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Interpretation of the Great Plains Polygonal Fault

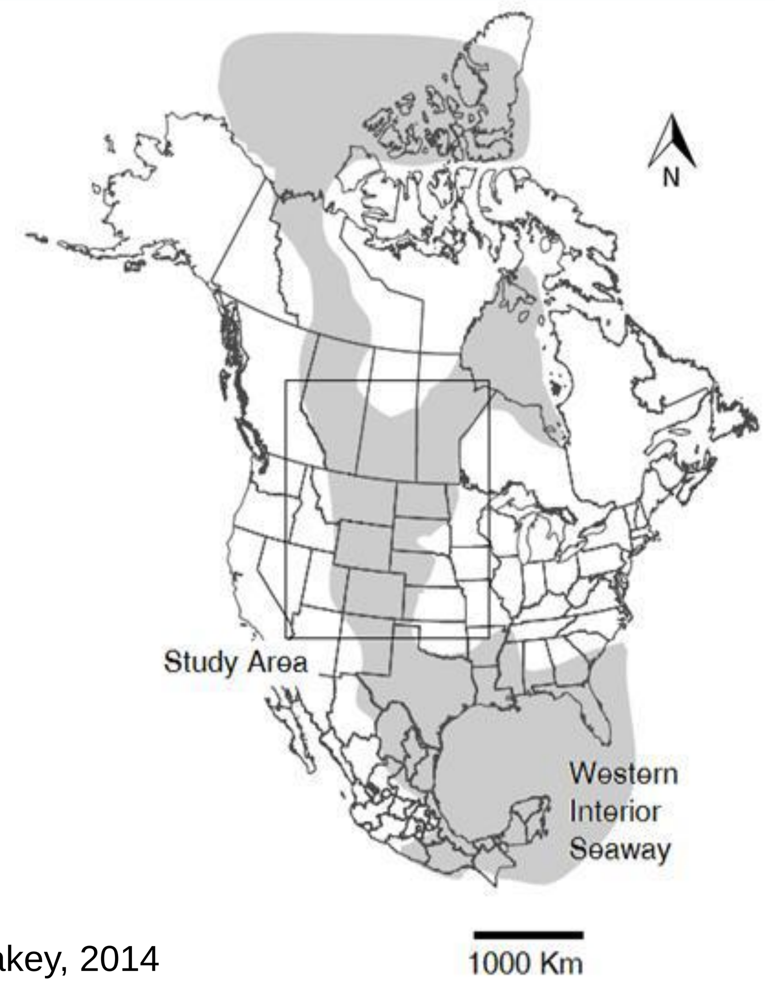
Andy St-Onge, Calgary geophysicist@shaw.ca

(i) Summary.

Fine-grained Cretaceous sediments of the Western Interior Seaway of North America host a previously unreported polygonal fault system (PFS). The Great Plains PFS (GPPFS) is an expansive network of fractures and faults that could be the Earth's largest PFS. Interpretation of seismic data in the Pierre Shale depositional area has identified faulted strata with a polygonal planform geometry of aggregated fault traces indicative of PFS.

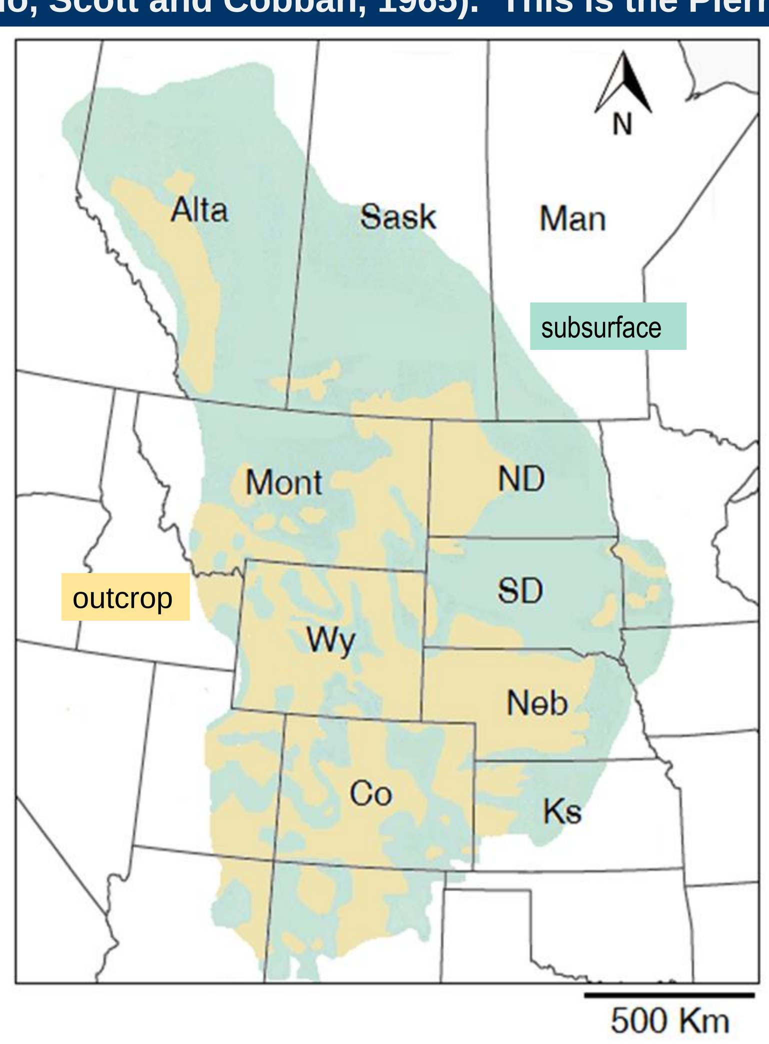
A 3-D seismic dataset from Alida, Saskatchewan provides some insight into fault timing and geometry for the GPPFS. Here, faulting in the GPPFS appears to have occurred in two stages. The lower tier is Coniacian to Campanian, has a base at ~25 m ASL, with larger faults having average throws of ~10-15 m and a fault density of ~10 faults/mile^2. This tier forms a series of grabens at the top, suggesting Middle Campanian local or regional extension. The upper PFS tier (Upper Campanian) has similar fault throws and areal densities, but the faults are longer in length and the predominant strike azimuth changes. Also, the upper PFS tier has developed into tilted fault blocks that increase in offset up to the base of the Tertiary at 500 m ASL, ~100 m below surface. The data presented here are representative of seismic data, surface geology, landslides, and well control that could be the GPPFS could be >2,000,000 Km^2 in area. The geotechnical engineering implications are numerous where the PFS is at outcrop or near outcrop.

1) Start ~ 100 MA (Cenomanian) and deposit siliciclastics in the Western Interior Seaway.



From Blakey, 2014

2) From the Cenomanian to the Maastrichtian, siliciclastics were deposited over ~2.6 million Km^2, up to 2,400 m thick (at Boulder, Colorado, Scott and Cobban, 1965). This is the Pierre Shale.



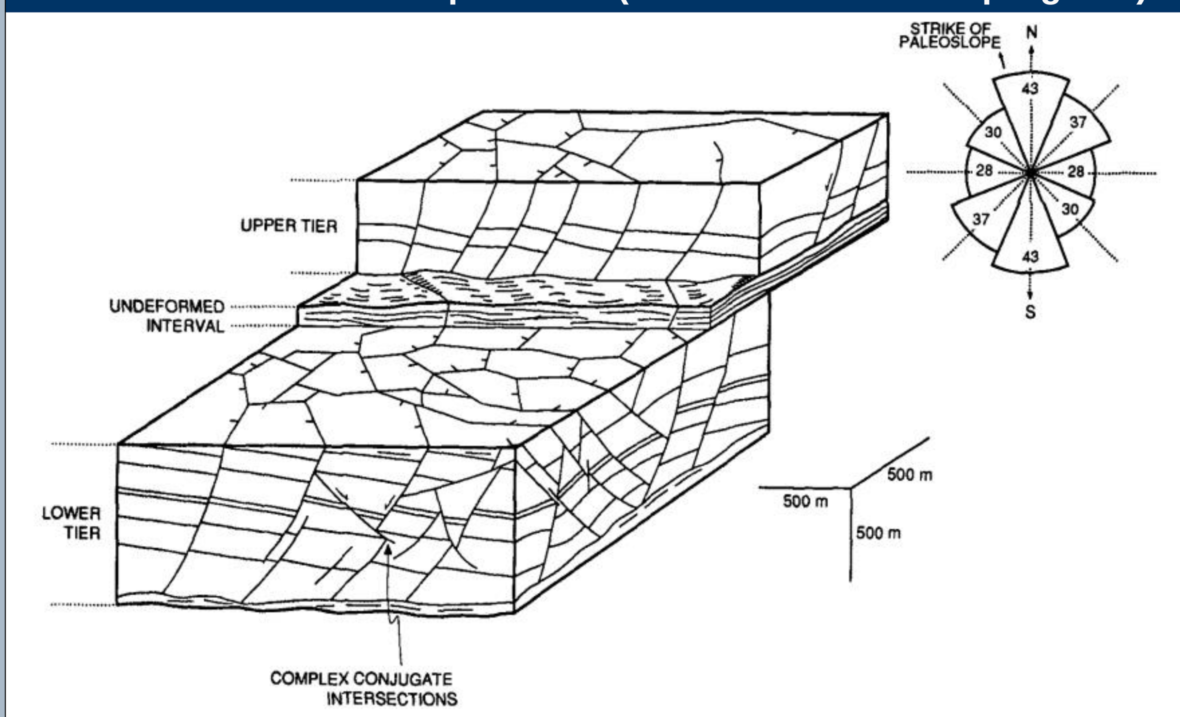
This entire area could host a polygonal fault system. (from Roberts and Kirschbaum, 1995)

