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Fast and Accurate Impedance Inversion by Well-Log Calibration

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Summary

Seismic impedance inversion is an inherently under-unconstrained problem that does not allow the use of rigorous joint inversion methods. In the absence of a true inverse, a unique and reliable solution can be obtained by defining a set of physical constraints that should be satisfied by the resulting images. Here, we propose a method for constructing "synthetic logs" that explicitly and accurately satisfy: 1) the convolutional equation; 2) time-depth constraints from the seismic data, 3) background low-frequency model from the logs or seismic/geological interpretation, and 4) spectral amplitudes and geostatistical information from spatially-interpolated well logs. The resulting synthetic log sections or volumes are readily interpretable in standard ways. The approach also allows direct quality control and assessment of the intermediate and final results, and the requirements to true-amplitude seismic processing are reduced. The method is applicable to multiple pre- and post-stack attributes and is illustrated on the acoustic impedance (AI) example.

Introduction

Inversion of seismic reflection data for various lithological and petrophysical attributes is broadly used for reservoir characterization and detection of hydrocarbons. Rock-property related attributes are easier to interpret than the seismic reflectivity, which is related to boundaries between zones of contrasting mechanical properties. Broadly, the commonality between all impedance-type properties is in their relations to the values measured from the seismic traces:

$$R_i = \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i}. \qquad (1)$$

In the case of acoustic impedance (AI), $R_{,i}$ in this equation denotes the normal-incidence *P*-wave reflectivity, and Z_i is the associated impedance.

It is well known that the inverse of equation (1) is non-unique. The fundamental problem is the lack of low-frequency information in the seismic data leading to many uncertainties in the solution. In a formal (also called recursive; Russell, 1988) AI inversion:

$$Z_k = Z_0 \prod_{i=0}^{k-1} \frac{1+R_i}{1-R_i}, \qquad (2)$$

this uncertainty manifests itself in the arbitrary factor Z_0, which is usually selected as the AI in some stable rock layer. However, more importantly, this uncertainty also leads to instabilities of the serial product (2) in respect to perturbations in $R_{,i}$ caused by fine layering, mode conversions, and noise. An arbitrary, smoothly varying factor can be applied to all values of $\{Z_i\}$ without significantly changing eq. (2) within the noise range. These and other instabilities can only be removed by utilizing non-seismic information, such as the background velocity/density model and well logs. This information can be added by either mixing the scaled low- and high-frequency results (Lindseth, 1979) or by using various joint inversion schemes (Cooke and Schneider, 1983; Russell, 1988; Russell and Hampson, 1991; Latimer et al., 2000).

Although several impedance-type inversion approaches are being used broadly and successfully, note that application of joint inversion has virtually no basis in the data. Only model (well-log) data can be used below the seismic frequencies, and therefore the result is entirely model-derived at low frequencies. Within the seismic band, the phase spectrum of the logs (i.e., the times and spatial patterns of reflections) can only be honoured in the vicinities of the corresponding wells, where the inversion is actually not needed. By contrast, only phase information from seismic reflectivity can be used reliably, whereas its amplitudes have to be scaled in order to produce the true-amplitude values $\{R_{,i}\}$ in eq. (1). Such scaling is again derived from the background model data.

Therefore, "seismic inversion" is inherently under-constrained. Strictly speaking, is not an inversion at all but rather a procedure for constructing a series $\{Z_i\}$ that leads to correct reflectivities and also satisfies certain properties that are considered essential. For educated and reliable interpretation, it is critical to clearly define what these properties are and how well they are achieved in the resulting sections. As long as the solutions reproduce the reflectivity series $\{R_{,i}\}$ in (1), the use of sophisticated inversion algorithms may not be necessary and may in fact obscure the meanings of the images obtained.

Here, we present a solution to the AI or similar inverse problems (eqs. 1-2) obtained by directly using the general principle above. The ultimate value of the seismic inversion to the interpreter is the ability to effectively extrapolate the desired properties away from the wells and into the seismic volumes, thereby creating continuous "synthetic log" sections (Lindseth 1979; Yilmaz, 1987). We construct synthetic log sections that explicitly: I) match the log data at the log positions, II) predict reflectivities (eq. 1) within the seismic frequency band everywhere in the seismic volumes, and III) match the time-variant well-log spectra (and consequently geostatistics) everywhere in the seismic volume. In the following, this procedure is called SILC (Seismic by Interpolated-Log Calibration).

