Amsterdam '14

WS12-A03

Shale Anisotropy Characterization in Heterogeneous Formations Using Multipole Sonic Data

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SUMMARY

Heterogeneity is a common phenomenon that needs to be taken into account when characterizing the elastic anisotropic properties of formations. This can be done successfully through a methodology involving careful binning of the velocity data on the basis of independent, petrophysical information, followed by an inversion process that is carried out on each bin individually. The resulting table of anisotropic parameters per bin can then be used to derive, among other results, correlations between formation petrophysical and anisotropic properties.
A workflow was successfully applied to determine the elastic, transversely isotropic properties of heterogeneous sand-shale sequences. The results of the methodology have significant practical implications. One of these is that synthetics based on the anisotropy-corrected deviated well logs yield stronger and more apparent reflections, as well as a significantly different time-depth relation. Additional applications include the use of the inversion workflow results as inputs into anisotropic seismic velocity models and AVOs.

Introduction

The presence of elastic anisotropy is a well-known critical issue in seismic inversion. Processing that fails to take anisotropy into account yields biased estimates of subsurface velocity, consequently resulting in misties in time-to-depth conversion. In conventional depth imaging, seismic anisotropy can have a significant influence on the focusing and positioning of migrated reflection events.

Typically, anisotropic parameters relevant to seismic processing are directly estimated from the seismic data with techniques that take into account the complexities of how elastic waves propagate in anisotropic media. Alternatively, anisotropic elastic properties can be obtained from comprehensive borehole sonic datasets consisting of monopole compressional, dipole fast and slow shear, and Stoneley shear velocities. A workflow was developed to extract from sonic data the elastic, anisotropic properties of transversely isotropic (TI) overburden shales, taking into account the presence of formation heterogeneity. The final output consists of the five independent TI parameters as a function of heterogeneity, including an estimate of their uncertainties.
The workflow results have important practical applications within the seismic domain, as illustrated in an example in which velocity logs acquired in a deviated well are corrected for anisotropy and subsequently used to generate a synthetic seismogram.

Sonic measurements in transversely isotropic (TI) formations

It is commonly understood that shales exhibit anisotropic behavior due to the constituent plate-shaped clay particles oriented parallel to each other (Sayers, 2005). Most shales can be described, to a good approximation, as being transversely isotropic (TI) with an axis of symmetry that is usually assumed to be orthogonal to the shale beds.

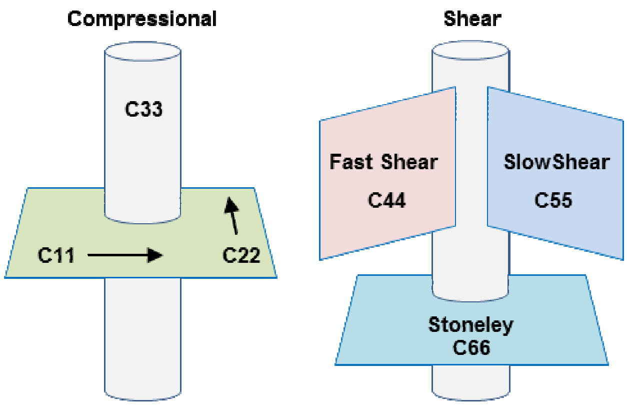

Figure 1 *Through a combination of monopole- and dipole-generated waveforms, wireline sonic technology allows for the determination of up to four independent velocities related to compressional and shear stiffnesses in directions parallel and orthogonal to the borehole axis.*

In terms of their mechanical properties, TI media are fully described by a total of five independent elastic parameters (Thomsen, 1986): the compressional (V_{P0}) and shear (V_{S0}) velocities perpendicular to the shale beds and three dimensionless parameters ε, γ, and δ. Here, ε and γ are related to the fractional difference between (assuming horizontal bedding) horizontal and vertical compressional (ε) and shear (γ) wave speeds, while δ is of particular practical importance for P-wave reflection data processing because it controls the normal moveout (NMO) velocity from horizontal reflectors as well as the small-angle reflection coefficient (Tsvankin, 2005).

Sonic logs are the primary source of information on the elastic properties of a formation. By acquiring both monopole and dipole waveforms at a single depth, a total of up to four independent elastic wave velocities can be acquired and related to formation properties (Figure 1).

