Estimation of density from seismic data without long offsets – a novel approach.

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Summary

Estimation of density plays an important role in characterizing subsurface reservoirs. Reliable determination of density from noise-free seismic data requires long offsets, or it can be determined from measured converted waves. As the acquisition, processing and interpretation of multicomponent seismic data entails more time and cost, their use has been slow in our industry. Considering the importance of the density attribute in the determination of lithology and fluid discrimination, we describe a novel approach for its determination from conventional (PP) seismic data. The key point of this approach is that it does not require long offsets. Though this methodology has been applied to a variety of reservoir characterization exercises, we describe its application to the Montney Shale Formation in the Montney-Dawson area of British Columbia, Canada. We also demonstrate a comparison of the proposed approach with simultaneous impedance inversion application to long-offset seismic data for determination of density. The proposed approach has shown encouraging results.

Introduction

The determination of density and fluid discrimination plays an important role in reservoir characterization exercises as its accuracy leads to the sinking of fewer wells in the ground, drawing higher recoveries from them, improving stimulation and completion practices, and lowering uncertainty in production forecasts (Jia et al., 2012). Both the compressional wave velocity (V_P) and shear velocity (V_S) are important for reservoir characterization, with the former being related to the rock matrix and the fluid contained in the pores of the rock, and the latter being only related to the rock matrix. Besides V_P and V_S, density is an important elastic parameter that relates to porosity, fluid type and its saturation, as well as mineral composition (Li, 2005). It has also been observed in several instances that hydrocarbon reservoirs do not show an appreciable lowering of V_P compared with the nonreservoir rocks, as would be expected. In contrast, density has proven to be a hydrocarbon indicator (Silva et al., 2013). Crossplotting between different rock parameters and pore fluids also demonstrates that density provides the best differentiation between hydrocarbon reservoirs and other rock/fluid types (Van Koughnet et al., 2003). However, the determination of density from seismic data is not an easy task. The two usual ways of obtaining density estimates are through the application of simultaneous impedance inversion to long-offset, good quality seismic data, and the joint-inversion of multicomponent seismic data. As the acquisition of multicomponent seismic data is still not a routine practice in our industry, density is commonly determined through prestack simultaneous inversion of seismic data with long offsets, through the 3-term approximation of the Zoeppritz equations. Such a density determination is dependent on the quality of the seismic data, and is not considered very reliable.

We discuss a novel way of estimating density through the application of extended elastic impedance without the need for long-offset seismic data.

The method

Elastic impedance (EI) as proposed by Connolly (1999) provides an absolute framework for calibrating and inverting non-zero offset seismic data. EI is a function of V_P, V_S, density (ρ) and the angle of incidence (θ), and is given as

$$EI = V_p^{(1+\sin^2\theta)} V_s^{(-8K\sin^2\theta)} \rho^{(1-4K\sin^2\theta)}. \quad (1)$$

While useful, Whitcombe (2002) pointed out that the elastic impedance units vary significantly with the incidence angle and so displaying acoustic impedance and elastic impedance logs together becomes inconvenient. He introduced normalizing constants that removed the dimensionality of EI on angle θ. Whitcombe et al. (2002) extended the elastic impedance concept so as to make it valid beyond the physically meaningful angles, by substituting tanχ for $\sin^2\theta$ in the two-term reflectivity equation. This changes the primary variable from θ to χ, which is now allowed to vary between -90º to +90º. The 2-term reflectivity equation can now be written as

$$R(\chi) = A + B\tan\chi. \quad (2)$$

where A and B and are intercept and gradient. Referring to this as extended elastic impedance, Whitcombe et al. (2002) recast equation (1) as follows

