Inversion of 4D seismic data for production facies

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Summary

Rapid and accurate characterization of time-lapse seismic data is important to enable operational adjustments to be made and provide a guide for future drilling. A facies-based Bayesian inversion offers some advantages over traditional simultaneous prestack inversion, primarily avoiding the laborious construction of low-frequency models. To implement a facies-based inversion method, we adjust the model parameterization to be the ratio of monitor to baseline elastic properties. With this parameterization, the set of facies is reduced to those corresponding to specific production scenarios (production facies) that characterize expected subsurface changes between the monitor and baseline acquisitions. Production facies' elastic properties are generally modeled through rock physics relationships. The inversion operates on the difference of the angle stacks directly, and hence requires properly calibrated and registered baseline and monitor data. The result is a rapid workflow that can image changes in elastic properties accurately. We demonstrate the technique on a synthetic example, and also on field data from an operating oil sands thermal recovery project in Alberta, Canada.

Introduction

Many custom approaches exist for 4D seismic reservoir characterization: from rapid relative inversion analysis to a fully coupled seismic-to simulation project (Tian et al., 2014). The inverse problem is highly non-linear (Thore, 2012) and seismic inversion for elastic properties from time-lapse data can be accomplished with varying levels of constraint, usually incorporating seismic amplitudes but also with time shifts between monitor and baseline (Zhan et al., 2017). The goal in many applications is to balance the often conflicting speed of the process against the accuracy and reliability of the results, enabling timely operational decisions to be made.

One recent advance in seismic inversion is a joint impedance and facies inversion (Kemper and Gunning, 2014), which has several advantages including its noise handling capabilities and the avoidance of explicit construction of a low frequency model (e.g. Nasser et al., 2016). This last aspect is important in 4D applications where subsurface changes are of significant vertical extent; expensive post-production logging is rarely sufficient for this purpose. The straightforward approach to 4D inversion using a facies-based inversion is to invert the monitor and baseline seismic surveys separately and then make comparisons of the resulting facies and elastic properties (Waters et al., 2016). However, this involves the characterization of both lithology and production changes in the inversion workflow when one is primarily interested in production changes. Also, regularization is required to reduce the impact of noise in all seismic inversions, and when carrying out two independent inversions this can lead to differences that are not related to subsurface changes. In addition, the monitor survey will contain information about the both lithology and the production related changes, which can lead to a large number of facies. Facies-based or stochastic inversions tend to have a limit to the number of facies that can be effectively inverted simultaneously from a single zone, as noted by Gunning and Sams (2018) and Connelly and Hughs (2016); therefore reducing the scope of the problem is of practical importance. With this in mind, we aim to limit the inverse problem to only production facies in the next section.

Method

Several linear approximations to the plane-wave Zoeppritz equations exist (Thomas et al., 2016) representing the P-wave reflection amplitude at a plane elastic interface. These all follow a similar pattern:

$$R_{pp} \approx \sum_{k=1}^{3} a_k \frac{\delta Z_k}{Z_k} \tag{1}$$

where Z_k represents one of three elastic properties required to characterize the medium, δ refers to a change in the elastic properties across an interface and the coefficients a_k contain angle dependence and average elastic property terms. We define

$$Z_k^* = Z_k^0 \frac{Z_k^{mon}}{Z_k^{base}} \tag{2}$$

where the superscripts refer to the elastic properties at the time of the monitor and baseline seismic respectively, and Z_k^0 is a constant (generally chosen to be the average baseline properties). Subtracting the seismic reflection coefficients and keeping only 1st order terms leads to

$$R_{pp}^{mon} - R_{pp}^{base} \approx \sum_{k=1}^{3} a_k \frac{\delta Z_k^*}{Z_k^*} \tag{3}$$

where we see after comparing with equation 1 that the amplitude differences can be viewed as the reflection data from a medium composed of the ratio of monitor to baseline properties. To employ this approximation, we need to properly process and calibrate the monitor and baseline surveys so that frequency content is harmonized and scaling has been made consistent. In addition, the monitor must be properly registered to the baseline so than no residual time shifts are present in the data. In this way, if we difference the angle stacks, we can invert for a medium that is the ratio of monitor to baseline properties and use a 3D inversion algorithm for a 4D set of data. This removes much of the lithology component from the inversion, leaving the 4D production-related changes as the source of the seismic difference signal.

