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Practical implications of low frequency model selection on quantitative interpretation results

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Summary

It has long been recognized that the inversion of seismic data can often add valuable information to quantitative interpretations but that the value of this information is susceptible to bias depending on the selected low frequency model required to generate absolute instead of relative elastic properties. Although the theoretical or conceptual link between the quality of seismic inversion results and the input low frequency model is well documented, the impact on quantitative interpretations is often ignored or dismissed in practice. Various examples are presented herein to highlight the significance of low frequency models constructed using varying degrees of sophistication currently seen in practice.

Keywords: *Inversion*

Introduction

The inversion of seismic data to elastic properties has become a standard part of many seismic reservoir characterisation workflows. Inversion to elastic properties is not an end goal but an intermediate step towards improved interpretation of the seismic data in terms of properties that are relevant to understanding the static and dynamic characteristics of the subsurface. This interpretation can be qualitative, such as locating the reservoir, or quantitative, such as reporting net pay. In some circumstances relative changes in elastic properties are sufficient to address the objectives of a study, whilst in other cases absolute values are required. Seismic data are bandlimited and thus do not contain very high or very low frequencies. Therefore, inversion of seismic reflectivity data to absolute elastic properties requires the addition of low frequency information. Even if only relative changes are required for interpretation, it is necessary to have some understanding of the lowest frequency content as the relationship between seismic reflectivity and elastic impedance contrast requires knowledge of the absolute impedance. There are other factors that make the introduction of low frequency information important, as will be discussed later.

There are a variety of approaches to constructing the low frequency component for inclusion in seismic inversion. These include using well log data, seismic velocity data, bandlimited inversion results and/or rock physics information. No matter the method of construction, each requires a degree of interpretation and the uncertainties in constructing the low frequency model may lead to a bias in the interpretation of the broadband impedance results. Because of this, a simple trend is often used to mitigate against such bias and the bandlimited results only are used. However, the interpretation of bandlimited results poses it owns problems. In this paper the importance of the low frequency model for seismic inversion is examined together with various methods (and their limitations) that have been used for building such models.

Need for low frequencies

Inclusion of the correct low frequencies for seismic inversion provides absolute values of impedance. In many cases the absolute reservoir properties that are required for static modelling, say, cannot be determined from relative impedances. This can easily be demonstrated with the simple wedge model depicted in Figure 1 where the absolute impedances within the wedge are constant, but the relative impedances are not. Low frequency models provide information on slowly varying vertical trends within reservoirs. The absence of low frequencies results in sidelobes around events that can constructively and destructively interfere and make relative impedance variations difficult to interpret as illustrated by the example in Figure 2.

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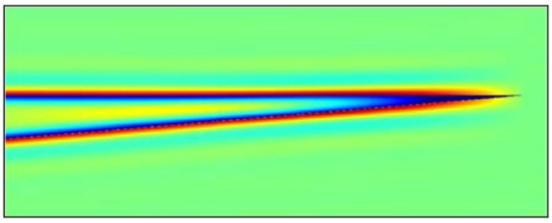

Figure 1: Simple wedge with the low frequency content removed. Above a certain thickness, ambiguity exists as to whether there is one body or separate bodies. Absolute properties within the wedge clearly cannot be determined from such relative variations alone.

Theoretical sensitivity

The relationship between reflectivity and impedance contrast can be exemplified by the two-term Fatti equation:

$$R_\theta = \frac{\Delta AI}{AI}(1 + tan^2\,\theta) - 8sin^2\theta\left(\frac{SI^2}{AI^2}\right)\frac{\Delta SI}{SI}$$

As an approximation the Δ terms can be considered the bandlimited impedances and the full terms the low frequency impedances. It is clear that any error in the low frequency of acoustic impedance (AI) will be propagated to an equivalent error in the relative impedance. For shear impedance (SI) and Vp/Vs the situation is more complex, being dependent on both errors in the low frequency components of AI and SI. This implies that the generation of accurate relative variations in impedance are dependent on accurate estimates of the corresponding low frequency components.

