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JOINT PP-PS-SS INVERSION IN NATIVE TIME DOMAIN OPTIMIZING REGISTRATION THROUGH TRAVEL TIMES ESTIMATION

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Summary

Pure S-wave (SS) seismic data have the potential to bring significant uplift to seismic imaging and reservoir characterization. Combining PP, PS and/or SS data in a joint inversion for seismic reservoir characterization presents some theoretical advantages for the estimation of shear-velocity and density related reservoir properties. The inversion stability of the various combinations of seismic modes is compared using a condition number analysis.
The biggest challenge of joint inversion comes from the difference in travel times between the seismic modes. To
overcome this issue, the joint inversion is performed in the native time domain where the travel times difference
between the seismic modes is optimized during the inversion.

Joint PP-PS-SS Inversion in Native Time Domain Optimizing Registration Through Travel Times Estimation

Introduction

Pure S-wave (SS) seismic data, when available, have the potential to bring significant uplift to seismic imaging and reservoir characterization. Deng et al. (2019) illustrated the benefits of SS data over PP and PS to image gas anomalies since pure shear waves are not affected by the absorption and attenuation of gas-bearing formations, resulting in higher lateral resolution near faults. Gaiser and Verm (2012) mentioned the benefits of SS data for shallow S-wave velocity model building to help PS-wave processing, and S-wave surface-consistent residual statics. Gupta et al. (2015) demonstrated the value of SS data in the characterization of a fractured carbonate formation considered for CO_2 storage, calibrated with well-to-seismic ties. Similar to PS data, SS amplitudes bring additional information on shear-related properties and density ρ based on the Amplitude Versus Offset theory. Also, SS travel times constrain the P- to S-velocity ratio V_P/V_S when the inversion is performed in native time domain, i.e. PP data in PP times, PS data in PS times and SS data in SS times (Roure and Russell, 2019).
This abstract expands on the preliminary results of Roure and Russell (2019) and looks at the pre-stack inversion of various combinations of the seismic modes PP, PS and SS. After briefly reviewing their amplitudes expression, an analysis of the condition number is used to compare the stability of the inversions for the different combinations. Finally, to overcome the registration challenge related to the difference of travel times between the modes, the joint inversion in native time domain is discussed and illustrated on a synthetic dataset.

Theory

Amplitudes of the different seismic modes PP, PS and SS are modelled using 1D convolution of the reflection coefficients (see Zoeppritz, 1919, for the non-linear expression or Aki and Richards, 1980, for linear approximations) using angle- and mode-dependent wavelets. A simplified expression of the reflection coefficients at an interface between two isotropic elastic media for a given angle of incidence is expressed as the following matrix formulation:

$$R = L\,m \tag{1}$$

where $R = \begin{bmatrix} R_{PP} \\ R_{PS} \\ R_{SS} \end{bmatrix}$ contains the PP, PS and SS seismic reflection coefficients, $m = \begin{bmatrix} R_{V_P} \\ R_{V_S} \\ R_\rho \end{bmatrix}$ contains the model reflectivities for V_P, V_S and ρ, and $L = \begin{bmatrix} W_{PP}^{V_P} & W_{PP}^{V_S} & W_{PP}^{\rho} \\ 0 & W_{PS}^{V_S} & W_{PS}^{\rho} \\ 0 & W_{SS}^{V_S} & W_{SS}^{\rho} \end{bmatrix}$ contains the mode- and model property-dependent weights $W_{\{PP,PS,SS\}}^{\{V_P,V_S,\rho\}}$. The full expression of the weights W is detailed in Aki and Richards (1980). For the special case of normal P-wave incidence angle, Equation (1) becomes:

$$\begin{cases} R_{PP} = \frac{1}{2}\left(R_{V_P} + R_\rho\right) \approx \frac{1}{2} R_P \\ R_{PS} = 0 \\ R_{SS} = -\frac{1}{2}\left(R_{V_S} + R_\rho\right) \approx -\frac{1}{2} R_S \end{cases} \tag{2}$$

where R_P and R_S are the P- and S-impedance reflectivities respectively. An observation from Equation (2) is that the sum of the PP and SS reflection coefficients at normal P-wave incidence angle in a common time domain provides an estimation of the V_P/V_S reflectivity:

$$R_{PP} + R_{SS} = \frac{1}{2}\left(R_{V_P} - R_{V_S}\right) \approx \frac{1}{2} R_{V_P/V_S} \tag{3}$$

