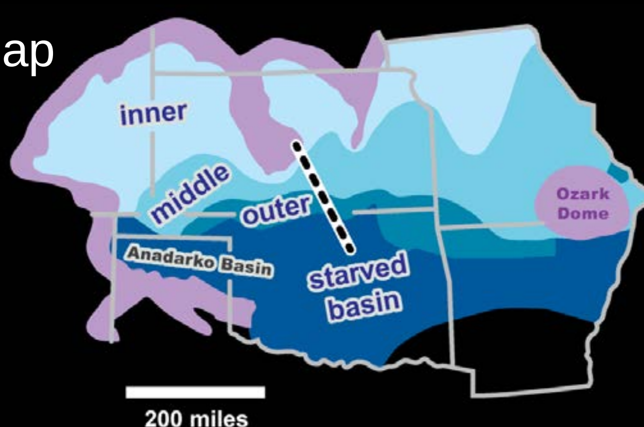
water depth from Gutschick and Sandberg, 1983

Mid-Continent Mississippian Cool-Water Ramp

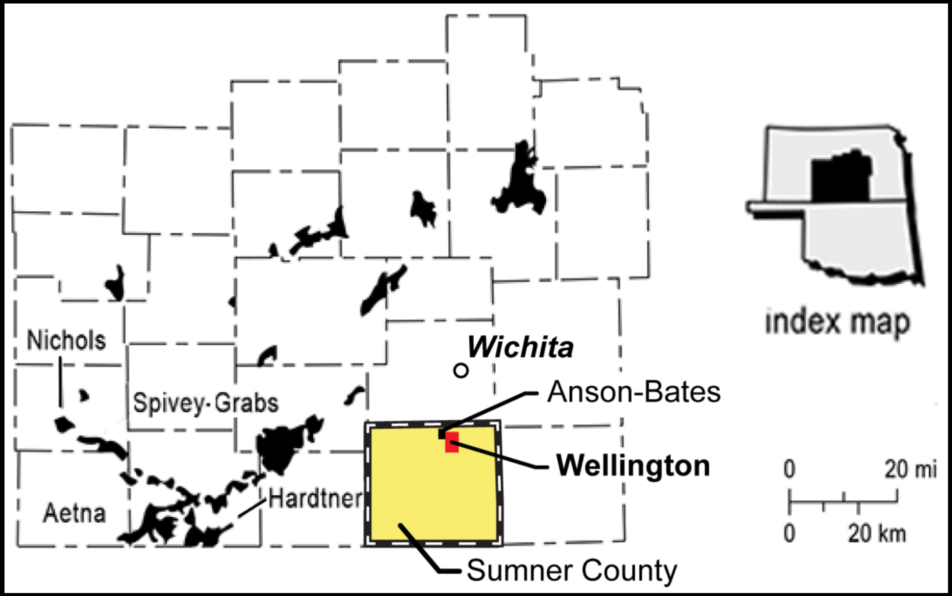


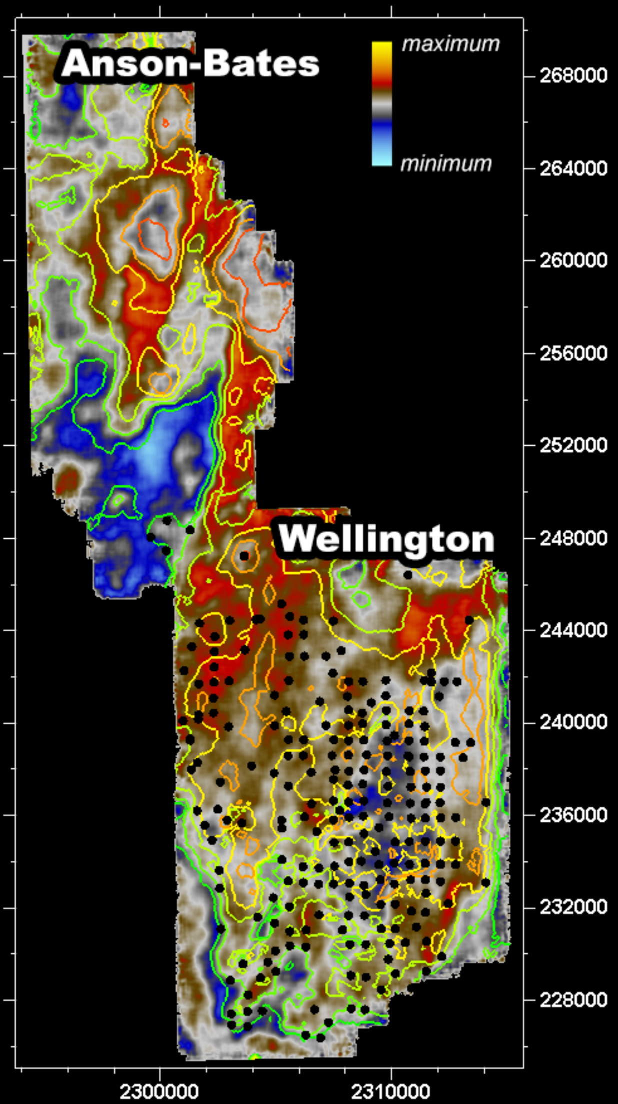
cf Mazzullo, Wilhite, and Woolsey, 2009

index map



Wellington Field

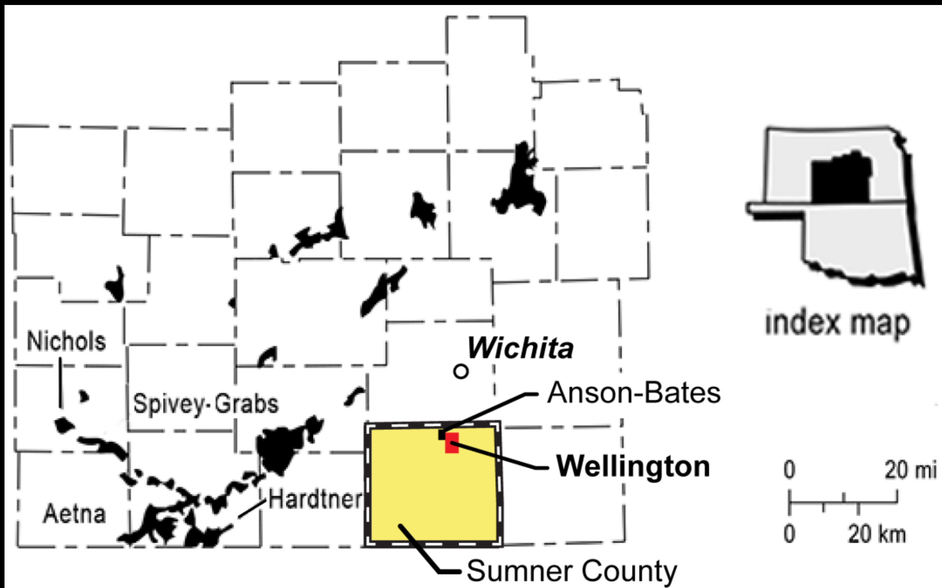


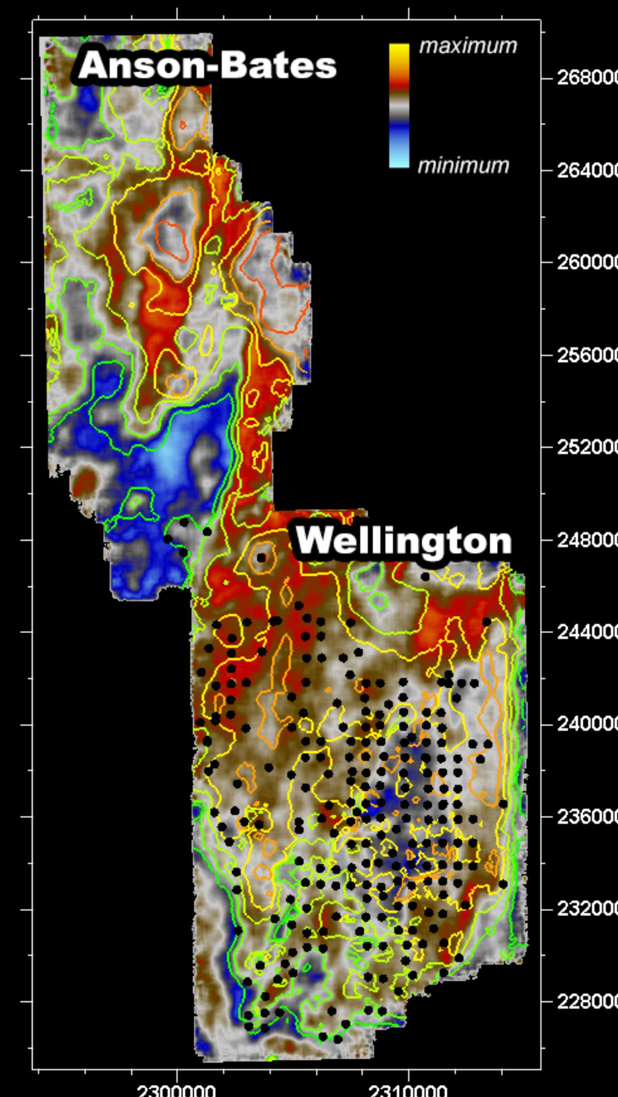


Background

- BEREXCO-operated
- Sumner County, Kansas
- Discovered 1929
- Cumulative: 20.7 MMBO
- 5-spot water flood

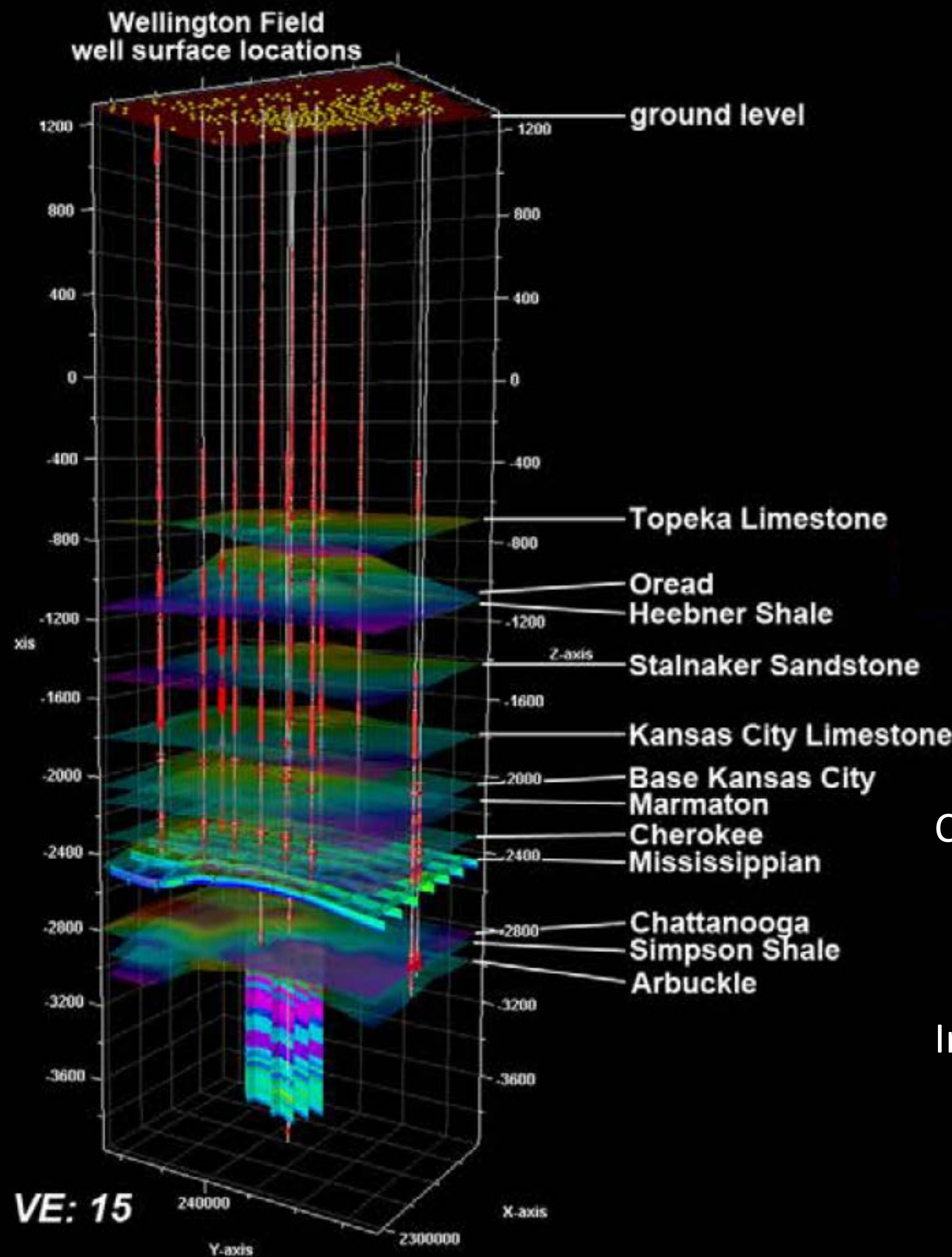
Wellington Field





New Data

- 3-D multi-component seismic
- Cores- extensive evaluation
- Exhaustive logging program
- Seismic monitoring network