Method

By using the AI as an example, log extrapolation can be performed by simply computing the recursive AI from the seismic data (eq. 2) for each frequency and scaling it so that the total time-variant frequency spectrum of the log is preserved. Note that the amplitude spectrum of the log AI is reproduced throughout the entire frequency interval, and time-domain pattern comes entirely from seismic data. The resulting algorithm resembles the well-known time-variant spectral whitening:

1) Build the desired AI series from the seismic trace and from the well log, e.g., by using eqs. (2).
2) Define a series of overlapping narrow zero-phase band-pass filters $F_i(f)$ spanning the frequency band of interest so that the sum of all filter amplitudes equals 1 at any frequency f: $\sum_i F_i(f) = 1$. The frequency bands should typically extend from $f = 0$ to the high end of the seismic spectrum.
3) Filter the log and seismic impedance series within each of these frequency bands and construct the final synthetic log at the position of seismic trace by balancing the seismic AI amplitudes to match those of the log AI.

Unlike the commonly used joint inversion algorithms, this method utilizes the log data more completely and contains no subjectively selected user parameters. The procedure is tolerant to noise and leads to high-resolution images. The method is efficiently implemented, fast, and suitable for application to 2D and 3D datasets. In its properties, it is most close to the “coloured inversion” (Lancaster and Whitcombe, 2000); however, unlike this method, the SILC procedure above guarantees correct scaling of AI, does not rely on a common power-law frequency dependence of log amplitudes, and performs interpolation between different wells. Because all amplitudes are calibrated by the logs, the approach also significantly reduces the requirements to true-amplitude seismic processing.

Examples

As a real-data example, consider a stacked seismic section and a well log in Figure 1. These data were taken from a demo dataset distributed with the Hampson-Russell (H-R) inversion package. Two different types of AI inversions of these data by using the H-R STARTA program are shown in Figure 2. Note the consistency of the two images, with the gas-sand reservoir corresponding to a zone of low impedances draping over the high-impedance carbonates (Figure 2a). Both of these sections reproduce the reflectivity data (Figure 2a) nearly perfectly; however, it is difficult to ascertain how closely the shorter-scale variations of AI correspond to those observed in the well log (Figure 2b).

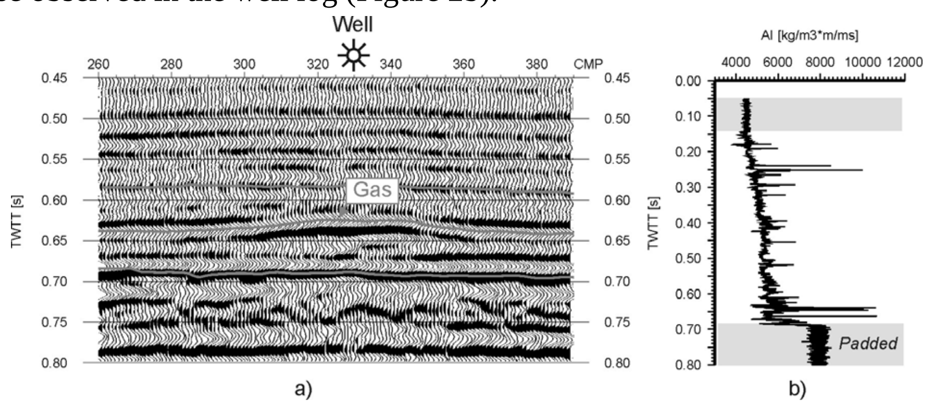

Figure 1: a) Stacked 2D seismic section used in the real data example. The location of the well, target gas reservoir, and three horizons for guiding the inversion are indicated in grey. b) AI well log through the gas some in plot a). Time intervals in which the log data were missing and padded are shown in grey. The data are from Hampson-Russell STRATA package, courtesy B. Russell.

Inversion of the same data by using the SILC procedure is shown in Figure 3a. Both background and seismic-frequency impedance values are consistent with both the reflectivity and the log, as guaranteed by the method. As expected, the inverted section is close to the benchmark inversions (Figure 2) but shows higher resolution. This improved resolution, for example, allows separating the two high-impedance layers underlying the gas reservoir (labelled “Carbonates” in Figure 3a). The image is also more coherent compared to those in Figure 2, apparently because it is closer to the input seismic data and does not contain numerical inversion noise.

