

Analysis of time-lapse, multicomponent seismic data from a potash mining area in Saskatchewan

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ABSTRACT

Seismic anisotropy is a subsurface property that can have a severe impact on the quality of subsurface seismic imaging. In this study, a multicomponent, time-lapse seismic survey is interpreted to determine if seismic anisotropy exists in a potash mining area in Saskatchewan. The focus of this study is the Devonian Dawson Bay Formation which is made up of fractured carbonates and thus may allow fluid to propagate downward from an aquifer into the underlying Prairie Evaporite Formation. The seismic volumes were split into 4 azimuthally sectored sub-volumes that are made up of a stack of source-receiver ray paths covering a 45 degree sweep. Through interpretation and travel-time analysis of these data, it has been found that carbonates of the Dawson Bay exhibit azimuthal velocity anisotropy, possibly due to fractures, although it is not possible to determine the cause of the anisotropy with this analysis.

INTRODUCTION

A conventional three-dimensional (3D) seismic survey is typically made up of a relatively square grid of shot points and receivers. Acoustic waves are propagated through the subsurface originating from each shot point across the survey area, and are recorded at every geophone in the area. This means that for a single seismic survey, geophones record data from different source azimuths (see figure 1). What will be referred to as a full seismic volume is made up of a stack of traces including all source-receiver azimuths in the survey. By isolating specific azimuths of incoming seismic waves it is possible to infer directional differences in rock properties related to seismic response.

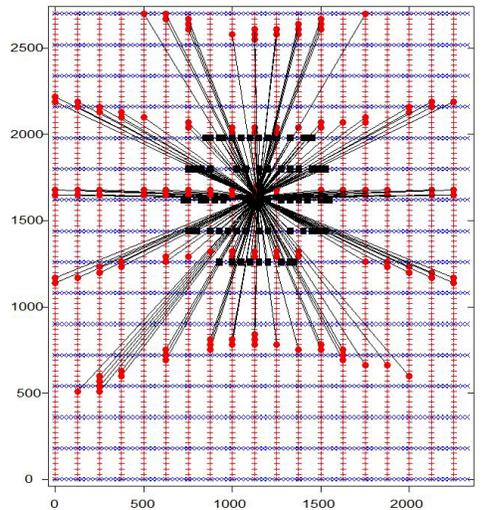


FIG. 1. Survey geometry with shot points in red crosses represent shot points and blue 'x' represents receivers. The red points with black lines represent shot points that provide proper coverage to a single receiver from different azimuths based on survey specifications.

In this paper, the subject of anisotropy will be discussed regarding the Devonian strata, more specifically, carbonates that are possibly fractured and which overly potash deposits currently being extracted using the “room and pillar” mining method (Zhang 2010). It is possible that the fracturing is due to natural fracturing from regional stresses, excavation and extraction of potash deposits or a combination of the two (Edgecombe 2011). Determining the orientation of the anisotropy will produce insight into fracture orientation within the layers of interest which can constrain possible mechanisms for fracture formation.

BACKGROUND

Geology

The stratigraphic layers that we take into consideration in this study are the Birdbear Formation, the Dawson Bay Formation, the Prairie Evaporite Formation, the Winnipegosis Formation and the Winnipeg sandstone. Their geologic age as well as lithology can be found in the stratigraphic column in Figure 2.

In this region, there is a potash mine approximately 1000m below the surface, and about 20-30m into the Prairie Evaporite Formation. The overlying the Second Red Beds and Dawson Bay Formations strata are made up of fractured red beds, which are comprised of mudstone and dolostone (Gu 1998) and fractured carbonates respectively (Edgecombe, personal communication 2011). Any groundwater seeping into the Prairie Evaporite Formation from an aquifer at the top of the above Dawson Bay Formation suggests that the Dawson Bay Fm might be fractured. This fracturing may create brine inflow issues at the mine level that would affect the operation and production of mining operations as well as concerns for the health and safety of the miners.

It is thought that mining is inducing fractures along pre-existing planes of weakness within the Dawson Bay, and that the ability to map these fracture networks could lead to the prediction of possible brine inflow locations and ultimately the ability to take preventative measures in order to mitigate the risk associated with mining operations due to the inflow problem (Edgecombe, personal communication 2011). Fractures, when oriented in the same direction, are known to induce azimuthal seismic anisotropy which impacts seismic wave propagation through the medium. If fractures are occurring in a preferential direction, their associated anisotropy may be visible through the traveltimes and velocity analysis of azimuthally sectorized seismic volumes.