First, there is the formation compressional velocity which is extracted from high-frequency monopole data. Next, two shear wave velocities - referred to as the “fast” and “slow” shears - are obtained from dipole data, both of which are measures of the shear moduli of (mutually orthogonal) planes parallel to the borehole. Finally, low-frequency monopole-generated Stoneley waveforms can be processed to obtain a fourth measurement. This Stoneley-based product is usually referred to as the “Stoneley shear”, and it is a measure of the shear modulus of the plane orthogonal to the borehole.

The relation between TI elastic properties and sonic velocities is well understood, though not further discussed here. The interested reader is referred to Tsvankin (2005) and Burridge et al. (1993).

TI anisotropy characterization in the presence of heterogeneity

With up to four inputs but five unknowns, it is apparent that a set of velocities acquired at a single orientation and depth will not provide a sufficient constraint. Hence, data from differently oriented wells need to be combined to extract the five independent elastic TI properties.

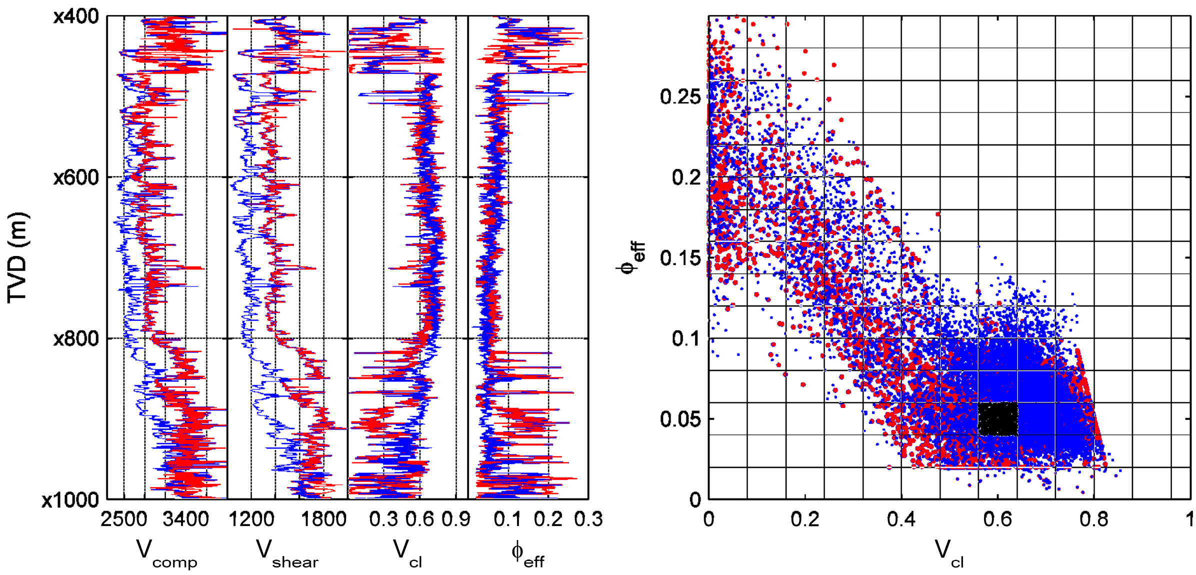

***Figure 2** Left:Composite with vertical well data in blue and deviated well data in red. Compressional velocities in track 1, shear velocities in track 2. Shale volume and effective porosity from petrophysical analysis are given in tracks 3 and, 4 respectively; Right:Crossplot of ϕ_{eff} versus V_{cl}.*

The methodology developed to achieve this objective will next be illustrated on the basis of data acquired in two nearby wells, one of which is vertical while the other is deviated between 30 to 45 degrees. A composite of the data is shown in Figure 2. In either well, the sonic data consist of compressional, dipole fast and slow shear velocities, and the Stoneley shear velocity. The complete logged intervals are characterized by shaly sand sequences with different thicknesses. In the interval x450 to x800 m TVD, both wells are drilled through the same thick shale characterized by large shale volumes and low effective porosities (see tracks 3 and 4 of Figure 2).

Comparing velocities in tracks 1 and 2, it is noticed that because of the anisotropic properties of the shales, the velocities in the deviated well (plotted in red) are significantly larger than those acquired across the same formations in the vertical well. At the same time, it is observed that both logs are characterized by formation heterogeneity.

