Sedimentologic and Stratigraphic Effects of Episodic Structural Activity during the Phanerozoic in the Hugoton Embayment, Kansas, USA*

W. Lynn Watney[1], John Youle[2], Dennis Hedke[3], Paul Gerlach[4], Raymond Sorenson[5], Martin Dubois[6], Larry Nicholson[7], Thomas Hansen[8], David Koger[9], and Ralph Baker[10]

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Abstract

The 10,000-km^2 Hugoton Embayment (HE) is a relatively shallow, <3 km deep, northerly extension of the Anadarko Basin, where sediment thickness is up to 12 km. The Anadarko Basin is bordered on its south by the NW-trending Amarillo-Wichita frontal fault zone with up to 10 km of total structural relief. The HE is defined by a set of regional fault zones, including high-angle reverse with offsets in excess of 200 m confirmed by regional 3-D seismic. The timing of these northern faults, located some 120 km north of the main frontal fault system, coincides with major tectonic activity (Late Mississippian through Middle Pennsylvanian). Abrupt shifts in the fault systems between NW-trending and N-NE trends are sites of large (5+ by 3 km long), parallelogram-shaped horst blocks on NE sides and adjoining grabens on SW side bounded by reverse faulting down to the west and south, suggesting a system of synthetic NW-trending right-lateral and antithetic N-NE-trending left-lateral strike-slip faults.

Faulting is closely associated with a 100-km-long, southward-draining Chester-age incised valley. While main faulting post-dates the valley incision, possible deep karst and faulting have created linear valley segments proximal to horst blocks while valleys meander in segments between. Later faulting linked to karst formed an updip trap for the Chester reservoir in Shuck Field. A NW-trending flexure north of Shuck Field separates a narrow valley system to the north from a broad, tidal-dominated, siliciclastic complex to the south.

Subdued structural movement, particularly along older structural features, continued during the Late Pennsylvanian and into the Late Permian expressed as persistent flexural folding. A series of N-S-trending horst blocks and satellite anticlines became the locus for stacked ooid/grainstone shoals.

Laramide and post-Laramide deformation led to additional flexure above deep structures leading to widespread dissolution of shallow (<450 m) halite beds in the Lower Permian strata. Dissolution fronts are closely related to the underlying structure and are expressed in surface geomorphology. This evaporite karst contributed to accommodation space for the Pliocene High Plains Aquifer.

The structural geometries in the HE suggest strike-slip faulting that extended from the Anadarko Basin during peak tectonism. Regional faults and flexure closely corresponds to a template of Precambrian basement structures that are revealed by multiple data types.

Selected References

Cole, V.B., 1976, Configuration of the top of the Precambrian rocks in Kansas: Kansas Geological Survey, Map M7, scale1:500,000.

Dickinson, W.R., and T.F. Lawton, 2003, Sequential intercontinental suturing as the ultimate control for Pennsylvanian ancestral Rocky Mountains deformation: Geology, v. 31, p. 609–612.

Dubois, M.K., and J.C. Youle, 2011, Southwest Kansas CO2 EOR Initiative: Chester and Morrow reservoirs: Western Annex to Regional CO2 Sequestration Project DE-FE0002056, 35 p. Web accessed September 18, 2013. http://www.kgs.ku.edu/PRS/Ozark/Reports/2011/SwKsCO2_KsNextStep_Dubois-Youle_0804-2011.pdf

Ebanks, W.J., Jr., 1991, Bindley field--U.S.A., Anadarko basin, Kansas: AAPG Treatise of Petroleum Geology, Atlas of Oil and Gas Fields, Stratigraphic traps II, p. 117-136.

Goes, S., and S. van der Lee, 2002, Thermal structure of the North American uppermost mantle inferred from seismic tomography: Journal of Geophysical Research, v. 107, no. B3, p. 2050.

Higley, D.K., S.B. Gaswirth, M.M. Abbott, R.R. Charpentier, T.A. Cook, G.C. Ellis, N.J. Gianoutsos, J.R. Hatch, T.R. Klett, P. Nelson, M.J. Pawlewicz, O.N. Pearson, R.M. Pollastro, and C.J. Schenk, 2011, Assessment of undiscovered oil and gas resources of the Anakarko Basin Province of Oklahoma, Kansas, Texas, and Colorado, 2010: U.S. Geological Survey, Fact Sheet, no. FS 2011-3003, 2 p.

Kluth, C.F., and P.J. Coney, 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, p. 10-15.

Kruger, J.M., 1996, On-line gravity and magnetic maps of Kansas: Kansas Geological Survey, Open-file Report, no. 96-51. Web accessed September 18, 2013. http://www.kgs.ku.edu/PRS/PotenFld/potential.html

Macfarlane, P.A., and B.B. Wilson, 2006, Enhancement of the bedrock-surface-elevation map beneath the Ogallala portion of the High Plains aquifer, western Kansas: Kansas Geological Survey, Technical Series 20, 28 p.

Marshak, S., K. Karlstrom, and J.M. Timmons, 2000, Inversion of Proterozoic extensional faults; an explanation for the pattern of Laramide and Ancestral Rockies intracratonic deformation, United States: Geology, v. 28/8, p. 735-738.

Montgomery, S.L.; and E. Morrison, 1999, South Eubank field, Haskell County, Kansas; a case of field redevelopment using subsurface mapping and 3-D seismic data: AAPG Bulletin, v. 83, p. 393-409.

Nelson, P.H., and N.J. Gianoutsos, 2011, Evolution of overpressured and underpressured oil and gas reservoirs, Anadarko Basin of Oklahoma, Texas, and Kansas: U.S. Geological Survey Open File Report 2011–1245, 3 sheets. Web accessed September 18, 2013. http://pubs.usgs.gov/of/2011/1245

Rascoe, B., Jr., and F.J. Adler, 1983, Permo-Carboniferous hydrocarbon accumulations, mid-continent, U.S.A.: AAPG Bulletin, v. 67/6, p. 979–1001.

Sorenson, R.P., 2005, A dynamic model for the Permian Panhandle and Hugoton fields, western Anadarko basin: AAPG Bulletin, v. 89, p. 921-938.

van der Pluijm, B.A.; and P.A. Catacosinos, P.A., eds., 1996, Basement and basins of eastern North America: Geological Society of America, Special Paper, no. 308, 209 p.

Website

Strike Slip Faults: University of Wisconsin, Stevens Point, Wisconsin. Web accessed September 18, 2013. http://www4.uwsp.edu/geo/faculty/hefferan/geol320/strikeslip.html

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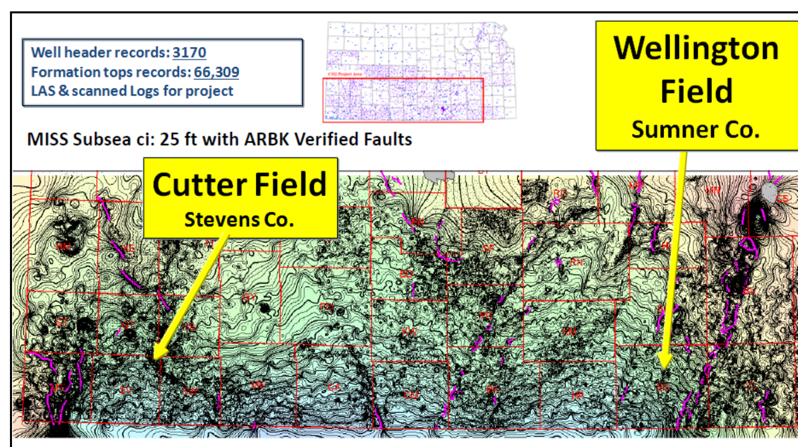
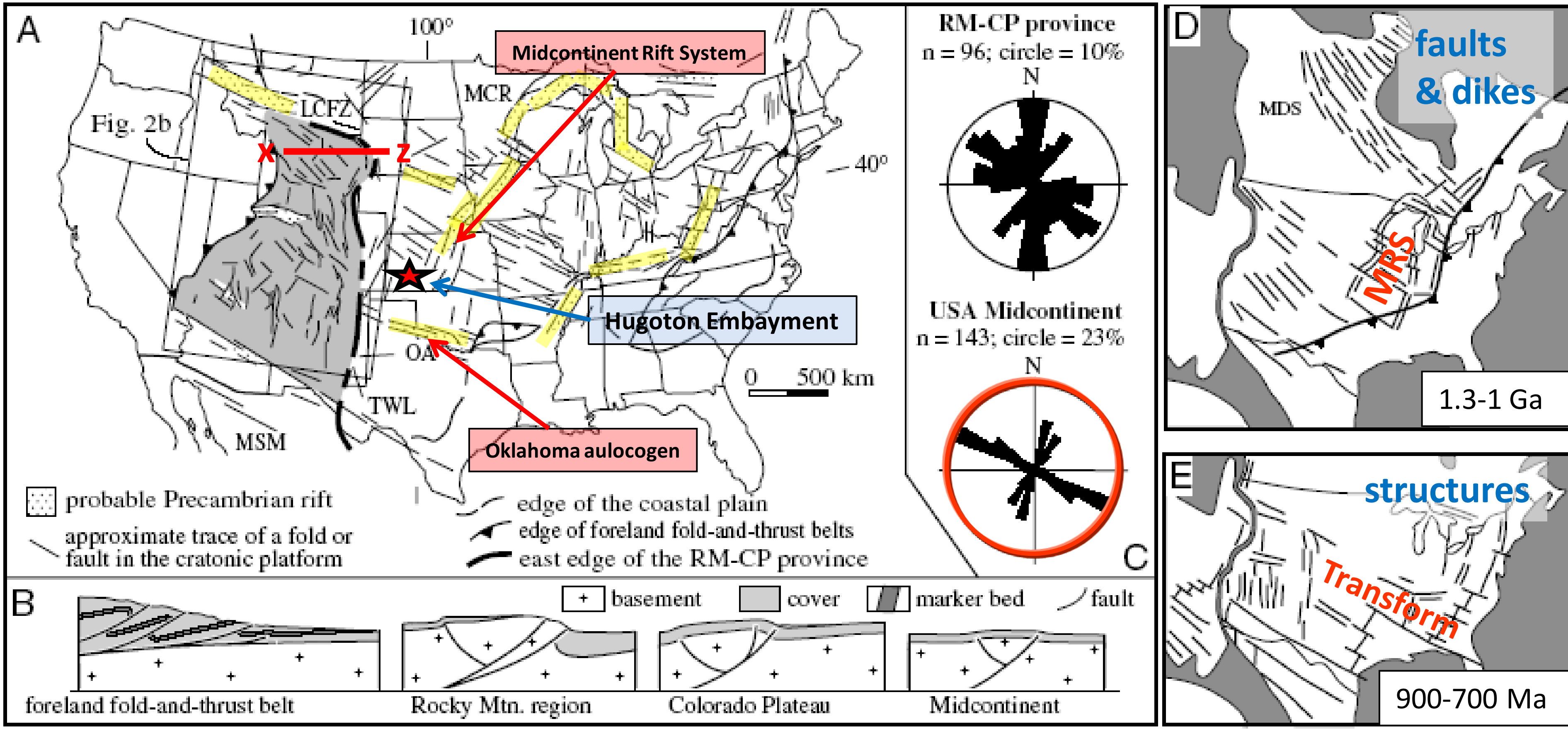
Outline

- **Anadarko Basin** – From Proterozoic structural extension to Phanerozoic compression
- **Hugoton Embayment (HE)** – 10,000-km^2 northern extension of Anadarko Basin
- **Major structures in the HE –** Evidence of systematic reactivation along dominant basement lineaments
- **Episodic structural movement** – Post-tectonic movement affecting sedimentation/stratigraphy throughout Phanerozoic (e.g., Late Miss-E. Penn; L. Perm; L. Tertiary; Holocene)
- **Pattern of deformation** – Strongly influenced by basement weaknesses (the template) and evolving stress field
- **Summary**



Extensional faults and folds dominated the cratonic platform during the Proterozoic