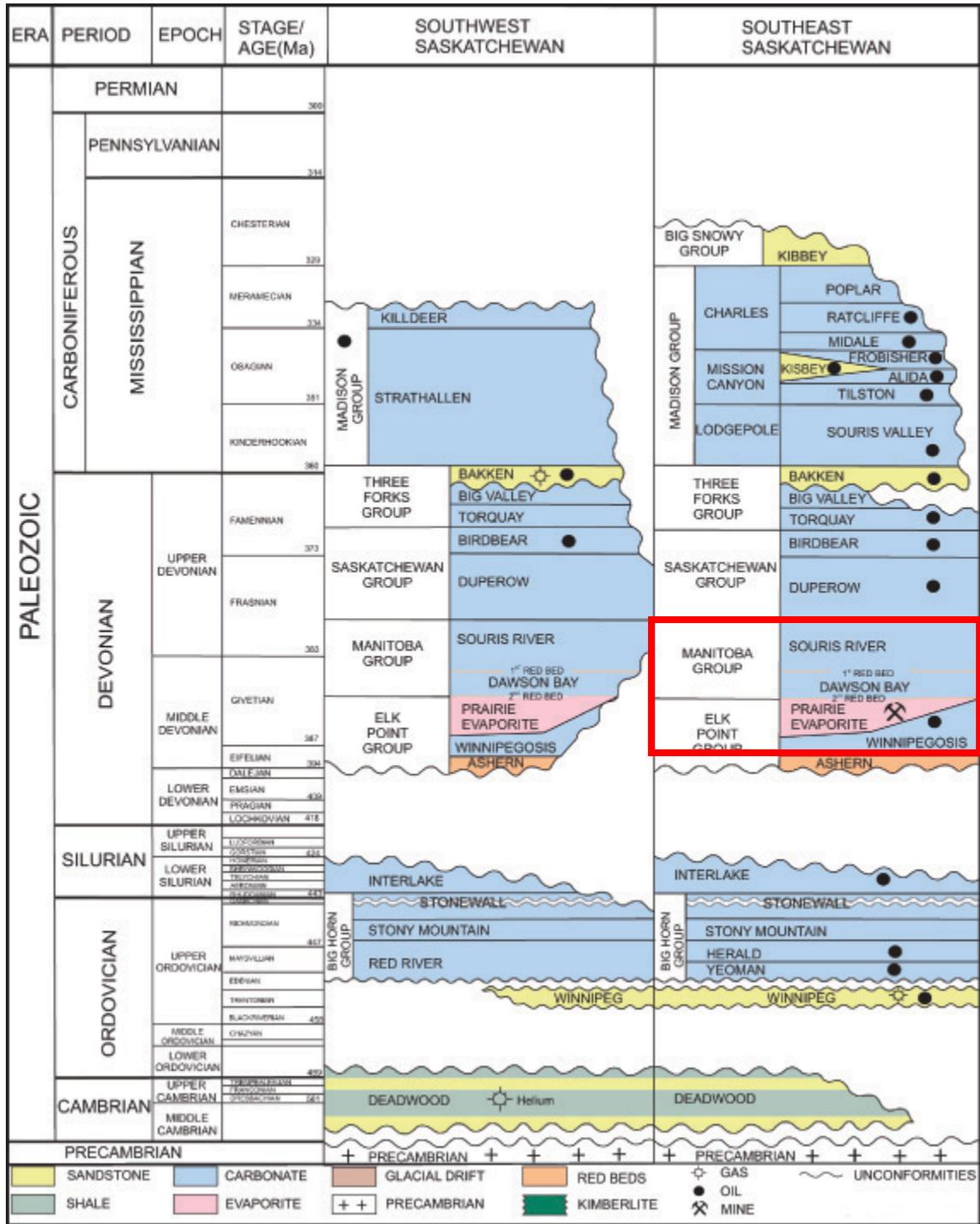


FIG. 2. Stratigraphic column showing the BirdBear Fm., the Dawson Bay Fm., the Prairie Evaporite Fm., the Winnipegosis Fm. and the Winnipeg sandstone (modified from http://www.er.gov.sk.ca/adx/asp/adxGetMedia.aspx?DocID=3966,3625,3384,5460,2936,Documents&MediaID=32484&Filename=strat+chart+Jan11_11.pdf)

Anisotropy

Isotropy when discussing seismology refers to the velocity at which an acoustic wave propagates through a medium at the same speed in every direction. The simplest case of anisotropy is that of transverse isotropy. The rocks that exhibit transverse isotropy (see Figure 3) allow acoustic wave propagation at the same speed in two orthogonal directions, in a third direction, however, the wave propagates at a different speed (Telford 1990). Some of the causes of anisotropy include the presence of fractures in the subsurface and the layering of beds, rock properties which result in faster wave propagation in one direction (e.g. shale) (Sadri 2009).

As is common to all regions with a relatively complex sedimentary stratigraphic column, due to the layering of the carbonates, shales and sandstones in the subsurface, vertical transverse isotropy (VTI) exists in the region. As mentioned above, fractures can also cause transverse isotropy. In this region, specifically, fractures in the Dawson Bay Formation are typically found to be vertical in nature (Dunn 1982). Fractures oriented in such a manner will induce a phenomenon called horizontal transverse isotropy (HTI).

