Great Plains Seismogenic Study
Andy St-Onge  geophysicist@shaw.ca
Chapter Summaries as at April 15, 2019

PFS project introduction

After 35 years of recommending the economic locations for the drilling oil and gas wells in Western Canada, I learned that to drill wells in an area, one must be comfortable with the geology. That requires myself (and usually others helping me) to learn about the geology surrounding a proposed well in an area about two townships in size (~72 square miles). When asked to drill wells in Manitoba about 10 years ago, I interpreted shallow faulting and fracturing in Upper Cretaceous strata on a scale that was hard for me to believe. It took about 10 years to get to the point of offering a study on these observations. The result is what you see here.

Continental Margin Model and the GPPFS

The Western Interior Seaway sediment observations are consistent with interpretations for a small passive continental margin, as shown in Figure CM-1, on either side of the Western Interior Seaway. Continental margins have many different characteristics such as water depth, deeper tectonic features, geomorphological features and several other characteristics that can define the margins such as sedimentation rate and water depth. The point to make here is that there are seven characteristics of continental margins that appear to apply to within the inland sea of the Western Interior Seaway. Linear chimneys, methane vents, faulted intervals, clinoforms, injectites, down-drop block overwash and polygonal fault systems are all features that will be briefly presented here. The locations for the figures are not given specifically, but they are all within the Great Plains polygonal fault system within the Western Interior Seaway in Canada as can be seen on Figure CM-2.
Interpretation tools for exploring the Great Plains polygonal fault system

This article presents several interpretation tools for reservoir traps that may have been affected by the Great Plains polygonal fault system (GPPFS). This is an extensive polygonal fault system (PFS) in fine-grained Late Cretaceous sediments deposited within the Western Interior Seaway of North America. PFSs are pervasive organizations of non-tectonic faults with fault traces that coalesce to form distinctive polygonal fault patterns. Interpretation of 3-D seismic datasets, well control and surface geology from Alberta, Saskatchewan and British Columbia provides insight into fault initiation, timing and geometry for the GPPFS. The faults can be timed with correlation offset calculations from closely drilled well control. New interpretation tools taking these factors into account should result in reducing the risk of drilling Upper Cretaceous reservoirs where encountered within the WIS.

Fractal characteristics and paleostress in the Great Plains polygonal fault system

Fine-grained Cretaceous rocks beneath the Great Plains of North America have been extensively faulted to form the Great Plains polygonal fault system (GPPFS). The GPPFS is a large area (potentially >2,000,000 km²) of layer-bound normal faults and fractures that formed in sediments early after deposition within the WIS. Two characteristics of the GPPFS will be presented and discussed here; the first being extensive normal faulting that occurred in the absence of changes in tectonic stress. The faulting can occur syndepositionally; growth faults have been observed at scales up to over 1 km in strike length and up to 30 m vertical offset. Simple fault analyses can determine the timing of the PFS occurrence. The second characteristic discussed here are planiform polygonal fault trace outlines formed by the faulting. These areas can extend over 100,000 km² with little variation. Inspection of fault strike alignment in some areas suggests that this may be used to indicate paleostress. These characteristics are presented and interpreted to encourage further identification of the effects of the GPPFS.
Figure FCP-2. Polygonal faulting at different scales: a) outcrop of Fox Hills sandstone at Boulder, Colorado (just overlying the Pierre Shale Formation) with cracks ~10 m apart (b) Cracks with ~800 m spacing imaged on the Milk River gradient map from Rocanville, (c) cooked corn starch (it is a simple non-Newtonian fluid made with corn starch and water. We contend that the corn starch mixture is similar to the rheology of bentonite, another non-Newtonian fluid); the cells are ~2 cm across and d) cooked cornstarch with cells ~1 cm diameter.

**Seismic Data Considerations**

There are several considerations for the seismic data identification of polygonal fault system characteristics within the Western Interior Seaway. The data quality is variable throughout the area; the signal to noise ratio for data acquired in certain areas can be greater than those in other areas for several reasons. Weak reflection energy from the zone of interest is possible if there are no impedance contrasts in the zone of interest. The applied data processing flow is important when trying to image shallow seismic reflections. Interpreting data acquired with different acquisition geometries, especially when comparing 2-D versus 3-D seismic data, can result in different interpretations.

A higher ‘quality’ 2-D seismic line is shown to exemplify an interpretation drawback. Finally, interpretation problems from poor quality data is briefly discussed.

**Fractal Work**

Several experiments were done to examine the fractal properties of non-Newtonian fluids. The purpose of these experiments was to compare the patterns observed in seismic data (at a km or so scale) acquired within the Western Interior Seaway to fractal patterns observed at a small (cm) scale. If the fractal patterns are observed at one scale, it is reasonable to assume that the patterns occur at different scales, as this is the nature of fractal phenomena.

