Comparison of shear impedances inverted from stacked PS and SS data: Example from Rulison Field, Colorado

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The reason why acoustic and shear impedances inverted from seismic data have become popular seismic attributes is because, unlike other attributes, they can also be easily estimated at log scale. Log-scale impedances are easier to interpret because at log scale we have additional information that provides more insight about reservoir properties, and this insight can be used to help the interpretation of seismic-scale impedances. The joint interpretation of acoustic and shear impedances estimated from seismic data can help to understand rock, fluid, and fracture variability in the reservoir.

Acoustic impedance can be estimated from stacked PP amplitude data using a variety of commercially available algorithms. The same algorithms can also be used to estimate shear impedances if the input data are an estimate of shear reflectivity derived from prestack PP data. Evidently, if the input of the inversion algorithm is stacked SS data, the output of the inversion is an estimate of shear impedance. However, if the input data are stacked PS data, the result of the inversion using conventional algorithms that work in the poststack domain is not shear impedance, but something else. Table 1 summarizes these input/output relationships.

Input	Estimate
PP stacked amplitudes	**Acoustic impedance (AI)**
PP reflectivity from prestack data	**Acoustic impedance (AI)**
SS reflectivity from prestack data	**Shear impedance (SI)**
SS stacked amplitudes	**Shear impedance (SI)**
PS stacked amplitudes	**Pseudoshear impedance**

Table 1. *Input/output relations between seismic data and impedances estimated from inversion of different types of data.*

Valenciano and Michelena (2000) show that the result of inverting stacked PS data is a pseudoshear impedance $\overline{Z}s$ that relates to the real shear impedance Zs of the medium through the formula

$$\overline{Z}s = Zs\rho^{(0.25 Vp/Vs - 0.5)} \qquad (1)$$

where ρ is the density of the medium and V_P/V_S is the ratio of compressional and shear velocities. Equation 1 can be used for two purposes. First, it can be applied to log data to transform shear-impedance logs into pseudoshear impedances that can help interpretation of inversion results of stacked PS data. Log-scale pseudoshear impedances can be used to compute near-offset reflectivities that in turn can be used to compute synthetic stacked PS traces using the convolutional model of the seismic trace. Second, it can be used to estimate real shear impedances (Zs) from inverted pseudoshear impedances. This formula, however, is easier to apply to log data than to seismic-derived $\overline{Z}s$. The reason is because, at a given well location, we usually have density and dipole sonic logs that can be used to calculate V_P/V_S whereas for the larger seismic volume density and V_P/V_S estimates are usually not available on a sample-by-sample basis. When V_P/V_S equals 2, pseudoshear impedances and shear impedances are the same. On the other hand, when V_P/V_S is not 2 (either lower for gas-saturated sands or higher for shales or unconsolidated sediments), the two parameters are different.

V_P/V_S has proved to be a key parameter to help in the characterization of Rulison Field, a tight-gas reservoir in the Piceance Basin, Colorado. Previous work by Rojas et al. (2005) shows how low values of V_P/V_S can be used to identify gas-saturated, overpressured sands from other rock types. Using a small 9-C survey recorded in 2003 by the Reservoir Characterization Project of Colorado School of Mines, Guliyev (2007) shows how to estimate high-resolution V_P/V_S volumes from stacked PP and PS data. More recently, Mesa et al. (2008) show how time-lapse changes in V_P/V_S estimated from PP and SS data can be used to map different pressure regimes in the reservoir. In all these cases, the estimation of V_P/V_S from stacked PP, PS, and SS data follows separate estimations of acoustic and shear impedances.

In this paper, we compare shear impedances obtained from the inversion of stacked PS data with shear impedances obtained from inversion of stacked SS data. To achieve this goal, we use the same data set used by Guliyev and Mesa et al. The results show that, after applying the proper corrections, shear impedances estimated from stacked PS data compare favorably with shear impedances derived from stacked SS data.

Poststack inversion workflow

The steps needed to perform model-based inversion of stacked PP or SS seismic data are well known: log preparation, wavelet estimation, seismic-well ties, background model construction, inversion, and QC. This workflow is performed in the time domain of the original data (either PP time or SS time) and the results are then converted to a common domain (usually PP time) for comparison and joint analyses.