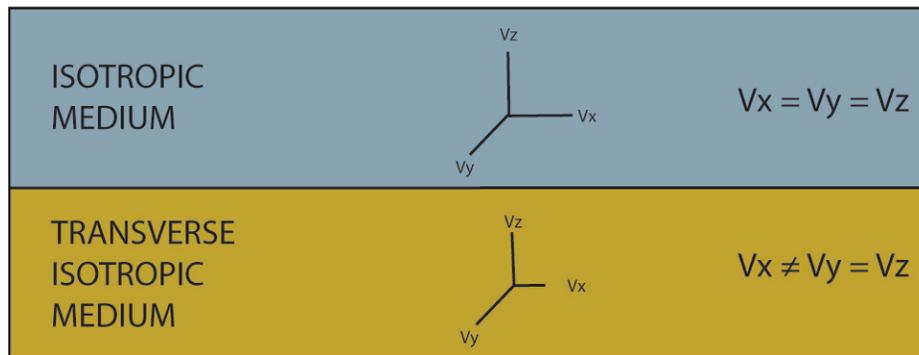


FIG. 3. A cartoon showing the difference in velocities associated with an isotropic medium and a horizontal transverse isotropic medium. The black lines represent velocity vectors with their length being magnitude.

Both types of transverse isotropy (horizontal and vertical), exhibit the same characteristics as an isotropic medium at near vertical offsets and lead to the creation of a wavefront which propagates differently in the surface when compared to the wavefront of an isotropy medium (see figure 5) depending on the parameters associated with the anisotropic strata (Thomsen 1986, Helbig 2005). For this reason, larger offset azimuthal data are required to view the velocity changes associated with anisotropy.

The energy associated with the azimuthal velocity anisotropy within the layers is corrected for during processing when the full azimuth gathers are stacked into a seismic volume. By stacking a narrower range of azimuths, the HTI should become evident when the sectorized volumes are compared to the full azimuth volume while analysing the volumes that are corrected for normal moveout (NMO) as seen in figure 4. When the NMO correction is applied to the full azimuth volume, it flattens the reflections from different strata using the average stacking velocity over all azimuths. Applying the same NMO correction to the azimuthally sectorized volumes will result in either over-corrected or under-corrected gathers if HTI is present. In order to account for this, a different

velocity model should be applied to properly flatten the gathers in each sector. A simpler, qualitative approach is to pick the horizon times of the stacked, sectorized volumes. For example, in figure 4 the green cdp gather is over-corrected, indicating that NMO velocity used is too low, whereas the blue gather is under-corrected, indicating that the NMO velocity is too high. The correct NMO velocity in each of these sectors would higher and lower, respectively.

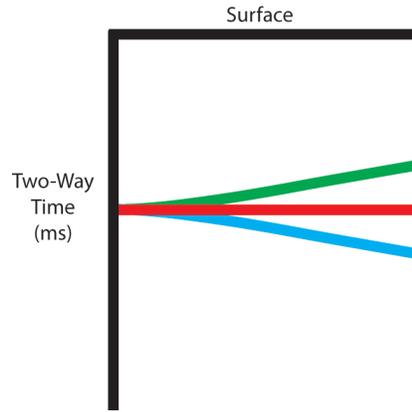


FIG. 4. This cartoon shows the difference between the full azimuth, fast velocity azimuth and slow velocity azimuth common depth point gathers. The red lines represent the full azimuthal gathers where the green and blue lines represent the fast and slow velocity events respectively.

Fractures contribute to anisotropy because they reduce the cohesion between rocks on across the fracture. A seismic wave traveling perpendicular to the fracture plane will experience a reduction in velocity as it propagates through the medium, which increases the travel time associated with that reflected (or refracted wave) and thus causes an anomaly in the seismic data when compared to a volume focusing on the wave propagating parallel to the fracture orientation. In order to determine the orientation of the fractures, the seismic dataset must be processed in a way that will make it possible to see these slight differences in travel time.

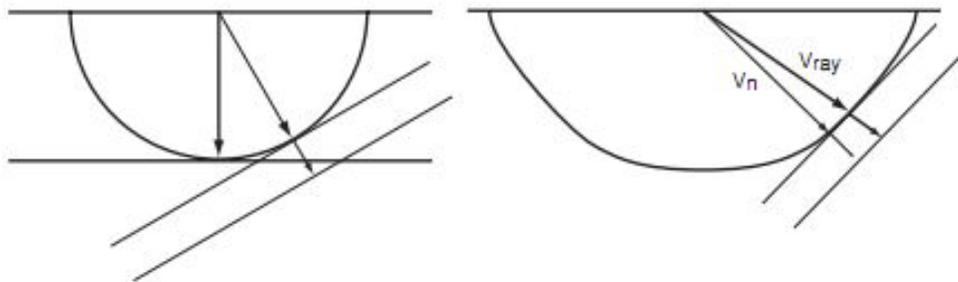


FIG. 5. A cartoon taken from Helbig (2005) showing the difference in propagation of a wavefront in an isotropic medium (left) and an anisotropic medium (right).

If the fractures in the study area are in fact vertical in nature, with a preferential orientation, azimuthal analysis of the seismic volumes should produce travel time differences between sectorized volumes that could be interpreted to be caused by fractures

within the formations in the subsurface. In order to test this hypothesis, we will examine 4D seismic datasets acquired in 2004 and 2008.