**PFS Statistical Analyses**
Three-dimensional seismic data and well control can be used to provide some statistical analyses of polygonal fault systems (PFSs). Part of the purpose of the statistical analysis is to summarize numerous observations for the PFS to describe complicated systems of faults. For example, average fault lengths for a zone can be used to summarize fault lengths within an area. Another analysis is analyzing well log correlations for wells drilled close to each other to look for the timing and amount of faulting. The statistical analyses presented below are reported here to encourage new interpretation methods and subsequent observations from the GPPFS.

**Methane Vents within the Great Plains PFS**

Within the Great Plains Polygonal Fault System, some seismic data images subsurface features that may be related to methane venting, similar to anomalies at outcrop. The anomalies are more widely distributed than currently recognized and may indicate extensive methane venting in a continental margin setting. The Campanian vent outcrops are temporally correlated to seismic data amplitude maps and/or 3-D time-slice displays. This novel use of oil industry seismic data may lead to a better understanding of methane venting.
Shock phenomena

Three meso-scale (centimeters to meters) geological features are interpreted to be caused by seismic shock. Septarian nodules found throughout the Western Interior Seaway (WIS), are interpreted to be caused by the seismic shock of point inclusions in sedimentary strata. Cone in cone structures, also found throughout the WIS, are interpreted to be caused by the seismic shock of a 2-D array of inclusions by Rayleigh waves. A third geological feature, rockburst, where mines tunnel can fail catastrophically, is a shock phenomenon found throughout the world in underground mines. These features are examined in this study because it is interpreted that they are part of a continuum of seismic shock anomalies. If this is the case, it is consistent with the premise in this study that polygonal fault systems could be caused by seismic shock on a larger scale.

In-Situ seismogenic fault model

Recent literature has reported on seismogenic faulting and fracturing in several areas. There are probably numerous reasons for this, the simplest reasons being improved monitoring for smaller earthquakes and the desire to go into the field to look for physical evidence of disruption. Field work in various earthquake zones has included trenching to determine the seismogenic effect of ground movement at various locations around the world. The result is a simple model of strata in the faulted zone as well as a ‘halo’ of strata on either side of the seismogenic faulted zone. This investigation will point out a few halos examined around the world to try to present a model that some seismogenic faults in the Western Canadian Sedimentary Basin may have a surrounding halo that, if recognized, could lead to the discovery of sediments deposited adjacent to a fault trace. It is argued here that these fault trace areas could be areas of enhanced reservoir development.
Surface expression of the Great Plains polygonal fault system

This article presents several examples of how the Great Plains polygonal fault system (GPPFS) is interpreted here to be expressed at outcrop. This GPPFS is an extensive polygonal fault system (PFS) in fine-grained Late Cretaceous sediments of the Western Interior Seaway of North America. PFSs are pervasive organizations of non-tectonic faults with fault traces that coalesce to form distinctive polygonal fault patterns. The PFS at outcrop displays many examples where bentonite in the strata is affected and weakened by groundwater. The recognition of the PFS at outcrop can have some important consequences for civil engineering as ubiquitous faulting can occur.

Polyangular Fault System initiation: seismic shock inundating non-Newtonian mud

This line of study, examining the Western Interior Seaway (WIS) to delineate evidence for a large polygonal fault system, began about three years ago. The WIS is host to the Great Plains Polygonal Fault System (GPPFS), one of largest in the world in size and probably one of the largest in terms of economy. Over 0.6 million barrels of oil per day comes out of Upper Cretaceous reservoirs within the Great Plains area; any scientific advance to increase that number should be met with positive acceptance.

Success, Saskatchewan seismic data interpretation for Upper Cretaceous faulting

At Success, Saskatchewan, two strata-bound geological sequences contain polygonal fault systems (PFSs). The upper PFS lies within the Lea Park Formation (Lower Campanian), while the lower PFS began during Westgate Formation deposition (Upper Albian) and continued through Turonian time. The Lea Park PFS fault characteristics are presented; the faults average 500 m in length, have random strike directions and on average ~+/-5 m vertical throw. It is believed that the fracturing and faulting should have positively affected formation reservoir characteristics, as the faulting is ubiquitous. The lower PFS faulting and movement initiated within the Westgate Formation appears to have had little influence on
the deposition of the beds deposited in the Lea Park PFS. Both PFSs have been interpreted on one seismic dataset from southwest Saskatchewan. Many displays from the seismic data interpretation show the faulting characteristics for both PFSs.

**Milk River/Medicine Hat Formations Mapping Ideas**

Natural gas in the Milk River Formation occurs in interbedded very fine-grained shallow biogenic gas reservoirs of shales and sandstones. The Alberta Energy Regulator supplies the stratigraphic chart as shown in Table MRMH-1. Ridgeley (2000) shows a similar stratigraphic chart with respect to eastern Montana, where the play may continue (Table MRMH-2). The purpose for this analysis is to show that the low porosity and permeability within the Milk River/Medicine Hat productive area (Figure MRMH-1) can be fractured within the seismogenic Great Plains polygonal fault system. It should be expected that the fracturing should enhance the reservoir permeability (Nadeem, 2011).

