A Maturing Mississippian Lime Play in the Midcontinent – A Perspective on What We Know and Need to Know*

W. Lynn Watney[1]

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Posted April 20, 2015

*Adapted from presentation at Tulsa Geological Society dinner meeting, February 3, 2015. Please refer to article by the author, "Fluid Migration and Accumulation within the Mississippi: Why 2% Oil Cut Here, 15% Oil Cut one Mile Away," Search and Discovery Article #50953 (2014) (http://www.searchanddiscovery.com/documents/2014/50953watney/ndx_watney.pdf).
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Abstract

The Mississippian Lime Play (MLP) continues to expand, and "sweet spots" are being honed in on by industry using both vertical and horizontal wells. Spiculte-bearing bioclastic packstones and grainstone, sucrosic cherty dolomite, moldic spiculitic wackestones, and organic-bearing shaly carbonate and siliciclastic lithologies, and locally bryozoan pack-grainstone and bafflestone reflect the diversity of pay zones being sought. Current challenges include: 1) resolution of meter-scale stratal architecture along the progradational ramp in southern Kansas and northern Oklahoma; 2) establishing the relative influence of a complex diagenetic history and 3) resolution of the distribution and effects of contemporaneous and post-structural deformation on MLP reservoir development.

The MLP ramp deposits closely resemble lithofacies and geometries of cool-water shelf margins from both ancient and modern analogs including in-situ demosponge and bryozoan colonization on the seafloor. The finer meter-scale sequence stratigraphy suggests that the relative changes in sea level during the Mississippian are notable and consistent with evidence offered in studies of strata external to the area. Sequence stratigraphy is and will be increasingly important toward resolving and mapping the high-resolution paleogeography needed to follow the "sweet spots." Current challenges to this effort involve both seismic and biostratigraphic resolution. In practical terms, lateral and vertically hydraulically isolated pays zones appear to be common, and mapping, drilling, and completing these reservoirs requires a coordinated, cost-effective geoscientific effort. Managing

produced water is one of the biggest challenges in economics, and growing concerns are that at least some of the increased seismicity in the area might be due to large volumes of disposed brine.

Paragenesis of the MLP strata reveals a range of important early and late diagenesis that has collectively influenced porosity and permeability distribution. Early and later subaerial exposure and burial diagenesis including hydrothermal fluid migration led to several episodes of silicification and dolomitization; evaporite precipitation; and porosity development including moldic, micro-vuggy, and fracture pores in brecciated and nodular chert, early sucrosic (intercrystalline porosity) dolomite, and less porous dolosiltite. Bryozoan bioherms identified along the ramp have yet to be established as petroleum reservoir. MLP strata are locally modified by karst where the strata subcrop along the base of the Pennsylvanian.

The significance of contemporaneous and post-depositional structural deformation of the MLP strata is unfolding as larger seismic volumes are acquired and horizontal wells drilled. Tectonism that peaked in the Atokan includes growing evidence for widespread strike-slip fault motion that extended well beyond sites of core tectonism. Directed stresses, occurring pre- and post-peak tectonism, episodically reactivated basement weaknesses, affecting deposition, diagenesis, local thermal maturation, and petroleum migration. Local structural expression of strike-slip faults, such as flower structures, restraining bends, and step-over and relay ramps, offers an additional means to improve prediction of the sweet spots. Effectiveness of horizontal wells and their completions are dependent on structure, rock strength, and stress field. Faults and fractures are often subtly expressed in seismic due to small offsets and discontinuous traces at the level of the Mississippian. Improved resolution will require methods and techniques in seismic acquisition and seismic attribute processing, in addition to careful logging and interpretation of well data.

The re-exploration of the MLP is a classic example of applying new ideas and adapting technologies to find remaining reserves. It is likely that what we will need to know will continue to challenge geoscientists as the play continues to mature.

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"A maturing Mississippian Lime Play in the Midcontinent – A perspective on what we know and need to know"

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Outline

- Reservoir Lithofacies
- Diagenetic History/Paragenesis
- Sequence Stratigraphy
- Structural Framework
- Managing Produced Water

Special Acknowledgement:

M.S. Thesis, KU by Luis Montalvo defended with Honors, Jan. 2015
PETROGRAPHY AND PARAGENESIS OF DIAGENETIC MINERAL PHASES IN CHERTY AND DOLOMITIC SPICULITE STRATA, MISSISSIPPIAN, SOUTH-CENTRAL KANSAS; co-advised by Luis Gonzalez

Kansas Mississippian Stratigraphic Column

(Maples, 1994)

Period	Stage	Formations/Members (Goebel, 1968)	Formations/Members (Maples, 1994)	Stage	Period
MISSISSIPPIAN	Chesteran	unamed unit(s)	Shore Airport Formation	Chesteran	MISSISSIPPIAN
	Meramecian	St. Genevieve Limestone	St. Genevieve Limestone		
		St. Louis Limestone	St. Louis Limestone / Stevens Mbr. / Hugoton Mbr.	Meramecian	
		Salem Limestone	Salem Limestone		
		Warsaw Limestone	Warsaw Limestone		
	Osagean	Keokuk Limestone / Burlington Limestone / Burlington-Keokuk Limestone	Short Creek Oolite Mbr. / Keokuk Limestone / Burlington Limestone / Burlington-Keokuk Limestone	Osagean	
		Fern Glen Limestone / Reed Spring Ls. Mbr. / St. Joe Ls. Mbr.	Reed Spring Ls. Mbr. / Elsey Fm. / Pierson Limestone		
	Kinderhookian	Gilmore City Limestone	Gilmore City Limestone / Northview Formation	Kinderhookian	
		Sedalia Dolomite (Northview Shale)	Sedalia Formation		
		Chouteau Limestone (Compton Limestone)	Compton Limestone		
		Boice Shale	Hannibal Shale		
DEVONIAN	?	Chattanooga Shale	Chattanooga Shale	?	DEVONIAN

Shelf Magin "Cowley facies" Thompson and Goebel, 1968)

Unconformity

duration

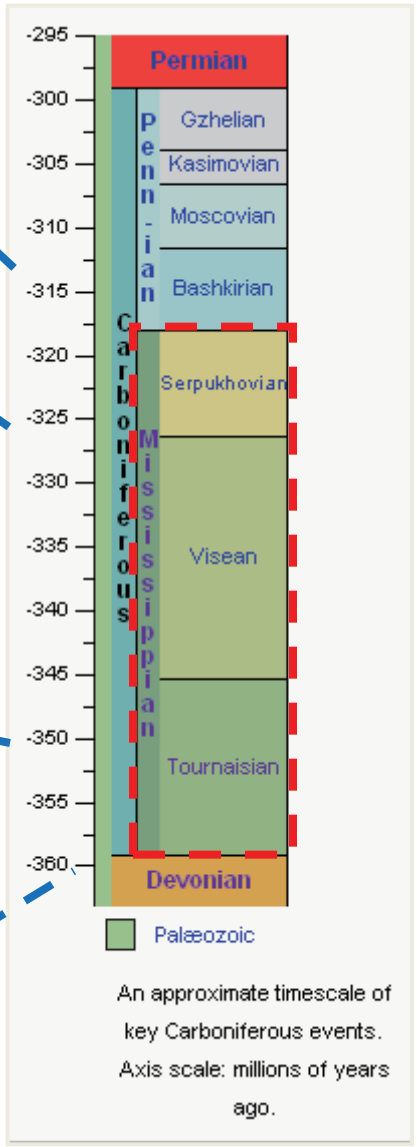
~12 Ma

~7 Ma

~15 Ma

~7 Ma

Lower Carboniferous – Mississippian Subsystem

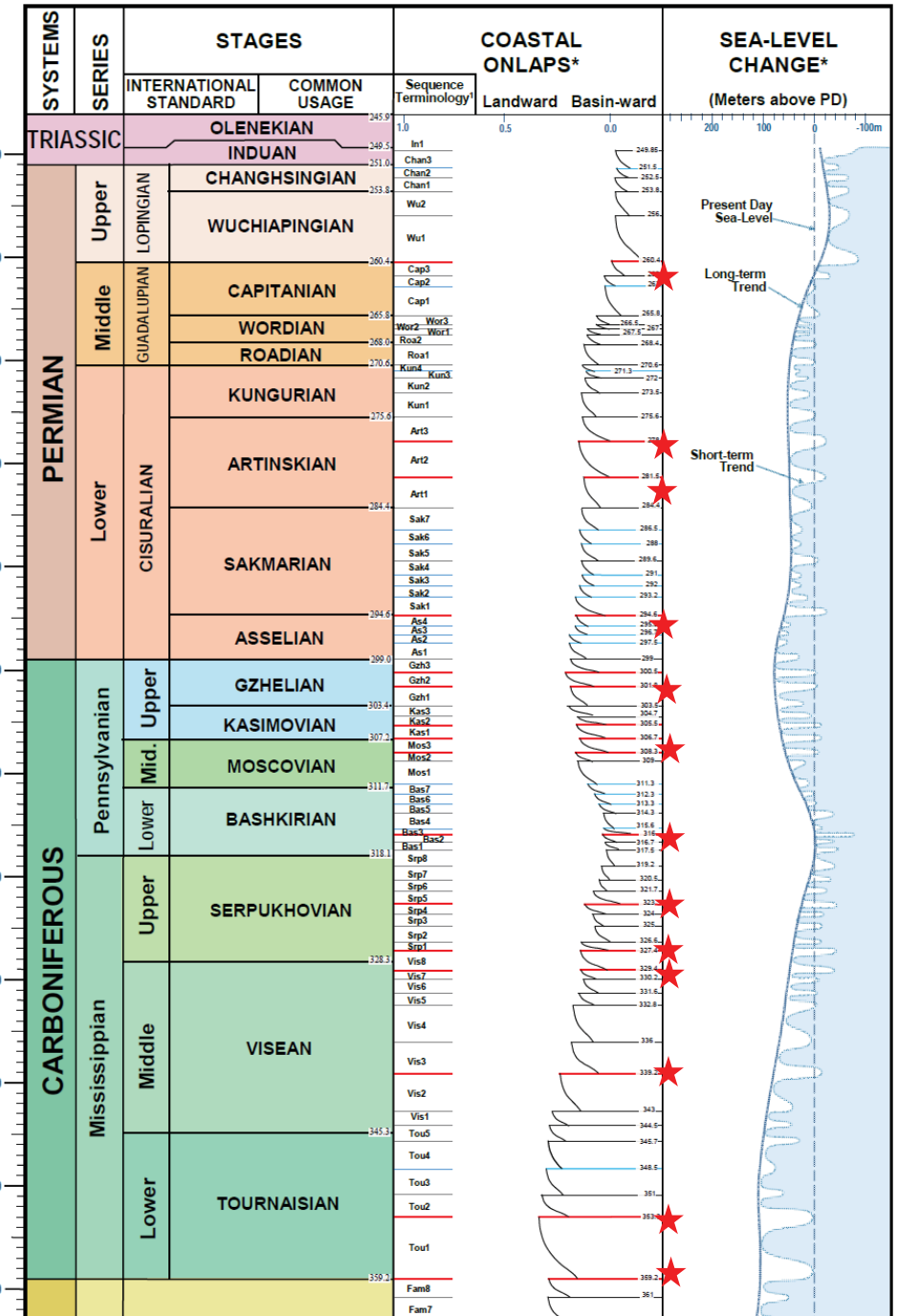


Arkoma Basin – Caney Shale Equivalent to Fayetteville & Barnett shales

41 Ma total

http://en.wikipedia.org/wiki/Carboniferous

PALEOZOIC SEA-LEVEL CHANGE AND COASTAL ONLAPS



[1] Sequence terminology is derived from combination of abbreviated stage names and a sequential numerical appendix similar to the sequence boundary names of Hadenbol et al. (1998). Coastal onlap curves of Paleozoic are from Haq and Shutter (2008) and that for the Mesozoic-Cenozoic are from Hardenbol et al. (1998) with minor revision.

Major relative sea-level change* (>75 m)
Medium relative sea-level change (25-75 m)
Minor relative sea-level change (<25 m)

** The magnitudes of sea-level change in this chart follow the estimation of Haq and Shutter (2008), and Hardenbol and others (1998). However, there is little consensus on the range of sea-level changes though it is a general belief that the sea-level during most of the Phanerozoic has been less than ±100 meters of the present day level.*

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★ Emphasis on significant lowstands

- Especially important for those working in basins and looking for incised valleys

e.g., 2 degree slope
100 meters change
= 2.8 km lateral shift in shoreline

100 m?

100 m?

100 m?

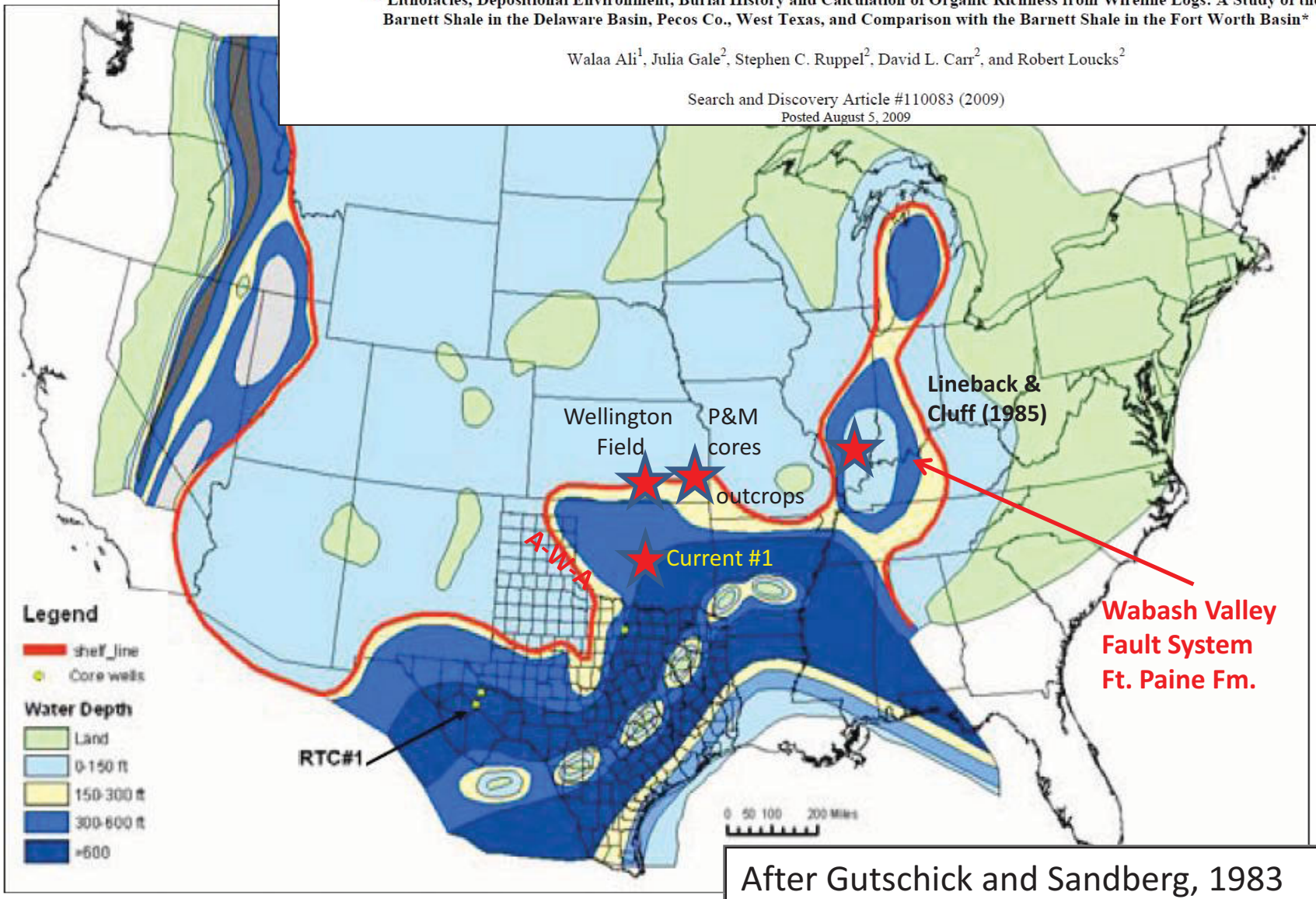
Sepmstrata.org

Paleogeography during mid-Mississippian expressed by water depth

AV Lithofacies, Depositional Environment, Burial History and Calculation of Organic Richness from Wireline Logs: A Study of the Barnett Shale in the Delaware Basin, Pecos Co., West Texas, and Comparison with the Barnett Shale in the Fort Worth Basin*

Walaa Ali[1], Julia Gale[2], Stephen C. Ruppel[2], David L. Carr[2], and Robert Loucks[2]

Search and Discovery Article #110083 (2009)
Posted August 5, 2009



After Gutschick and Sandberg, 1983

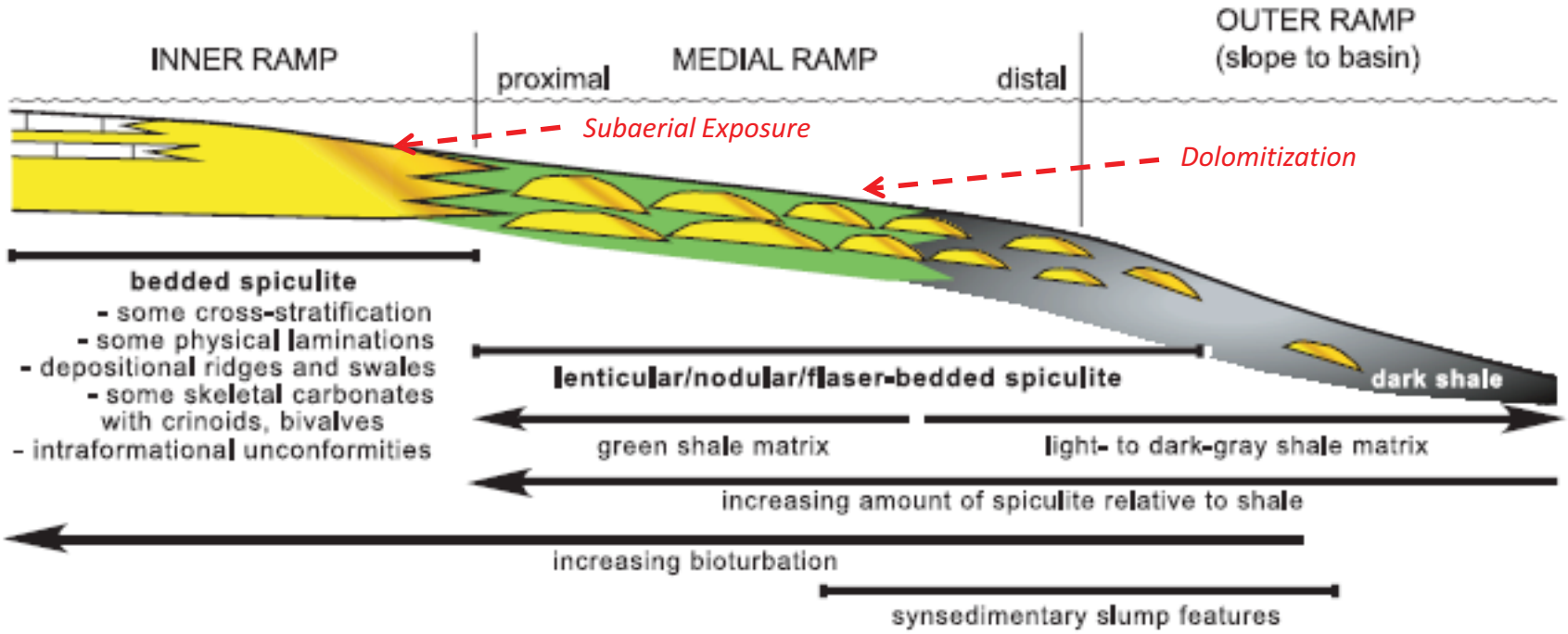
Spectrum of Potential Reservoir Lithofacies

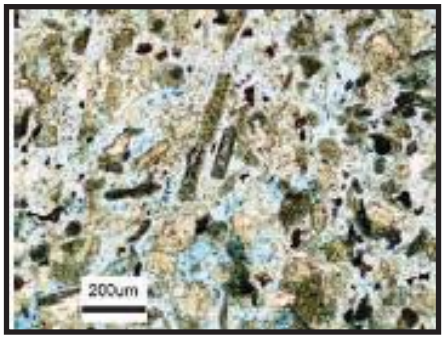
Inner Ramp Tripolite to Outer Ramp Basinal Deposits

North

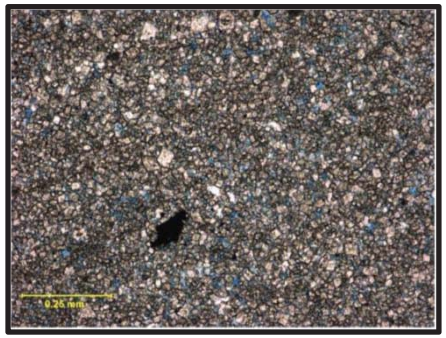
Modified from S. J. Mazzullo, Brian W. Wilhite, and I. Wayne Woolsey (2009)

South

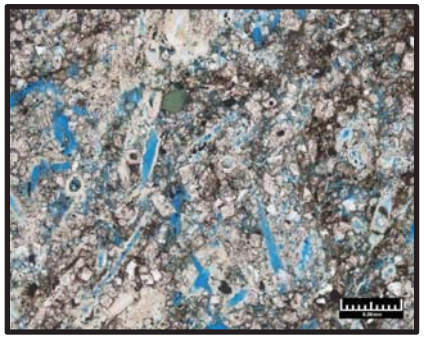




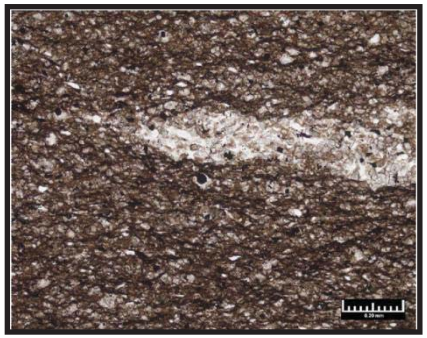
tripolite



cherty dolomite



dolomitic spiculite

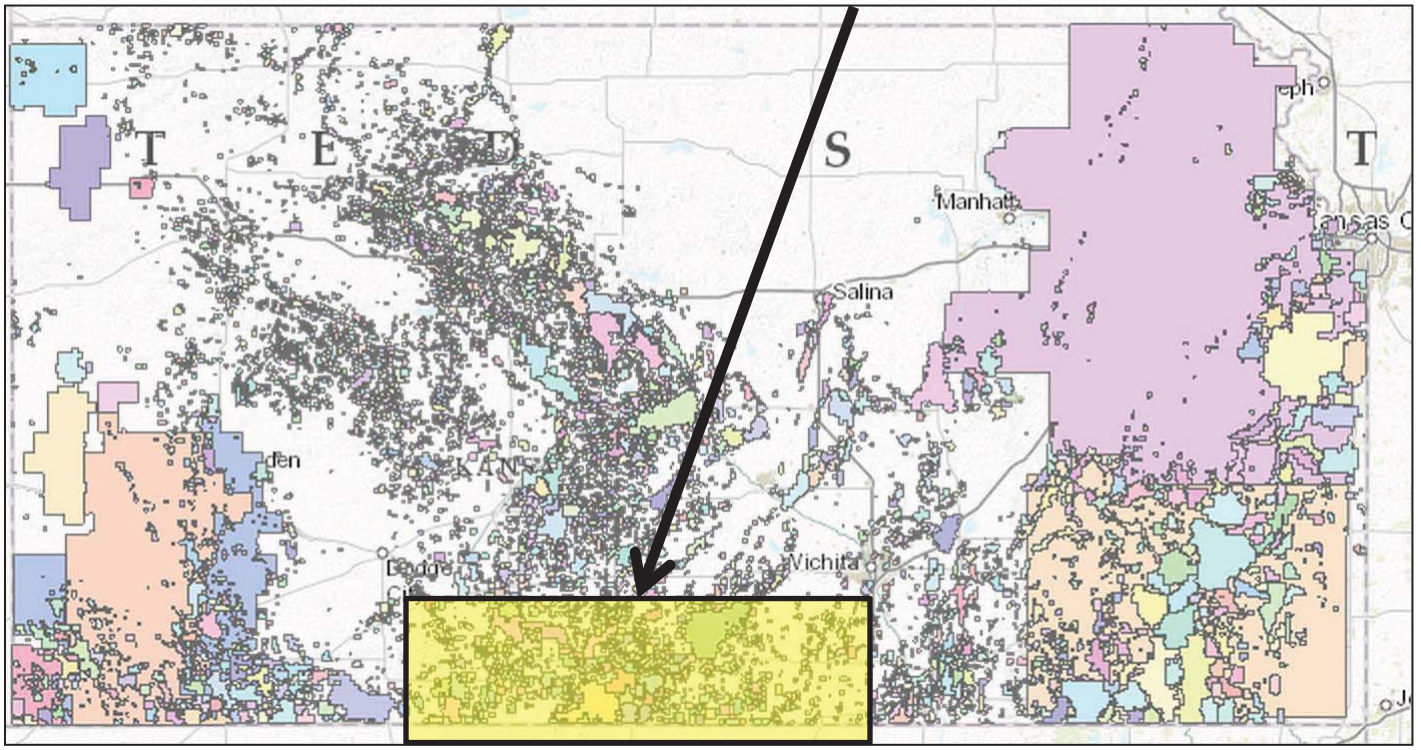


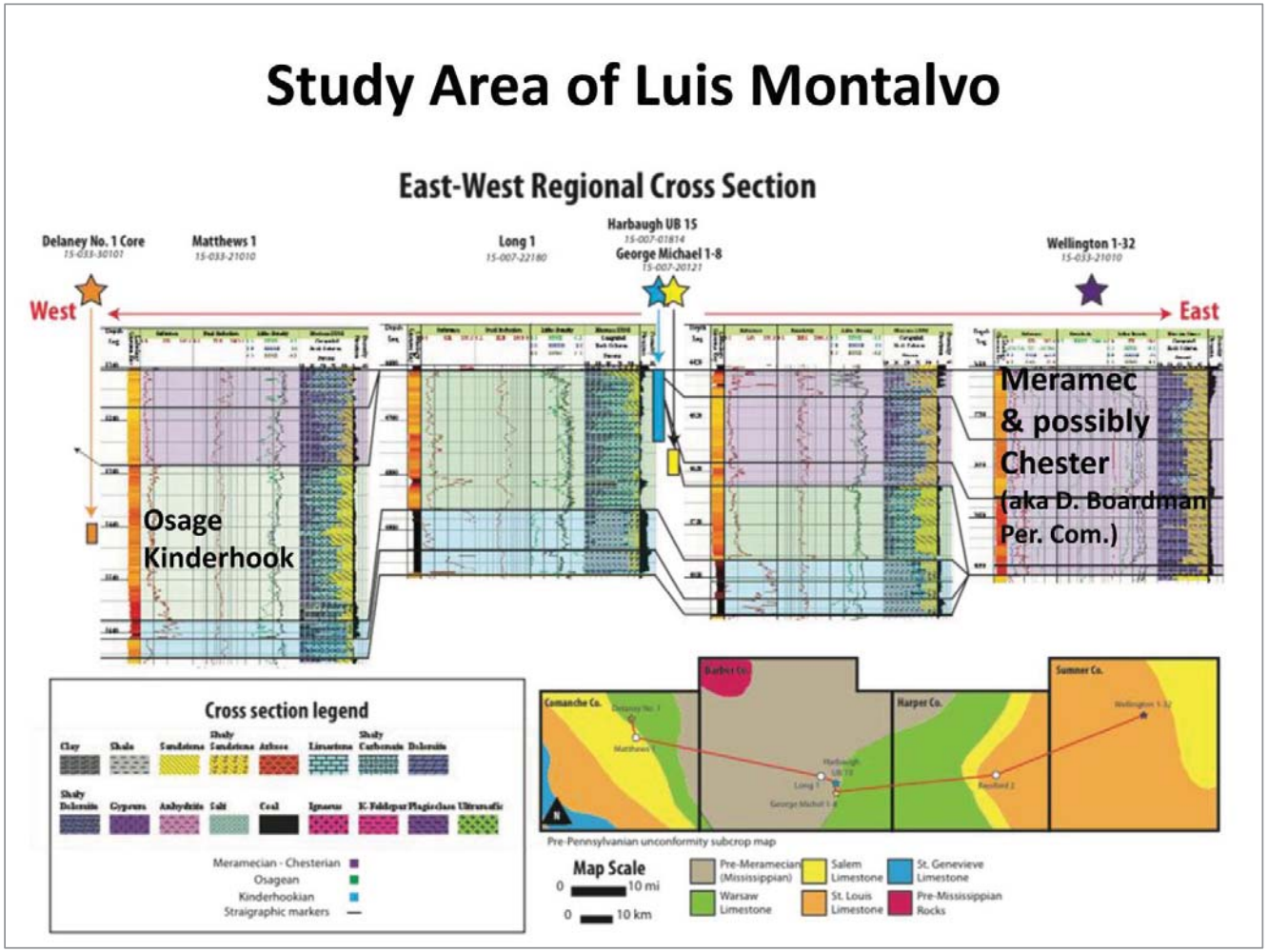
argillaceous, organic dolomitic siltstone

Reservoir Lithofacies

- Conventional
- Unconventional

Study area of Luis Montalvo



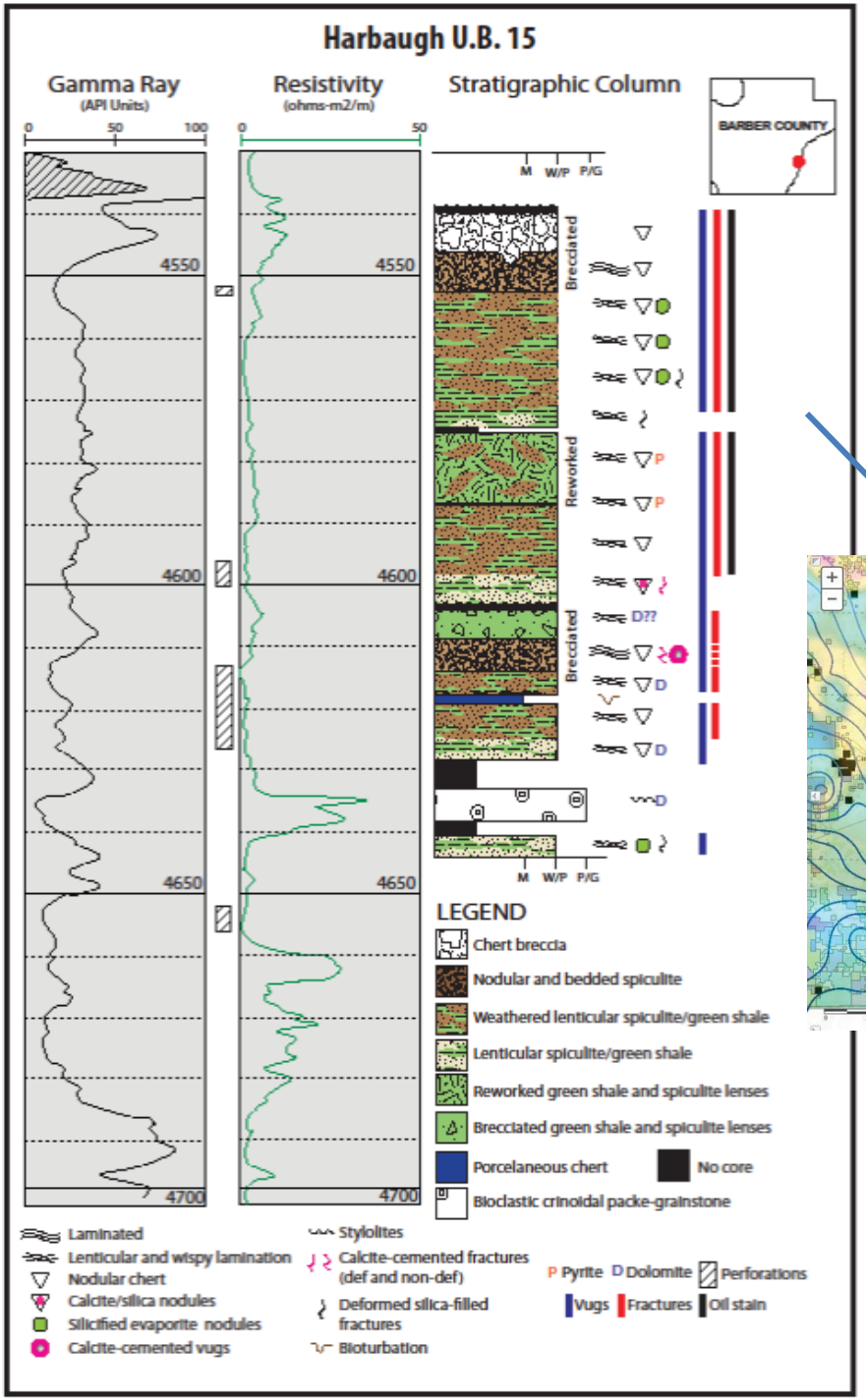


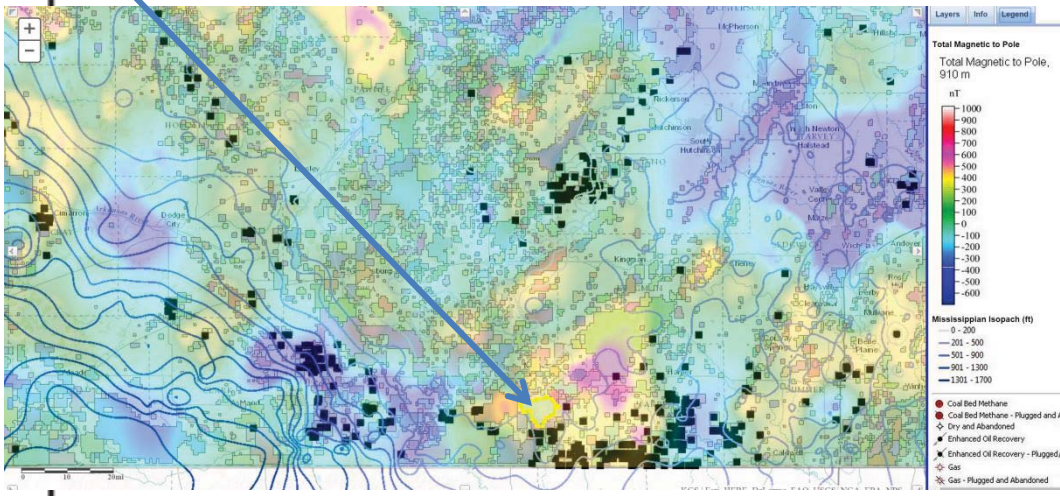
Presenter's notes: East-west trending cross section in south-central Kansas (Comanche, Barber, Harper and Sumner Co.) showing the structural, stratigraphic and petrophysical character of the Mississippian. The approximate stratigraphic position of the Mississippian interval studied in cores is shown (orange star and orange rectangle – *Delaney No. 1*; blue star and blue rectangle – *Harbaugh UB 15*; yellow star and yellow rectangle – *George Michael 1-8*; purple star – *Wellington 1-32*). Cross section is flattened to the Mississippian top. Well logs are not to scale. All well logs are modified versions from Kansas Geological Survey online databases (<*http://maps.kgs.ku.edu/co2/*> and <*http://www.kgs.ku.edu/PRS/Ozark/Summary/*>).