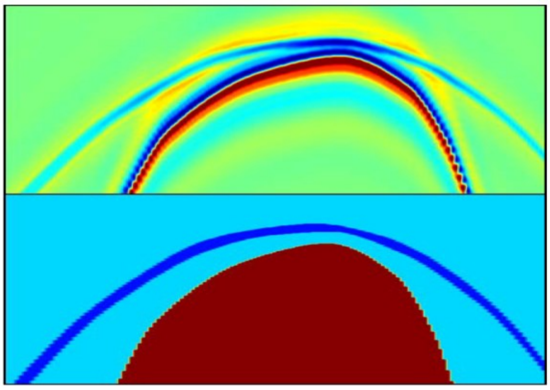

Figure 2: The upper figure contains relative impedances that could incorrectly be interpreted as a complex structure due to the presence of significant side lobes. The lower figure with the absolute impedances in fact shows quite a simple structure.

Low frequency model building

A variety of methods for building low frequency models have been published. A number of others, perhaps not published, are in common currency. The least sophisticated method, though probably the most used, at least up until a few years ago, was the simple interpolation and extrapolation of well log data within a structural and perhaps stratigraphic framework. The results of the interpolation were then filtered back to the frequency range required for inversion. These results were therefore dependent on the mathematical process chosen for interpolation, such as kriging, inverse distance, triangulation etc, all of which are clearly devoid of geological context and heavily dependent on the number and spatial distribution of wells included. An obvious example is that of a gas filled channel. A well that penetrates the channel in the gas leg cannot have its elastic properties extrapolated beyond the limits of the gas and certainly not beyond the limits of the channel. The use of pseudo wells, with fluid substitution to brine and without the channel, strategically placed, can be used to supplement the model. Clearly this will only work well if the distribution of the channel and the fluids within the channel are known to some degree of accuracy before the model is built. This then begs the question as to why the inversion is being carried out in the first place. If the inversion is being used to delineate the channel and the fluids, the low frequency model building would seem irrelevant if their distribution must be determined beforehand. On the other hand, if the objective is to determine the porosity distribution and reservoir quality within the channel, then the low frequency model building becomes important. This example suggests any optimal approach to low frequency model building should be both interpretative and iterative.

Interpretative approaches to model building rely on using the information within the seismic bandwidth to drive the low frequency model. For example, it might be possible based on a simple inversion, or even seismic interpretation, to determine the upper and lower bounds of a channel. If a model is constructed with the top and base of the channel represented by sharp boundaries, this will in itself introduce low frequency information. There are then two components to such a process. The first is to determine a facies model from the seismic data, potentially through applying cutoffs to the seismic, AVO attributes, spectral attributes or prior inversion results. Note that such methods are only likely to work for bodies below a certain thickness as outlined by the simple wedge model of Figure 1. For bodies thicker than this limit, manual intervention will be required. Once these facies have been identified, the second component to this process is to populate these with elastic properties based on rock physics models, constant properties or depth trends depending on the situation. In some cases, a more elaborate approach might be required. For instance it might be recognised that properties within a particular facies vary laterally. If such a body is within a homogeneous background then the absolute deviation of the layer from the background trend is equal to the difference between the side-lobe and peak amplitudes in a relative representation once tuning has been removed. The difference can therefore be used to populate the facies more accurately as shown by Mesdag et al. (2010). Naturally, the interpretative approach must be applied with a clear understanding of both the geology and the physics of the rocks.

Seismic velocities provide a source of low frequency information. However, the use of seismic velocities for constructing low frequency models is not without problems. Although the quality of seismic velocities has improved over the years they are still in general noisy. Recently the use of automated techniques during processing produces highly detailed velocity profiles at every trace. Although these profiles contain information to a reasonably high frequency, comparison with well velocities usually indicates that only the lowest one or two Hertz only are reliable. Seismic velocities require calibration to match well data. Care must be taken to avoid edge effects when filtering well log data to the low frequencies in the seismic velocities and decisions need to be made about how to interpolate any calibration factors between wells. Seismic velocities cannot be used directly in low frequency models but must be converted to acoustic and shear impedance and density. These models may also require calibration to the well to ensure a match. There is an argument that full calibration to the wells is not necessary, as the final mismatch at the wells will give an indication of the uncertainty in the overall inversion. By forcing the low frequency models to match the wells precisely, this understanding of uncertainty is lost from the final product. The seismic velocity based models will only contribute up to 2Hz of information and therefore need to be combined with other models to fill the gap below the seismic reflectivity data. This combination produces problems especially if advanced iterative techniques are being employed.