The steps of the workflow to invert stacked PS data are the same, but some need to be adapted to account for PS mode conversions. The modified workflow at each well location consists of:

Log preparation. Transform shear impedances into pseudoshear impedances using Equation 1. Create a one-way, PS

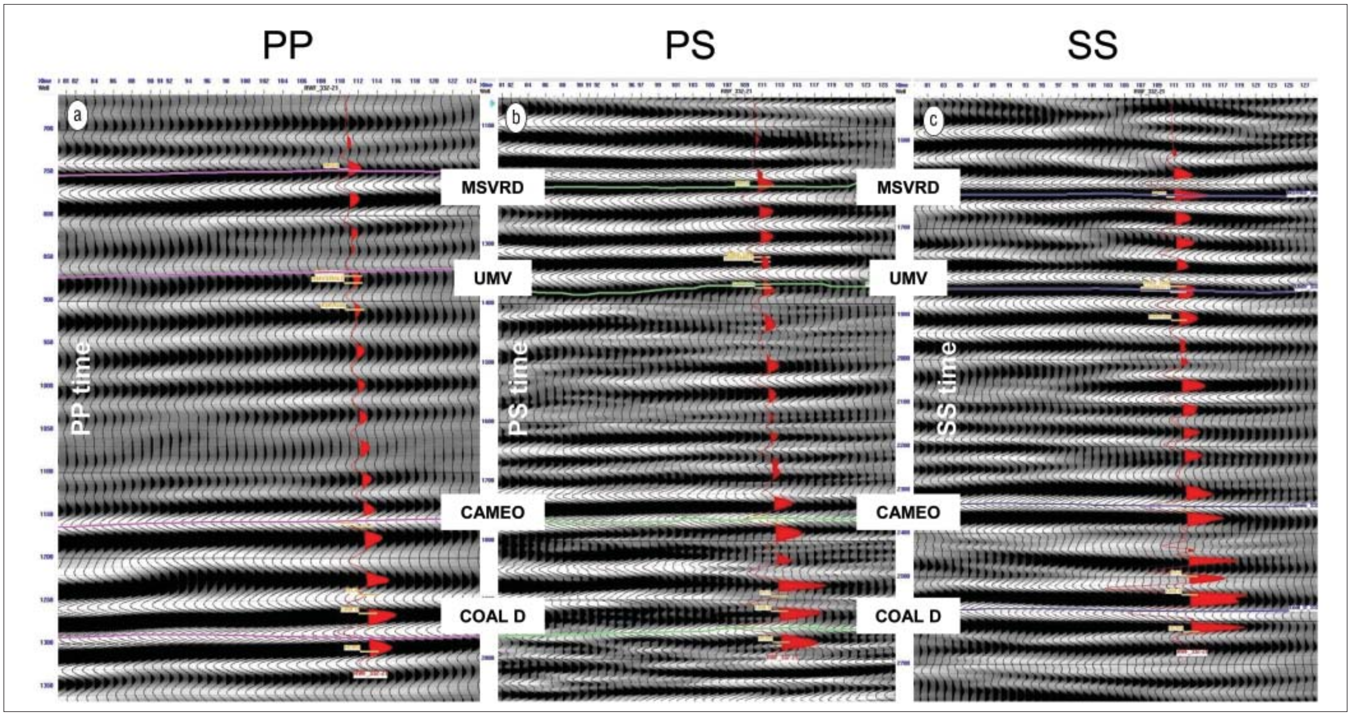

Figure 1. *Multicomponent seismic data around reservoir interval. (a) Stacked PP data in PP time. (b) Stacked PS data compressed to PP time for display purposes. (c) Stacked SS data compressed to PP time for display purposes. No point-to-point registration of the different data sets has been performed. Synthetic seismograms generated at the well are red. Notice the good agreement between synthetic PP, PS, and SS traces with their corresponding field traces. The correlation coefficients between synthetic and field traces are 0.87 for PP data, 0.69 for PS data, and 0.70 for SS data.*

time log (DTPS) by averaging compressional (DT) and shear times (DTS) from dipole sonic data. Compute poststack PS reflectivities in PS time from pseudoshear impedances. Crossplot shear impedances versus pseudoshear impedances to estimate a regression that will be used later in the estimation of real shear impedances from the results of the inversion of PS data.

Seismic-well ties. Once the wavelet from stacked PS data has been estimated, compute synthetic near-offset stacked PS traces by using the poststack PS reflectivities (estimated from DTPS and density logs) and assuming the convolutional model for the seismic trace.