Rhodes Field Core

Proximal Ramp

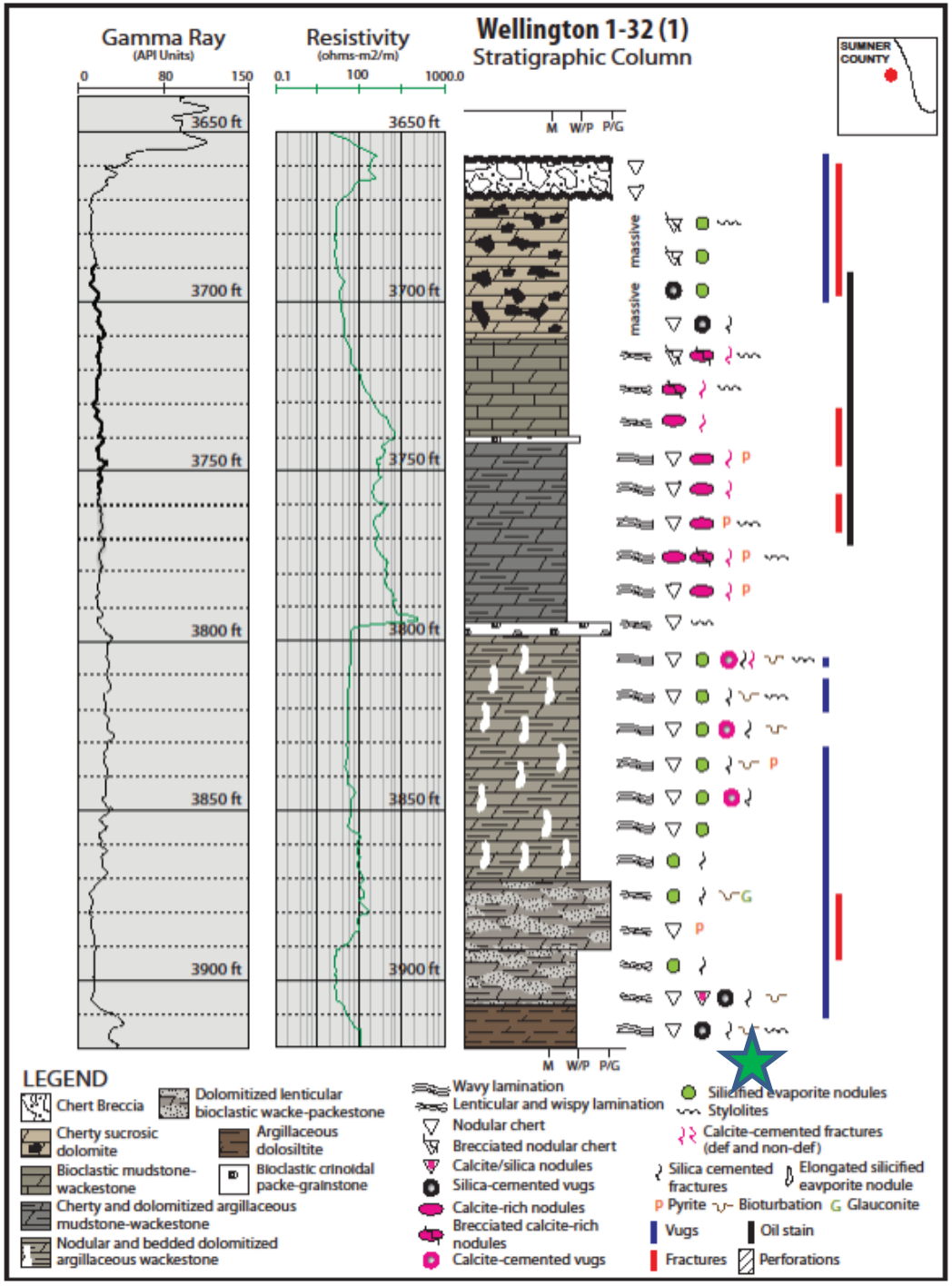
Osagean-Kinderhookian age

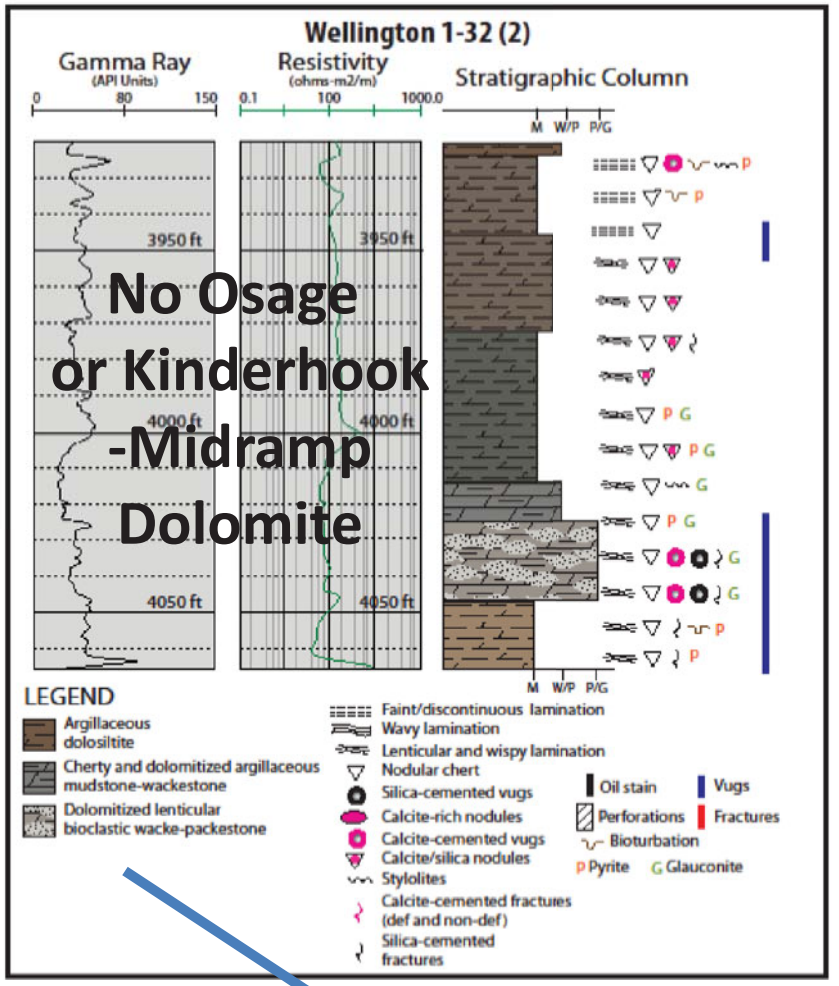


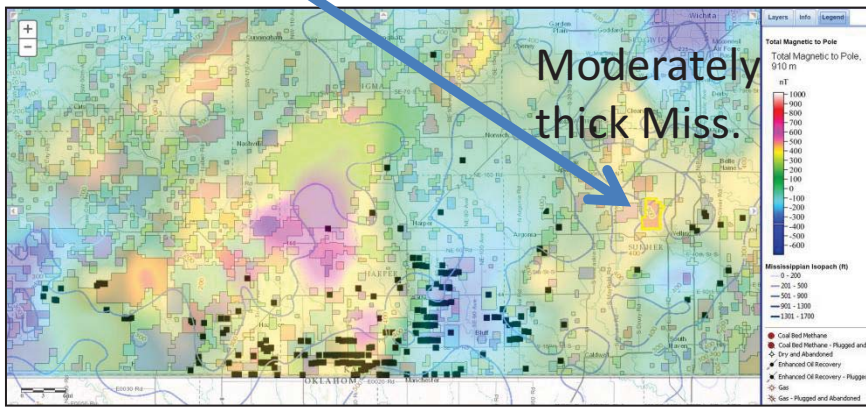


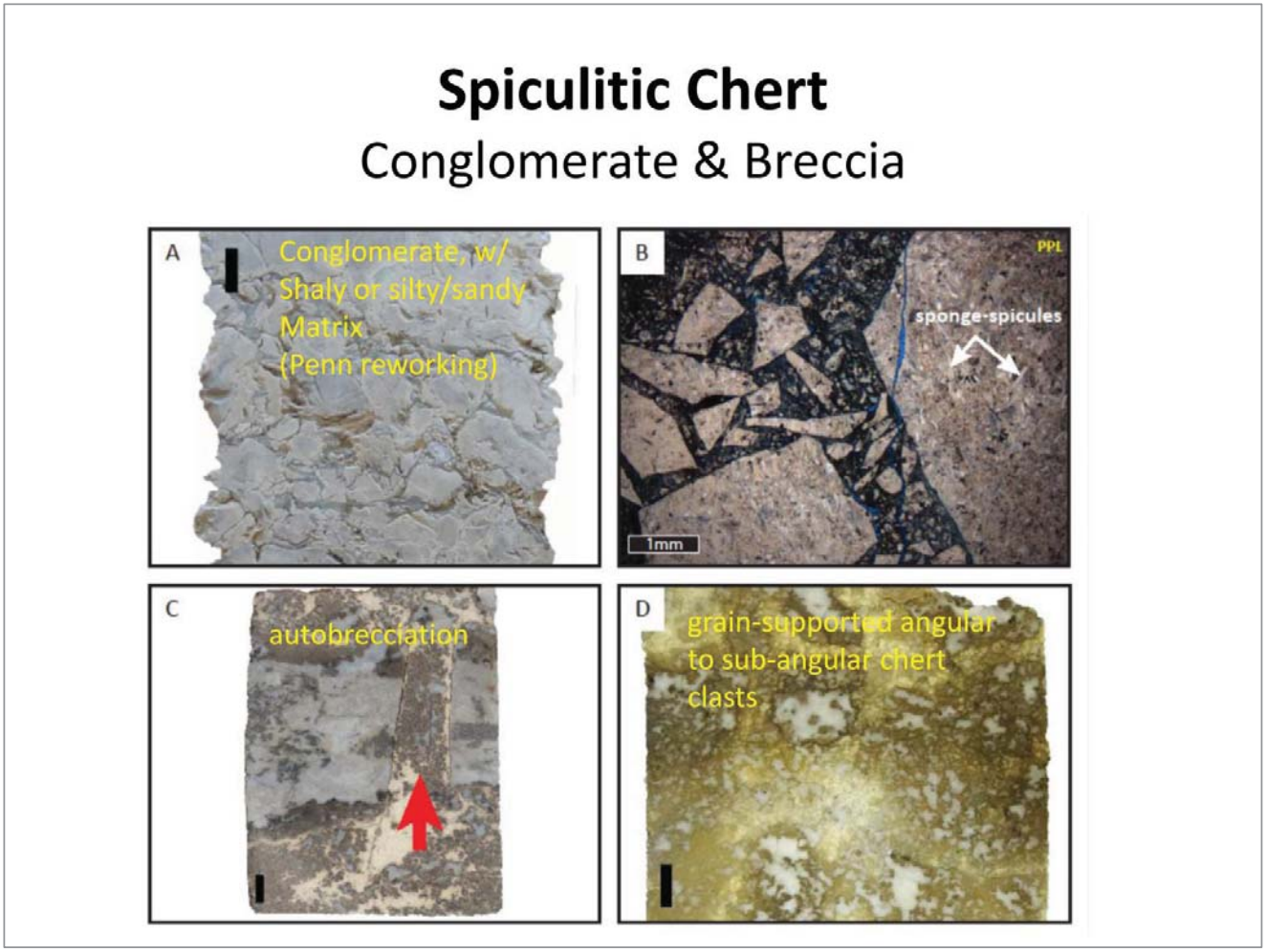
Mississippian isopachous map (contours) and total magnetic field reduced to pole (color)

- **Thin Mississippian**
- **Weathered spiculite**

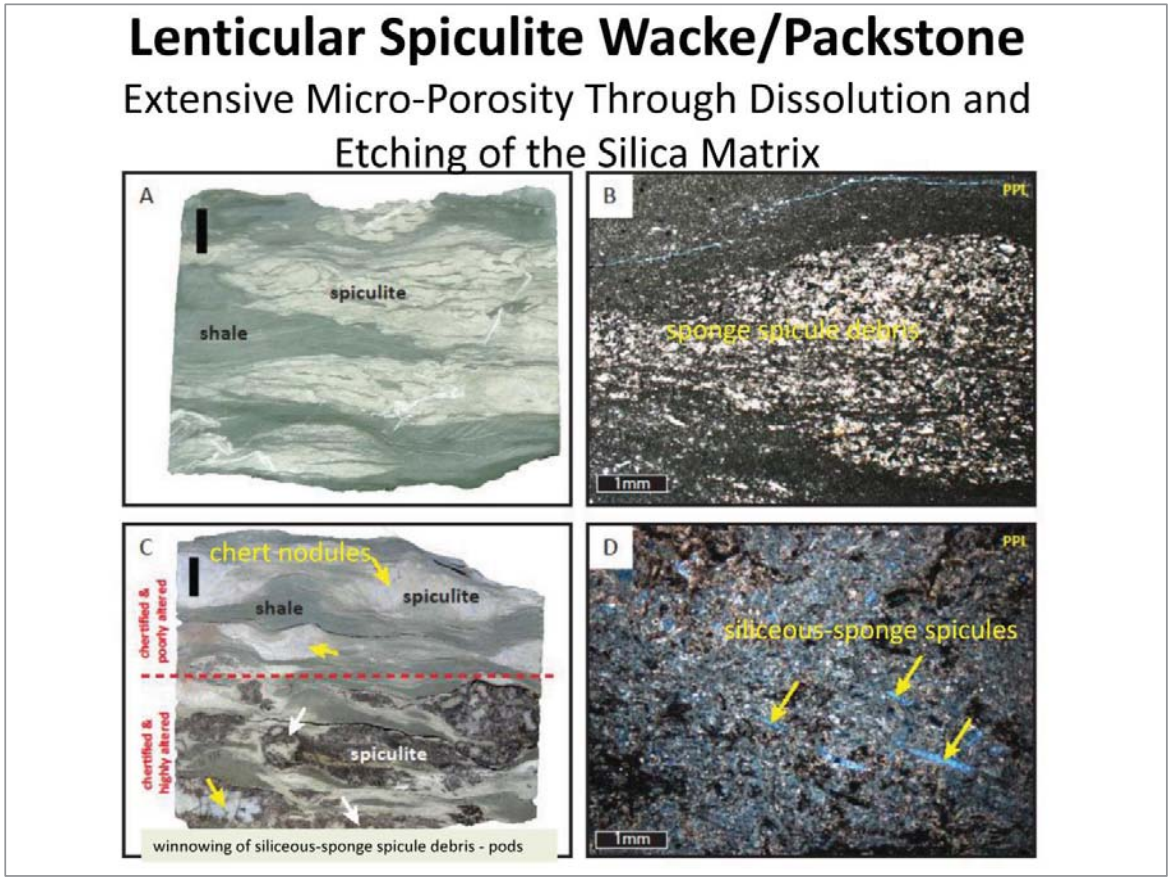

Wellington 1-32 (1)
Stratigraphic Column
Gamma Ray
(API Units)
Resistivity
(ohms-m2/m)
SUMNER COUNTY
3650 ft
3700 ft
3750 ft
3800 ft
3850 ft
3900 ft
M W/P P/G
massive
massive
LEGEND
Chert Breccia
Cherty sucrosic dolomite
Bioclastic mudstone-wackestone
Cherty and dolomitized argillaceous mudstone-wackestone
Nodular and bedded dolomitized argillaceous wackestone
Dolomitized lenticular bioclastic wacke-packestone
Argillaceous dolosiltite
Bioclastic crinoidal packe-grainstone
Wavy lamination
Lenticular and wispy lamination
Nodular chert
Brecciated nodular chert
Calcite/silica nodules
Silica-cemented vugs
Calcite-rich nodules
Brecciated calcite-rich nodules
Calcite-cemented vugs
Silicified evaporite nodules
Stylolites
Calcite-cemented fractures (def and non-def)
Silica cemented fractures
Elongated silicified evaporite nodule
Pyrite
Bioturbation
Glauconite
Vugs
Oil stain
Fractures
Perforations


Wellington 1-32 (2)
Gamma Ray
(API Units)
Resistivity
(ohms-m2/m)
Stratigraphic Column
3950 ft
4000 ft
4050 ft
M W/P P/G
No Osage
or Kinderhook
-Midramp
Dolomite
LEGEND
Argillaceous dolosiltite
Cherty and dolomitized argillaceous mudstone-wackestone
Dolomitized lenticular bioclastic wacke-packestone
Faint/discontinuous lamination
Wavy lamination
Lenticular and wispy lamination
Nodular chert
Silica-cemented vugs
Calcite-rich nodules
Calcite-cemented vugs
Calcite/silica nodules
Stylolites
Calcite-cemented fractures (def and non-def)
Silica-cemented fractures
Oil stain
Vugs
Perforations
Fractures
Bioturbation
Pyrite
Glauconite


Moderately
thick Miss.



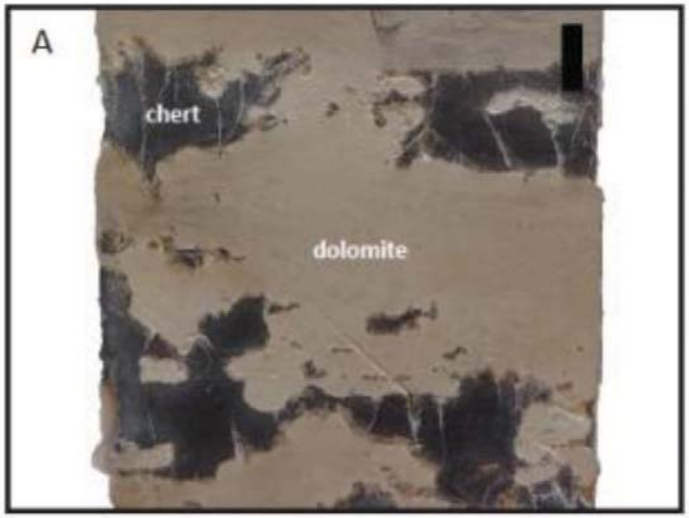
Presenter's notes: Scale bar on slab photos is 1 cm. **A**) Core slab of a chert breccia. This breccia consists of grain-supported angular to sub-angular chert clasts on a shaly matrix. (*Wellington 1-32, 3668 ft*). **B**) Photomicrograph of a breccia consisting of angular cherty spiculite clasts floating on a silicified clay matrix. (*Harbaugh U.B.15, 4588 ft*). **C**) Core slab of a chert breccia. Note the abundance of chert clasts varying largely in size and floating on a clay-rich matrix. Autobrecciation is suggested from the large gray mottled clast that has fractured but remains relatively in-place. The fracture is filled with brecciated material (red arrow). (*George Michael 1-8, 4592 ft*). **D**) Core photograph of a chert breccia consisting of grain-supported angular to sub-angular chert clasts in a clayey silicified matrix. (*Harbaugh U.B.15, 4547 ft*).

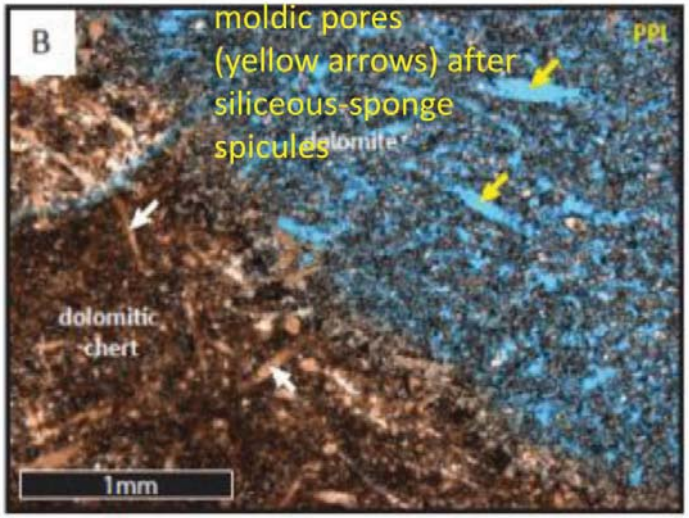


Presenter's notes: Scale bar on slab photos is 1 cm. **A**) Core slab of interbedded green shale and lenticular spiculite wacke/packstone. Note that the green shale looks wispy laminated inside the spiculite lenses. Spiculite lenses result from winnowing of siliceous-sponge spicule debris by waves creating small pods where the coarse material accumulates. (*Harbaugh U.B.15, 4642 ft*). **B**) Photomicrograph of illustrating a lens of sponge spicule debris surrounded by the green shale matrix. Note that the lens consists of disarticulated and broken siliceous-sponge spicules. The original hollow siliceous spicules are cemented and replaced with microcrystalline quartz. (*Harbaugh U.B.15, 4643 ft*). **C**) Core slab of interbedded green shale and lenticular spiculite wacke/packstone. This sample is similar to A, but it has undergone significant diagenetic alteration. Pervasive silicification of spiculite lenses results in the formation of chert nodules (yellow arrows). After weathering and possibly hydrothermal alteration of the chert nodules, they generate extensive micro-porosity through dissolution and etching of the silica matrix. Some refer to this micro-porous chert texture (white arrows) as tripolite (Costello et. al., 2012; Ramaker et al., 2014). (*Harbaugh U.B.15, 4594 ft*). **D**) Photomicrograph illustrating a highly porous spiculite lens after leaching of siliceous-sponge spicules (yellow arrows) and the cherty matrix. Note that after impregnation with blue epoxy the micro-porous chert sections are stained blue. (*Harbaugh U.B.15, 4566 ft*).

Cherty Sucrosic Dolomite

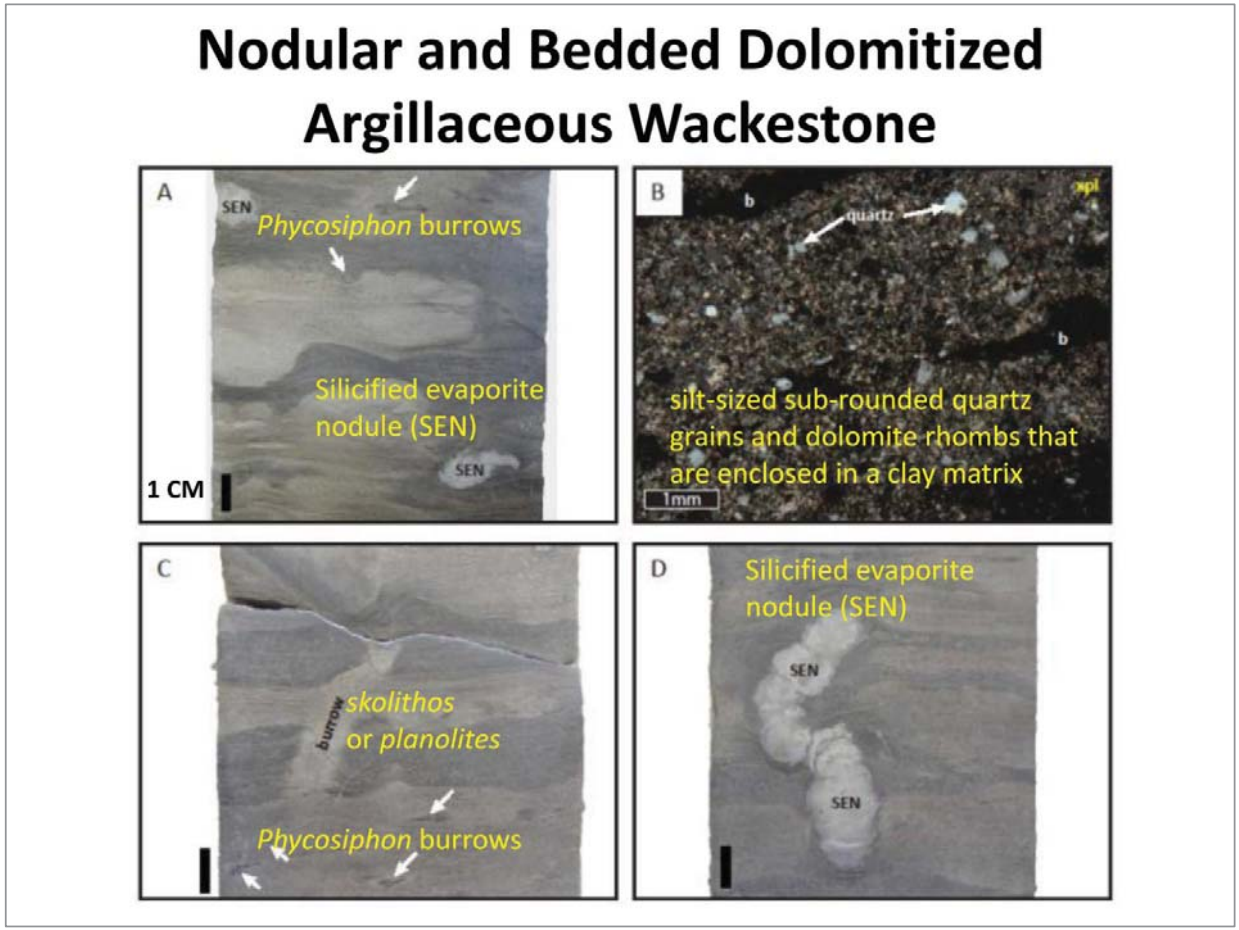
Sedimentary Features Have Been Masked During Dolomitization



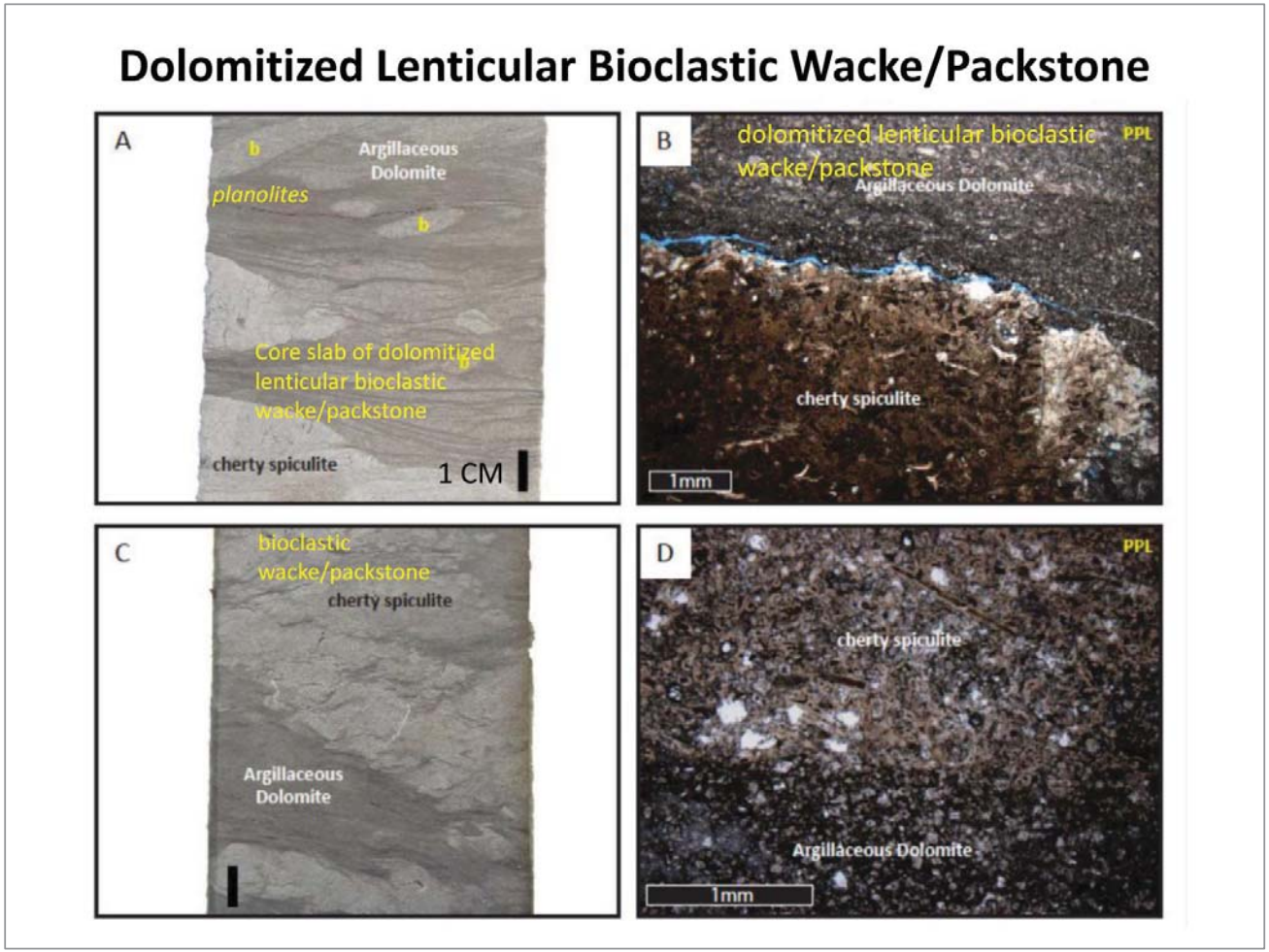


Convoluted dark gray chert nodules are scattered in the matrix and appear autobrecciated

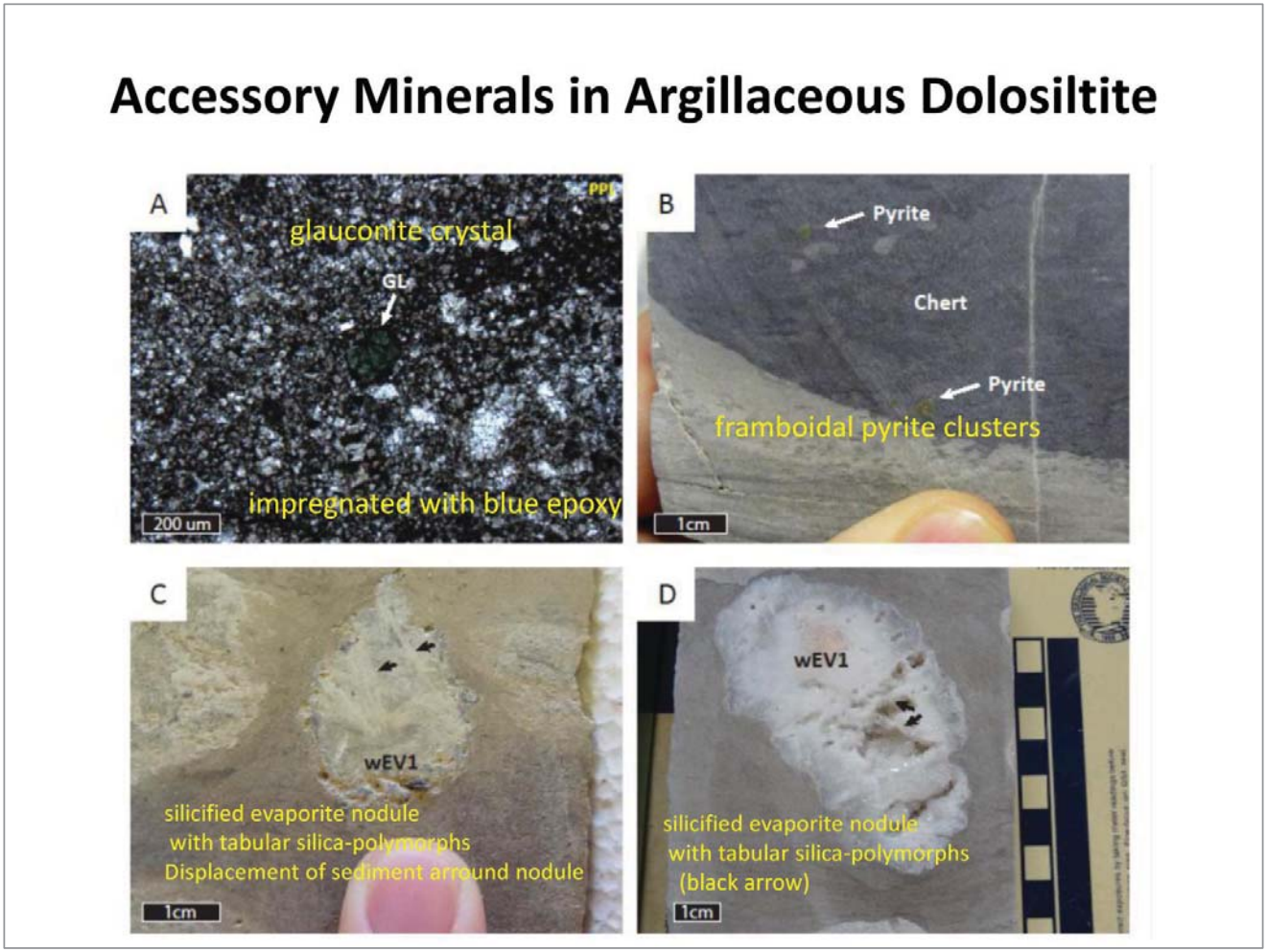
Presenter's notes: Scale bar on slab photos is 1 cm. **A**) Core slab of a cherty sucrosic dolomite. Sedimentary features have been masked during dolomitization. Convoluted dark gray chert nodules are scattered in the matrix and appear autobrecciated (*Wellington 1-32, 3671 ft*). **B**) Photomicrograph of cherty sucrosic dolomite. Note the large amount of intercrystalline pores and moldic pores (yellow arrows) after siliceous-sponge spicules. The chert nodules are partially replaced with dolomite and the sponge-spicules inside the nodules (white arrows) are preserved with microcrystalline quartz. Porosity is low inside the chert nodules (*Wellington 1-32, 3671.8 ft*).