**Bad Heart Formation Mapping Ideas**

The Bad Heart is a productive Upper Cretaceous formation; however, there is little in the literature regarding the Bad Heart Formation. A stratigraphic chart (Chart BH-1) shows the Upper Cretaceous (mid to late Coniacian) Bad Heart Formation. The formation consists of a ‘coarser’ clastic succession of sandstone and ooidal ironstone, typically ~ 5 to 15 m thick within a much thicker shale succession (Kafle, et al., 2013). It is interesting to note that at outcrop, the Bad Heart Formation is of interest because of the extensive ooidal ironstone deposits (Kafle, et al., 2013) in the Western Canada Sedimentary Basin.
Barons Formation Mapping Ideas

The Cenomanian Barons sandstone is an economic hydrocarbon producer from reservoirs below Lethbridge, Alberta to about 70 km northwest of Lethbridge (Figure BARO-1). Production from several bodies within the Barons Sandstone unit appears as isolated muddy sandstone and conglomeratic bodies between the Westgate and Fish Scales Formation (see Table BARO-1). These are irregularly distributed at several northwest to southeast orientations (Vessey and Pedersen, 2013) that can be observed in Figure BARO-1. Leckie, et al, (2000) argue that coarse sediment was flushed out during sea-level lowstand and then reworked by a subsequent transgression associated with the middle to late Cenomanian Belle Fourche Formation. Finally, muddy sandstones of the Baron member of the early Cenomanian Fish Scales Formation is a potential emerging light tight oil play in SW Alberta (Pedersen and Vessey, 2014).

Tertiary Coal Mapping Ideas

Tertiary-aged coal is mined, and coal bed methane is produced from various zones throughout the Western Interior Seaway (see Table TCM-1). Several faults in Tertiary coal have been shown in images; some of them are reproduced here. It was difficult to obtain data from mining companies for an examination of Tertiary coal beds. Also, sometimes the government waves the requirement for well logs if the interwell spacing for boreholes is less than a certain distance (on the order of a few 100 meters). So, there are no logs to correlate in these areas.

Polygonal faulting in Westgate Shale Formation Caprock

Polygonal faulting within the Westgate Shale Formation is encountered in the Marie Lake area of northeastern Alberta. This is an area of cyclic steam injection of reservoirs directly below the Westgate Shale Formation, the shale forming a shallower caprock for the producing reservoirs. It is interpreted here that the Westgate Shale Formation in the area
could be a ‘leaky’ seal in areas where the steam injection at higher than reservoir pressures could open pre-existing fractures within the Westgate shale, allowing for some flow of oil vertically through the strata. An explanation for this could be a pervasive polygonal fault system within the Westgate Shale Formation in the area.

Glacial Strata Hydrocarbon Trapping

Natural gas has been produced from glacial strata deposited within the Western Interior Seaway of North America since the late 1800’s; this paper presents a revised trapping model for natural gas occurring in glacial deposits in the Western Interior Seaway. An examination of production, wells and seismic data are used to interpret the trapping mechanism and the reservoir properties for glacial strata. Many deeper wells could have encountered shallow gas from these reservoirs. A new Glacial Exploration Model (GEM) is presented to show how natural gas can migrate up through Upper Cretaceous strata and become trapped below glacial clay just below ground surface. Operators producing from deeper formations should be aware of the model in the case that economic gas accumulations may be explored for within the glacial sediments.
The Great Plains Polygonal fault system phenomenology: Second White Speckled shale reservoir enhancement

Borehole logs and 3-D seismic data are used to determine the characteristics of a Cretaceous polygonal fault system hosted in the Westgate Formation that may extend from western Saskatchewan to eastern Alberta and south into Montana where the formation strata and homotaxial equivalents are deposited. The Cretaceous Westgate Formation is a siltstone to mudstone deposited in the Western Interior Seaway beneath the Great Plains of North America. The faulted zone is layerbound within the ~80 m thick Westgate Formation and the overlying Second White Speckled Shale Formation at Swift Current, Saskatchewan. Most faulting results in graben formation, each ~125 m wide and ~10 m deep in the Westgate Formation strata. The grabens are interconnected, have random strike directions and lengths up to 800 m.

The continuous depositional environment of the Westgate Formation enables timing and compacted sediment thickness estimates for the PFS initiation. Interpretation of the seismic dataset and accompanying wellbore data has resulted in a simple model that can be used to look for PFS indications using only wellbore data. Wellbore data interpretations from Alberta and Saskatchewan show that the PFS identified at Swift Current may range across a large area. Moreover, some of the faulting has occurred after the deposition of the Second White Speckled Shale Formation. Formation of extensive faulting within the Westgate Formation can enhance reservoir permeability and/or degrade trap effectiveness for shallower strata such as the Second White Speckled Shale Formation.