[PS]Polygonal Fault Systems: A New Structural Style for the Niobrara Formation, Denver Basin, CO*

Stephen A. Sonnenberg[1] and David Underwood[2]

Search and Discovery Article #50624 (2012)**
Posted June 25, 2012

*Adapted from poster presentation at AAPG Annual Convention and Exhibition, Long Beach, California, April 22-25, 2012

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Abstract

Polygonal fault systems (PFS) are present in the Niobrara Formation of the Denver Basin. This type of fault system is recognized primarily on 3D seismic.

The PFS is detached from basement faults and occurs in distinct layer-bounded systems (Niobrara and lower Pierre Shale). The faults are minor extensional faults, randomly oriented and form polygonal networks in map view. Faults dip 30 to 80 degrees; have throws of 30 to 70 ft; and lengths of generally less than 4000 ft.

The polygonal fault system deforms the Niobrara over a large part of the Denver Basin. Relatively undeformed sequences occur above and below the Niobrara faulted interval. This type of fault structure may also be present in other Rocky Mountain basins.

An additional and separate PFS zone is seen towards the base of the Larimer-Rocky Ridge Member of the Pierre Shale.

The faults are similar to ones reported in North Sea shale sequences. PFS are thought to represent volumetric contraction resulting from compaction-driven fluid expulsion. PFS are probably common features in thick shale sequences in sedimentary basins.

Layer-bounded faults in the Niobrara and Pierre have previously been interpreted as listric faults. The new interpretation does not support the listric interpretation. This new interpretation explains the random orientation of the faults which previously was not explained. Recognition of this structural style is important for future wells targeting the Niobrara petroleum system.

Other types of fault systems also occur in the Cretaceous section of the Denver basin.

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Colorado School of Mines

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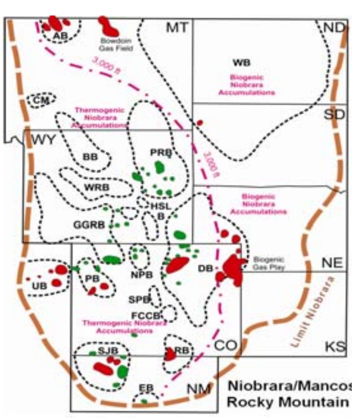


Niobrara/Mancos Fields Rocky Mountain Region

Fracture Related Fields

Florence Cañon City (Pierre Shale)
- 1881
- 15.3 MMBO

Boulder (Pierre Shale)
- 1901
- 1 MMBO

Rangely (Mancos)
- 1902
- 11.7 MMBO, 12.2 BCF

Salt Creek
- 1907
- "Upper shale" Cretaceous

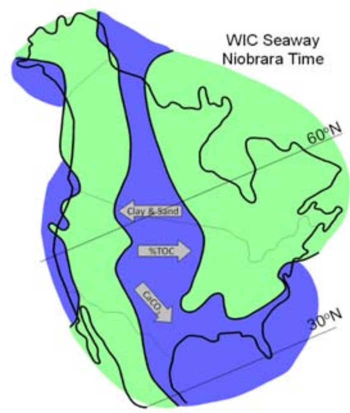
Tow Creek (Niobrara)
- 1924
- 3 MMBO; 0.3 BCF

Buck Peak (Mancos, Nio)
- 1956
- 4.7 MMBO; 8.2 BCF

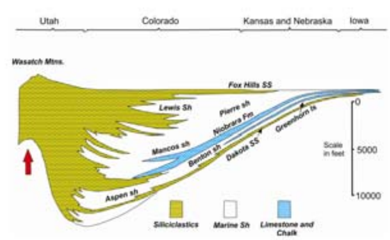
Puerto Chiquito (Mancos/Nio)
- 1960
- 18.7 MMBO; 52 BCF

Wattenberg (Nio, Codell)
- 1970
- 86 MMBO, 1.1 Tcf

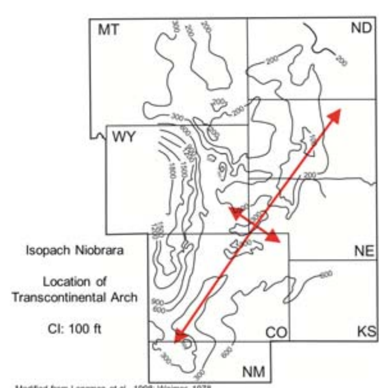
Silo (Niobrara)
- 1981
- 10.4 MMBO; 8.2 BCF