In an iterative scheme, the properties assigned to a body interpreted from the bandlimited data can be adjusted through a scheme of trial and feedback. Sams et al. (2012) showed that the absolute porosity of a thick channel with oil and gas could be modelled by using rock physics relationships to convert an initial porosity to impedance. This impedance was then used as a low frequency model for inversion. The error between the inversion result and the initial model at seismic bandwidth could be fed back to update the porosities. The process could be iterated to convergence.

Impact on net pay

In the following section, net pay computed from impedances inverted using two different low frequency models discussed previously are compared. In one instance, the low frequency model was constructed using the most conventional approach of stratigraphically interpolating well logs. The second low frequency model was constructed using the approach where facies are first interpreted from bandlimited inversion results and then filled with fluid-dependent properties using a simple constant rock physics model. The two low frequency models are depicted in Figure 3.

As expected, the two low frequency models are similar at the two well locations and the main differences become increasingly apparent away from well control, near the top of the structure. The gas-oil contact is more distinctly captured in the lower figure where the rock physics trends are used. The differences are perhaps more easily detected in the low pass filtered versions of the low frequency models shown in Figure 4.

Cross sections of the impedances inverted using these two low frequency models are given in Figure 5. There are two noteworthy observations. First, although similar in character, the inversion using the low frequency model based on rock physics trends contains significantly more and thicker gas sands between the two wells than that using the low frequency model based on interpolated logs.

Second, the inversion results using the low frequency model contain indications that there might be a side lobe issue that needs to be investigated, suggesting that although this low frequency model at first hand appears more appealing, may actually end up being less appropriate than a simple log interpolation for these particular data conditions.

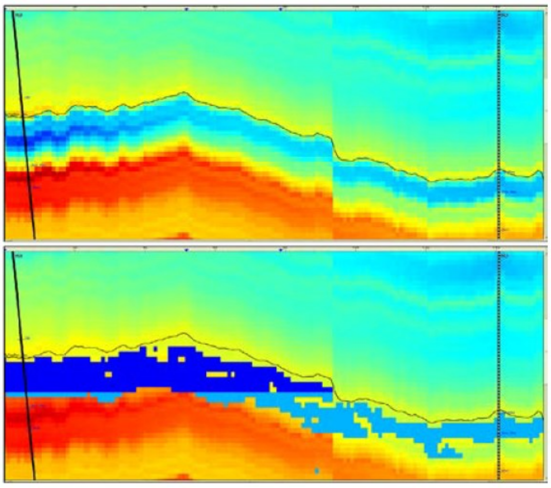

Figure 3: The low frequency model in the upper part was constructed by stratigraphic interpolation of well logs; that of the lower part by a combination of bandlimited inversion interpretation and rock physics modeling. The impedances are on the same scale and increase from blue to red.

Additional observations on the practical impact of the low frequency model selection can be made from looking at maps of net pay coming from the two inversions. The inverted net pay map corresponding to the rock physicsbased low frequency model is show in Figure 6. There is significant pay indicated by the red body moving from the southwest corner in a northerly direction. A similar map was made for the net pay inverted using the loginterpolated low frequency model. The difference between these two maps is shown in Figure 7, where the dark blues correspond to significant differences in net pay on the order of 10% whilst the yellows correspond to negligible differences below 2%. The practical impact of the two low frequency models is nicely illustrated in this lower map, as clearly the larger differences in net pay occur in the thicker parts of the reservoir, just as one would have predicted from the conceptual discussions on the simple wedge model of Figure 1.

All in all, the examples given herein illustrate clearly that low frequency models do matter in practice, that whatever methods are used, quality control is important and cross validation is a useful technique to understand the uncertainties. The use of different modeling approaches can also help to highlight the sensitivities.