3) Use Age names over the large area:

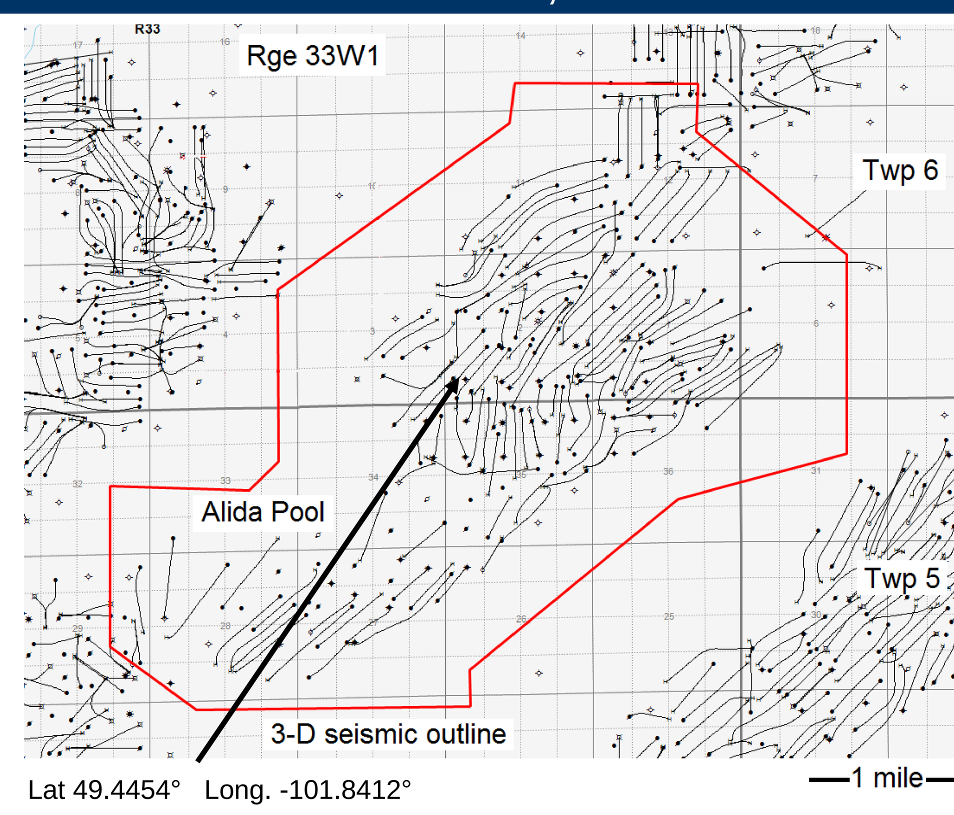
Period			Formation	Age	Picks	Elevation at Alida	Comments
						600 m	flat surface topography
Quat			Glacial Drift	Pleistocene	2.6 Ma	550	water wells (www.wsask.ca)
Tert			Ravenscrag	Paleocene	65		
Late Cretaceous			Eastend	Maastrichtian	72.1	500	borehole imaging
Late Cretaceous	Pierre Shale	Bearpaw	Demaine	Campanian	74.7	380	upper PFS tier
Late Cretaceous	Pierre Shale	Bearpaw	Sherrard				
Late Cretaceous	Pierre Shale	Bearpaw	Matador			275	
Late Cretaceous	Pierre Shale	Bearpaw	Broderick				
Late Cretaceous	Pierre Shale	Bearpaw	Outlook			200	seismic data imaging
Late Cretaceous	Pierre Shale		Lea Park		79? 83.6	150	lower PFS tier
Late Cretaceous	Colorado Group	Niobrara	Niobrara	Santonian	86.3	75	
Late Cretaceous	Colorado Group	Niobrara	Govenlock	Coniacian	89.8	25	
Late Cretaceous	Colorado Group		Carlisle	Turonian			
Late Cretaceous	Colorado Group		Morden				
Late Cretaceous	Colorado Group		2WS		93.9	-50	
Late Cretaceous	Colorado Group		Belle Fourche	Cenomanian			
Late Cretaceous	Colorado Group		Fish Scales		100		

Tops here are correlated to Christopher and Yurkowski (2004)

4) After deposition, the subaqueous muds underwent normal faulting. Cartwright (1994) and others have researched this topic; the cause of the faulting is still being discussed. The work here is focused on the GPPFS presence (the cause is work in progress).

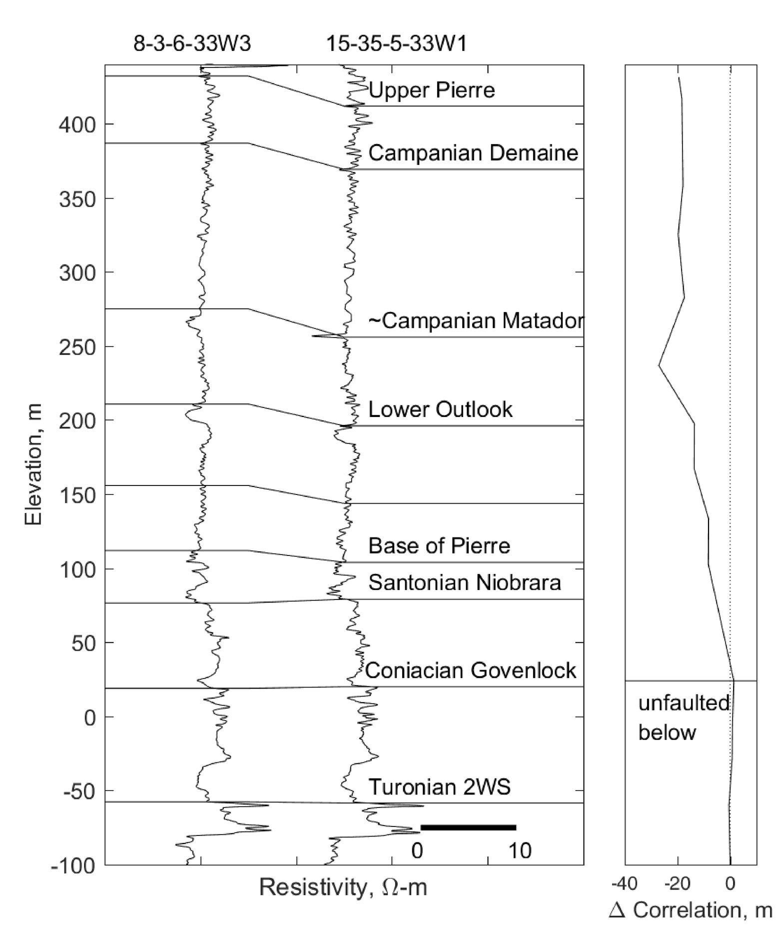


5) Let's examine the results of this phenomenon at Alida, Saskatchewan. The Alida pool is ~830 miles northeast of Denver. It has a 3-D seismic volume, as outlined in red:



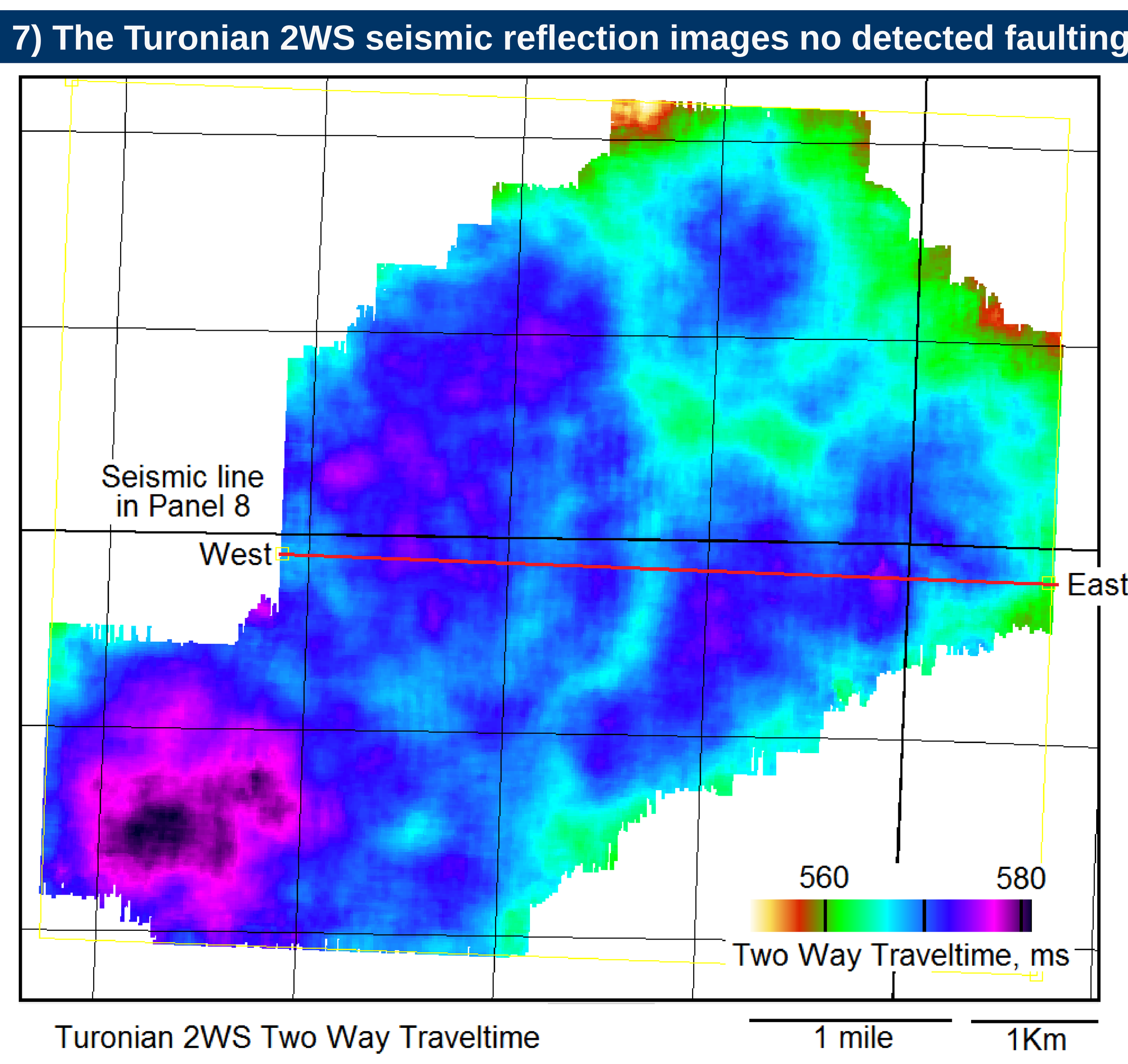
- Mississippian age grainstone shoals at ~1200 m have produced 31 MM BOE from 164 producing wells since 1954.
- 3-D seismic dataset acquired in 1995 to image the Mississippian beds. The 350 m source line interval, 235 m receiver line interval and 25 m bin size resulted in low fold at depths < 500 m.
- The Mississippian reservoir is unassociated with any process presented here.

6) At Alida, the Pierre shale is ~ 400 m thick.

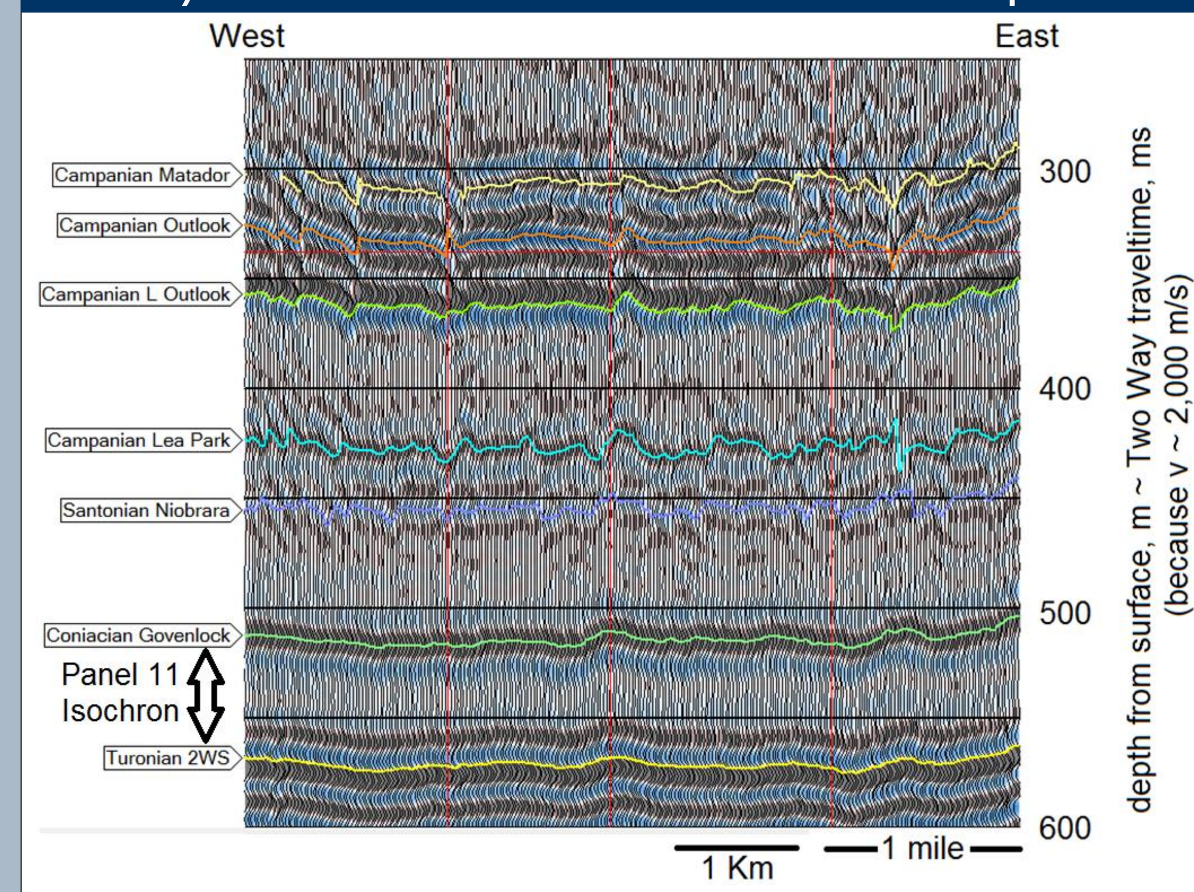


- At Alida, the Upper Pierre is overlain by ~100m of Tertiary and glacial strata above 500 m above sea level (ASL).
- Note the faulted Pierre strata in the simple cross-section.

7) The Turonian 2WS seismic reflection images no detected faulting.



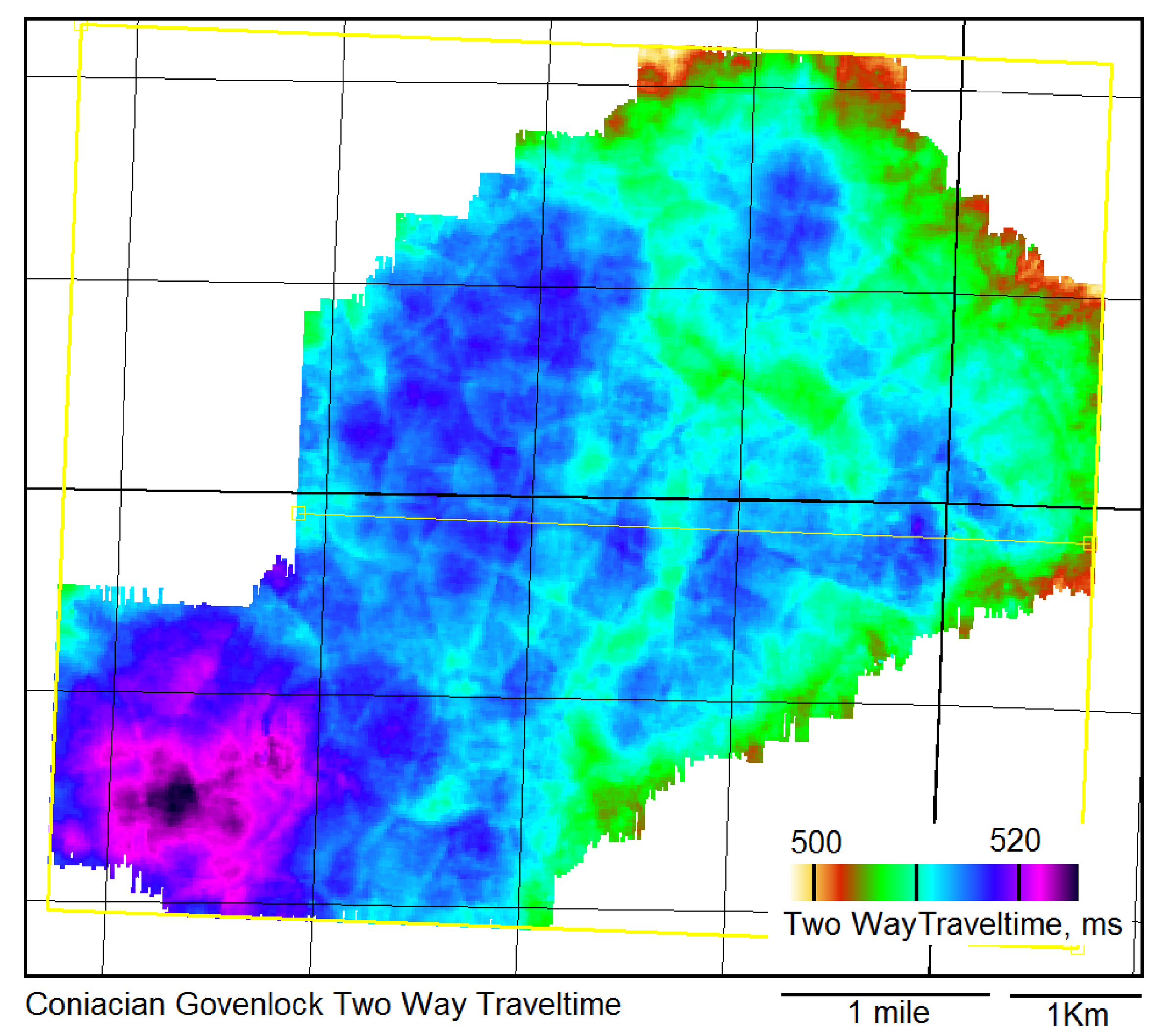
8) West to east seismic line from ~250 – 600 m depth:



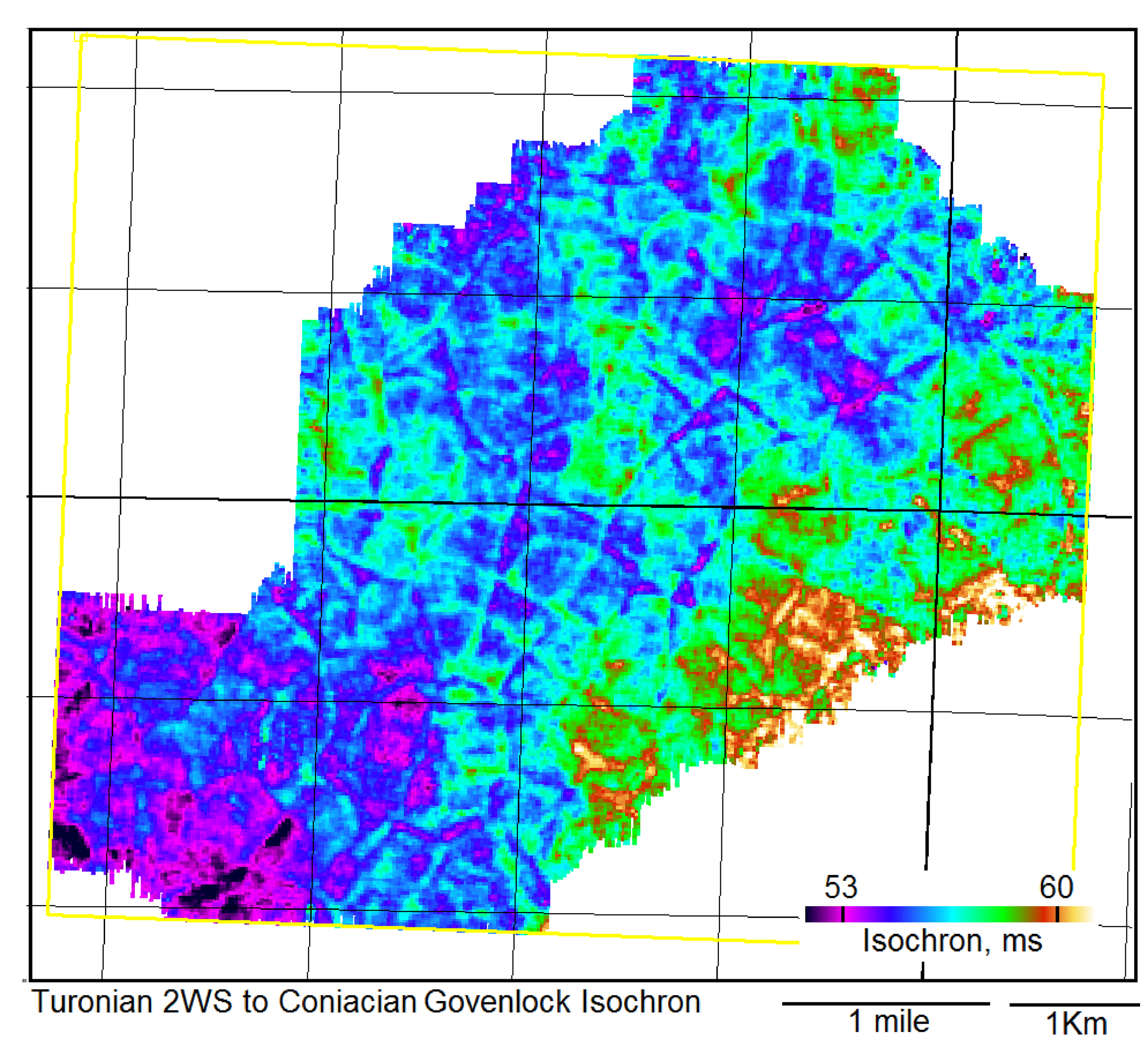
9) Summary so far:

- The Turonian 2WS two way traveltime map shows a southwest to northeast structural rise consistent with regional dip without faulting.
- The west to east seismic line images faults above the Turonian 2WS.
- Consider the Coniacian Govenlock Two Way Traveltime map, the next shallowest reflection above the Turonian 2WS.

10) The Coniacian Govenlock Two Way Traveltime.



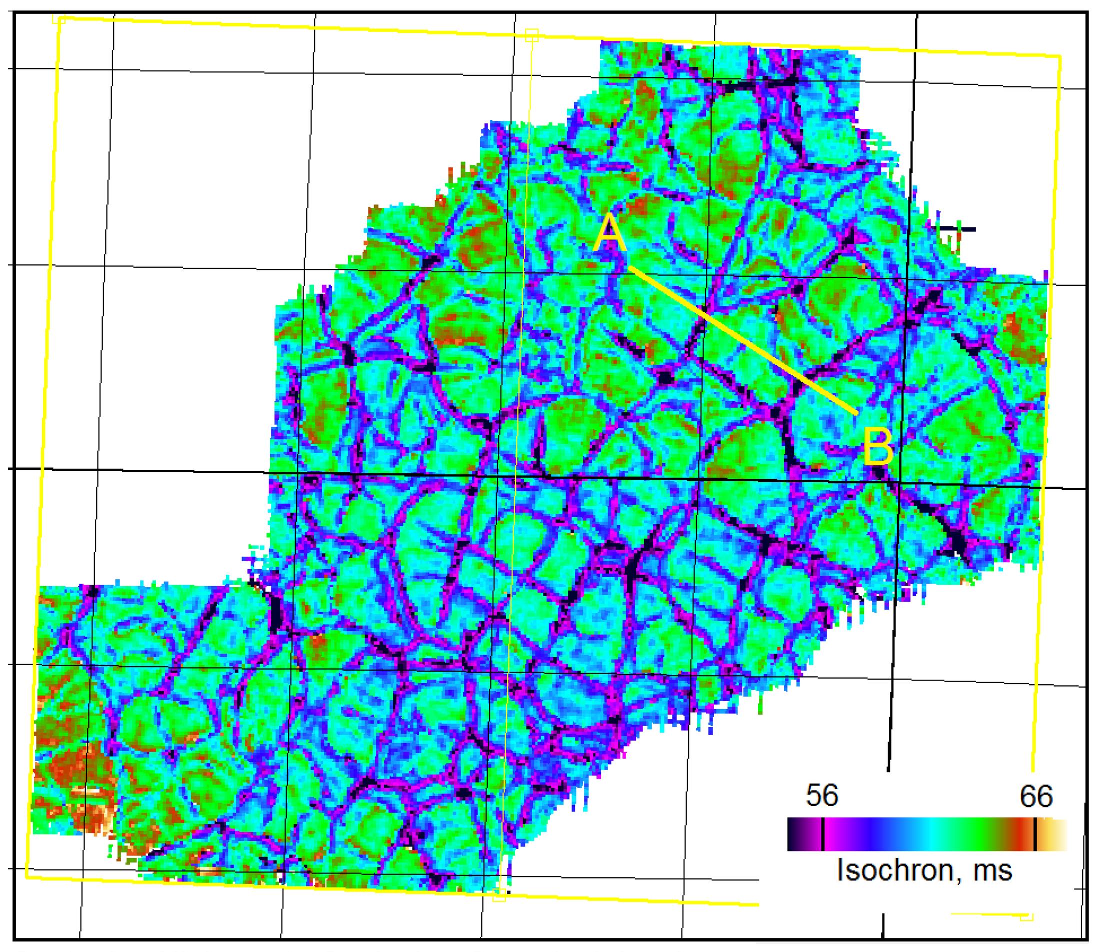
11) Coniacian Govenlock to 2WS Isochron (time difference).