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$$\mathrm{EEI}(\chi) = \alpha_0 \rho_0 \left[\left(\frac{\alpha}{\alpha_0}\right)^p \cdot \left(\frac{\beta}{\beta_0}\right)^q \cdot \left(\frac{\rho}{\rho_0}\right)^r \right] \quad (3)$$

where $p = \cos\chi + \sin\chi$, $q = -8k\sin\chi$ and $r = \cos\chi - 4k\sin\chi$, α_0, β_0 and ρ_0 are the average values of compressional velocity, shear velocity and density respectively, and k is the average of $(V_S/V_P)^2$. The advantage of EEI is that it allows impedance inversion to be applied to the data for determination of lithology or fluid information. EEI approaches acoustic impedance (AI) as χ tends to zero, and it tends to gradient impedance (GI) as χ tends to 90º. Applications of AI and GI for AVO analysis and calibration as well as determination of net-to-gross have been discussed by Vernik and Fisher (2001) and Davis (2002).

Whitcombe et al. (2002) described a workflow wherein a cross-correlation analysis is first carried out between extended elastic impedance logs for various values of χ and the available petrophysical logs, and the pair of curves that shows the highest measure of correlation yields the optimal value of angle χ for a given rock property. This way the estimation of various rock properties such as bulk modulus, shear modulus, and Lame' parameter can be carried out in the extended elastic impedance domain. The application of this workflow to seismic data begins with the derivation of the intercept and the gradient attributes from AVO analysis. The linear combination of the intercept, gradient and angle χ results in a poststack data volume for the reservoir property for which the optimal χ value was determined. We have made use of this workflow for determination of density from seismic data with the use of simultaneous impedance inversion. In this respect we believe the results from this approach are more robust than obtained from first deriving the AVO attributes and then putting them through poststack impedance inversion.

By putting χ = 90º, and k = 0.25, equation (3) can be written as

$$GI = \rho_0^2 \beta_0^2 \left[\frac{\alpha}{\rho\beta^2}\right] = \rho_0^2 \beta_0^2 \left[\frac{\alpha\rho}{\rho\beta^2\rho}\right] = \rho_0^2 \beta_0^2 \left[\frac{I_P}{I_S^2}\right]. \quad (4)$$

In a similar way, extended elastic impedance at angle χ = 45º can be written as

$$EEI(45^{\mathrm{o}}) = \alpha_0 \rho_0 \sqrt{\frac{\beta_0}{\alpha_0}} \frac{I_P}{I_S}. \quad (5)$$

While simultaneous inversion facilitates the derivation of I_P and I_S, α_0 and β_0 can be computed using well log data. Equations (4) and (5) can be algebraically manipulated to arrive at what we refer to as *pseudodensity*, which may be written as

$$Pseudo\ density = \frac{[EEI(45^{\mathrm{o}})]^2}{GI}. \quad (6)$$

As the computation of density using equation (6) may be a scaled version instead of absolute density, we refer to it as pseudodensity.

Validation of pseudodensity on Montney Formation

We sought the validation of our pseudodensity approach on well log data as well as seismic data from different areas. The case study we discuss here is from the Montney shale play in British Columbia, Canada, for which we had the well log curves as well as seismic data with long offsets. Picking up the well log data first we computed the GI attribute using extended elastic impedance, and then using our proposed approach discussed above. A crossplot of the two versions of GI is shown in Figure 1, where we notice a correlation of 99%. Similarly, a crossplot of the measured density curve against the pseudodensity attribute derived using equation (6) is shown in Figure 2, where a correlation of 91% is noticed. This analysis lent confidence in our proposed approach. Satisfied with the application of the approach on well log data, next we turned to its application to seismic data. Simultaneous inversion was run on the prestack data to obtain I_P, I_S and density, noting that the accuracy of derived pseudodensity would depend on the accuracy of the inversion. As the seismic data was acquired with long offsets, density attribute could be determined. In Figures 3, 4 and 5 we show an arbitrary line extracted from the I_P, I_S and density volumes respectively and passing through a blind well. A reasonably good match is noticed between the inverted attributes and the respective log curves overlaid on them.

