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

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Outline

• **Anadarko Basin** – Proterozoic extension to Phanerozoic compression

• **Hugoton Embayment (HE)** – 10,000 km$^2$ Anadarko Basin extension

• **Major HE structures** – reactivation along basement lineaments

• **Episodic movement** – Phanerozoic sedimentation/stratigraphy

• **Pattern of deformation** – basement weaknesses (the template) and evolving stress field

• **Summary**
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
Kansas has three distinct basement terrains

Keller and Stephenson (2007)
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).
Peak Late Paleozoic Tectonism during Morrowan and Atokan

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

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

(Higley, 2011)
Isopach - Top Thirteen Finger Limestone to Top of Morrow Shale

Cutter KGS #1
NE Stevens County, KS

(Higley, 2011)
Atokan sample at 5233.5 ft is organic rich (3.77% TOC) and TTI of 443 indicates sample is in the oil generating window.

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Notes:
- "*" = not measured or invalid value
- TOC = Total Organic Carbon, wt. %
- S1 = volatile hydrocarbon (HC) content, mg HC/g rock
- S2 = remaining HC generative potential, mg HC/g rock
- S3 = carbon dioxide content, mg CO2/g rock
- Tmax (°C) = maximum temperature of oil generation
- Meas. % Ro = measured vitrinite reflectance
- HI = Hydrogen index = S2 x 100 / TOC, mg HC/g TOC
- OI = Oxygen index = S1 x 100 / TOC, mg CO2/g TOC
- PI = Production Index = S1 / (S1 + S2)
- Pyrogram:
  - f = flat S2 peak
  - n = normal
  - lowTemp2Shoulder = low temperature S2 shoulder
  - lowTempS2peak = low temperature S2 peak
  - highTempS2peak = high temperature S2 peak
  - LEKO = LECO on LECO Instrument
  - SRA = Programmed Pyrolysis on SRA Instrument
  - RE = Programmed Pyrolysis on Rock-Eval instrument
  - EXT = Extracted Rock
  - NOFR = Normal Preparation

Weatherford Lab
Correlation of sequence boundaries illustrates retrogradation of Atokan units in Kansas.

Blue arrows show units that onlap the Miss. Atokan carbonates grade into shoreline SS.s near the point of onlap of each sequence.

J. Youle (2012)
Facies changes in an ideal Atokan “cycle” across Kansas.

Anadarko basin towards the Central Kansas uplift

lower-shelf

Porosity seams, perhaps enhanced by subaerial exposure, can form locally productive “Johnson Zone” reservoirs at or near sequence and parasequence surfaces.

mid-shelf

“Sediment starved” basinal deposition. Stacked thin Ls./black shale couplets in the Anadarko basin characterize the “13 Finger LS” of Oklahoma.

proximal

Locally preserved paralic sands and IVF reservoirs***.

Porosity seams, perhaps enhanced by subaerial exposure, can form locally productive “Johnson Zone” reservoirs at or near sequence and parasequence surfaces.

Lithofacies

Cyclothem equivalents (Heckel, 1977, 1989)

Limestone

upper limestone

Shale

upper core shale

Proximal siliciclastics and paleosols

Black shale

Transgressive lag

outside shale

lower core shale

middle limestone

*** significant producers

J. Youle (2012)
Top Paleopressure – Morrowan Shale Resistivity

Cutter Field
NE Stevens
County, KS

Top of paleopressure in rocks of Morrowan age
Top of paleopressure in rocks of Desmoinesian age
Northern limit of well control

Top of paleopressure in rocks of Atokan age
Top of paleopressure in rocks of Virgilian age
Top of paleopressure in rocks of Missourian age
Top of paleopressure in rocks of Springer age

EXPLANATION
- Wells with resistivity log reversal
- Wells with no resistivity log reversal
- Precambrian faults
- Basin axis

Nelson and Gianoutsos (2011)
Proterozoic correlations – Magnetic Field and Phanerozoic Structures

- Correspondence of Phanerozoic structures to magnetic anomalies
- Local and subregional changes in strike and dip appear to closely correlate to magnetic map
- Major influence on lithofacies distribution and sequence characteristics