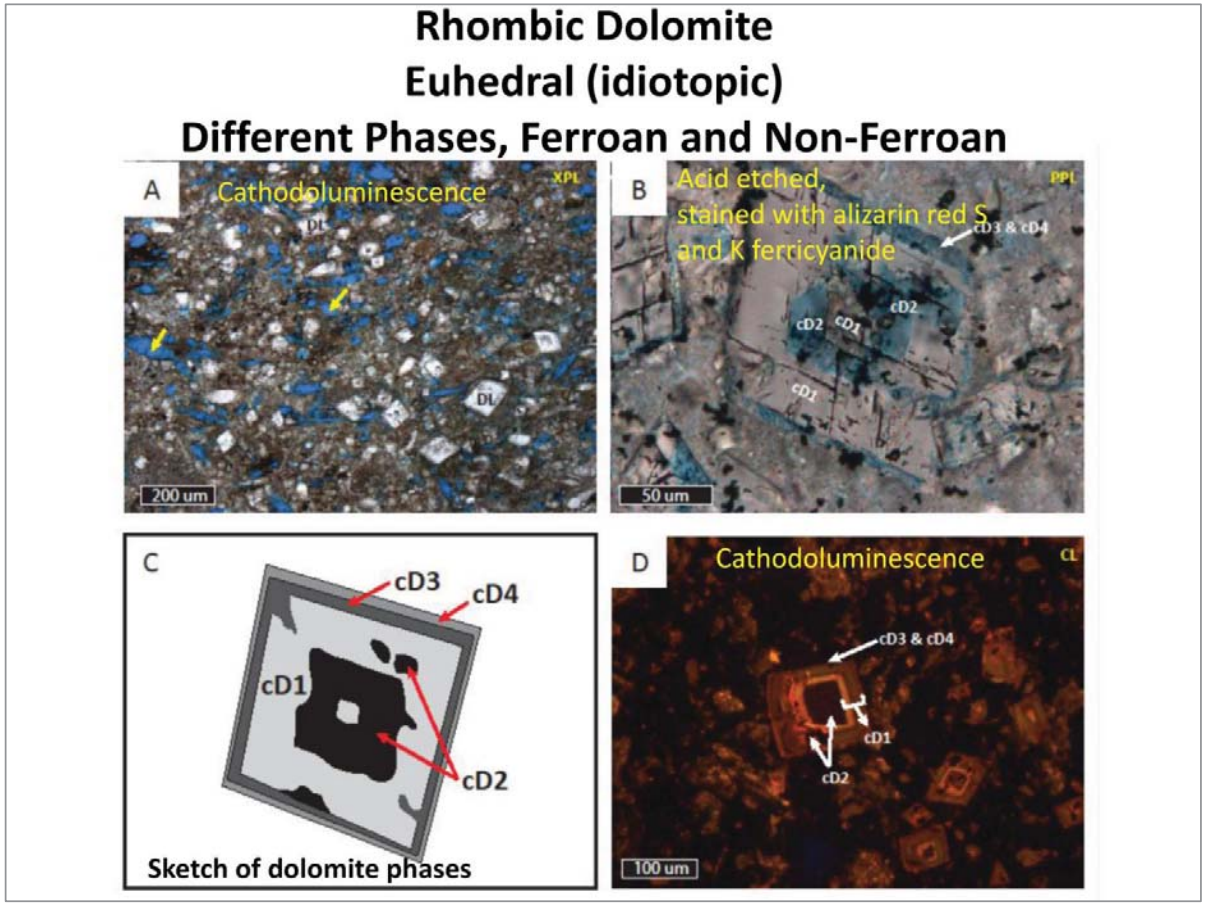
Presenter's notes: Scale bar on slab photos is 1 cm. **A**) Core slab of nodular and bedded dolomitized argillaceous wackestone. The bedding is present as cm-scaled wavy beds alternating in color from light to dark gray. Wispy laminations within can also be identified. Silicified evaporite nodules (SEN) are found scattered in the matrix, and they range widely in size (mm- to cm-sized). *Phycosiphon* burrows are pointed with the arrows. (*Wellington 1-32, 3808 ft*). **B**) Photomicrograph of the matrix NBDAW facies illustrating the silt-sized sub-rounded quartz grains and dolomite rhombs that are enclosed in a clay matrix. Burrowed (b) sections in the matrix are also observed. (*Wellington 1-32, 3807.5 ft*). **C**) Core slab of nodular and bedded dolomitized argillaceous wackestone. In this slab a vertical, cylinder-like burrow, possibly *Skolithos* or *Planolites* is cross-cutting the sediment beds. *Phycosiphon* burrows are pointed with the white arrows. (*Wellington 1-32, 3817 ft*). **D**) Core slab of nodular and bedded dolomitized argillaceous wackestone. In this sample various SEN are arranged in vertical patterns that seem previously to have been burrows. Numerous examples like this one occur in this facies, and it is possible that burrowed sections were the preferred paths for evaporite fluids to precipitate nodular evaporites. Note the characteristic "chicken wire" texture of the nodules. (*Wellington 1-32, 3816 ft*).



Presenter's notes: Scale bar on slab photos is 1 cm. **A**) Core slab of dolomitized lenticular bioclastic wacke/packstone. Lenticular beds of cherty spiculite are scattered in an argillaceous dolomite matrix that is laminated. Burrow (b) structures occurs as elliptical shaped sub-vertical coarse-grained patches and are probably *Planolites*. (*Wellington 1-32, 3886 ft*). **B**) Photomicrograph of dolomitized lenticular bioclastic wacke/packstone. This section shows the contact between the argillaceous dolomite matrix (top) and a cherty spiculite lens (bottom). Note that the spiculite lens is highly chertified and poorly dolomitized. In the other hand, the argillaceous lime-mud matrix is highly dolomitized. (*Wellington 1-32, 3872.75 ft*). **C**) Core slab of dolomitized lenticular bioclastic wacke/packstone. Similar to C but it is found deeper in the same core. (*Wellington 1-32, 4033 ft*). **D**) Photomicrograph of dolomitized lenticular bioclastic wacke/packstone. This section shows the contact between the argillaceous dolomite matrix (bottom) and a cherty spiculite lens (top). Note the lenses are dominated by siliceous-sponge spicule debris. (*Wellington 1-32, 4045.9 ft*).

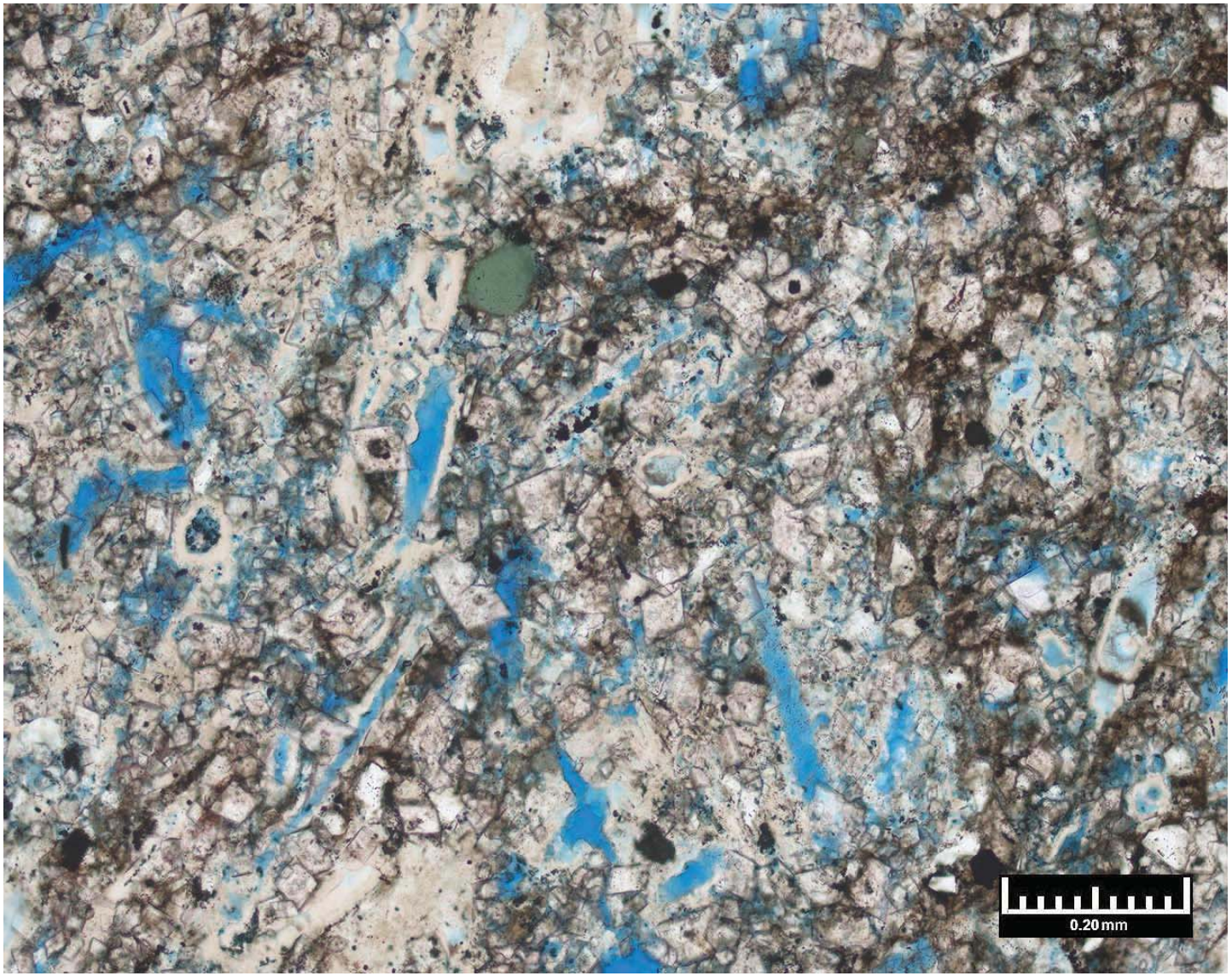


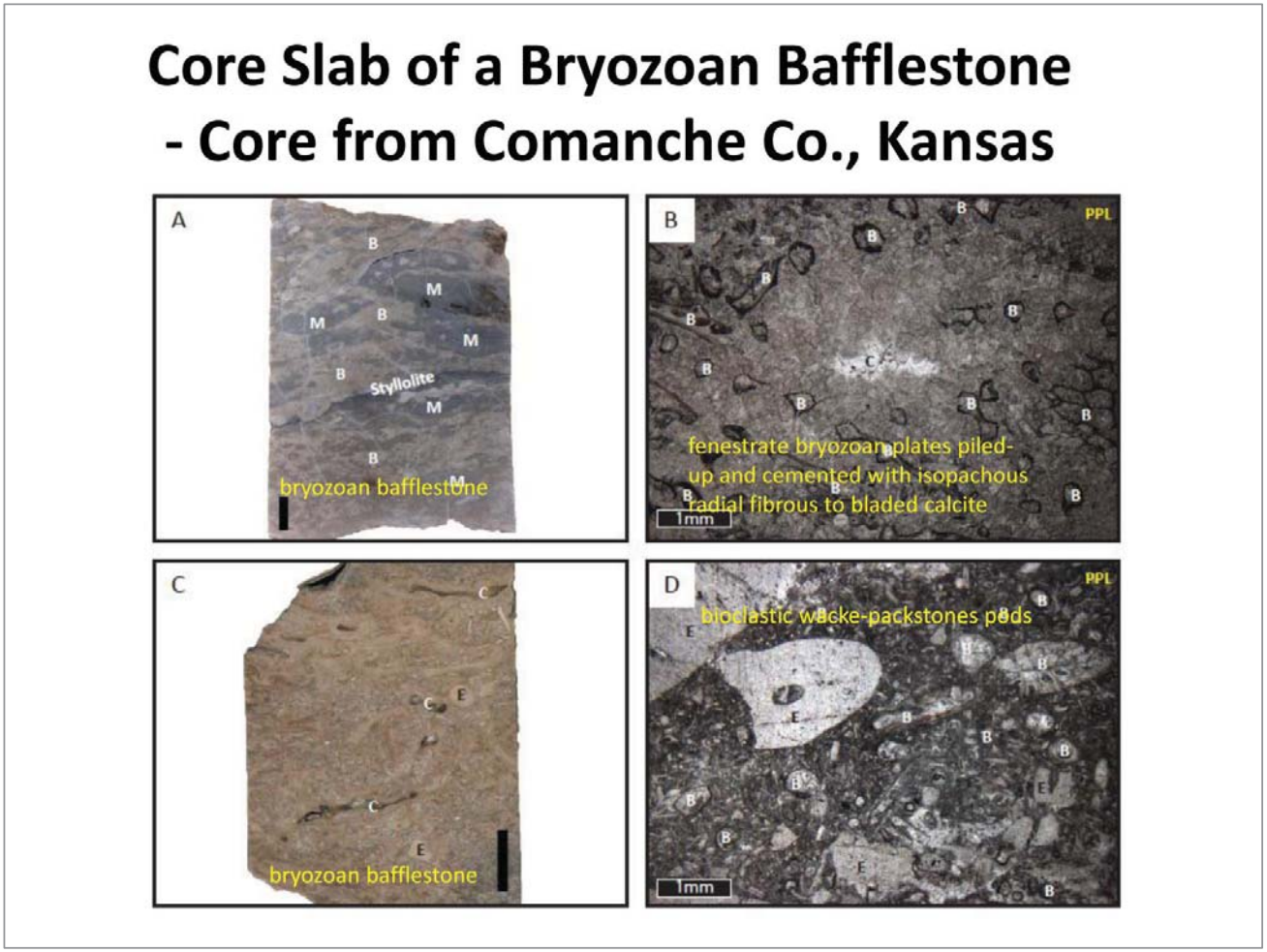
Presenter's notes: Photomicrograph illustrates an isolated, ovoid-shaped and internally featureless glauconite crystal in the matrix of an argillaceous dolosiltite. Thin section was impregnated with blue epoxy, and photomicrograph was taken in plane-polarized light (*Wellington 1-32, 4026.4 ft*). **B)** Core photograph of framboidal pyrite clusters trapped inside a chert nodule. Note that sedimentary textures can be traced across the chert-sediment boundary. This texture suggests that chert nodules have a replacement origin. (*Wellington 1-32, 3770 ft*). **C)** Core photograph illustrates an example of a silicified evaporite nodule. Note the presence of randomly oriented tabular silica-polymorphs (black arrows) that resemble evaporite rosettes. This texture is typical in nodular evaporites and it is sometimes preserved after silicification. Also note the displacement of the sediments around the nodule. (*Wellington 1-32, 3695 ft*). **D)** Core photograph illustrates an example of a silicified evaporite nodule. Tabular anhydrite silica-polymorphs are pointed with black arrows. Also note the displacement of the sediments around the nodule. (*Wellington 1-32, 3873 ft*).



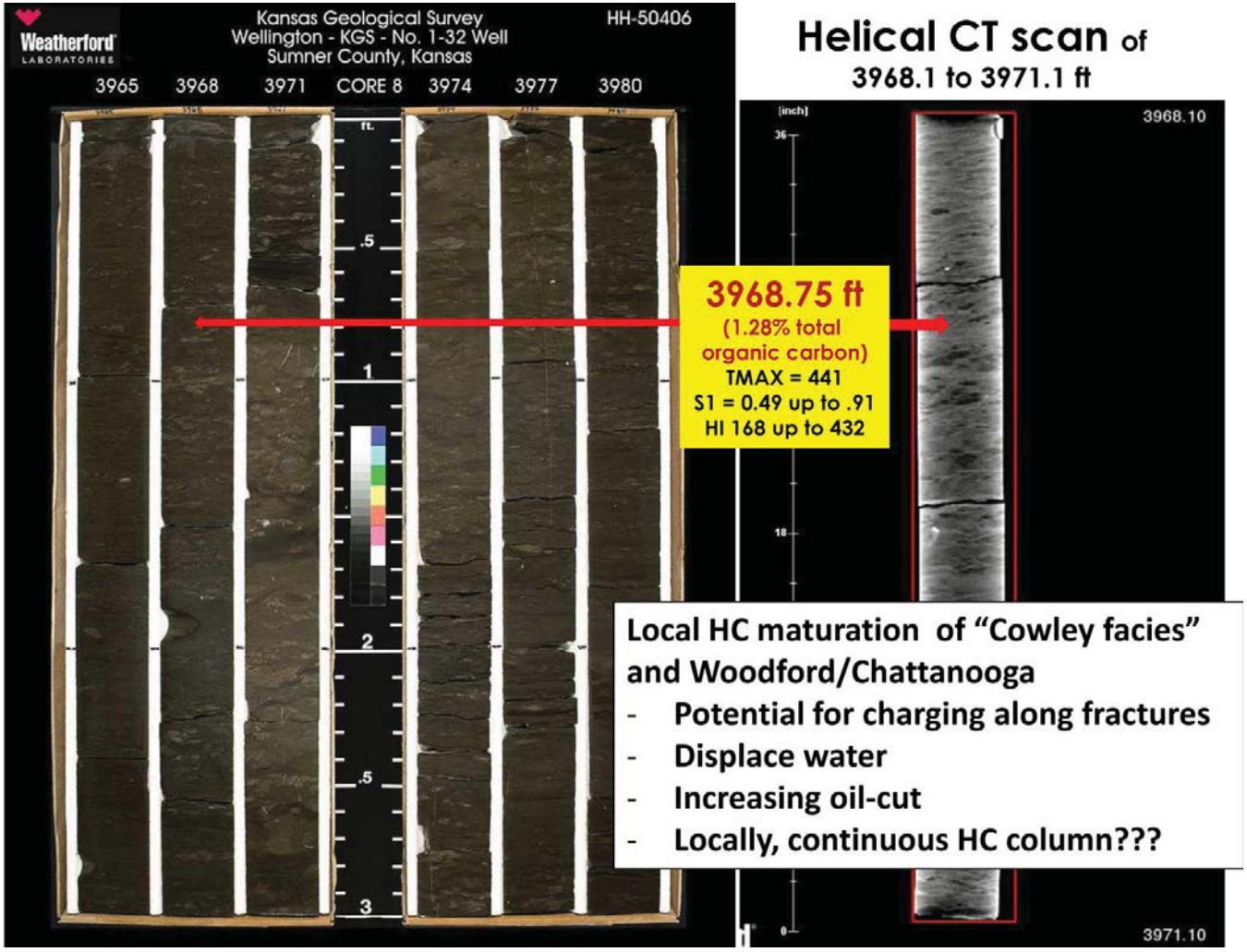
Presenter's notes: Photomicrograph illustrating the finely crystalline to medium crystalline (20-140 μm) dolomite rhombs (DL) observed in the Cowley Formation. Note that most of the crystals are euhedral (idiotopic texture) and are scattered in the matrix. Yellow arrows point to sponge-spicule molds. (*George Michael 1-8, 4610 ft*). **B)** Photomicrograph illustrating dolomite rhombs after being etched and stained with a solution of alizarin red S and potassium ferricyanide. Dolomite portions stained blue (cD2, cD3 and cD4) indicate the presence of iron, while clear portions (cD1) indicate the absence of iron (Dickson, 1965). Note the presence of blue-stained patches of cD2 that cross-cut cD1. These patches represent precipitation of ferroan dolomite (cD2) after dissolution of non-ferroan cD1. (*George Michael 1-8, 4611 ft*). **C)** Schematic diagram of the different dolomite phases and their morphologies within a single dolomite rhomb as seen under cathodoluminescence and backscattered electron images. **D)** Different dolomite phases under cathodoluminescence. Four luminescent zones can be identified. cD1 has a bright to dull-luminescence while the other phases are non-luminescent (cD2, cD3, cD4). The lack of luminescence in cD2, cD3 and cD4 is caused by the concentration of Iron revealed in stained samples. (*George Michael 1-8, 4614*).

Wellington 4029.73 ft (Cowley facies)
deep-water, porous and permeable dolospiculite (oil-bearing)

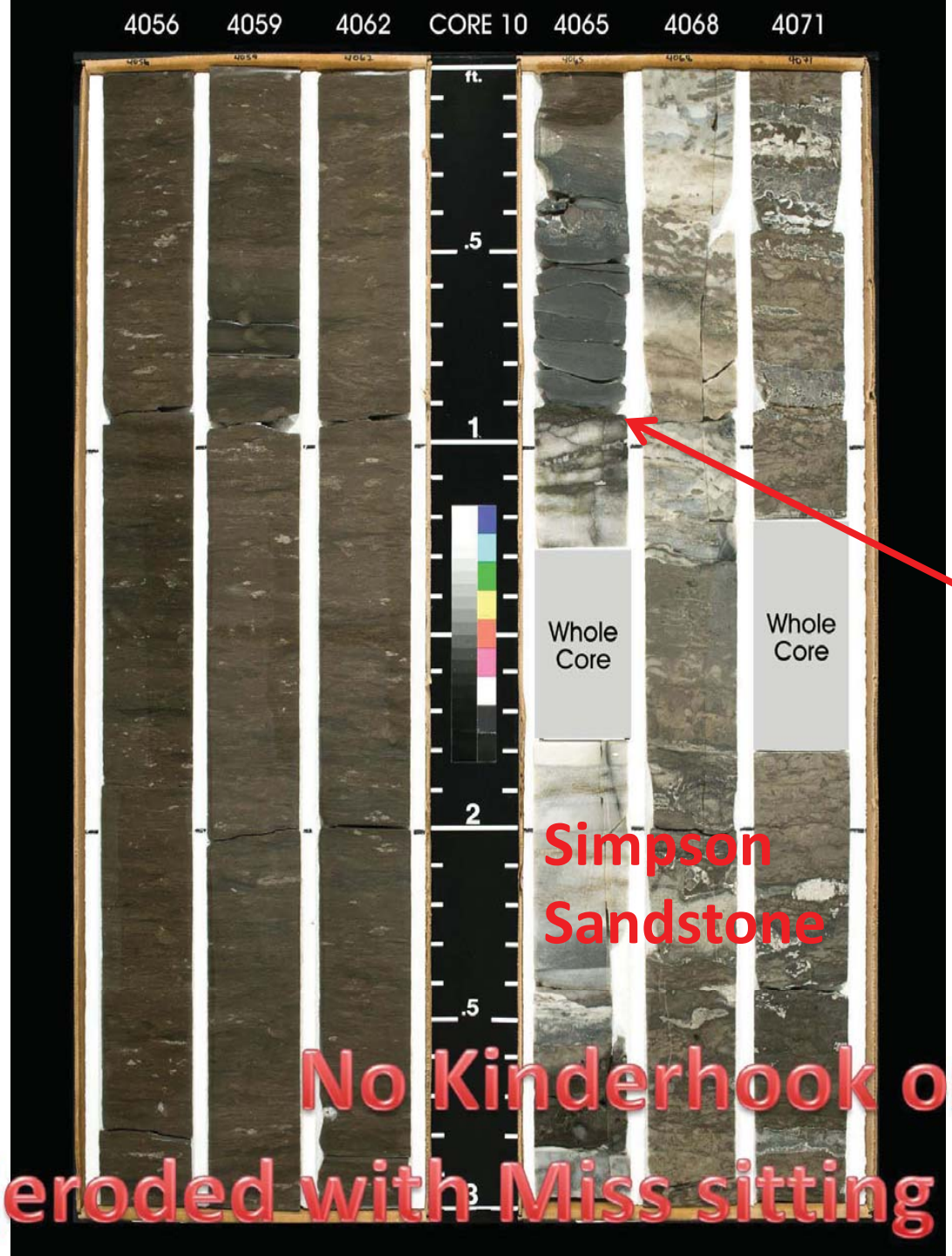




Presenter's notes: Scale bar on slab photos is 1 cm. **A**) Core slab of a bryozoan baffle stone. Note the patchy texture of these facies consisting of in-place cemented bryozoans (B) with interstitial pods of bioclastic wacke-packstones (M). (*Delaney no. 1, 5202 ft*). **B**) Photomicrograph showing fenestrate bryozoan plates piled-up and cemented with isopachous radial fibrous to bladed calcite. Early calcite cementation of amalgamated bryozoan plates results in the formation of sediment barriers ("bafflers") where the bioclastic sediment is trapped. (*Delaney no. 1, 5181 ft*). **C**) Polished core slab of a bryozoan baffle stone. Note the presence of scattered crinoid fragments (E) and sparry calcite masses (C) that resembles *Stromatactis*. (*Delaney no. 1, 5217 ft*). **D**) Photomicrograph showing a bioclastic wacke-packstones pods. Pods consist of skeletal debris in a micrite or pellodial matrix. Skeletal grains are mostly fenestrate bryozoans (B) and crinoids (E) with a minor component of brachiopods and ostracods (*Delaney no. 1, 5195 ft*).



Presenter's notes: Weatherford Labs analyzed a series of samples in the Mississippian and Arbuckle for total organic carbon. Several samples in the Pierson Limestone contain significant organic carbon suited for further organic characterization. This sample is a moderately dark interval as shown in the core slab photo. The corresponding helical CT scan shows the internal structures. Image was taken before the whole core was slabbed. The core has evenly distributed wavy laminations. In general, interval is tight without visual fractures.



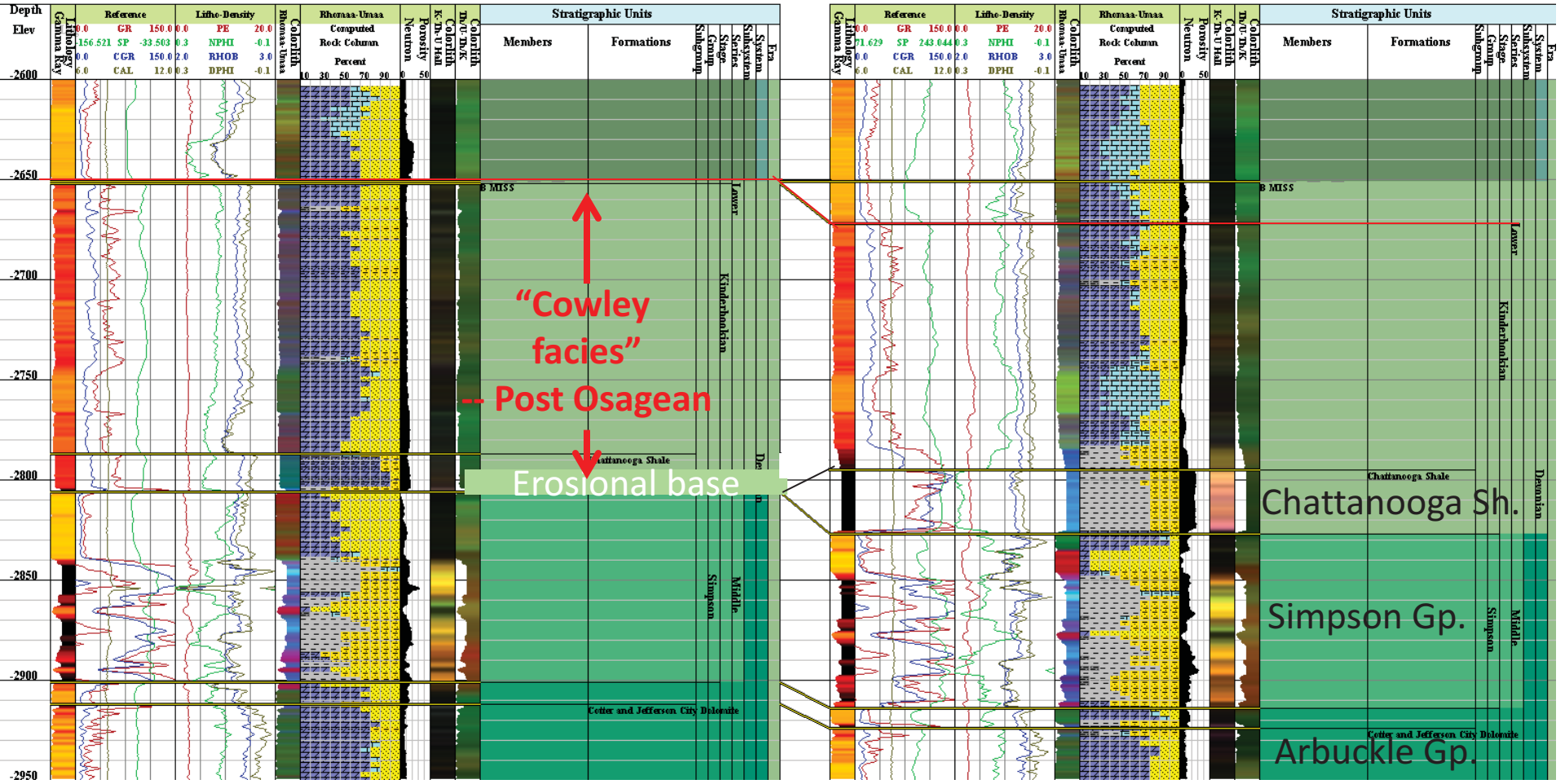
Base of the Mississippian in Berexco KGS #1-32

Base Mississippian – NO Kinderhook, Osage, and probably Meramec on erosional base

- No Chattanooga Shale
- No Kinderhookian Ls. (Compton)

No Kinderhook or Osage (eroded with Miss sitting on Simpson Ss.)