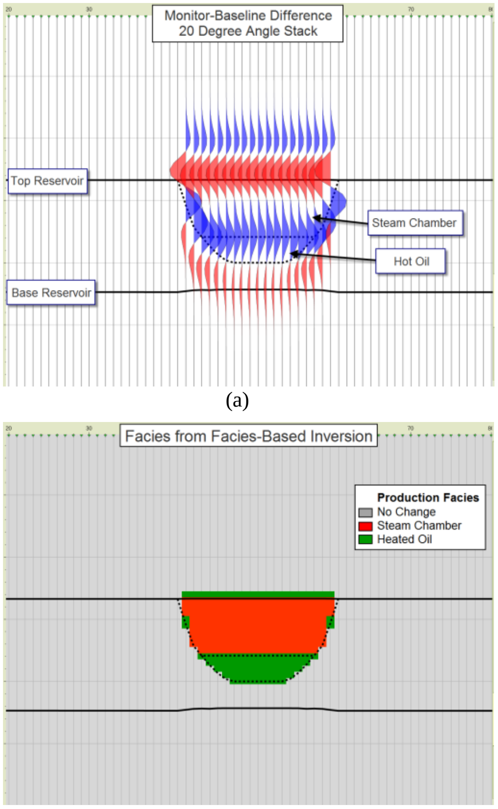
For a facies-based inversion, using this formulation requires the creation of a set of production facies based upon measured or modelled logs of 4D elastic property changes. We have sacrificed acquiring absolute property changes by adopting this approach, but believe that this is of secondary importance to imaging the locations and relative amounts of production changes. Indeed, if absolute properties are required, the results can be combined with a baseline inversion using $Z_k^{mon} = Z_k^{base} Z_k^* / Z_k^0$. The method's accuracy is theoretically limited by Equation 1, representing the small perturbation approximation to the exact plane-wave reflection equation. However, this is a common assumption that is made in most commercial simultaneous inversion algorithms, which have met with success. Indeed, many 4D inversion methods make this assumption, for example Zhan et al. (2017), who translate the elastic ratios described above to fractional changes in elastic parameters. We shall start by showing a synthetic example to demonstrate the feasibility of our approach, and then proceed to an application with data from a producing heavy oil field.

Synthetic Example

We apply this method to a SAGD (Steam Assisted Gravity Drainage) project, where 4D seismic is generally collected for production optimization during thermal recovery. The production method simultaneously injects steam and produces heated oil and water in a pair of horizontal wells that are aligned vertically. The production facies are listed in in Table 2 and shown in Figure 1. These describe regions of no change between the monitor and baseline; a subsurface steam chamber where oil has drained and steam is now present; and the accumulation of heated oil, which can pool in places that have not drained sufficiently rapidly.

Litho-Facies	Vp (m/s)	Vs(m/s)	Rho(g/cc)
Shale	2555	1105	2.23
Oil Sand	2519	1153	2.07

Table 1: Absolute elastic properties for synthetic modelling.



(a)

(b)

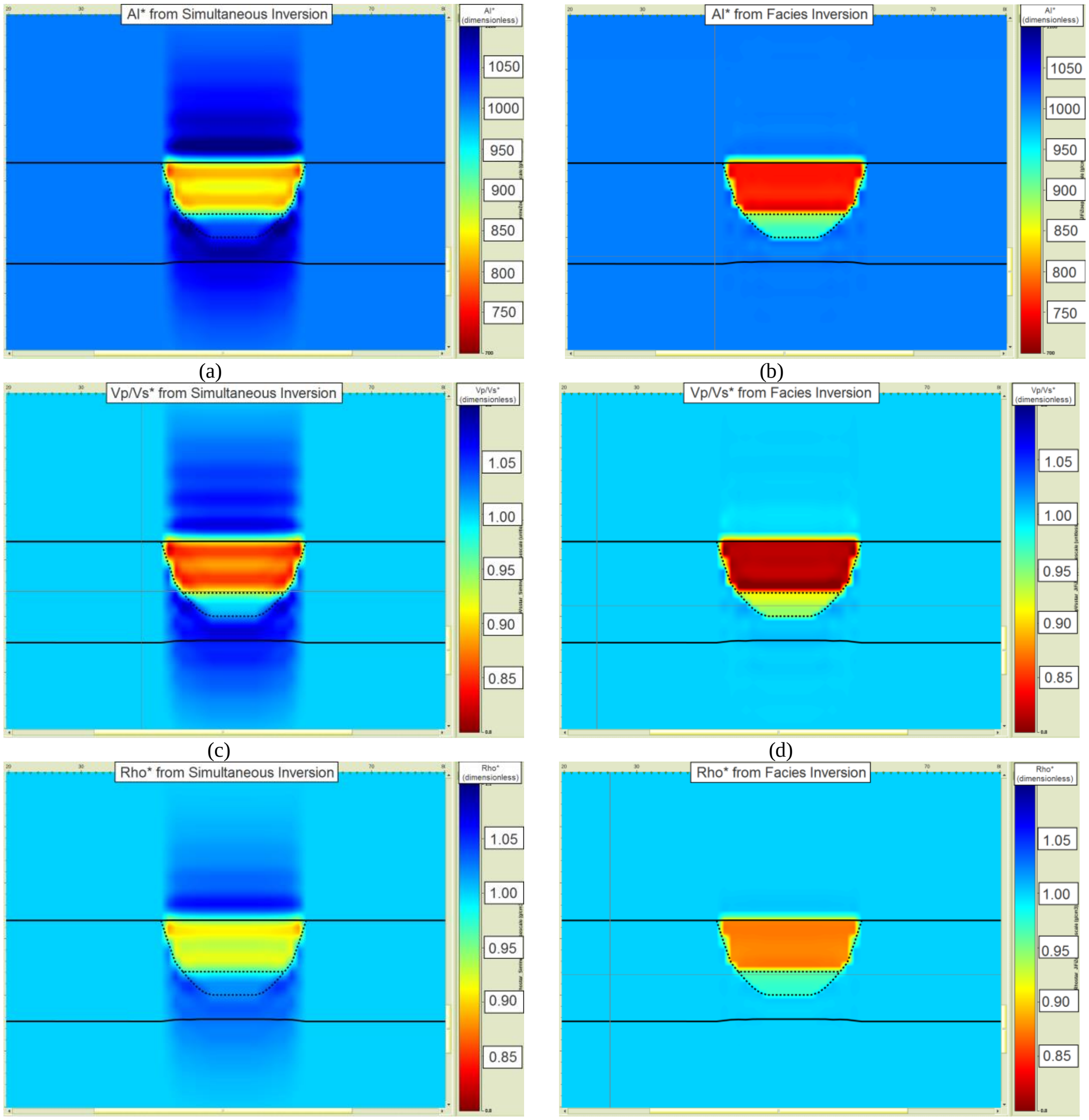
Figure 1: (a) Synthetic monitor-baseline difference for 20 degree angle stack. (b) Most likely facies from a facies-based inversion.