(Cole, 1976; Kruger, 1999)
Reprocessed Kansas Magnetics -- Tilt Angle, Total Magnetic 2-10 mi +
Total Magnetic Reduced to Pole (910m)

Modeling Carbon Dioxide Sequestration Potential in Kansas

http://maps.kgs.ku.edu/co2/?pass=project
Interactive map to compare control well with well to be classified

Seward County

-- 700+ ft of Proterozoic arkose in SW portion of Seward County

Cross section index
SW-NE Structural Cross Section of Lower Paleozoic in Seward County
Tilt Angle Total Magnetic Reduce to Pole

Oil fields in western 2/3rd of Kansas

http://maps.kgs.ku.edu/co2/?pass=project
Stratigraphic setting

Chester sands

CO2-EOR Initiative

Approximate field locations

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.

Generalized stratigraphic column (Montgomery and Morrison, 1999).

Dubois (2013)
Chester Isopach delimiting incised valley system (~100 miles long)
Structure Top
Meramec
Mississippian
*Horst with faulted southwest and west flanks*
Subsea structure on top of Mississippian Meramec (mostly Ste. Gen.)
- 25’ C.I. (smoothed)
- White line: Chester incised valley axis
- Pink rectangles: Chester valley fill fields
- **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

Chester valley incision and fill predated post-Mississippian – pre-Middle Pennsylvanian Ouachita related structural events
- Traps in valley fill sand pools sprung by Ouachita events
- No channel deflection around features.
- Ubiquitous fractures in Chester IVF cores.
- Antecendent paleogeomorphology

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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)
Mississippian-U. Orodovician Expansion
Chester incised valley & fracture set

Disrupted beds within the St. Louis interval that are suggestive of karst collapse.

Arbitrary Time Profile B-B', W – E

Mississippian-U. Orodovician Expansion:
- Chester incised valley & fracture set
- Disrupted beds within the St. Louis interval suggestive of karst collapse.
Pleasant Prairie structural block
Fault orientation-right lateral component along restraining bend

Arbitrary Profile A-A', SW – NE

Morrow to basement isochron

Morrow – U. Ordo. Viola

20% thinning

Arbuckle

basement

Flower structure
Right lateral fault?

Hedke (DOE-CO2)
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
Arbuckle Time Structure
(Pleasant Prairie Field)

Fault bounded orthogonal structural block:
- Regional NW-trending lineament
- Paleo Arbuckle karst (Ordovician)

- Meramec age karst define partly define location of Chester incised valley
- Intersecting with NW-trending Arbuckle karst trend with north-trending fault corresponding with location of Chester IVF

Hedke (DOE-CO2)
**Subsea structure on top of Mississippian Meramec** (mostly Ste. Gen.)

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

- However, traps in valley fill sand pools were sprung by Ouachita events.
- No channel deflection around features.
- Ubiquitous fractures in Chester IVF cores.
- Antecendent paleogeomorphology – stepwise subsidence and slope to south controlled regional drainage

**Horst blocks**: Cutter, Victory-Eubank and Pleasant Prairie (faul ted on south and west flanks)
- **Horst blocks**: north sides of regional NW-trending lineaments
- **Contour Interval**: 25' (smoothed)
- **White line**: Chester incised valley axis
- **Pink Rectangles**: Chester valley fill fields (DOE investigated)

Youle (DOE-CO2)
COMPARTMENTALIZATION:
Structural Compartments: Post Chester Fault Seals?

Could Chester sands be locally sealed on the downthrown side of NW-SE trending faults?....if juxtaposed against tight Meramec Limestones?

Meramec Datum

Structural Section

- 380’ offset Meramec
- 122’ offset Base Atoka
- 258’ Morrow + Chester thickening
- ~180’ Morrow Thickening (70%)
- ~78’ additional Chester preserved on downthrown side.

Erosion

Perforations

St. Louis

Youle (DOE-CO2)

Cutter & Cutter South Field Areas
Up to at least Wellington time, subsidence continued on downthrown side of fault. However, amount of downthrown subsidence 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 dip reversal on the Wellington in the downthrown well.

