3D Seismic Evidence for Strike-Slip Faults in Kansas*

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Abstract

Interpretation of a set of 3D seismic volumes totaling 120 mi^2 (311 km^2) substantiates strike-slip faulting in the Hugoton Embayment in southwest Kansas. The seismic data was used to assess the potential for CO_2-EOR in Chester and Morrow sandstone reservoirs in four fields including Pleasant Prairie, Eubank, Cutter, and Shuck. The fields lie on or adjacent to horst blocks that are each bounded by a large reverse fault that may also be part of a flower structure, a radiating pattern of faulting that is diagnostic of strike-slip motion. The horsts are also accompanied by karst features aligned on lineaments crossing the horsts. Seismic indicates the lineaments are due to fractures and disturbed amplitude correlations that span the Mississippian strata into the Lower Ordovician Arbuckle Group. The bounding faults bend around the horst blocks and are considered to be restraining bends along the strike slip fault. Normal faults and fracture zones occur on the side opposite to the bounding fault indicating extension, a feature common to a restraining bend. In the area immediately south of Shuck Field seismic time and isochron maps indicate a minimum of 2 miles (3.2 km), perhaps up to a maximum of 4 mi (6.4 km) of lateral offset of a bounding fault. The timing of the primary tectonic movement is Morrow-Atokan, but seismic data reveals thinning extended movement across the bounding faults, indicating that the structures were active for considerable amount of time.

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“3D Seismic Evidence for Strike-Slip Faults in Kansas“

AAPG Mid-Continent Meeting

October 5, 2015

Session #3: 8:40-9:10 a.m.

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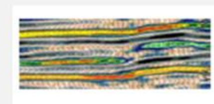

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KU KANSAS GEOLOGICAL SURVEY The University of Kansas

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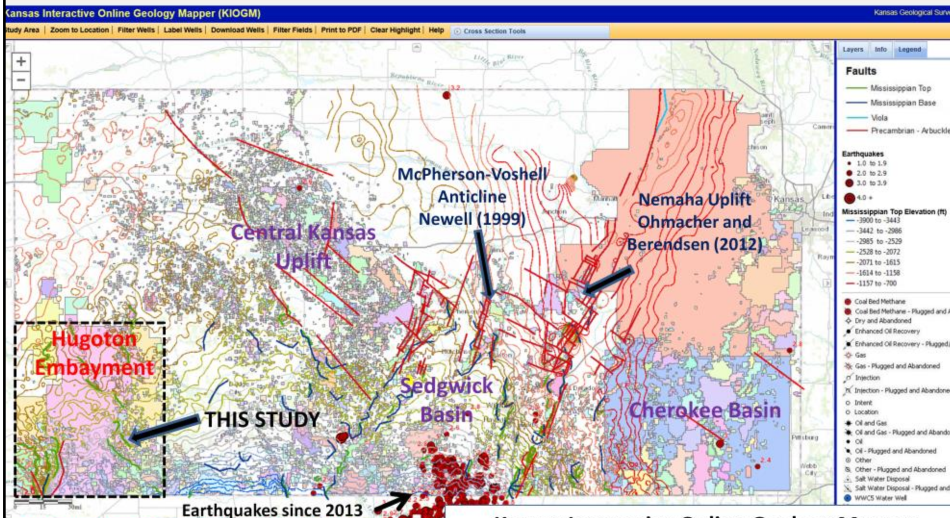
Outline

- Geologic setting and prior work
- Characteristics of strike-slip faults
- Regional geology
  - Late Paleozoic tectonics
  - Structural coupling of Amarillo-Wichita-Arbuckle Uplift, Anadarko Basin, and Kansas shelf
- Case studies of 3D seismic in the Hugoton Embayment

Top Mississippian structural contour map with published (red) and new inferred faults (green) from regional mapping with study locations



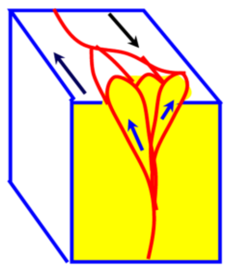
Many others have documented reverse faults in Kansas, e.g., D. Merriam, Parker Gay, D. Baars, L. Gerhard, et al. Lateral offset of basement magnetics, Parker Gay

Kansas Interactive Online Geology Mapper (KIOGM) -- http://maps.kgs.ku.edu/co2/

Characteristics of Strike-Slip Faults

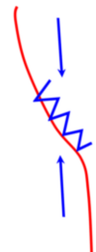
–> flower/palm tree structures, restraining bends, relay ramps

Flower Structures along right lateral (dextral) fault
Positive (Palm Tree) → Transpression

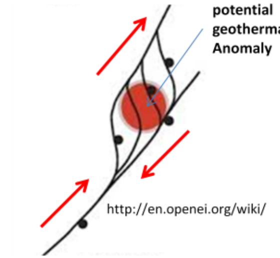


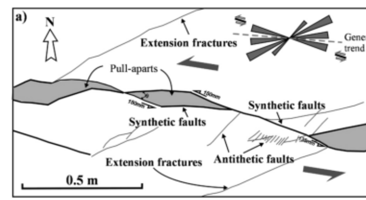
Modified from http://www4.uwsp.edu/geo/faculty/hefferan/geol320/strikeslip.html

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



Stepover or Relay Ramp





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

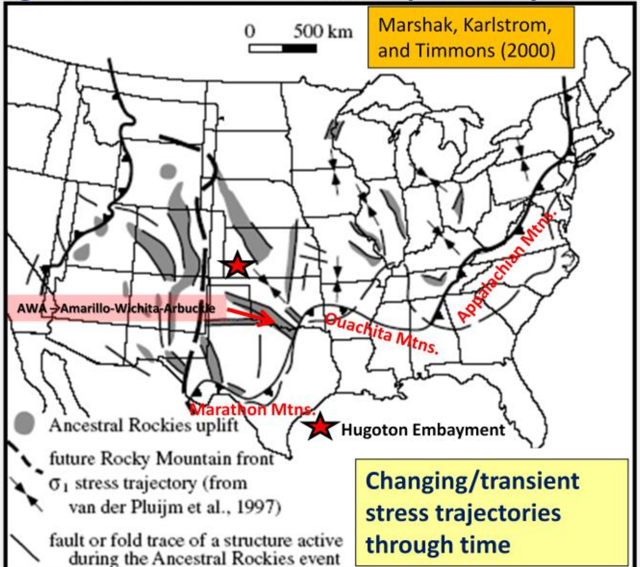
Regional Geology – Structural Evolution

1. **Anadarko Basin** – Climax Late Paleozoic tectonism during Atokan resulting from oblique, left lateral wrenching along the Wichita Uplift
2. **Hugoton Embayment (HE)** – 3,900 mi^2 (10,000 km^2) extension of Anadarko Basin linked by directed stress from wrench faulting
3. **Major HE structures** – Episodic reactivation along basement lineaments/weaknesses; pre- and post tectonism, movement influenced by far-field stress
4. **Petroleum system** – Hydrocarbon maturation, migration, and accumulation closely related to structural evolution.