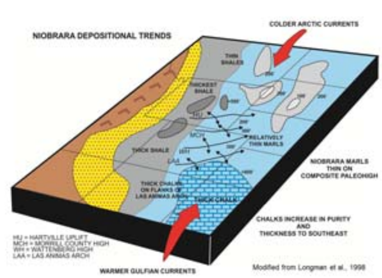
Modified from Longman et al., 1998



Cretaceous Cross Section, Western Interior Basin
Modified from Kauffman, 1977

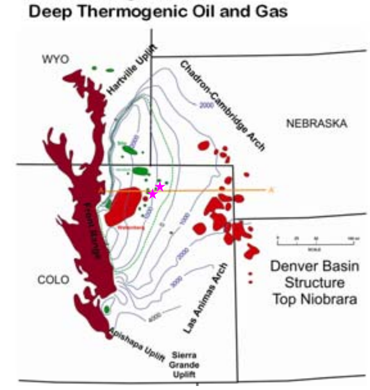


Isopach map of total Niobrara Formation, Rocky Mountain Region.

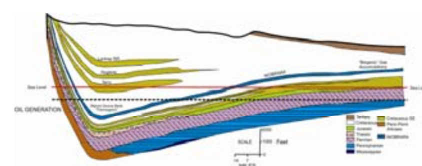


Niobrara facies map, Western Interior Cretaceous Basin.

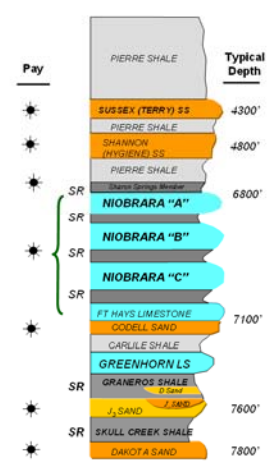
Niobrara Petroleum System - Denver Basin
Shallow Biogenic Gas
Deep Thermogenic Oil and Gas



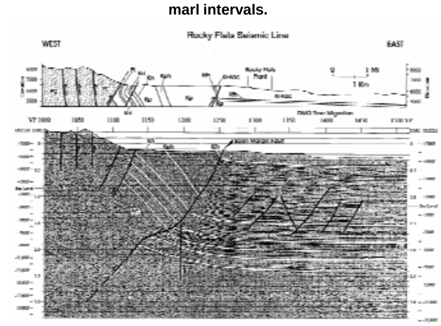
Structure map Niobrara Fm. Denver Basin, stars show location of Bunting and Sooner 3-D surveys.



Diagrammatic cross section Denver Basin. Niobrara is in the oil maturity window in the basin center.



Cretaceous Stratigraphic column, Denver Basin, Niobrara consists of four chalks and three marl intervals.



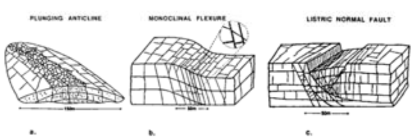
Rocky Flats Seismic Line, Western Denver Basin
Note: Reverse faults east of basin margin fault

Niobrara Fault Systems, Previous Interpretations

Origin of Fractures

- **Folding and Faulting**
  - Tectonic, diapiric, slumping
  - Wrench faults
- **Geologic History of Fractures**
  - Recurrent movement on basement shear zones
- **Solution of Evaporites**
- **High Fluid Pressure**
  - Maturation of source rocks
- **Polygonal Fault Systems (PFS)**
- **Regional Stress Field**
- **Regional Epeirogenic Uplift**

Structures and Associated Fractures

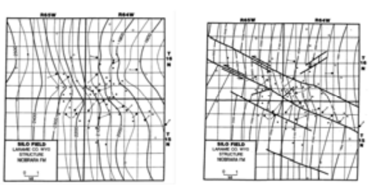


From Austin Chalk Outcrops

Friedman et al., 1992

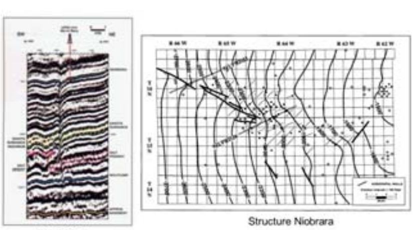
Structural models for fracture development from Austin Chalk.