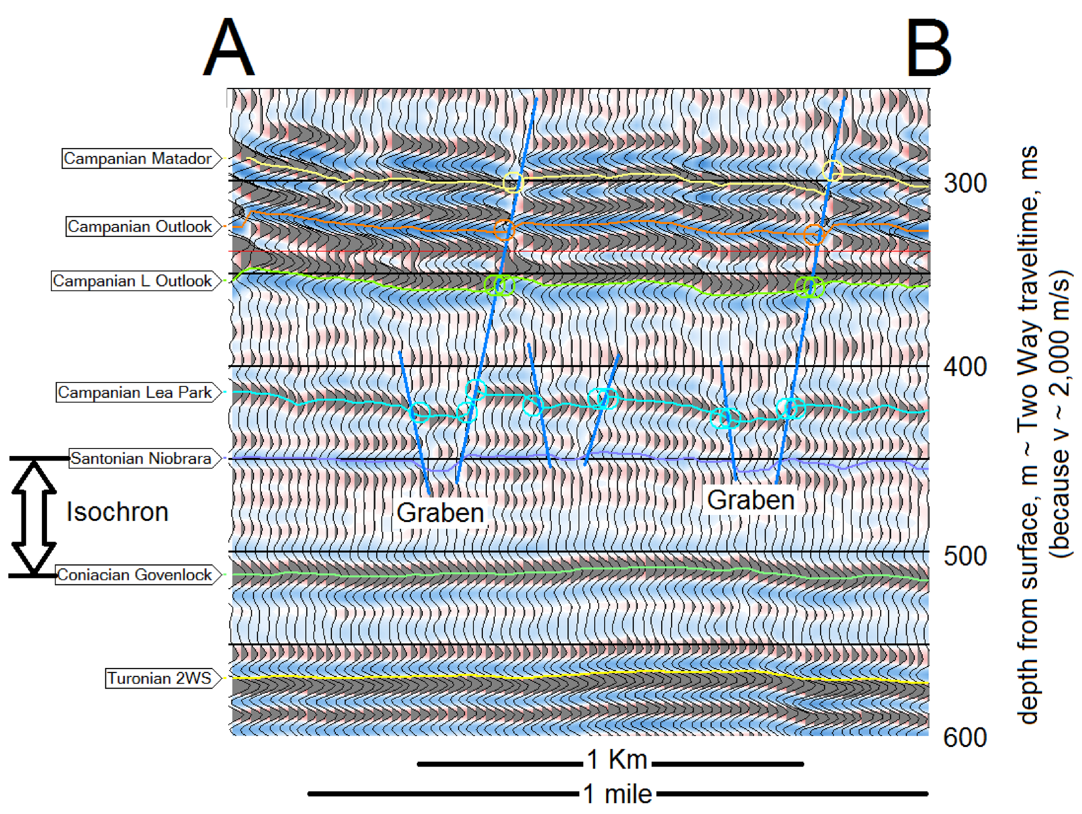
- This map shows Upper Cretaceous fault traces as local isochron thins.
- The isochron map shows minor variations in traveltimes that are lost in the dynamic range of the two way traveltime maps in panels 7 and 10.
- The next adjacent and shallower traveltime interval is the Santonian Niobrara to Coniacian Govenlock Isochron.

System at Alida, Saskatchewan

12) Santonian Niobrara to Coniacian Govenlock Isochron (time difference).

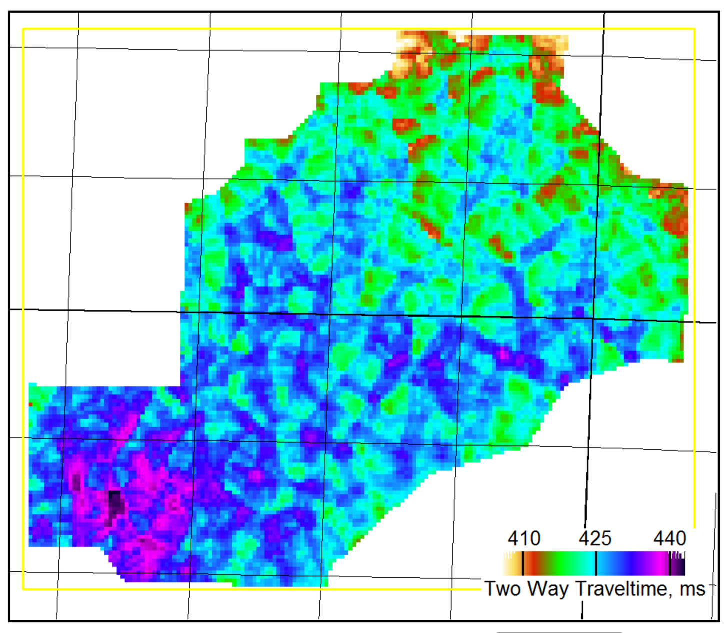


Santonian Niobrara to Coniacian Govenlock Isochron 1 mile 1Km



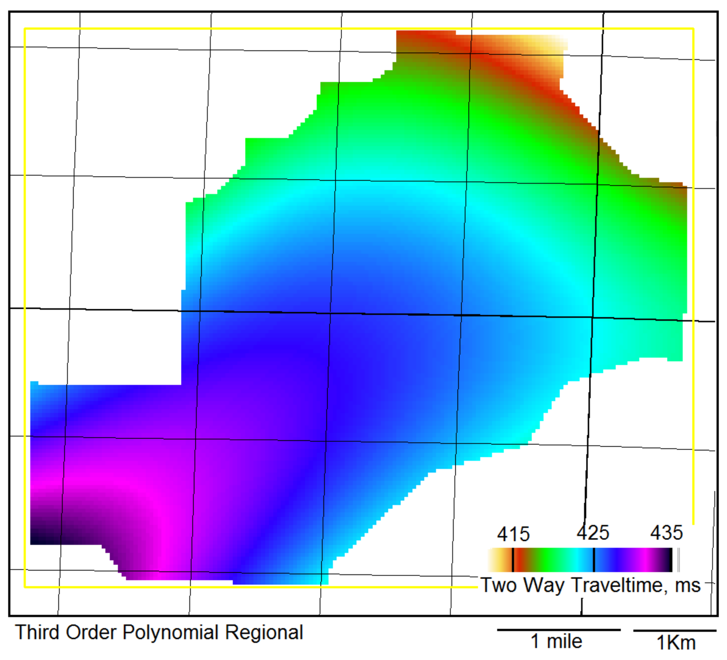
The map and seismic line show the Santonian reflection. Numerous grabens occur after Campanian Lea Park but before the Campanian L Outlook reflection. This is confirmed by well control.

13) a, b, c Three maps show how we can compute a residual map for the Campanian Lea Park to estimate the graben geometries.

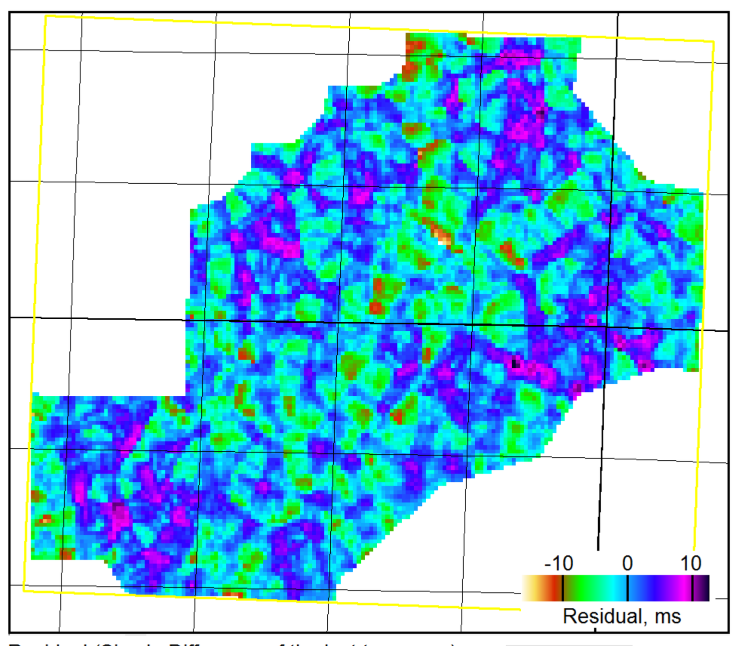


Campanian Lea Park Two Way Traveltime 1 mile 1Km

The regional map is defined as the least squares fit of a cubic surface to the Lea park Two Way Traveltime map above.



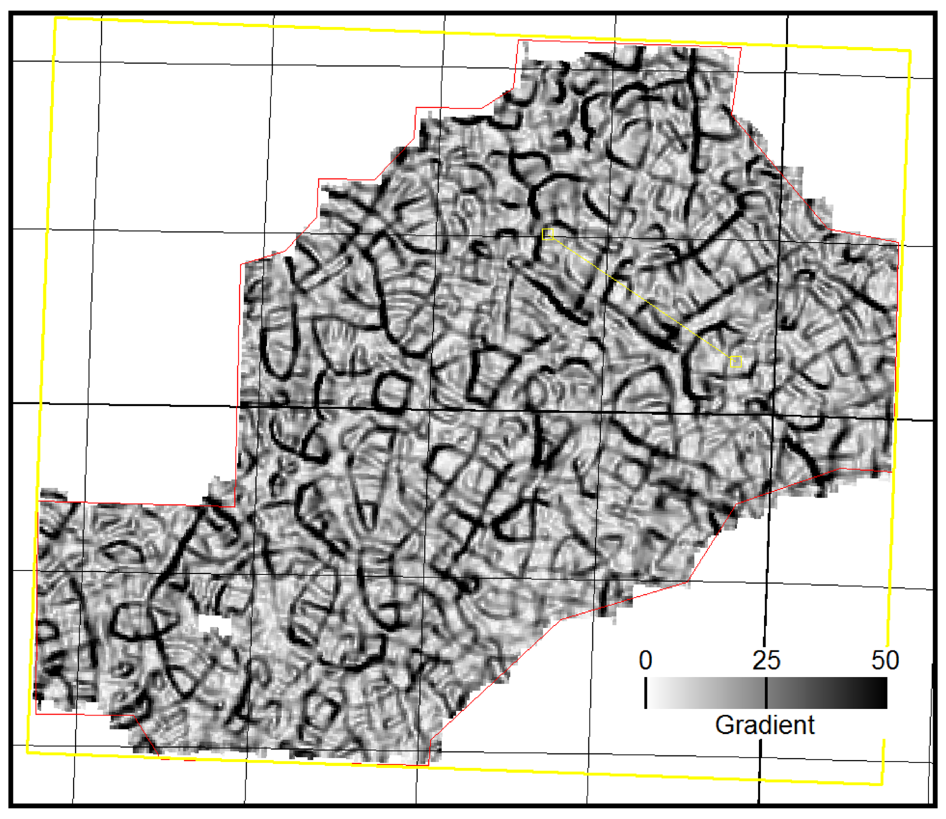
Third Order Polynomial Regional 1 mile 1Km