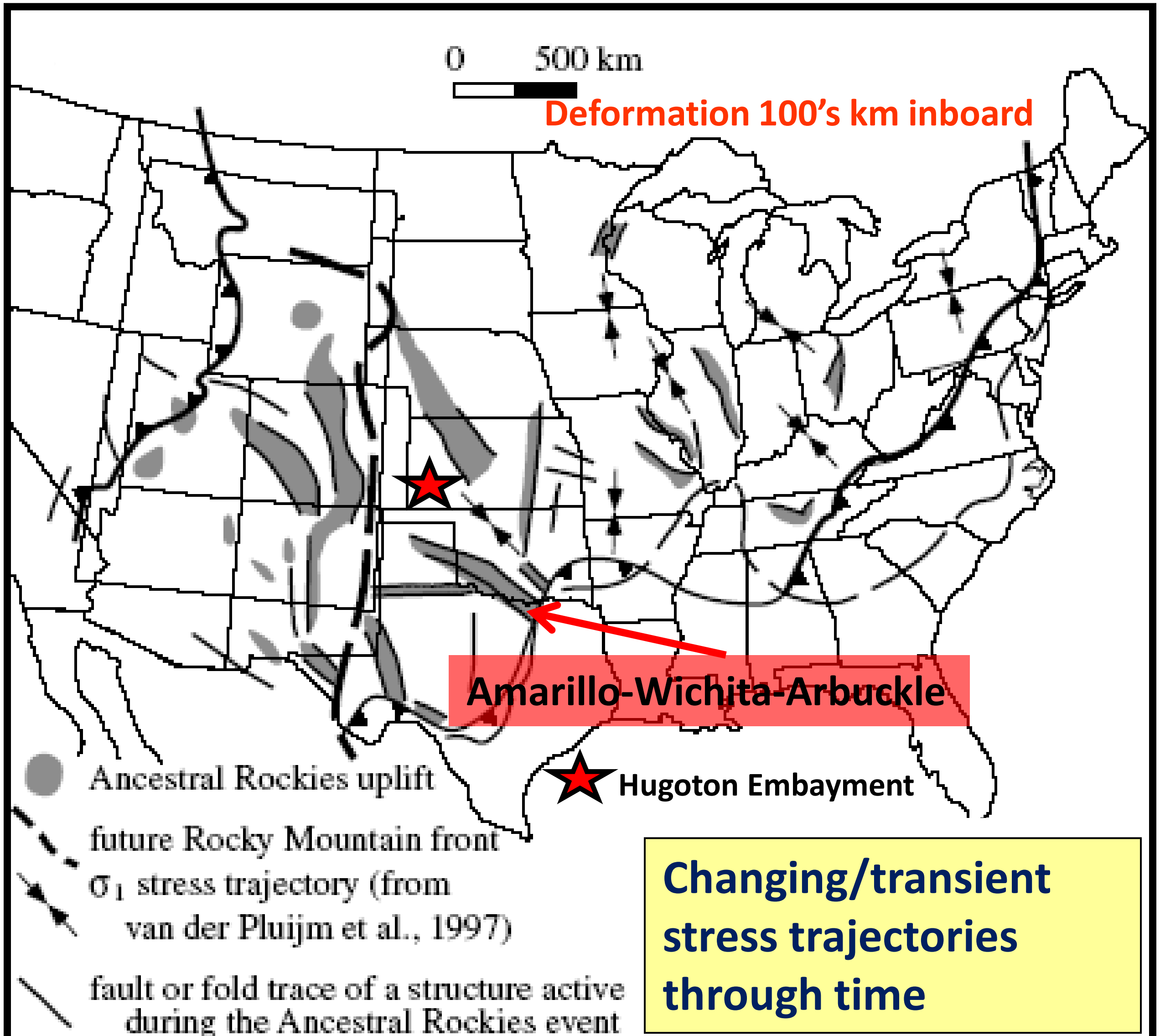


- Two dominant directions of extensional structures in Proterozoic
- Faults reactivated during Phanerozoic compressional orogenies (Kluth and Coney, 1981)
- Inversion of once normal faults leading to *reverse & oblique-slip*

Marshak, Karlstrom, and Timmons (2000)

Ancestral Rockies compressional structures

Early Chesterian - Late Leonardian deformation



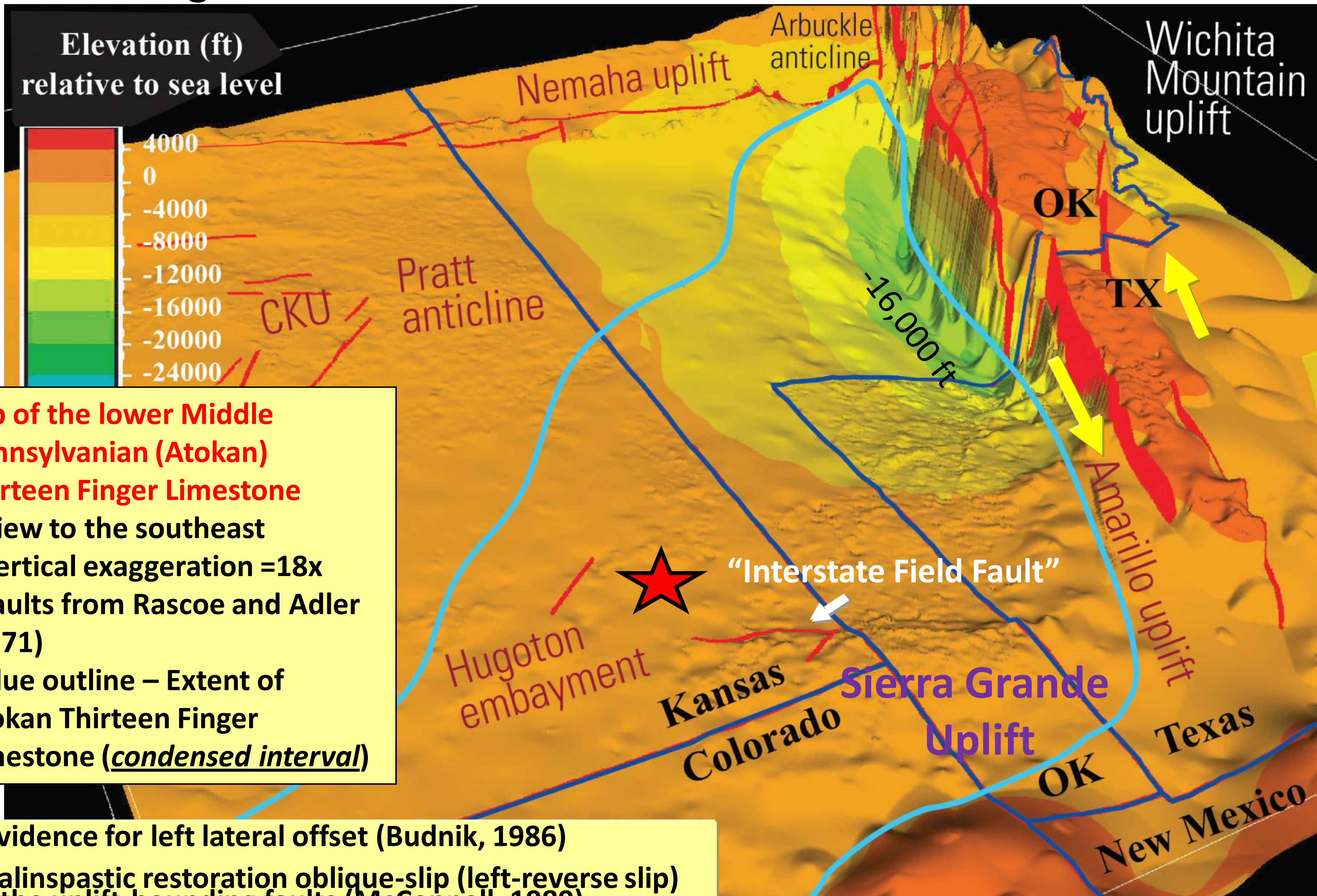
Changing/transient stress trajectories through time

Intraplate fault reactivation is mainly dependent on orientation of (weak) fault zones relative to plate margin... deformation in interior can be represented by simple rheological models (van der Pluijm et al., 1997)

Marshak, Karlstrom, and Timmons (2000)
Ages from Dickinson and Lawton (2003)

Apex of Late Paleozoic tectonism

during Morrowan and Atokan time in the Midcontinent U.S.



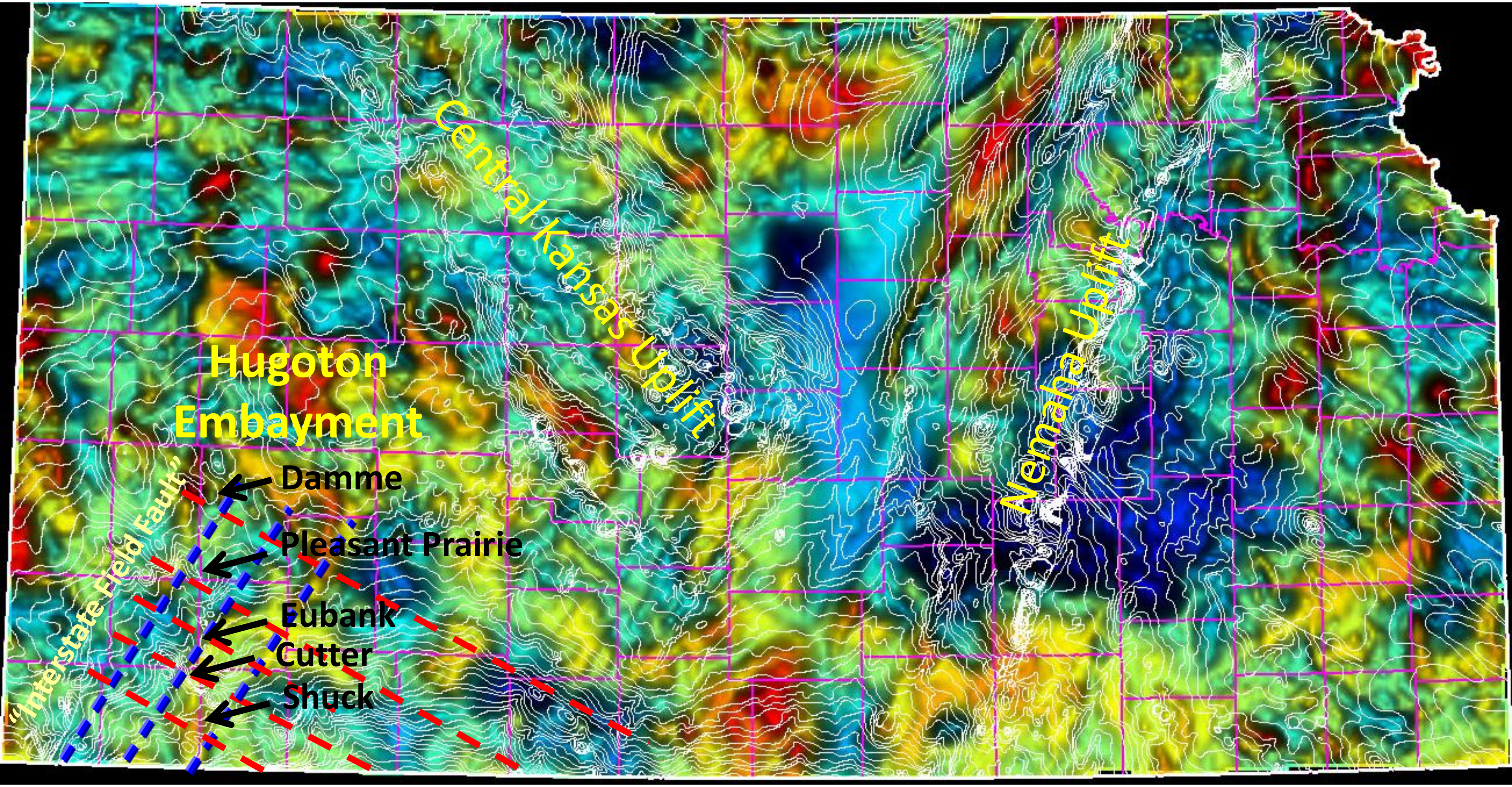
Top of the lower Middle Pennsylvanian (Atokan) Thirteen Finger Limestone

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

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

~700 km W-E length **(Higley, 2011)**

Strong correlation between many Proterozoic and Phanerozoic structures



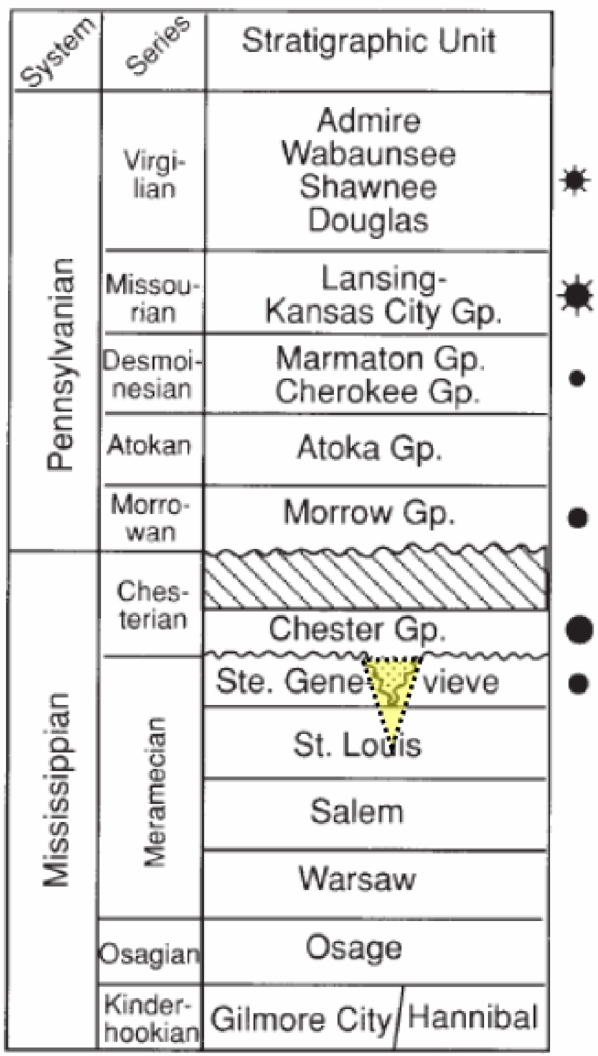
Total magnetic field intensity reduced to pole overlain with configuration of Precambrian surface