Presenter's notes: **Anadarko Basin** – Proterozoic extension to Phanerozoic compression.
Hugoton Embayment (HE) – 10,000 km^2 northern extension of Anadarko Basin.
Major structures in the HE – prominent evidence of compressional reactivation along basement lineaments.
Episodic structural movement – post tectonic movement affecting sedimentation/stratigraphy throughout Phanerozoic.
Pattern of deformation – strongly influenced by basement weaknesses (the template) and evolving stress field.

Ancestral Rockies Structures

Regional tectonic deformation spans Early Chesterian-Late Leonardian



Intraplate fault reactivation

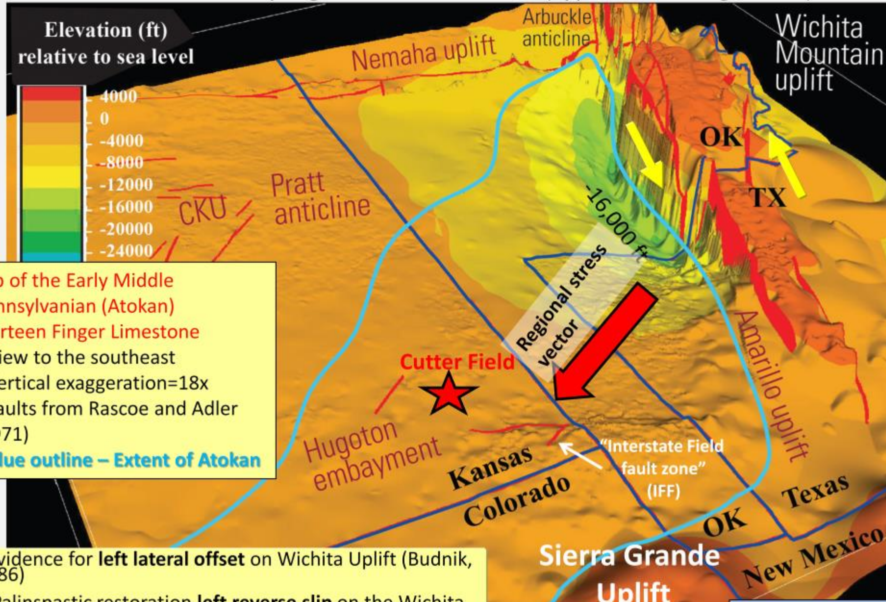
- Dependent on orientation of (weak) fault zones relative to plate margin…
- Deformation in interior can be represented by simple rheological models
- **Deformation extend beyond tectonic zones 100's km**

(van der Pluijm et al., 1997)

Stress interacted with dominant basement structural grain – NW- and NE-trending

Presenter's notes: Gondwana Laurentia collision resulting in evolving stress trajectory.
Stress interacted with basement structural grain – NW and NE
deformation in Kansas part and parcel of Ancestral Rockies.

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



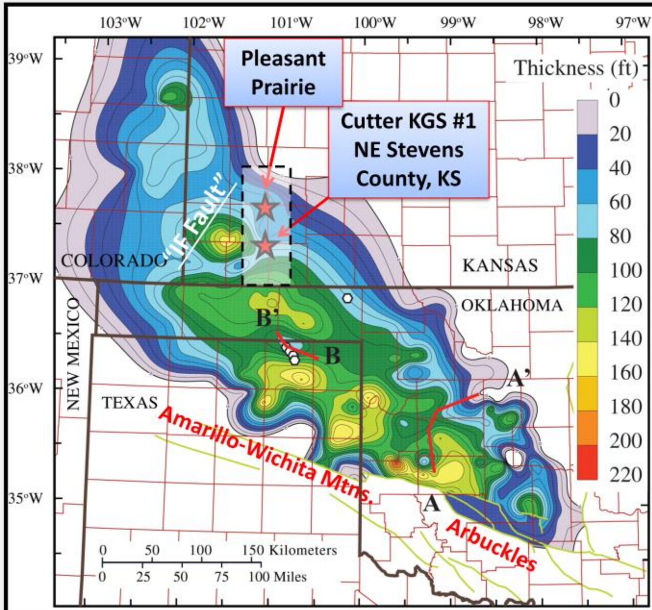
Top of the Early Middle Pennsylvanian (Atokan) Thirteen Finger Limestone

- View to the southeast
- Vertical exaggeration=18x
- Faults from Rascoe and Adler (1971)
- Blue outline – Extent of Atokan

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

(Higley, USGS, 2011)

Simultaneous drowning of the shelf and basin during the Atokan



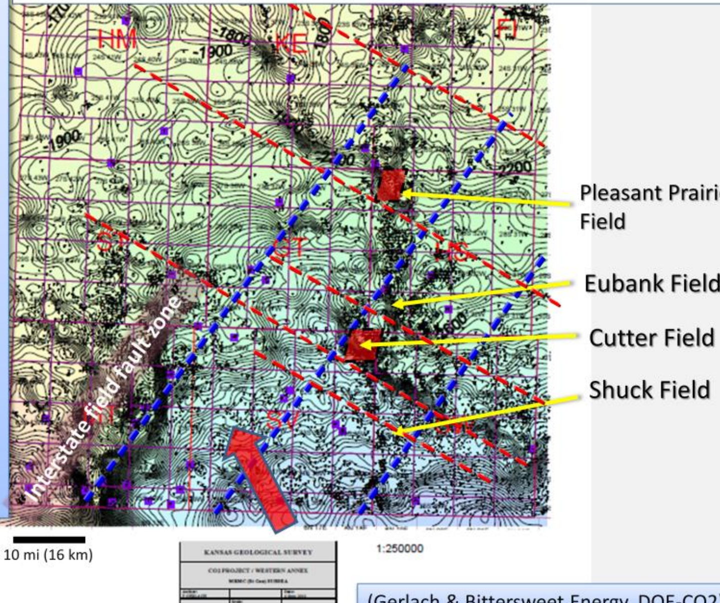
Isopach - Top Thirteen Finger Limestone to Top of Morrow Shale

(Higley, USGS, 2011)