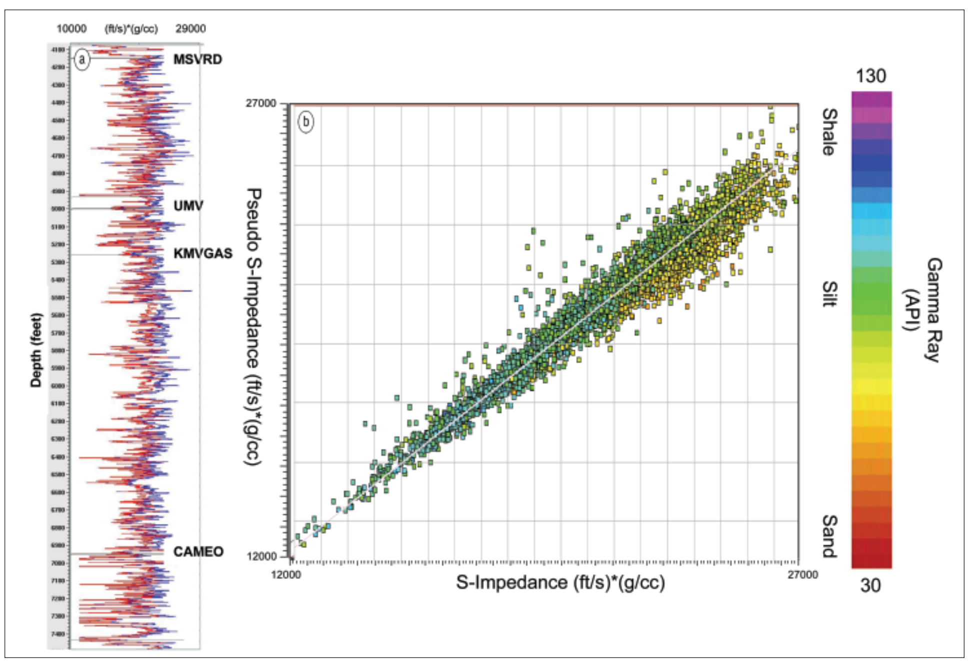

Figure 2. *(a) Comparison of shear impedance (blue) with pseudoshear impedance (red) logs in depth. Shear impedances (blue) are slightly higher than pseudoshear impedances (red). (b) Crossplot of shear impedance versus pseudoshear impedance logs color-coded by gamma-ray log. The regression line that relates these two logs is y = 0.8581x + 1949.08. This regression line fits shales better than sands, since there is more dispersion in the crossplot for low gamma-ray values than for high values.*

Background model construction. Build a low-frequency background model using pseudoshear impedances from different well locations as input.

Quality control. Compare inversion results against expected log pseudoshear impedances and convert to PP domain to compare with acoustic impedances derived from PP data.

Final transformations. Transform pseudoshear impedances into shear impedances using V_P/V_S and density information (if available) or using the regression line estimated in the log-preparation step.