Heterogeneity is defined as the variation of a property with location, whereas anisotropy is defined as the variation of a property with measurement direction. Spatial variations in properties such as shale volume and porosity can have a larger effect on wave speeds than elastic anisotropy may have. Logs are rarely truly homogeneous; hence, quantifying and taking into account formation *heterogeneity* is a critical step in characterizing formation *anisotropy*.

A simple and effective way to deal with heterogeneity is to bin the data on the basis of petrophysical volumes whose variations are expected to have a significant impact on wave speeds. Two volumes that are known from rock physics studies to have this impact are shale volume V_{cl} and (effective) porosity ϕ_{eff}. Hence, we proceed to bin the velocity data on the basis of these two volumes. For instance, the black bin in the crossplot in Figure 2 represents all data along the logs for which V_{cl} is between 56 and 64% and for which ϕ_{eff} is between 4 and 6 p.u.

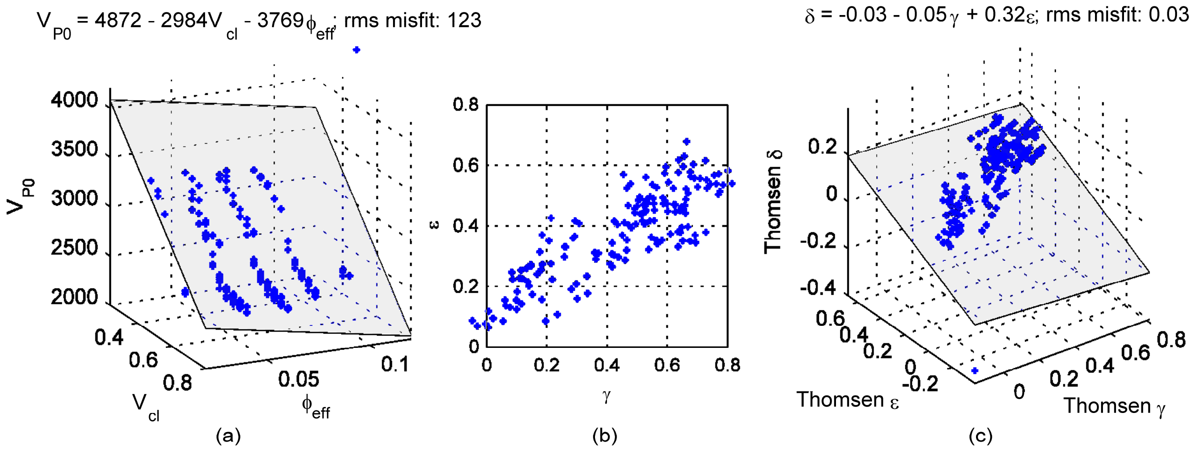

***Figure 3** Analysis of the TI inversion results. (a)V_{P0} as a function of V_{cl} and ϕ_{eff}, (b)ε versus γ, and (c) δ as a function of ε and γ.*

The binned velocity data are input into the inversion process. This process, carried out on each bin individually, consists of two steps: a root-mean-square-based iterative process followed by a Bayesian-based approach to assess the confidence that can be put into the iteration results. Ultimately, the inversion methodology results in a table of best-fitting TI parameters and an estimate of standard deviations, all as a function of the binning parameters. Figure 3 shows examples of some of the relations that can be derived on the basis of these results.

Application example: Anisotropy-correction of deviated well logs

A highly relevant application of the TI inversion results is "verticalization" or anisotropy-correction of velocity logs acquired in deviated wells, i.e., determination of sonic velocities that would have been obtained if a deviated well had been drilled vertically instead (Figures 4a and 4b).

An important aspect of the anisotropy correction applied here is that it is lithology dependent. Because the presence of formation heterogeneity is explicitly taken into account in the inversion workflow, the velocity correction varies from depth-to-depth and from one formation to another. As a result, the highly anisotropic shales are observed to be corrected by as much as 300 m/s, whereas the isotropic sands at the bottom of the logs are hardly corrected at all (compare the red curves in the left- and right-hand side plots of Figure 4a). In the end, the corrected velocities from the deviated well are very similar to the measured velocities in the vertical well (Figure 4b).