Finally, the computation of pseudodensity was carried out with the workflow as discussed above. As a quality check, a crossplot of P-impedance versus density was generated from well log data from the Montney zone as shown in Figure 6, and compared with a similar crossplot between the inverted P-impedance and pseudodensity from seismic data shown in Figure 7. Both the crossplots exhibit comparable trends which provides the necessary assurance of the quality or accuracy of pseudodensity. In Figures 8 and 9 we show an arbitrary section through the inverted density and pseudodensity respectively covering the Montney zone, with the density curve overlaid on both. We notice that similar patterns of the events are noticed on both the sections, but more detailed information is apparent on the pseudodensity section. Horizon slices extracted from both these volumes are shown in Figure 10, with again the pseudodensity display showing higher frequency content. The main reason for this difference is perhaps due to the fact that the pseudodensity computation makes use of the near- and the mid-angle stacks, and the inverted density is derived from the far-angle stacks, which have a lower frequency content.

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Conclusions

Considering the importance of density in defining hydrocarbon reservoirs and the problems associated with its estimation, a novel approach of computing density has been established. The application of the proposed approach to the Montney play in Canada has been demonstrated by considering both the well and seismic data. With well data, the computed pseudodensity when compared with the measured density in the Montney interval showed good correlation. Pseudodensity derived from seismic data not only compared nicely with the inverted density extracted using simultaneous inversion, but provided more detail as well, which was encouraging. Key to this approach of deriving the density attribute is that neither the conventional seismic data with long offsets, nor the converted-wave PS data are required. Both these types of data are usually not readily available.

The proposed pseudodensity approach has been applied to other datasets which have also provided encouraging results.

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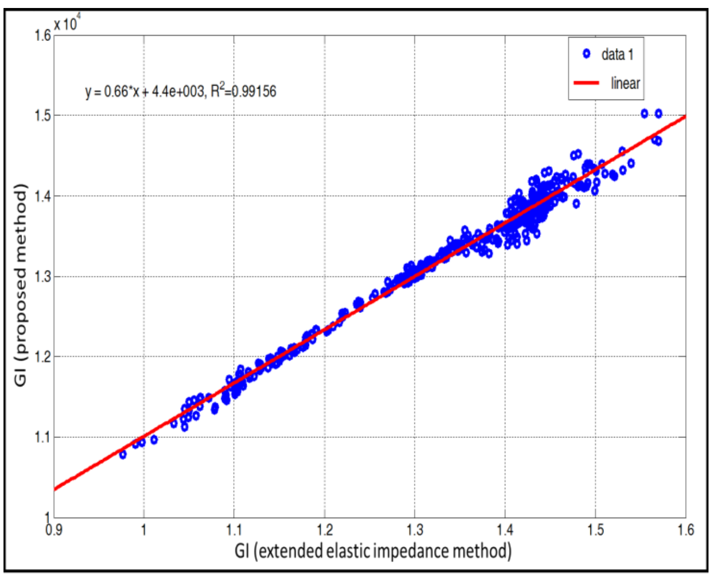

Figure 1: A crossplot of GI computed using extended elastic impedance method (equation 3) against GI computed with the proposed method (equation 6) making use of well log data. A correlation of 99% is noticed.

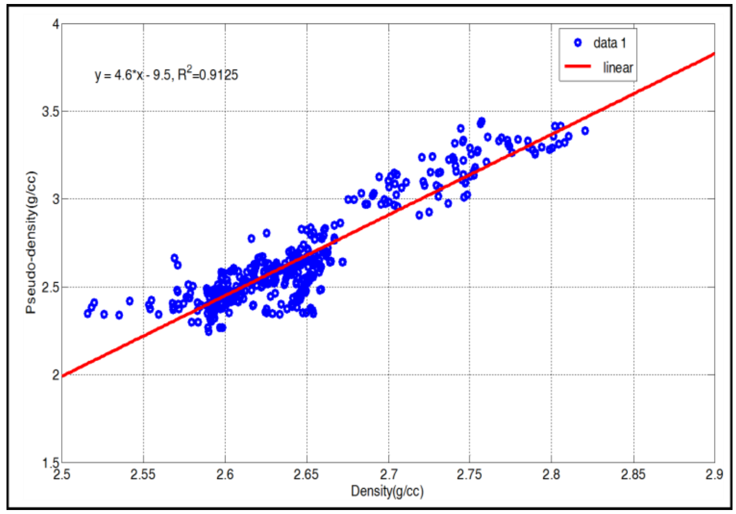

Figure2: A crossplot of measured density and pseudo density computed using GI and EEI (45^0) as shown in equation 6, using well log data. A correlation of 91% is noticed.