DATASET

The dataset used in this analysis of anisotropy in the Devonian carbonates and evaporites is made up of seismic data from two surveys, the first of which was recorded in 2004, and the second in 2008. The survey was conducted using a dynamite source and was gridded such that the sources and receivers were spaced 30 m and 25 m apart in lines oriented N-S and E-W, respectively. The source lines were spaced at a 125 m interval, while the receiver lines were spaced 180 m apart to build a survey area that is 2330 m by 2750 m.

The vertical component data for each year were compiled into 5 separate seismic volumes for analysis including the 10-360 degrees full azimuth volume, and 4 reciprocal volumes, namely 0&180 degrees, 45&225 degrees, 90&270 degrees and 135&315 degrees. The sectorized data is then stacked using data from azimuths ± 22.5 degrees to either side of the sector axes (see figure 6) then stacked and time migrated to produce the seismic volume, an example of which can be seen in Figure 7.

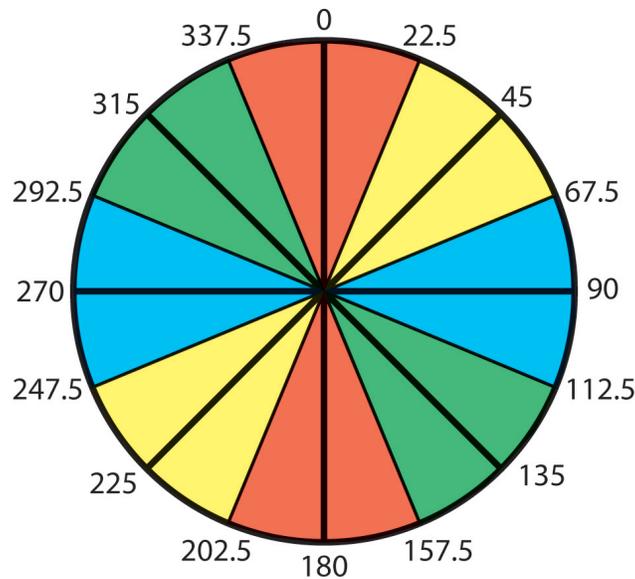


FIG. 6. This chart shows the distribution of ray paths which make up the azimuthally sectorized volumes. The central azimuths are used to define the dataset ie. 0&180 degrees is comprised of all of the azimuths in the red region of the chart.

Once the 2004 and 2008 vertical data had been sectorized into its azimuthal volumes, travelttime analysis of the data was undertaken.

INTERPRETATION

Horizons

The seismic volumes provided had some horizons (most notably the Birdbear Formation, the Dawson Bay Formation, the Prairie Evaporite Formation, the

Winnipegosis Formation and the Winnipeg sandstone) already picked for both 2004 and 2008 volumes by Boyd Exploration (see Figure 9, and 10). These datasets included the 2004 vertical component, filtered and migrated volumes which were used as a base to pick the horizons in the azimuthally sectorized volumes.

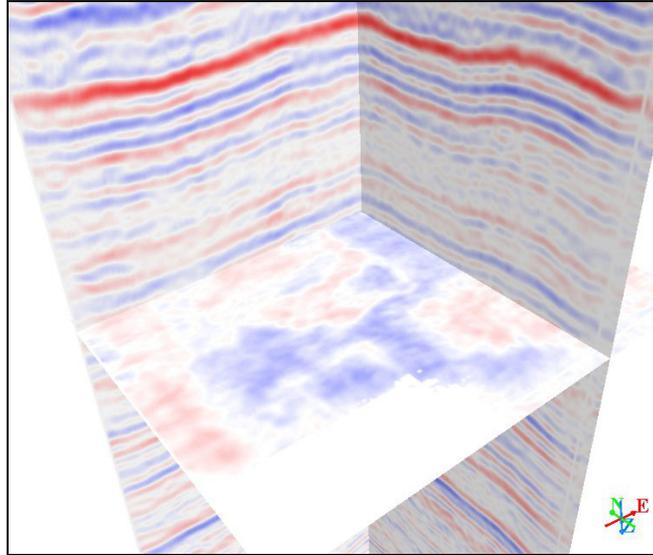


FIG. 7. A snap shot of the 2004 full-azimuth 3D seismic volume showing a crossline, an inline and time-slice through the Dawson Bay Formation.

Horizon re-picking on the 2004 full azimuth, 0&180 degree azimuths, 45&225 degree azimuths, 90&270 degree azimuths and 135&315 degree azimuths was done manually and using SeisWare’s “Snap Stream” picking algorithm. The 3D Auto Picker function was used with a search gate of 2 ms or 4 ms depending on the horizon. Each line was then checked manually in order to determine the accuracy of the auto picker, and any adjustments were then made. Finally, the auto picked horizons were smoothed using the horizon Smoothing/Attributes function (input parameters found in Table 1).

Table 1 - Smoothing function input parameters.

Parameter	Value
Grid Size – Inline	3
Grid Size – Crossline	3
Apply inline versus crossline bin size correction	YES
Fill Holes	YES
Expand Edges	NO
Expansion and fill distance (traces)	NO

Once this is done for each of the 2004 and 2008 azimuthally sectored data sets, horizon travel-times were assessed for evidence of azimuthal anisotropy.