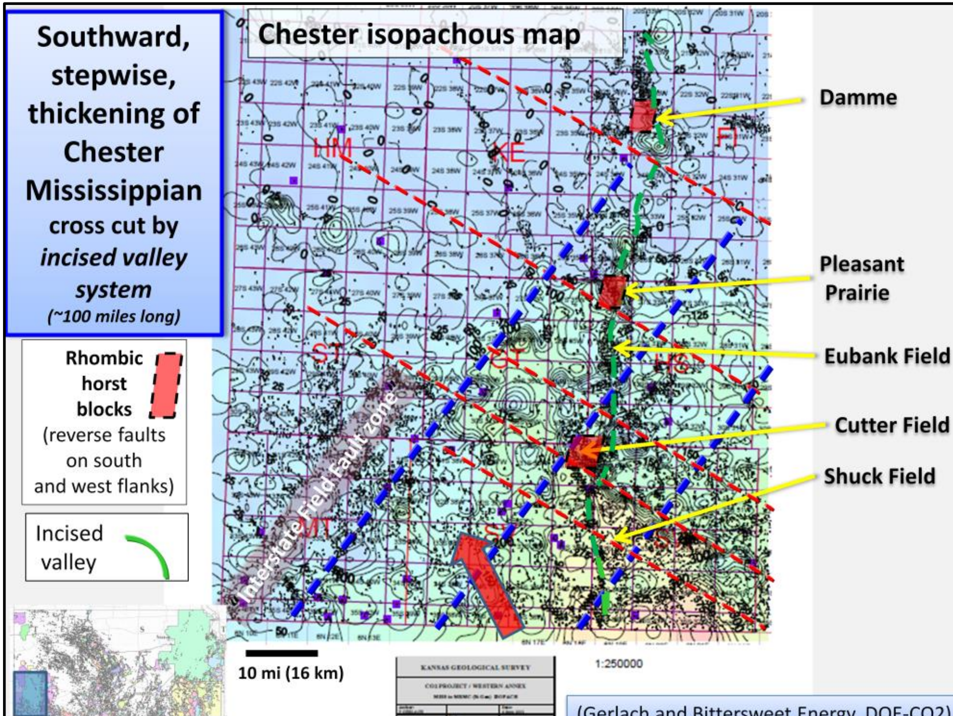
Structure Top Meramec Mississippian

Chester (*Upper Mississippian*) incised valley system cuts coeval structures at intersections of regional lineaments

- → *Overlying Chester age Mississippian locally incised into Meramec*
- → *Regional lineaments act as template for regional subsidence*
- → *Horsts or tilted blocks with faulted southwest and west flanks*
- → *Local evidence for oblique strike-slip faulting*

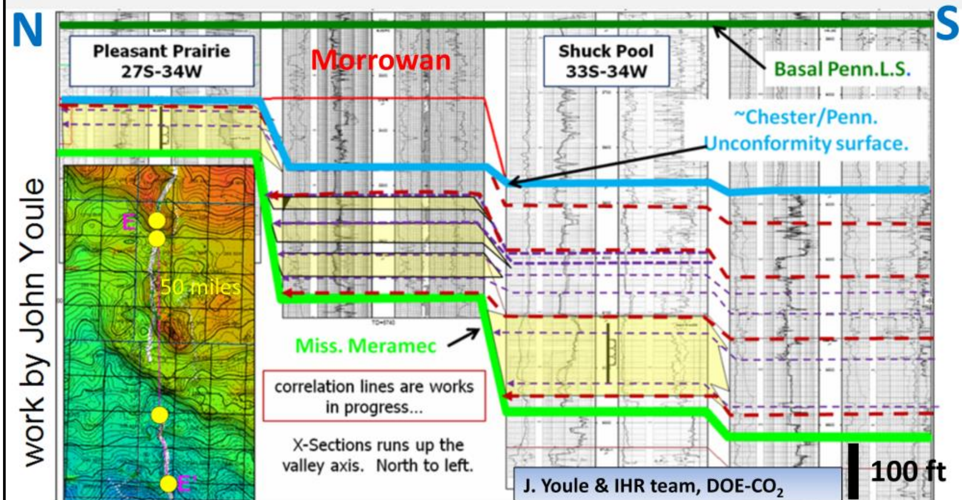


(Gerlach & Bittersweet Energy, DOE-CO2)


Southward, stepwise, thickening of Chester Mississippian cross cut by *incised valley system* (~100 miles long)
Chester isopachous map
Rhombic horst blocks (reverse faults on south and west flanks)
Incised valley
Damme
Pleasant Prairie
Eubank Field
Cutter Field
Shuck Field
Interstate Field Fault zone
10 mi (16 km)
1:250000
KANSAS GEOLOGICAL SURVEY
(Gerlach and Bittersweet Energy, DOE-CO2)

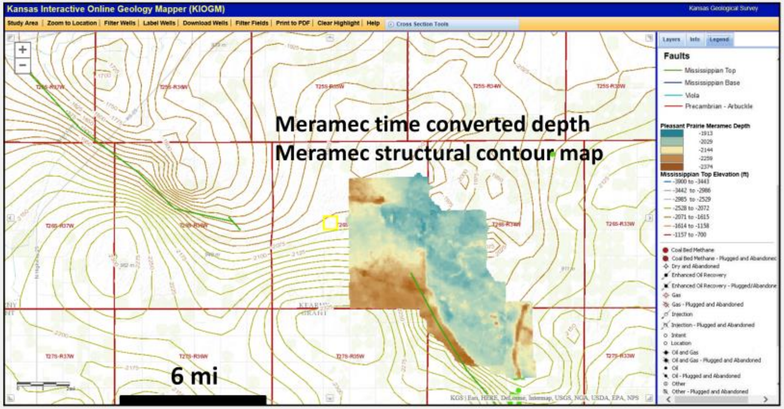
North-south structural dip along Chester incised valley

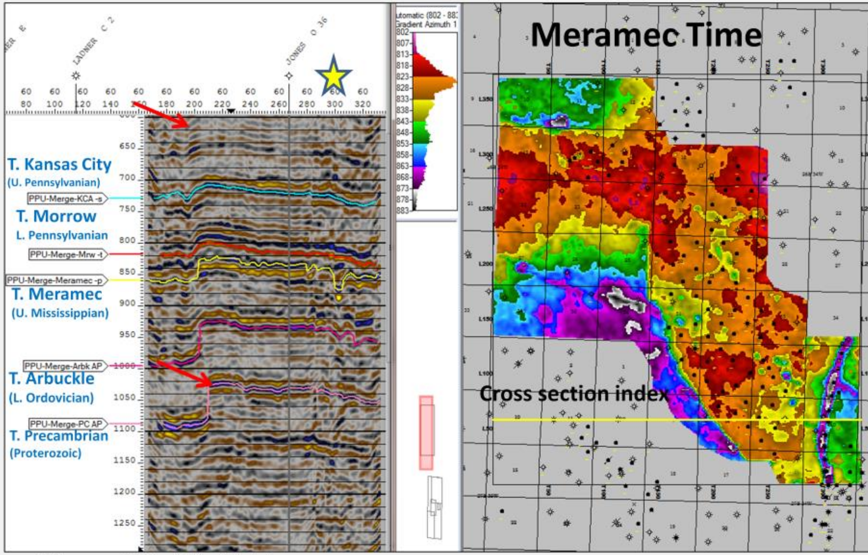
interrupted by structurally controlled fall lines as valley crosses regional lineaments