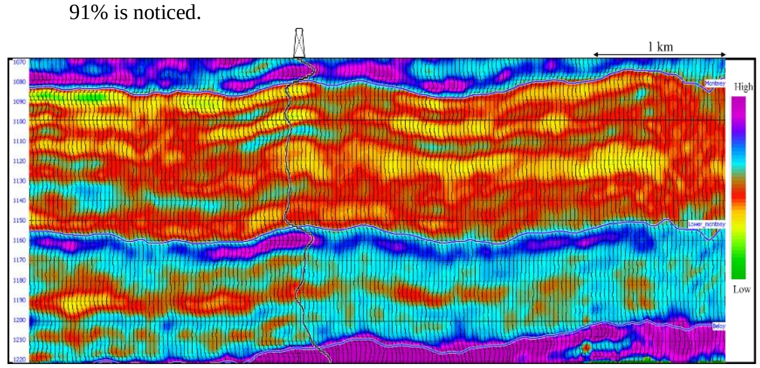

Figure 3: Segment of a section from the inverted P-impedance volume (computed using simultaneous inversion) passing through a blind well. A reasonably good match is noticed with impedance curve at the well location.

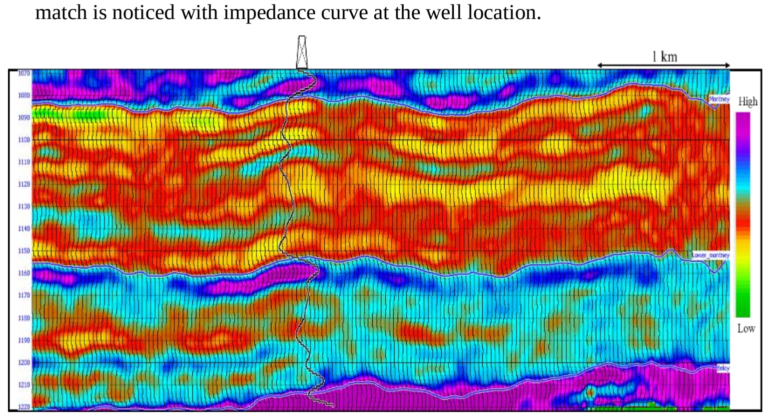

Figure 4: Segment of a section from the inverted S-impedance volume (computed using simultaneous inversion) passing through a blind well. S-impedance log curve shows good match with inverted impedance at the well location.

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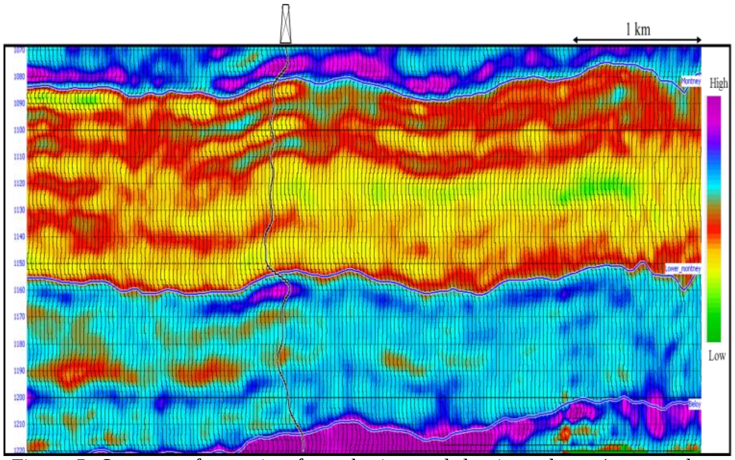

Figure 5: Segment of a section from the inverted density volume (computed using simultaneous inversion) passing through the blind well. A reasonably good match is noticed with measured density at the well location.