Stratigraphy

Wellington Field

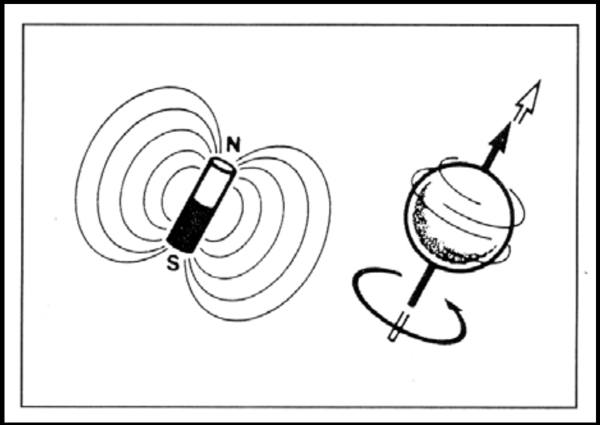
Period	Stage	Wellington Field
MISSISSIPPIAN	Chesterian	Cowley facies*
	Merramecian	
	Osagean	missing
	Kinderhookian	missing
DEVONIAN		Chattanooga Sh
ORDOVICIAN		Simpson

***sensu Goebel, 1968**
conodont biostratigraphy Darwin Boardman

Chattanooga Shale onlaps and is absent across some positive structures

In contrast to many Mississippian Lime fields Kinderhookian–Osagean-age strata is missing (eroded)

Nuclear Magnetic Resonance measurements:



POLARIZATION :

Time to align the protons with the magnetic field :

T1 distribution

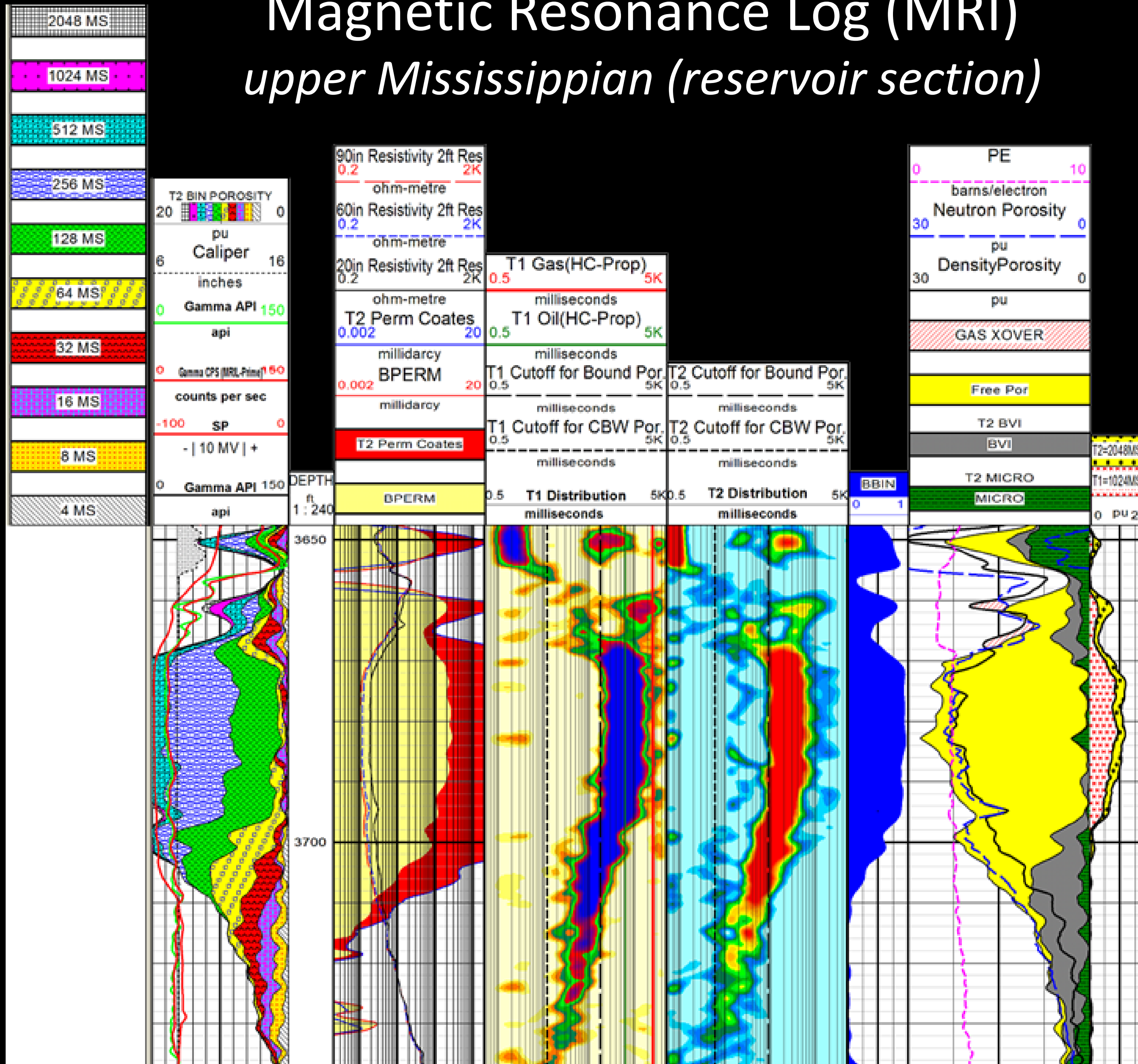
RELAXATION :

Time for protons to recover, through bulk, diffusion, and surface relaxivity effects :

T2 distribution

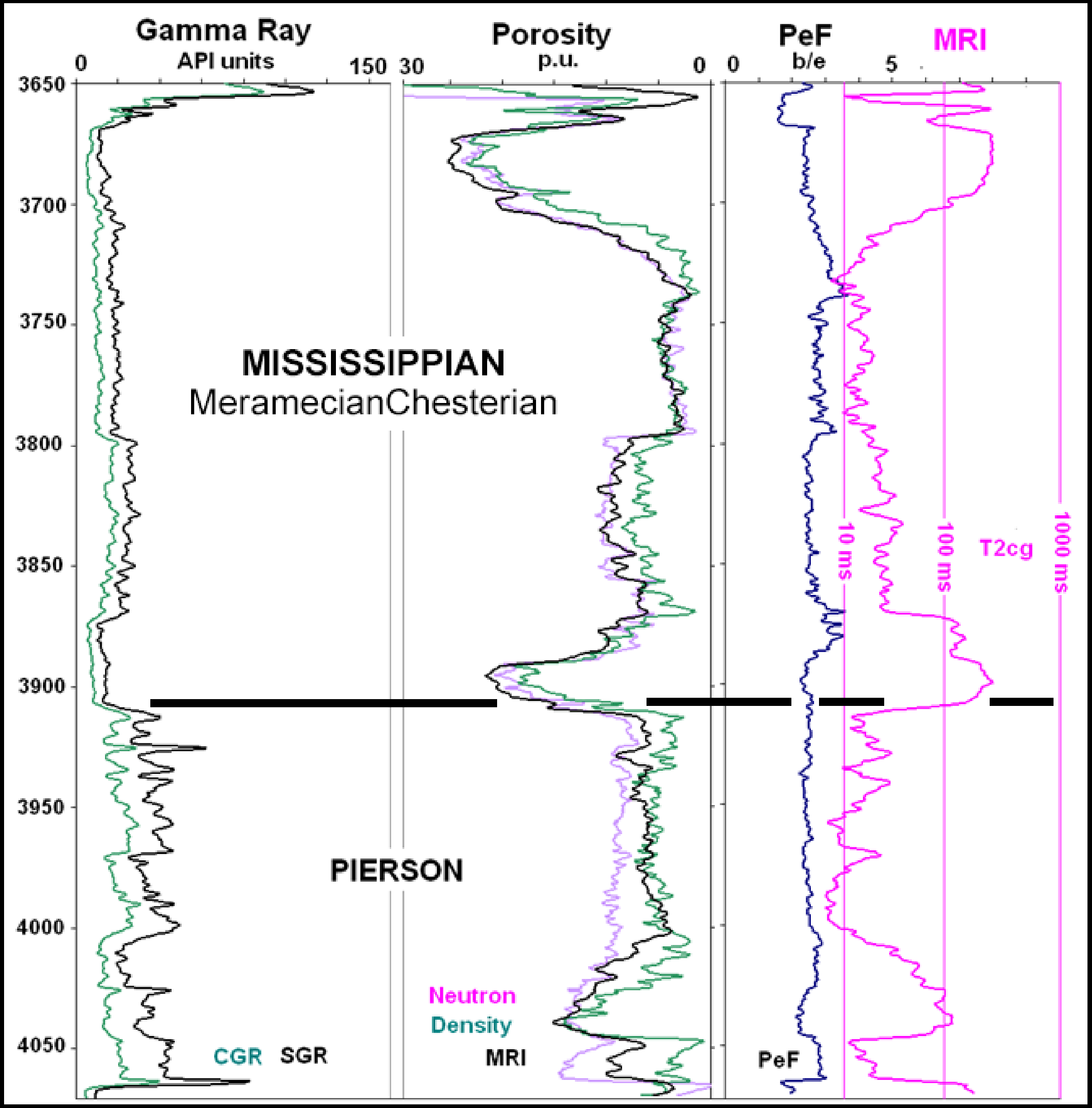
Magnetic Resonance Log (MRI)

upper Mississippian (reservoir section)



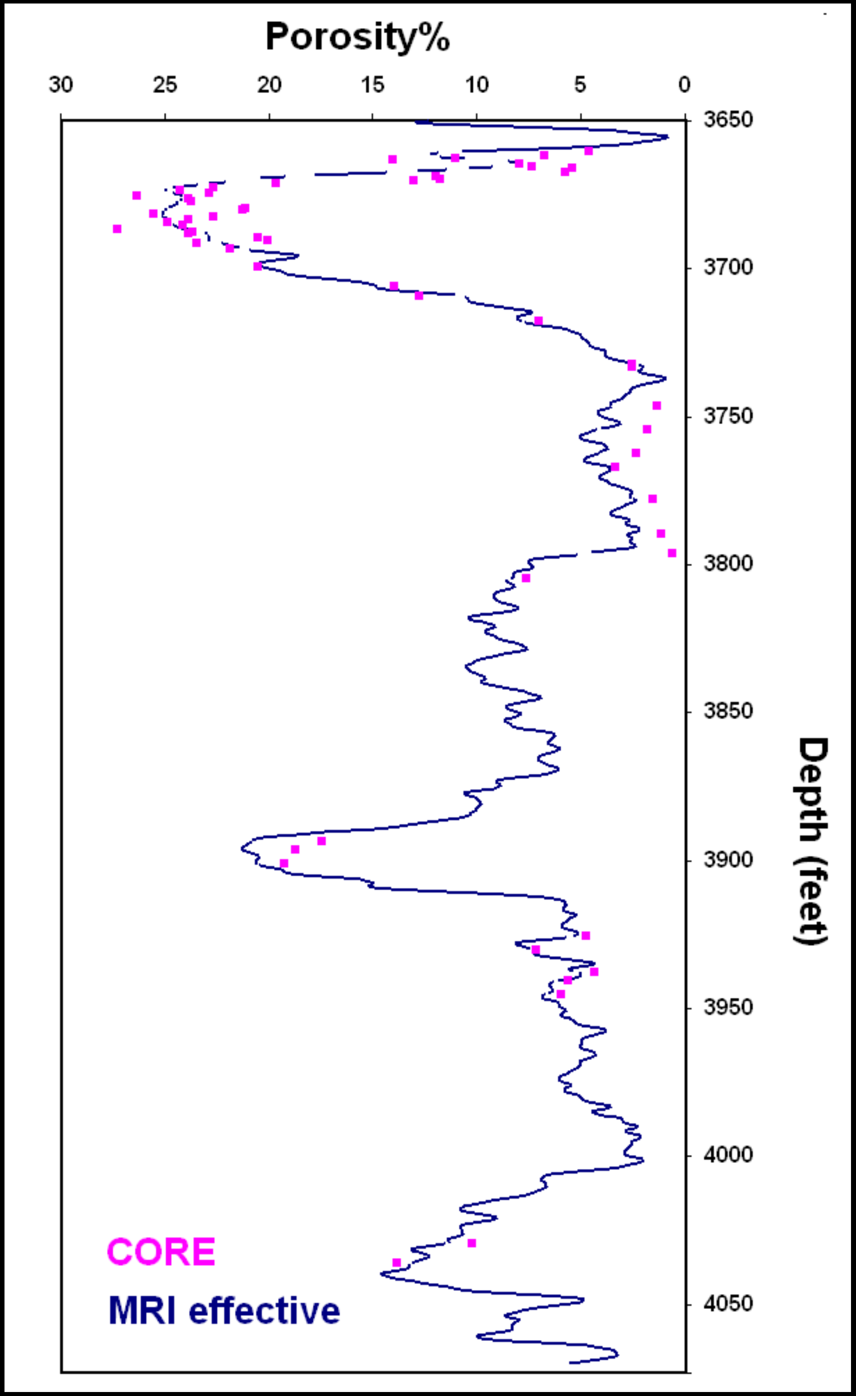
KGS #1-32 Wellington

Mississippian



KGS #1-32 Wellington:

Match of core porosities with MRI effective porosities



MRI estimation of permeability

Coates equation

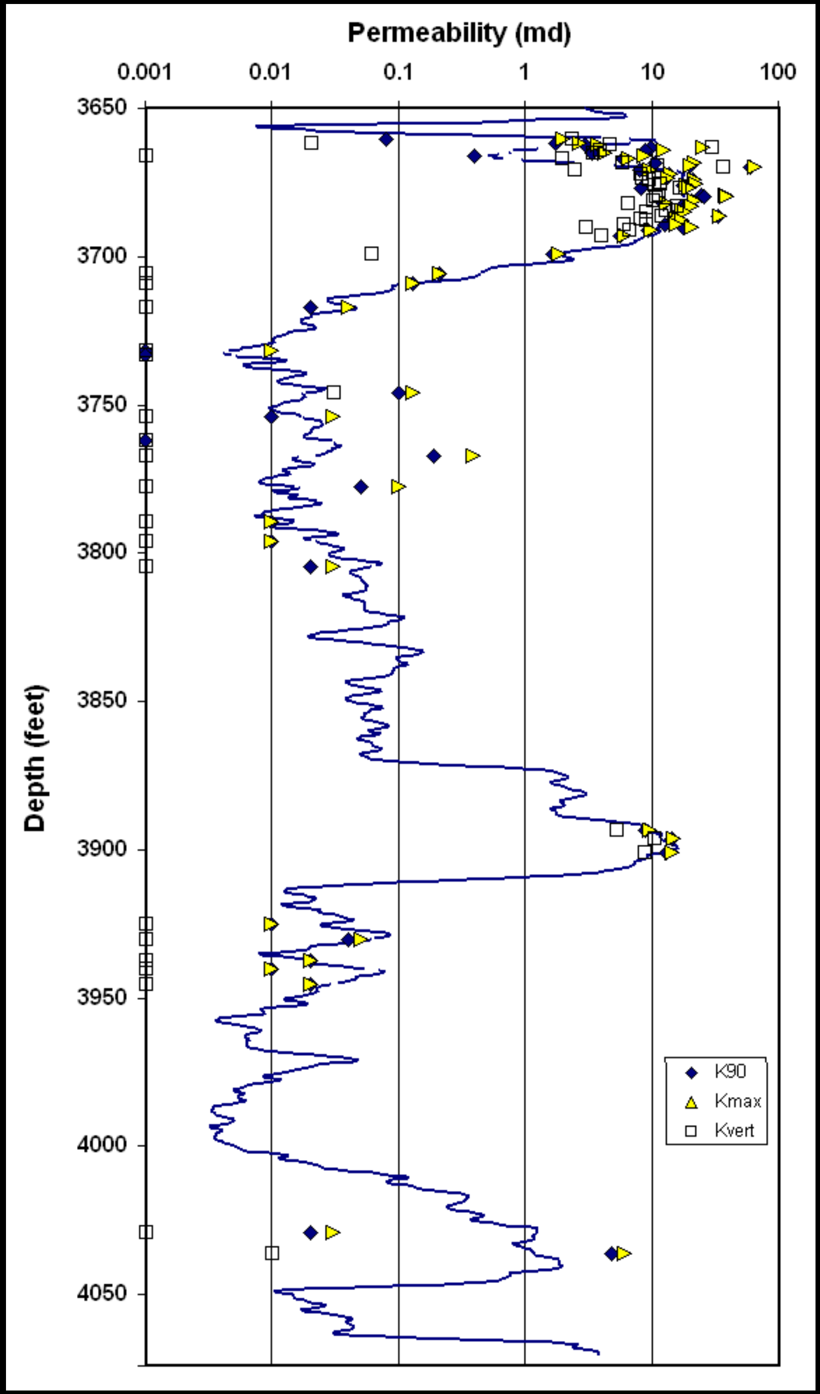
$$k = a^* \left[\Phi_{nmr}^{2} \left(\frac{FFI}{BVI} \right) \right]^{2}$$

FFI = Free fluid index   BVI = Bulk volume irreducible Φnmr = FFI + BVI

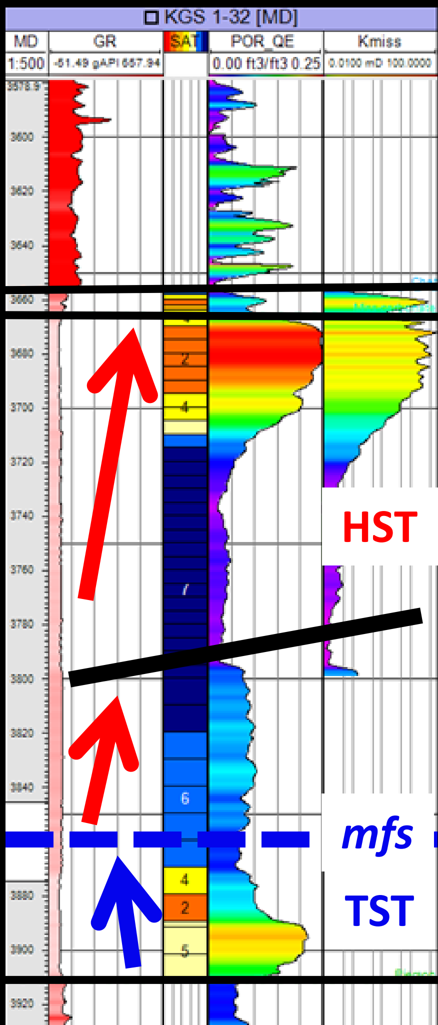
SDR equation

$$k = b^* \left[\Phi_{nmr}^{2} \left(\mathrm{logav}T_2 \right) \right]^{2}$$

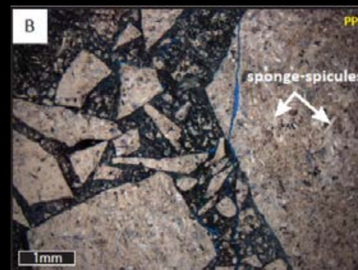
Calibrated SDR equation prediction of K90 permeability based versus core Kmax, K90, and Kvert permeabilities