- **Very close correspondence of Phanerozoic structures to magnetic anomalies**
- **Local and subregional changes in strike and dip appear to closely correlate to magnetic map**
- **Influence on lithofacies distribution and characteristics of sequences**

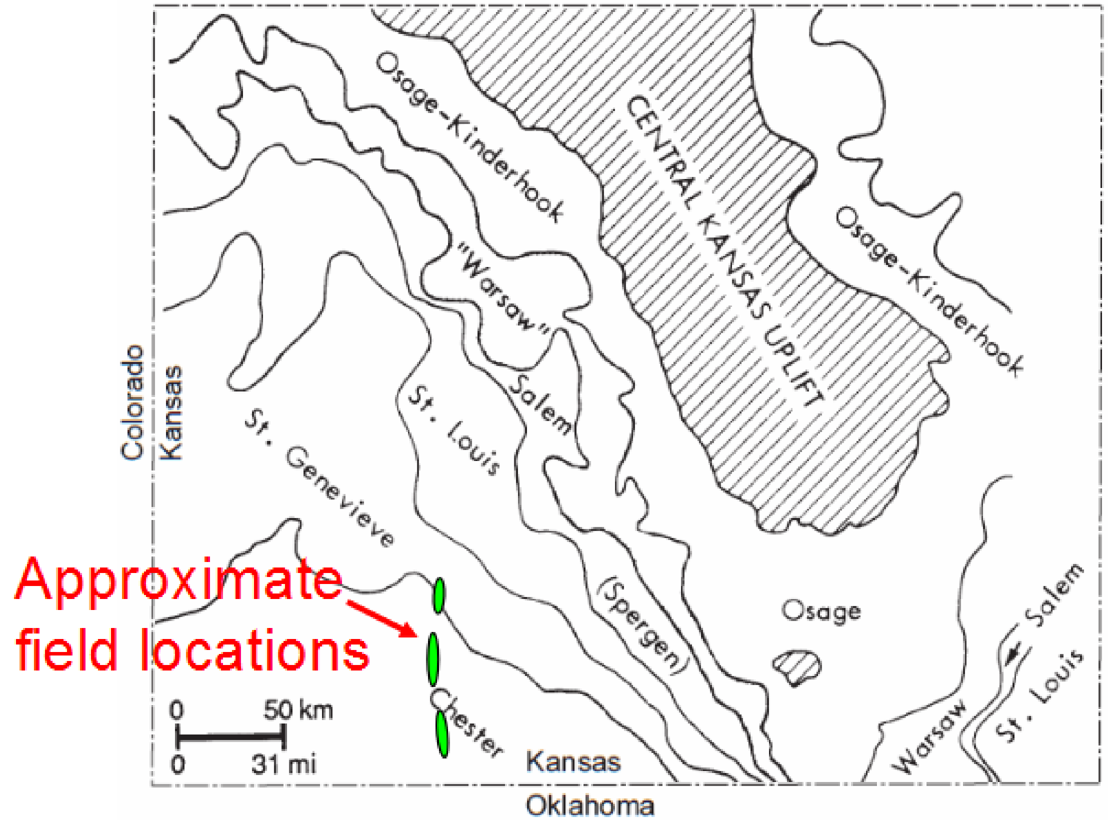
50 mi

(Cole, 1976; Kruger, 1999)

Stratigraphic setting



Generalized stratigraphic column (Montgomery and Morrison, 1999).

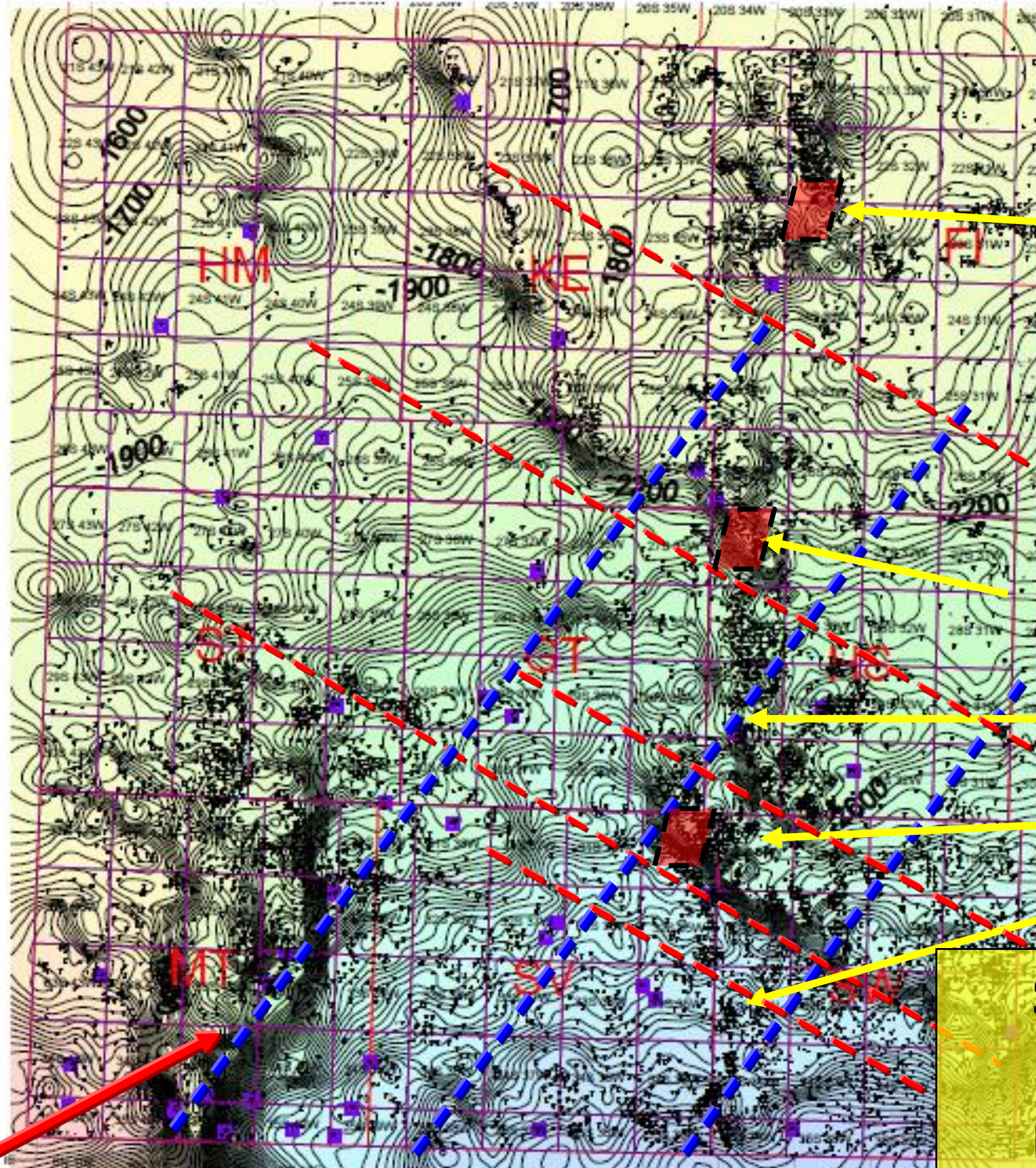


Subcrop pattern for Mississippian strata, western Kansas (Ebanks, 1991).

Valley incision took place during exposure of the Meramecian. Subsequent Chesterian transgression, punctuated by still-stands filled the narrow, nearly linear valley with fine-grained reservoir sand.

Dubois (2013)

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



Damme Field

Pleasant Prairie Field

Eubank Field

Cutter Field

Shuck Field

10 mi (16 km)

Structure Top Meramec Mississippian

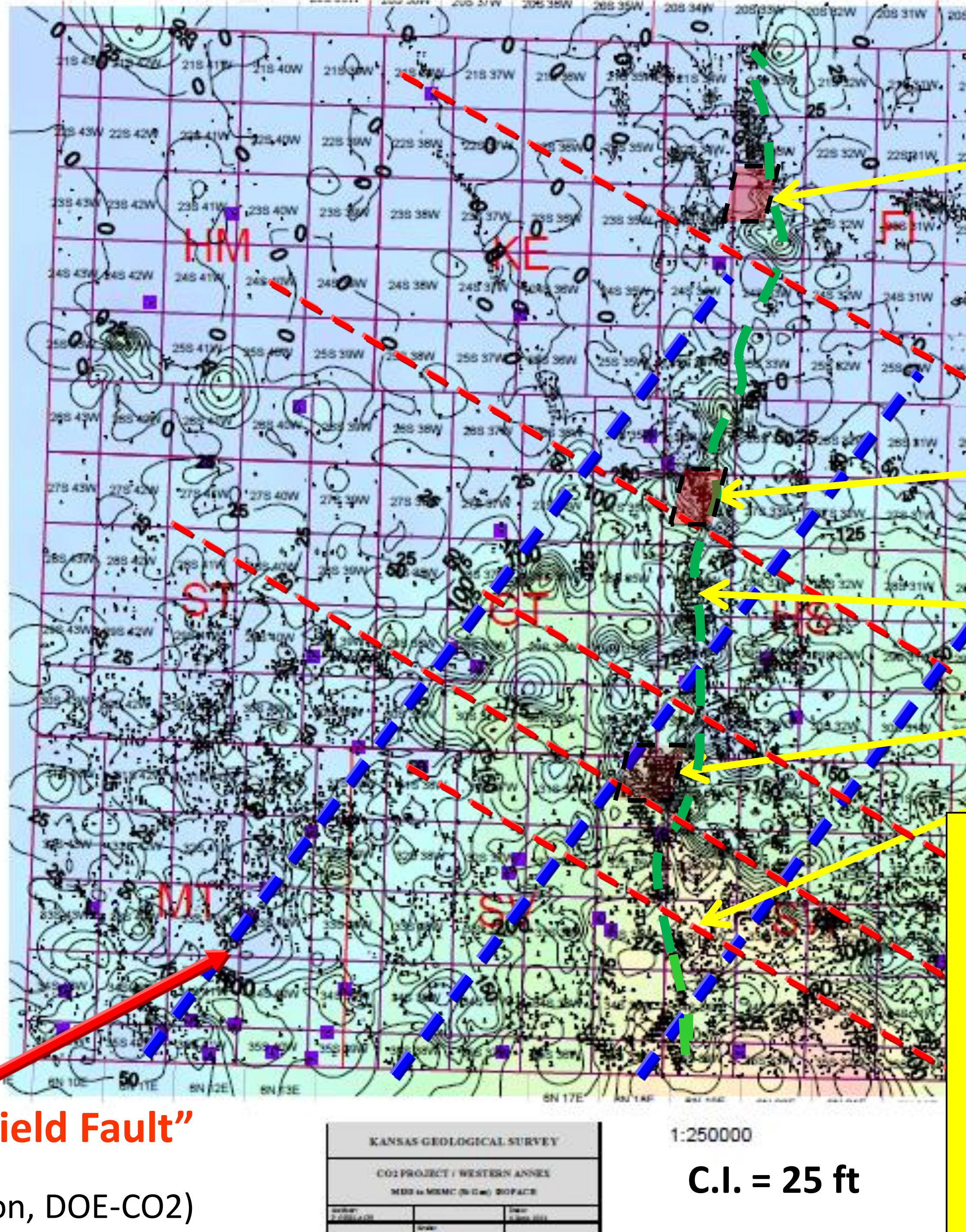
Horst with faulted southwest and west flanks

“Interstate Field Fault”

1:250000

C.I. = 25 ft

(Gerlach, Nicholson, DOE-CO2)



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

Incised valley

10 mi (16 km)

C.I. = 25 ft

Isopach of Chester delimiting *incised valley system*

(~100 miles (30 km) long)