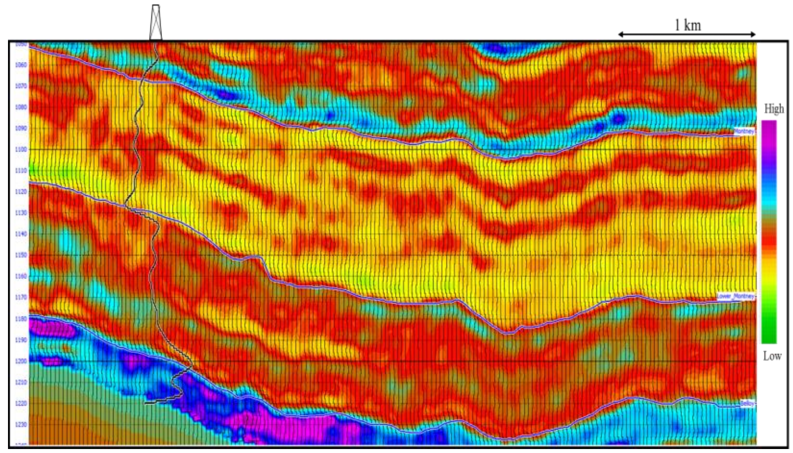

Figure 8: An arbitrary section extracted from the inverted density volume(simultaneous inversion).

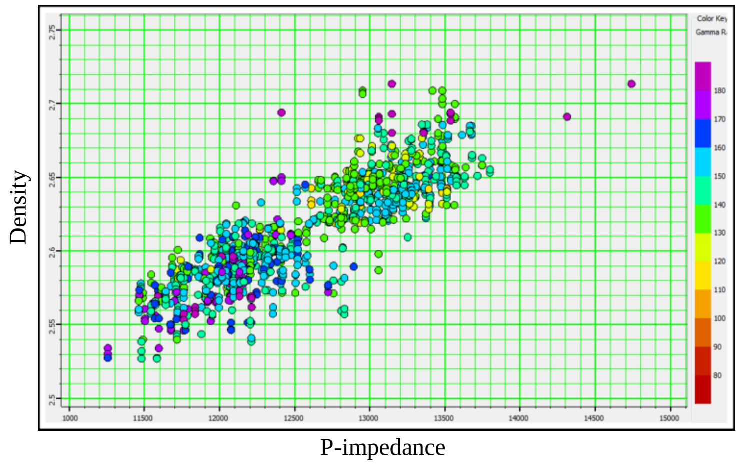

Figure 6: Cross-plot of measured P-impedance and density using well log data for 4 wells.

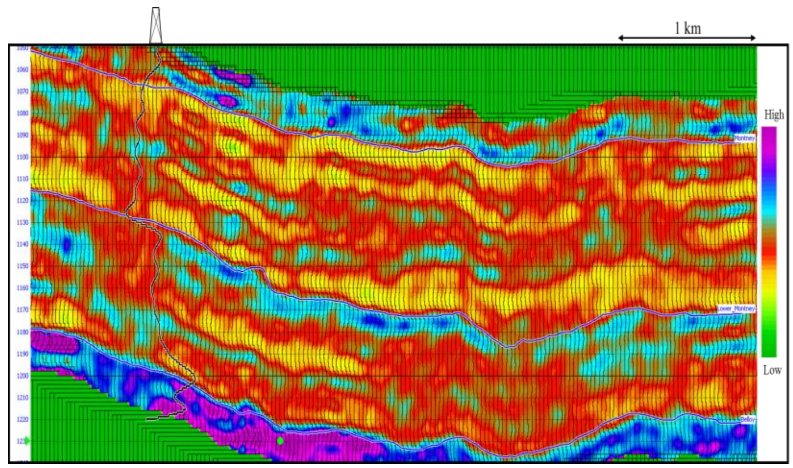

Figure 9: An arbitrary section extracted from the pseudo density volume. On comparison with figure 8, in addition to a similar pattern of events, detailed information is seen.