The weights W are simply a function of the incidence angle but also depend on the background V_P/V_S ratio making Equation (1) non-linear. However, if we assume the background velocity ratio is known, the problem becomes linear and can be resolved in a least square fashion as follows:

$$m = (L^T L)^{-1} L^T R \tag{4}$$

where the upperscript T denotes the transpose of the matrix. The stability of the inverse problem is then dependent on our ability to invert the following matrix:

$$L^T L = \begin{bmatrix} \left(W_{PP}^{V_P}\right)^2 & W_{PP}^{V_P} W_{PP}^{V_S} & W_{PP}^{V_P} W_{PP}^{\rho} \\ & \left(W_{PP}^{V_S}\right)^2 + \left(W_{PS}^{V_S}\right)^2 + \left(W_{SS}^{V_S}\right)^2 & W_{PP}^{V_S} W_{PP}^{\rho} + W_{PS}^{V_S} W_{PS}^{\rho} + W_{SS}^{V_S} W_{SS}^{\rho} \\ & & \left(W_{PP}^{\rho}\right)^2 + \left(W_{PS}^{\rho}\right)^2 + \left(W_{SS}^{\rho}\right)^2 \end{bmatrix} \tag{5}$$

This is a 3x3 symmetric matrix whose diagonal elements represent the overall energy of each elastic property contained in the various seismic modes: V_P in (1,1), V_S in (2,2) and ρ in (3,3). The non-diagonal terms of the matrix express the cross-energy coming from the interaction between the elastic properties: (V_P, V_S) in (1,2), (V_P, ρ) in (1,3) and (V_S, ρ) in (2,3).

Inversion stability

To quantify the stability of the inversion, we calculate the condition number (see e.g. Downton (2005)) as a metric to compare the various combinations of seismic modes and look at the impact of the P-wave incidence angle and background velocity ratio. The condition number is by definition the ratio of the largest to the smallest eigenvalues of the matrix defined in Equation (5) and in simple terms, the lower the condition number, the more stable the inversion.
Figure 1 shows the condition number analysis results with the first obvious well-known observation that increasing the range of incidence angles decreases the condition number and therefore improves the stability of the inversion. The condition number of the PP-PS inversion (orange curves) is always lower than the one of the PP inversion (blue curves) so the PP-PS inversion is theoretically more stable than the PP inversion. The stability is further improved by jointly inverting PP and SS data (green curves). However, the benefit of jointly inverting PP, PS and SS data depends on the angle considered and the background velocity ratio. In some cases, its condition number (grey curves) does not show any improvement compared to the PP-SS one or only marginal differences. This observation is consistent with the results of de Haas and Berkhout (1990).

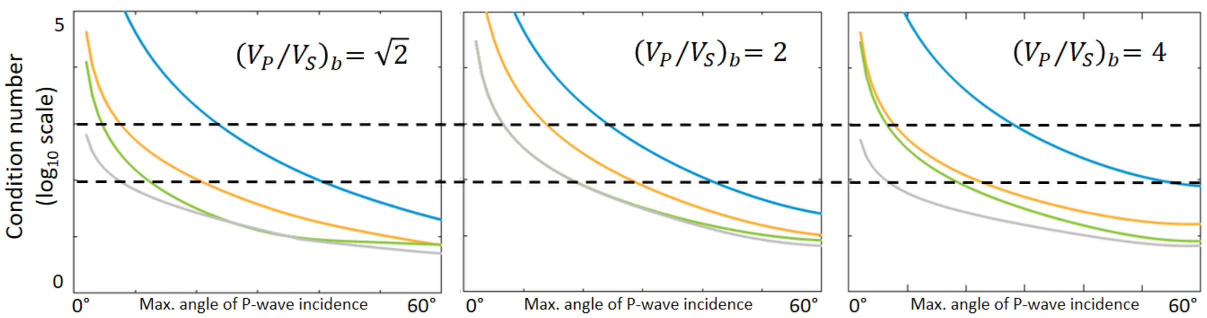

Figure 1 *Condition number of various combinations of seismic modes inversion (PP in blue, PP-PS in orange, PP-SS in green, PP-PS-SS in grey) for different background velocity ratios (V_P/V_S)$_b$, as a function of the maximum P-wave incidence angle used in the inversion.*

The above observations are only valid under the following assumptions: linearized formulation, known and constant background velocity ratio, perfectly registered PP, PS and SS data aligned in a common time domain. The last assumption on registration is the biggest challenge of joint inversion. Methods based on matching directly PP and PS/SS data should be avoided since the frequencies and amplitudes are different between the modes. Several options exist to address the registration issue. Hampson and Russell (2013) propose horizon-based matching between the different seismic modes. Clochard et al.

(2017) perform the alignment using the S-impedance estimated from different modes. PS/SS synthetics generated from PP only inversion can be compared to real PS/SS seismic data (Colnard et al., 2019). Using seismic velocities from depth processing is also another option. Another approach to tackle the registration issue is to invert in native time domain with an optimization of the registration during the inversion (Roure et al., 2015) which can be extended to SS data as illustrated in the next section.