Youle (DOE-CO2)
Berexco Cutter
KGS #1
Cutter Field
Multiple pay & shows

Test intervals

12
Morrow

11
Chester

10
St. Louis

9
Warsaw

8
Osage

Upper half of cored interval

Oil Pay Zones

200 ft

Oil show

no show
Berexco Cutter KGS #1 Cutter Field

- Extended oil shows (fluorescence) in lower Paleozoic
- Upthrown structural block near regional fault
- Prior work: Chester oil in Hitch Field has Ordovician source (Kim et al., 2010)

Tested minor oil

Top Viola

Top Simpson

Top Arbuckle

Gasconade

Top Gunter Ss.

Top Proterozoic basement

200 ft

Lower half of cored interval
Subsea structure on top of Mississippian Meramec
(mostly Ste. Gen.)

Chester valley incision and fill predated post-Mississippian - pre-Middle Pennsylvanian Ouachita related structural events
- However, traps in valley fill sand pools were sprung by Ouachita events.
- No channel deflection around features.
- Ubiquitous fractures in Chester IVF cores.
- Antecedent paleogeomorphology controlling valley location is discussed in context of more subtle structural deformation

- **Horst blocks**: Cutter, Victory-Eubank and Pleasant Prairie (faulted on south and west flanks)
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Youle (DOE-CO2)
Shuck Seismic depth-converted Meramec surface
Seismic interpretation by Hedke

Post-Chester sinkhole forms trap

800 ft wide
100 ft deep

1200 ft wide
130 ft deep

VE = 7.5X
CI = 20 ft

VE = 7.5X
CI = 20 ft
Chester IVF deposition not influenced by Ouachita Faulting and structuring

- Sandy estuarine parasequences into unconfined (regional) clay-rich lime mudstones in the Shuck area.
- Identical facies change seen from Shuck to south
- Northern fault influenced Chester IVF deposition, not southern
- Chester constant across southern fault; but over 100’ removed on footwall
- Morrow thickens in headwall
- Southern fault occurred post Chester; north fault may have moved before Chester valley filled
Chester Valley Cross Section: timing of fault movement

A. Datum on top of Notch Shale. No indication of major pre-Chester valley fill movement on fault.
B. Datum on Atoka Limestone marker. ~100' of Chester eroded from up thrown side of fault (section shaded green has been removed). Also, ~100' of Morrow thickening on downthrown side of fault. Ouachita orogeny dated as starting post Chester & pre-Morrow.
C. Present day structural section. 300' of post Atokan movement on fault shows most offset on fault occurred post Atokan. IVF sands shaded yellow.

Insert Map: Hot colors thin BP Lime to MRMC. MRMC Structure - 25'C.I. Faults in white.

East-west profile, Seward County

- Near southern end of Adamson 3D
- Provides more evidence of reverse faulting
- Vertical offset in Meramec is ~200 ft
Isopach
Lower Permian
Hutchinson Salt
to Neva Ls.
(top Pennsylvanian)

NE-trending
regional lineaments
controlling lower
Permian deposition
in SW Kansas
(more northerly
paleo $\sigma_1$?)

25 mi (40 km)

(Gerlach, Nicholson, DOE-CO2)
Shallower structures and surface lineaments
Movement along N-S Chester IVF
NW- and NE-trending deep-seated structures

- Meramec Mississippian structural contours (colors)
- Gray-scale image of Lower Permian Ft. Riley structural curvature (Dubois)
- Surface lineaments (red)

Fault bounded Keys Dome extension of Sierra Grande Uplift

20 mi (32 km)

http://maps.kgs.ku.edu/co2/?pass=project
• Lower Permian evaporite dissolution (~1000-2000 ft below surface)
• Accommodation Space for High Plains aquifer
• Influence of NW- & NE-trending basement structures
• Timing of dissolution 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)
Accommodation space for High Plains Aquifer
- major influence by contemporaneous dissolution of underlying Permian evaporites
Structural reactivation along fractures provide template linear edges of dissolution and drainage

Isopach of Blaine Fm.
- Green/yellow thicker evaporite
- Red dots – wells in Hugoton Field
- note coincidence of dissolution of salt and location of gas field
- gas migrated into Hugoton coinciding regional uplift Sorenson (2005) and evaporite dissolution

Cumulative Gas in Hugoton Field
(Dubois, 2005)
Gas migration from Amarillo-Wichita to create Hugoton Gas Area post-Laramide (Late Tertiary) during regional uplift and tectonic adjustment closely corresponding to timing of salt dissolution.