Structure Top Niobrara



Sonnenberg and Weimer, 1993

Basement wrench fault model for Silo Field.

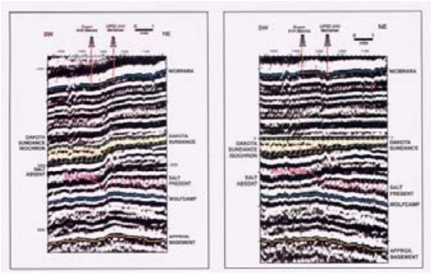


91UPRDJ3

Structure Niobrara

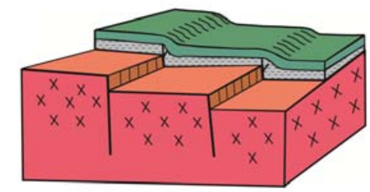
Svoboda, 1995

Basement faults influencing structure at Silo Field; basement faults also control salt dissolution edge and fracturing in Niobrara.

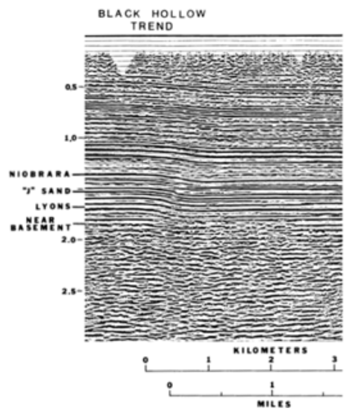


Seismic illustrating timing of salt dissolution, Silo Field. Dissolution is interpreted to be Upper Jurassic and Lower Cretaceous.

Force Folds, Faults, and Fractures



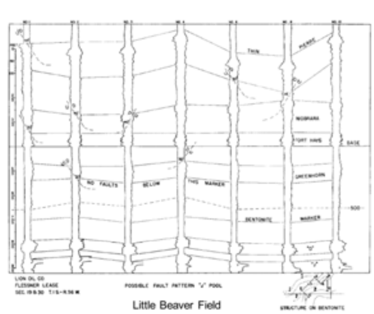
Force (drape) folds over basement fault systems. Fracturing is expected where radius of curvature is the greatest.



Seismic line over Black Hollow Field showing fold over basement fault system (from Stone, 1985).

Detached Niobrara Faults

- Recognized early by many workers
- Normal faults
  - Interpreted as Listric
  - Interpreted as Slump faults
  - Low to high angle normal faults
- Polygonal Fault Systems (NEW)

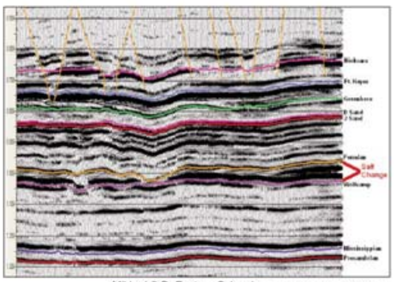


Little Beaver Field

Fentress, 1955

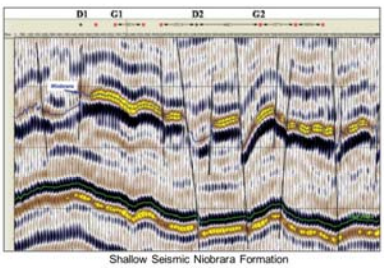
Examples of Niobrara faults in Little Beaver Field. Note faults do not extend below upper Greenhorn.

Examples of Detached Faults
Niobrara Formation



Mildred 3-D, Eastern Colorado (Sigume and Estes-Jackson, 2011)

Eastern Colorado shallow biogenic gas play.

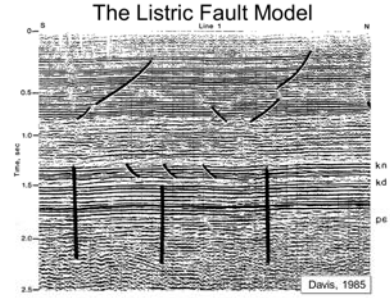


Shallow Seismic Niobrara Formation

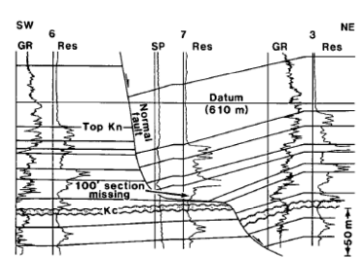
Kelso et al., 2006

Eastern Colorado shallow biogenic gas play.
Note seismic bright spots.