The picks of the full azimuth volume (brown) and the 0&180 degree sectored azimuth volume (green) differ where there are travel time discrepancies that could be associated with fracture induced HTI.

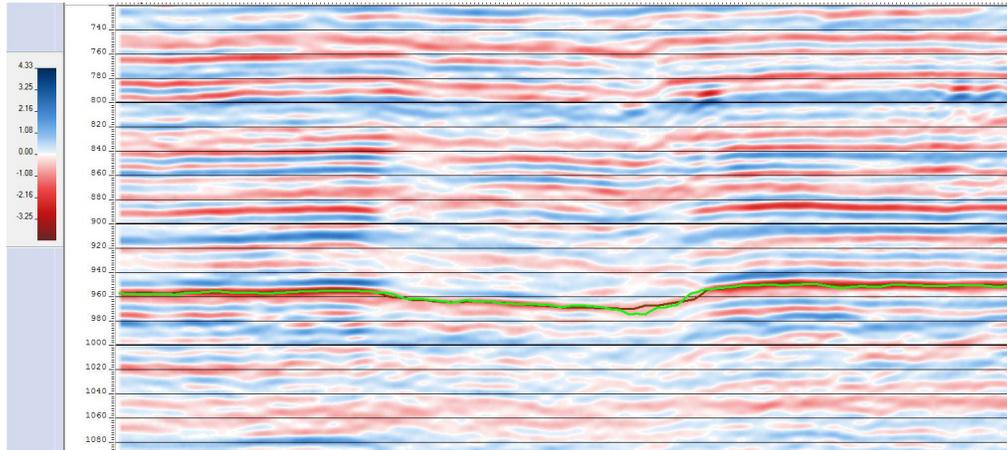


FIG. 8 – Crossline 76 showing the Winnipeg Sandstone horizons picked for the 2004 full azimuth seismic volume (brown) and the 0&180 degree sectored azimuth volume (green).

Analysis

Preliminary indicators of anisotropy, as mentioned above, are travel-time differences between the azimuthally sectored volumes. If the discrepancies are the result of fracturing there should be discernable differences in horizon travel-times between the full azimuthal volumes and the sectored azimuthal volumes. In order to determine if there is general HTI isotropy in the area, the horizon times associated with the sectored azimuthal volumes were compared to those associated with the full azimuthal volume. This was done between horizons within the same year. It is possible for evaporates in the Prairie Evaporite Formation to dissolve in water and create weakness in the formation, which, of course, has the potential to induce collapses and subsequent fracturing (Zhang 2010).

Difference grids were also created between horizons picked from each of the azimuthally sectored volumes. A focus was placed on perpendicular sectored azimuthal volumes, as they are most likely to show the largest differences in anisotropy associated with oriented vertical fractures (Figure 11).

A positive two-way travel time difference indicates that the travel time for the sectored azimuth volume (t_s) is less than that of the full azimuth volume (t_f). If $t_1 < t_2$, then $V_1 > V_2$ (shown in red on all difference plots). Similarly, if $t_1 > t_2$, then $V_1 < V_2$ the travel time difference will be negative (shown in blue on all difference plots).

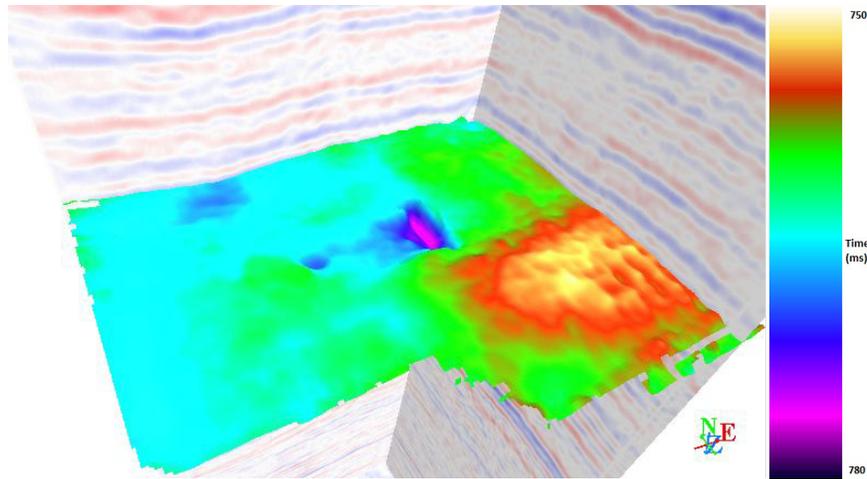


FIG. 9 – The 2004 Dawson Bay horizon picked in the full azimuth seismic volume.