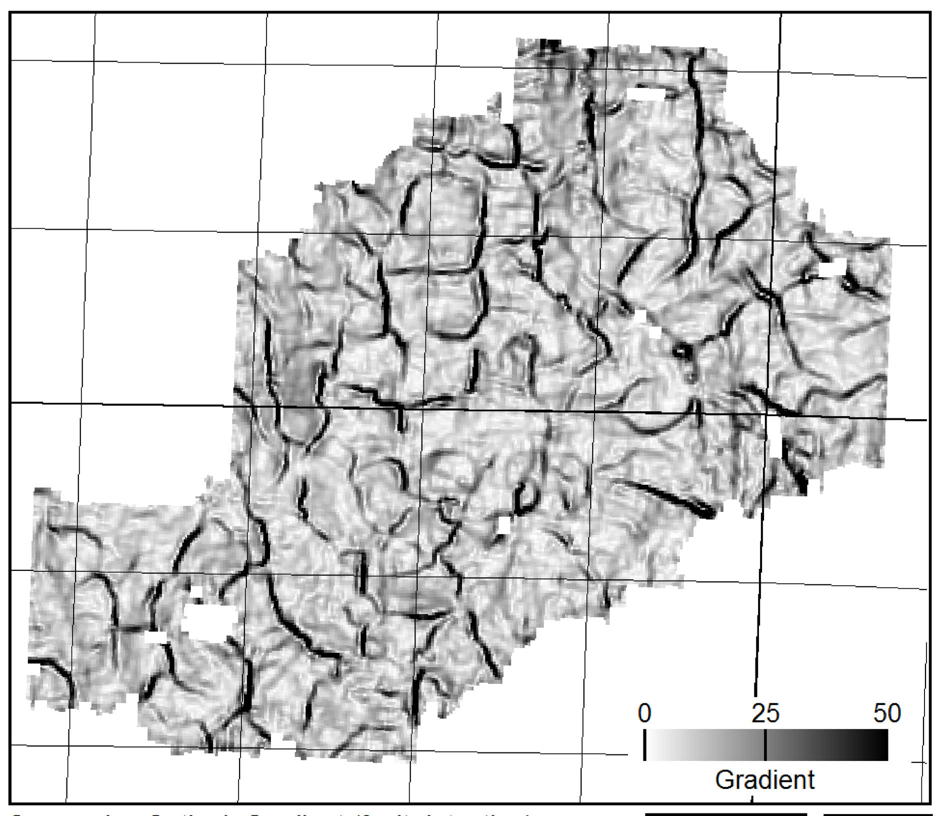
Residual (Simple Difference of the last two maps) 1 mile 1Km

This map is a difference of the upper two maps. The Campanian grabens are ~200 m wide, 800 m long and ~10-15 m deep with almost random strike directions.

14) Another way to characterize the faulting is to display horizon gradient maps. Observe the difference between the Campanian Lea Park gradient map and the shallowest continuous horizon, namely the Campanian Outlook.



Campanian Lea Park Gradient (fault detection) 1 mile 1Km



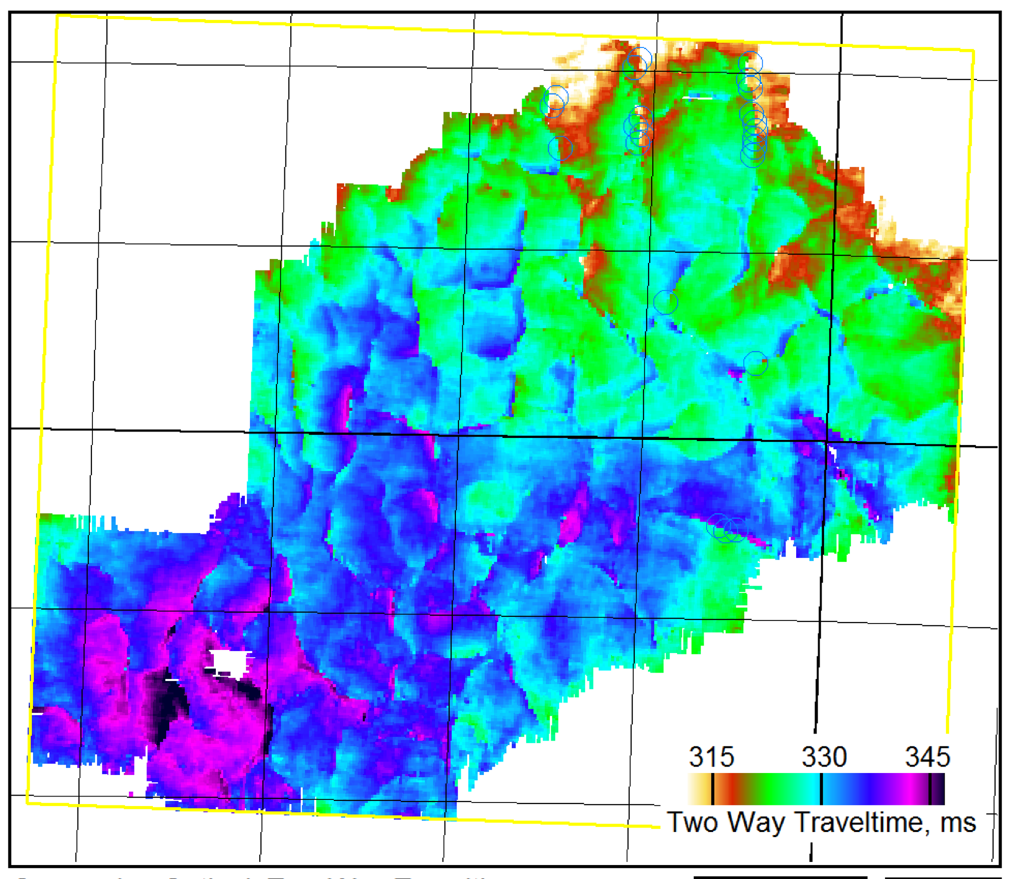
Campanian Outlook Gradient (fault detection) 1 mile 1Km

A gradient map is the product of two 3x3 convolution masks, as defined by:

$$X = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}, \quad \text{and } Y = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}.$$

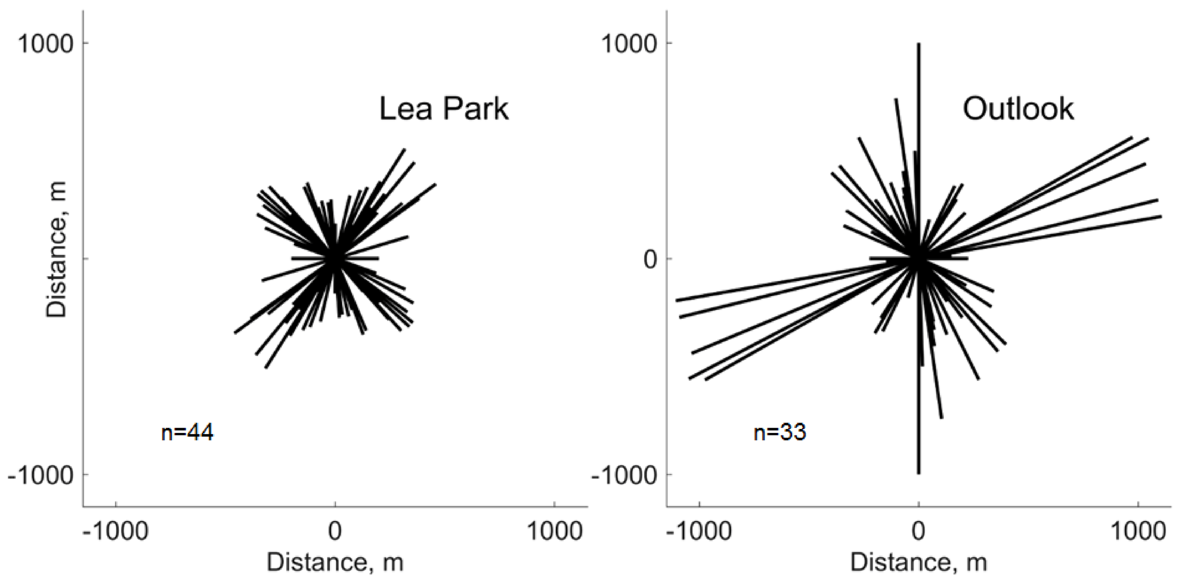
The computed gradient values increase in value at fault locations with larger vertical offset.

15) The Campanian Outlook two way traveltime map resembles tilted fault blocks that were influenced by the Campanian Lea Park grabens (panel 13c, to the left).



Campanian Outlook Two Way Traveltime 1 mile 1Km

16) Fault strike direction and length for the largest gradients on the two maps in Panel 14.