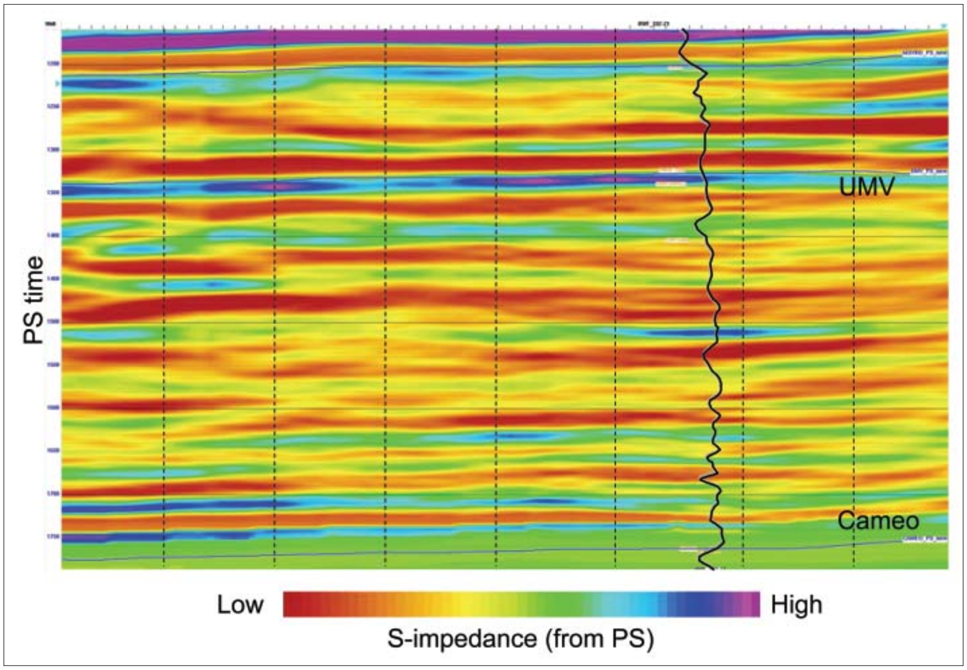

Figure 3. *Shear impedancs after scaling pseudoshear impedance estimated from inversion of stacked PS data. The scaling is performed by using the regression line derived from the crossplot in Figure 2b.*

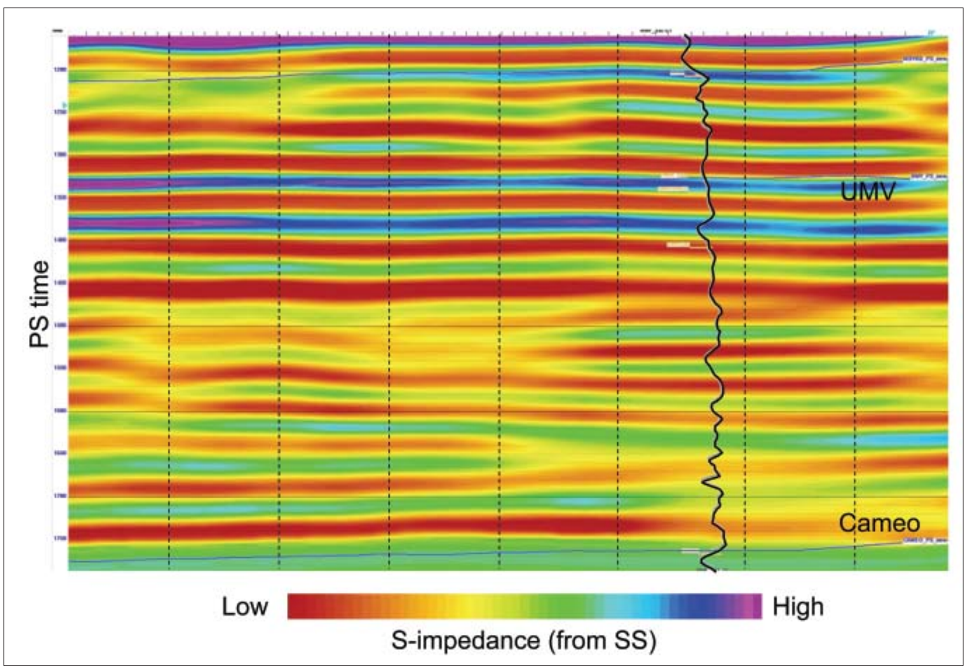

Figure 4. *Shear impedances estimated from inversion of SS data, compressed to PS time to facilitate comparison with shear impedance estimated from stacked PS data shown in Figure 3.*

Application to Rulison Field data

We applied the previous workflow on stacked PS and SS volumes from a 3D 9-C multicomponent seismic data recorded at Rulison Field in 2003. The area of investigation is about 2.5 mile^2. The reservoir interval consists of gas-charged tight sandstone lenses that are hard to interpret in conventional PP amplitude data. PP data were generated with a vertical vibrator with sweep frequencies of 5–120 Hz; the SS data were generated with a horizontal vibrator with sweep frequencies of 5–50 Hz. Only one well with dipole sonic information was available to calibrate seismic data.

As Figure 1 shows, PS and SS amplitudes are more continuous and easier to follow than PP amplitudes in the reservoir interval between the UMV and Cameo markers, which is an indication of the additional value 3-C data bring to the characterization of this field. PS and SS data have been compressed to PP time for display purposes to facilitate comparisons. Only one well with dipole sonic data was available for this study. Red traces in Figure 1 indicate the synthetic zero- or near-offset seismograms for PP, PS, and SS data. Even though the correlation coefficients between field and synthetic traces for PP and SS data are the best (0.87 and 0.70, respectively), the correlation for PS data is also very good (0.69) which shows the adequacy of using the convolutional model and pseudoshear-wave reflectivity to model stacked PS data.