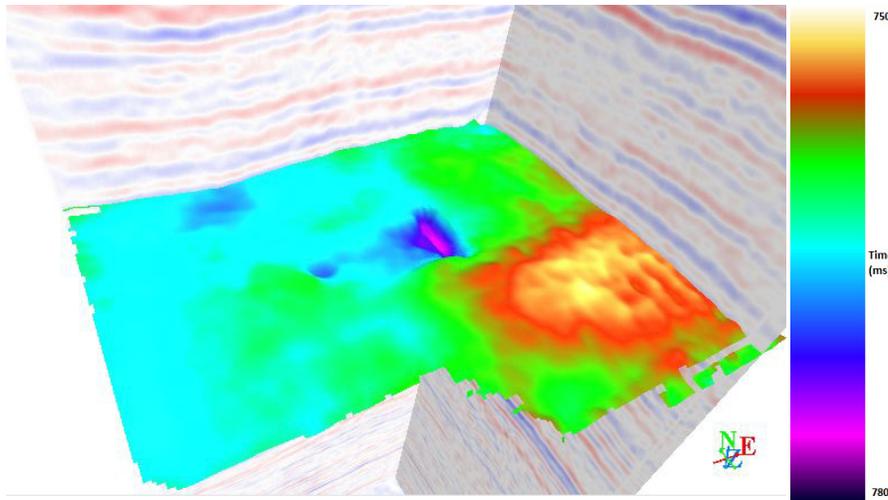


FIG. 10 – The 2008 Dawson Bay horizon picked in the full azimuth seismic volume.

Anisotropy due to fracture planes that are perpendicular to the direction of wave propagation will result in a slowing of the acoustic wave velocity associated with the azimuthally sectorized volume.

If V_1 is higher than V_2 then the fast plane of the HTI medium is in line with that of the initial volume versus the subtracted volume. When V_1 is lower than V_2 then the opposite is true. If fractures are inducing the anisotropy, the fractures can be interpreted to have an orientation parallel to the fast direction of wave propagation, or perpendicular to the slow direction of wave propagation.

RESULTS

In order to determine the extent of anisotropy in the strata of interest, as one would expect, the difference in travel times between horizons in the volumes with perpendicular stacked azimuths should show the most significant variations.

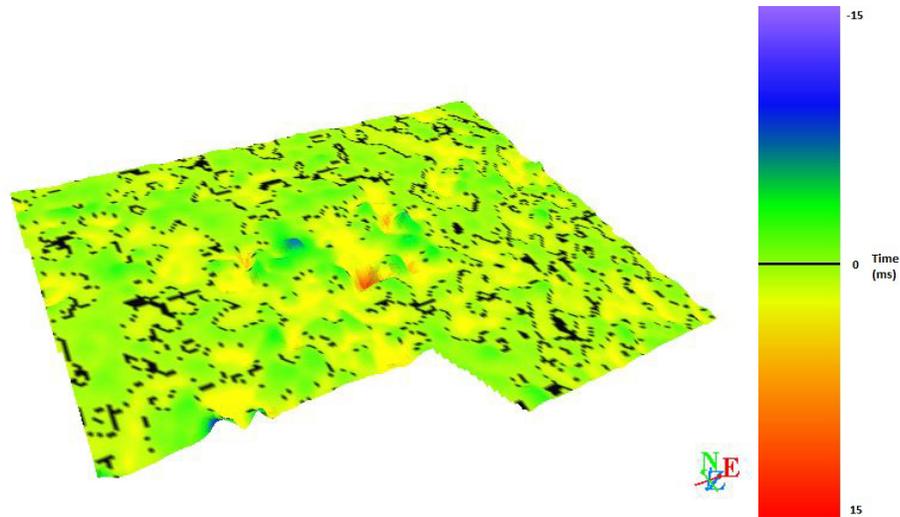


FIG. 11 – The 2004 two-way travel time difference grid for the Winnipegosis Formation shown in 3D. The blue represents a negative travel time difference and the red represents a positive travel time difference between the horizon picked from the 45&225 degree sector volume and the horizon picked from the 135&315 degree seismic volume.

In Figure 12 the difference plots of 0&180 and 90&270 for 2004 are placed in sequence from top to bottom of the stratigraphic column going from left to right, top to bottom. It is evident that when we compare the sector volume for deeper horizons the variation in travel time between these horizons increases significantly from approximately zero to +11ms in places. This positive travel time difference means that the travel times in the 0&180 degree azimuthally stacked volume are greater than those in the 90&270 degree volume, and thus implies a fracture orientation in the 90&270 direction. The most obvious variation is in a similar location to that of the low amplitude, low velocity anomaly shown in Figure 9.

Figures 13 and 15 show the 45&225 – 135&315 plots. The differences for this case are much less significant, although they are certainly still present. A positive result here indicated a fracture orientation of 135&315 degrees. Interestingly the top of the Winnipeg Sandstone exhibits a localized -10ms negative travel time difference. Should these differences be interpreted as being due to vertical fractures in the subsurface, this change of polarity in the plots would indicate a change in fracture orientation from 135&315 to 45&225 degrees over a very short distance, a change in fracture orientation from 135&315 within the Prairie Evaporite Formation to 45&225 within the Winnipegosis Formation.

Similar plots for the 2008 volumes can be found in Figures 13 and 14 and exhibit the same features, although there are slight discrepancies between the plots when it comes to amplitude and size of a specific anomaly (typically anomaly amplitude and size increase from 2004 to 2008).