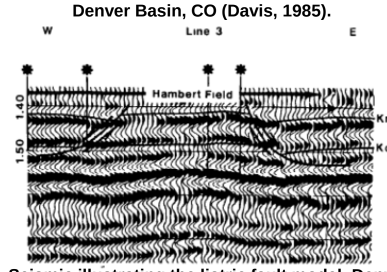
The Listric Fault Model



Basement faults and detached faults, Denver Basin.



Cross section illustrating the listric fault model, Denver Basin, CO (Davis, 1985).

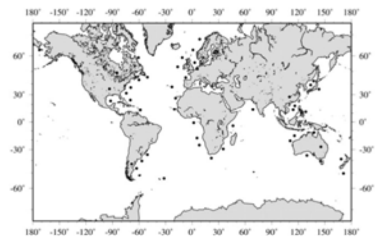


Seismic illustrating the listric fault model, Denver Basin, CO (Davis, 1985).

Polygonal Fault Systems

Polygonal Fault Systems (PFS)

- Layer-bounded fault systems
- Small extension faults
  - 10-50 m throw
  - Faults dip 30 to 70º
    - Compactional flattening with depth
- Random oriented fault patterns



Areas where PFS have been identified.

PFS

- Form early in burial history
- Pervasively deformed fine-grained sediments
  - claystones and biogenic mudstones: carbonate and biosiliceous
  - Hemipelagics
- Shear fractures and normal faults aggregate into networks which are polygonal planforms
- Non-tectonic in origin
- Recognized in over 100 basins

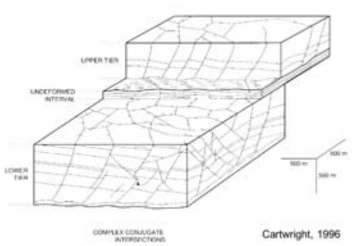


Diagram illustrating two tiers of polygonal faults. Note the polygonal shape in planform.

Polygonal Fault Systems

- Volumetric contraction resulting from compaction-driven fluid expulsion
- Compaction dewatering occurs at shallow depth
- Vertical effective stress exceeds horizontal effective stress and inclined fractures result
- Stress state in plane in which polygons are developed is either isotropic or close to isotropic

PFS
The Origin Debate

- Non-tectonic nature of deformation and its relationship to early dewatering recognized

- Gravity collapse
- Density inversion
- Compactional loading
- Syneresis
- Diagenetically-induced shear failure

Cartwright et al., 2003; Cartwright, 2011

Diagrams illustrating compaction of fine grained sediment with depth. Most porosity loss is early.

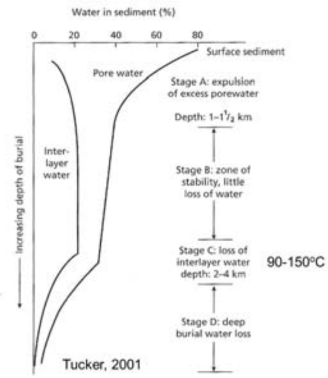


Diagram illustrating compaction & loss of water in fine-grained sediments with depth. Note early water loss or compaction.

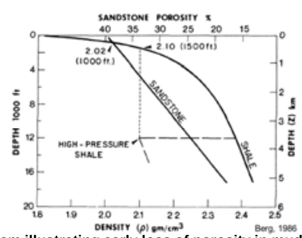
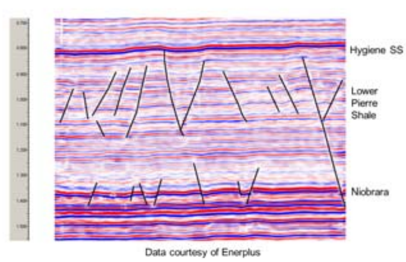
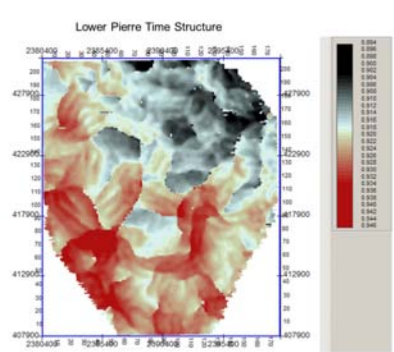


Diagram illustrating early loss of porosity in mud rock intervals (expulsion of pore water and compaction).