100- to 300-ft-thick incision

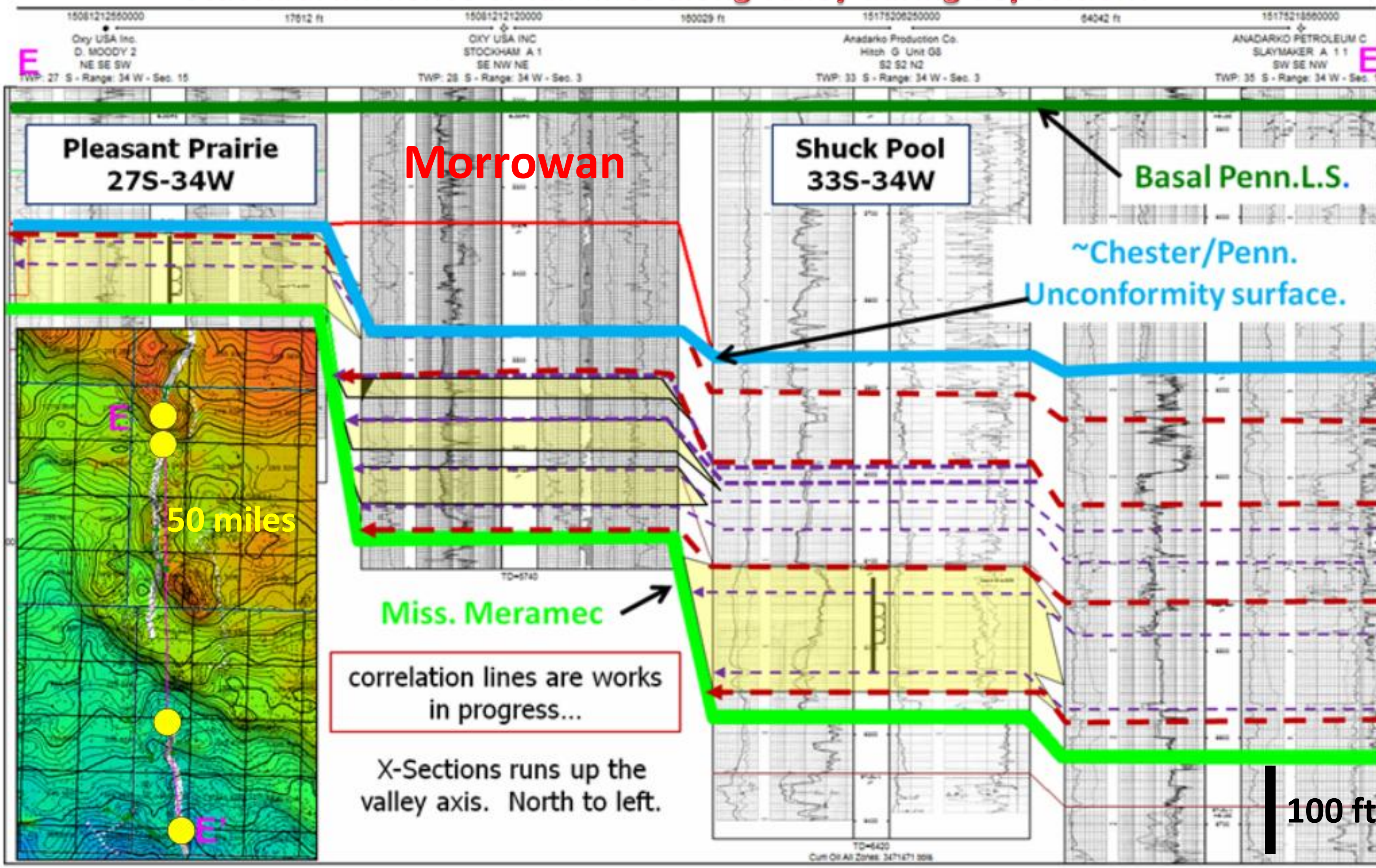
(Gerlach, Nicholson, DOE-CO2)

North

Chester Sequence Stratigraphy

Stuctural influence of fall lines along valley during deposition?

work by John Youle

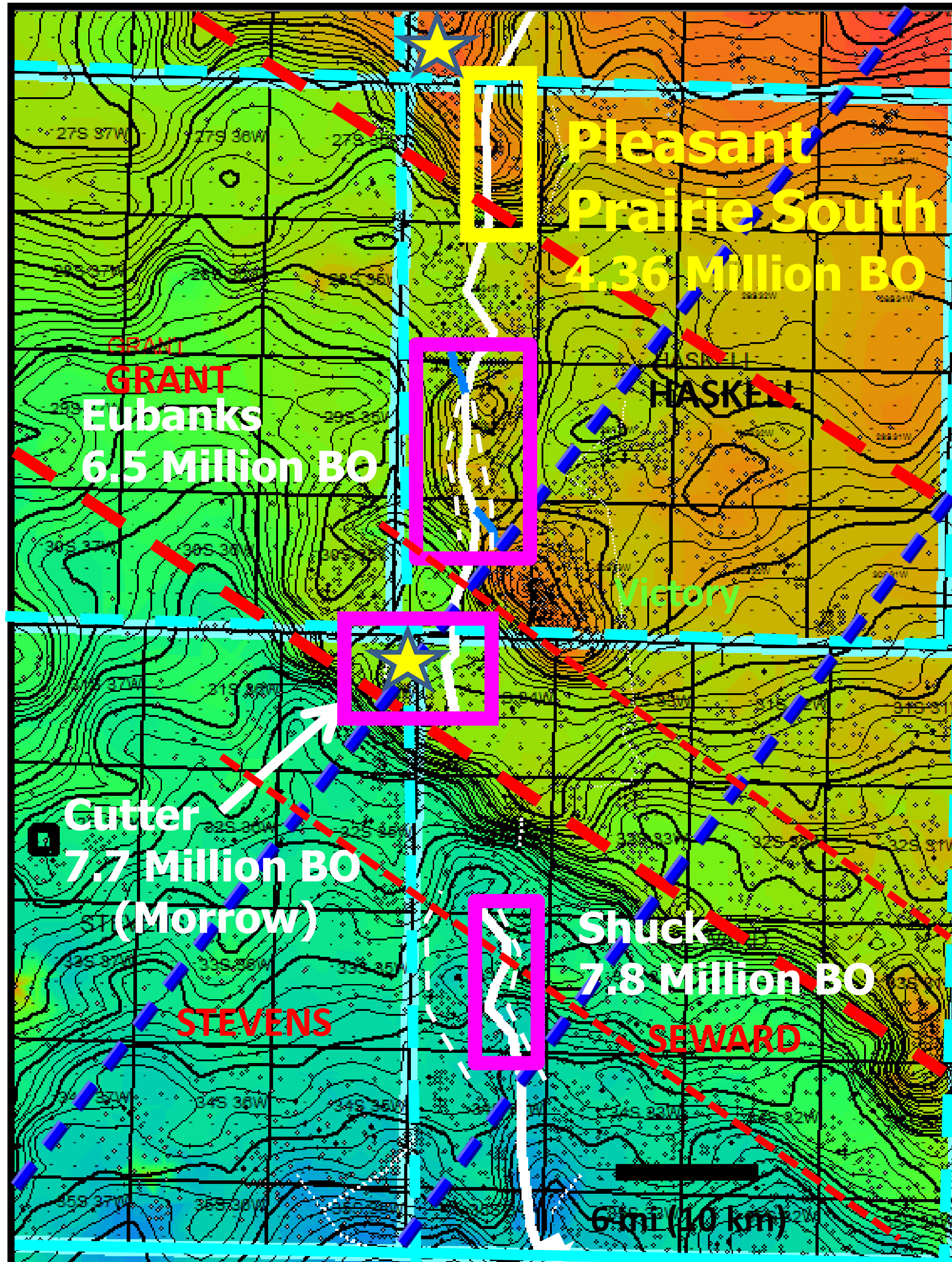


The cyclic retrogradational nature of Chester shoreline advances into Kansas are interpreted to have filled incised valleys with a series of 'back-stepping' stacked estuarine sandstone reservoirs. Red dashed lines are postulated sequence boundaries, and purple lines are possible parasequences. *(Youle)*

Chester valley incision and fill predated "main event " post-Mississippian – pre-Middle Pennsylvanian Ouachita-related regional tectonism

- However, traps in valley-fill sand pools were sprung by Ouachita events
- Ubiquitous fractures in Chester IVF cores.
- Subtle to no channel deflection around features
- Antecedent paleogeomorphology controlling valley location results from subtle structural deformation

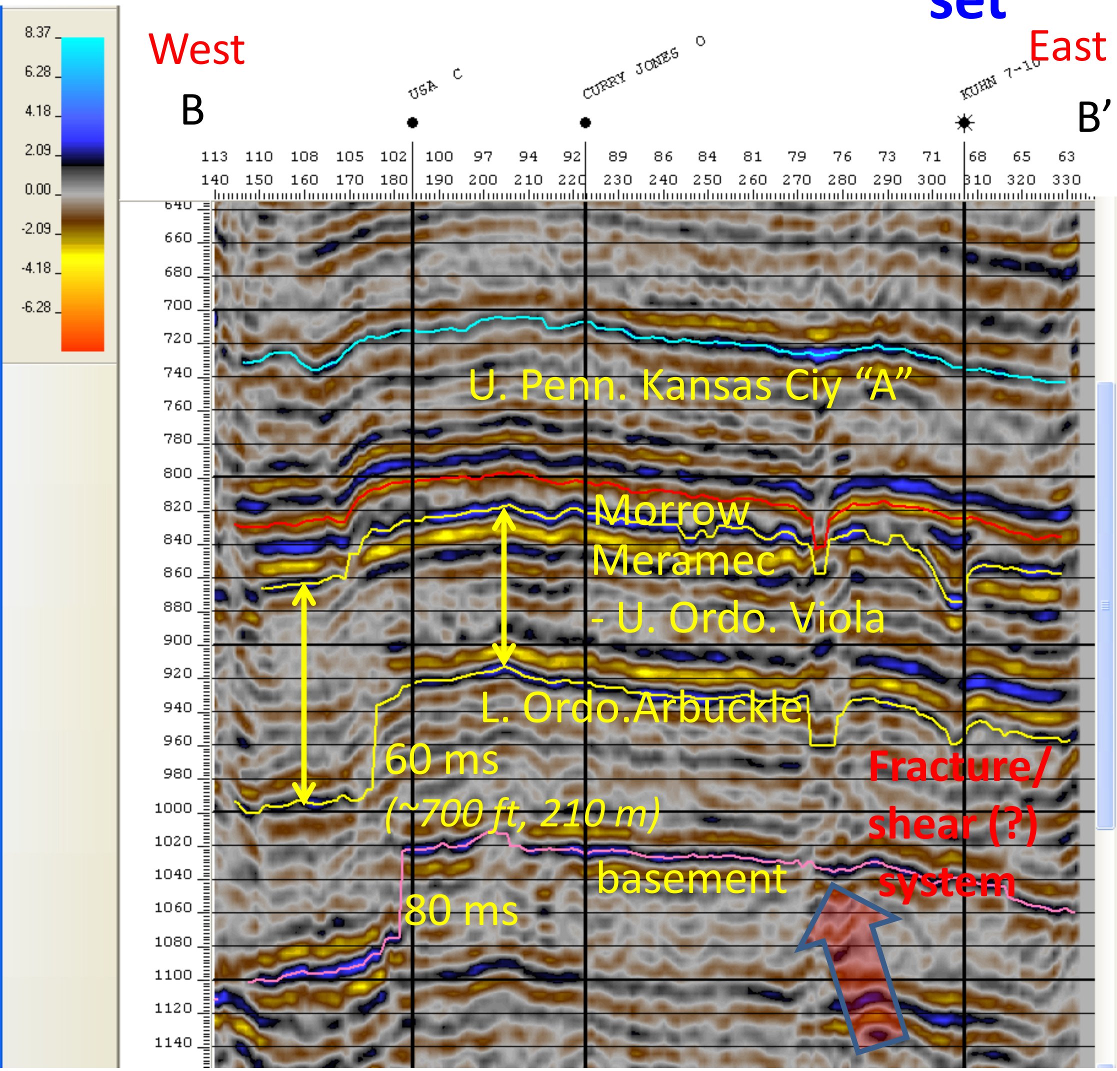
- **Subsea structure on top of Mississippian Meramec** (Ste. Gen. in most of the area) 25′ C.I. (smoothed)
- Chester incised-valley axis shown as white line.
- Chester valley-fill fields located within pink rectangles
- **Horst blocks** at Cutter, Victory, Eubank, and Pleasant Prairie are faulted on south and west flanks
- **Horst blocks** on north sides of regional NW-trending lineaments



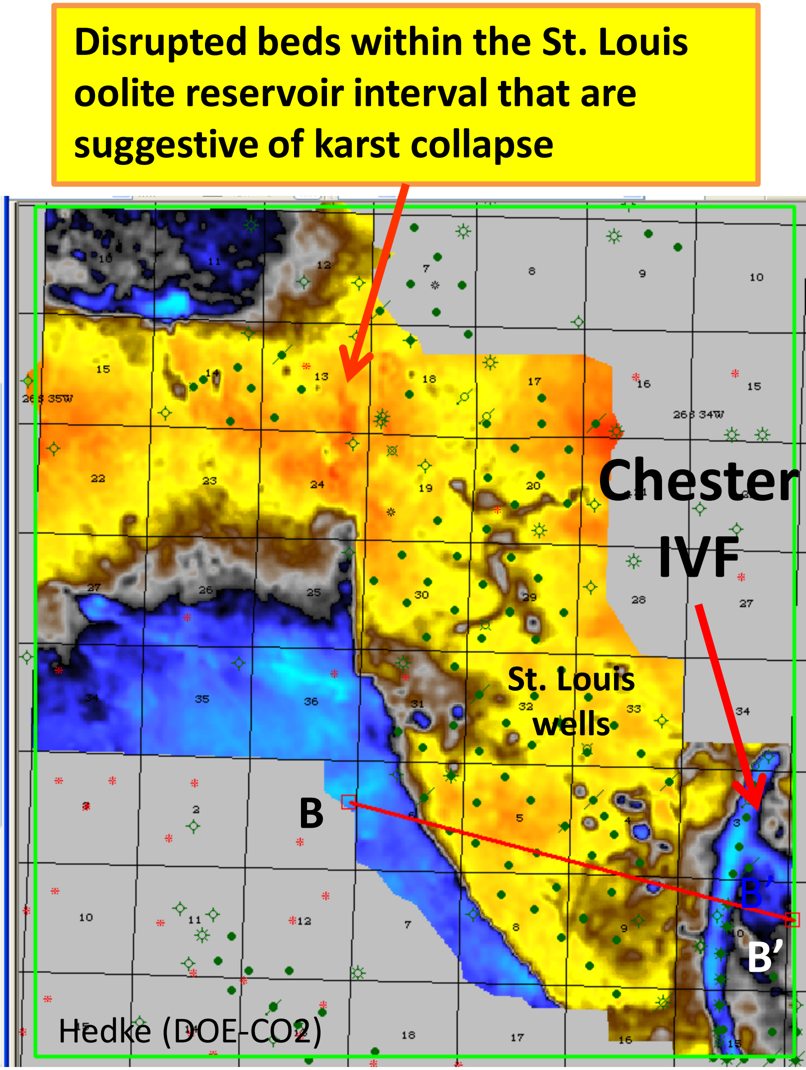
Youle (DOE-CO2)