Native time domain inversion

One of the benefits of the native time domain inversion is that the PS/SS data are not squeezed in PP times, a process that might significantly alter the amplitudes considering the amount of time-shift that needs to be applied on the PS/SS data. This alignment step might also affect the stationarity of the signal. As a result, the inversion results will over or underestimate elastic properties contrast to compensate for the change of signal (Roure et al., 2015). In native time domain, amplitudes and travel times differences between the three modes are inverted at the same time and jointly for the different seismic modes. This approach can be viewed as a model-based registration process constrained by amplitudes. A single detailed V_P/V_S model reconciles amplitudes through Equation (1) and travel times differences between the three seismic modes PP, PS and SS (Roure and Russell, 2019).
Figure 2a illustrates a synthetic example of native time domain non-linear inversion results. Only one seismic angle stack per mode is shown but several stacks were actually inverted. No prior alignment is required in the native time domain approach. Each seismic mode is expressed in a different time scale. The corresponding time axes, shown on the left, are dynamically linked through the V_P/V_S ratio being inverted and are iteratively optimized during the inversion. To better visualize the difference of travel times, the various seismic modes can also be displayed using the same time axis without any alignment (Figure 2b). The relationship between the travel times as a function of V_P/V_S ratio is also displayed.

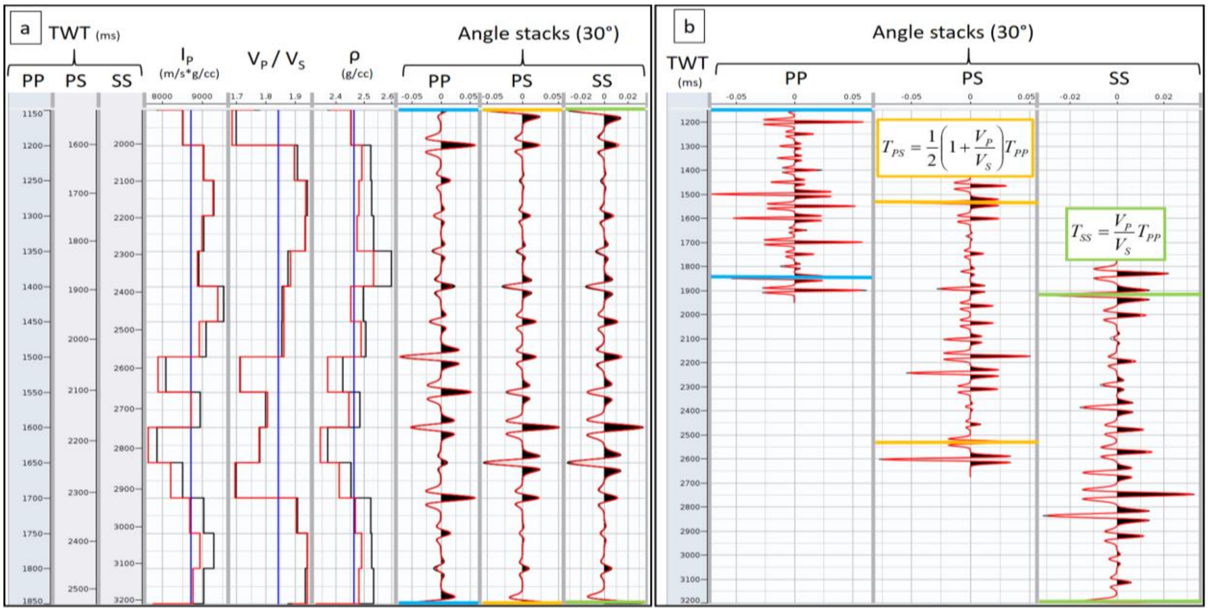

Figure 2 *a) Synthetic example of joint PP-PS-SS inversion in native time domain. From left to right: PP, PS and SS time axes, elastic properties (true model in black, constant initial model in blue and inversion results in red) and some of the PP, PS and SS angle stacks being inverted. b) Same angle stacks displayed in a common time domain without any alignment. The colored lines (blue for PP, orange for PS and green for SS) identify the inversion time windows used in a).*

Conclusions

The use of SS data for reservoir characterization shows some promising results. At normal incidence, SS data allow the estimation of the S-impedance where there is no PS reflection coefficient. Based on the condition number analysis, SS amplitudes bring more stability than PS when inverted jointly with PP. However, the joint inversion of PP, PS and SS amplitudes does not guarantee improved stability depending on the incidence angle and the background velocity ratio considered. Similar to PS data, it is possible to invert SS data in native time domain and travel times bring extra constraints on the V_P/V_S ratio estimation. However, in practice, the success of joint inversions is highly dependent on the consistency of the data between the modes (in terms of both amplitudes and travel times) which must be QCed quantitatively. Consistent data between modes will improve the joint inversion results but inconsistent data may damage the results compared to PP only inversion. Native time domain brings extra constraints on the V_P/V_S ratio and preserves amplitudes but requires consistency between amplitudes and travel times. The alternative is to work in a common time domain but a pre-inversion alignment is then required and the quality of the inversion highly depends on the quality of the alignment. The next step is to validate on real data the results and observations from this abstract.

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