"Cowley facies" in SW to NE Cross Section
-- Berexco Wellington KGS #1-32 (left) & #1-28 (right)
(3000 ft distance between wells)



50 ft

http://www.kgs.ku.edu/stratigraphic/CROSS_SECTION/

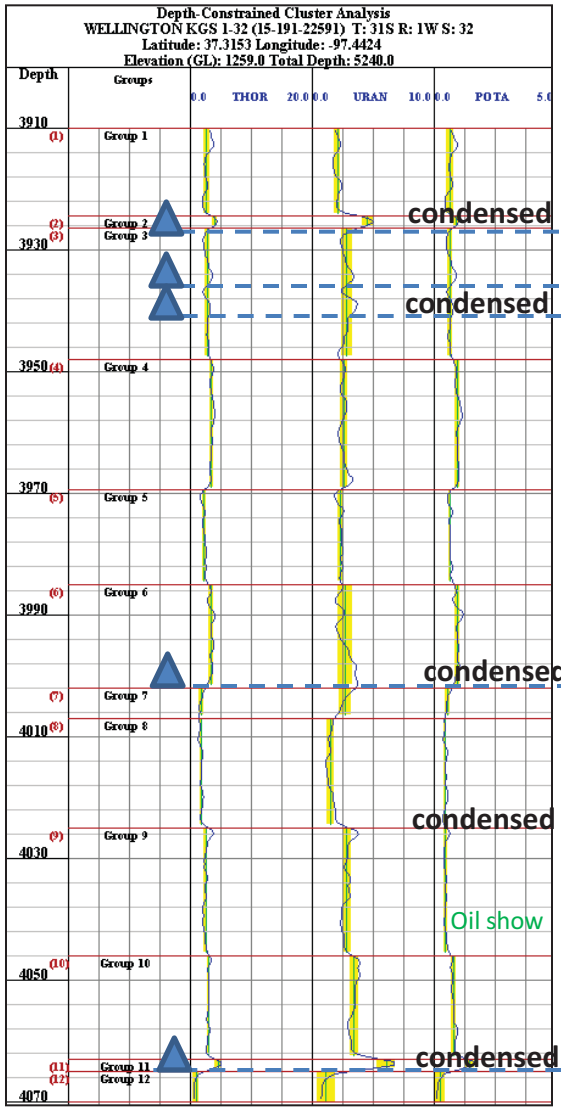
Cross Section Java Appet – J. Victorine, KGS, DOE-CO2

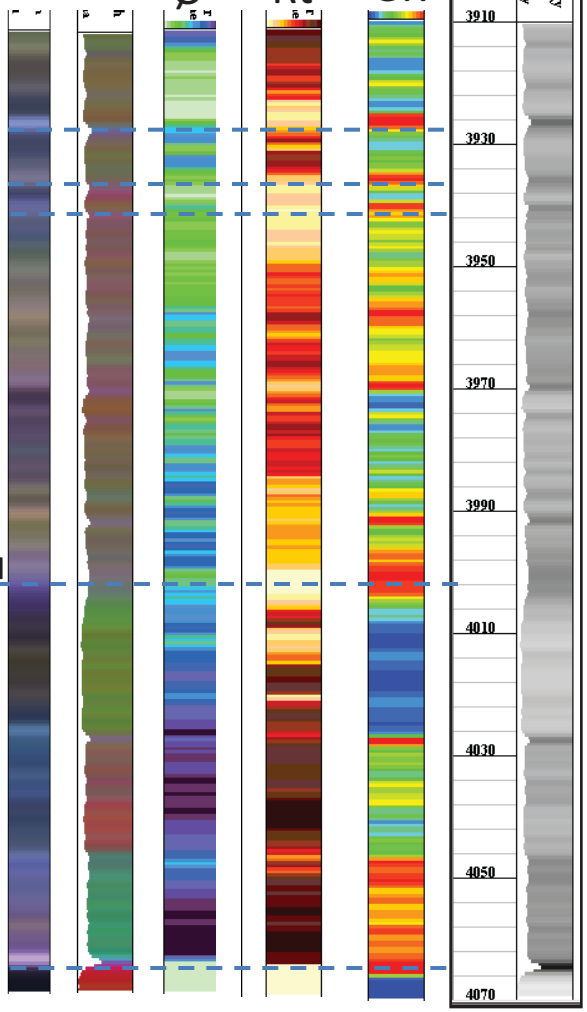
Correlations – regional team (Bittersweet), DOE-CO2

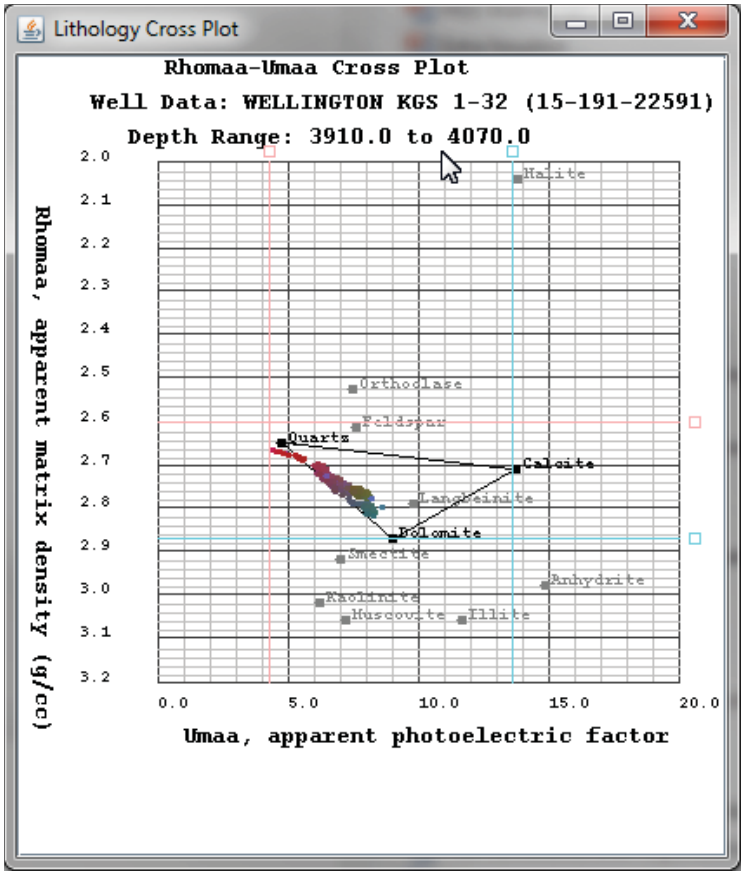
Nonlinear/zonal scaling of color imaging of logs for Argillaceous, organic-bearing "Cowley facies" on lower ramp

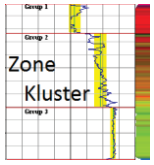
in Berexco Wellington KGS #1-32

Depth-Constrained Clustering using Potassium, Uranium, Thorium









Zone Cluster & KIMELEON Applet

J. Victorine & J. Doveton

http://www.kgs.ku.edu/stratigraphic/ZONATION/

http://www.kgs.ku.edu/stratigraphic/KIMELEON/

▲ Significant flooding surface from core description

Conclusions – Depositional Setting and Lithofacies

- **Normal marine subtidal conditions in the inner-, mid- and outer-ramp depositional environments**
- **Thirteen lithofacies were described**:
  - *lenticular spiculite wacke-packstone, bioclastic crinoidal pack-grainstone, nodular and bedded cherty spiculite, porcelaneous chert, cherty sucrosic dolomite, bioclastic mudstone-wackestone, cherty and dolomitized argillaceous mudstone-wackestone, nodular and bedded dolomitized argillaceous wackestone, dolomitized lenticular bioclastic wacke-packstone, argillaceous dolomite, chert breccia, bryozoan bafflestone and bryozoan pack-grainstone*.
- **Much of the deposition consisted of sponge-spicule debris from *in situ* sponge colonies (demosponges) and/or reworking of these particles by wave action**
- **Spiculites where deposited in quiet, nutrient-rich, moderate-oxygenated waters as indicated by moderate bioturbation and interbedding with shales and clays**

Depositional Setting and Lithofacies

- **Cross stratification and laminations found on some spiculitic facies**
  - periods of higher energy and possibly shallower conditions
  - inferred relative sea-level falls discussed in literature
- **Brief episodes of deposition of calcareous skeletal debris during storms**
- **Facies associated with bryozoan mounds were described**
  - not regionally widespread.
  - bryozoan mounds are a potential source for the calcareous debris found in mid- and outer-ramp settings.
- **Facies associated with karstification were found on top of the Mississippian**
  - variable solution-collapse and residual chert breccias
  - correspond to the Mississippian “chat” reservoirs.
- **Residual chert breccias are also found beneath internal surfaces of subaerial exposure**
  - cap high-frequency cycles of the Mississippian in the shallow ramp settings in inner ramp
- **Lithofacies represents a *Heterozoan Association* of particle types**
  - produced by coralline algae and benthic invertebrates that feed through a variety of heterotrophic means.
  - modern cool-water, temperate, platform carbonates accumulate in seawater that is generally colder than 20°C.

Diagenetic History/Paragenesis

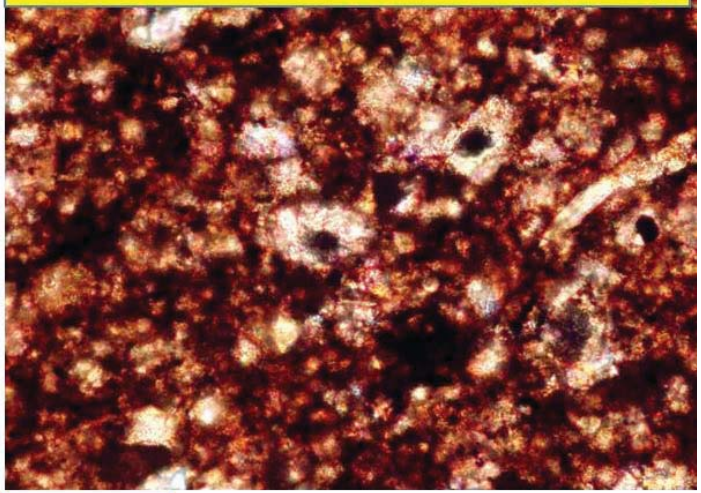
- **Silica (mostly chert) and dolomite are the two most abundant mineral phases**
- **Observable paragenetic relationships and geochemical interpretations → events occur early in the diagenesis**
- **Fluid inclusions in early megaquartz (MGQZ-1) indicate the presence of seawater and evaporated seawater (hypersalinity) during silica precipitation**
- **Bacterial decay of organic matter, including desulfurization triggered by sulfur-reducing bacteria, generates CO_2, causing the dissolution of calcium carbonate and decreasing the pH of pore-fluids →** simultaneous precipitation of silica and dissolution of calcium carbonate (Eley and Jull, 1982)
- **Finer grained facies appeared to be more susceptible to pervasive dolomitization and silicification**
- **The widespread distribution of dolomitic and cherty facies is difficult to explain by a single diagenetic event**
- **First crystals of dolomites (cD1 and wD1a) precipitated in a near-surface environment from potentially seawater-derived fluids**
- **Secondary dolomite precipitation most likely occurred in the meteoric and subsurface realms →** elevated trace-element concentrations and void-filling textures
- **Evaporite nodules precipitated in marine subtidal sediments →** regional-scale event that transported sulfate-enriched fluids through the sediments from adjacent areas where seawater was evaporating
- **All the evaporite nodules appear to be replaced with a similar sequence of silica cements**: beginning with quartzine → mosaic of megaquartz and microflamboyant quartz, a predictive texture of evaporite replacement with silica (Milliken, 1979)
- **The timing of evaporite precipitation and silica replacement of the nodules is paragenetically similar in all areas where they were found**, suggesting a widespread event that affected the ramp locations covered in this study

Source Rocks

– Organic richness, maturity, timeframe of generation

"Cowley facies appears to be an oil-prone source rock where it is thermally mature"

4003.7 ft dark cored dolomite (x-nic)



Pierson Ls. Member (Cowley facies) is *organic-bearing and thermally mature* and probably local source rock for MLP

Weatherford LABORATORIES

TOTAL ORGANIC CARBON

Received 2-13-13

Client ID	Well Name	State	County	Top depth (ft)	Formation	Sample Type	Prep	TOC, wt. %	Verified	Lab Id	Comments
	Berexco LLC Wellington KGS No. 1-32			3605.40		Core	NOPR	0.10		3402822662	Penn sh
	Berexco LLC Wellington KGS No. 1-32			3738.25		Core	NOPR	0.39		3402822664	MSSP
	Berexco LLC Wellington KGS No. 1-32			3754.00		Core	NOPR	0.19		3402822666	MSSP
	Berexco LLC Wellington KGS No. 1-32			3784.50		Core	NOPR	1.87	TOC	3402822668	MSSP
	Berexco LLC Wellington KGS No. 1-32			3937.25		Core	NOPR	0.94		3402822670	MSSP
	Berexco LLC Wellington KGS No. 1-32			3968.75		Core	NOPR	1.28		3402822672	MSSP
	Berexco LLC Wellington KGS No. 1-32			3982.00		Core	NOPR	0.60	TOC	3402822674	MSSP
	Berexco LLC Wellington KGS No. 1-32			4024.00		Core	NOPR	0.21		3402822676	MSSP
	Berexco LLC Wellington KGS No. 1-32			4048.50		Core	NOPR	1.11		3402822678	MSSP
	Berexco LLC Wellington KGS No. 1-32			4059.75		Core	NOPR	0.69		3402822680	MSSP
	Berexco LLC Wellington KGS No. 1-32			4065.50		Core	NOPR	1.59	TOC	3402822682	M-D Chat Sh

OPERATOR AND WELL NAME

SEC	T	R	SPOT	SAMPLE INTERVAL	SUBSURF.	AGE	FORM	LITH	TOC	S1	S2	S3	HI	OI	TMAX	PI	S1+S2
32	31S	01W	SW NE NE		3784.50	Mssp		ls	1.87	0.71	8.06	0.93	432	50	442	0.08	8.77
32	31S	01W	SW NE NE		3937.25	Mssp		ls	0.94	0.77	3.28	0.43	350	46	439	0.19	4.05
32	31S	01W	SW NE NE		3968.75	Mssp		ls	1.28	0.49	2.14	0.54	168	42	441	0.19	2.63
32	31S	01W	SW NE NE		3982.00	Mssp		ls	0.60	0.66	1.92	0.58	321	97	440	0.26	2.58
32	31S	01W	SW NE NE		4024.00	Mssp		ls	0.21								
32	31S	01W	SW NE NE		4048.50	Mssp		ls	1.11	0.79	4.02	0.41	361	37	437	0.16	4.81
32	31S	01W	SW NE NE		4059.75	Mssp		ls	0.69								
32	31S	01W	SW NE NE		4065.50	Dev	CHAT	sh	1.59	0.91	7.75	0.27	487	17	440	0.11	8.66
32	31S	01W	SW NE NE		4099.60	OrdM	SMPS	sh	0.17								

Compilation of Hydrocarbon Source-Rock Analyses for Wells in East-Central and Northeastern Kansas, and adjacent areas in Missouri and Nebraska
by K. David Newell (Kansas Geological Survey, University of Kansas, Lawrence, KS, 66046-3726), August, 2013

Sequence Stratigraphy

- Shelf-to-basin framework
- Lowstand prograding system on ramp margin
- High-resolution paleogeography

Depositional Setting and Lithofacies

Cool-water carbonate/siliciclastic accumulation

THE COOL-WATER CARBONATE DEPOSITIONAL REALM

NOEL P. JAMES (1997)

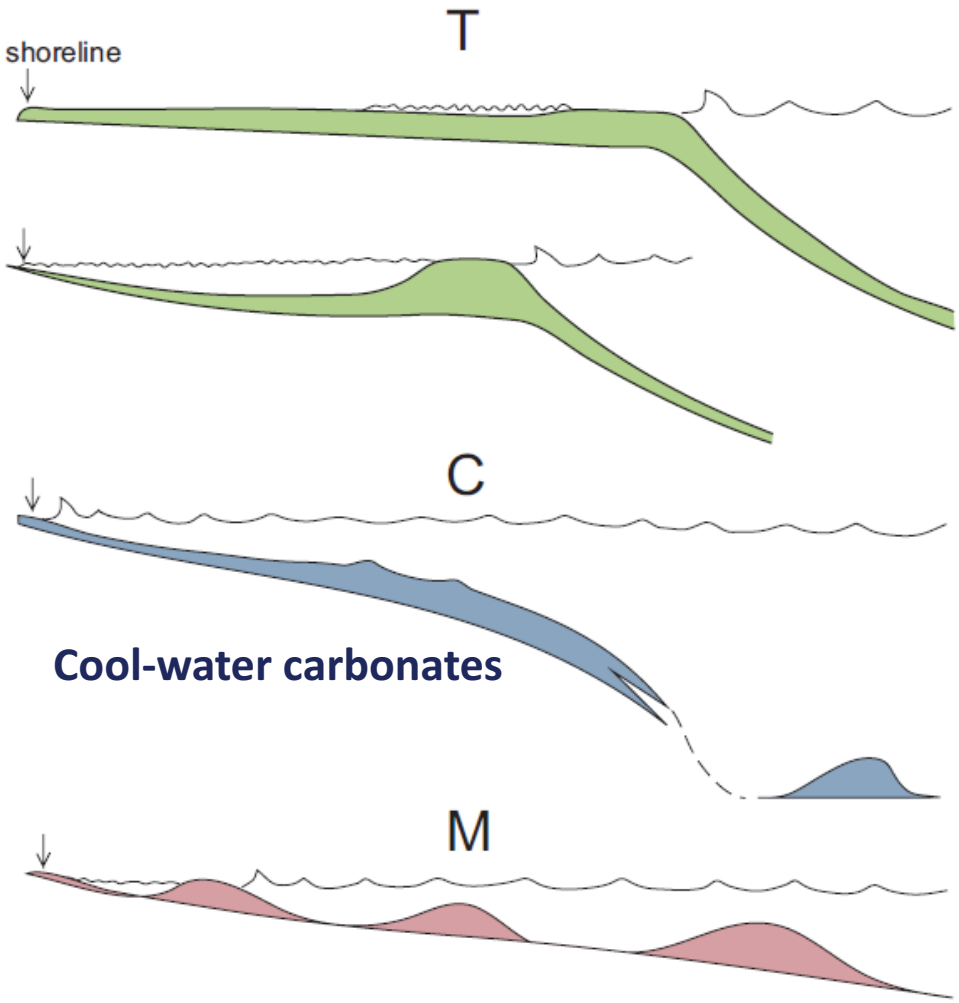
- Heterozoan carbonates form unrimmed ramps and open-shelves with their style being determined by local terrigenous clastic sediment input, oceanography, nutrient supply and sea-level history. Cool-water, temperate platform carbonates are typically grainy with discrete hydrodynamically-controlled facies.

- Slope or outer ramp environments are muddy with abundant sponge spicules and local sponge/bryozoan/coral buildups.

- Physical sedimentary processes on cool-water carbonate shelves and banks are dominated by traction currents, storm-, swell- and tide-induced suspension of fines, active shallow-water particle abrasion and patchy development of subtidal hardgrounds.

- Thus, modern cool-water carbonates may provide excellent analogues for the interpretation of many ancient ramp and shelf successions.

Cartoons of the depositional geometries of the three carbonate factories



The cross sections show sea level and wave patterns, bottom morphology and thickness variation of a typical growth increment. The arrow marks the shoreline.

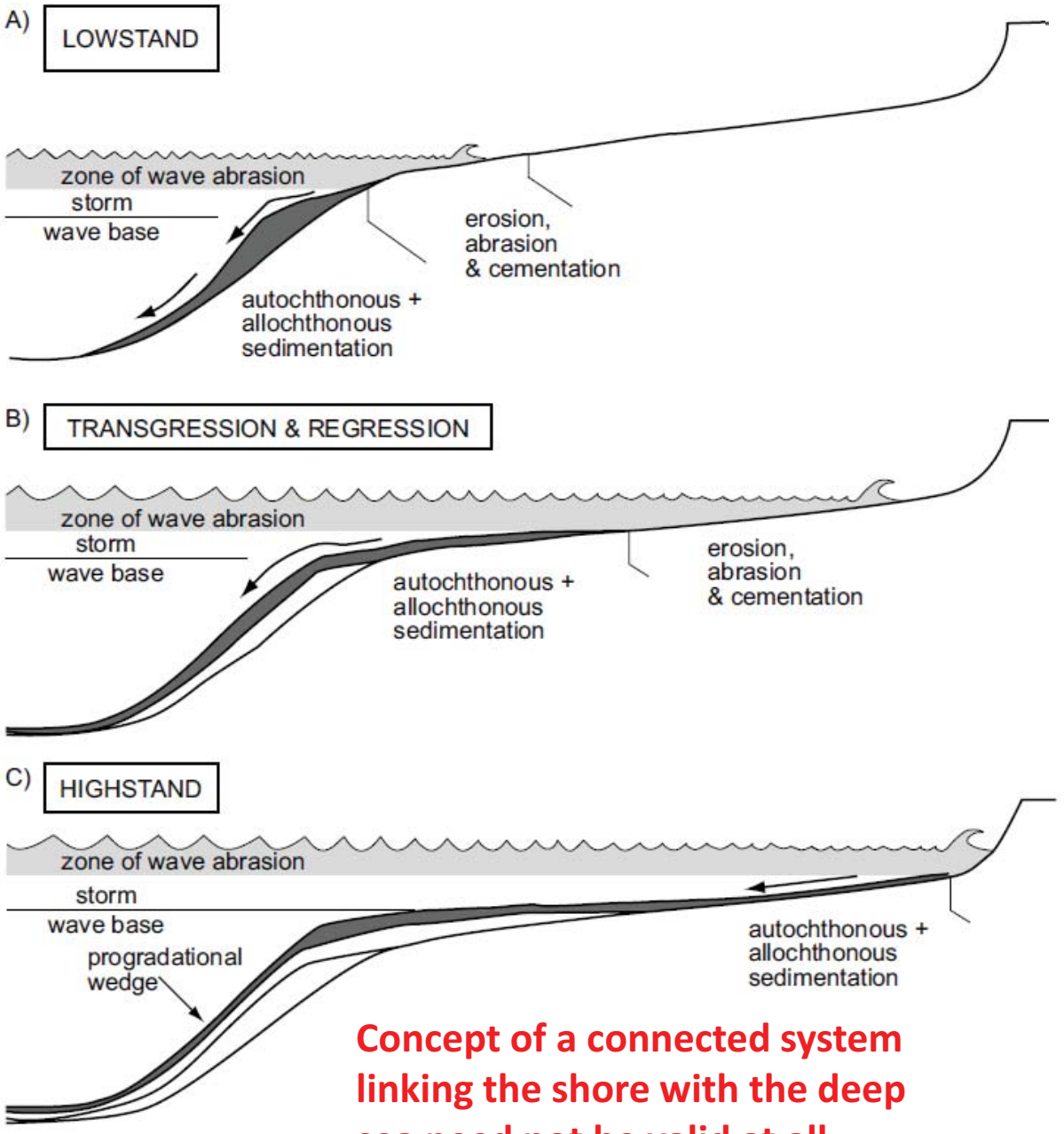
T factory (green) produces platforms rimmed by reefs or sand shoals

C factory (blue) cannot build shallow offshore rims, only scattered deeper-water skeletal mounds.

The geometry of the accumulations is that of a ramp with the highest energy conditions close to shore.

M factory (red) forms convex mounds on gentle slopes below the zone of wave action.

Schlager (2005)



Concept of a connected system linking the shore with the deep sea need not be valid at all

The depth window of production of the cool-water carbonate factory is 5 – 10 times wider than that of the tropical factory

- **Width of the production window exceeds the amplitude of nearly all eustatic fluctuations in the sequence-stratigraphically relevant time domain of 10^3 – 10^6 years.**
- **Difference in production area between highstands and lowstands is much smaller.**
- **Cementation in the meteoric and the marine environment is slow because seawater is less supersaturated with calcium carbonate and there is less metastable aragonite to dissolve.**

Schlager (2005)

Depositional Settings for Siliceous Sponge-Microbe Reef Mounds

A) Differentiated carbonate shelf

B) Reef-rimmed shelf

C) Carbonate ramp or non-rimmed shelf

D) At least in part fault-controlled

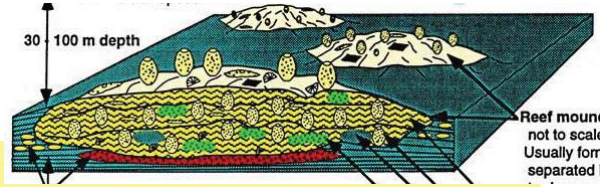
Siliceous Sponge-microbe Biotic Associations and Their Recurrence Through the Phanerozoic as Reef Mound Constructors

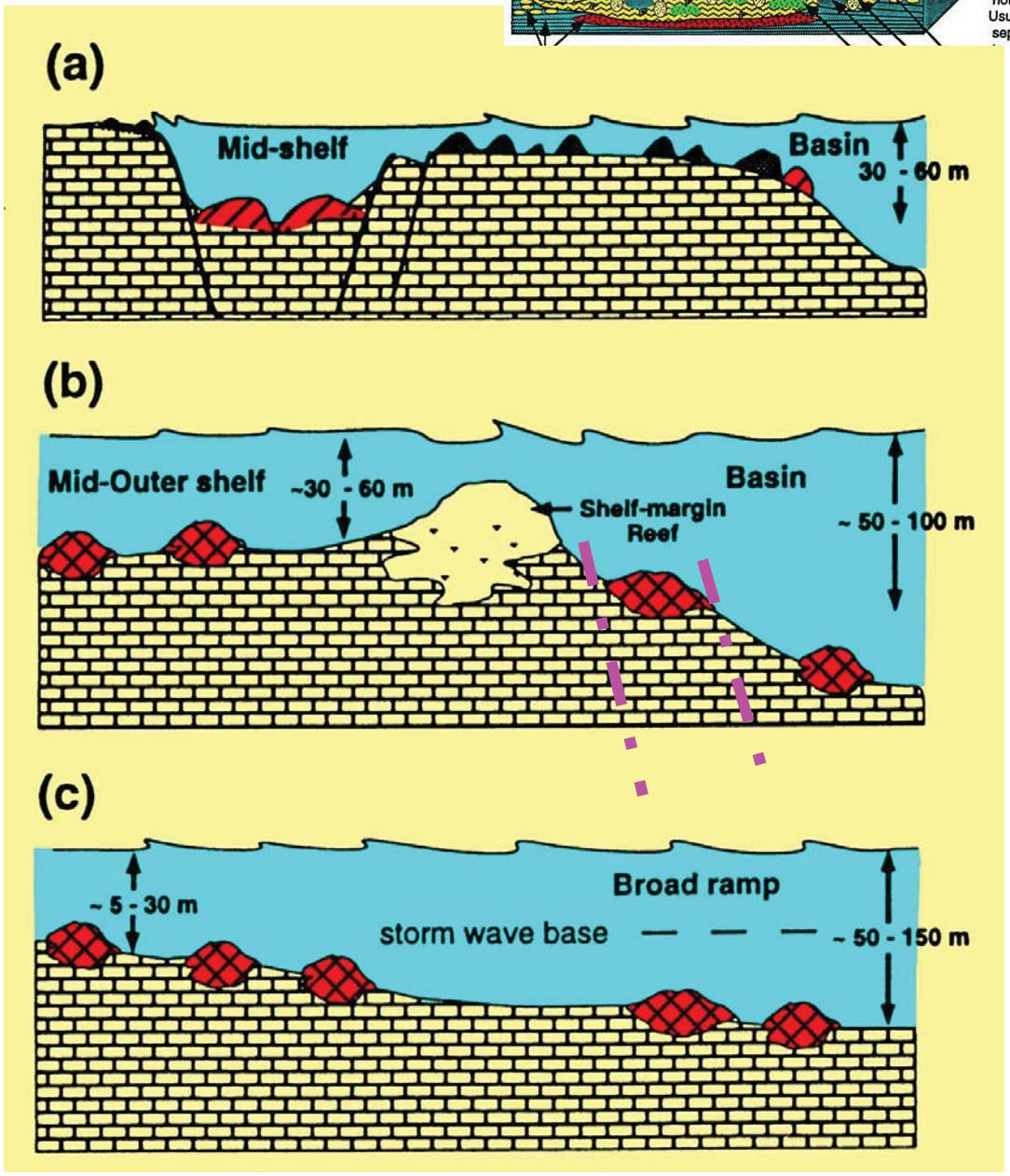
FRANK R. BRUNTON and OWEN A. DIXON

Ottawa-Carleton Geoscience Centre and Department of Geology, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada

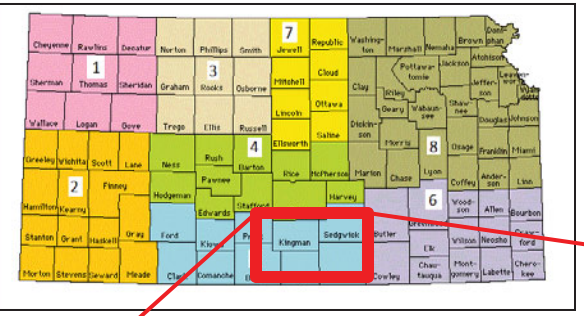
PALAIOS, 1994, V. 9, p. 370–387

areas where, at lowstand, reef-building metazoans such as stromatoporoids, corals and calcareous sponges usually





(after Brunton and Dixon, 1994)



Index for SW to NE Cross Section showing tilt angle of total magnetic field and top Arbuckle structural contours

Modeling Carbon Dioxide Sequestration Potential in Kansas

Study Area | Zoom to Location | Filter Wells | Label Wells | Download Wells | Filter Fields | Print to PDF | Clear Highlight | Help

Cross Section Tools

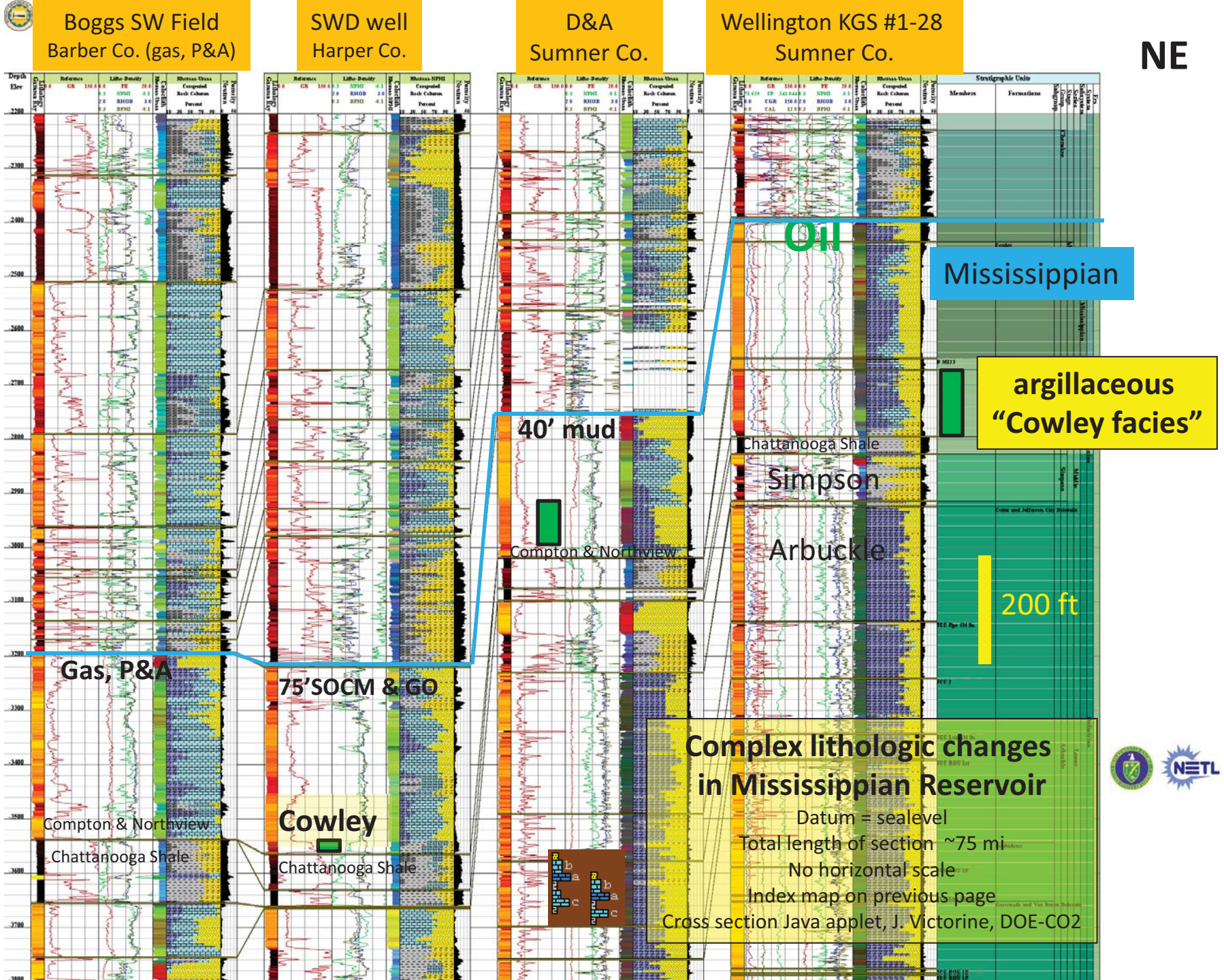
Help
Show Type Wells
Add Well
Remove Last Well
Remove All Wells
Create Cross Section

Selected: 4
(select 4 max.)

Wellington Field

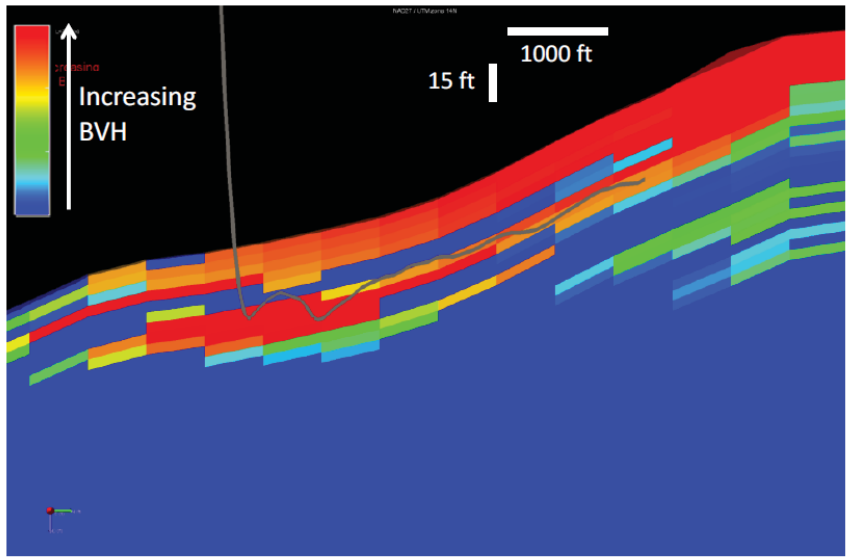
KGS | Esri, HERE, DeLorme, TomTom, USGS, NGA, USDA, EPA, NPS

~75 miles


SW
Boggs SW Field
Barber Co. (gas, P&A)
SWD well
Harper Co.
D&A
Sumner Co.
Wellington KGS #1-28
Sumner Co.
NE
Oil
Mississippian
argillaceous
"Cowley facies"
40' mud
Compton & Northview
Chattanooga Shale
Simpson
Arbuckle
200 ft
Gas, P&A
75'SOCM & GO
Cowley
Chattanooga Shale
Compton & Northview
Chattanooga Shale
Complex lithologic changes
in Mississippian Reservoir
Datum = sealevel
Total length of section ~75 mi
No horizontal scale
Index map on previous page
Cross section Java applet, J. Victorine, DOE-CO2

Factors in water-cut?