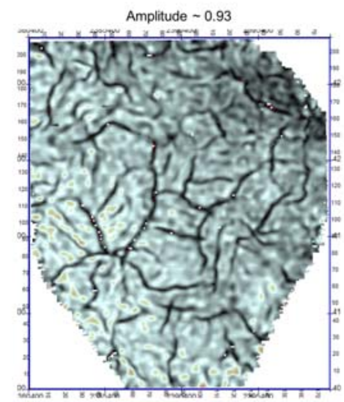
North Bunting 3-D
T6N-R60W
16 square miles
1998
Data provided by Enerplus



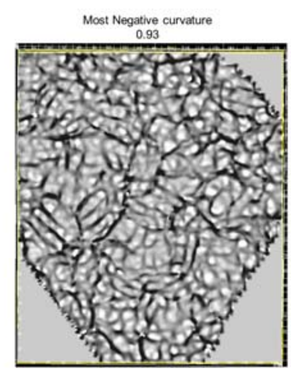
Seismic line, Bunting survey, showing two tiers of normal faults.



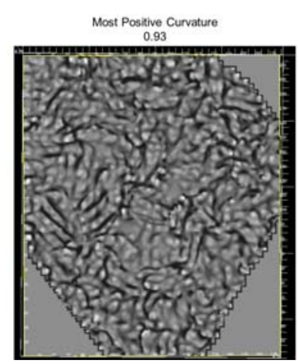
Lower Pierre Shale time structure. Note polygonal shapes.



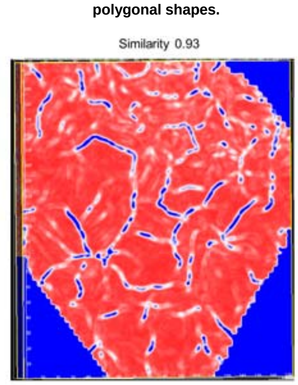
Lower Pierre Shale amplitude map. Note polygonal shapes.



Lower Pierre Shale most negative curvature attribute. Note polygonal shapes.

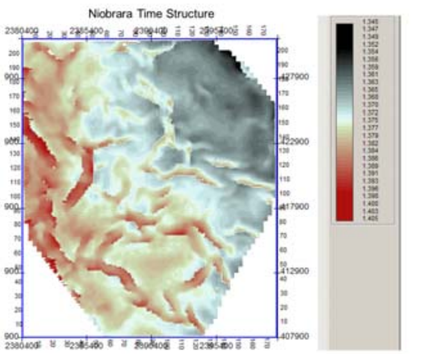


Lower Pierre Shale most positive curvature attribute. Note polygonal shapes.

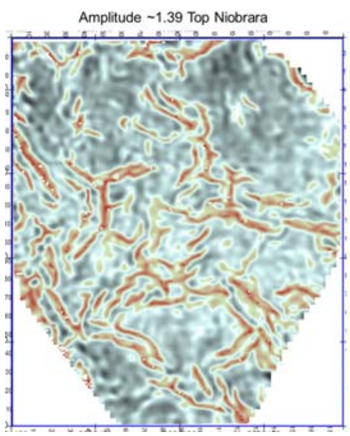


Lower Pierre Shale similarity attribute. Note polygonal shapes.

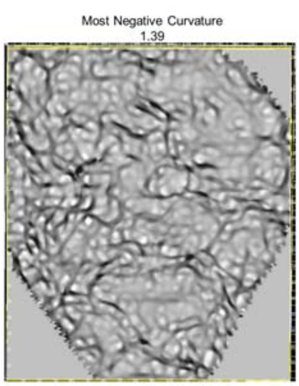
Polygonal Fault Systems



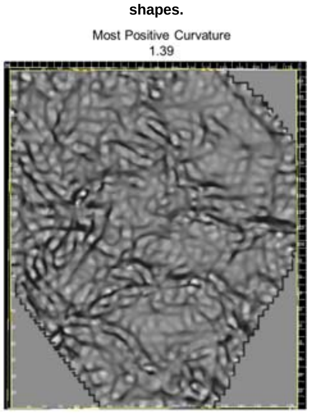
Niobrara time structure, note polygonal shapes.



