Identification of thin sweet spots in the Duvernay Formation of north central Alberta

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Summary

The Duvernay shale liquids play running along the foothills east of the Rocky Mountains, possesses all the prerequisites of being a successful unconventional play, and has gained the attention of the oil and gas industry in Alberta, Canada. Even though, the net shale thickness ranges between 25 and 60 m for most of the play, in places it thins further. Considering the poor vertical resolution of the available seismic data, it is not possible to identify and characterize the thin Duvernay sweet spot zones using seismically-derived attributes. In a recent case study, we found it to be challenging to characterize the thin Duvernay reservoir zone, and consequently developed a workflow that successfully addressed the challenge and identified the thin sweet spots.

Introduction

Although conventional reservoirs remain a very important part of the world's natural gas supply, horizontal drilling and multistage fracturing have now made it possible to develop and exploit unconventional reservoirs. With the successful development of unconventional shale reservoirs in North America, the oil and gas industry has shifted its attention to the Devonian Duverney shale liquids play in Alberta. The Duvernay shale play has been recognized as the source rock for many of the large Devonian oil and gas pools in Alberta, including the early discoveries of conventional hydrocarbons near Leduc. The Duvernay shale basin spans approximately 50,000 square miles, with an estimated 7,500 square miles within the thermally mature or wet gas window (Davis et Al. 2013), from northwest to southeast across Alberta. Its stratigraphic age is equivalent to the Muskwa Formation of the Horn River dry shale gas play to the northwest in the neighboring province of British Columbia (Rivard et al. 2013).

The Duvernay was deposited in a broad marine setting as a basin-filling shale, surrounded by equivalent aged Leduc reef build-ups. Due to rapid basin filling during maximum sea-level transgressions, enormous quantities of organic sediments were dumped in this deep, oxygen-starved basin that are the present day Duvernay source rocks, where TOC (total organic carbon) is as high as 20% (McMillan et al.,2014). The Duvernay shale is fine-grained and silica rich. As a result of the fine grains, rocks have increased total surface area that leads to a higher absorbed gas component in organic-rich rocks. Moreover, silica-rich rocks are more brittle and favorable for fracking. It is also known that the Duvernay formation is overpressured that leads to better storage of hydrocarbons. For these reasons the Duvernay shale is considered as an emerging shale liquids play in Canada.

The workflow

A successful shale resource play can be identified based on the maturation, mineralogy, pore pressure, thickness, organic richness, permeability, brittleness and gas in place (Chopra et al., 2012). However, the determination of elements such as maturation and mineralogy from the seismic data is difficult. The organic richness refers to the total organic content (TOC) in the shale rocks and influences properties such as compressional and shear velocities, density and anisotropy. Therefore, it should be possible to detect changes in TOC from the surface seismic response.

Brittleness is a key property that reservoir engineers are interested in as brittle rocks fracture much better than ductile rocks. This information can be extracted using Young's modulus (E) or $E\rho$ and Poisson's ratio (Sharma and Chopra, 2013). These properties are a function of P-impedance (I_P), S-impedance (I_S) and density. Simultaneous inversion run on prestack seismic data allow us to compute I_P, I_S, V_P/V_S, Poisson's ratio and density (depending on the data quality). Mostly, zones with high Young's modulus and low Poisson's ratio are found to be brittle. Similarly, zones with higher TOC as well as higher porosity are better reservoirs.

Usually the shale formations considered for reservoir characterization are thick, where the resolution of seismic data is not considered a serious issue. However, the Upper Duvernay formation being considered in this case study is not thick throughout and for most of the survey falls below seismic resolution. Thus a method to enhance the resolution of the seismic data is needed as part of the workflow. The method of choice for us was the thin-bed reflectivity inversion that has been described and illustrated elsewhere (Chopra et al., 2006; Puryear and Castagna, 2008).

In this process, the time-varying effect of the wavelet is removed from the data and the output of the inversion process can be viewed as spectrally-broadened seismic data, retrieved in the form of broadband reflectivity which can be filtered back to any desired bandwidth. This usually represents useful information for interpretation purposes. Filtered thin-bed reflectivity, obtained by convolving the reflectivity with a wavelet of a known frequency band-pass,

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not only provides an opportunity to study reflection character associated with features of interest, but also serves to confirm its close match with the original data.