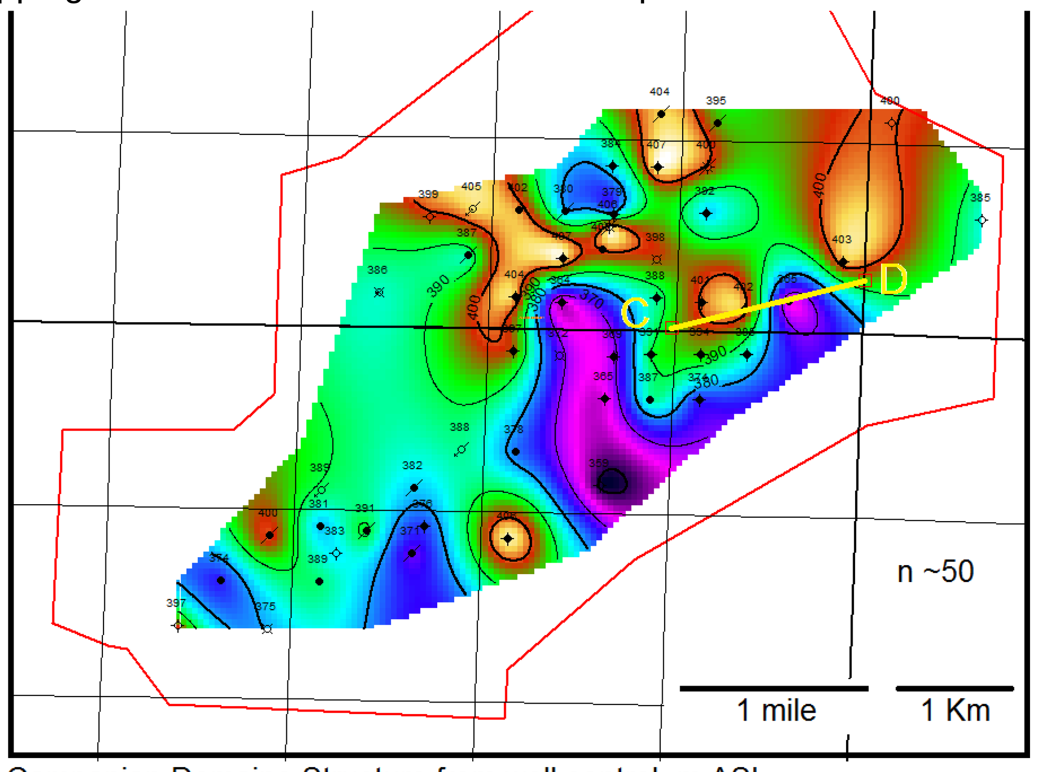


The Campanian Lea Park reflection has shorter fault traces relative to the shallower PFS. These fault traces strike NW/SE & NE/SW.

The Campanian Outlook reflection has longer strike lengths, oriented ENE/WSW. Some of the deeper faults extend to the shallower layers, as can be seen on the seismic line 'AB' in panel 12 above. The process by which some faults extend to shallower layers is under examination.

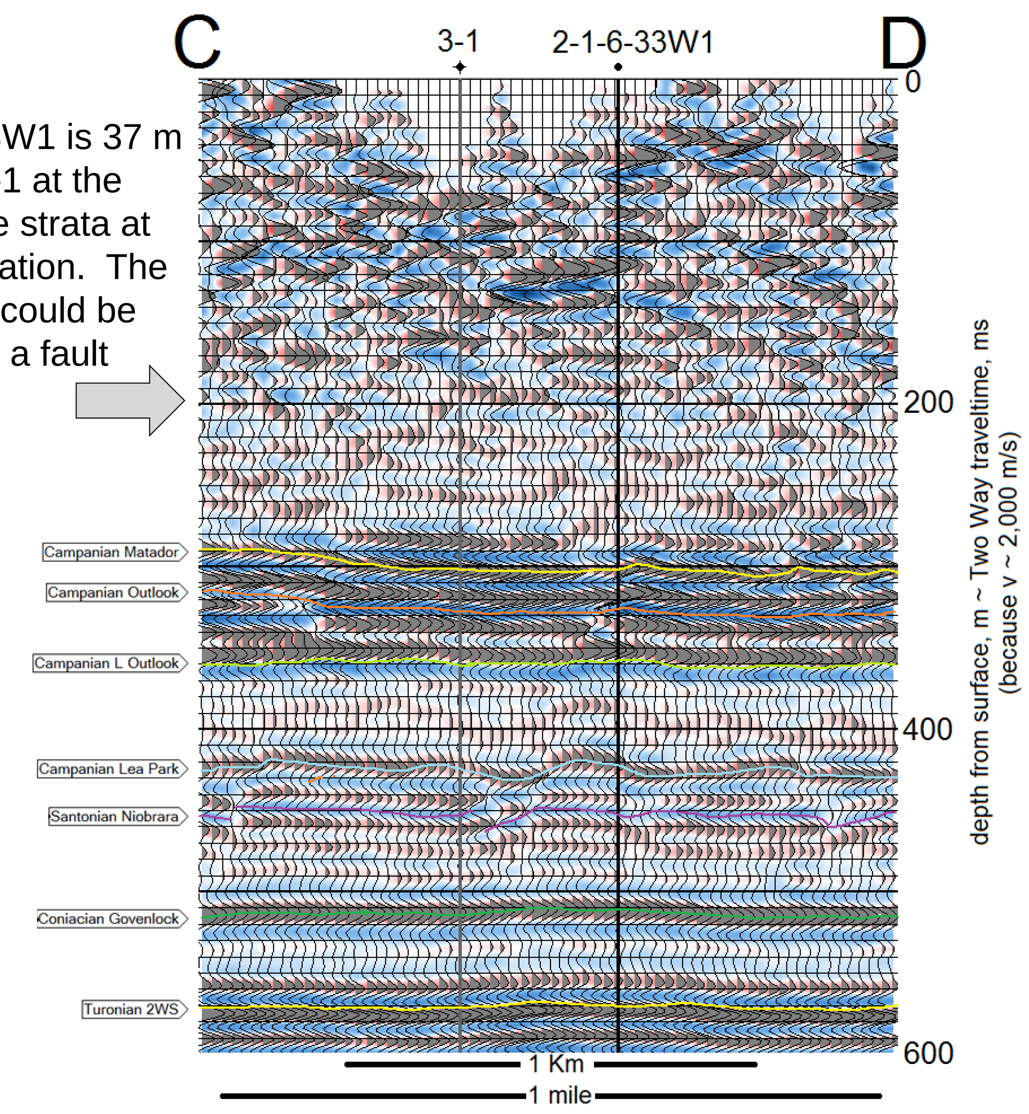
17) Geology Map.

The Demaine marker (from well control – see Panel 3 and 6 has ~37 m of structural difference between 3-1 and 2-1-5-33W1. Well control mapping underestimates the structural complexities.



Campanian Demaine Structure from well control, m ASL
only wells with correlative events were used

2-1-6-33W1 is 37 m low to 3-1 at the Demaine strata at this elevation. The 2-1 well could be drilled in a fault trace.



18) Geotechnical engineers have studied this area.

Rational design treatment of slides in overconsolidated clays and clay shales
Elmer Brooker and Ralph Peck, R. 1993.
Canadian Geotechnical Journal, 1993, 30(3): 526-544. doi: 10.1139/t93-045.

"During the early part of the past century, engineers were repeatedly surprised by unforeseen movements of valley slopes on overconsolidated, flat-bedded clays and clay shales. Movements have occurred, and still persist, throughout the Cretaceous Sea area of North America. During the past 20 years the profession has been developed to the point where the element of surprise should not be an issue."

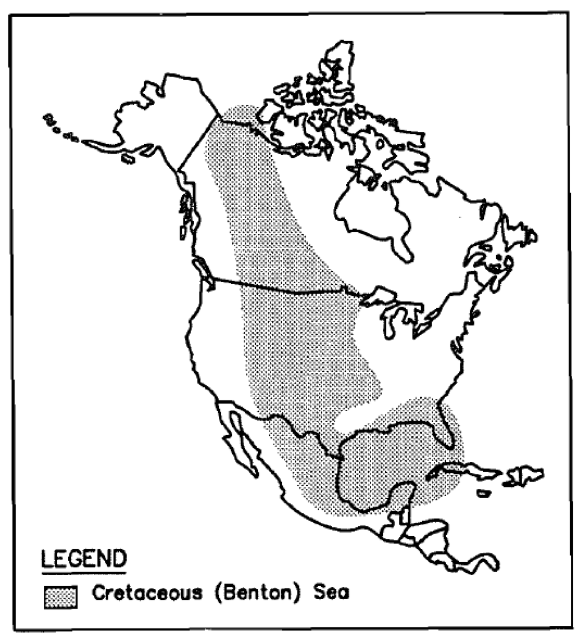


FIG. 1. Extent of Cretaceous (Benton) Sea deposits in North America.

19) The GPPFS has been recognized at outcrop.

Strata-bound vein array in the basal Pierre Shale, Lake Francis Case, South Dakota, U.S.A.