Figure 2a compares shear impedance and pseudoshear impedance logs in depth. Both logs are highly correlated, but shear impedances are slightly higher. Figure 2b shows a crossplot of these two logs. The regression line shown in the figure will be used later to perform a simple transformation from pseudoshear impedances to real shear impedances since sample-by-sample information of velocities and density is not available to perform the transformation by applying Equation 1. Notice that the regression line does not fit all lithologies equally well, since there is more dispersion in the crossplot for sand points (typically with lower V_P/V_S and gamma ray) than for shale points (closer to 2 and high gamma ray). This behavior is expected from Equation 1 which relates real shear impedances with pseudoimpedances.

The background model used for the inversion of stacked PS data was a simple, horizon-guided extrapolation and low-pass filtering of the pseudoshear impedance log at the well. Since this model is based on a single well, it does not capture lateral changes in impedance trends across the field and,

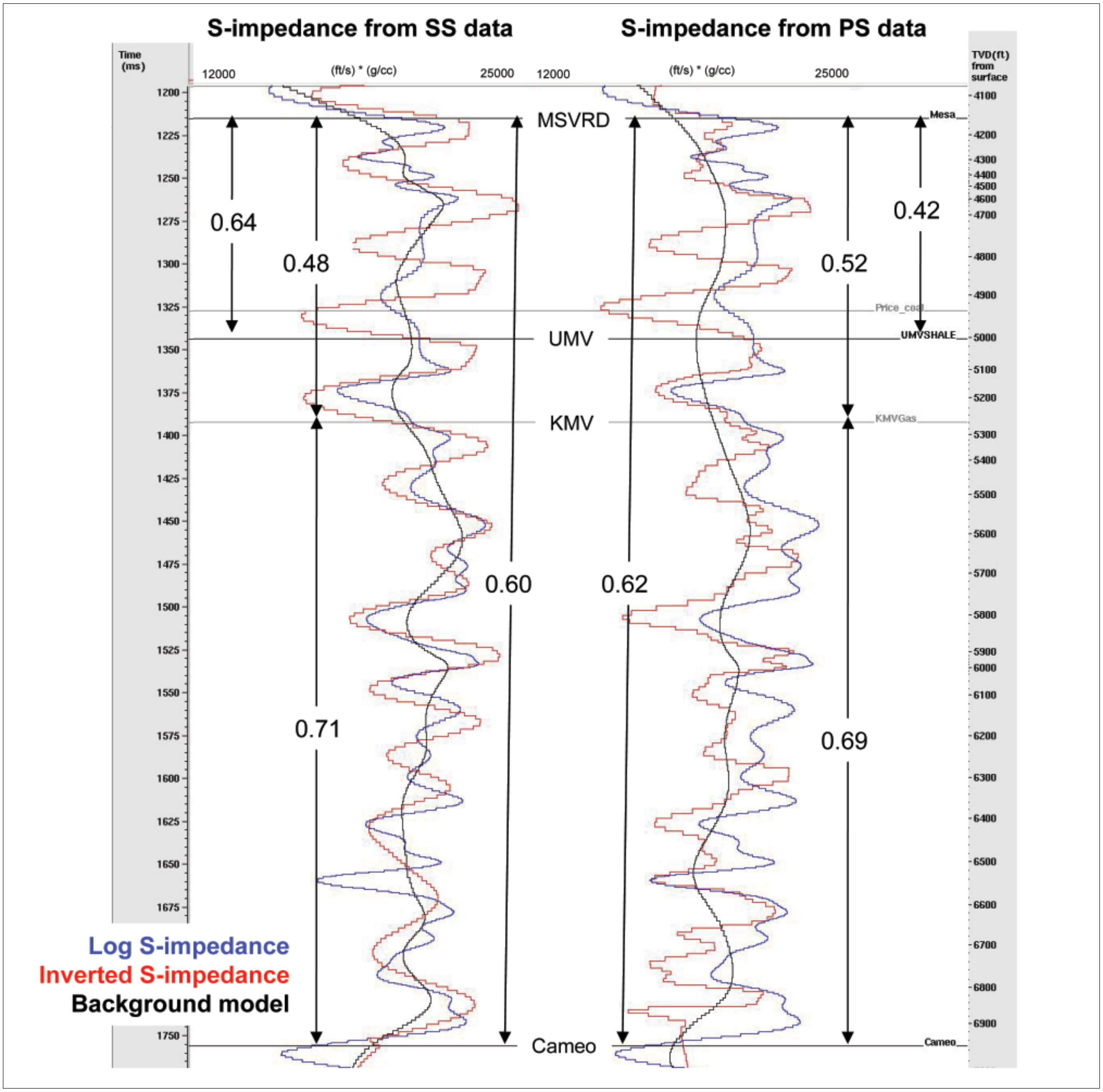

Figure 5. *Comparison of seismic-derived shear impedances with log shear impedances at the well location used to create the background model. Vertical arrows indicate different intervals where the correlation coefficient between filtered log impedance and inverted impedance was calculated. Overall, impedances inverted from seismic data compare favorably with log impedances, but impedances from SS data show slightly better agreement with log data. Correlations in the upper MSVRD-UMV interval are poorer than correlations in the lower KMV-Cameo interval for both inverted results. Notice that higher-frequency information in the inverted results is not included in the background model (black).*

therefore, the reliability of results may decrease away from the well. The result of the inversion of PS data is a volume of pseudoshear impedance that can be used to estimate real shear impedances by applying the regression line in Figure 2b. The result (Figure 3) shows variations of shear impedance in the interval of interest between the UMV and Cameo markers. Since the regression line that relates shear impedances with pseudoshear impedances fits shales better than sands, we expect shear impedances derived from pseudoshear impedances by using this regression line to be more reliable in shales.

A similar workflow was applied for the inversion of stacked SS data for shear impedance to compare with shear impedances estimated from PS data. The result, in PS time, is shown in Figure 4 for the same inline shown in Figure 3. Except for errors in registration of the two results in the PS domain, both sections show similar anomalies, although shear impedances from PS data seem to have more details and higher resolution than smoother and more continuous impedances derived from lower-resolution SS data. The quality of the inversions can be assessed by comparing the results with a filtered shear-impedance log at the well location (Figure 5). Notice how impedances derived from both PS and SS data are similar and compare favorably with log data, although impedances derived from SS data show slightly better agreement with filtered log data.