Conclusions

A new type of seismic inversion for “synthetic logs” is proposed and illustrated on post-stack Acoustic Impedance (AI). The approach works by extrapolating the seismic properties modeled from the well logs into the seismic sections or volumes. In this interpolation, the complete phase information from the seismic traces is retained and combined with spectral amplitude information from the logs. The resulting synthetic AI logs are readily interpretable in the ways any logs normally are. Unlike the broadly used joint inversion algorithms, the procedure allows a direct quality control, clear understanding of the properties of the images obtained, and assessment of the intermediate and final results.

Acknowledgements

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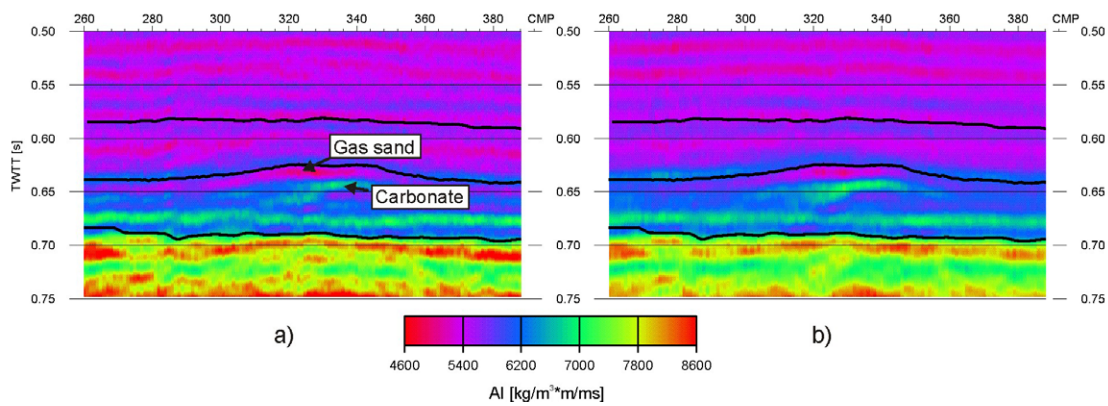

Figure 2: Two types of post-stack AI inversion of the dataset in Figure 1 performed by using the H-R STRATA package: a) model-based and b) band-limited recursive. Note that the low-AI gas sand drapes the high-impedance carbonate (labelled). Model horizons from Figure 1a are shown in black.

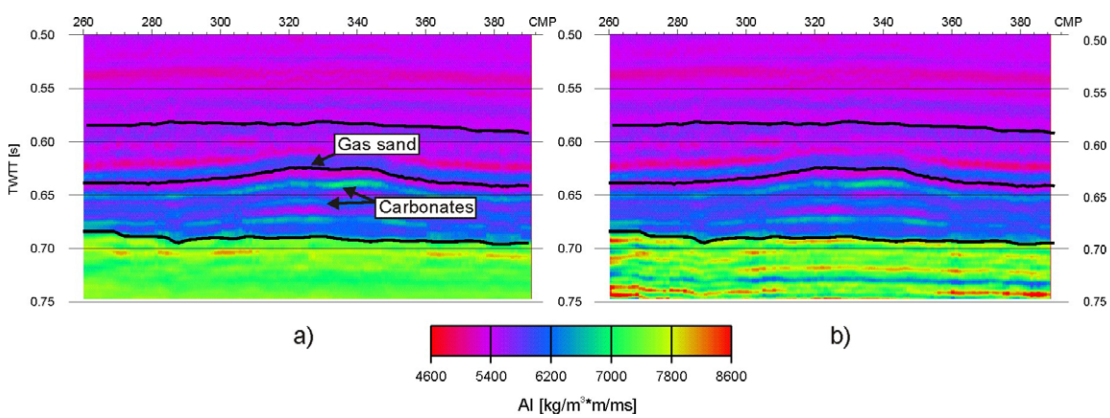

Figure 3: Results of AI inversion using our SILC method with different treatments of the depth range below the bottom horizon where log data are absent: a) by using "white" stochastic reflectivity (Figure 1b), b) by assuming that the log-to-seismic amplitude ratio to be the same as in the layer above. Note the improved resolution and continuity of the images. Model horizons from Figure 1a are shown in black.