Harmon Maher, Jr.[1*], Sarah Ferguson[1], Ryan Korth[2], Justine Marshall[1], Laura Pickett[1]
[1]Department of Geography and Geology, 6001 Dodge Street, University of Nebraska Omaha, Omaha, Nebraska 68182-0199, U.S.A. [2]Terracon, 15080 A Circle, Omaha, Nebraska 68144, U.S.A.
*Correspondence should be addressed to: harmon_maher@unomaha.edu

ABSTRACT

A distinctive strata-bound vein array occurs in the basal Pierre Shale exposed along the shores of Lake Francis Case, a reservoir on the Missouri River in south-central South Dakota. Typically 2–4 meters in thickness, the array consistently outcrops over a >50-km distance, a significant areal footprint. Ash layers define the upper and lower bounds of the vein array. Two, suborthogonal, preferred directions of vertical veins (northeast and southeast strike) define a regional pattern. By volume, vertical veins comprise 1–2% of the rock. Thinner, more discontinuous, and irregular horizontal veins also occur. Comparisons between array orientations and the joint/vein pattern in the immediately underlying marls of the top of the Niobrara Chalk identify distinct differences. Traverse data suggest that the vein arrays are characterized by uniform horizontal extension. Vertical veins in the array are typically 1–2 centimeters thick and contain massive jarosite, selenite, and fibrous gypsum. The abundance of jarosite and fibrous gypsum distinctly correlates with position in the weathering profile, and these phases are interpreted as due to replacement of original selenite during modern weathering. However, for initial vein array formation, the following suggests that they are not related to modern weathering and formed at depth: (1) a lack of correlation of vein width/frequency with position in the weathering profile; (2) the regional extent; (3) the consistent preferred orientations; (4) the uniform horizontal extension; and (5) the coarse-grained character of the selenite. The consistent strike pattern suggests influence of a regional stress field. The mechanism/timing of vein array formation is unclear. Formation due to diagenetic processes, which are especially significant in mud rocks, would explain the strata-bound character and isotropic horizontal strain and is considered most likely. Formation during glacial loading is one intriguing possibility. Localization of the vein array may be due to the organic-rich character of the host Burning Brule Member of the Sharon Springs Formation.

20) Regina Beach is subject to slides from toe slope erosion in the Qu'Apelle Valley, Saskatchewan.

Regina Beach – a town on a landslide

Wayne Clifton, Richard Yoshida and Roy Chursinoff, 1985.

Canadian Geotechnical Journal, 1985, 23, 60-68.

"The town of Regina Beach is constructed on landslides along the Last Mountain Lake valley, a glacial meltwater channel in south-central Saskatchewan, Canada. The landslides are retrogressive in nature and are seated in bentonitic clay shale of the Bearpaw Formation (Pierre shale)."

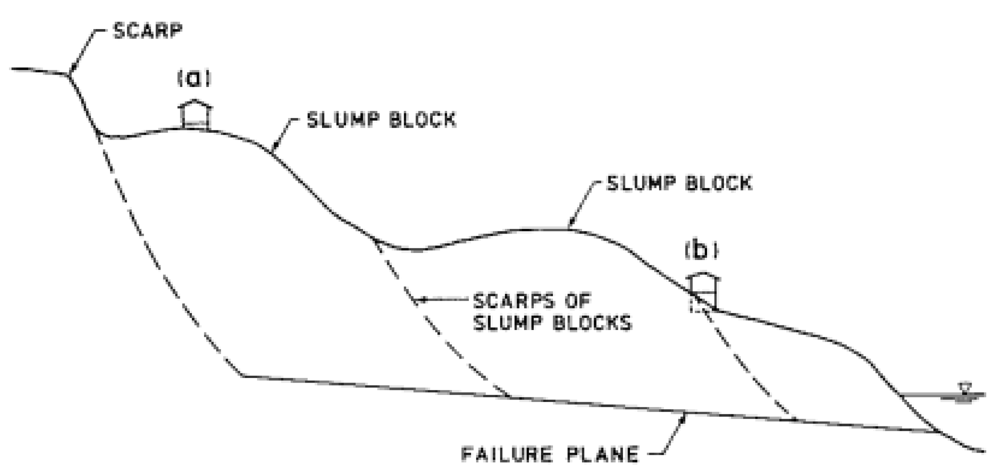


FIG. 8. Position of structure on slump block affects degree of damage experienced: (*a*) structure fully on one slump block, less susceptible to damage; (*b*) structure across scarp between two slump blocks, very susceptible to damage.

21) The Weyburn CO_2 storage model presented below characterizes the overlying Bearpaw and Colorado (Pierre equivalents) as an aquitard. The PFS faulting suggests an aquifer, if the faults are open.

Geological Characterization of the Weyburn Field for Geological Storage of CO_2: Summary of Phase I Results of the IEA GHG Weyburn CO_2 Monitoring and Storage Project [1]

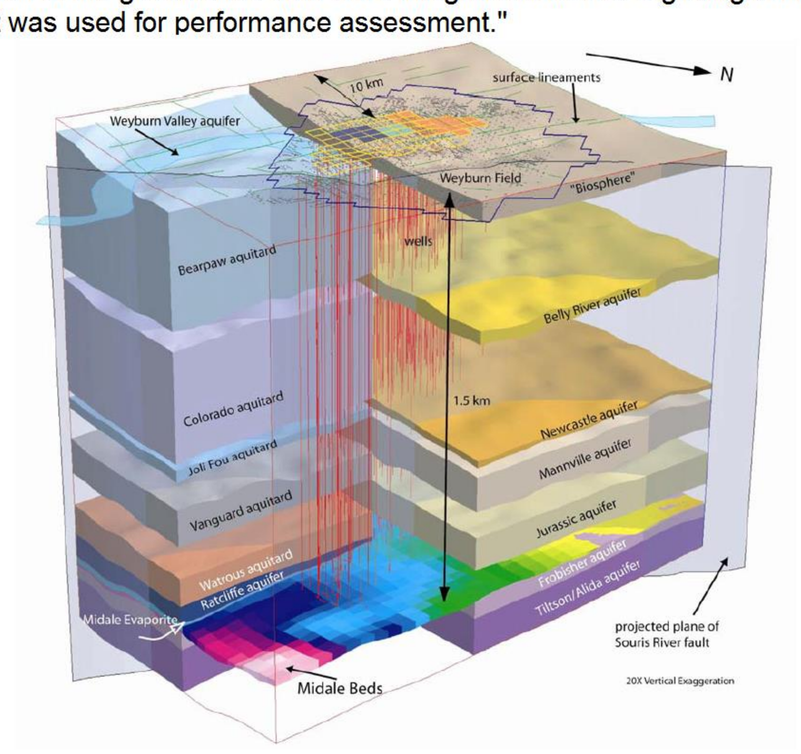
Steve Whittaker

Summary of Investigations 2005, Volume 1, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep. 2005-4.1

Abstract

The IEA GHG Weyburn CO_2 Monitoring and Storage Project was designed to study methods for monitoring CO_2 movement in the subsurface and to determine the security of storing CO_2 in depleting oil reservoirs for hundreds to thousands of years. The Weyburn Project was associated with EnCana Resource's CO_2-miscible flood operations at the Weyburn Field in southeastern Saskatchewan. Initial planning of the research program began in July 2000 and the first phase of research was completed in September 2004. The project was highly diverse and contained programs involving regional geoscience investigations, reservoir simulations, 4-D geophysical monitoring surveys, reservoir fluid and mineral sampling, geochemical modeling, well-bore integrity studies, geomechanical property investigations, risk and performance assessment, and economic viability studies, among others. Geological characterization was undertaken at two scales: one a regional investigation of a 200 x 200 km area centred on the Weyburn Field; the other a more detailed examination of the geosphere in an area extending 10 km beyond the limits of the planned CO_2 flood. The geological framework was defined through geological mapping, regional seismic data, shallow and deep hydrogeological investigations, high resolution aeromagnetic geophysical surveys, airphoto and satellite remotely sensed imagery analyses, and detailed stratigraphic and diagenetic studies. The geological characterization portion of the project provided fundamental information for other areas of study regarding geological storage of CO_2 such as reservoir simulation and risk assessment. Much of the geoscience data were integrated into a 3-D geological model, or System Model, that was used for numerical risk and performance assessment. The results of the geoscience studies indicate that the Weyburn Pool is a very suitable location in which CO_2 may be stored securely for several thousand years. Numerical modeling studies suggest around 23 million tonnes (MT) CO_2 will remain in the reservoir at the end of EOR operations, and that no CO_2 will migrate above the reservoir caprock in over 5,000 years.

"Much of the geoscience data were integrated into a 3-D geological model... that was used for performance assessment."



22) Conclusions.

Some fine-grained Cretaceous sediments of the Western Interior Seaway of North America host a previously unreported polygonal fault system (PFS). At Alida, Saskatchewan, 3-D seismic data can image the PFS from ~200 m ASL to its origin at ~25 m ASL. The PFS can be geologically mapped below a depth of ~500 m ASL using wellbore logs. Faulting of the Pierre Shale resulted in a graben system and a tilted fault block system at Alida. The graben system is basal Campanian and suggests local or regional extension. These grabens have affected the upper tier of the PFS. Both tiers have faults with similar displacements, but the upper tier average fault strike length is longer and the strike direction is rotated ~30° E. How the graben and tilted fault blocks and shallow bed geometries are related is still under investigation.

23) Implications and further work.

- Probably affects groundwater hydraulic conductivity.
- Faults and fractures near the ground surface or at outcrop require further examination for evidence of PFS faulting.
- Estimates of millions of faults with strike lengths of ~500m.
- Graben formation suggests extension – is this local, forebulge movement, or tectonic?
- Present day slumping from toe erosion within incised valleys could reactivate PFS fault traces.
- Surface geology work must be an integral part of this analysis.

24) References.

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