Conclusions

Shear impedances derived from more commonly available stacked PS-wave data compare favorably with shear impedances estimated from less common stacked SS-wave data. The workflow to estimate shear impedances from stacked PS data is the same as the workflow to invert stacked PP data for acoustic impedances, but some modifications are required to account for mode conversions. Estimates of shear impedance from stacked PS and SS data are not expected to be identical for a variety of reasons. First, vertical resolution of PS and SS data differs because the sweeps used by vibrators that generated each data set are also different. Second, the different data types are affected differently by subsurface properties (in particular anisotropy) and the algorithms and assumptions used to process the data are also different. Third, point-by-point comparison of impedances requires a careful registration of results in the same domain that was beyond the scope of this paper.

Since pseudoshear impedances that result from the inversion of stacked PS data can be easily estimated at log scale, they can be interpreted as easily as shear impedances or used jointly with P-impedances to create crossplots. This may be a better alternative than having to go through the additional step of transforming pseudoshear impedances into "real" shear impedances by using a regression equation that may leave behind many important details in the pseudoshear impedance results. In other words, pseudoshear impedance should be included in the initial rock physics diagnostics if the goal of the project is to interpret inversion results from stacked PS data.

Suggested reading. V_P/V_S Estimation from Multicomponent Seismic Data for Improved Characterization of a Tight Sandstone Gas Reservoir, Rulison field, Colorado by Guliyev (Master's thesis, Colorado School of Mines, 2007). "Time-lapse V_P/V_S analysis for pressure mapping, Rulison Field, Colorado" by Meza et al. (SEG 2008 *Expanded Abstracts*). "V_P/V_S ratio sensitivity to pressure, fluid, and lithology changes in tight-gas sandstones" by Rojas et al. (SEG 2005 *Expanded Abstracts*). "Stratigraphic inversion of poststack PS converted waves data" by Valenciano and Michelena (SEG 2000 *Expanded Abstracts*). TLE

Acknowledgments: We thank the sponsors of the Reservoir Characterization Project of Colorado School of Mines for their support. Thanks also to R. Randy Ray for his review and comments.

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