Thin-bed reflectivity inversion is a poststack process and rather than using simultaneous inversion in our workflow, we modified it by including the application of Fatti's approximation to Zoeppritz equations (Fatti et al., 1994) and extracting P-reflectivity, S-reflectivity and density-reflectivity (which depends on the data quality) from the angle gathers. Once these reflectivities were obtained, thin-bed reflectivity inversion was run on each individually. Next, the output of thin-bed inversion is considered as input for a model-based inversion to compute P- impedance, S-impedance and density. These attributes are then used to derive λρ, μρ μρ and V_P/V_S.

The case study

As stated earlier the Duvernay Formation is an Upper Devonian source rock that covers a significant part of west-central Alberta of the Western Canadian Sedimentary Basin (WCSB), as shown in the index map in Figure 1 (Rokosh et al. 2012). In Alberta, the Duvernay shales are found in the East shale basin and West shale basin, both of which differ in the geological setting and their characteristics. The present study focuses on a dataset, from central Alberta and situated in the West Shale Basin. Here, even though the Duvernay formation is 44 m thick, the thickness of Upper Duvernay (productive zone) is only 17 m in thickness.

In order to characterize the Duvernay Formation, we begin with the appropriate log curves for crossplotting. We first derive those attributes that can be derived seismically and can be used for characterization of the zone of interest. Through this analysis we found that the Upper Duvernay can be characterized in λρ - μρ and Eρ - Poisson's ratio domains. Armed with this information from the well-log data, we decided to derive these attributes from seismic data. Amplitude spectra of seismic data within the zone of interest suggested that 20 Hz is the dominant frequency. Using an average P-wave velocity for the ZOI, the vertical resolution for this data set was found to approximately 48 m, which meant that geological features below 48 m thickness would not be identified using seismic data. Therefore, characterization of a 17 m thick Duvernay Formation was a challenging prospect.

Simultaneous inversion facilitates the estimation of P- and S-impedances and density from the prestack seismic gathers. In this inversion we began with initial low-frequency model and generated synthetic traces. Generation of the synthetic traces requires an angle dependent wavelet that is convolved with the modeled reflectivity. Further, the model impedance value is gradually perturbed such that the mismatch between modeled angle gather and real angle gather is minimized in a least squares sense. Once impedances were obtained, we computed Young's modulus and Poisson's ratio volumes which were then interpreted for brittleness information. Although, density estimation from seismic data requires the far-offset information, its quality and fidelity deteriorate significantly at large angles of incidence. So, in the absence of the density attribute, estimation of Young's modulus is difficult. In this scenario, the Eρ attribute is very useful for obtaining brittleness information (Sharma and Chopra, 2012, 2015).

Crossplots of λρ - μρ and Eρ - Poisson's ratio attributes are shown in Figures 3 and 4, respectively. Based on the crossplot analysis that had been carried out on the well log data earlier, points that have characteristics of the Duvernay sweet spots have been enclosed by the red polygon. The back projection of this polygon onto the seismic section helped us understand where these points were coming from, as shown on the lower portion of Figures 3 and 4 respectively. It was noticed here that points enclosed with the red polygon were coming from a zone that comprised both Upper and Lower Duvernay Formation. Thus, the obvious conclusion was that attributes computed from simultaneous inversion could not differentiate between the Upper and Lower Duvernay zones, due to the poor resolution of prestack seismic data.