Mississippian Facies/ Stratigraphic Architecture



chat



chat

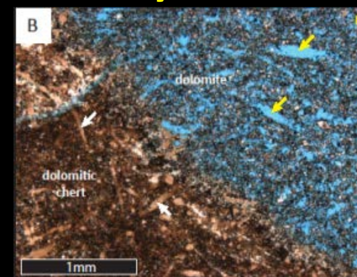
Mississippian

micro-crystalline dolo-packstone and spiculite

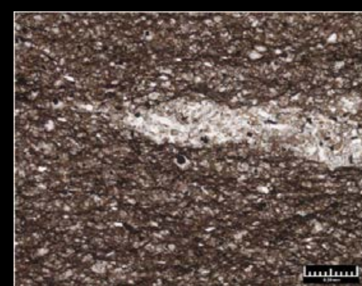
argillaceous wackestone

Pierson

cherty dolomite



cherty dolomite



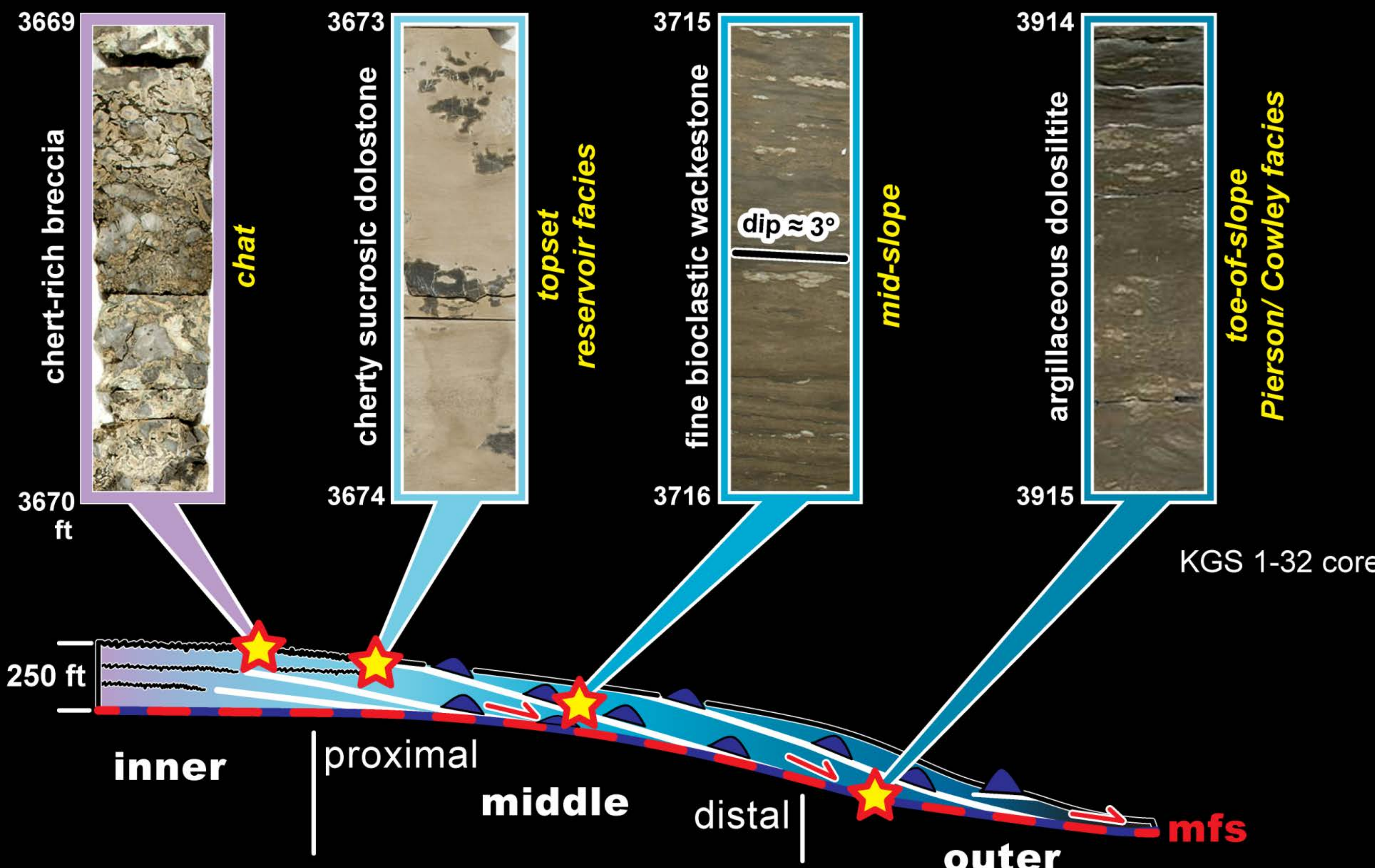
wispy dolo-siltstone

dolo-spiculite

photomicrographs from Louis Montalvo, 2015

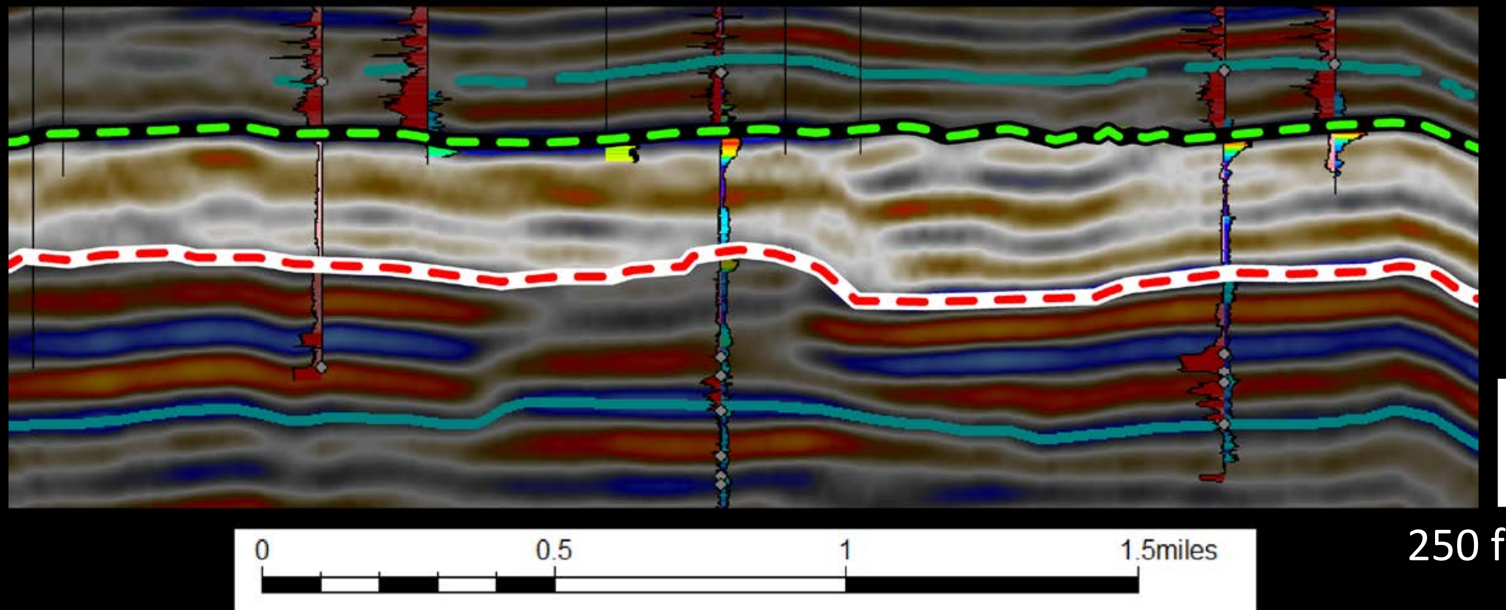
Mississippian — Wellington Field

vertical facies stacking pattern

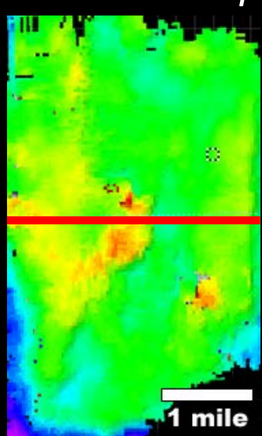


Seismic Stratigraphy

Cherokee Sh
Mississippian
Pierson
Arbuckle

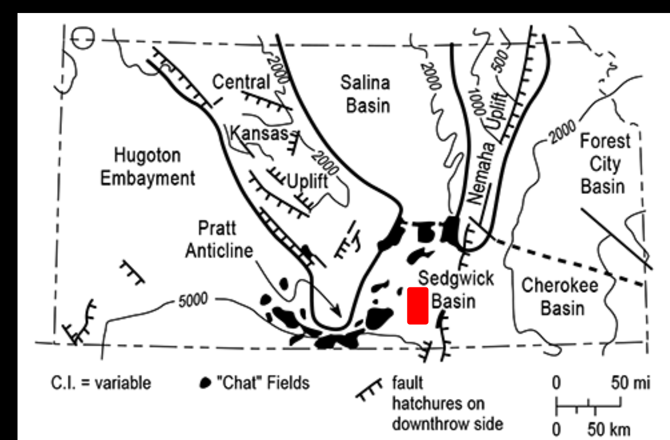


Pierson structure map



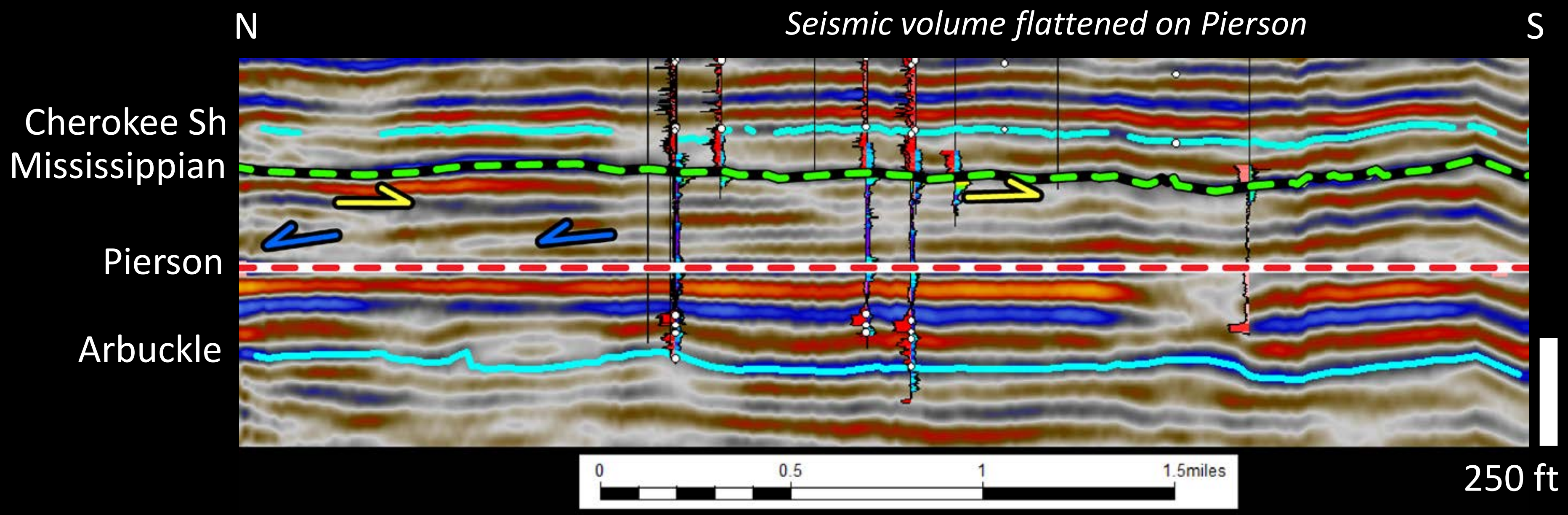
Reflector Geometries

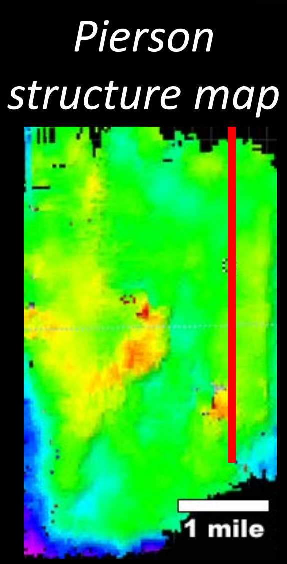
- Semi-transparent
- Anomalous thicks/thins
- Abrupt terminations
- Locally inclined
- Toplap
- W or S progradation?



from Watney et al., 2001

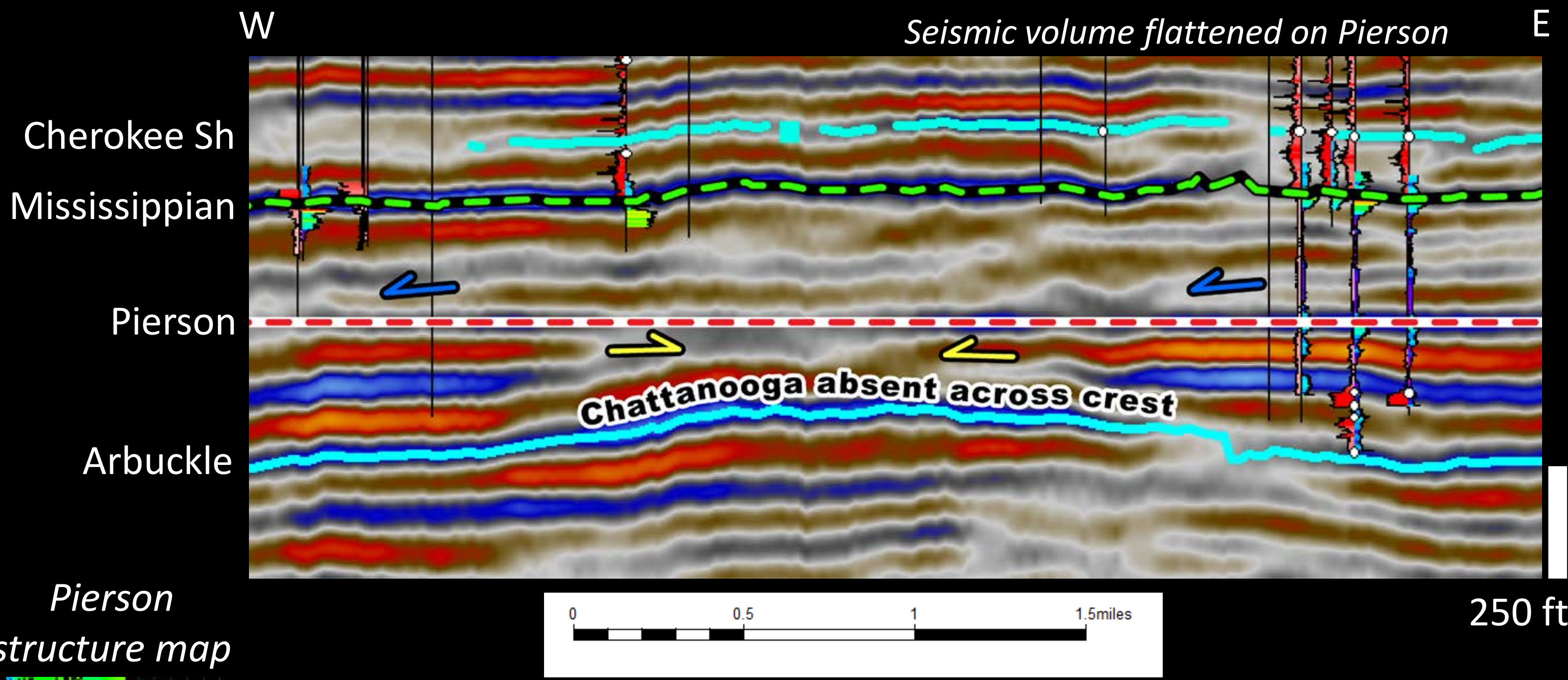
Seismic Stratigraphy



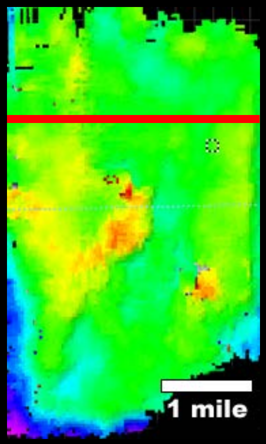


- Chattanooga present along east side
- lower Miss — low-angle progradation to north
- middle Miss — onlaps to south
- upper Miss — near-horizontal
    - toplap of westward prograding clinoform