Synthetic monitor logs were created from actual oil sands baseline logs using solid-fluid replacement modeling (Ciz and Shapiro, 2007) relevant for the very heavy oils present in these reservoirs. Temperatures for the time-lapse calculations ranged from 12 to approximately 200ºC, with pore pressure being roughly maintained at the in situ value. For the synthetic example, we used constant properties taken from averages of these logs, which are summarized in Tables 1 and 2. A synthetic 2D line was constructed modeling a cross-section perpendicular to a hypothetical well pair, with a steam chamber and hot fluids symmetrically placed above the wells.

Production Facies	AI*	Vp/Vs*	Rho*
No Change	1.0	1.0	1.0
Steam	0.76	0.81	0.88
Heated Oil	0.92	0.93	0.92

Table 2: Properties ratios for synthetic modeling production facies with no scaling applied, hence the values are dimensionless.

The elastic properties were populated for both baseline and a monitor models using the data in Tables 1 and 2. Baseline and monitor synthetic angle stacks were created for angles from 5-35 degrees in 5 degree increments using a 75Hz Ricker wavelet and the Zoeppritz reflectivity equation. The difference section for the 20 degree angle stack is shown in Figure 1, where the surfaces bounding the oil sands reservoir and the steam and heated oil zones are plotted with solid and dotted lines respectively.



(a) (b)

(c) (d)

(e) (f)

Figure 2: The elastic ratio properties for a simultaneous inversion (left column) and a facies-based inversion (right column) on a 2D synthetic line. (a,b) AI* (c,d) Vp/Vs* and (e,f) Rho*. Note AI* has been scaled by 1000.

This synthetic data was then used as input to both a facies-based inversion and a simultaneous inversion. We use the method of Kemper and Gunning, (2014) and Gunning and Sams (2018) for the facies-based in version, which constructs a most-likely solution for the facies and elastic properties by balancing seismic data fit with a Markov random field spatial constraint. Above and below the reservoir, facies are constrained to be ’no change’. The starting point is an equal proportion for each facies within the reservoir zone. For this simple noise-free case we see that the inverse problem is well constrained, and that the most-likely facies (Figure 1b) are accurately placed. We do note some of the hot oil facies incorrectly placed on the side edge and top edge of the steam chamber where there is some sub-resolution ambiguity. Figure 2 (b,d,f) shows the corresponding elastic property estimates. Next to these Figure 2 (a,c,e) are elastic property results from a simply parameterized simultaneous inversion. The background low-frequency model that simultaneous inversions require was left constant in this case; we note that this could be improved through careful iteration of facies classification, filtering and repeated inversion (Sams and Carter, 2017), which is both time consuming and interpretive. Some oscillation artifacts in the facies-based inversion properties are apparent in AI* and Vp/Vs*, but in general they are very close to the true values in Table 2. There is less than 1% average error in the property estimates in the steam and hot fluid regions. The simultaneous inversion properties possess greater deviations, with up to 12% average error inside the regions of change, and would require significant adjustment from additional background modelling to achieve what the facies-based inversion has accomplished after a simple parameterization.