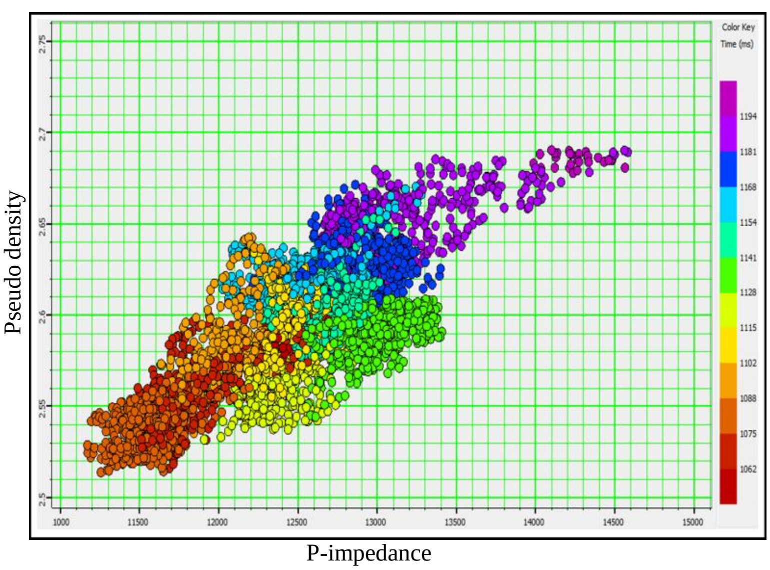

Figure 7: A cross-plot of inverted P-impedance and pseudo density exhibits a similar trend as noticed on well log data.

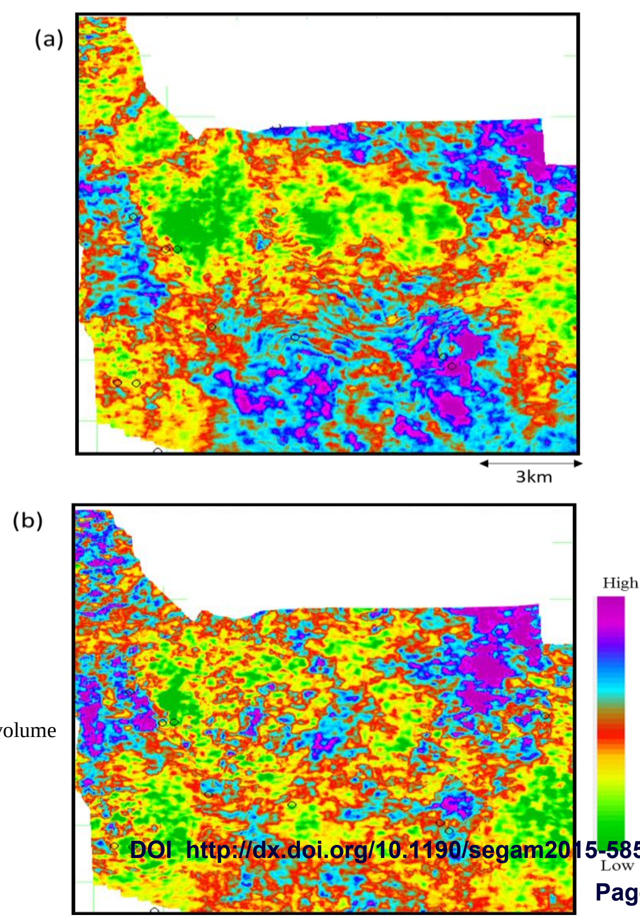

Figure10: Horizon slices in the Montney interval extracted from (a) inverted density volume (b) pseudo density volume. High frequency content is noticed in (b).

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EDITED REFERENCES

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