55% expansion of the Mississippian-to-Upper Ordovician Viola Limestone interval across major fault

-- Chester incised valley coincides with location of N-NE fracture set



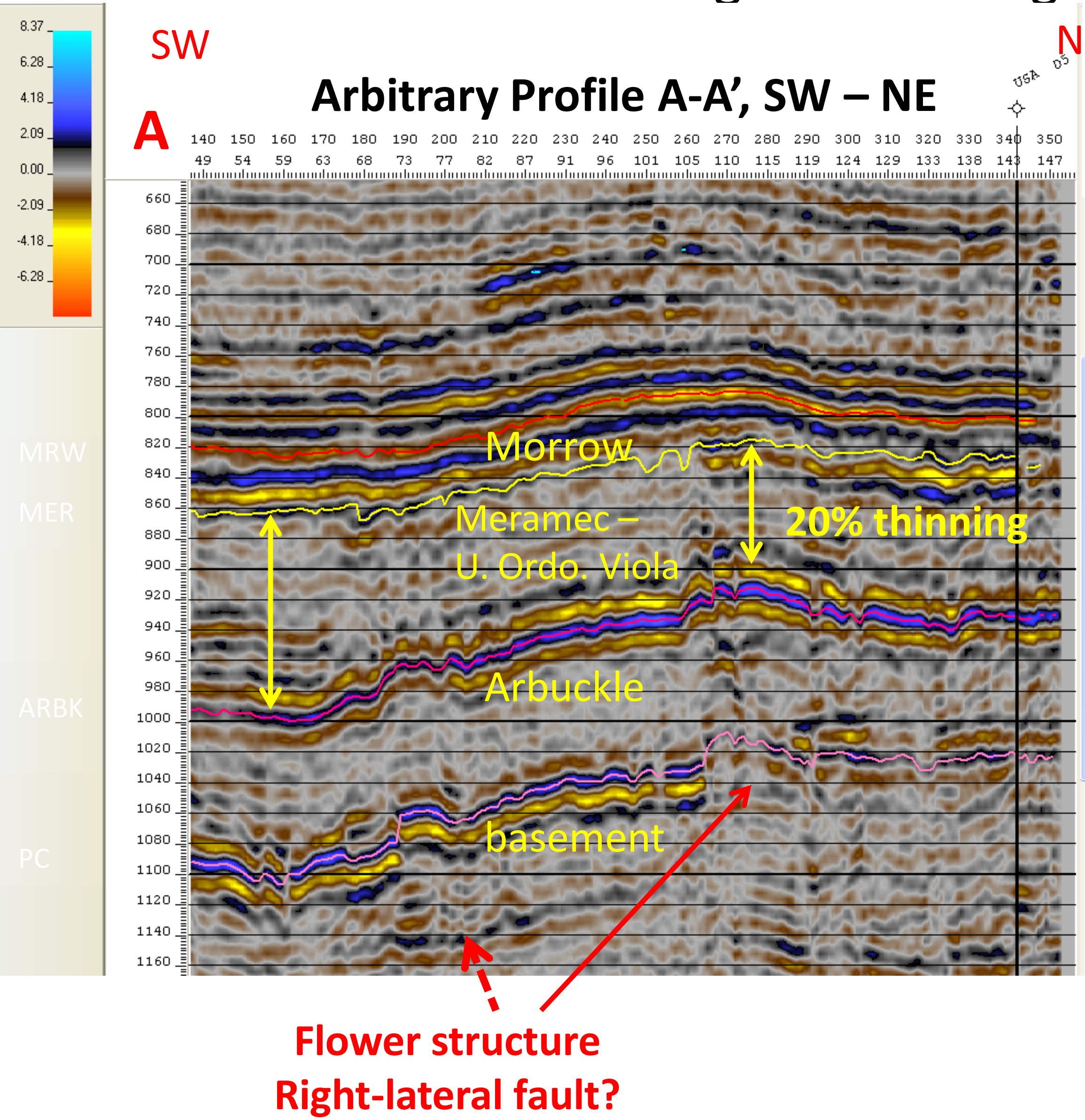
Arbitrary Time Profile B-B', W – E

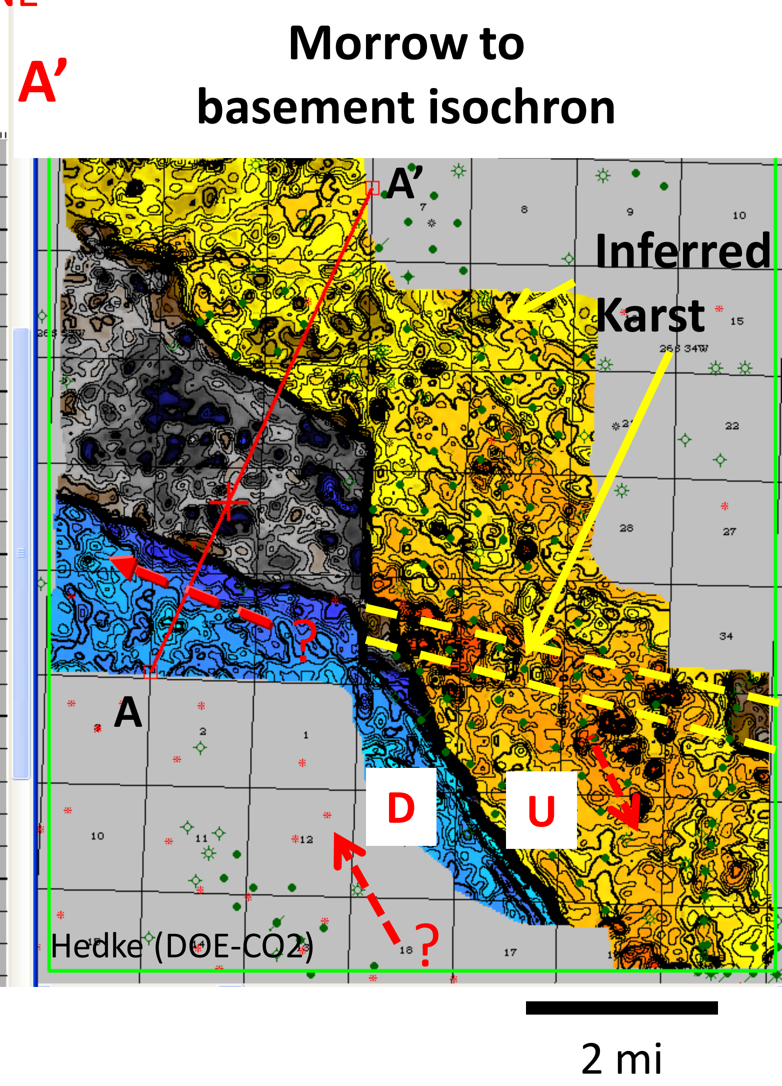


Meramec Time Structure
Pleasant Prairie Field

Pleasant Prairie structural block

orientation of faults suggests right-lateral component of faulting along a restraining bend



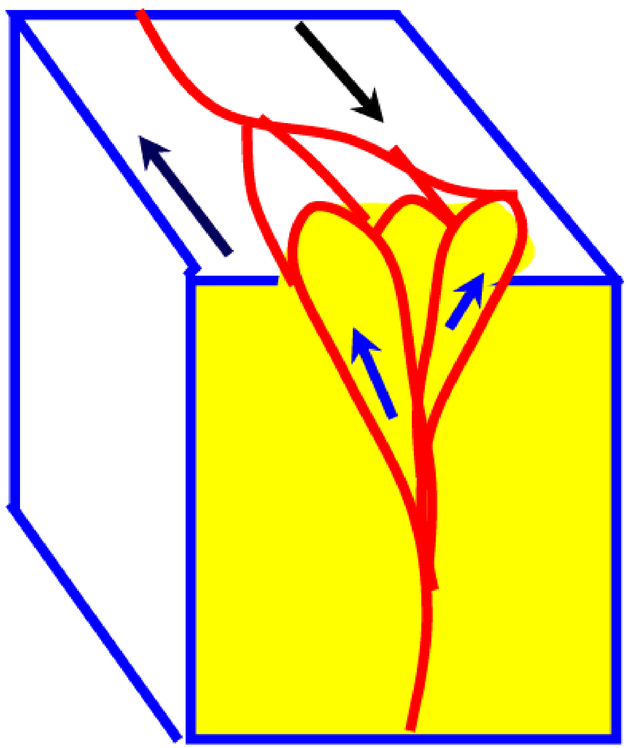


Strike-Slip Faults – flower structures & restraining bends

Flower Structures

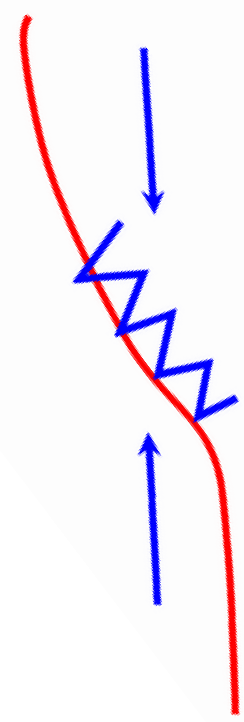
Positive (Palm Tree) → Transpression

Right lateral



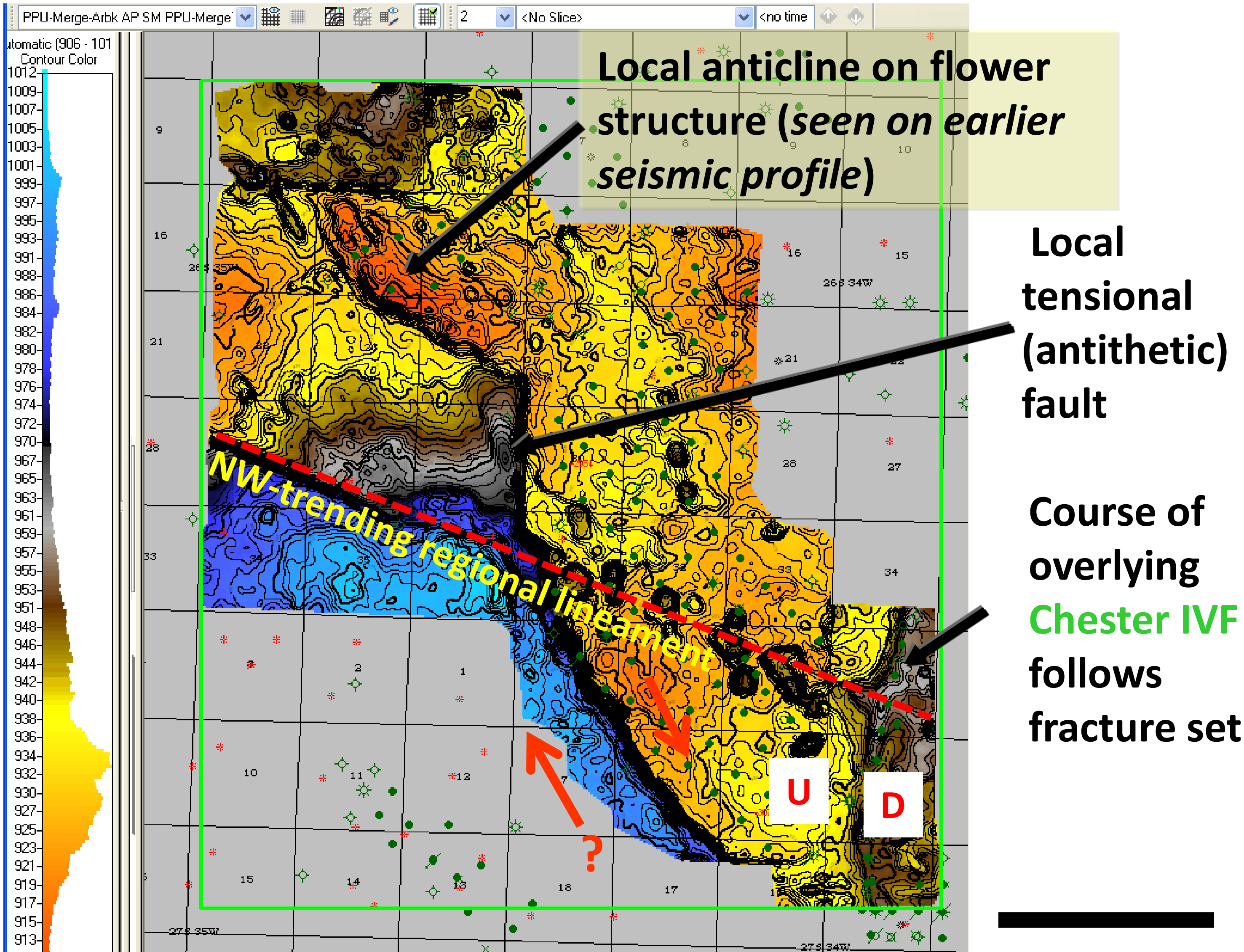
Restraining Bends –

Transpressional zones occurring at fault bends (Push-Up Ridges)