Seismic Stratigraphy

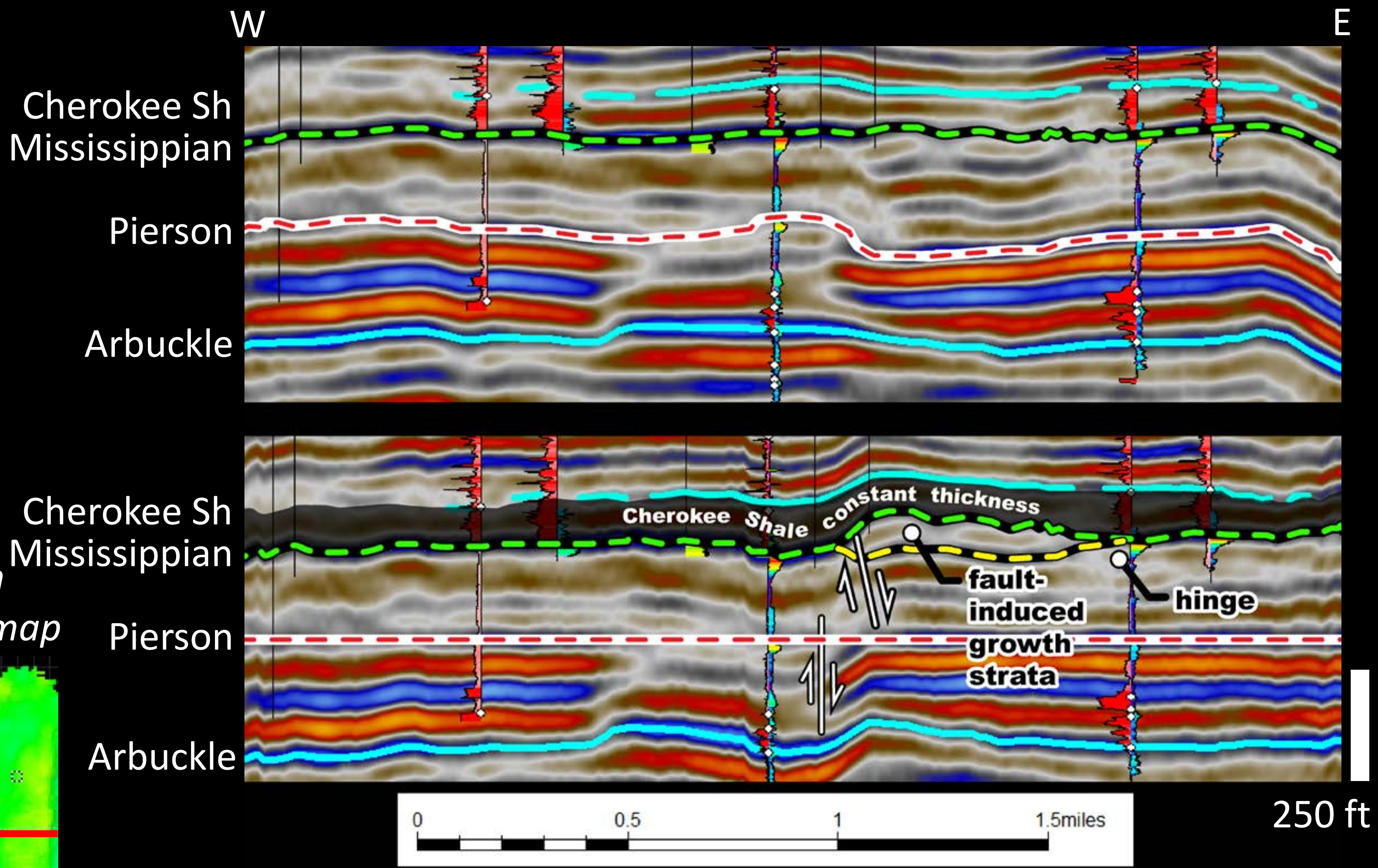


Pierson structure map

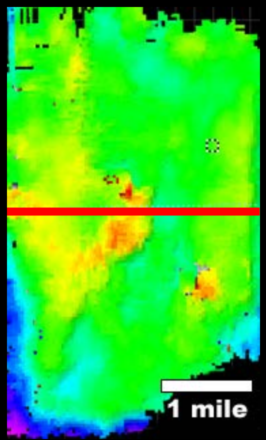


- Chattanooga onlaps absent across crest
- Complete Miss section low-angle progradation to west

back to the 1st —problematic— inline

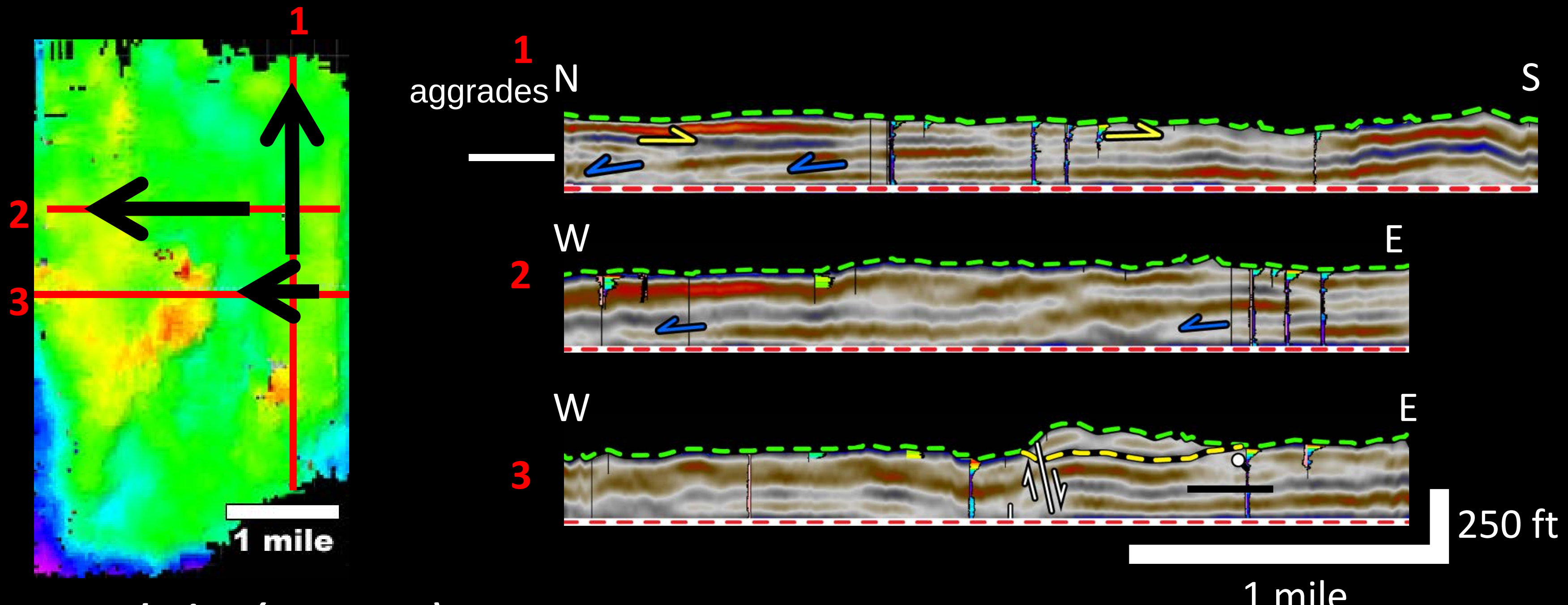


Pierson structure map



Growth strata consistent with syndepositional faulting

Seismic Interpretation



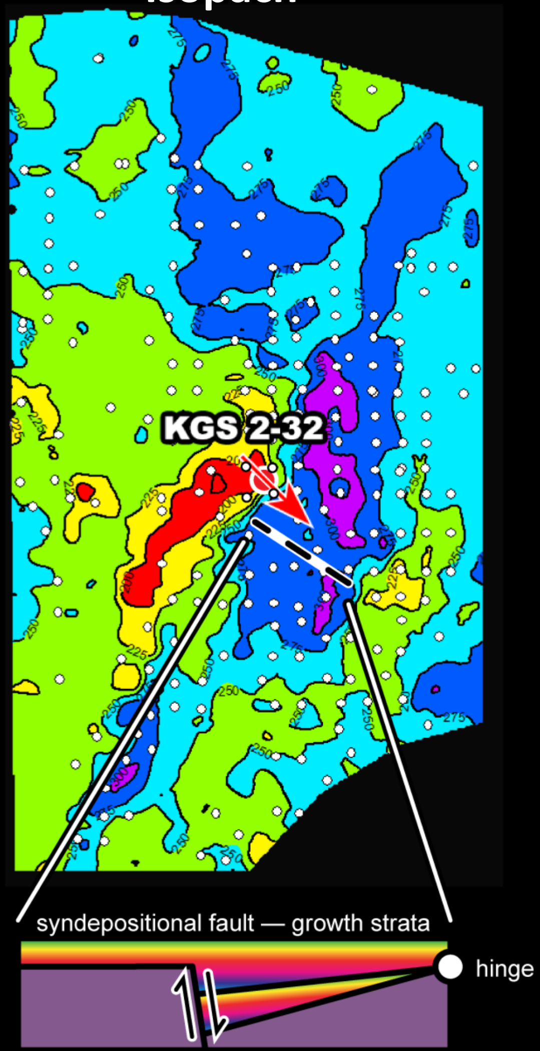
progradation (apparent)

Complex progradation!

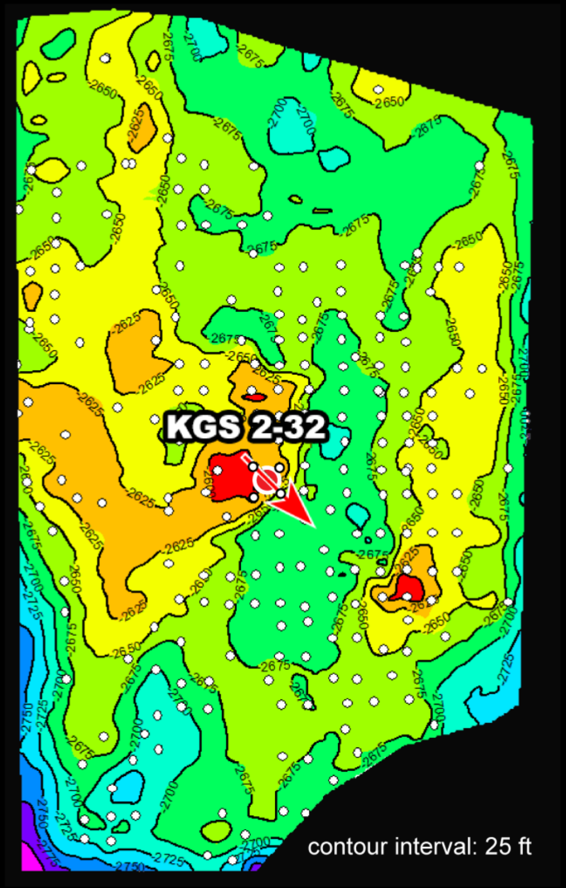
- Local antecedent and syndepositional structures impact
- stratal geometries/terminations
- 1 – line 1 progrades north off structure then aggrades
- 2 – line 2 progrades west from Nemaha uplift
- 3 – line 3 thickens west across hinge, thins over positive crest

