geoconvention
Calgary • Canada • June 17-19 2024

Examining the bias - variance tradeoff for seismic inversions characterizing the Montney formation

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Summary

There is an inherent bias present in all seismic inversions that is required to provide reasonable estimates in the presence of noise. The choice of inversion type and prior model will have an impact on the final characterization, and we examine an example of a facies-based inversion carried out on a Montney development. We show that increasing noise levels require stronger constraint and reliance on prior models. This leads to some bias in the resulting impedances, but that the overall characterization is improved using these constraints. The type of inversion method determines the prior models, and these will have a particular influence on final estimates. Ultimately careful selection of these prior assumptions is required to produce the most reasonable assessment of in-situ reservoir properties.

Workflow

The process of seismic inversion aims to predict the 3D subsurface elastic properties. This is a difficult challenge, with the precision of the results limited by both bandwidth and noise. Typically, a reasonable prior model of the properties is introduced to reduce the impact of noise and bandwidth limitations. This involves a tradeoff where we bias our results with a pre-determined model rather than accepting a direct interpretation of the seismic amplitudes, to reduce the overall error in our estimates. Understanding this tradeoff is important for all geoscientists, as it has a direct impact on subsequent reservoir characterization and development decision making.

In statistics this is known classically as the 'Bias-Variance' trade-off, and is related to seeking the maximum posterior probability (MAP) estimate in a Bayesian formulation. Simultaneous inversion and facies-based inversion are two important Bayesian seismic inversion methods that differ in how they specify the prior model, and this has a predictable impact on the elastic property estimates. To illustrate, we consider a simplified model to show how the estimates behave, omitting seismic wavelets and convolution for brevity.

A simultaneous inversion employs a prior model corresponding to interpolated well data, possibly augmented with imaging velocities, which we denote by μ_{LFM}. For a single point measurement of acoustic impedance (*d*) in a noisy environment, the MAP estimate of the impedance can be written

$$m_{siminv} = w\, d + (1 - w)\, \mu_{LFM} \tag{1}$$

where the weight (*w*) is typically selected by trial and error to produce the best fit at available wells, but can be formally stated as

$$w = \frac{1}{1 + s_N / s}$$

where s is the variance of the true impedances and s_N is the variance of the noise in the measurement d. We can see that there is a linear weighting between the prior model μ_{LFM} and the measurement d, and the weight favors the prior model when the noise level is high. This is a bias built into the estimate, but it reduces the overall mean square error of the result.

For a facies-based inversion with just two facies, the corresponding MAP estimate can be written

$$m_{faciesinv} = w_0\, d + w_1\, \mu_1 + w_2\, \mu_2 \qquad (2)$$

where

$$w_0 = \frac{1}{1+p_1 s_N/s_1 + p_2 s_N/s_2},\; w_1 = \frac{p_1 s_N/s_1}{1+p_1 s_N/s_1 + p_2 s_N/s_2}\; and\; w_2 = \frac{p_2 s_N/s_2}{1+p_1 s_N/s_1 + p_2 s_N/s_2}\;,$$

the symbol μ_k represents the average impedance for the kth facies, and p_k is the probability of the facies given the impedance estimate m. What we can see directly is that when the noise level is high, the estimate is again weighted to a prior model, but now the prior model is built from a combination of the average impedances from the facies. This form of constraint is especially effective when the facies are well characterized by the impedance.

Observations

We show an example of the bias-variance tradeoff by examining a facies-based seismic inversion carried out on the Montney formation. The Montney is a major source of unconventional gas production that is comprised of turbiditic sandstones, siltstones and shales with organic content. Variation in porosity from sandier event beds form important targets for development, and we focus on one such area. A standard workflow consisting of rock physics, seismic data conditioning and seismic inversion was carried out using AVO compliant processed seismic gathers covering the region. Limited well control was available, and two elastic facies were identified from the bimodal distribution of properties corresponding to a clay-rich siltstone and a target sandstone. The left side of Figure 1 shows an example of a facies-based inversion result in which a weak constraint was placed on the inversion (i.e. low s_N/s). Non-geologic features appear that are triggered by residual noise in the seismic data. This corresponds to a low bias, high variance result. The right-hand image shows an improved inversion that has been parameterized with a higher noise level, which corresponds to a higher bias and lower variance option.