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

Paleo-Arbuckle karst developed along regional NW-trending lineament



Hedke (DOE-CO2)

Arbuckle Time Structure (Pleasant Prairie Field)

Chester valley incision and fill predated "main event " post-Mississippian – pre-Middle Pennsylvanian Ouachita-related structural events

Cutter Field Example

- **Subsea structure on top of Mississippian Meramec** (Ste. Gen. in most of the area). 25′ C.I. (smoothed)
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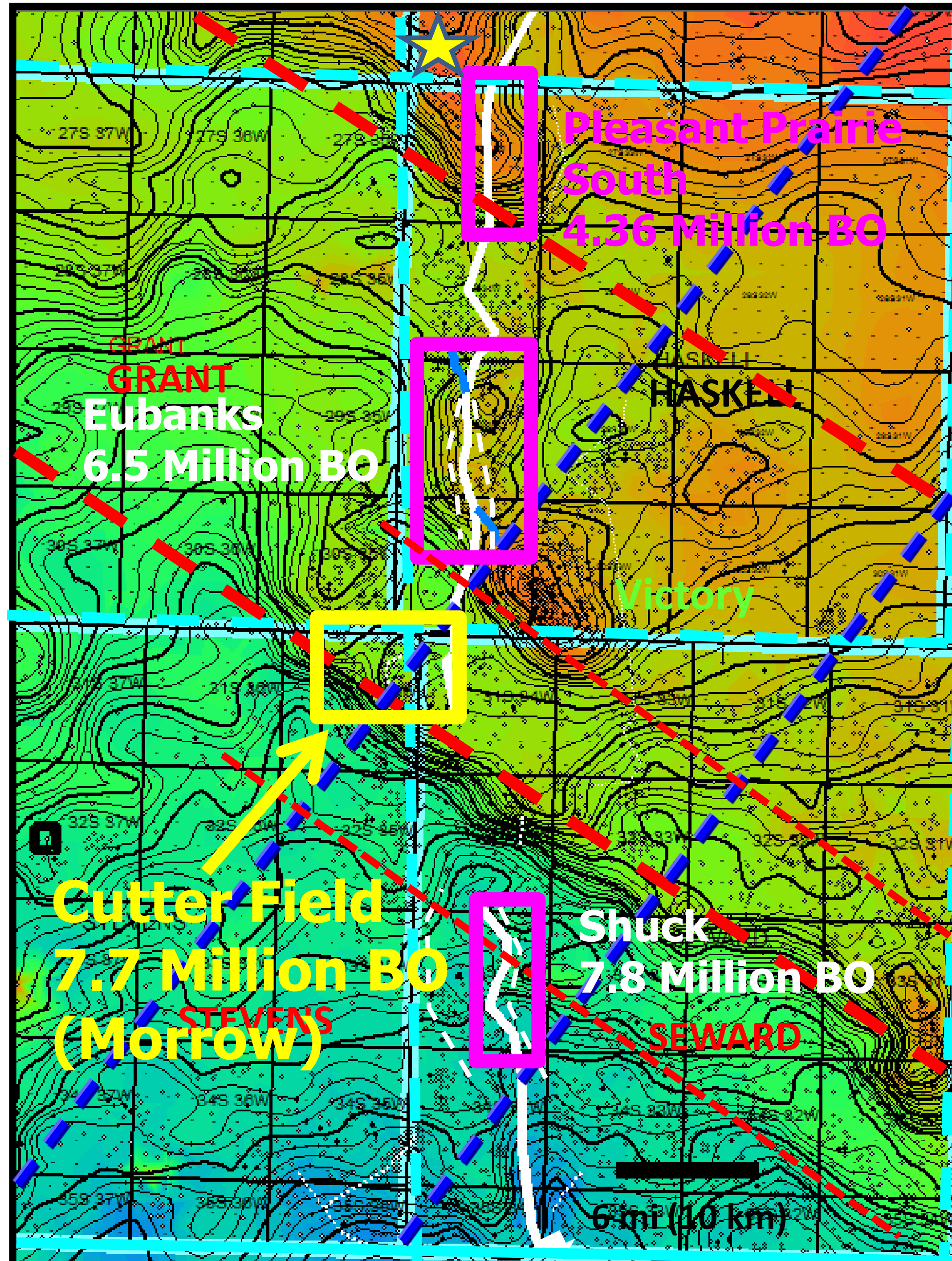
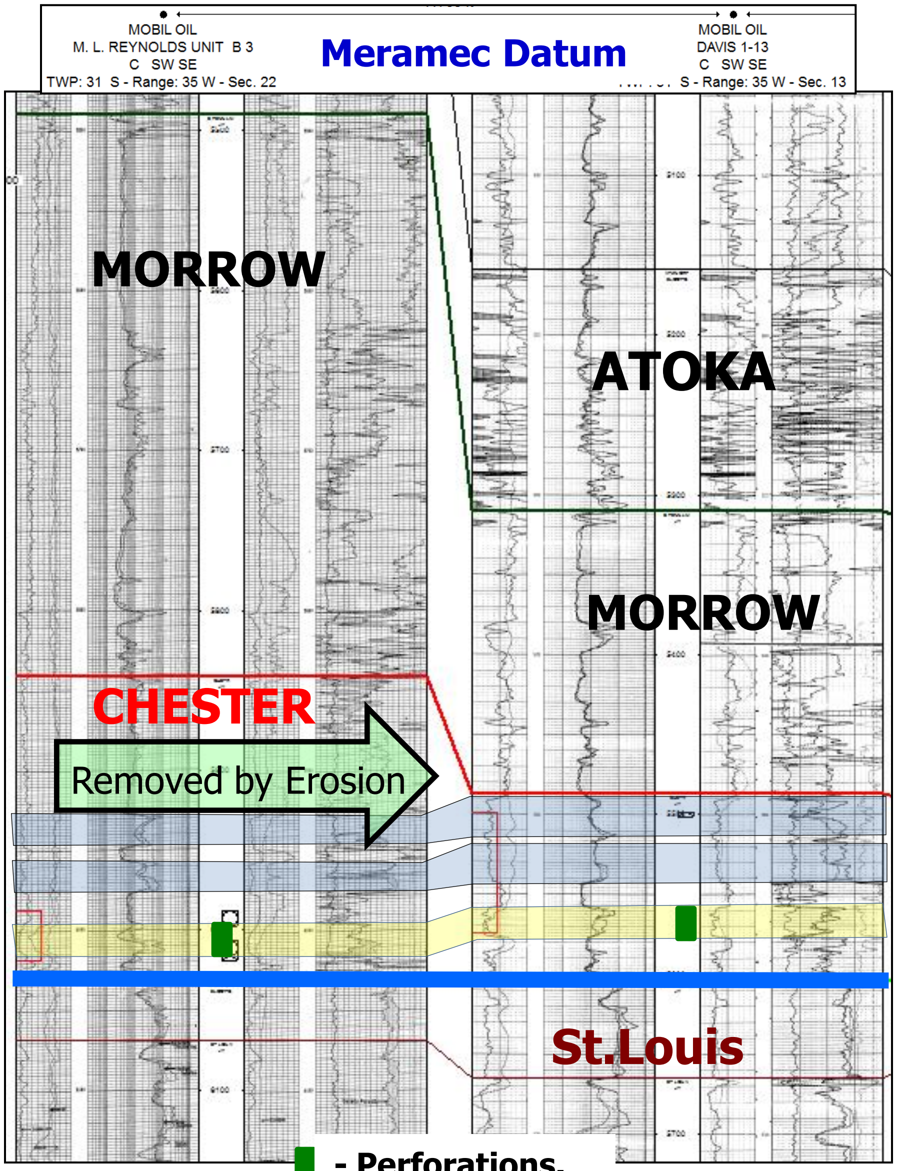


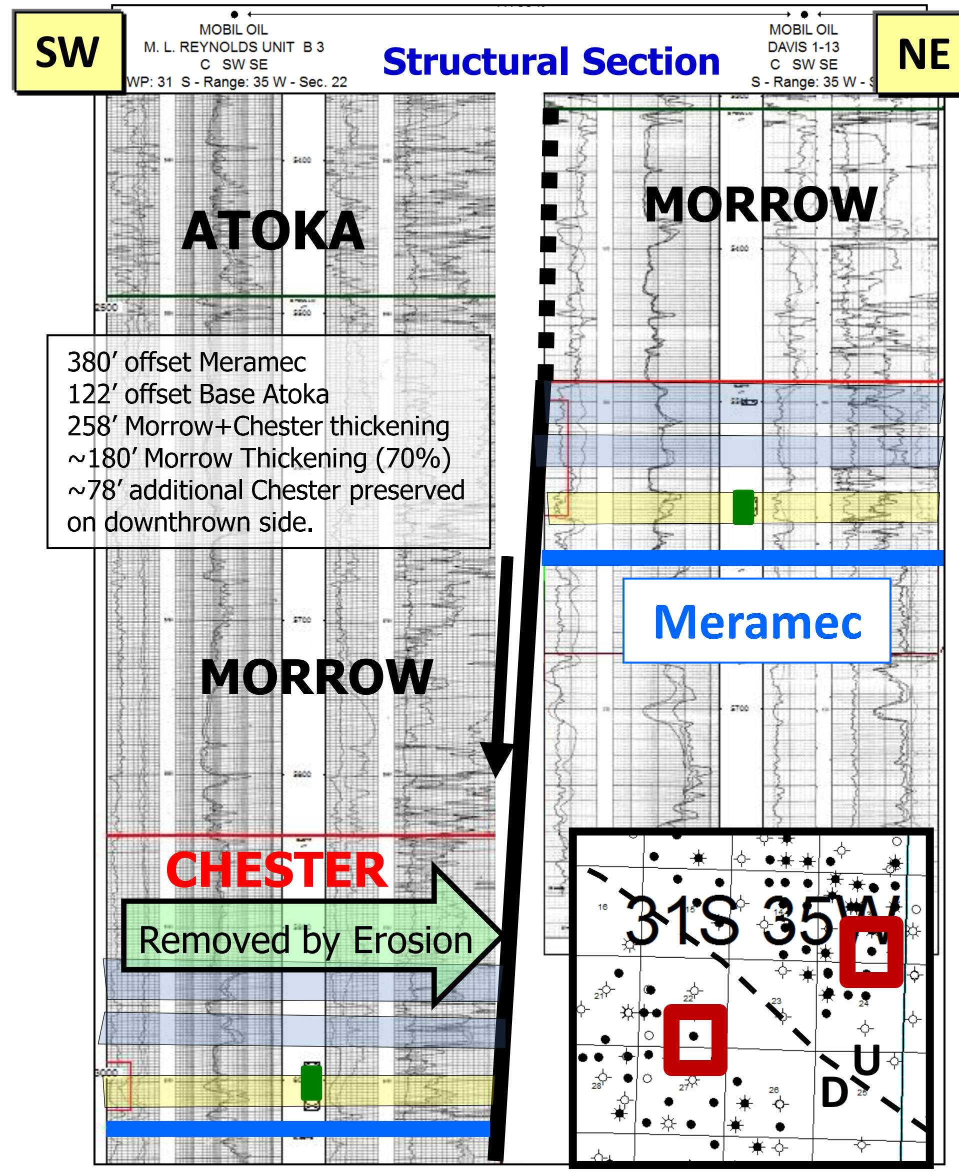
Youle (DOE-CO2)