South North



Example view of horizontal wellbore planned using geocellular model. Grid is displaying modeled distribution of bulk volume hydrocarbon (BVH). Vertical exaggeration 30x.

~135 ft oil column

- Prograding and downlapping Osage and Meramec strata along ramp
- Variable pore types along the lateral
- Not simple oil:water contact
- ~135 ft of oil column
- Reservoir pressure, drive?
- Locally charged with thermally mature, underlying Woodford Shale or "Cowley facies"?
- Fractures? Water or oil?
- How was well completed?

Core to Characterization and Modeling of the Mississippian, North Alva Area, Woods and Alfalfa Counties, Oklahoma

Dan Costello1, Martin Dubois2, and Ryan Dayton1
1 Chesapeake Energy Corporation
2 Improved Hydrocarbon Recovery, LLC

2014 Mid-Continent Section AAPG Core Workshop

Structural Framework

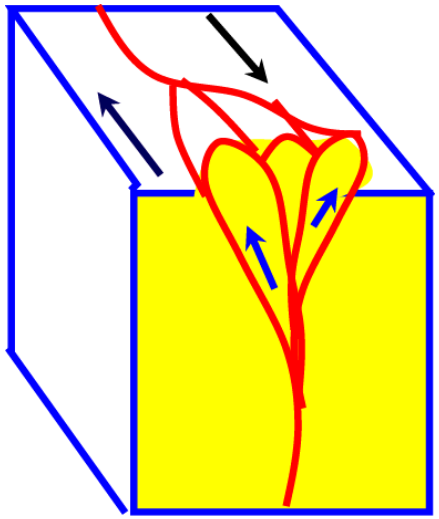
- local and regional
- tectonic and local episodic deformation

Relevant structural elements of Arkoma and Anadarko Basin

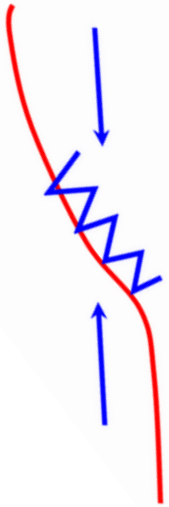
- Concurrent and post-Mississippian structural deformation
- Systematic reactivation of basement weaknesses defined by potential fields & basement terrain
- Inherited fracture systems
- Major wrench fault systems directed stress into craton during Late Paleozoic
- Major influence on maturation of organic matter, migration routes and trapping of oil and gas

Characteristics of Strike-Slip Faults
–> flower structures, restraining bends, relay ramps

Flower Structures
Positive (Palm Tree) → Transpression
Right lateral

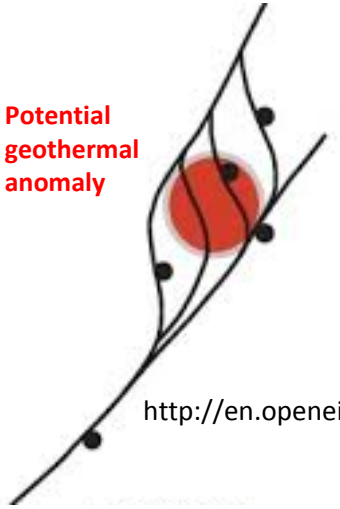


Restraining Bends-
transpressional zones
occurring at fault bends
Push Up Ridges

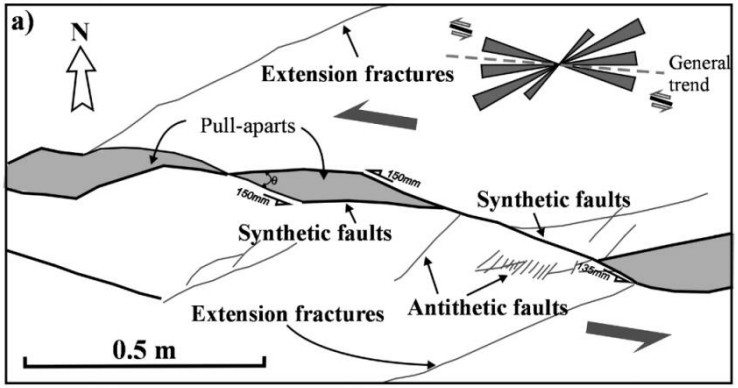


Modified from:
http://www4.uwsp.edu/geo/faculty/hefferan/geol320/strikeslip.html

Stepover or Relay Ramp

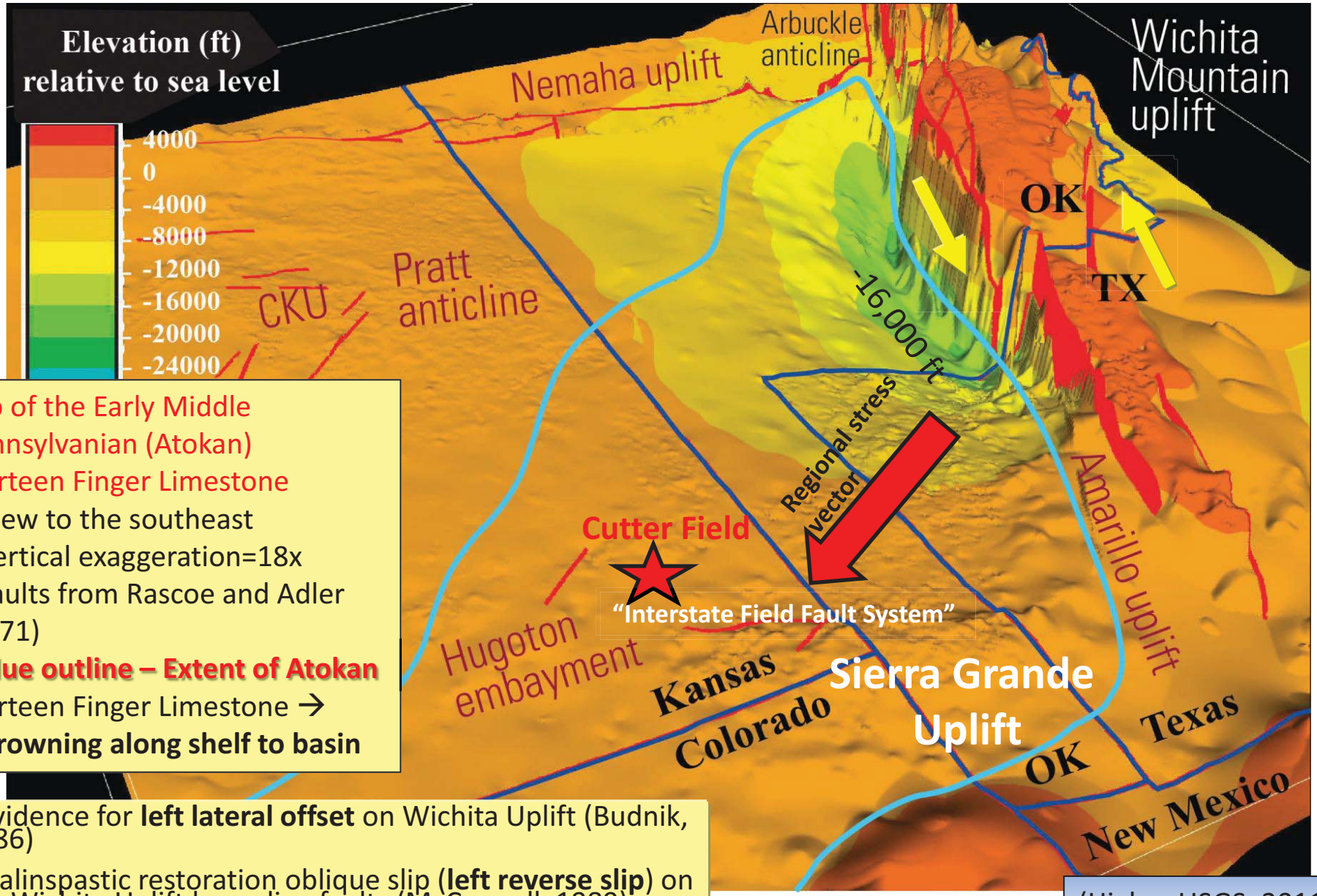


http://en.openei.org/wiki/



Complex geometries of strike-slip faults -- Kim et al. (2003)

Left lateral wrench faulting along ARM was at maximum during Atokan time
→ simultaneous regional drowning of shelf and basin
in area affected by regionally directed stress (*hypothesis being tested*)



Top of the Early Middle Pennsylvanian (Atokan) Thirteen Finger Limestone

- View to the southeast
- Vertical exaggeration=18x
- Faults from Rascoe and Adler (1971)
- **Blue outline – Extent of Atokan** Thirteen Finger Limestone →
- **Drowning along shelf to basin**

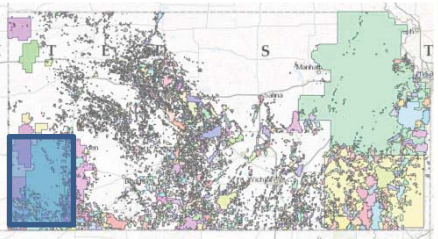
- Evidence for **left lateral offset** on Wichita Uplift (Budnik, 1986)
- Palinspastic restoration oblique slip (**left reverse slip**) on the Wichita Uplift bounding faults (McConnell, 1989)

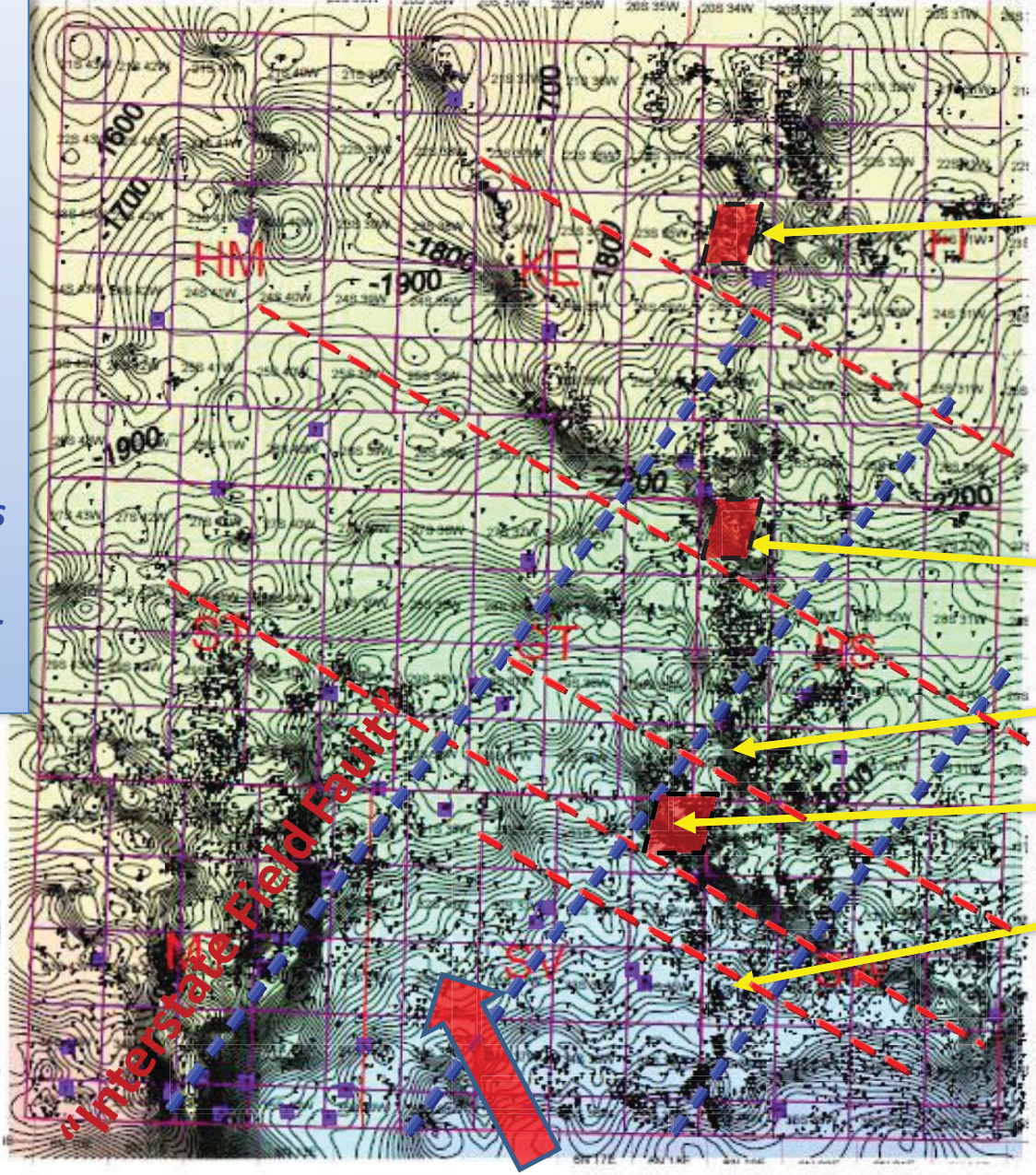
(Higley, USGS, 2011)

Structure Top Meramec Mississippian

Horsts or tilted blocks with faulted southwest and west flanks

→ Restraining bends
→ Present evidence for oblique strike-slip faults





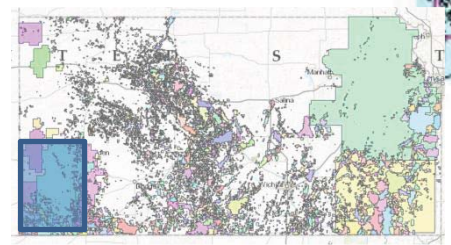
(Gerlach & Bittersweet Energy, DOE-CO2)

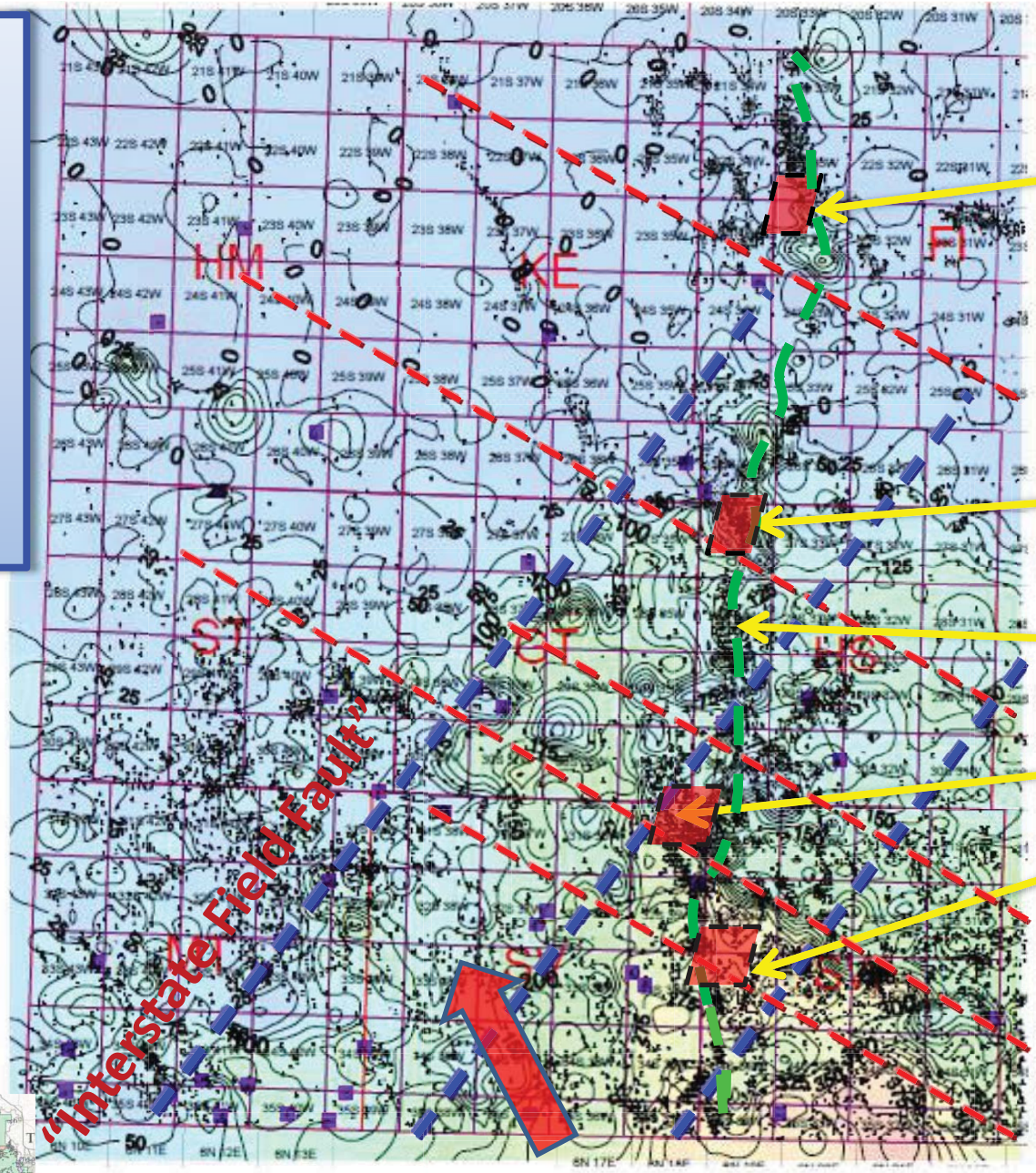
Southward, stepwise, thickening of Chester Cross-cut by *incised valley system*

(~100 miles long)

Rhombic horst blocks (reverse faults on south and west flanks)

Incised valley





10 mi (16 km)

1:250000

KANSAS GEOLOGICAL SURVEY

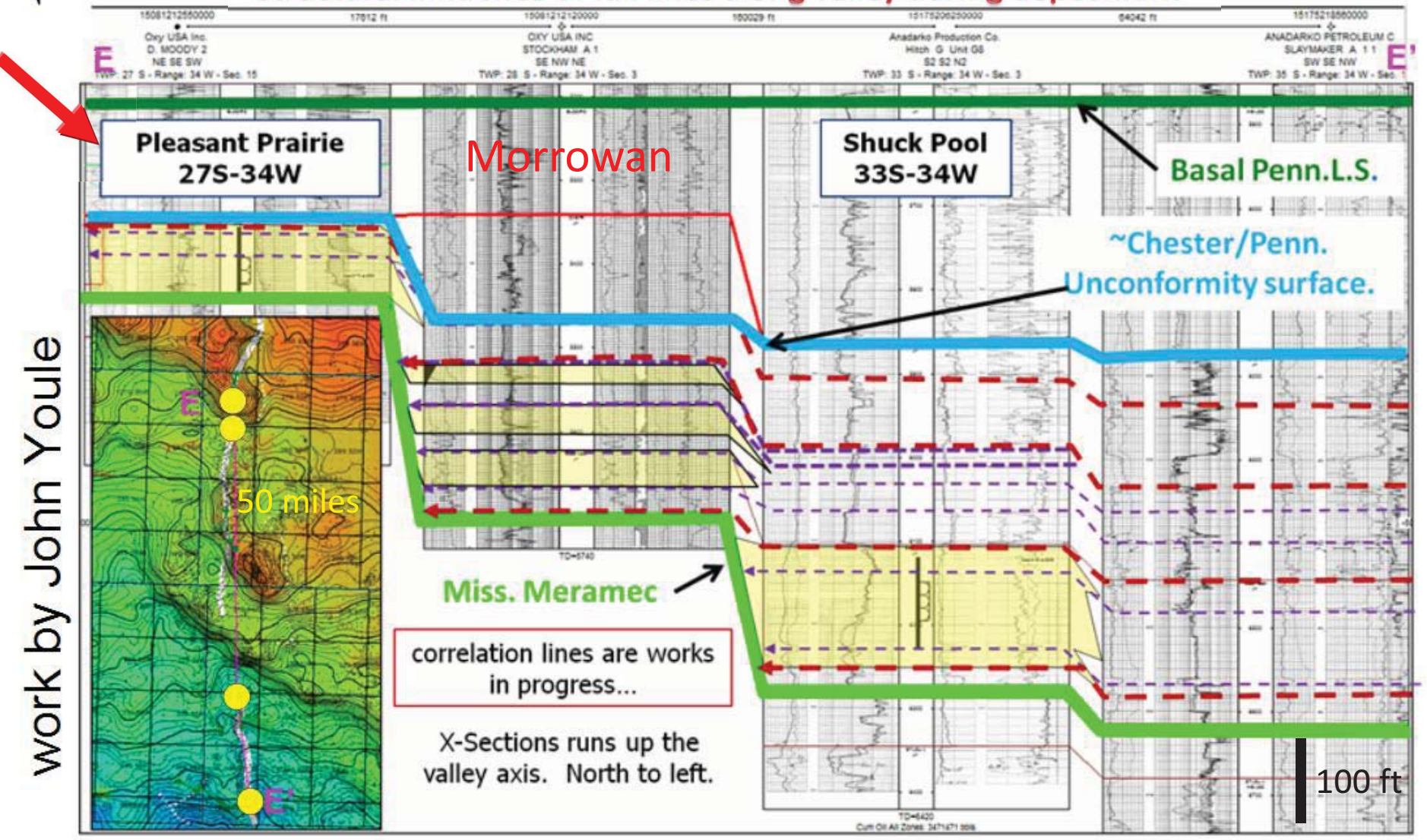
CO2 PROJECT / WESTERN ANNEX

(Gerlach and Bittersweet Energy, DOE-CO2)

Chester Sequence Stratigraphy

North

Structural influence of fall lines along valley during deposition?



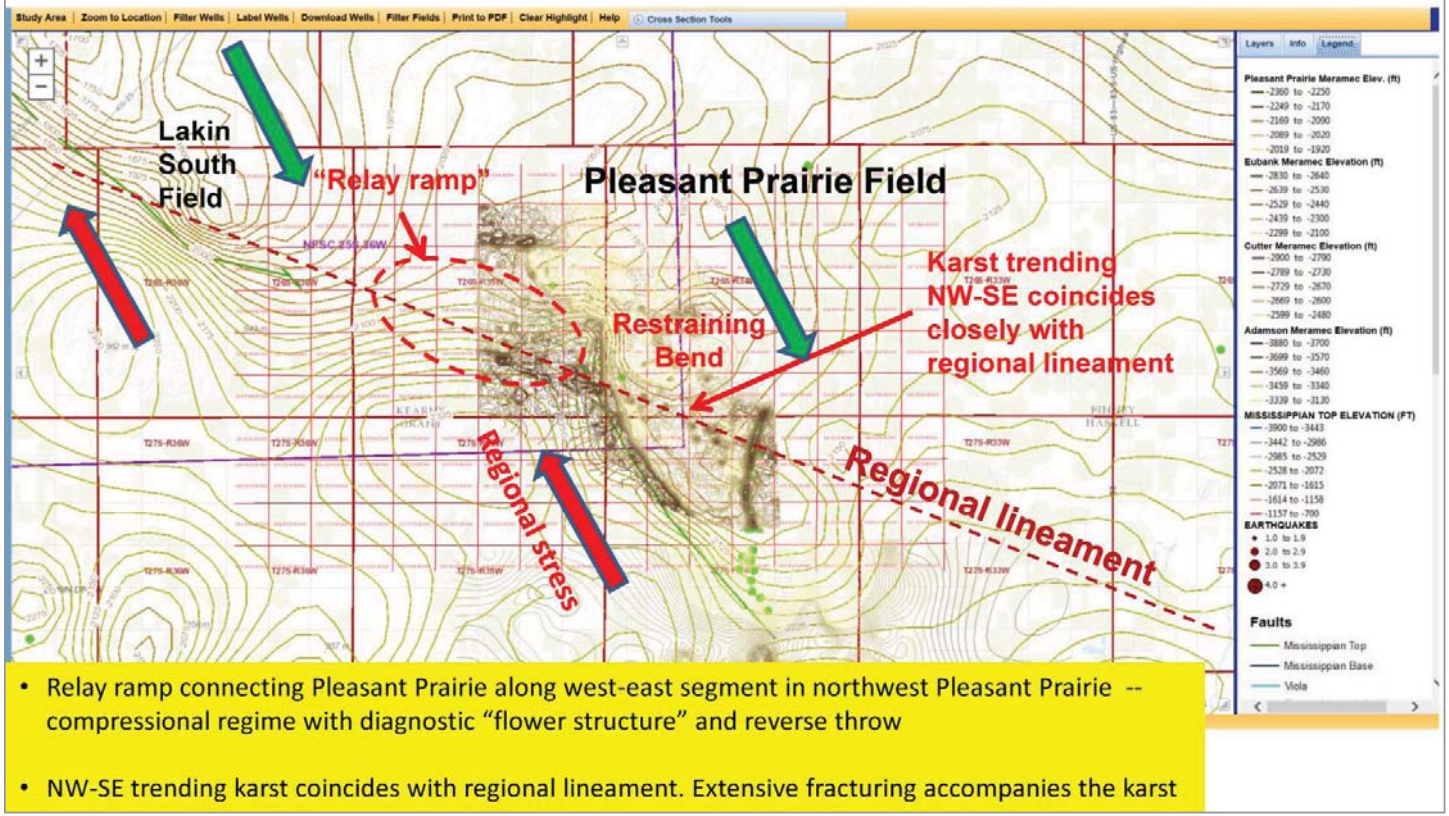
The cyclic retrogradational nature of Chester shoreline advances into Kansas are interpreted to have filled incised valleys with a series of 'back-stepping' stacked estuarine sandstone reservoirs. Red dashed lines are postulated sequence boundaries, and purple lines are possible parasequences.

J. Youle & IHR team, DOE-CO2

Regional Meramec Structure & Local Depth Converted Seismic at Pleasant Prairie Field

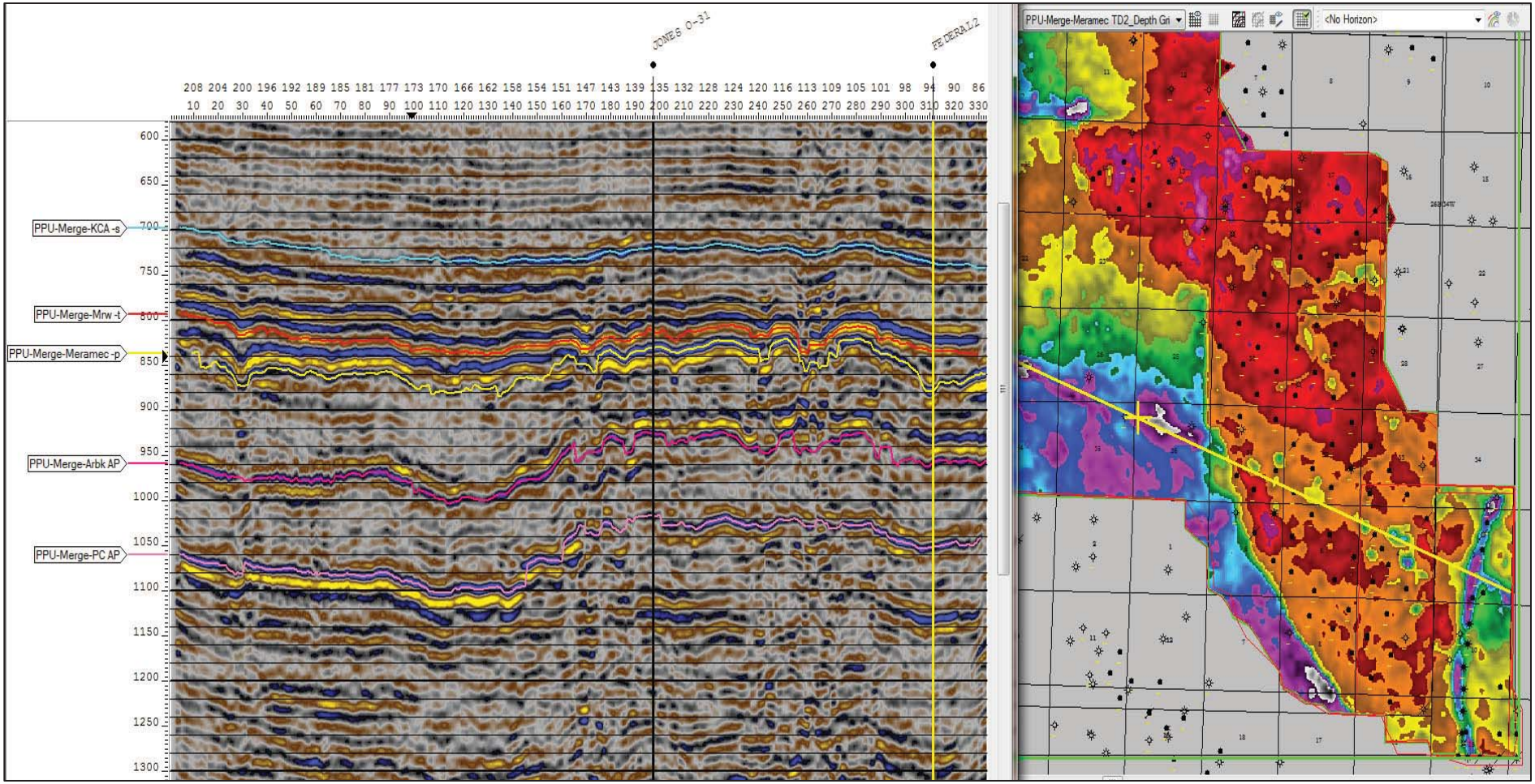
-- illustrating restraining bend, relay ramp with flower structure →

indications of strike-slip faulting



- Relay ramp connecting Pleasant Prairie along west-east segment in northwest Pleasant Prairie -- compressional regime with diagnostic "flower structure" and reverse throw
- NW-SE trending karst coincides with regional lineament. Extensive fracturing accompanies the karst

Presenter's notes: Relay ramp connecting Pleasant Prairie along west-east segment in northwest Pleasant Prairie -- compressional regime with diagnostic "flower structure" and reverse throw shown on seismic.
NW-SE trending karst coincides with regional lineament. Extensive fracturing along with karst; western bounding fault more vertical and reverse.