We then turned our attention to the enhancement of the input data for impedance inversion, so that the derived attributes lead to better interpretability. After generating angle gathers from the conditioned offset gathers, Fatti's approximation to Zoeppritz equations (Fatti et al., 1994) is used to compute *P*-reflectivity (R_P) and *S*-reflectivity (R_S). The density attribute could not be extracted as the seismic data was not acquired with long offsets. Once reflectivities were extracted, thin-bed reflectivity inversion (Chopra et al., 2006) was performed on each individually. In Figure 5, we show a comparison of the filtered thin-bed reflectivity inversion with the P-reflectivity seismic data. Additional reflection event cycles are present in the zone of interest (ZOI), and the overlaid impedance logs confirmed that the additional events were genuine. Next, a well-tie analysis was performed using the filtered P-wave reflectivity with a broader bandwidth than the input seismic, and is shown in Figure 6. On comparison it is noted that additional events created by the thin-bed reflectivity inversion match fairly well with the well data, and therefore could be trusted. Having gained the confidence in the frequency enhancement of R_P and R_S, these reflectivities were filtered and inverted into P- and S- impedances, individually, using poststack model-based inversion. Having extracted the impedances, other attributes such as λρ, μρ and Eρ, Poisson's ratio were also computed. The crossplotting of these attributes is usually used to delineate the

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hydrocarbon-bearing shale pockets. Figure 7 shows the crossplot of λρ vs μρ. As in Figure 3, two polygons have been drawn on this crossplot and then back projected on the seismic section shown in the lower part of Figure 7. It was noted that points enclosed by the blue polygon were coming from the Lower Duvernay interval while the points enclosed by the red polygon come from the Upper Duvernay interval.

Next, for extracting information on brittleness, we crossplot Eρ vs Poisson's ratio which is shown in Figure 8. Brittle rocks usually exhibit low Poisson's ratio and high Eρ. Two polygons corresponding to low and high Eρ are drawn on the crossplot. Both the polygons share the same range of Poisson's ratio. Back projection of these polygons on the seismic section reveals that Upper Duvernay interval is more brittle than Lower Duvernay interval.

To study the areal distribution of the sweet spots, a 3D volume was created for the broad zone of interest, by restricting the values of different attributes (λρ, μρ, Eρ, σ) based on the crossplots shown in Figures 7 and 8. Instead of interpreting the individual attribute volumes, such a constrained volume is very convenient for identifying the sweet spots. Figure 9 shows the horizon slices from the constrained data over the ZOI. Green color represents the characteristics of Upper Duvernay interval (sweet spots) while Lower Duvernay interval is represented by yellow color.

Conclusions

Considering the Duvernay Formation as an emerging shale liquids play in Canada, an attempt was made to characterize it using seismic data from the study area in central Alberta. Understanding the importance of λρ - μρ and Eρ - Poisson's ratio attributes for identifying the sweet spots in an unconventional play, simultaneous inversion was performed first to extract these attributes. As the thickness of the zone of interest was far below the vertical resolution of the seismic data, it was not possible to identify the sweet spots in the Duvernay interval using inversion attributes. Next, we adopted a workflow in which P- and S-reflectivities processed through a thin-bed reflectivity inversion before being inverted into P- and S-impedances. This workflow, enabled us to differentiate between the Upper and Lower Duvernay intervals. Sweet spots were identified based on the constrained volume that was created using multiattributes.

Acknowledgements

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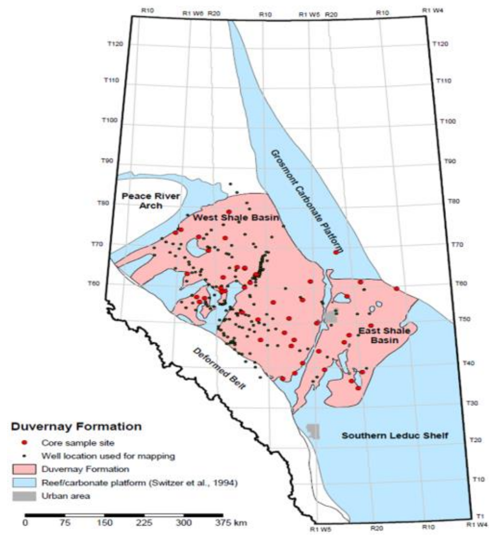

Figure1: Index map showing the Duvernay Formation in the province of Alberta (After Rokosh et al. 2012).