Pleasant Prairie Field

- Original seismic acquisition by Helmerich & Payne, ~pre 1990
- 4 ms sample rate
- Evaluated off the shelf, no additional processing



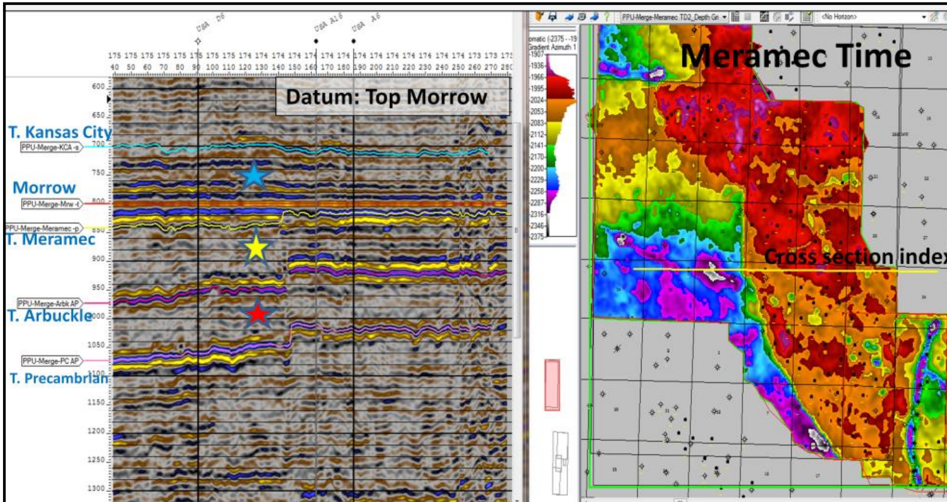


Pleasant Prairie Field

West Bounding Reverse Fault & Flower Structure

- Fault tip at 650 ms (above KCA horizon) occurs at Crossline 196.
- Tip at Basement at 1028 ms occurs at Crossline 209.
- West-east offset is 1430 ft.
- Middle of IVF is seen at Crossline 302. Map is Meramec Time.

Presenter’s notes: Western Reverse fault – compressional.
East side – extensively fractured below location of IVF – tensional.



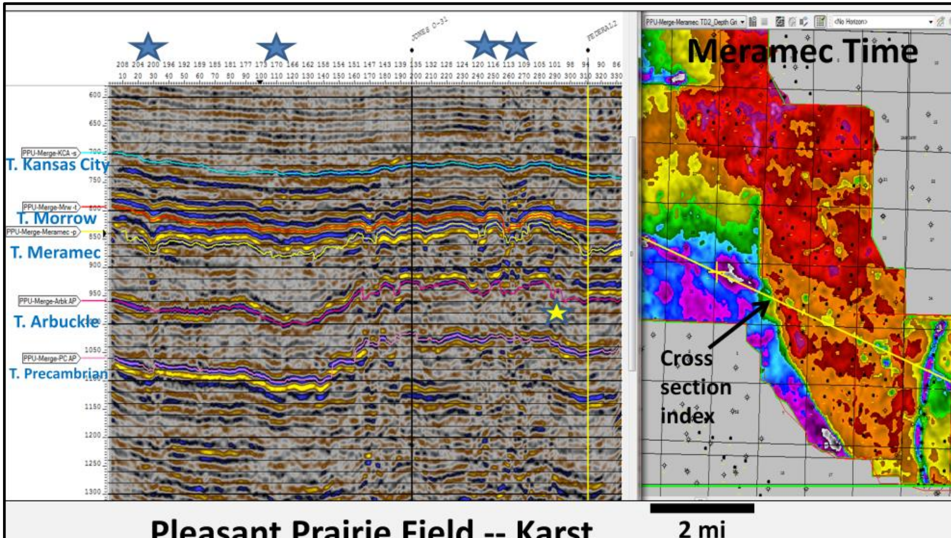
Pleasant Prairie Field stratigraphy indicates episodic growth of fault in lower Paleozoic → persistent basement weakness

2 mi

- <u>West-East Profile flattened @ Morrow = 800 ms</u>
  - Note that Meramec – Arbuckle thickens ~ 15 – 30 ms on downthrown side;
  - Arbuckle-PreCambrian also thickens ~ 15 ms on downthrown side
  - Note also that KCA – Morrow thickens ~ 8 ms on downthrown side

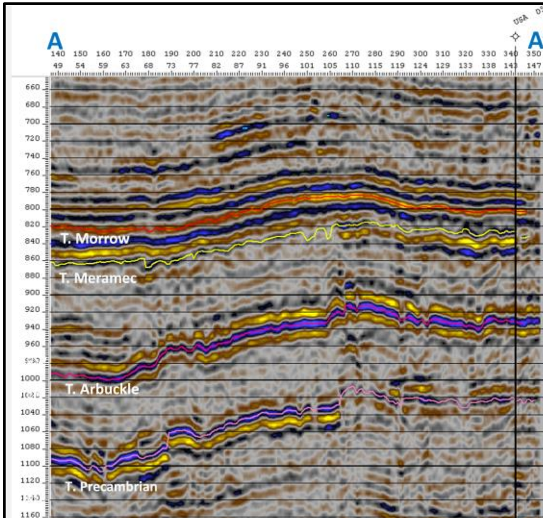
Presenter's notes:

- Erosion on top of the Mississippian not account for thinning. Rather St. Louis oolite pay zone thickens across top (Ernie Morrison's work). Concentration of ooid shoal over the crest of the structure suggest concurrent uplift and paleotopography.
- Thicken west of fault .