Pleasant Prairie Karst

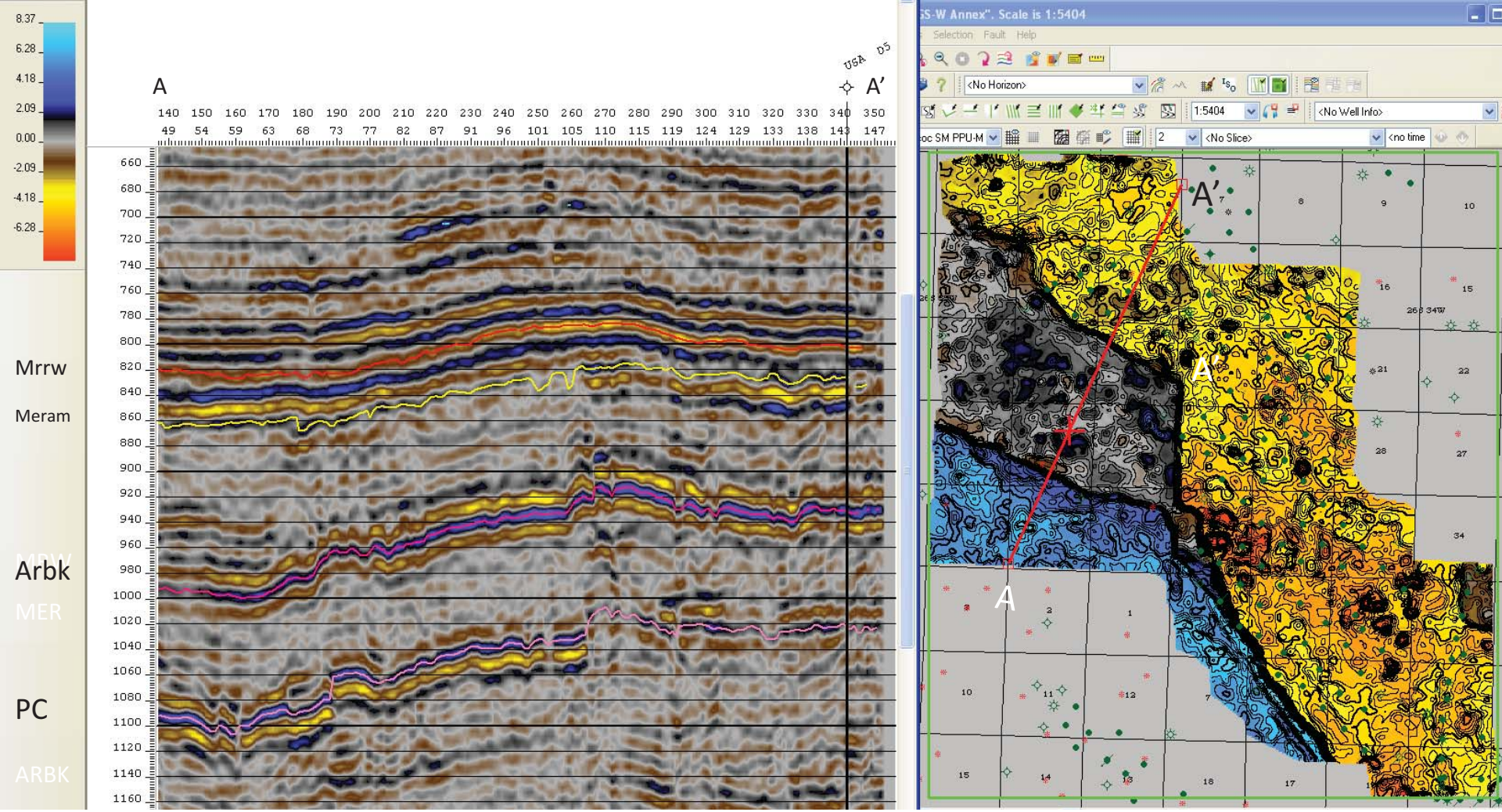
Arbitrary Profile illustrating multiple Karst features

In most cases, ‘pipes’ extend well below Meramec, into Arbuckle

Prominent features noted at stations 30, 170, 242, 260;

IVF system at sta 310; note that profile continues SE of Federal 2 into tributary

D. Hedke, DOE-CO2



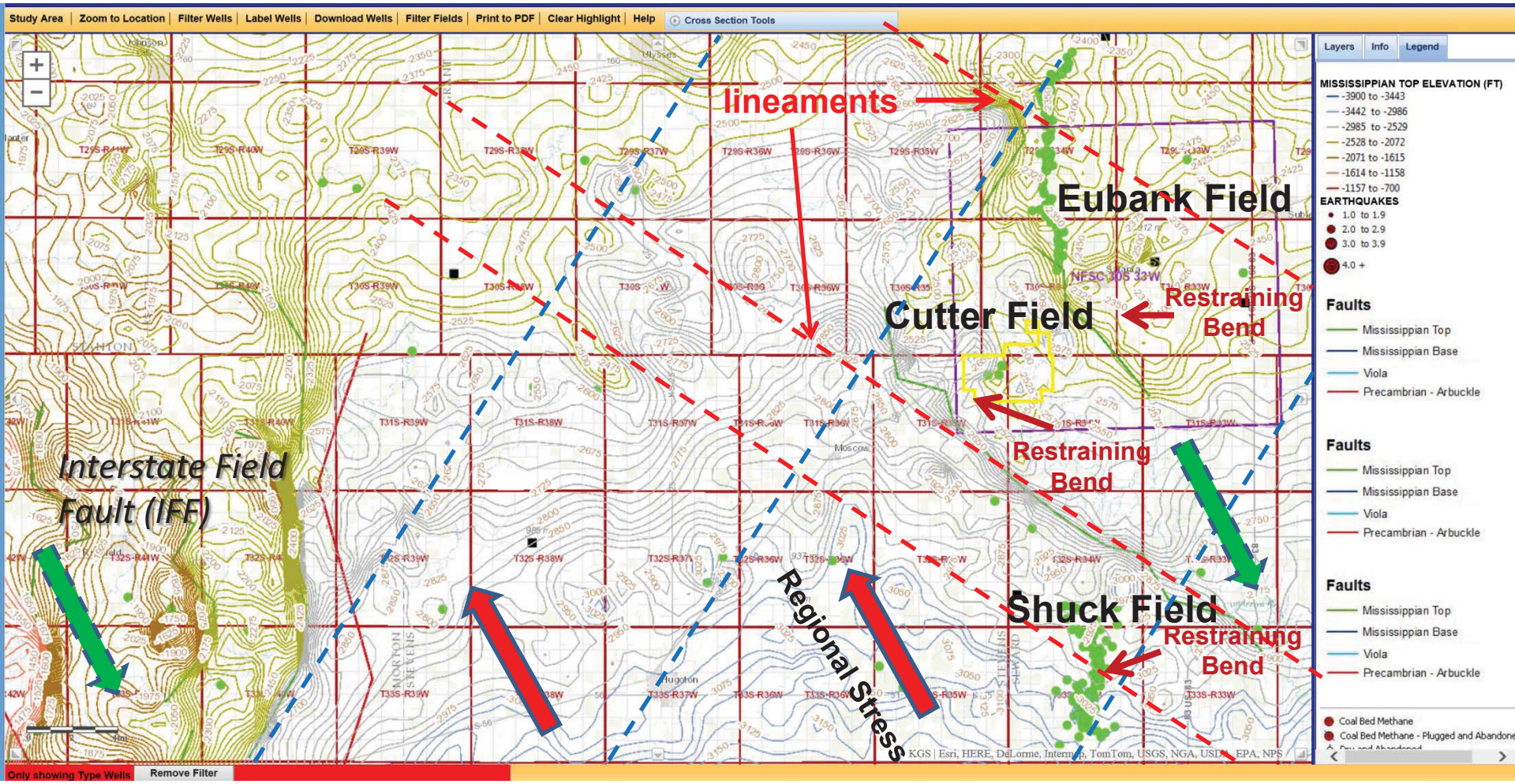
Pleasant Prairie – Morrow - PC Isochron

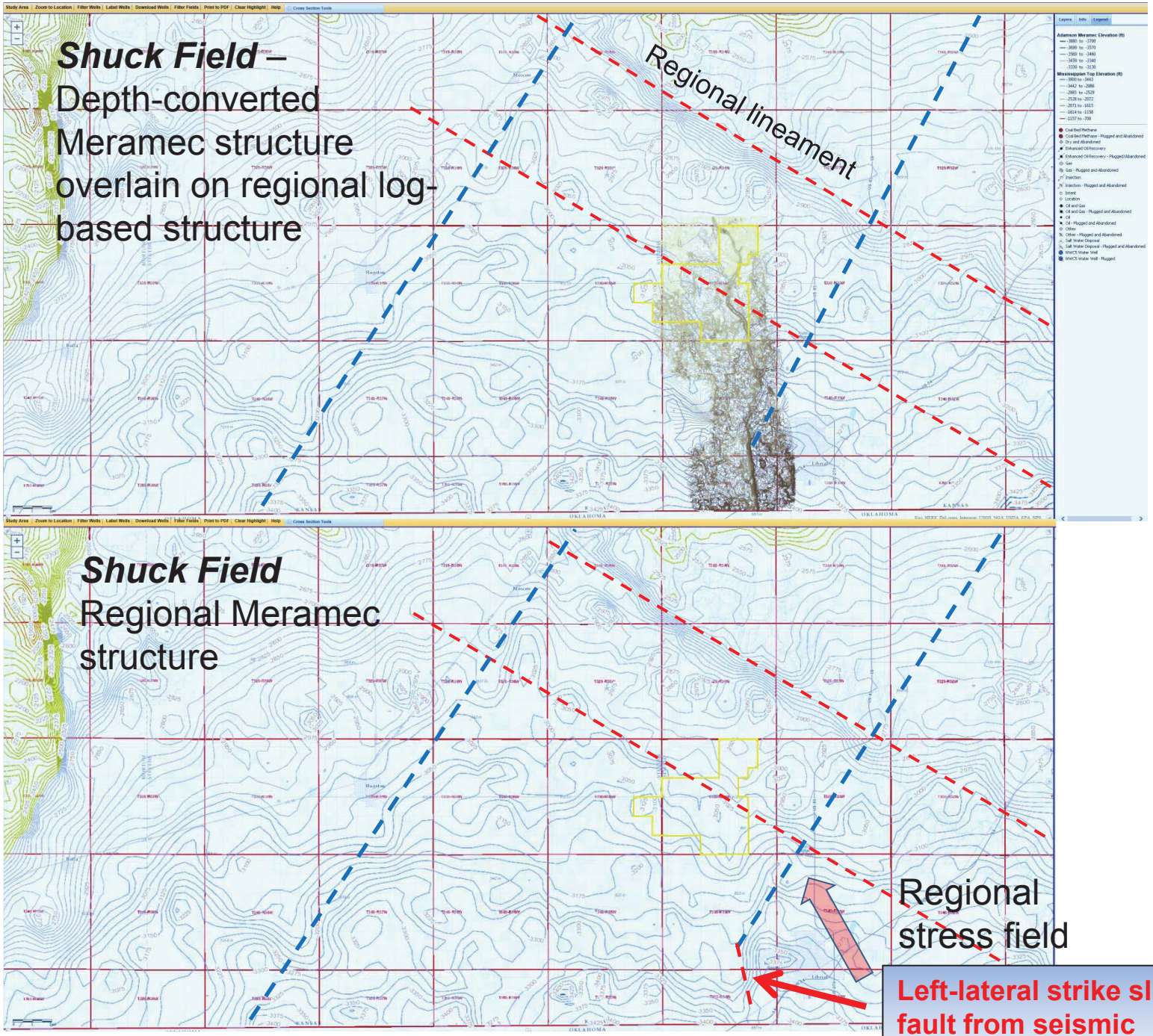
Note that while structural arch is clearly exhibited, isochronal thickening occurs in discrete step changes at faults.

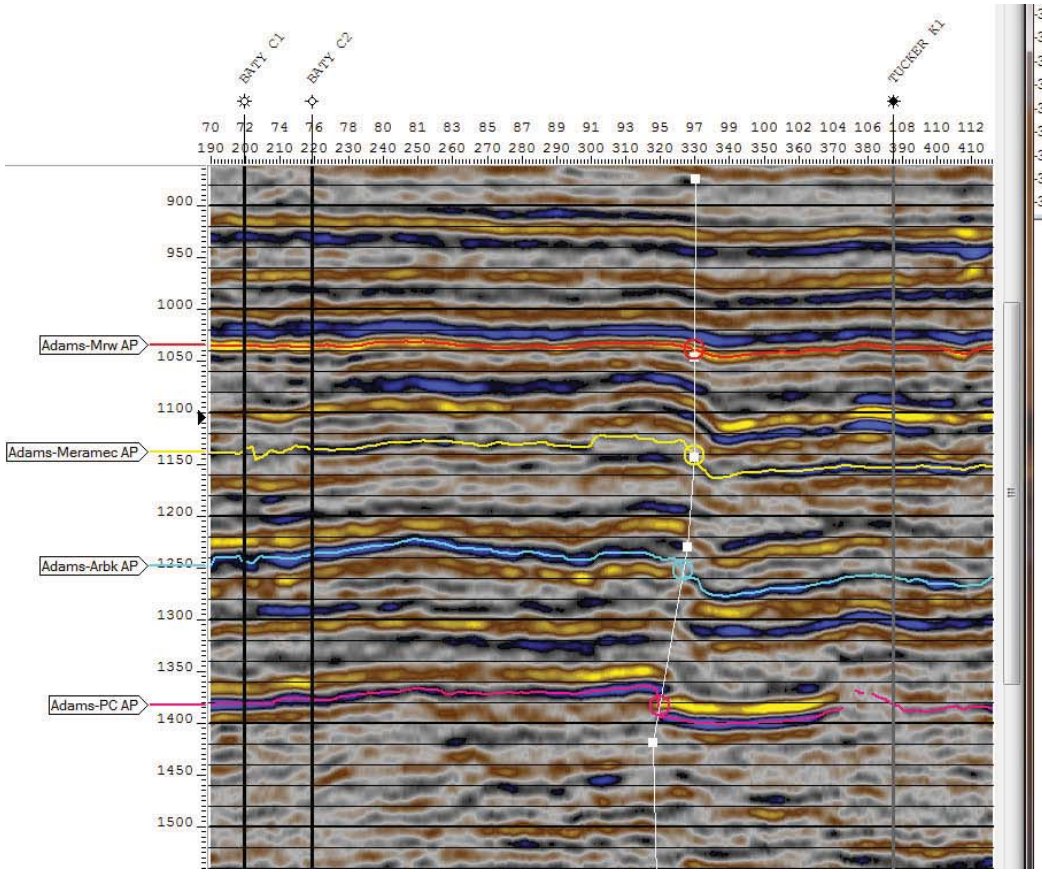
Note that the IVF is not expressed in this isochron; Karst is accentuated.

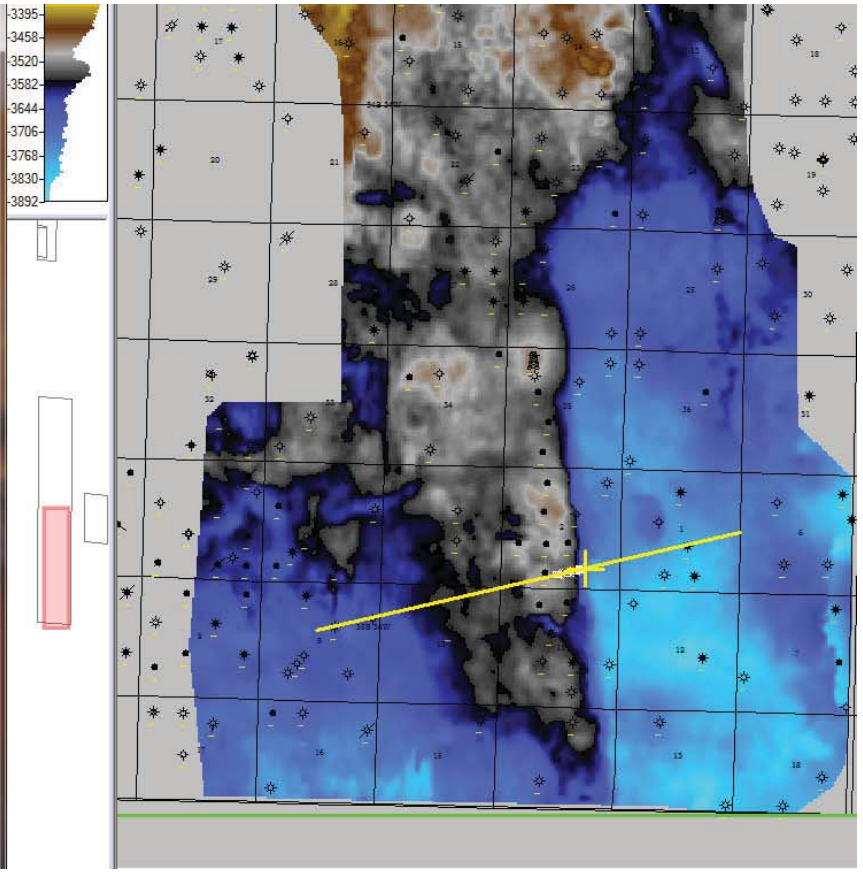
D. Hedke, DOE-CO2

Cutter Field is interpreted as another restraining bend bounded by NW-SE lineament




Shuck Field –
Depth-converted Meramec structure overlain on regional log-based structure
Regional lineament
Shuck Field
Regional Meramec structure
Regional stress field
Left-lateral strike slip fault from seismic

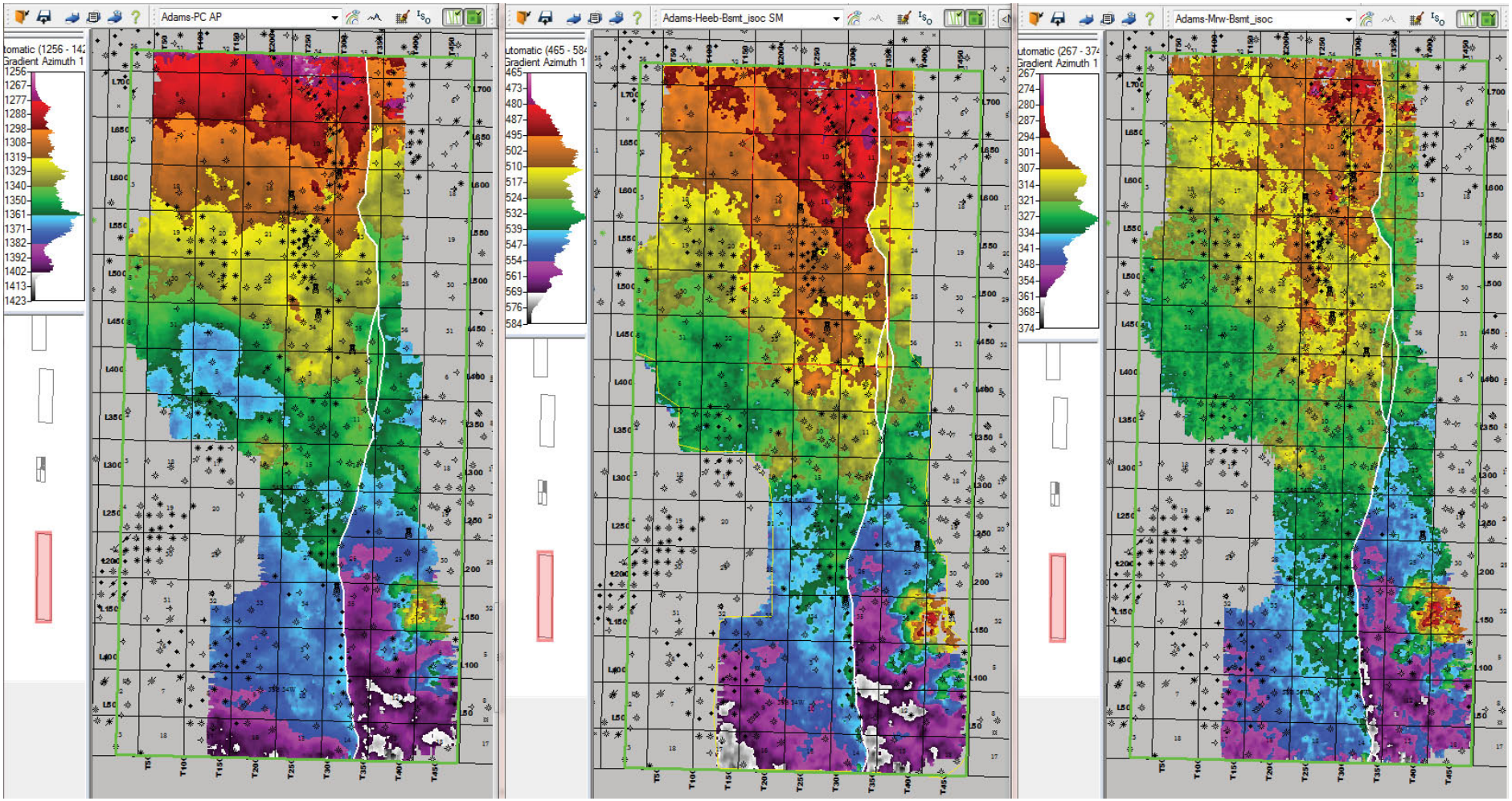




Archer – Liberal West Reverse Fault

Horizontal offset from trace 330 (fault tip) to trace 319 (below Precambrian) is approx 1200 ft. Meramec datum at Baty C1 (-3648), that at Tucker K1 (-3809); Vertical relief 161 ft.

D. Hedke, DOE-CO2



5 mi

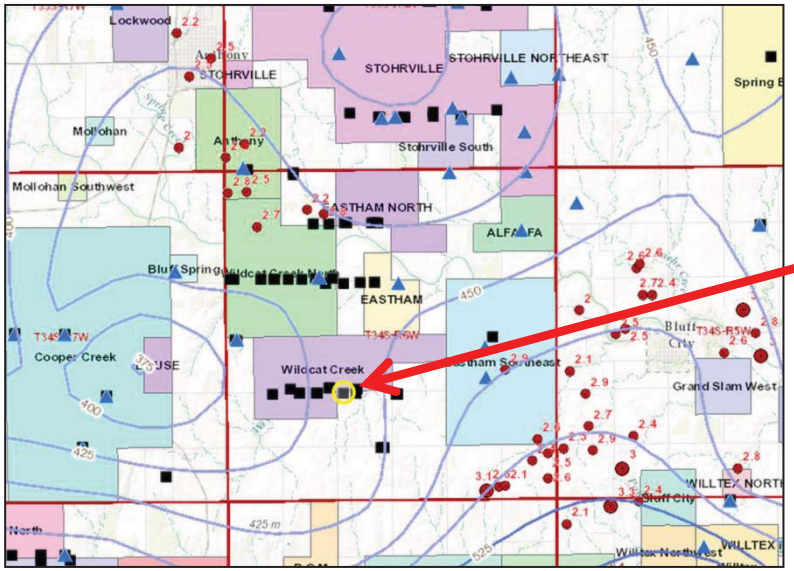
Shuck –West Liberal Strike-Slip Evidence in Isochrons

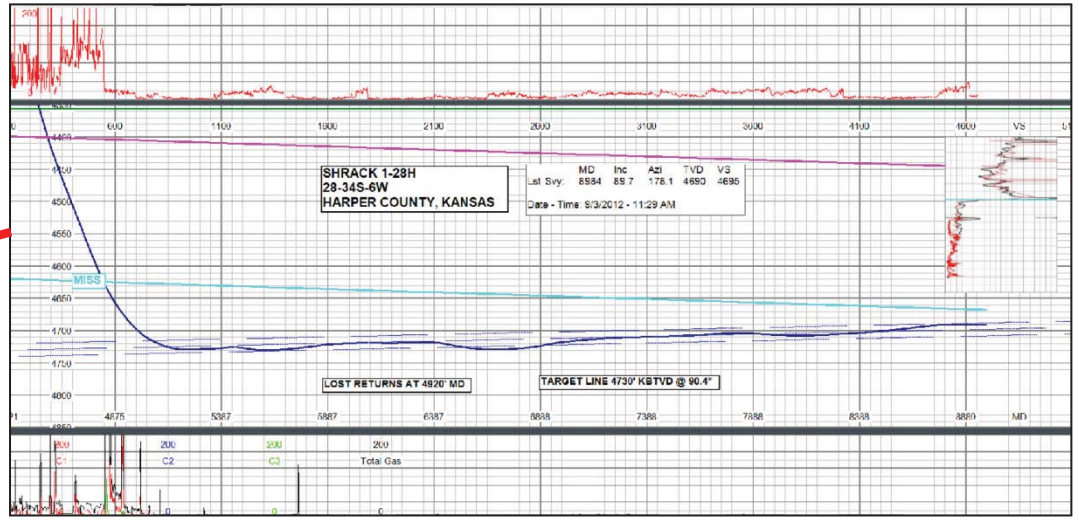
Left Image Basement Time, Middle Image Heebner-Basement Isochron, Right Image Morrow-Basement Isochron.

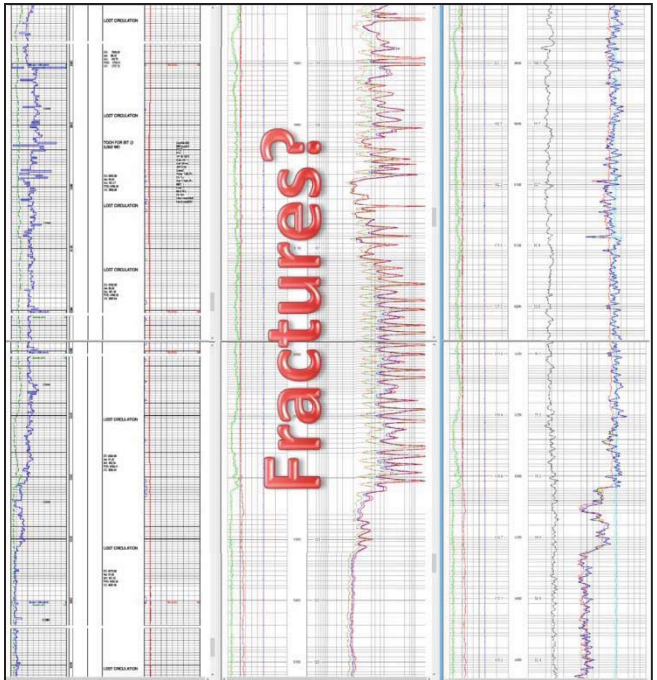
It would appear that the corroboration of strike-slip movement is evidenced in each of these isochrons, probably more so in the Heebner to Basement.

D. Hedke, DOE-CO2

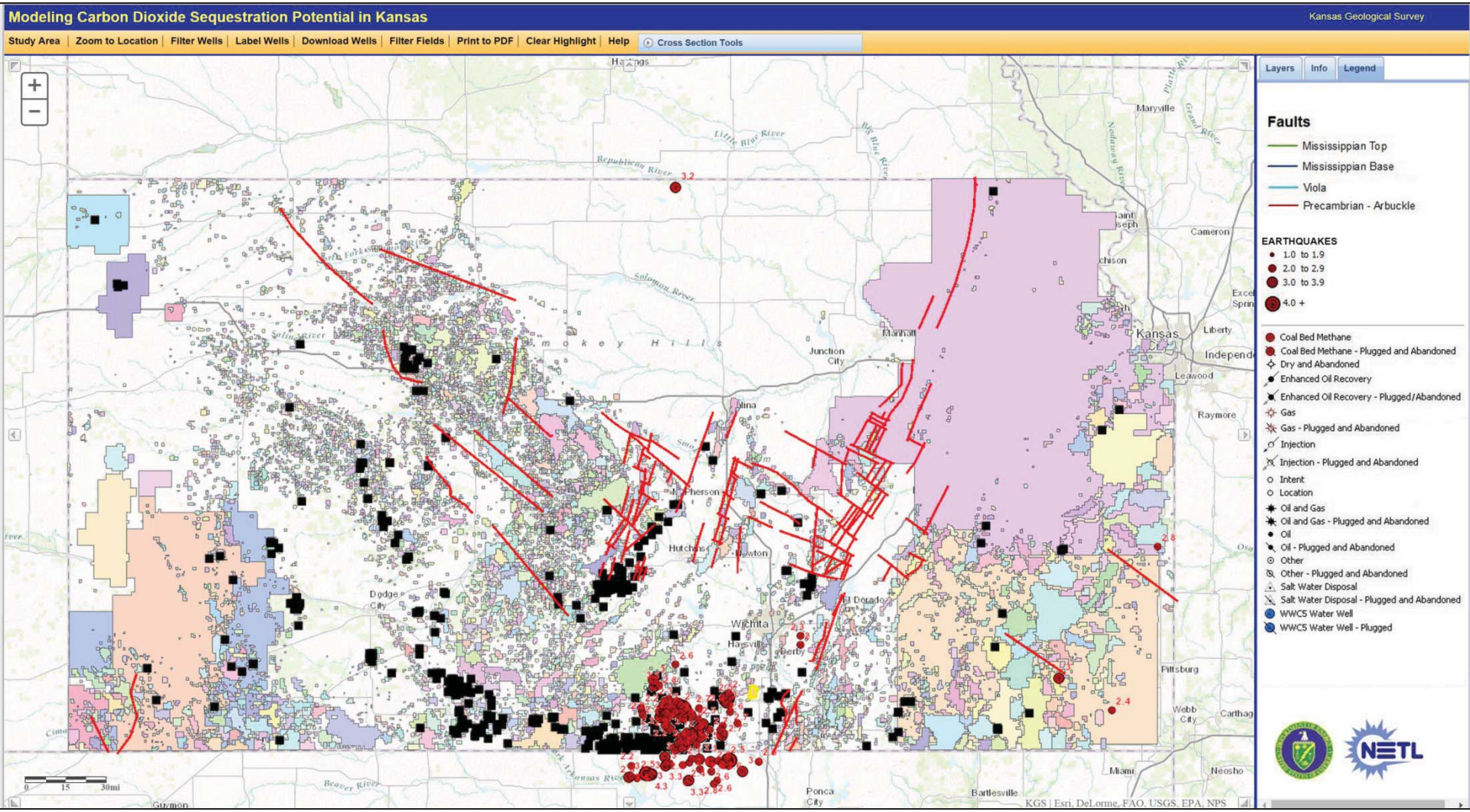
Managing Produced Water in a Complex Structural Setting







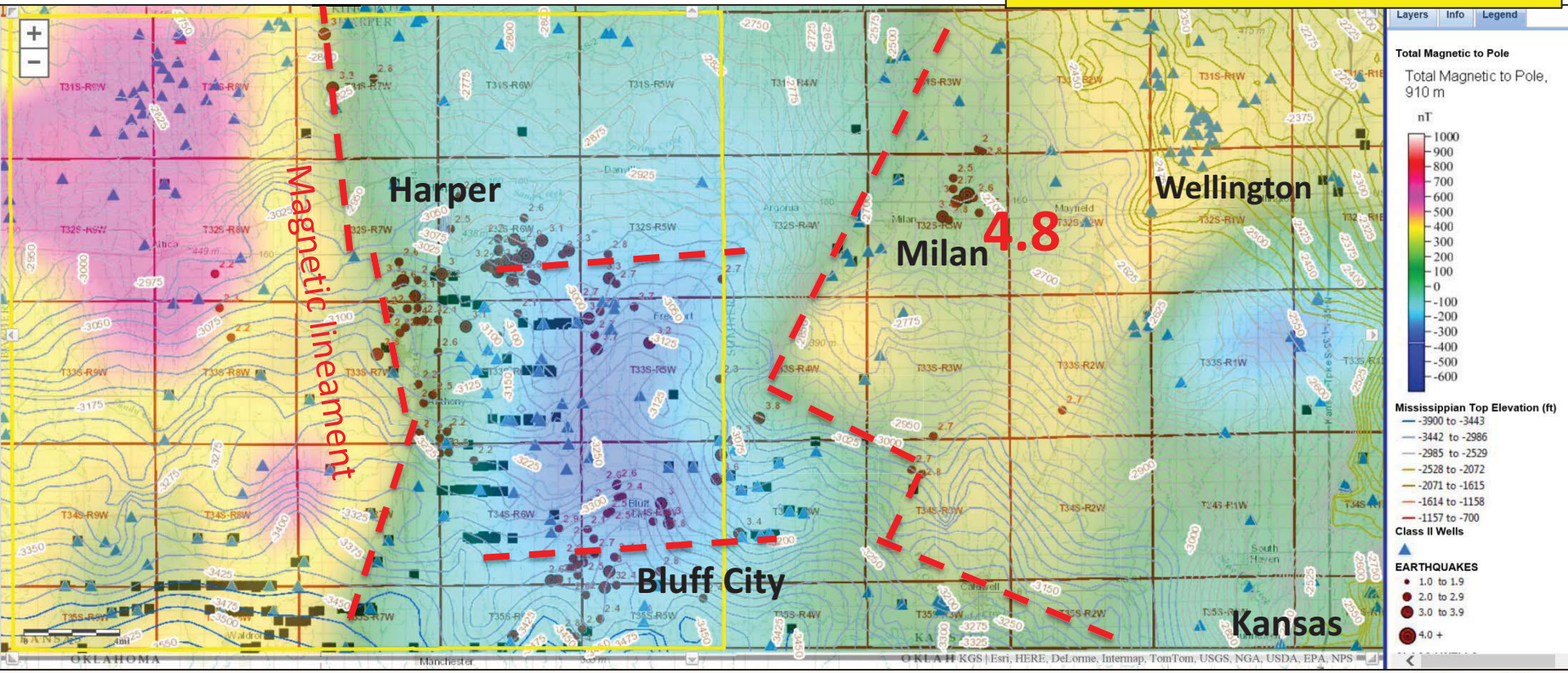
Managing Produced Water in a Complex Structural Setting



Heart of Mississippian Lime Play in Sedgwick Basin along northern edge of the Anadarko Basin

Total magnetic field intensity reduced to pole 910 m + top Mississippian structure

Harper County (yellow outline)



5 mi

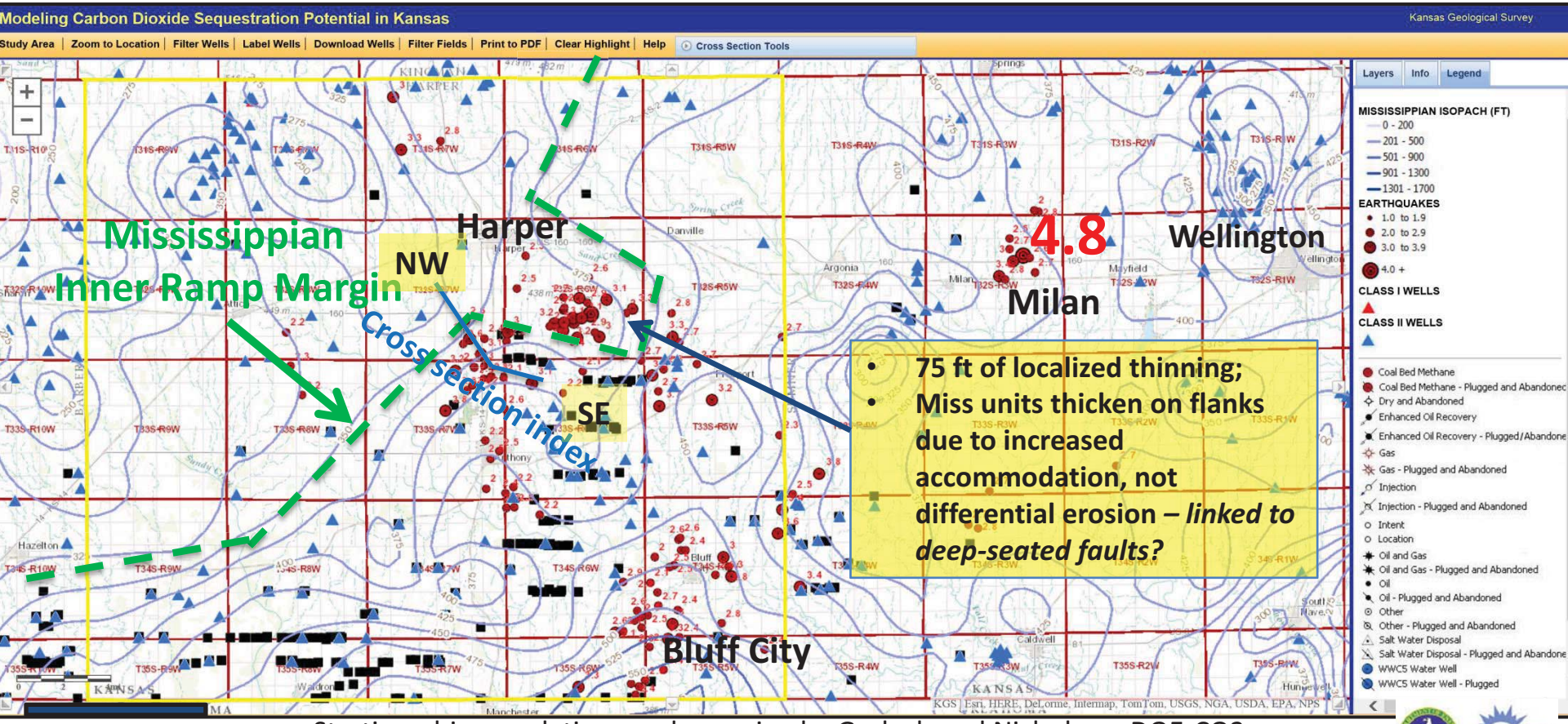
Stratigraphic correlations by Gerlach & Nicholson – DOE-CO2
http://maps.kgs.ku.edu/co2/