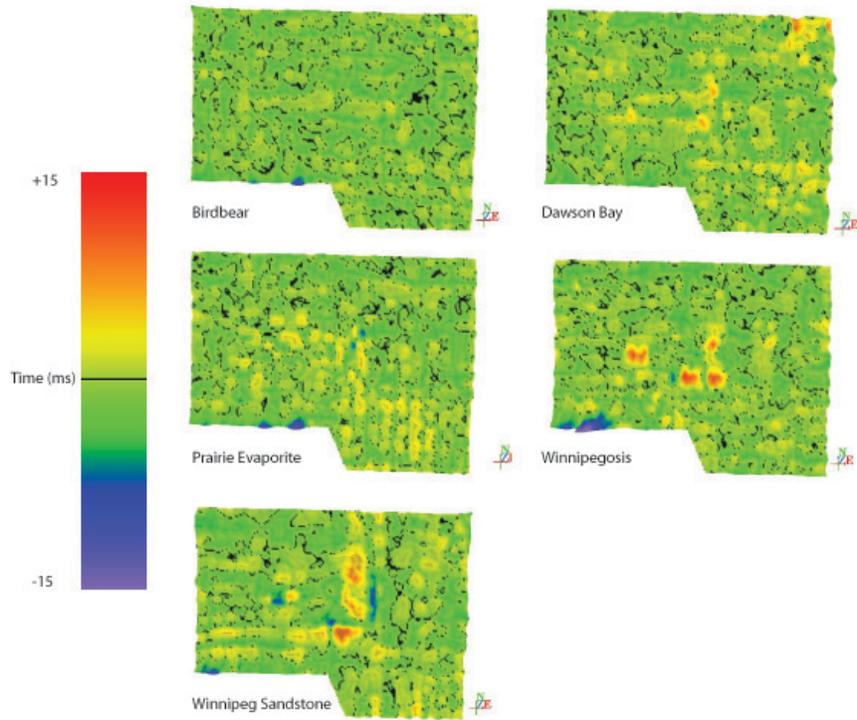


FIG. 12. 2004, 0&180 – 90&270 difference plots with positive and negative travel time differences indicating a preferential fracture orientation in the 90&270 and 0&180 directions respectively. Some acquisition footprint residual is also visible in the difference plots

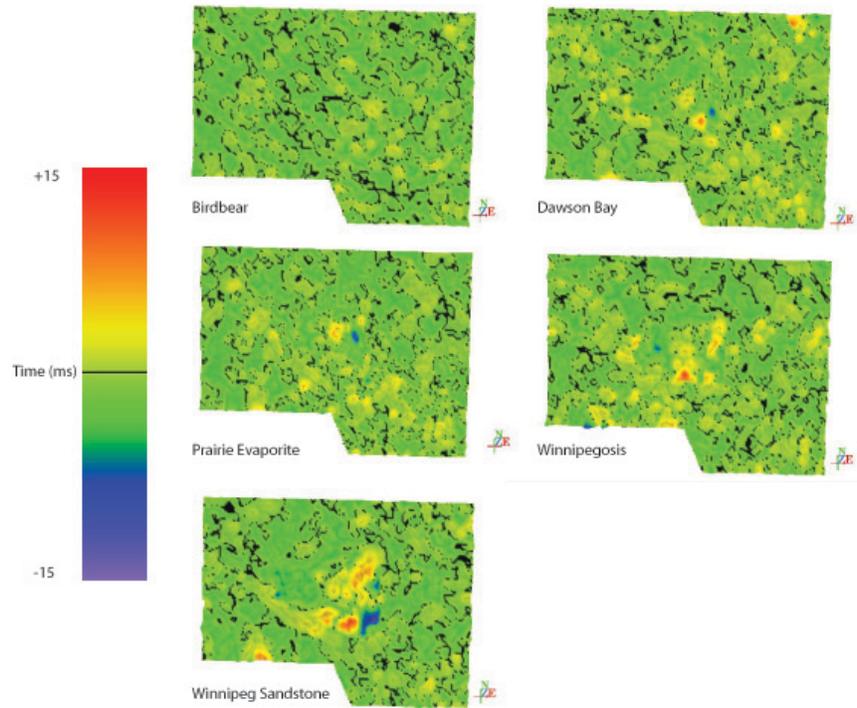


FIG. 13. 2004, 45&225 – 135&315 difference plots with positive and negative travel time differences indicating a preferential fracture orientation in the 135&315 and 45&225 directions respectively.