Accommodation Generated by Syndepositional Faulting

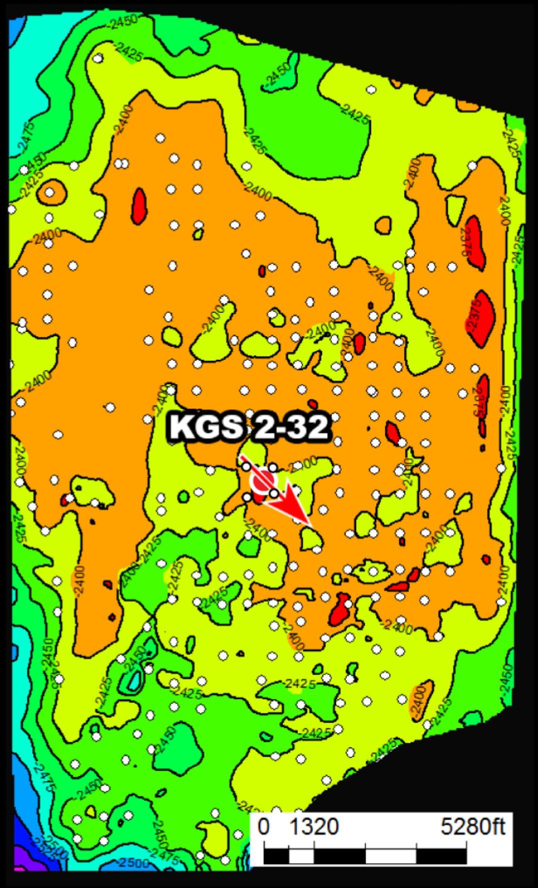
Pierson–Mississippian Isopach



Pierson Structure



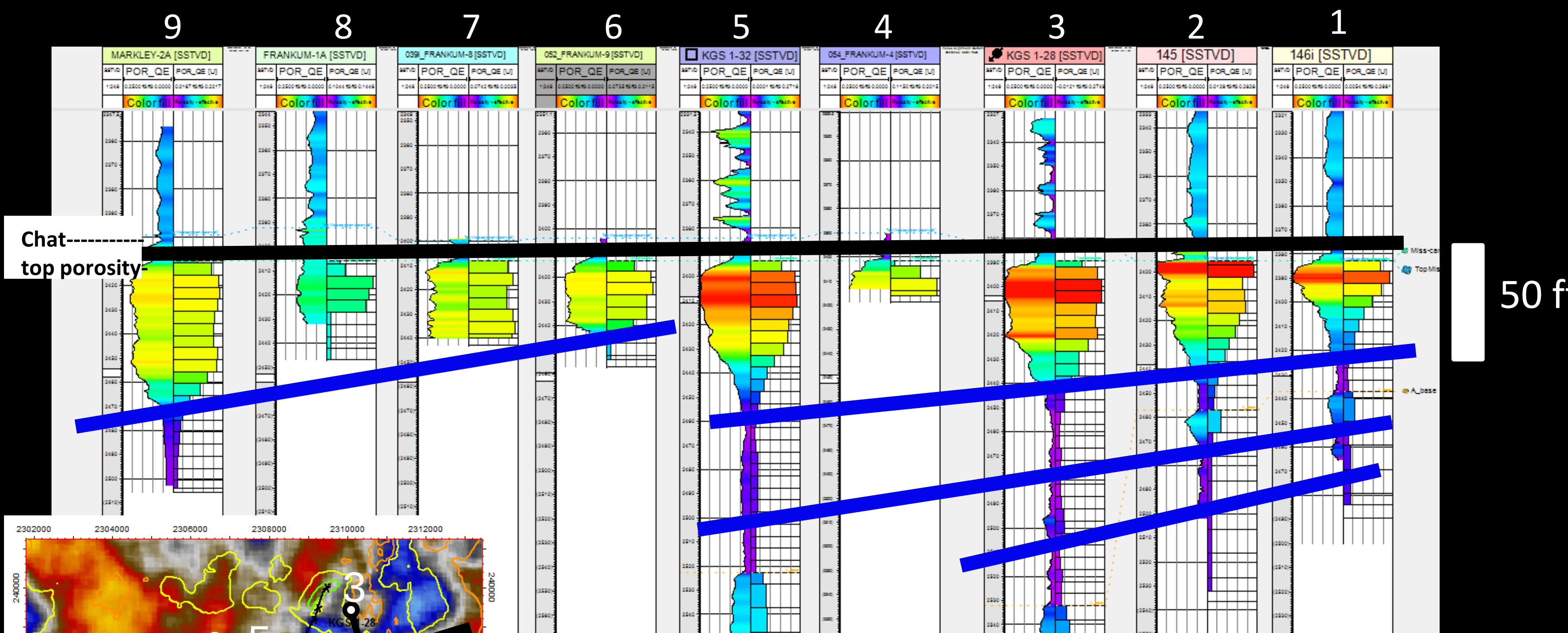
Mississippian Structure

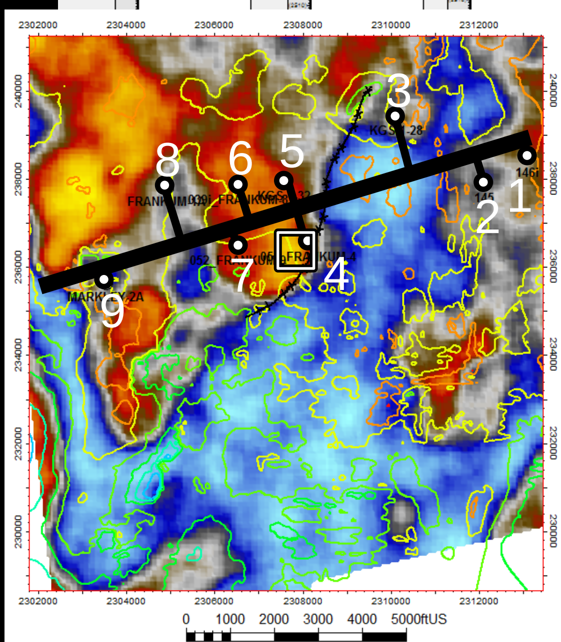


Different seismic motifs recorded across Wellington

- *Aggradation*
- *Progradation*
- *Thickening*

Log Stratigraphy

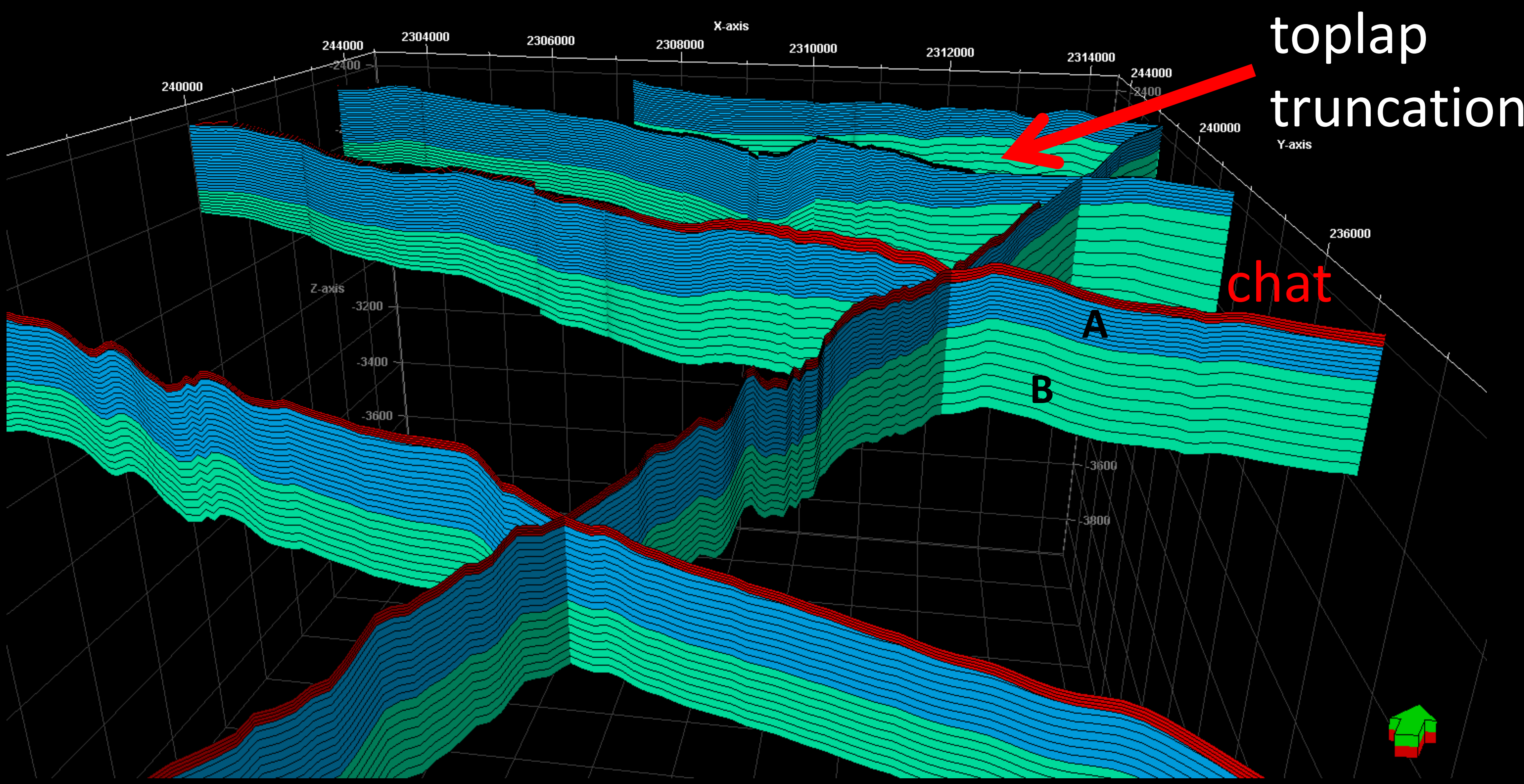




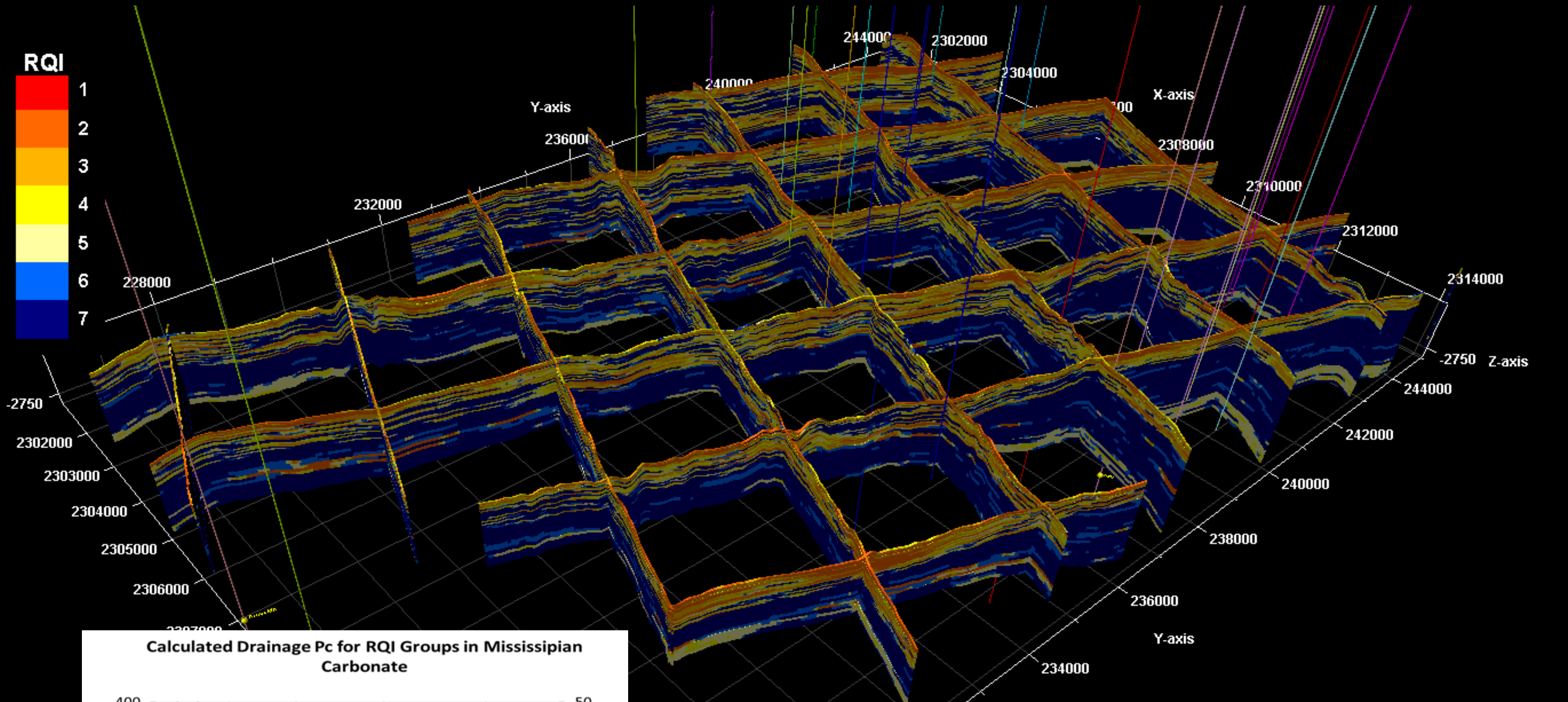
porosity thickening indicative of low-angle, westward progradational wedges