Oklahoma

Earthquakes along edges of magnetic lineaments

-- Suggest link of earthquakes to basement structure

Mississippian isopachous map (Harper-Sumner Co., Kansas) with horizontal (■) and Class II wells (▲)



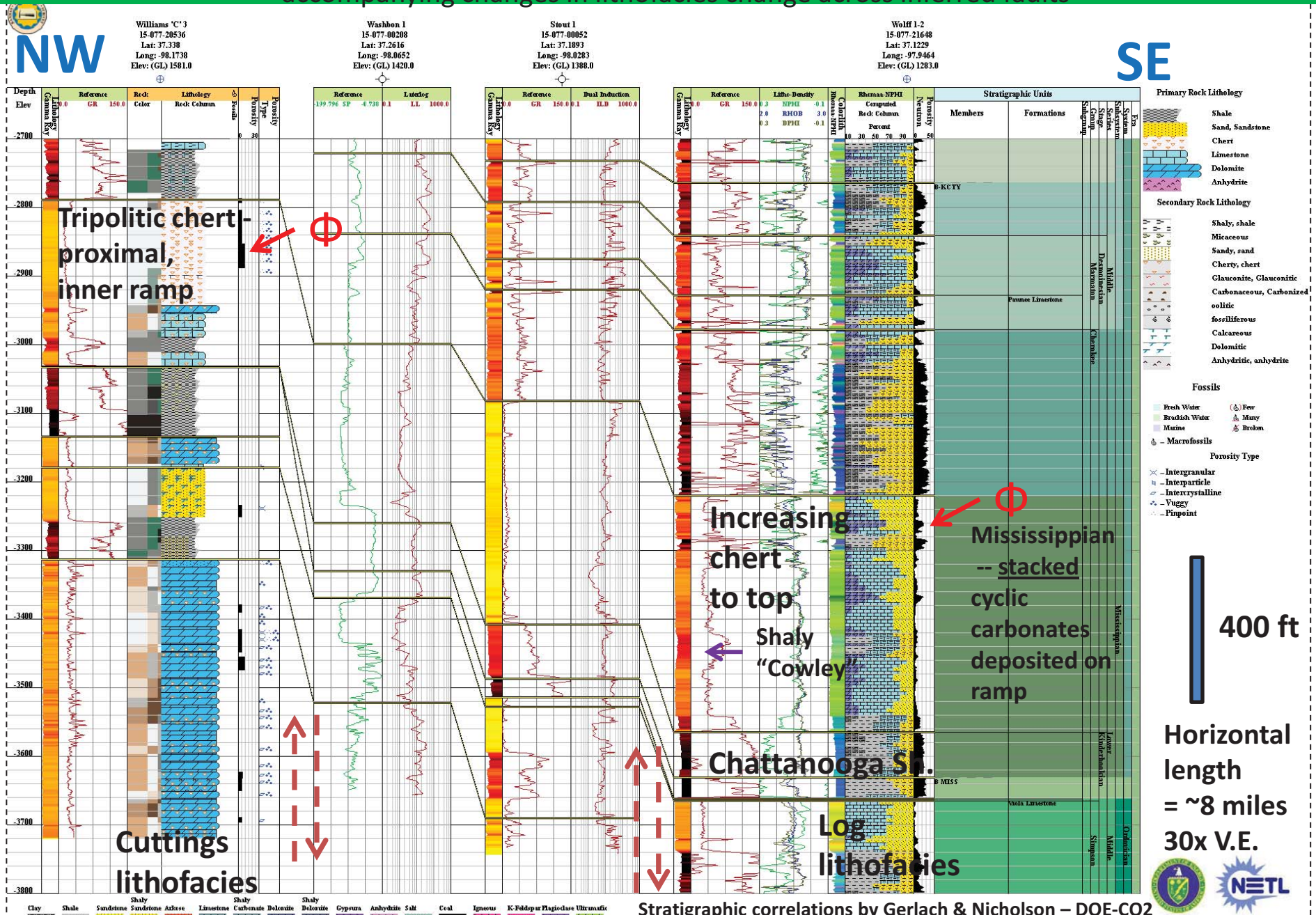
10 mi

Stratigraphic correlations and mapping by Gerlach and Nicholson, DOE-CO2

Earthquakes and magnitude 2.2

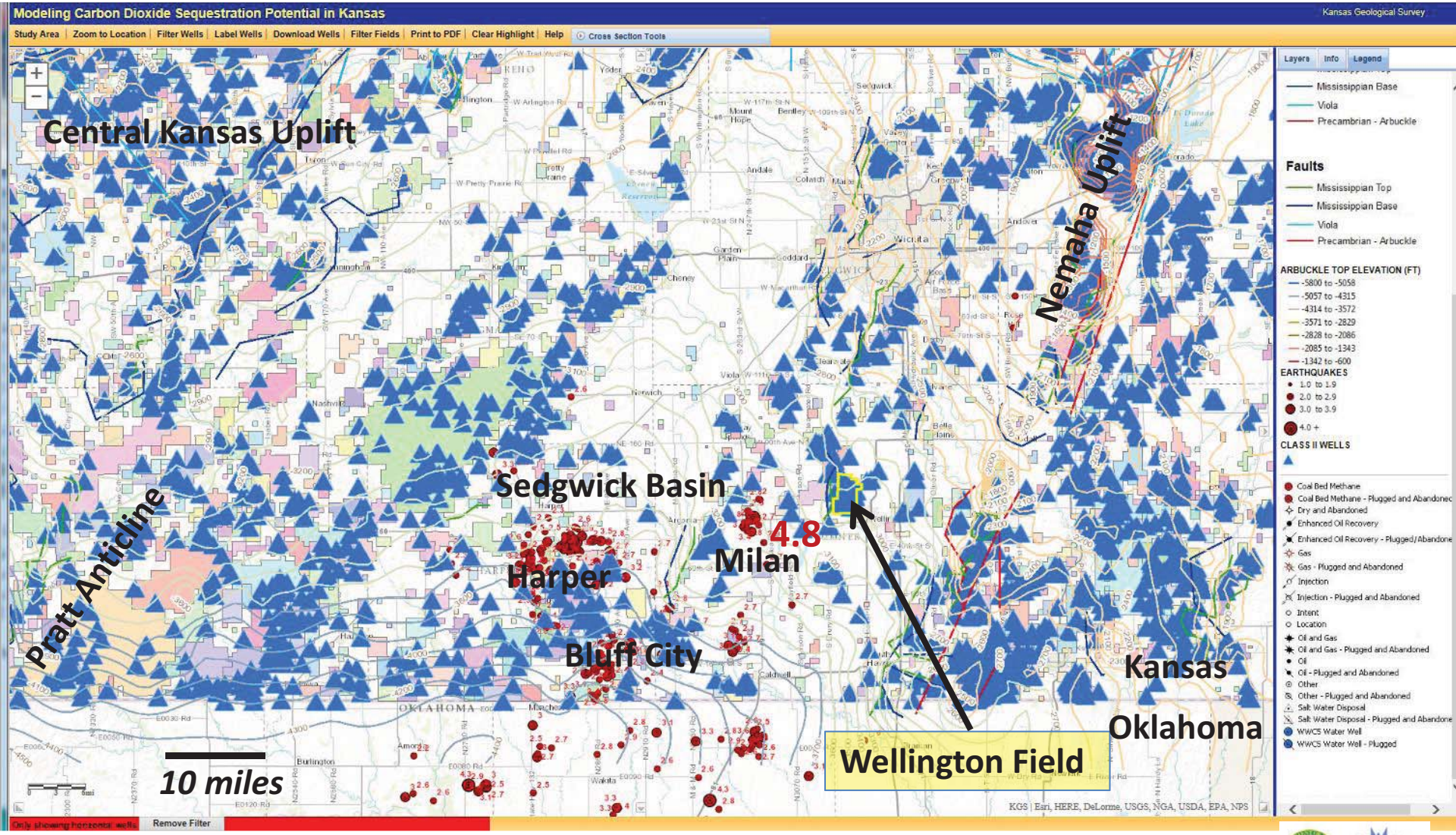
NW-SE Structural Cross Section Across Updip Edge of Miss Ramp

- accompanying changes in lithofacies change across inferred faults



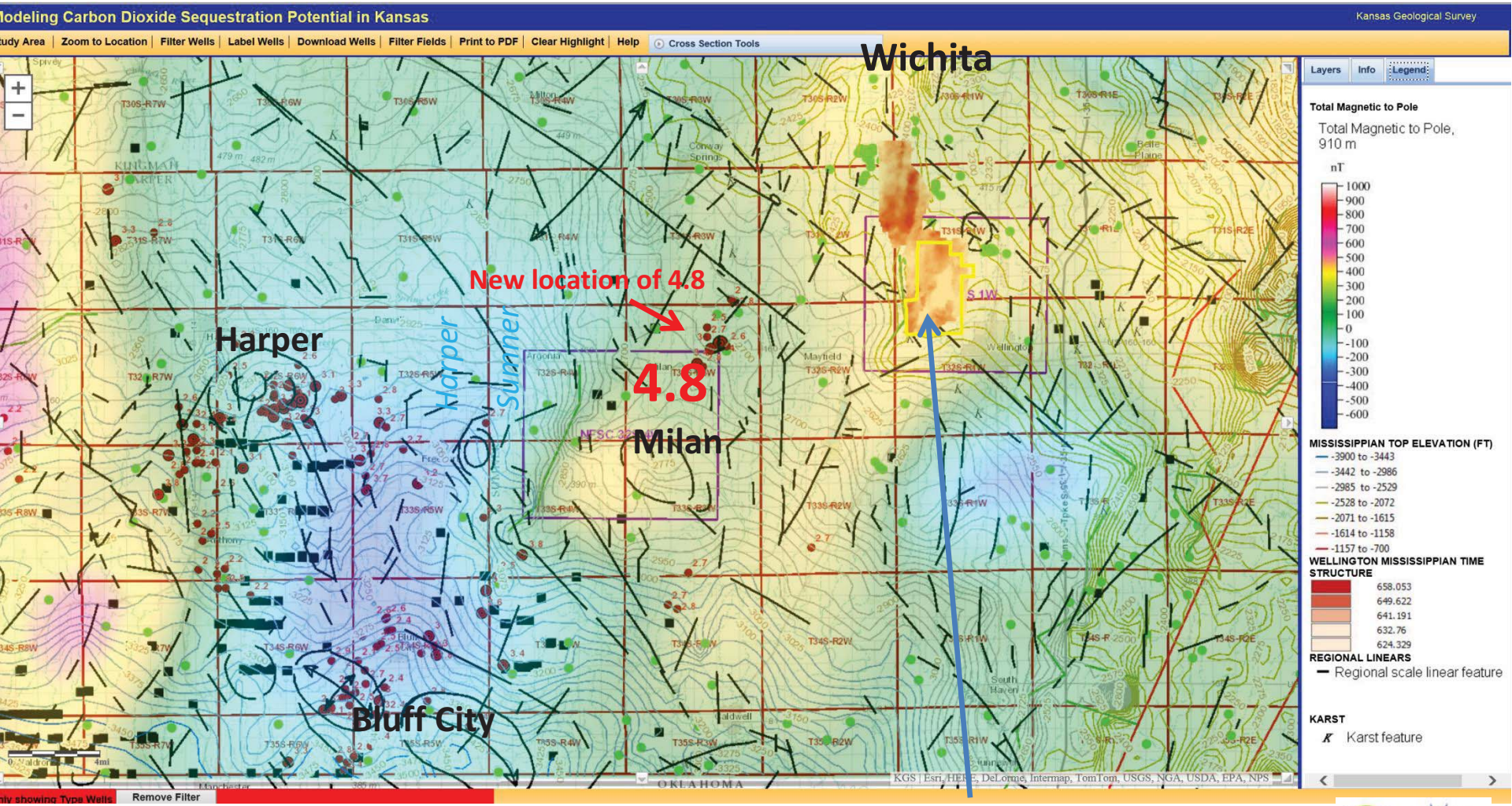
Stratigraphic correlations by Gerlach & Nicholson – DOE-CO2

Top Arbuckle Structure, Mapped Faults, Earthquakes, Class II Disposal Wells, Oil Field Outlines



http://maps.kgs.ku.edu/co2/

Top Mississippian Structure
Total Magnetic Field Reduce to Pole
Earthquakes
Horizontal Wells
Regional Surface Lineaments
Wellington Field – Miss Time Structure

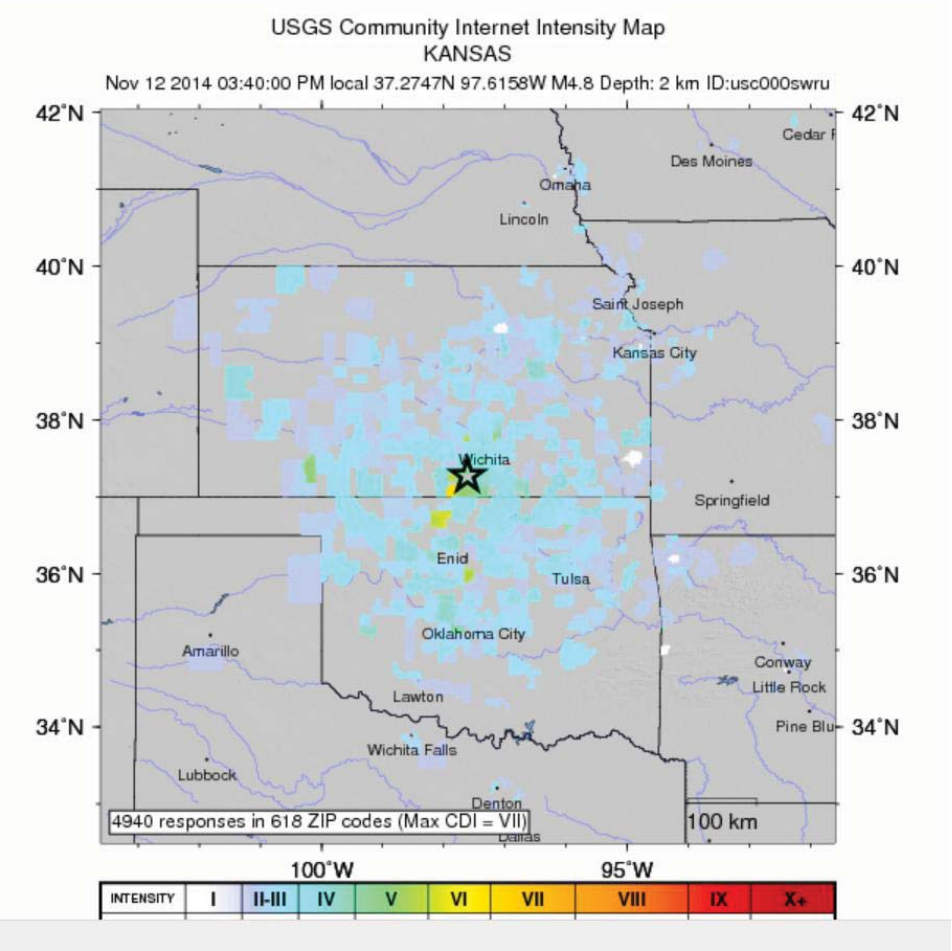


Wellington-Anson/Bates

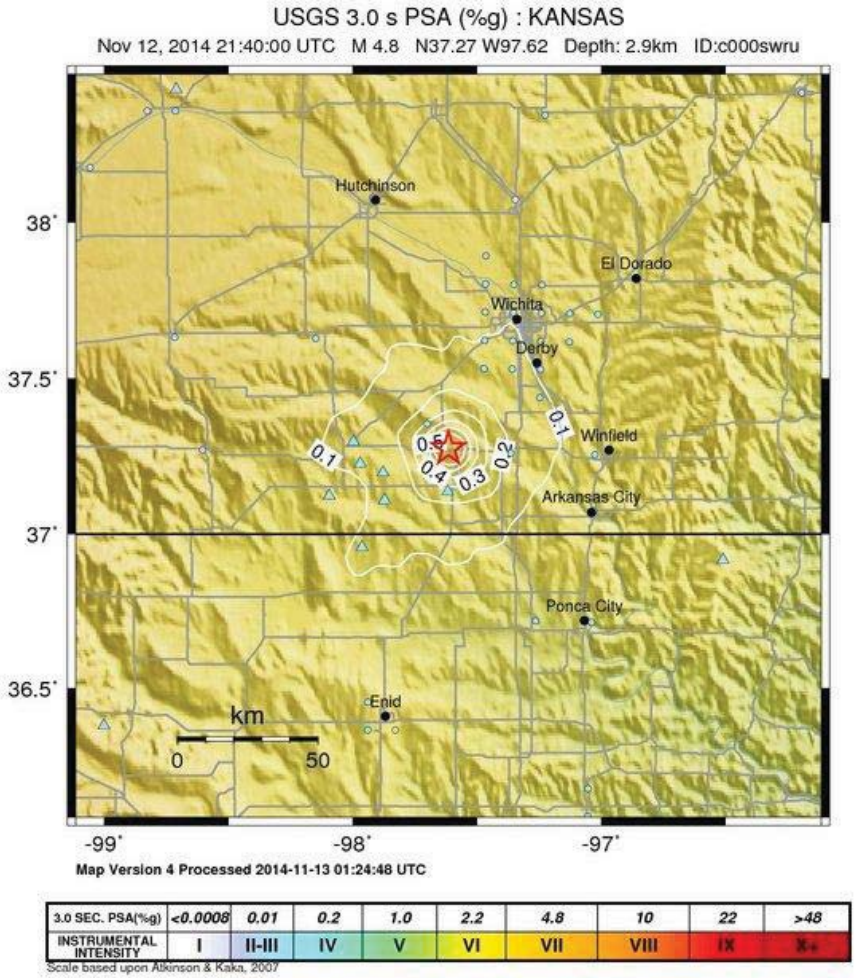
Time structure -Mississippian

4.8 Earthquake – SW of Wichita

Did you feel it?



Peak acceleration (%gravity)



Summary
ShakeMap
PAGER
Did You Feel It?
Scientific
Summary
Contributed Solutions
Moment Tensor
Downloads

M4.8 - 13km S of Conway Springs, Kansas

2014-11-12 21:40:00 UTC

PAGER - GREEN | ShakeMap - V | DYFI? - VII

Google Earth KML

Return to the EQ List/Map/Search

Scientific

Location and Magnitude contributed by: USGS National Earthquake Information Center

Contributed Moment Tensors

	Type	Magnitude	Depth	NP1	NP2	Author	Catalog	Contributor
	Mwr	4.8	5.0 km	290°, 86°, -24°	22°, 66°, -175°	us		us

Regional Moment Tensor (Mwr)

Moment magnitude derived from a moment tensor inversion of complete waveforms at regional distances (less than ~8 degrees), generally used for the analysis of small to moderate size earthquakes (typically Mw 3.5-6.0) crust or upper mantle earthquakes.

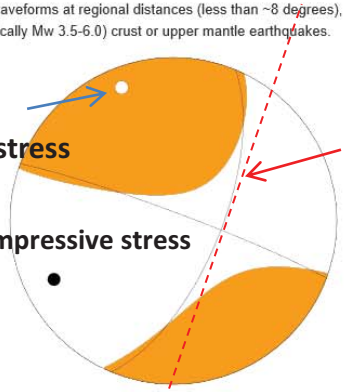
Moment	1.94e+16 N-m
Magnitude	4.8
Percent DC	62%
Depth	5.0 km
Updated	2014-11-13 01:24:16 UTC
Author	us
Catalog	us
Contributor	us_c000swru_mwr
Code	

Principal Axes

Axis	Value	Plunge	Azimuth
T	2.109	13°	339°
N	-0.400	66°	101°
P	-1.709	20°	244°

Nodal Planes

Plane	Strike	Dip	Rake
NP1	290°	86°	-24°
NP2	22°	66°	-175°



OBLIQUE STRIKE-SLIP MOTION

The figure above shows a visual representation of the style of faulting (focal mechanism) derived from the estimated moment tensor. Shaded areas show quadrants of the focal sphere in which the P-wave first-motions are away from the source, and unshaded areas show quadrants in which the P-wave first-motions are toward the source. The dots represent the axis of maximum compressional strain (in black, called the "P-axis") and the axis of maximum extensional strain (in white, called the "T-axis") resulting from the earthquake.

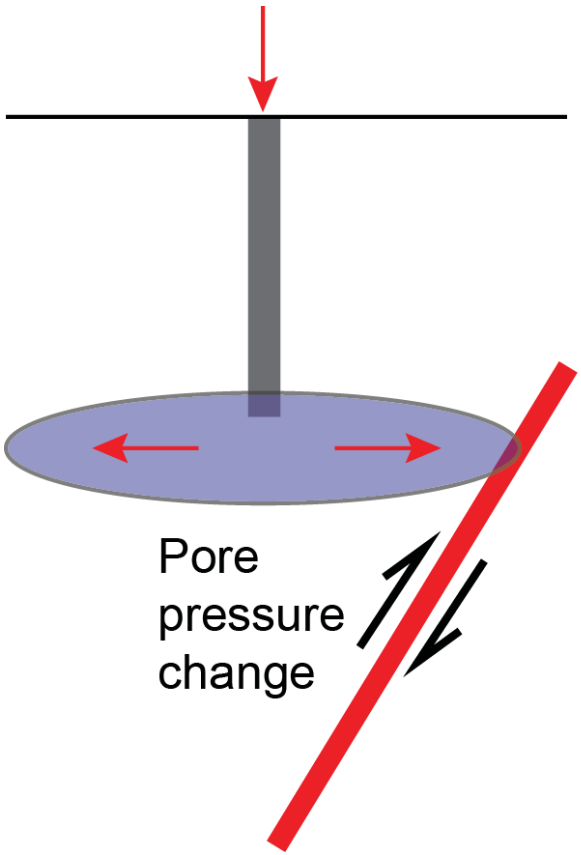
Additional Content

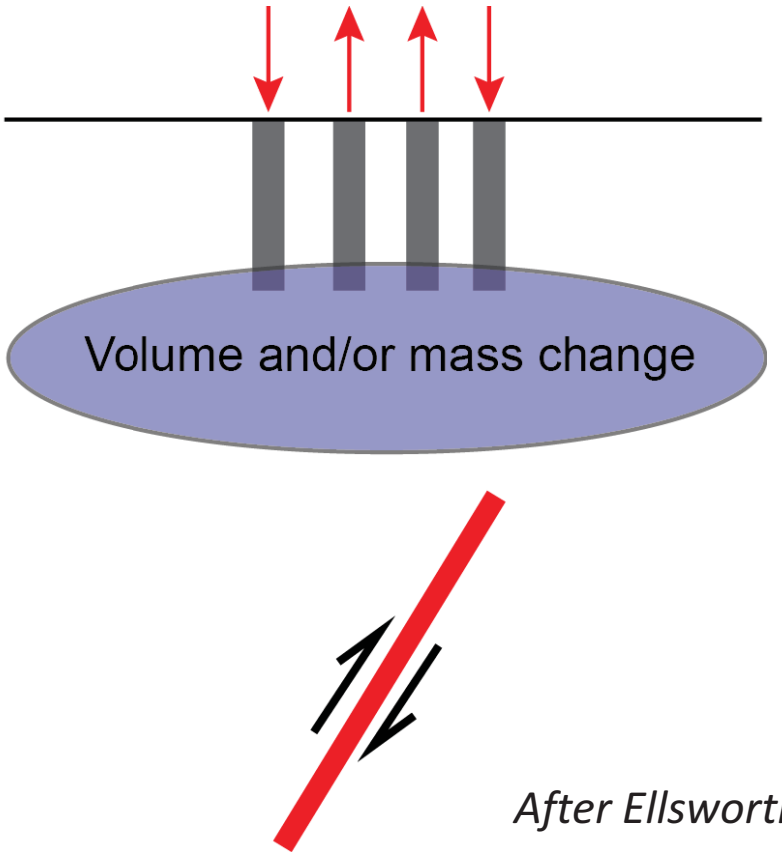
Earthquake XML (Quakeml)
Available Formats: XML (22 Kb)

Mechanics of induced earthquakes

1. **Increase pore fluid pressure acting on a fault**
   - Brine disposal (e.g., Healy et al.,1968)
   - Fracking (e.g., Holland, 2011)
   - Hydraulic connection needed

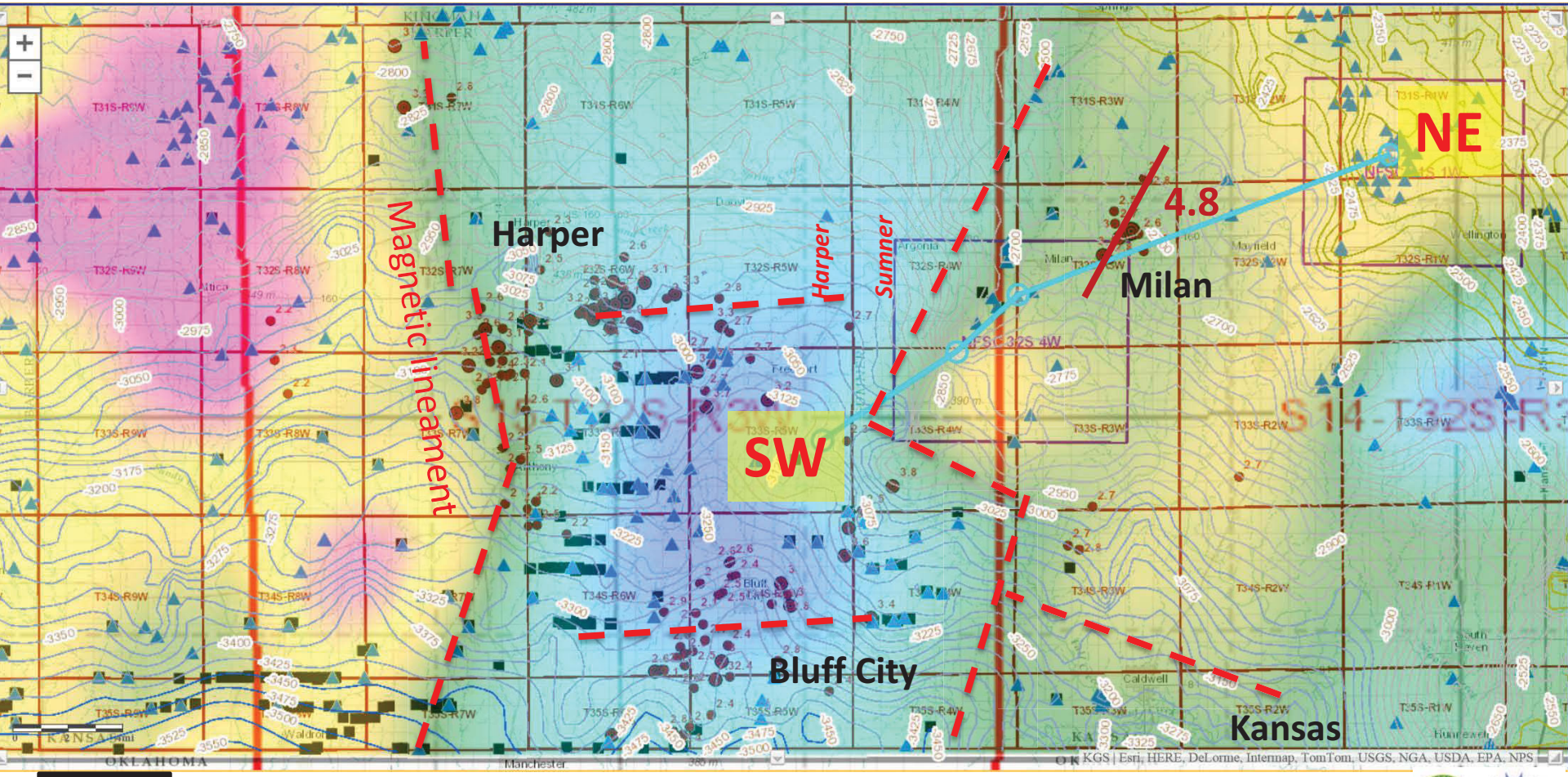
2. **Change shear or normal stress acting on fault**
   - Reservoir depletion or repressurization (e.g., McGarr, 1991)
   - No direct connection to fault

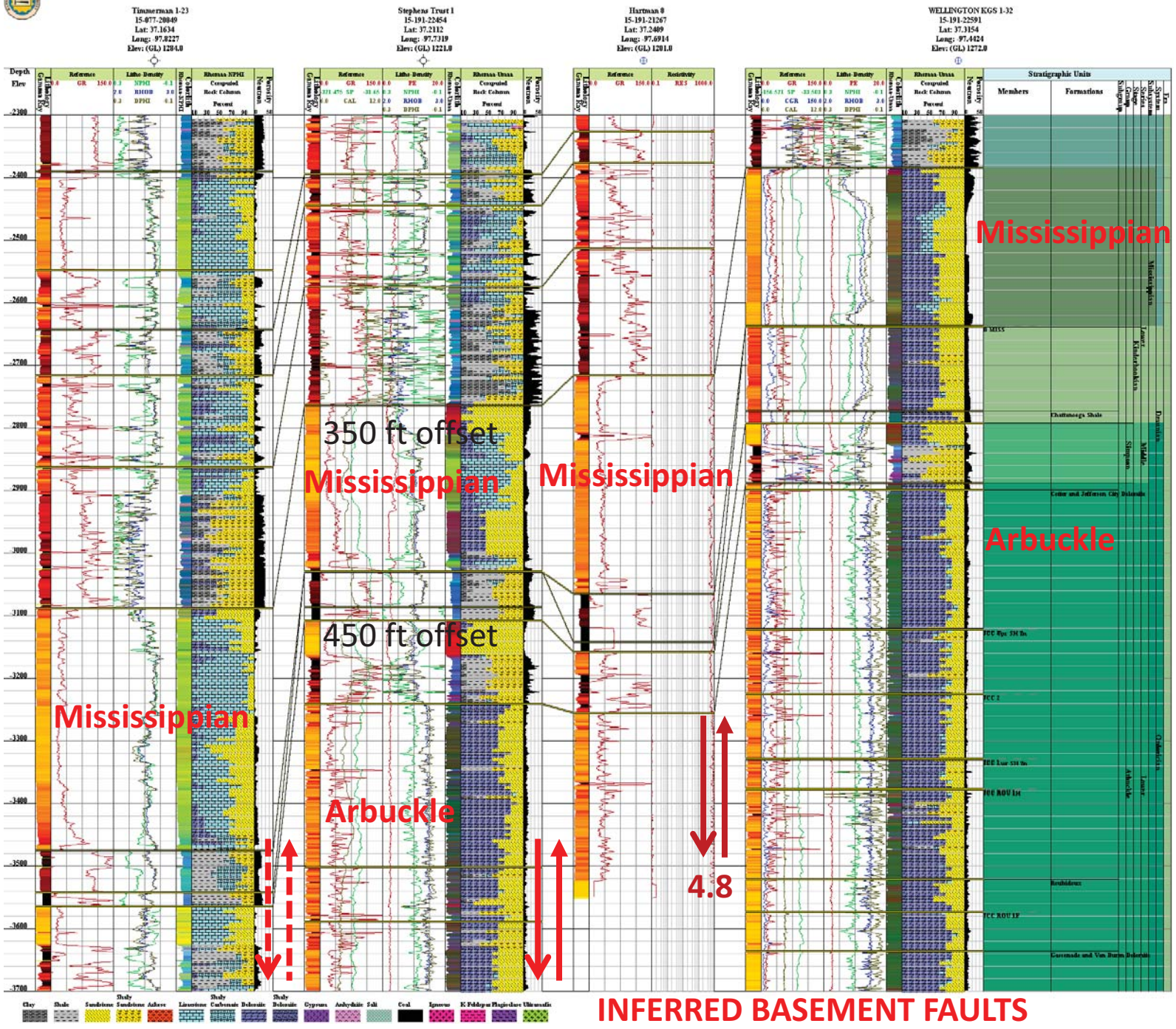




After Ellsworth, 2013

SW-NE Cross Section Index
Mississippian Embayment & Magnetic Low of MRS to NE-trending Magnetic High
-- *Manually drawn lineaments*