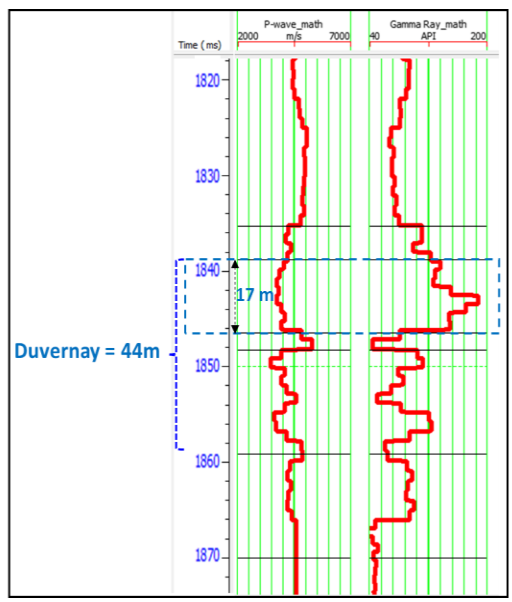

Figure2: The Duvernay interval of interest highlighted by the rectangular zone. Even though thickness of Duvernay interval is 44 meter, the Upper Duvernay interval with thickness of 17 meter is below the vertical resolution of the seismic data.

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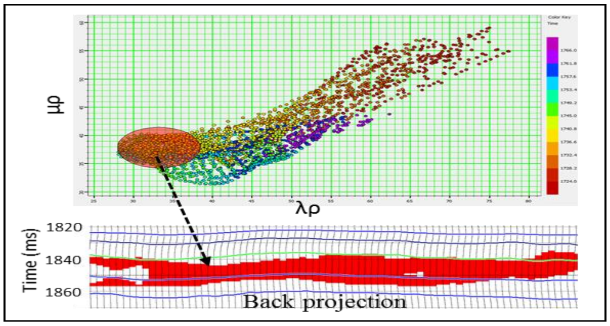
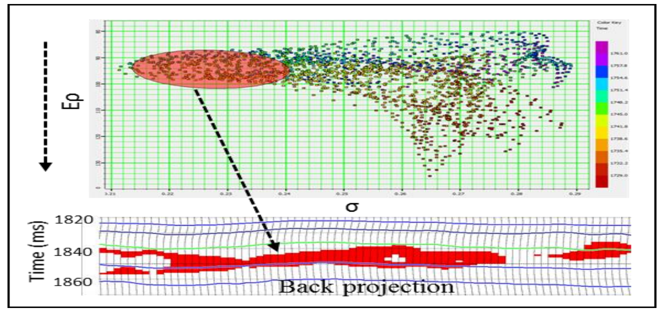


Figure 3: Crossplot of λρ vs μρ (upper) derived using simultaneous inversion. Points enclosed by red polygon shows the characteristics of the source rock. Back projection on the seismic section (lower) reveals that it is not possible to differentiate between U. and L. Duvernay here.



4: Crossplot of Eρ vs Poisson's ratio derived using simultaneous inversion. Interpretation similar to that in Figure 3 can be considered.

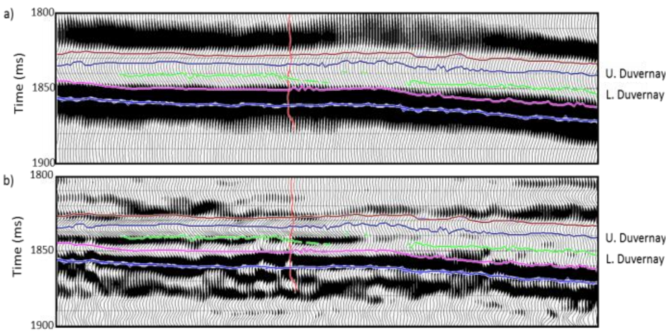


Figure 5: P-wave reflectivity section (a) before and (b) after thin-bed reflectivity process. Notice the extra events and more detailed information over the ZOI.