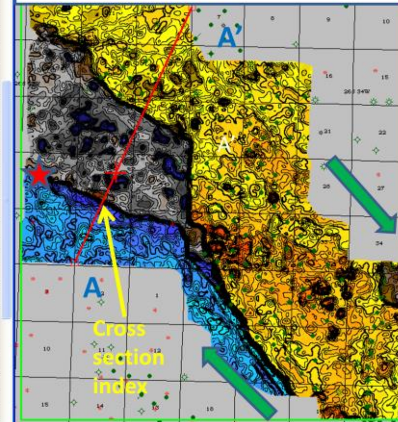


Pleasant Prairie Field -- Karst

- NW-SE arbitrary profile (*coincident with NW-SE regional lineament*) illustrating multiple karst features
- Prominent features/"pipes" noted at stations 30, 170, 242, 260 ★
- In most cases, 'pipes' extend well below Meramec, into Arbuckle IVF system at sta 310 ★
- Profile continues SE of Federal 2 into a tributary



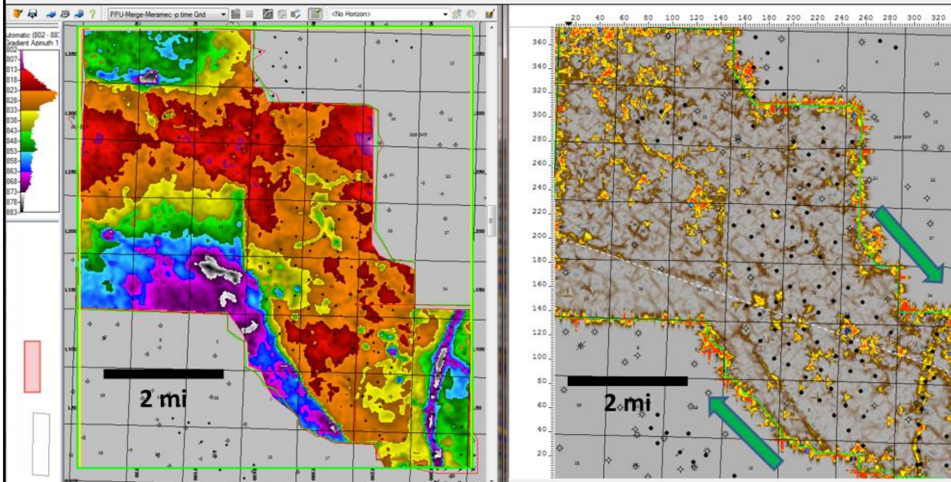
Morrow to Precambrian Isochron



Pleasant Prairie – En Echelon NW-SE trending faults extending NW of main structure → *Relay ramp with flower structure*

- **Structural arch is clearly exhibited.**
- **NW-SE trending flower structure in apex of structure as fault blocks step down basinward.**
- **Isochronal thickening occurs in discrete step changes at faults.**
- **Note that the IVF is not expressed in this isochron. Karst is accentuated.**
- **Southern fault coincident with N-SE regional lineament → translates stress westward.**

Meramec Time | Most Negative Curvature at 860 ms

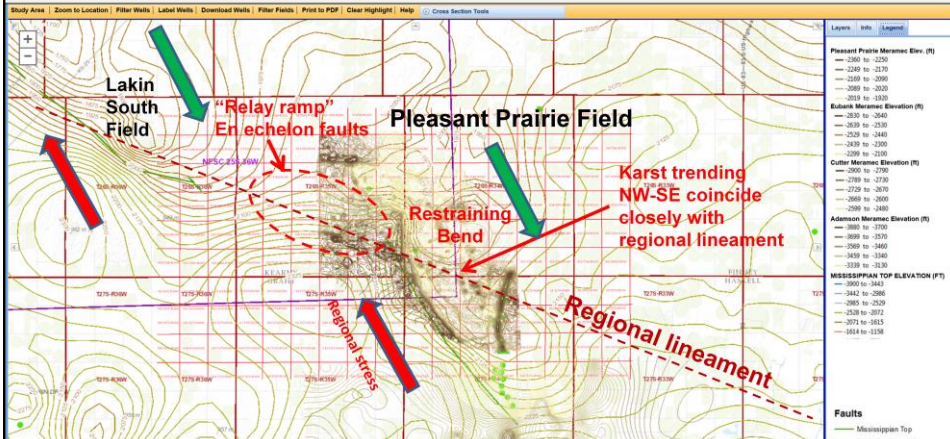


Pleasant Prairie Field

- West bounding fault
- NW-trending cross cutting fault & karst correspond with regional lineament (white dashed lined)
- NE-SE trending karst coincident with IVF

Regional Meramec structure & local depth converted seismic at Pleasant Prairie Field

-- illustrating restraining bend, relay ramp with flower structure → indications of strike-slip faulting

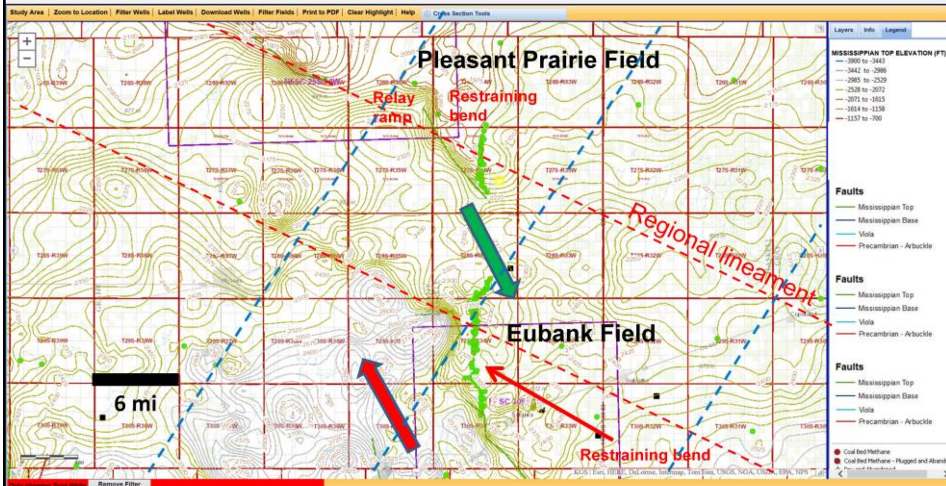


- **Relay ramp connecting Pleasant Prairie along west-east segment in northwest Pleasant Prairie -- compressional regime with diagnostic "flower structure" and reverse throw**

Presenter's notes:

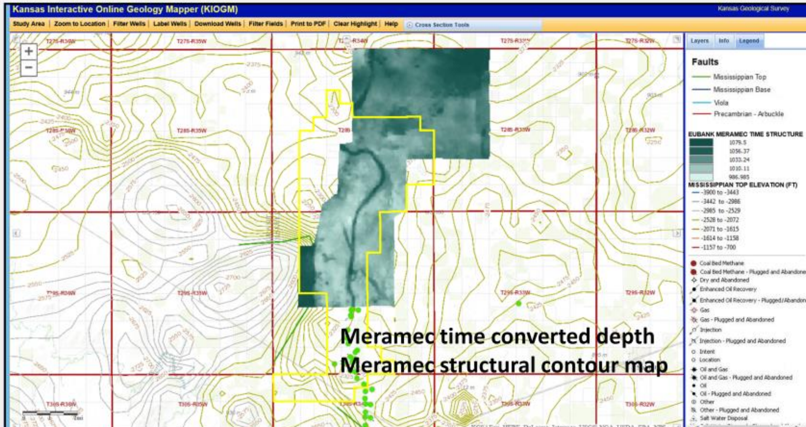
- Relay ramp connecting Pleasant Prairie along west-east segment in northwest Pleasant Prairie -- compressional regime with diagnostic "flower structure" and reverse throw.
- NW-SE trending karst coincides with regional lineament.

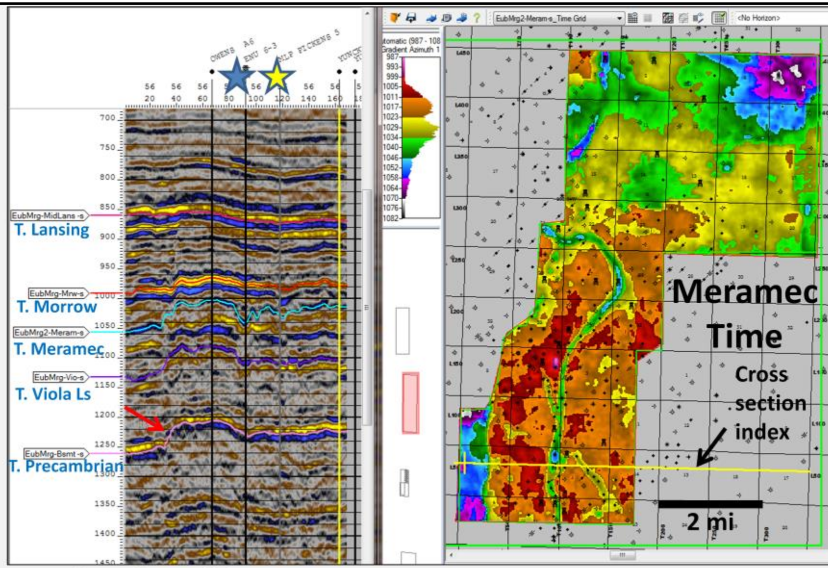
Eubank Field
-- another restraining bend at lineament intersection, possible relay ramp



Eubank Field

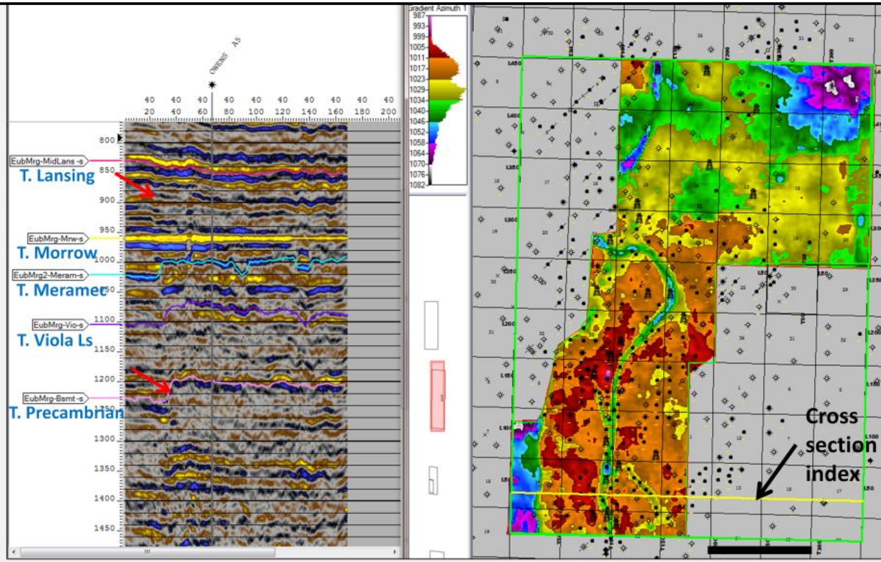
- Seismic data acquired ~1990
- 2 ms sample rate
- Merged 3 separately acquired surveys
- Applied Pre-stack and Post-stack Inversion





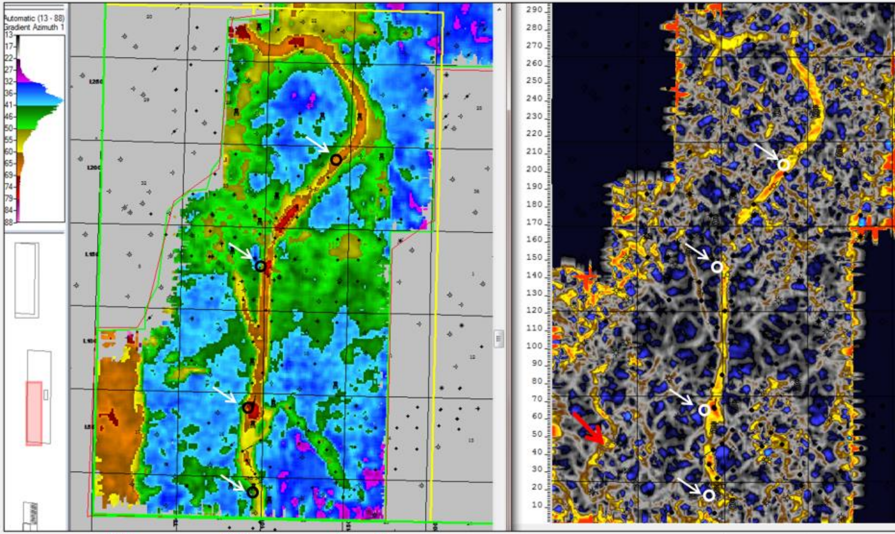
Eubank Field – time structure

- Note bounding reverse fault at crossline 40 forming western border of the field
- IVF cut (Crossline 92) is not as deep as downthrown block at Meramec
- Pickens 5 not drilled in deepest Meramec cut in tributary.



Eubank Field – T. Morrow Datum

- Downthrown block thickens at Meramec, but uniform thickness below → most of movement occurred post-Meramec.
- Reverse fault on bounding west side -- Fault tip at Mid Lansing occurs at Trace 26, tip at Basement occurs at Trace 36, yielding a west-east drift of 1100 ft.