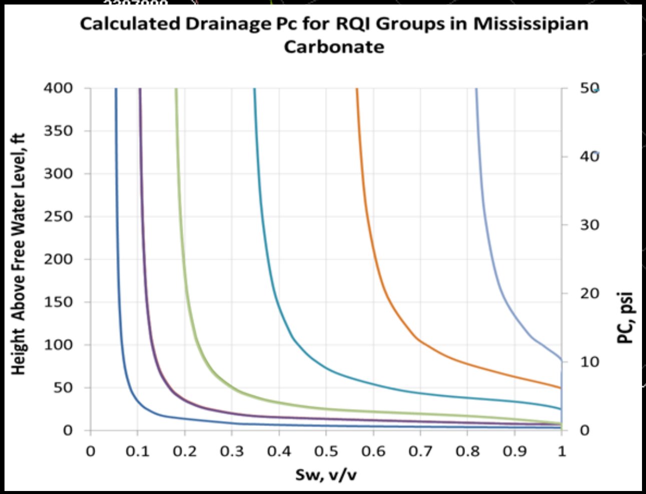
☐ **5-spot CO_2 pilot**

Layering & Erosional Chat

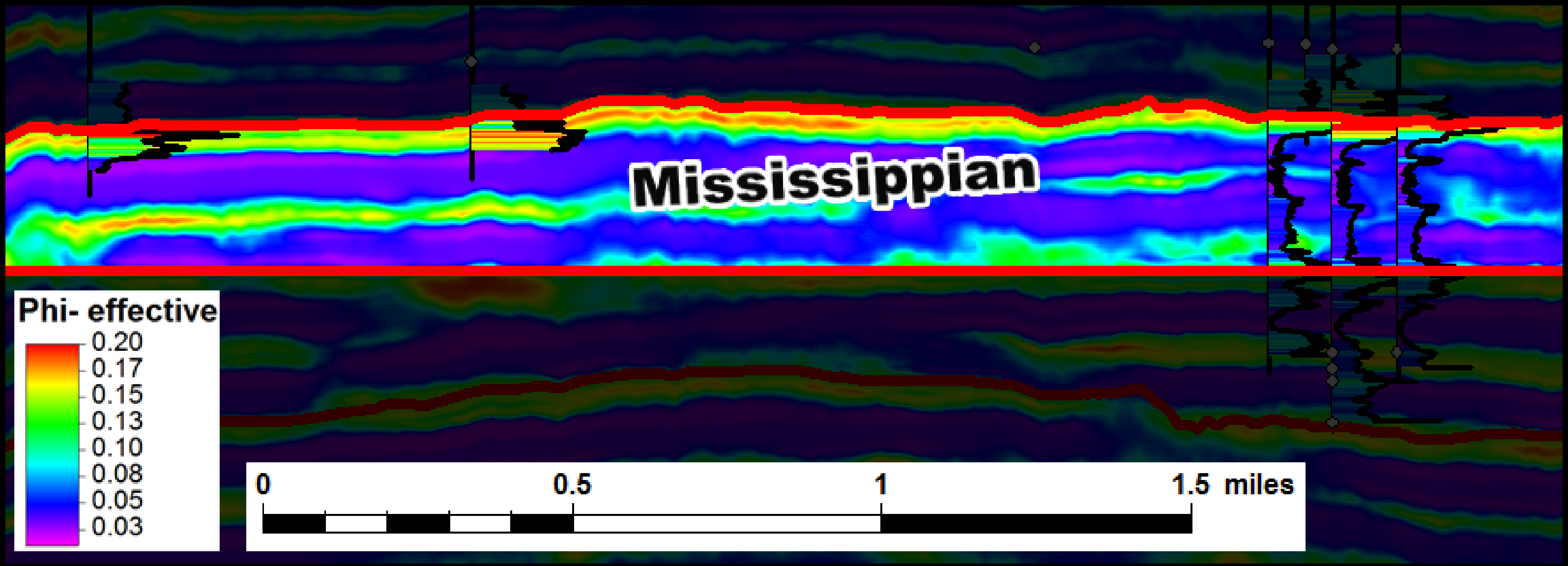


Reservoir Quality Index (Rock Fabrics)

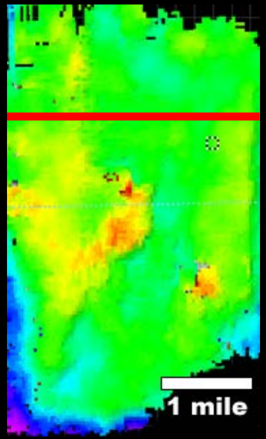




Petrel Genetic Inversion for Porosity

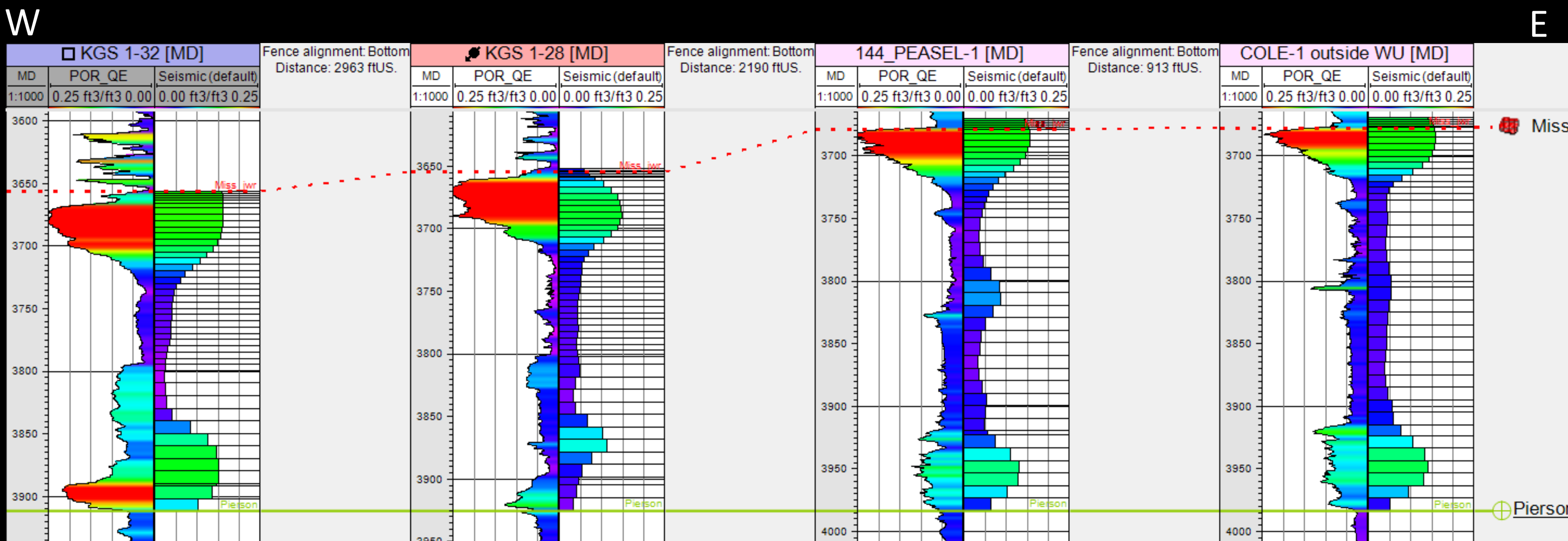


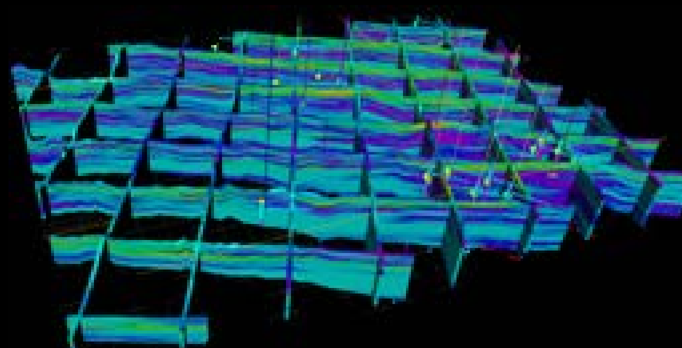
Pierson structure map



- Correlates using smoothed porosity logs
- Best correlation coefficient (0.82)
- In depth!
- Use as a 3-D soft-trend for conditioning between wells
- Fast turn-a-round
- Clinoformal porosity trends

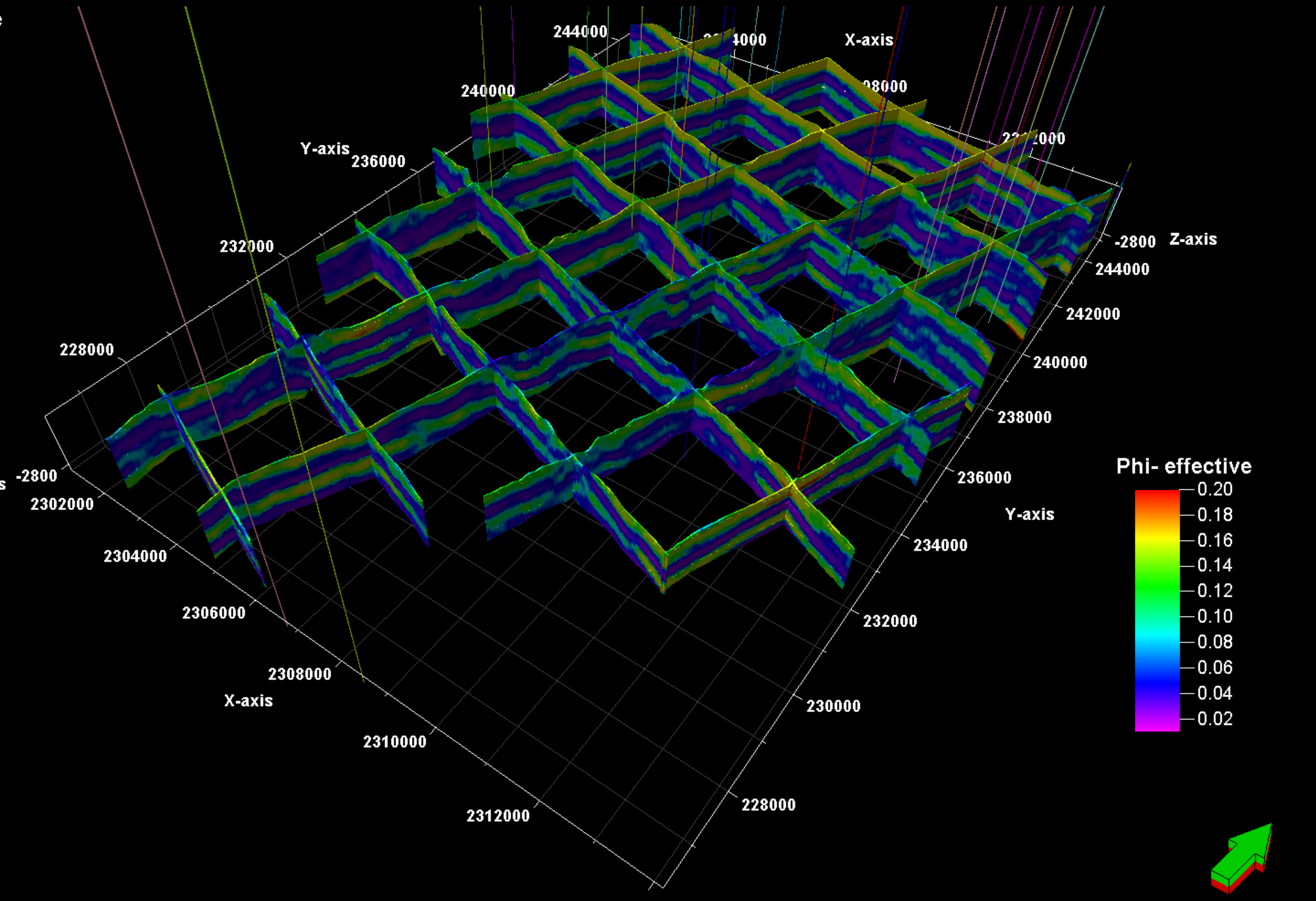
Seismic Porosity Attribute and Upscaling Results