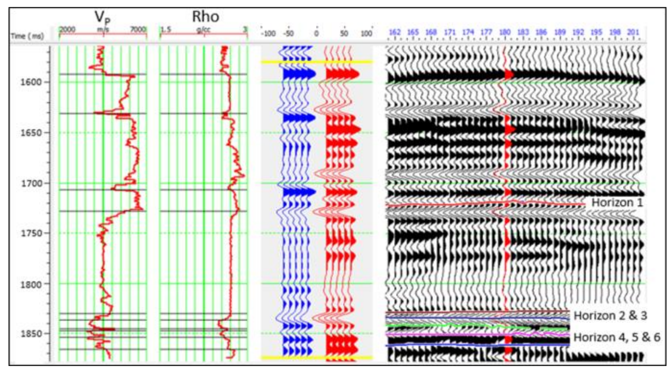


Figure 6: Well to seismic tie with the filtered P-wave reflectivity. Correlation of extra events in the ZOI provide the confidence in frequency enhancement.

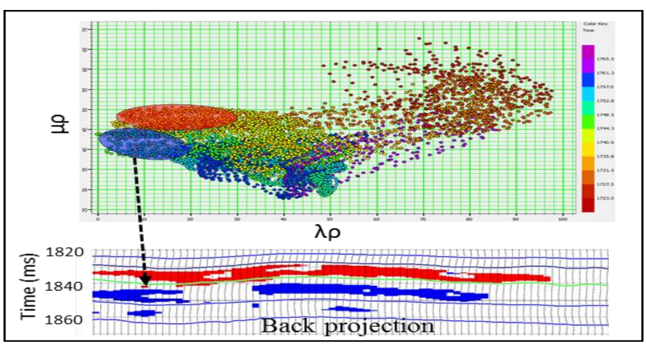


Figure 7: Crossplot of λρ vs μρ when the new approach is used. Back tracking of the polygons help differentiate between Upper and Lower Duvernay intervals.

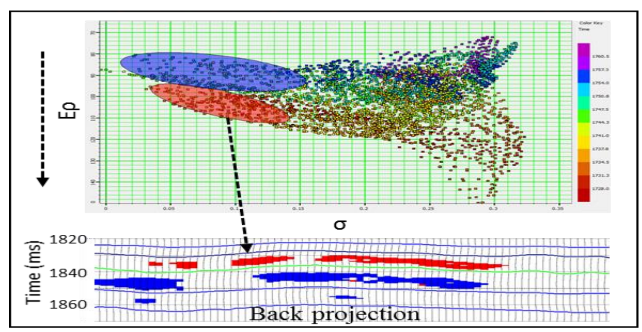


Figure 8: Crossplot of Eρ vs σ when the new approach is used. With the help of it we are able to differentiate between Upper and Lower Duvernay intervals.

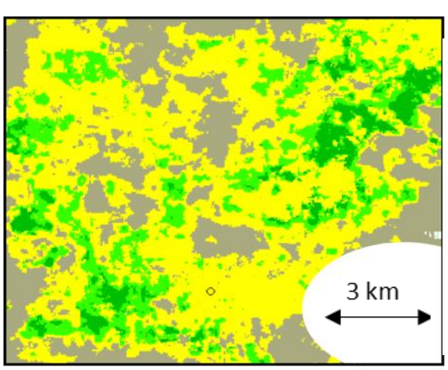
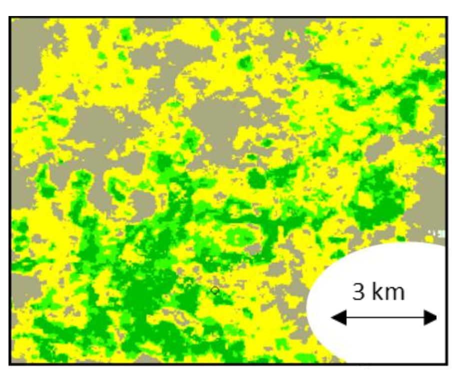


Figure 9: Horizon slice from the constrained data volume in a (left) 10ms interval below the Duvernay top marker, and (right) in another 10ms interval below the one shown in left. The distribution of Upper Duvernay is shown in green color and Lower Duvernay in yellow.



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EDITED REFERENCES

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