“Northward migration up the Anadarko shelf yielded most of the oil and gas in Pennsylvanian and Mississippian reservoirs in the Hugoton embayment” – Sorenson (2005)
Notable correlation between surface lineaments and base of High Plains Aquifer Elevation

Surface lineaments

High Plains Aquifer bedrock elevation, 25 ft C.I.

http://maps.kgs.ku.edu/co2/?pass=project
Notable correlation between surface lineaments and elevation of top of the Blaine Formation

**Surface lineaments**
**Top Blaine Formation, 25 ft C.I.**

Blaine Fm./Flower Pot Sh. salt present

375 ft relief

Blaine Fm./Flower Pot Sh. absent

525 ft relief

Structure closely correlates in location and amount of local structural relief along areas of salt dissolution

http://maps.kgs.ku.edu/co2/?pass=project
Notable correlation between surface lineaments and High Plains Isopach

http://maps.kgs.ku.edu/co2/?pass=project
Significant post Laramide uplift in western Kansas during and after deposition of the High Plains Aquifer

"Modern gradients are up to an order of magnitude greater than the paleoslope calculated from preserved gravels in the Miocene-Pliocene Ogallala Formation in the Cheyenne Tablelands" (McMillian et al., 2006)

Relatively recent uplift in the western Great Plains has been significant and could have initiated or at least renewed evaporite dissolution, SW Kansas Arkansas River evaporite dissolution basin.

Timing of dissolution fronts for Permian evaporites in western Kansas appear to be late Miocene and younger. Lithofacies and thickness patterns in Ogallala and configuration of the bedrock and surface all support late evaporite dissolution.
A sinkhole, which is 200 to 300 feet wide, was discovered last week in a pasture ~ 8.5 mi N & 1.5 mi W of Wallace, Wallace County, Kansas

Read more here:
http://www.kansas.com/2013/08/06/2928066/large-sinkhole-draws-curious-to.html#storylink=cpy
August 2013 Wallace County Sinkhole near other prominent sinkholes along headwaters of the Smoky Hill River.
Rotated blocks of Niobrara Chalk are common along exposures along Smoky Hill River in Logan and Thomas counties.
Potentiometric surface of brine in Permian strata is ~1650 ft below the land surface in the vicinity of the sinkhole.

from Nelson and Gianoutsos, 2011, USGS OFR 2011-1245

- Difference between the potentiometric surface of fluids in the Permian and the shallow aquifers provides a potential for downward flow, if communication is established.

- Extensional fractures during regional post Laramide (Late Tertiary) uplift is believed to have led to extensive dissolution of Permian halite beds in western Kansas.

- Headwaters of the Smokey Hill River appear to be site of incipient dissolution of Flower Pot/Blaine salt.

- Paleocavity collapse & paleodisturbed bedding and rotated blocks of Niobrara Chalk along river.
Blaine/Flowerpot halite isopach suggests dissolution of salt on the west side in Wallace County

Isopach of Halite-Bearing Flower-Pot Shale below Blaine Formation In Northwest Kansas

Harold #1 salt is absent

Sinkhole

Thinning of Blaine salt in Wallace county
"Structural relief" related to both actual structure and salt dissolution in western Wallace County.

410 ft of relief on the top of Blaine
220 ft of relief on the top of Stone Corral Fm.
Summary & Conclusions

- **Anadarko Basin** – Proterozoic extension to Phanerozoic compression from rift basins to horst & graben system
- **Hugoton Embayment (HE)** – 10,000 km² 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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