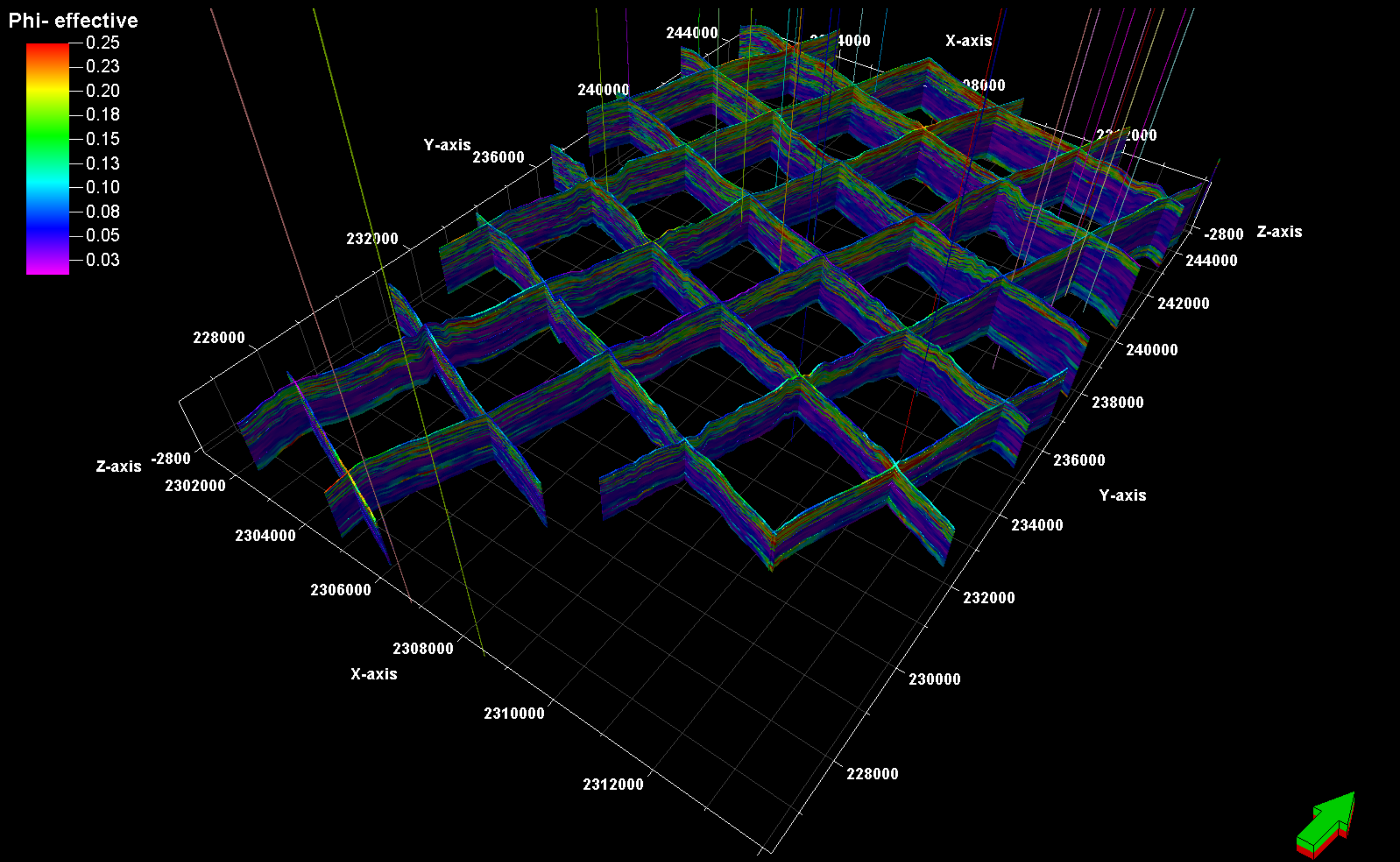


- Smooth porosity log (26 wells)
- Genetic inversion
- Resample to 3-D grid using exact
- Soft trend for Sequential Gaussian Simulation
- Permits clinoformal (i.e., dipping) porosity trends

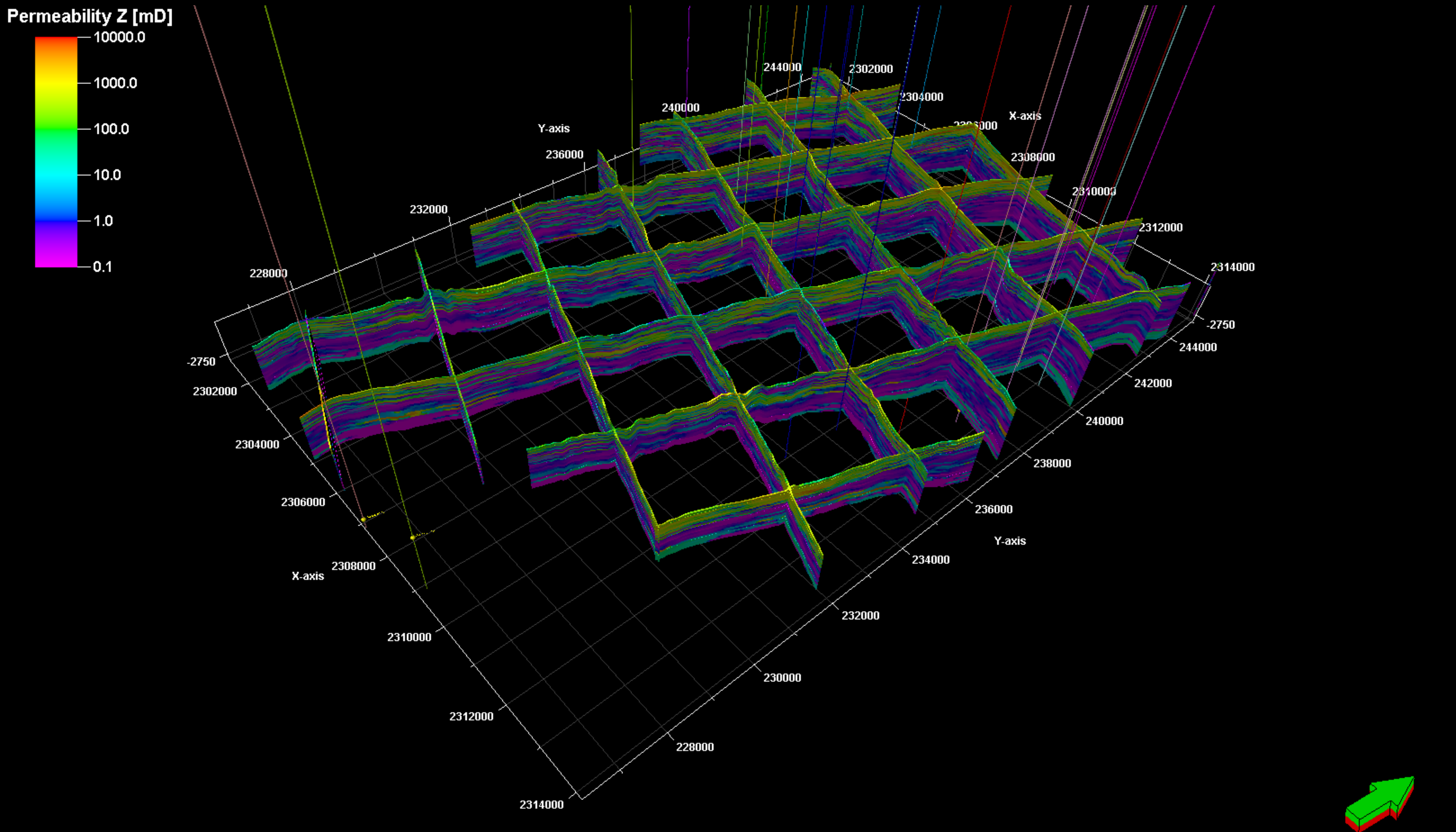
Seismic Porosity sampled to 3-D grid



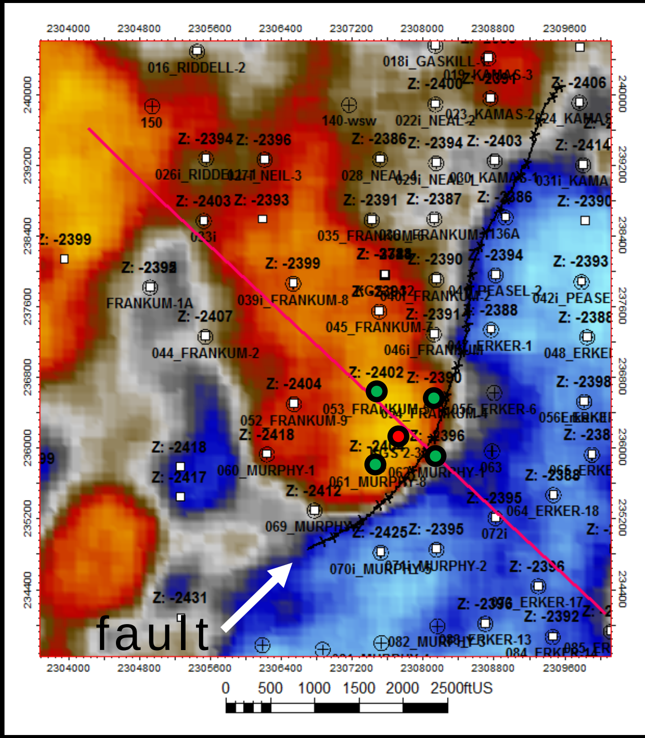
Effective Porosity Model



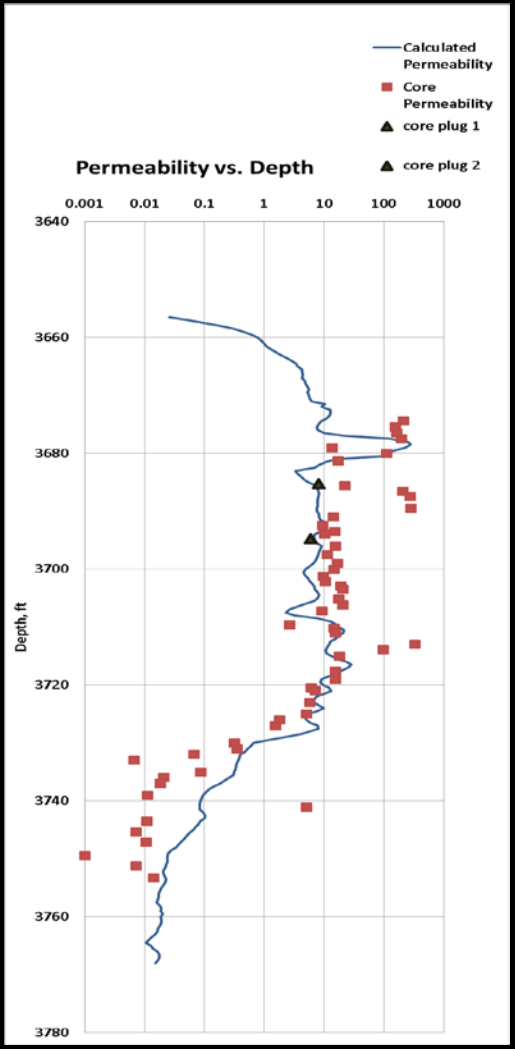
Horizontal Permeability Model



CO_2 Pilot

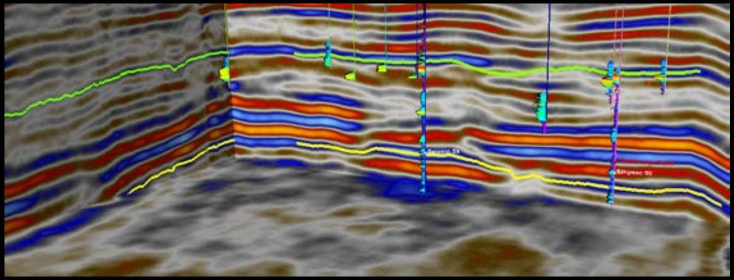


Step-Rate Test



- Good water-flood response – amenable to CO_2 flood
- Inject 30,000 metric tonnes
- Commence late 2015
- Simulations indicate plume resolvable
- Step-rate test indicates transmissibility across fault and has similar permeability as derived from whole core analyses

Summary



1. Mississippian platform margin complex
2. Lower Mississippian has “expected” stratal geometries
3. Upper Mississippian strata impacted by syndepositional tectonics
4. Quachita orogeny impacts Mississippian structure and stratigraphy
5. PSDM-seismic provides 3-D attributes

   benefits modeling structure, stratigraphy, and 3-D petrophysical trends

6. Geostatistical/ geocellular model projects provide an inclusive 3-D workspace for integration of data from multiple disciplines