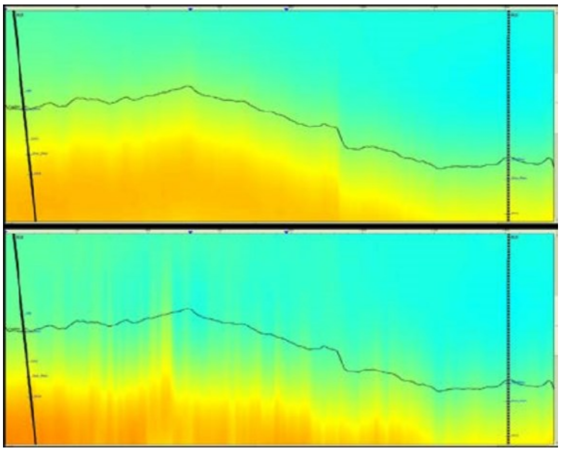

Figure 4: Low pass filtered cross sections corresponding to the low frequency models illustrated in Figure 3. The upper is from a log interpolated low frequency model; the lower is from a rock physics-based model.

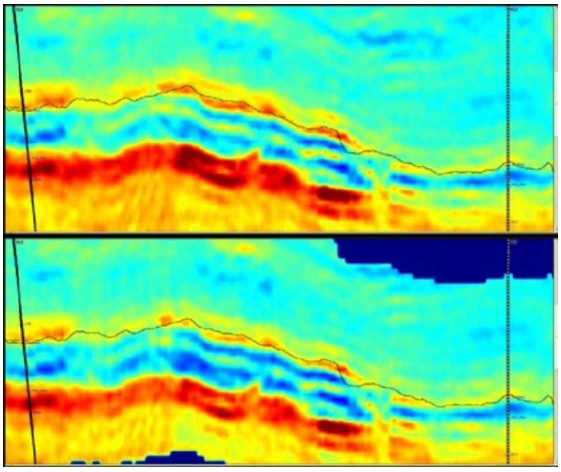

Figure 5: Inverted impedances based on the low frequency model constructed using interpolated well logs (upper) and interpreted rock physics trends (lower).

Conclusions

The use of low frequency models is important for seismic inversion as they provide absolute properties, gradual changes and remove sidelobes. Inverting for relative impedances also requires a reasonable low frequency model to ensure the correct conversion from reflectivity to impedance contrast. Even though building low frequency models is often complex and errors can produce bias in the interpretation of the absolute results, the interpretation of relative impedance can also be very complicated. There is a broad range of techniques for constructing low frequency models and the choice should depend on the objectives of the project, the quality and availability of the data, the geology and the rock physics.

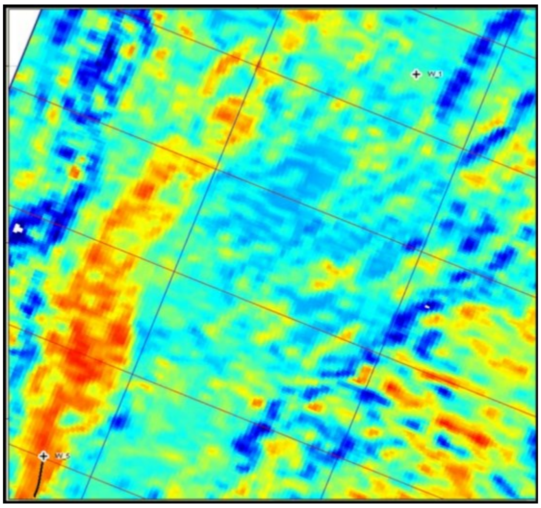

Figure 6: Net pay map from inversion using rock physics-based low frequency model. Net pay increases from blue to red.

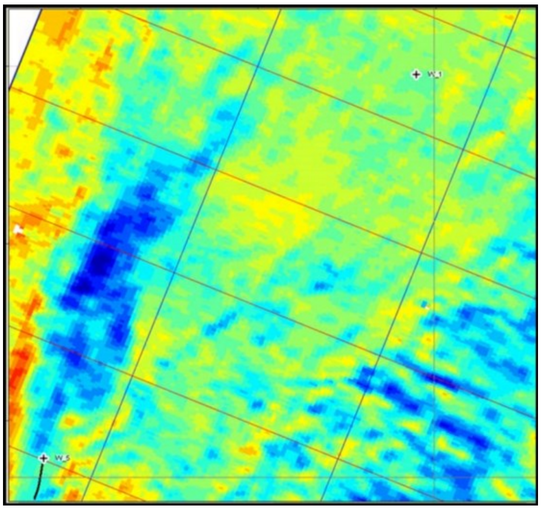

Figure 7: Difference between net pay inverted using rock physicsbased and log-interpolated low frequency models. Differences range from ~0% (yellows) to ~10% (blues).

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