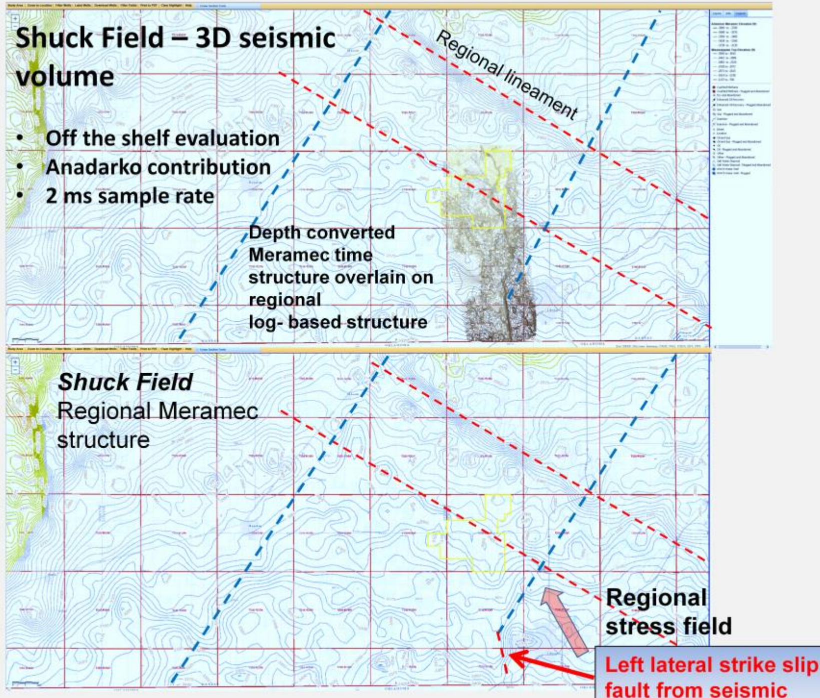


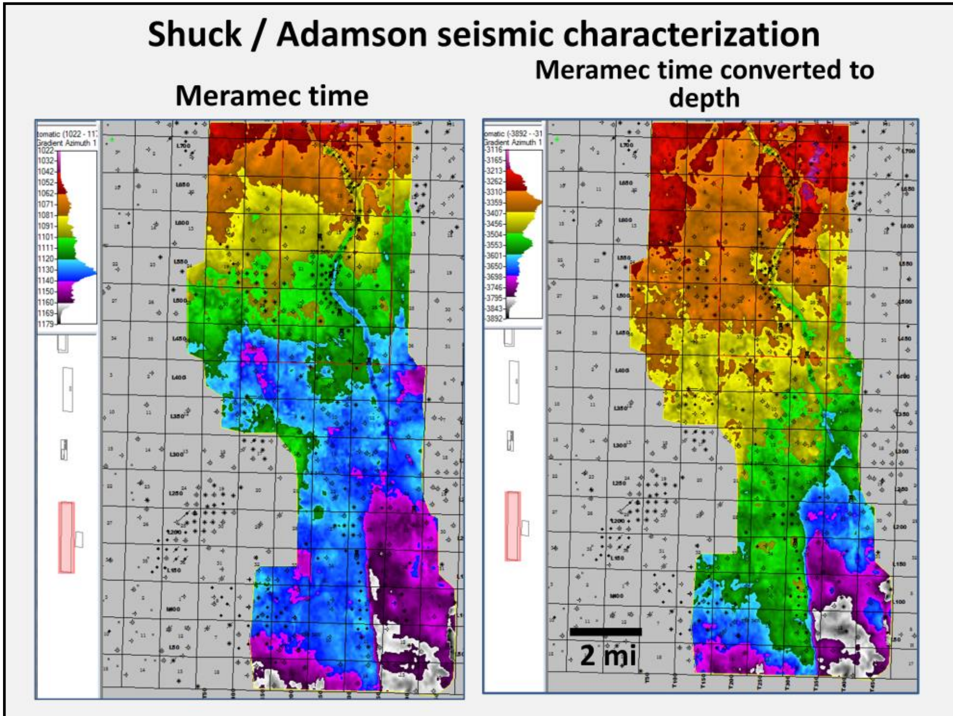
Morrow – Meramec Isochron

Most Negative Curvature Near Base IVF Time

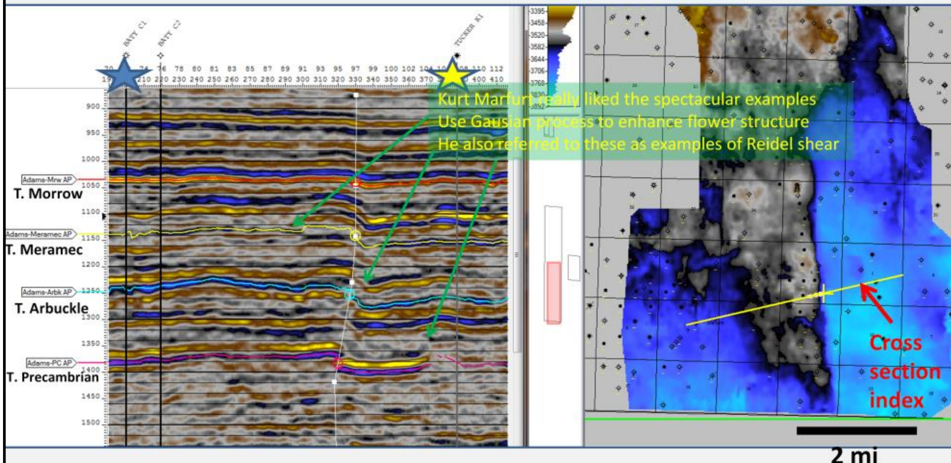
1 mi

- **Lattice fabric in Background generally independent of IVF orientation**
- **West bounding fault roughly expressed on curvature in W/2 Section 17** ↘
- **Sinkholes… apparent loss of fluid during waterflood assessed during history matching**


Shuck Field – 3D seismic volume
• Off the shelf evaluation
• Anadarko contribution
• 2 ms sample rate
Regional lineament
Depth converted Meramec time structure overlain on regional log- based structure
Shuck Field
Regional Meramec structure
Regional stress field
Left lateral strike slip fault from seismic



Presenter's notes: Near surface velocities coupled with real stratigraphic complexity render the overall time structure indications to be of somewhat limited use. However, Depth Converted Structure is reasonably well adjusted due to significant well control availability. The structural nose in the south central portion of the Meramec Depth contains a reverse fault on the east flank.