Episodic deformation on main SW-bounding fault

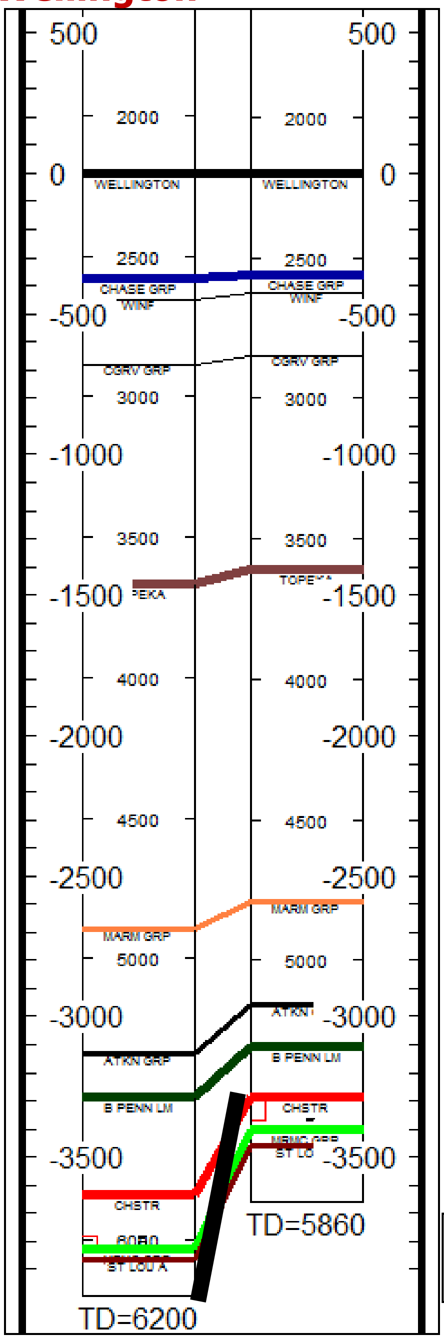
- primary post-Chester deformation
- syndepositional Morrowan deformation that is accompanied by overpressuring (Nelson, 2011; Higley, 2011)

Cutter & Cutter South Field Areas





Datum: Lower Permian Wellington



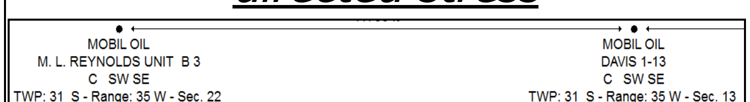
Cutter & Cutter South Field Areas

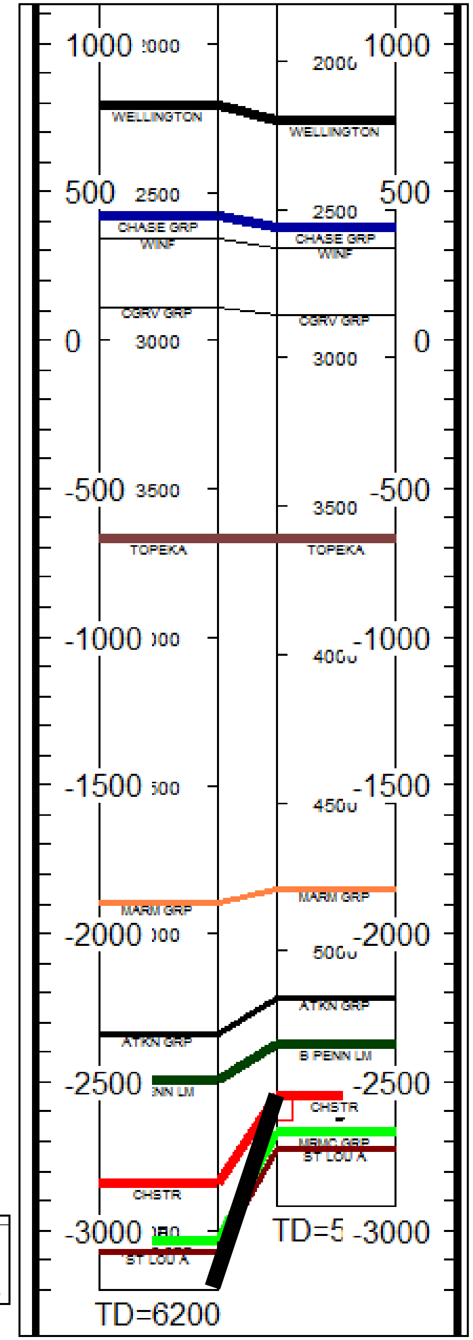
Structural Section

Up to at least Wellington time, subsidence continued on downthrown side of fault. However, amount of downthrown movement appears to have decreased over time at close to a constant rate.

Since Wellington time Laramide tectonic events impacting the Keyes Dome, Sierra Grande Uplift, and Las Animas Arch resulted in 55' of uplift and <u>dip reversal</u> on the Wellington in the downthrown well.

-- <u>*Compression with east-directed stress*</u>





Chester valley incision and fill predated "main event " post-Mississippian – pre-Middle Pennsylvanian Ouachita-related structural events

Shuck Field Example

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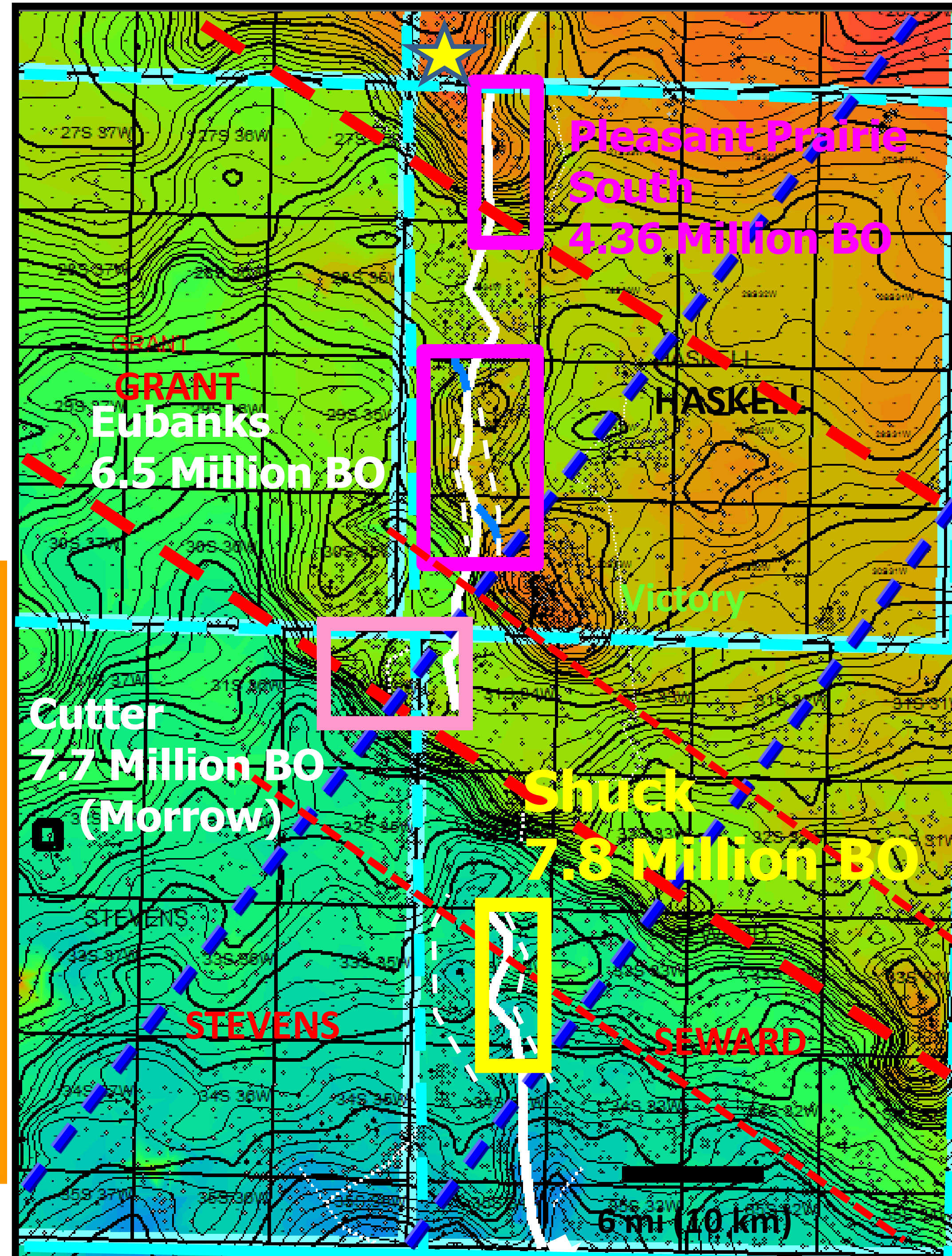
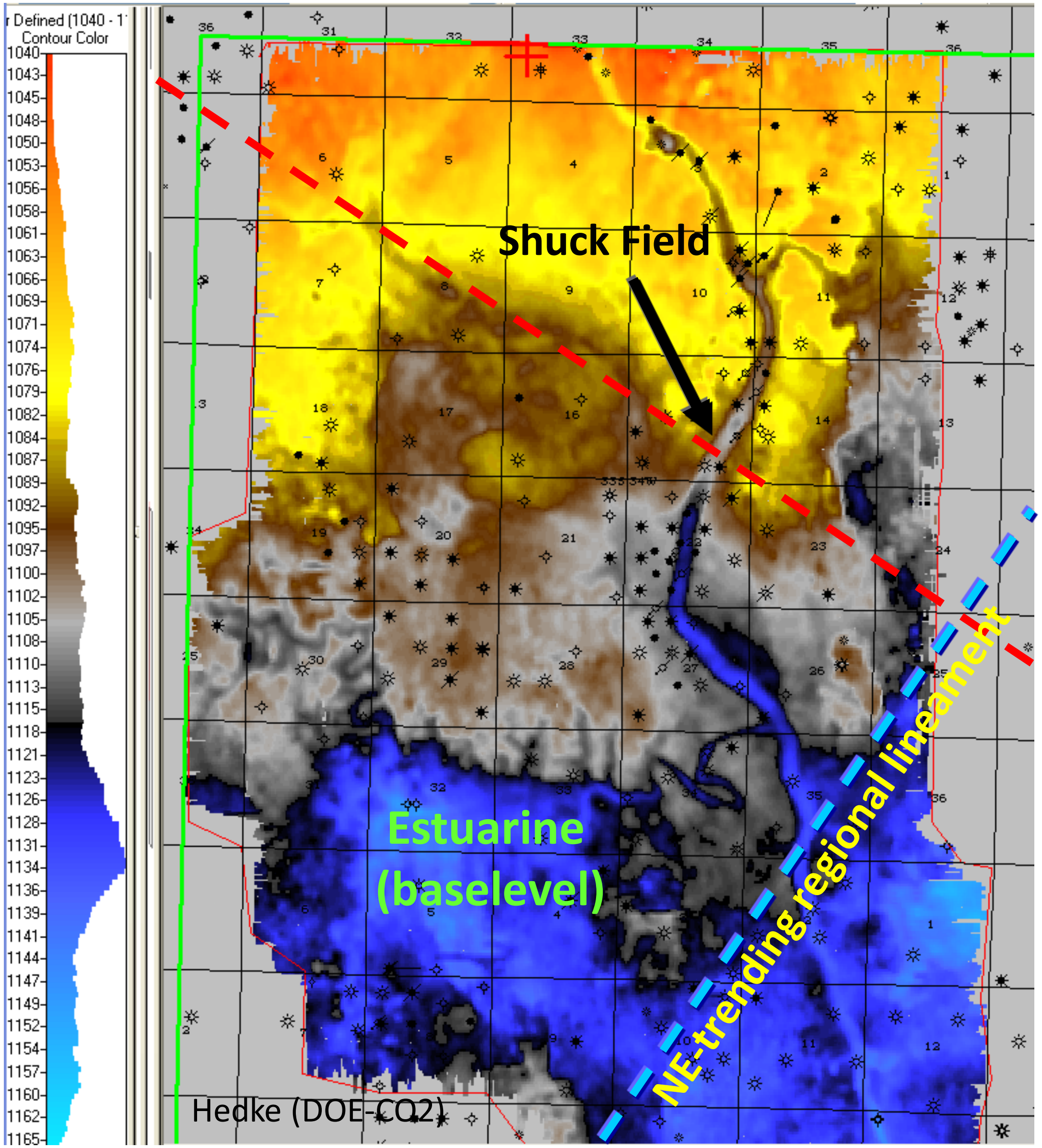
Youle (DOE-CO2)