Field Example

We apply the same facies-based of Kemper and Gunning (2014) to field data from an operating oil sands project in Alberta, Canada, imaging elastic property ratios. Rock physics modelling of the logs was again carried out to parameterize the same production facies that were used in the synthetic example, where some adjustment of the velocities was required to account for changes in the reservoir rock matrix under thermal conditions. The facies and elastic property ratios are shown in Figure 3 for a profile perpendicular to two horizontal well pairs (not shown). We can see that the abrupt elastic changes expected at a steam interface are well imaged in all of the properties, and that the heated oil accumulation is readily apparent. The results also match a vertical observation well (plotted in the center of Figure 3) that had temperature logs confirming the steam and heated oil facies imaged from seismic.

Discussion and Conclusions

We have shown that imaging the ratio of elastic properties is a way to implement a facies-based inversion in time-lapse applications, with the associated benefits. The process eliminates some of the more difficult inputs that simultaneous inversion requires, and can be carried out rapidly to minimize the time between acquisition of the seismic and delivery of subsurface interpretation to asset teams. However, it does require proper calibration of the monitor and baseline data, including removal of any time shifts between the volumes. The process also requires 4D modelling to parameterize the elastic ratios of the production facies, and hence proper rock physics calibration is an important component of the workflow.

Acknowledgements

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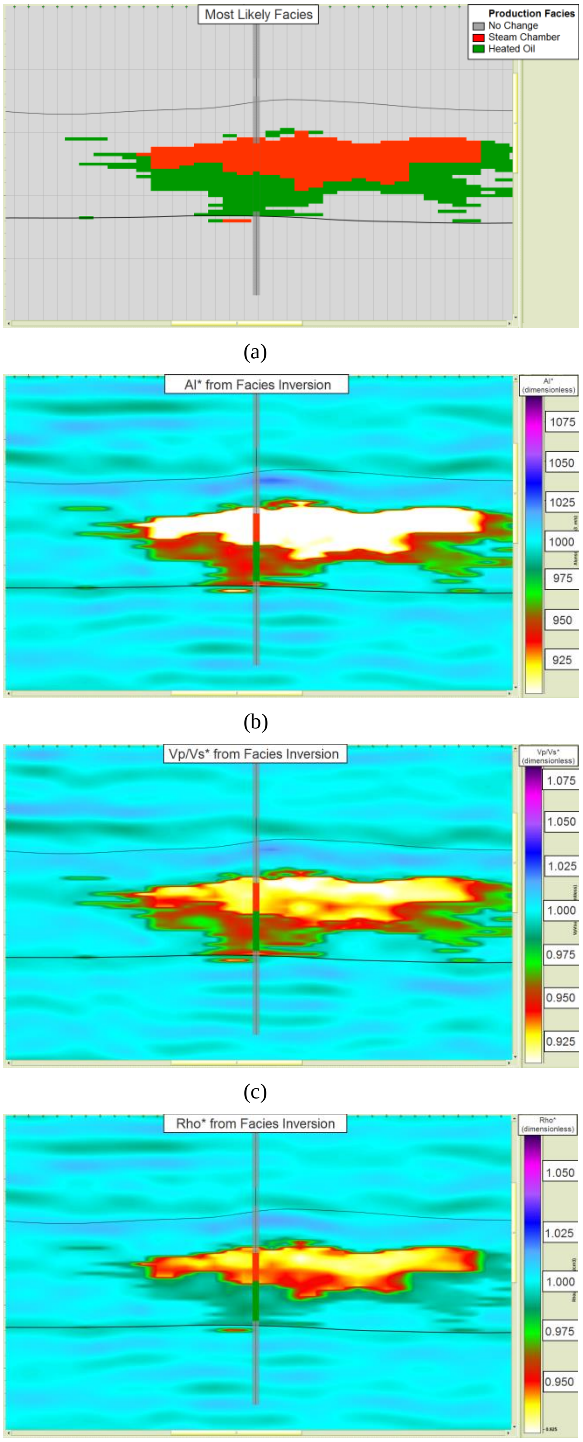

(a)

(b)

(c)

(d)

Figure 3: The elastic ratio properties from a facies-based inversion on an operating SAGD field. An observation well is displayed in the center with exact production facies constructed from a temperature log. (a) Most likely facies (b) AI*, (c) Vp/Vs* and (d) Rho*.