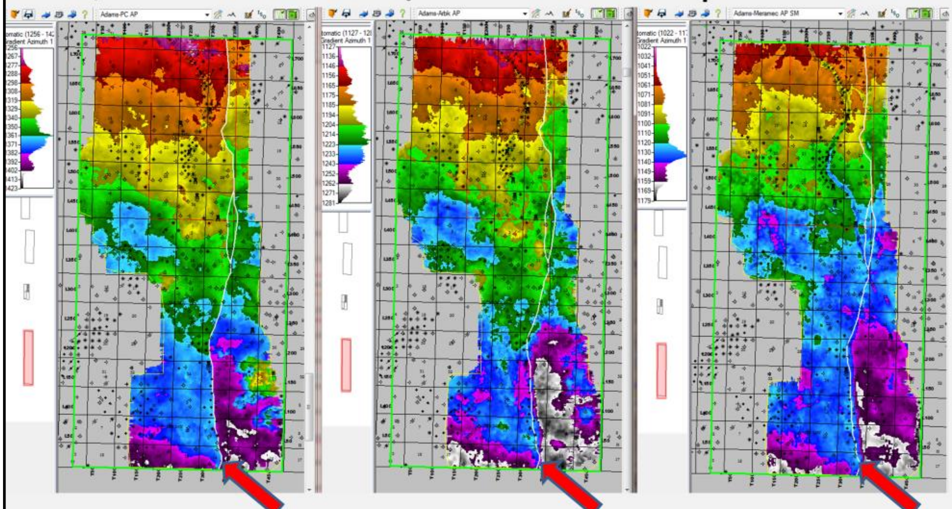


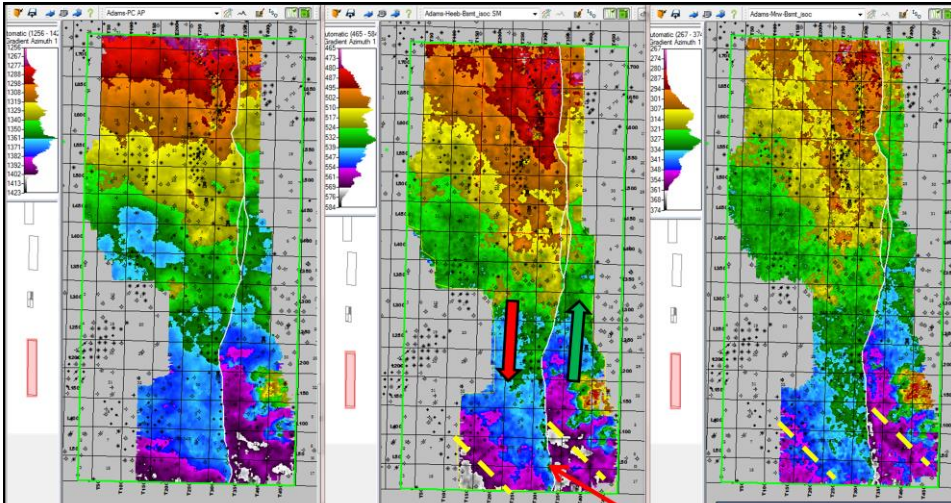
Archer – Liberal West strike-slip fault

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

Primary East Bounding Fault --
Shuck to Liberal West fields

Top Basement Time Top Arbuckle Time Top Meramec Time





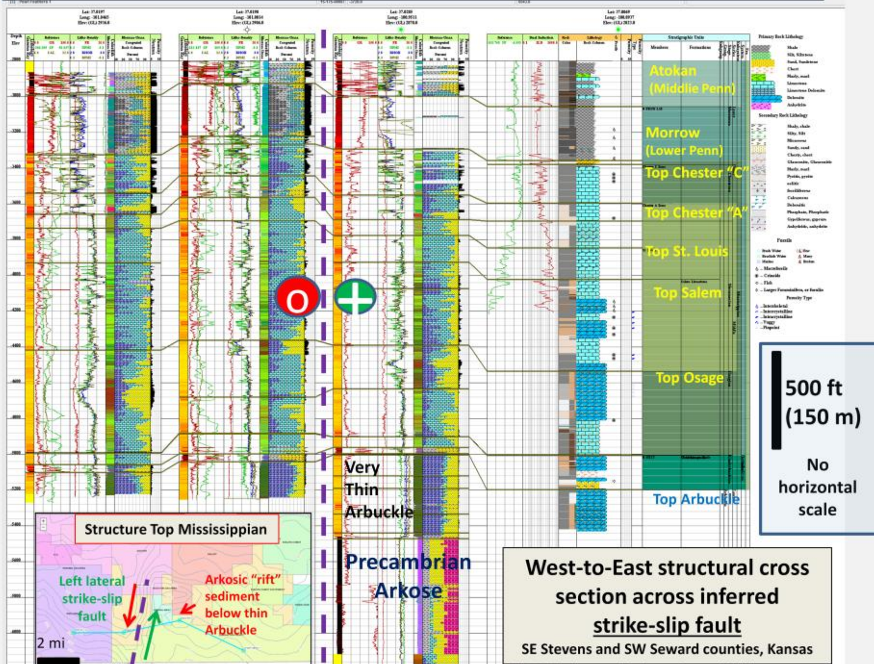
Shuck –West Liberal Thrust Strike-Slip Evidence in Isochrons

- **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.

Left lateral (sinstral) strike-slip fault (~2 mi lateral displacement

Cross section generated from KIOGM interactive mapper (maps.kgs.ku.edu/co2)



West-to-East structural cross section across inferred strike-slip fault

SE Stevens and SW Seward counties, Kansas

Conclusions Regarding Seismic Data

- Conventional amplitude data, coupled with processed volumetric curvature data demonstrate that vertical connectivity from Basement to near surface rocks is possible, if not probable;

- Strike-slip faulting occurs in both the northernmost and southernmost study areas, adding additional structural complexity, and opportunity of fracture system enhancement.

Geological Conclusions

1. **Major HE structures** – Reactivation along basement lineaments affected sedimentation during the Paleozoic; occurred pre- and post tectonism, influenced by far-field stress
2. **Anadarko Basin** –Late Paleozoic tectonism climaxed during Atokan resulting from oblique, left lateral wrenching along the Wichita Uplift
3. **Hugoton Embayment (HE)** – 3,900 mi^2 (10,000 km^2) extension of Anadarko Basin linked by directed stress from wrench faulting along the Wichita Uplift
4. **Petroleum system** – Hydrocarbon maturation, migration, and accumulation closely related to systematics and timing (kinematics) of the complex, but often subtle fault system

Acknowledgements & Disclaimer

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Thank You