The bias in the two inversions can best be seen by examining the posterior elastic properties in Figure 2. The left image represents well data, while the center and right images show the distribution of inverted elastic properties calculated with low and high constraints applied respectively. We see that with a stronger constraint (high noise), the data are more clustered around the facies averages, which is a form of bias that we have accepted to reduce the variance seen in Figure 1.

We see that it is necessary to have some bias to produce realistic seismic inversion results in the presence of noise, and it is natural to question the impact of any bias on subsequent characterization of the reservoirs.

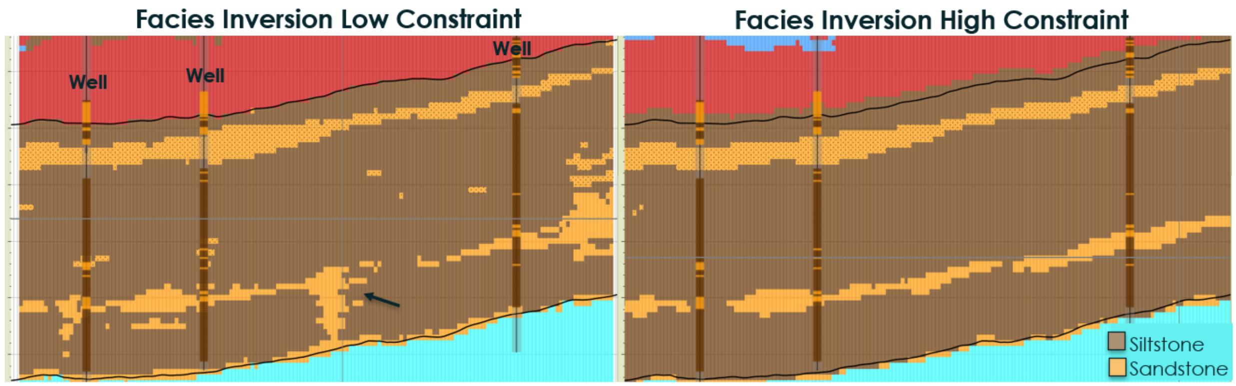

Figure 1: Facies based- inversion results along a section through the Montney formation. The left image was calculated assuming a low noise level in the seismic, while the right image shows the final result employing a more appropriate noise level.

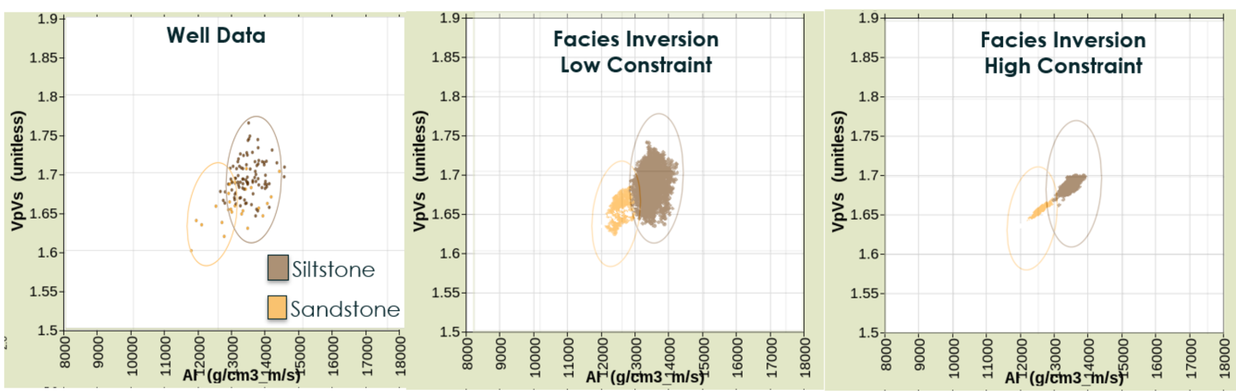

Figure 2: Acoustic impedance and Vp/Vs ratio distribution for siltstone and sandstone facies from well logs (left), facies-based inversion results assuming a low level of seismic noise (center) and the same inversion assuming a higher noise level, which introduces more bias in the properties (right).