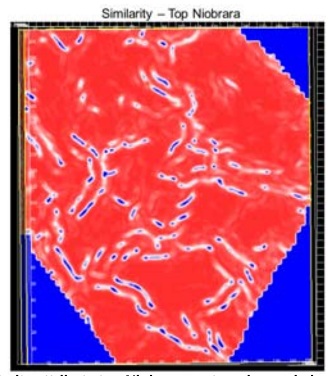
Niobrara amplitude map, note polygonal shapes.



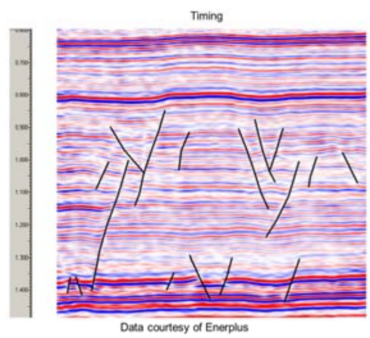
Most negative curvature top Niobrara, note polygonal shapes.



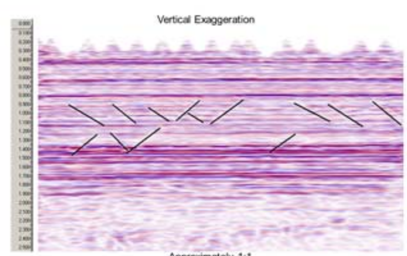
Most positive curvature top Niobrara, note polygonal shapes.



Similarity attribute top Niobrara, note polygonal shapes.

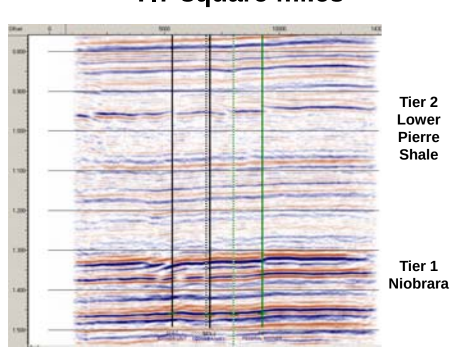


Analysis of timing of the faults suggests early origin.



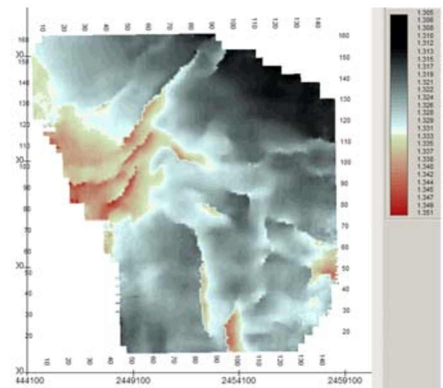
Seismic line with no vertical exaggeration. Note orientation of faults is approximately 45º.

Sooner 3-D
DOE Study
D SS Reservoir
1992
7.7 square miles



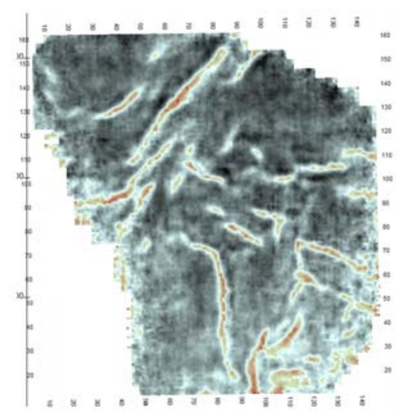
Seismic line, Sooner Survey. Two tiers of normal faulting are present.

Niobrara Time Structure
Sooner Survey



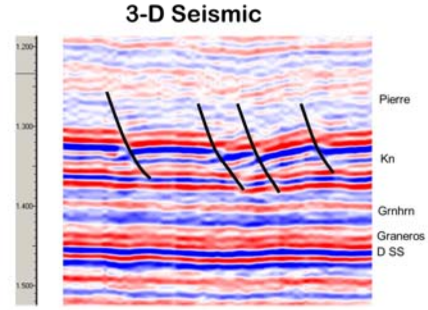
Niobrara time structure map, Sooner Survey. Note partial polygonal shapes.