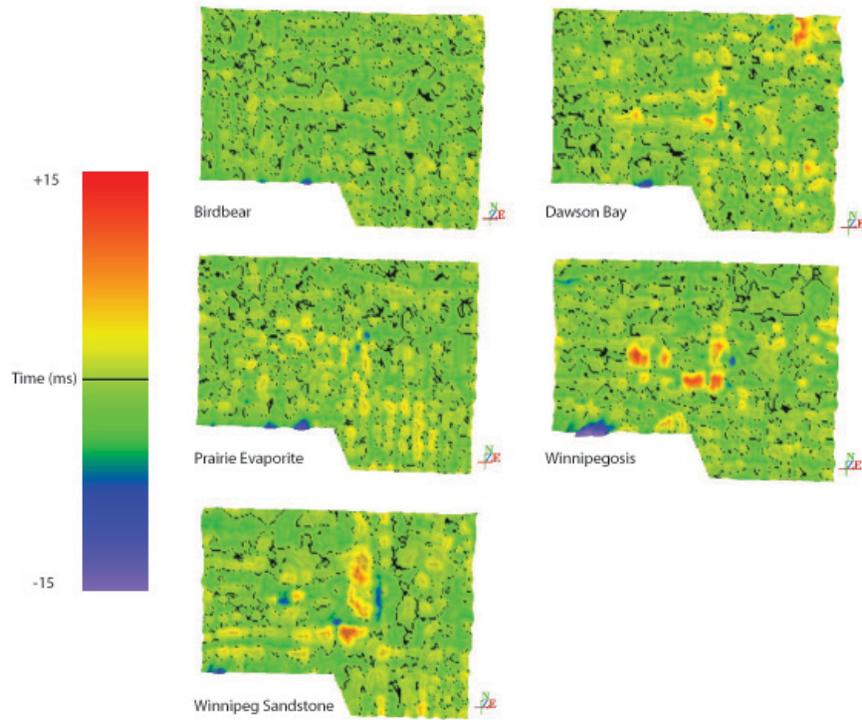


FIG. 14. 2008, 0&180 – 90&270 difference plots with positive and negative travel time differences indicating a preferential fracture orientation in the 90&270 and 0&180 directions respectively.

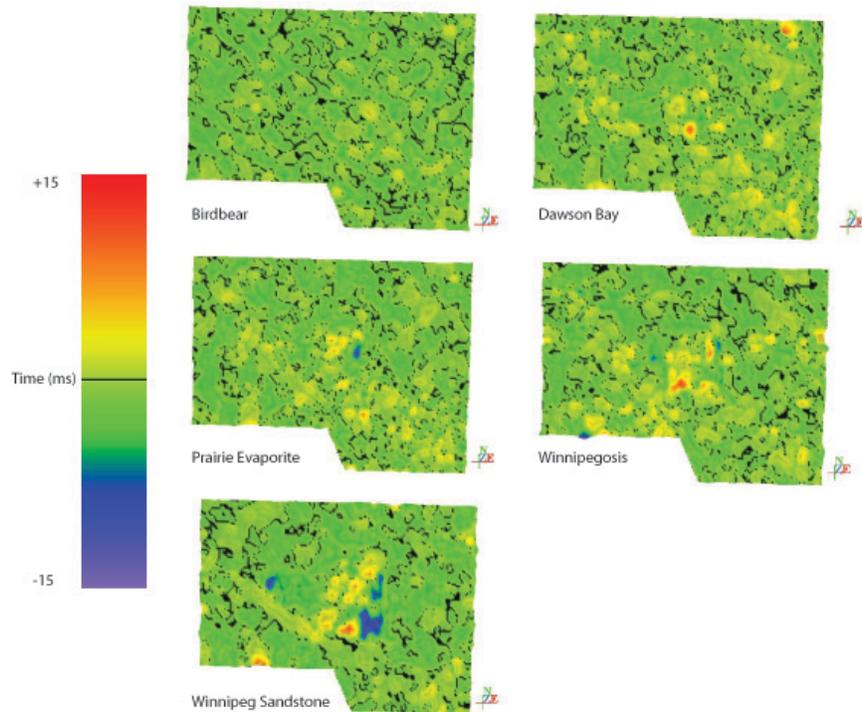


FIG. 15. 2008, 45&225 – 135&315 difference plots with positive and negative travel time differences indicating a preferential fracture orientation in the 135&315 and 45&225 directions respectively.

DISCUSSION

The results obtained through analysis of the two-way time difference plots show the possibility of a dominant reduction in seismic velocity in the 0&180 degree orientation. There is a constant trend between the 2004 and 2008 surveys which suggests that the lithology between the top of the Dawson Bay Formation and the top of the Winnipeg Sandstone exhibit a horizontal transverse isotropy. The stratigraphy above the Dawson Bay has travel time differences that are relatively small with respect to that of the zone of interest implying very low levels of anisotropy in the overlying formations.

These findings support that the Dawson Bay Formation may have been fractured down to the Prairie Evaporite Fm. The reflections from the subsequent layers, the Winnipegosis Formation and the Winnipeg Sandstone, show azimuths of slowness in the two-way travel time difference grids, but it is unclear as to whether or not the anisotropy originates in the strata above the Dawson Bay Formation, in the Dawson Bay Formation or within the Prairie Evaporite and Winnipegosis formations.

In order to determine the cause of these anomalous two-way travel time differences, further analysis of the multicomponent data acquired during these two surveys is needed. The analysis of P-wave data alone does not have the ability to show the full extent of the fracture networks within the subsurface and the analysis of the shear wave data may give some insight depending on the properties of the stratigraphy. Also, the analysis of seismic attributes will help constrain the lithology of the subsurface, and the extent of the discontinuities present that may be influencing or a part of the fracture networks.

ACKNOWLEDGEMENTS

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