Observations at a well are shown on the left side of Figure 3, where we compare the well log acoustic impedance with the facies-based inversion acoustic impedance for both a strong and weakly constrained inversion. It should be noted that the well was not used in either inversion. In addition, the total porosity calculated from the acoustic impedance using a linear regression is shown for comparison with the actual well porosity. We see that the porosity estimates appear reasonable for both inversions, despite the low variability seen in Figure 2. The right side of Figure 3 shows summary thickness and porosity distributions for the target sandstone over the entire area, using the same color scheme for strong and weak constraints on the inversions.

The strong constraint narrows the distribution of porosity, which is a form of bias, although a very mild one. The thickness distribution exhibits a more dramatic difference between the inversions, with the low constraint inversion displaying a large range that is geologically unlikely. From the limited well control, the sandstone is typically 4ms in thickness.

Figure 3 demonstrates that the small bias introduced in porosity leads to a much better overall characterization of the reservoir volumes for this target sandstone. We have focused on the bias-variance tradeoff for a facies-based inversion, but the same dynamic occurs for more conventional simultaneous inversions. One difference is that in the latter, the bias pulls the solution towards an average sand-shale low-frequency model, rather than towards a pure sandstone facies. This leads to an overall reduction in the sandstone porosity to control the influence of noise, and so the bias variance tradeoff has a greater impact on the reservoir characterization result. Naturally, advanced algorithms using co-located well log and seismic inversion results can provide corrections to 3D reservoir property estimates. However, we have shown how the fundamental inversion algorithm and prior models can alter the estimates in predictable ways.

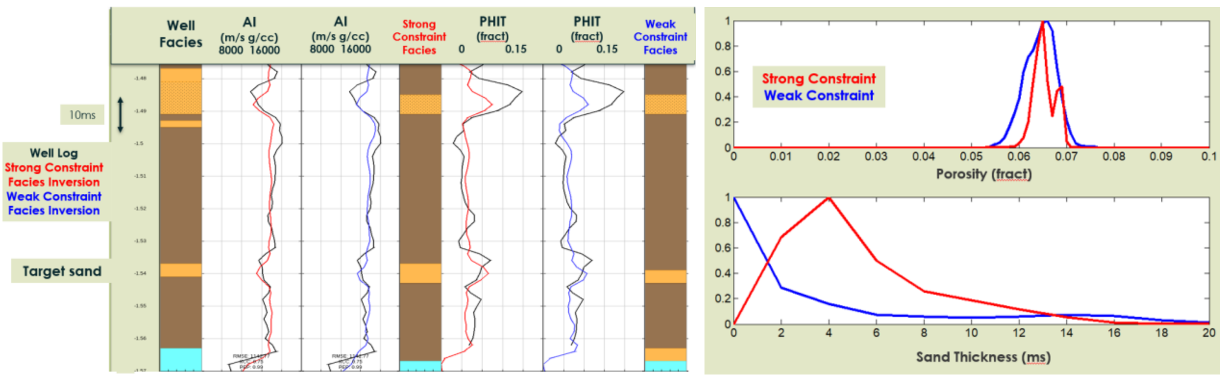

Figure 3: Facies-based inversion results at a local calibration well with acoustic impedance and total porosity shown (left); full field summary plot of thickness and porosity estimates from facies inversion with strong constraints (red) and weak constraints (blue).

Additive Information

We have provided some perspective on the way bias and variance manifest in a facies-based seismic inversion as we strive to achieve the overall best prediction. The impact of this tradeoff on the resource distribution has also been highlighted, which is important for geoscientists to understand. This analysis was performed using an example from the Montney, an important Canadian resource.

Acknowledgements

We would like to thank Whitecap Resources Inc. for permission to publish these data.

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