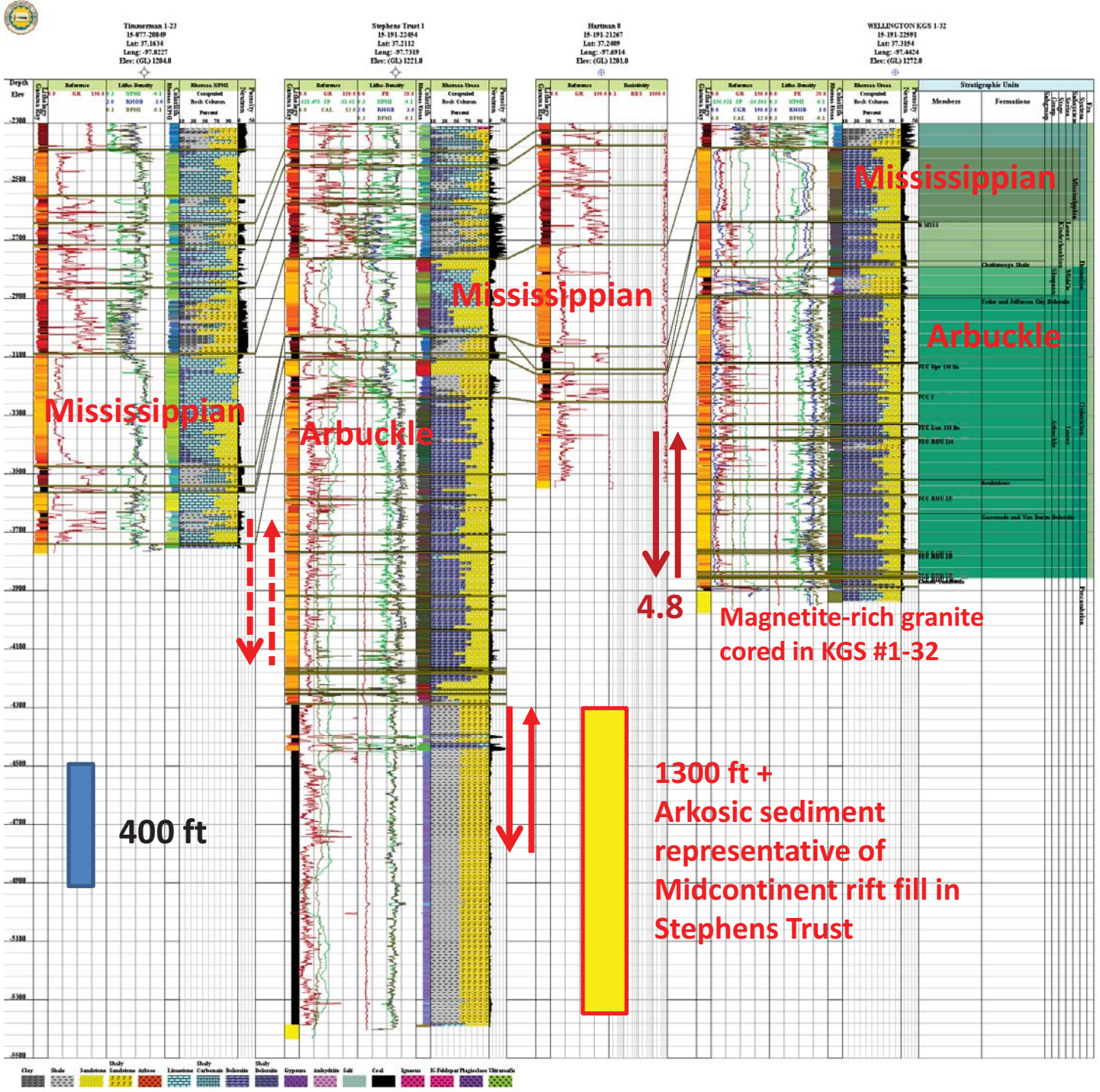


SW-NE Structural Cross Section

~40 miles long

- Notable offset at Miss
- Increasing with depth

200 ft

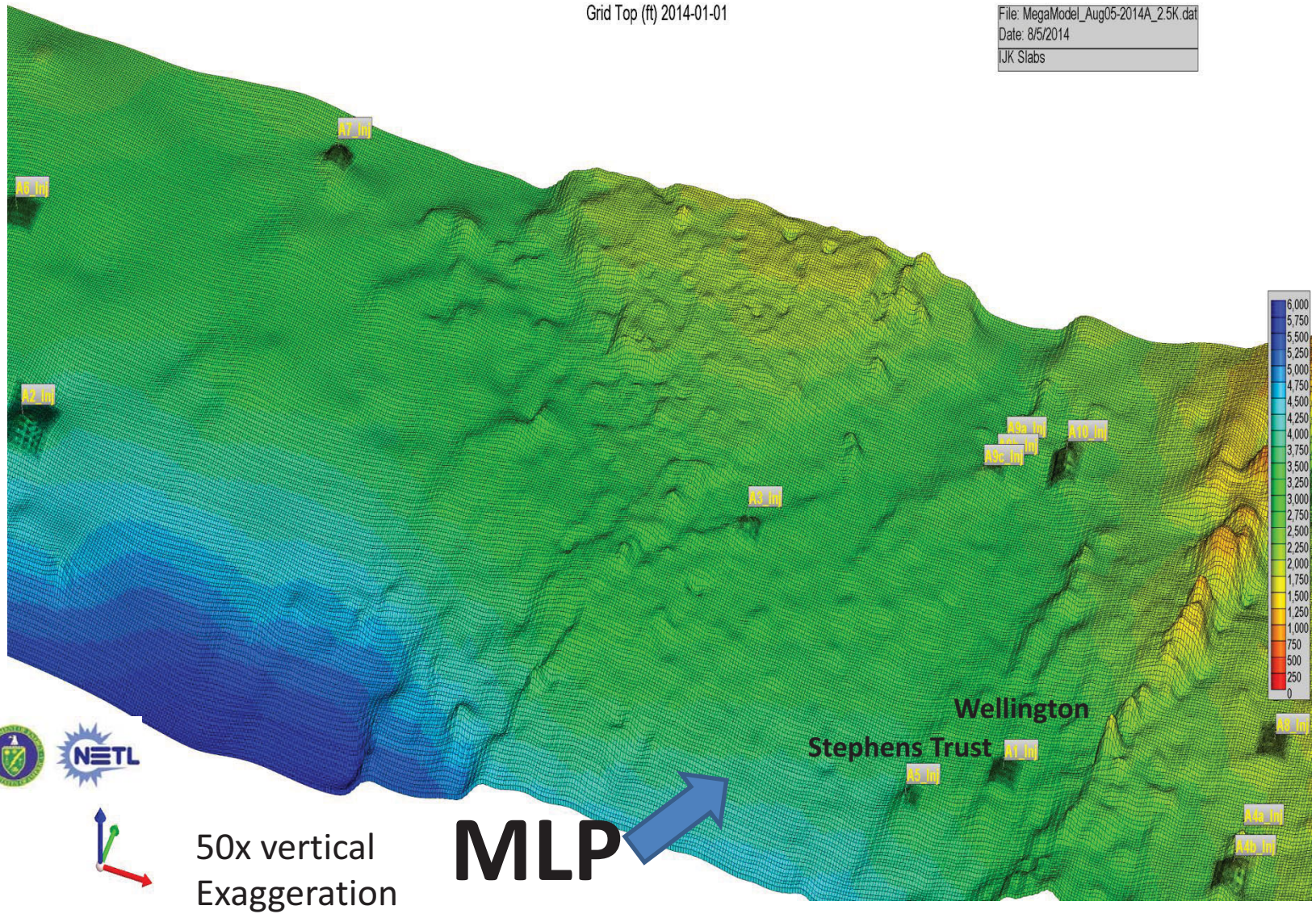


Same SW-NE Structural Cross Section

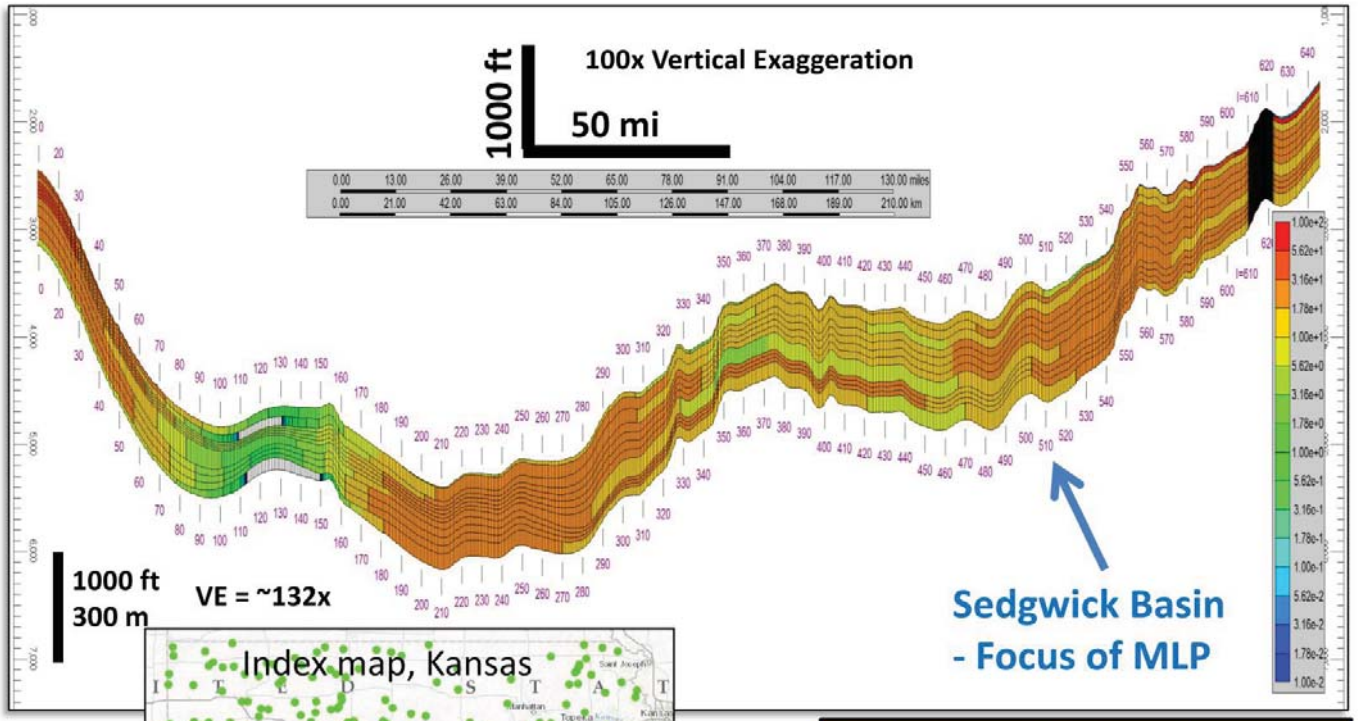
~40 miles long

Stepwise-faulting into the core of the Sedgwick Basin and Proterozoic rift basin

MegaModel Grid of Arbuckle saline aquifer for CO_2 Storage assessment in southern Kansas



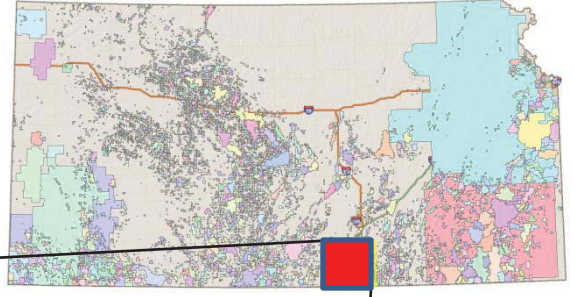
West-East Structural Cross Section Showing Permeability Distribution in Arbuckle Flow Units, Southern Kansas

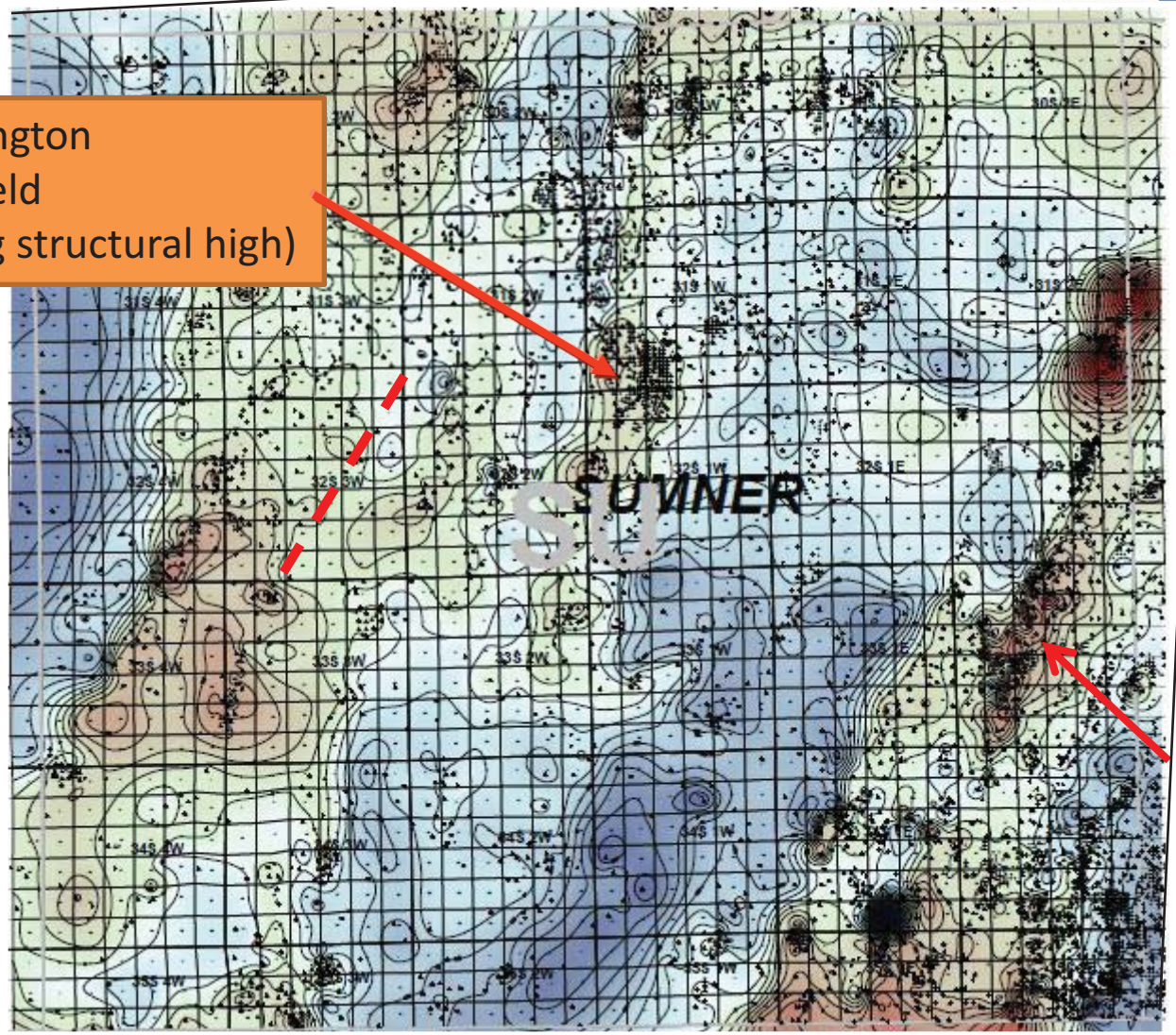


Williams, Gerlach, Fazelalavi, Doveton, KS CO_2

Presenter's notes: Entire Arbuckle saline aquifer as it varies across the regional study area. Brown colors are over 100 md. Greens are less.

Third-order structural residual
Top Mississippian
Sumner County, KS





Wellington
Field
(NE-SW trending structural high)

Nemaha
Uplift

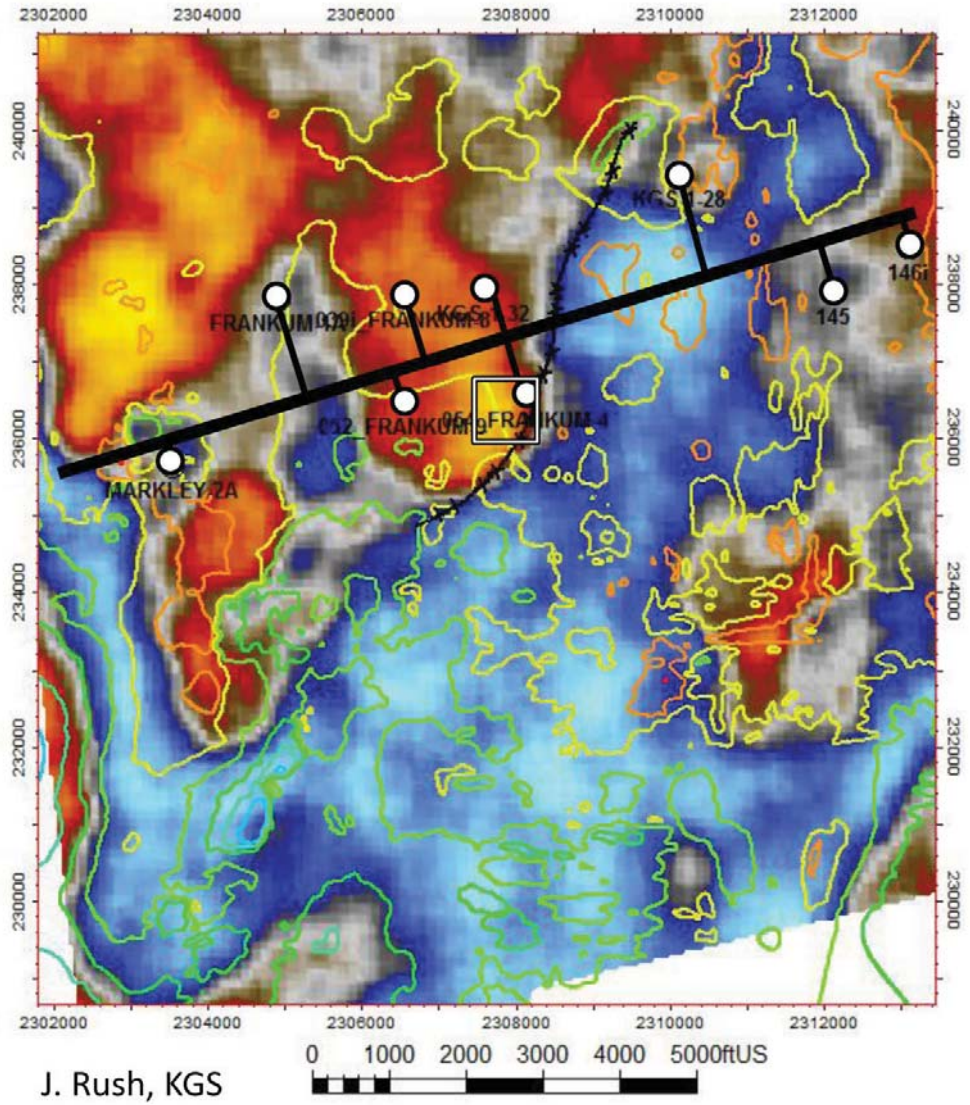
6 mi

6 mi

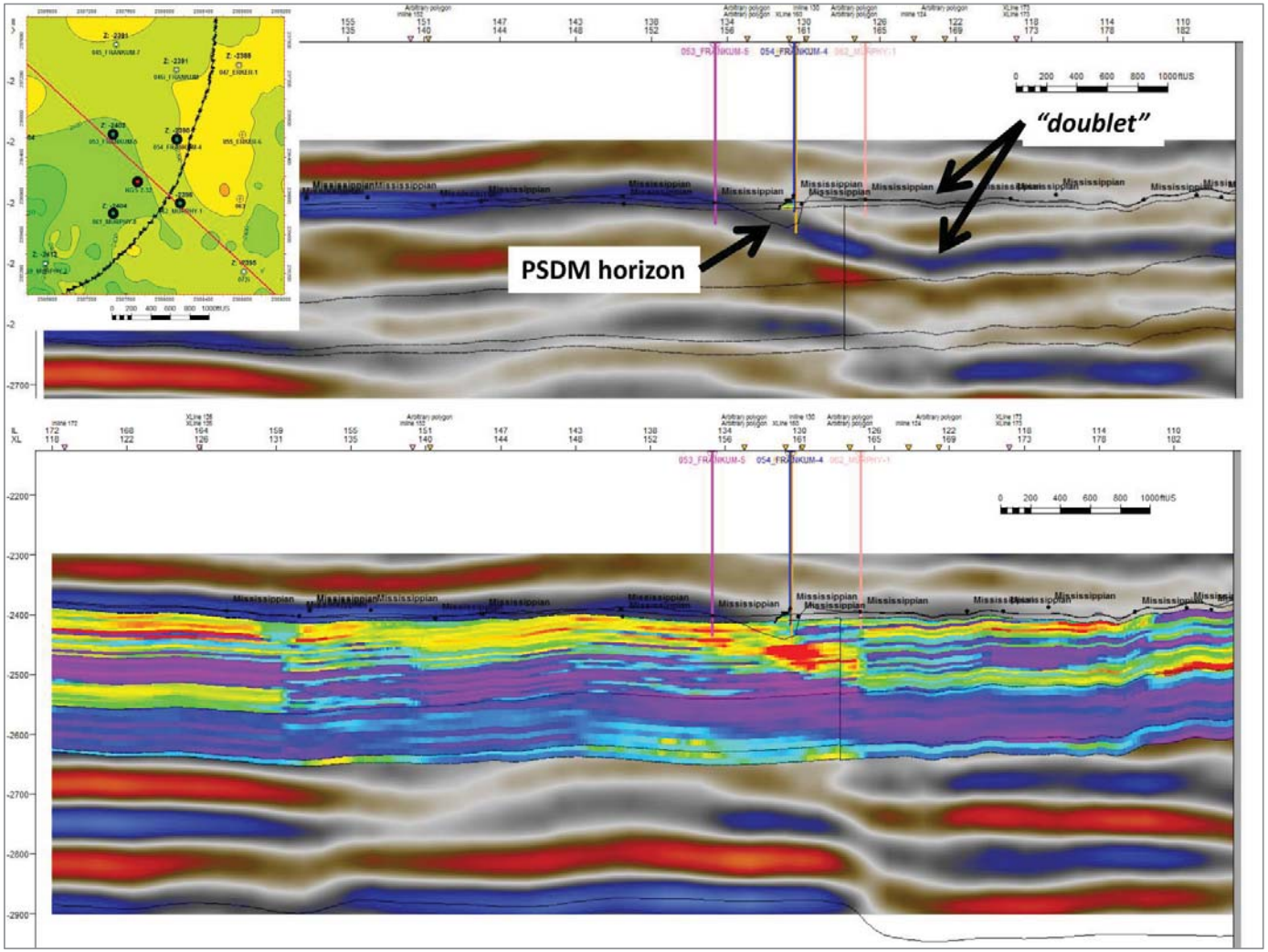
P. Gerlach, DOE-CO2

Wellington Field

- **Contours are top Mississippian.**
- **NE-SW fault**
  - **20+ ft of reflector offset** is best imaged at this depth (2810-ft TVDSS)
  - Fault tips out at top Mississippian
  - **Within the Mississippian, the fault may record strike-slip movement** as opposed to vertical offset in older strata
  - **Fault is discontinuous**
  - **Fault underwent episode of later movement** just prior to deposition of Upper Pennsylvanian Oread Limestone

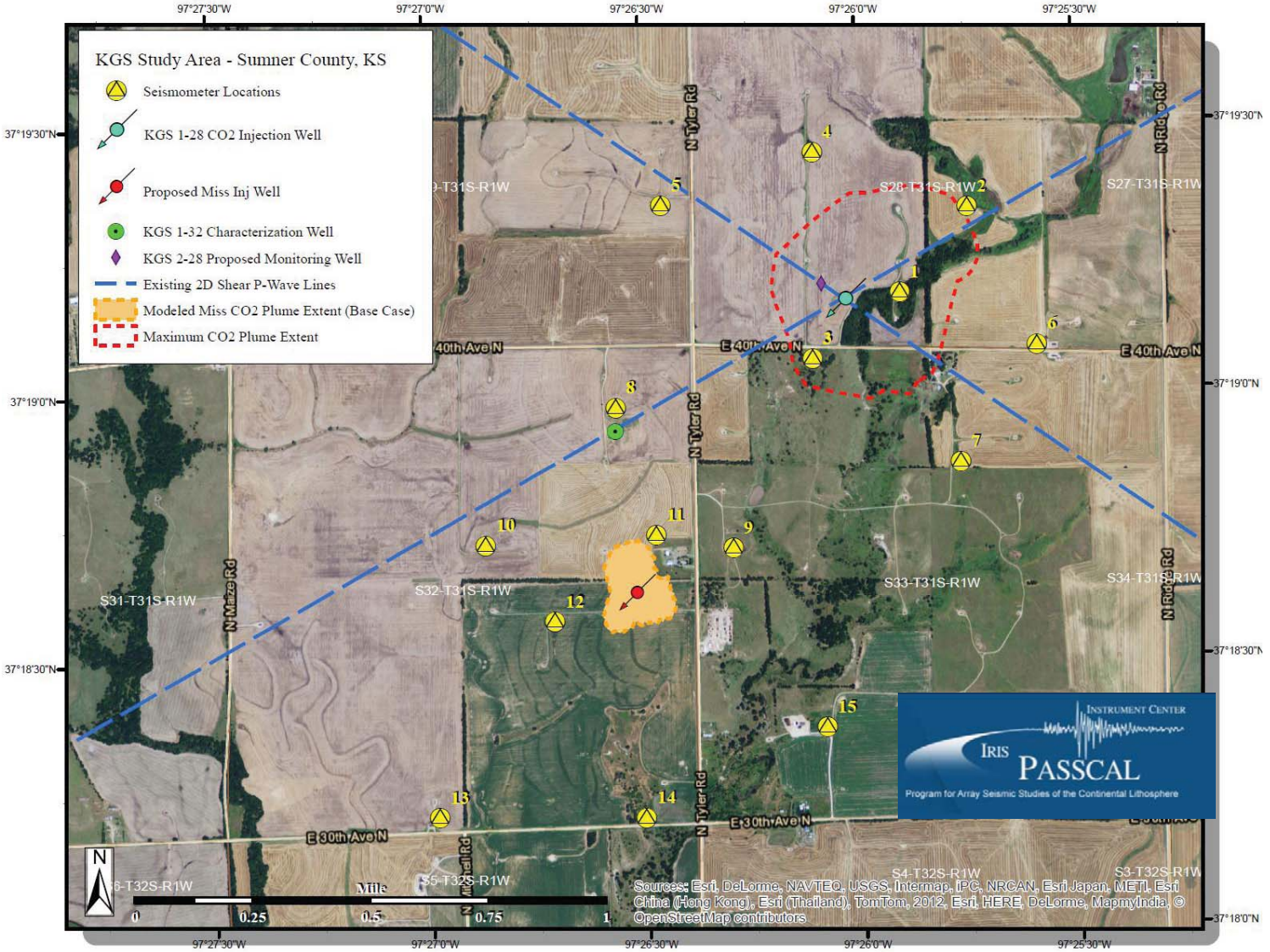


Presenter's notes: Contours on top Mississippian. PSDM Seismic horizon at -2810 ft is 20 ft above the top Arbuckle. NE-SW fault with 20+ ft of reflector offset is best imaged at this depth (2810-ft TVDSS). This fault tips out at top Mississippian.Within the Mississippian, the fault may record strike-slip movement as opposed to vertical offset in older strata.

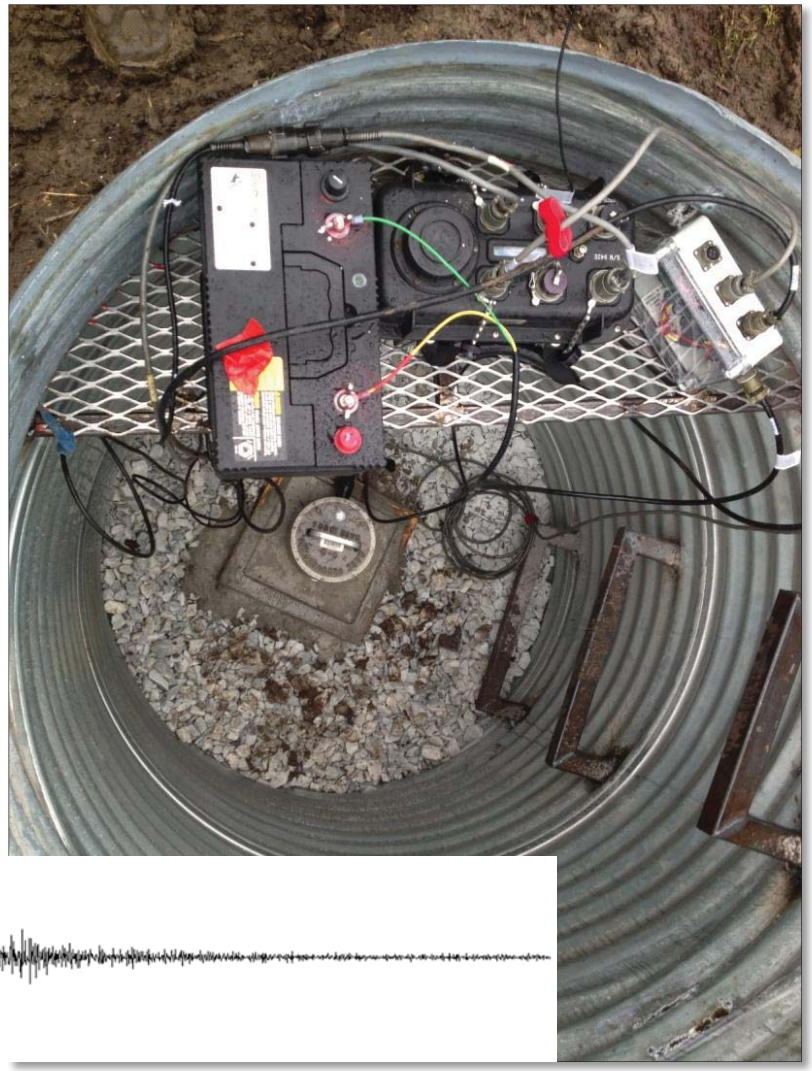


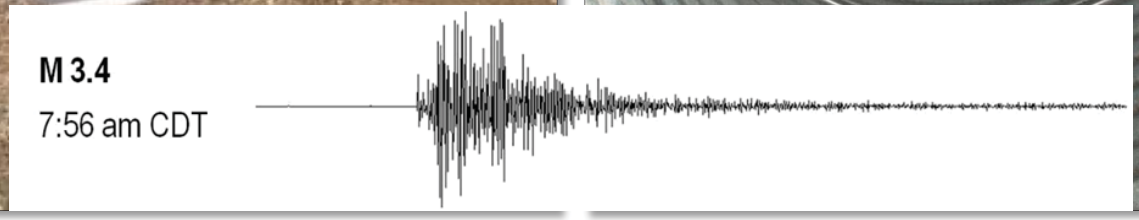
Presenter's notes: PSDM seismic line projected through 5-spot CO2 EOR area. Top Mississippian contrained by well control. Note offlapping, progradational layering consistent with Mississippian depositional model and Oread margin.
Doublet complicates PSDM seismic Mississippian correlation and attribute work. Logging program for KGS 2-32 includes sonic, which will aid future interpretation and depth-migration. Currently, sonic logs are absent where doublet is present.

15 Seismometers @ Wellington Field for 52,000 Tonnes of CO_2 Injection in Mississippian Oil Reservoir and Arbuckle Aquifer



Wellington Field Seismic Network





Courtesy of R. Miller and S. Petrie, KGS

Conclusions

- **Reservoir Lithofacies**
  - Normal marine subtidal conditions
  - Thirteen lithofacies were described
  - Sponge-spicule debris from in-situ sponge colonies (demosponges)
  - Spiculites where deposited in quiet, nutrient-rich, moderate-oxygenated waters
  - Indicative of cool-water/heterozoan carbonate
- **Diagenetic History/Paragenesis**
  - Early silicification, dolomitization, and evaporite precipitation
- **Sequence Stratigraphy**
  - Heterozoan carbonates form unrimmed ramps and open shelves
  - Slope or outer ramp environments are muddy with abundant sponge spicules and local sponge/bryozoan/coral buildups
  - The geometry of the accumulations is that of a ramp with the highest energy conditions close to shore
  - Cementation in the meteoric and the marine environment is slow
- **Structural Framework**
  - Tectonism peaked in the Atokan
  - Accompanied by widespread strike-slip faulting
    - flower structures,
    - restraining bends, and
    - step-over and relay ramps offers an additional factor
  - Directed stresses occurred pre- and post-peak tectonism
  - Episodically reactivated basement weaknesses
  - Stuctural movement affected deposition, diagenesis, local thermal maturation, and petroleum migration.
  - Faults and fractures are often subtly expressed in seismic
- **Managing Produced Water**