Niobrara Amplitude
Sooner Field



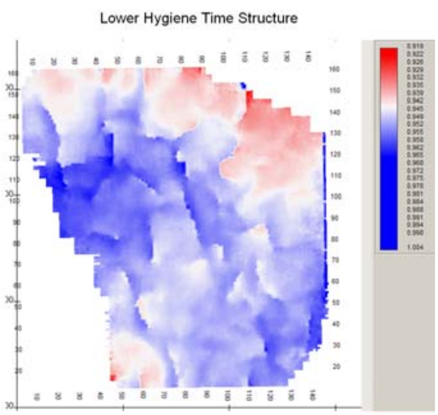
Niobrara amplitude map, Sooner Survey. Note partial polygonal shapes.

3-D Seismic

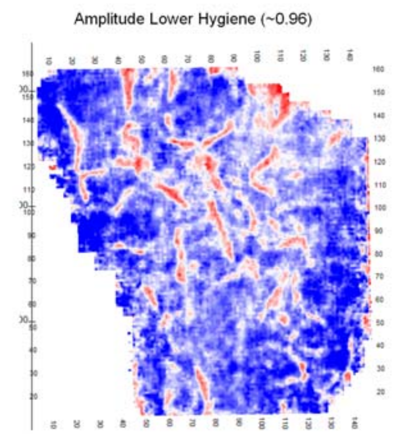


Seismic line, Sooner survey, showing normal faults at Niobrara level. Faults do not extend below Greenhorn.

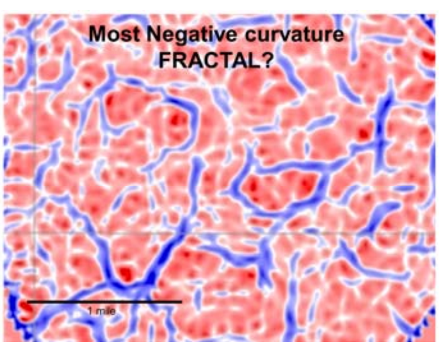
Polygonal Fault Systems



Lower Hygiene time structure. Note polygonal shapes.

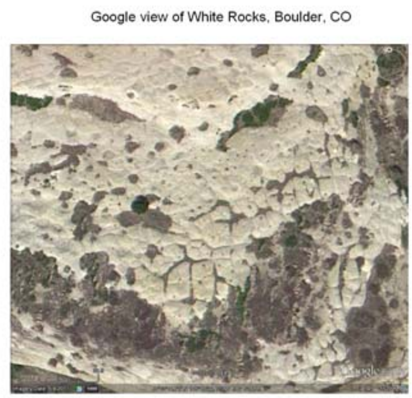


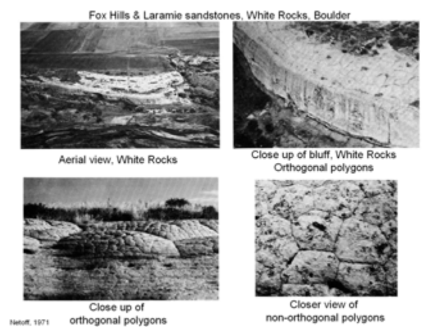
Lower Hygiene amplitude map. Note polygonal shapes.

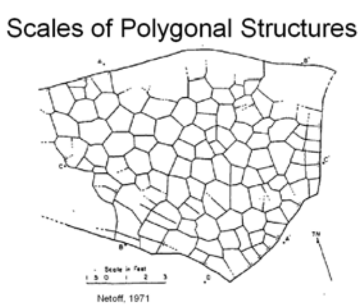


Most negative curvature through lower Pierre Shale time slice. Note the presence of smaller polygons within the larger polygons.

Polygonal weathering fractures, Fox Hills Sandstone, Boulder, CO. Two or more scales of polygons are present.







Summary

- Two layer bounded polygonal fault systems are recognized in Denver Basin
  - 1) Below Hygiene Sandstones
  - 2) Niobrara Formation
- PFS common in fine grained systems (shales and chalks)
- Most faults are NOT listric but low angle

- Basement faults still important
- Permian salt dissolution creates faults
- Compactional features over D SS

Discussion Points

- Impact of deeper structures on polygons
- Impact of salt dissolution on polygons
- Impact of regional uplift on polygons
- Horizontal Stress field – isotropic?
- Hydrocarbon migration
- Scales of polygons
- Partial polygons

Acknowledgements

- Enerplus: North Bunting 3-D data
- Anadarko: Silo 2-D data
- IHS-SMT-Kingdom
- IHS-Petra
- CSM Niobrara Consortium

Colorado School of Mines Niobrara Consortium

HRM Resources, LLC

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