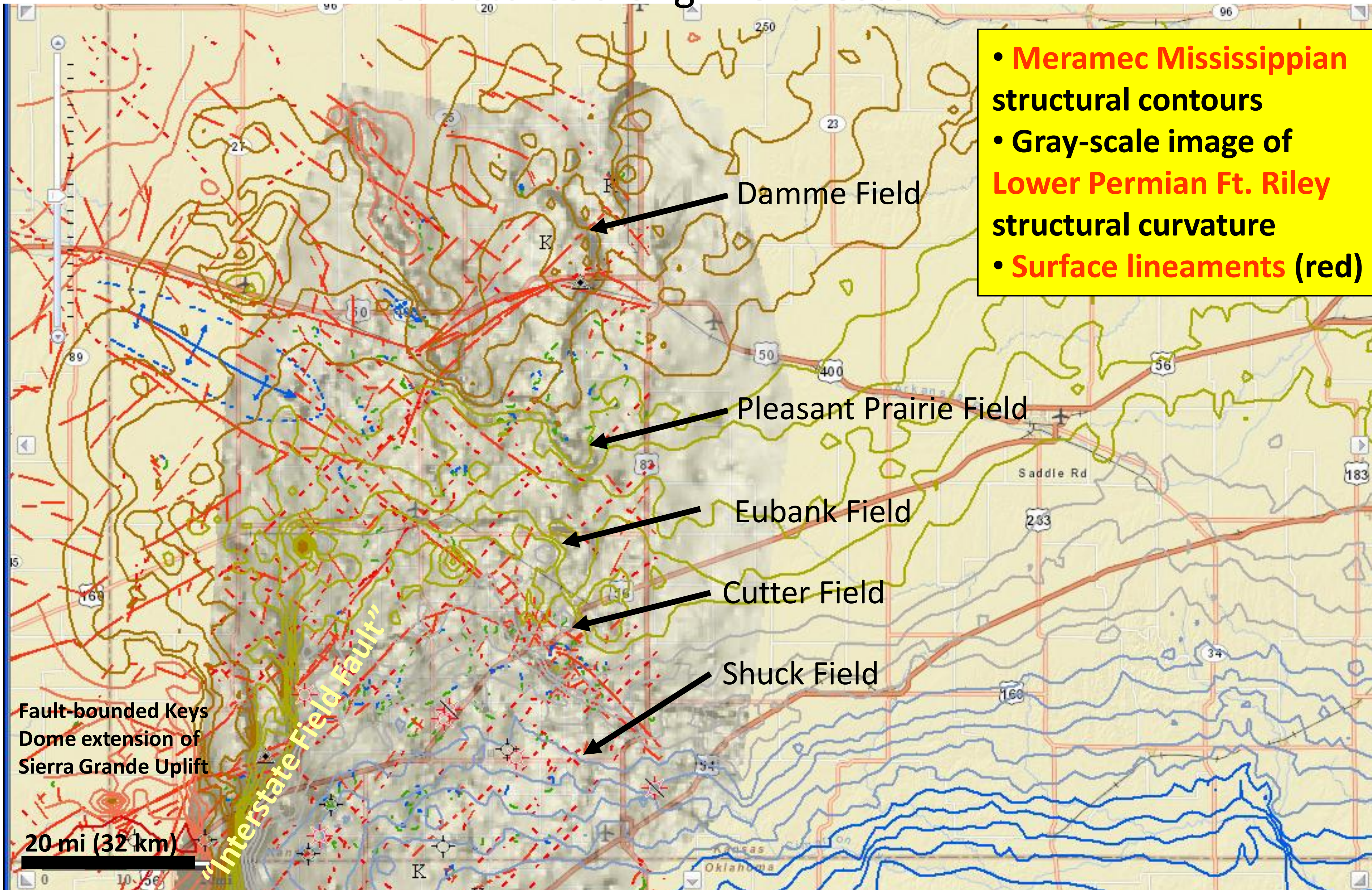
Shuck Field - Chester incised valley broadening into estuarine embayment to south near Oklahoma-Kansas line

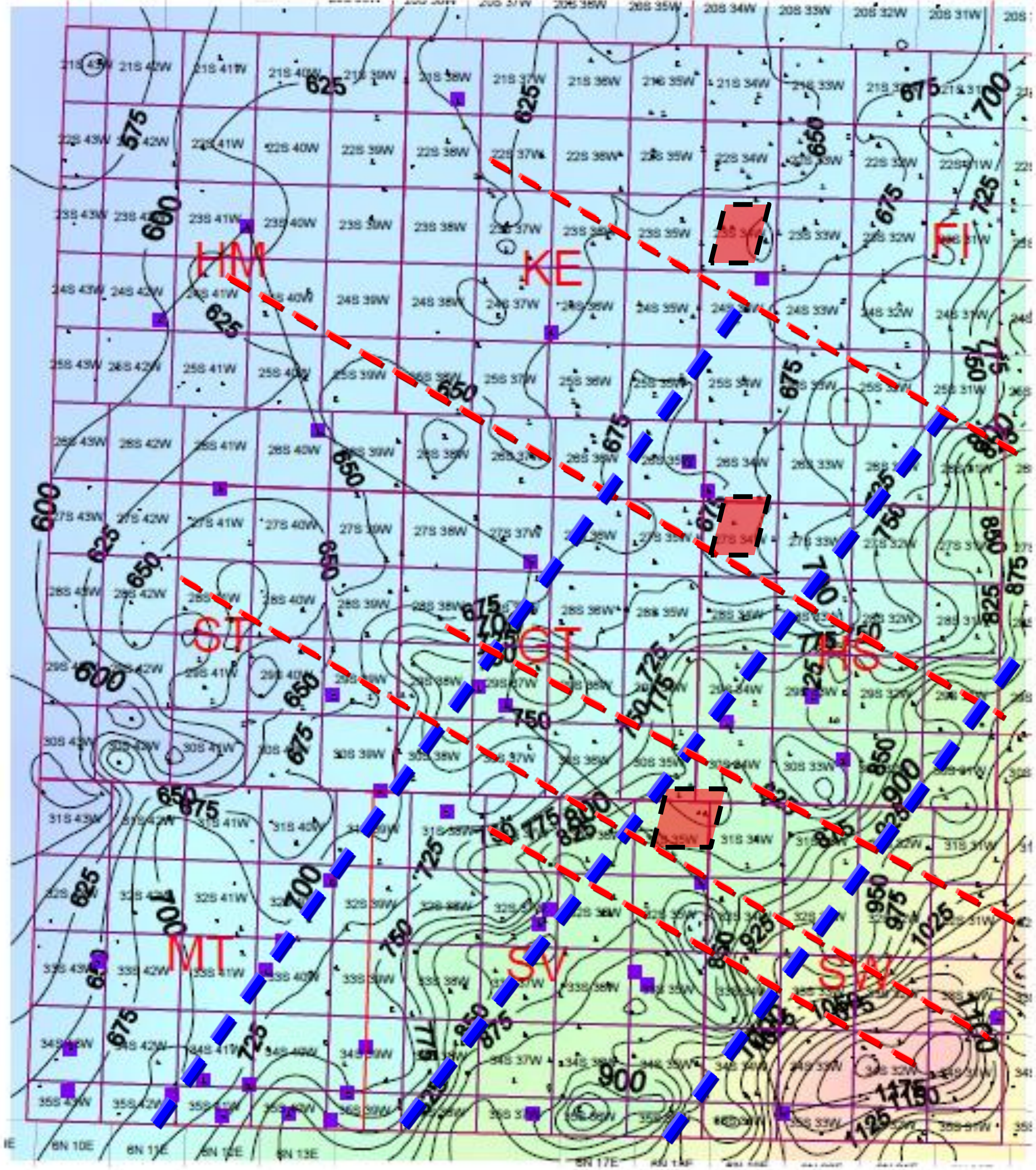


- Time Meramec surface (unconformity)
- Prominent Chester IVF with rectilinear NW and NE trend
- Multiple drainage features on edge of topographic break
- Channel widths ~ 300 ft
- NW-trending and NE-trending regional structural lineaments

2 mi (3.2 km)

Shallower structures and surface lineaments suggest episodic movement of NW- and NE-trending deep-seated structures along N-S Chester IVF





Dominance of the NE-trending regional lineaments controlling Early Permian deposition in SW Kansas (more northerly paleo-σ_1?)

Isopach Lower Permian Hutchinson Salt to Neva Ls. (top Pennsylvanian)

25 mi (40 km)

KANSAS GEOLOGICAL SURVEY

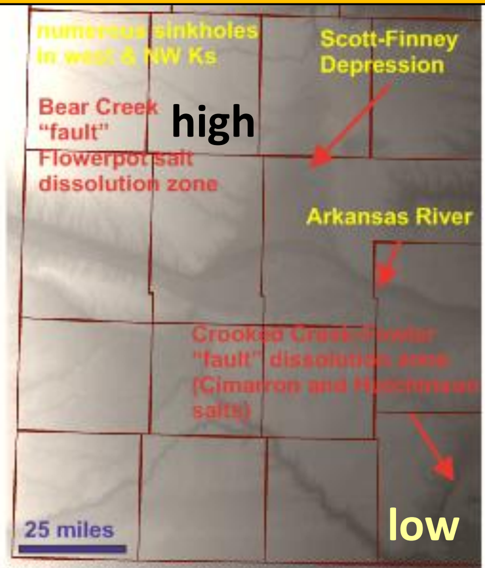
CO2 PROJECT / WESTERN ANNEX

1:250000

C.I. = 25 ft

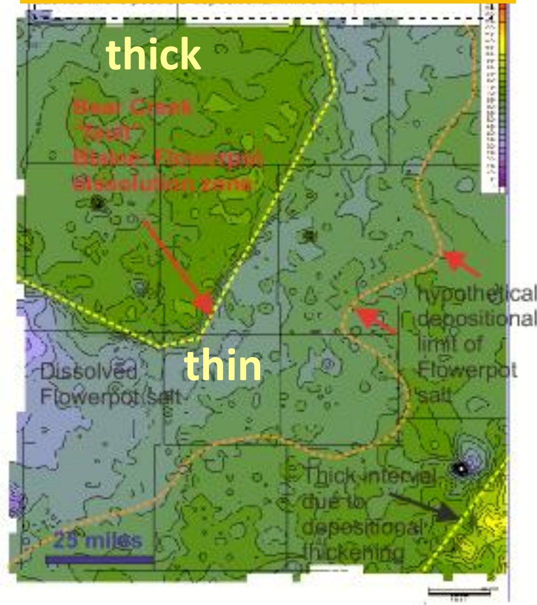
(Gerlach, Nicholson, DOE-CO2)

Gray scale DEM of SW KS
Postive above thicker Blaine halite



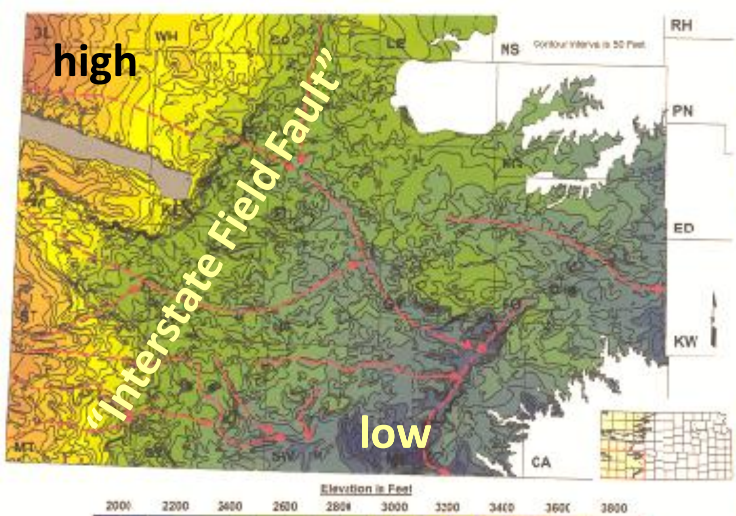
Surface elevation, gray scale (light = higher). Central portion of mapped area is topographically low.

Isopach of halite-bearing
Lower Permian Blaine Fm.

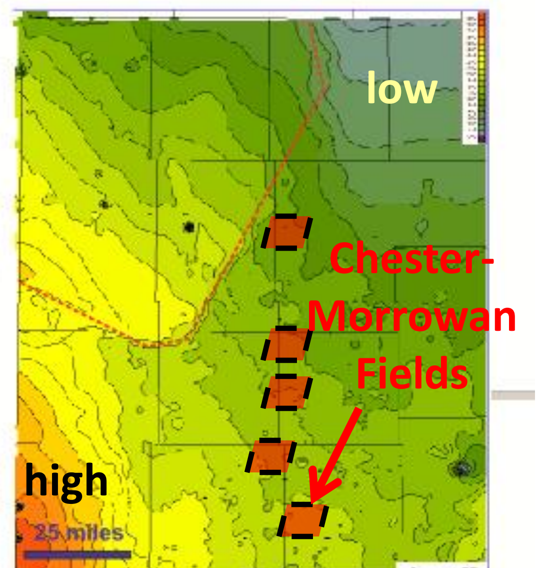


Proposed dissolution of Lower Permian evaporites (~1000 ft below surface) during Late Tertiary & Neogene providing accommodation space for High Plains (Ogallala) aquifer

- Inferred influence of NW- & NE-trending basement structures
- Timing of dissolution corresponds to regional uplift and tilting of Rocky Mountains and Great Plains during mid-Miocene (McMillian et al., 2006; Goes and van der Lee, 2002)
- Timing similar to emplacement of gas into Hugoton Field (Sorenson, 2005)



Bedrock elevation at base Pliocene Ogallala formation
Macfarlane and Wilson (2006)



Structure top of Blaine Formation

Summary & Conclusions

- **Anadarko Basin** –Proterozoic extension to Phanerozoic compression from rift basins to horst & graben system
- **Hugoton Embayment (HE)** – 10,000-km^2 northern extension of Anadarko Basin and structurally integrated
- **Major structures in the HE –** prominent evidence of coupled and complex compressional events from far field stresses including diagnostic features, such as flower structures and restraining bends developed along reactivated basement lineaments
- **Episodic structural movement** – post-tectonic movement affecting sedimentation/stratigraphy throughout Phanerozoic including High Plains Aquifer and surface lineaments and topography
- **Pattern of deformation** – strongly influenced by prominent basement weaknesses (the template) revealed by potential fields and lineament analysis interacting with an evolving stress field

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