Since the shale velocities decrease as a result of the anisotropy correction whereas the sand velocities remain intact, the velocity contrasts between the slower shales and the faster sands have increased after correction. In turn, this results in stronger and more apparent reflectors on synthetic seismograms. Depending on the anisotropic elastic properties of adjacent formations, anisotropy correction can even result in sign changes of reflector polarizations as well as new reflectors where there were previously none. Finally, the correction process results in a time-depth relation that is significantly different from the same relation based on the deviated well log, as illustrated in Figure 4c. In conclusion, besides incorrect well ties due to incorrect time-depth relations (as also described by Hornby et al., 2003), quite importantly, the reflectivity pattern itself may also be different after anisotropy correction.

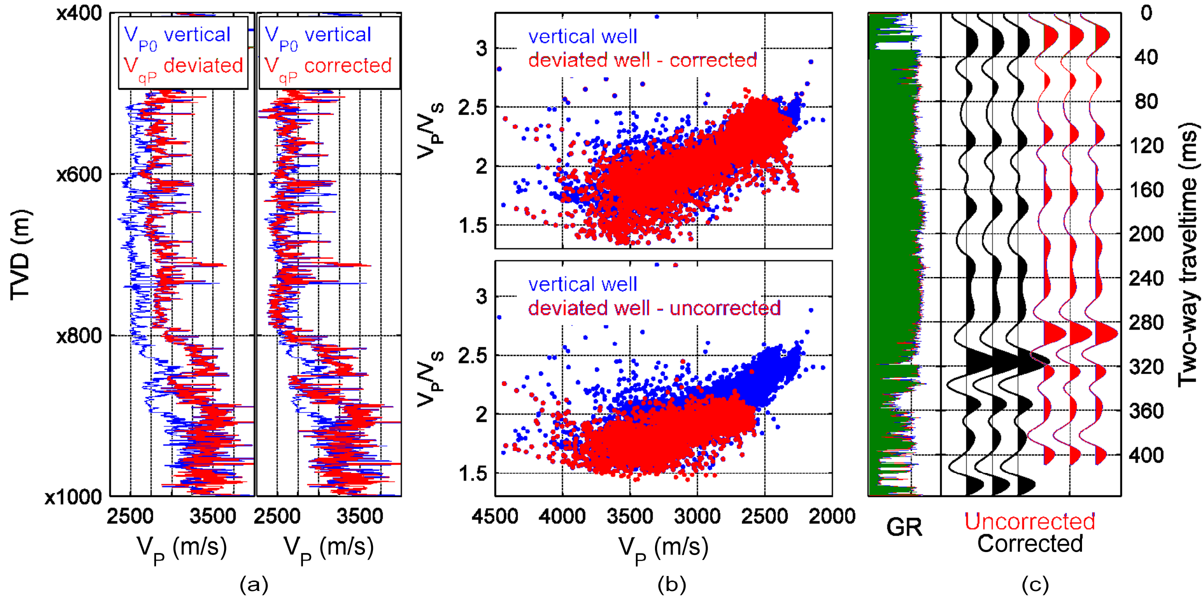

Figure 4 *(a) Comparison between the measured compressional velocity in the vertical well (blue) and the velocity in the deviated well (red) before (left) and after (right) anisotropy correction;(b)* V_P/V_S *versus* V_P *crossplot before (bottom) and after (top) anisotropy correction; (c) Synthetics generated with the uncorrected (red) and corrected (black) compressional velocity from the deviated well.*

Summary

Heterogeneity is a common phenomenon that needs to be taken into account when characterizing the elastic anisotropic properties of formations. As demonstrated here, this can be done successfully through a methodology involving careful binning of the velocity data on the basis of independent petrophysical information, followed by an inversion process that is carried out on each bin individually. The resulting table of anisotropic parameters per bin can then be used to derive, among other results, correlations between formation petrophysical and anisotropic properties.
The workflow summarized briefly in this paper was successfully applied to determine the elastic, transversely isotropic properties of heterogeneous sand-shale sequences. The results of the methodology have significant practical implications. One of these is that synthetics based on the anisotropy-corrected deviated well logs yield stronger and more apparent reflections, as well as a significantly different time-depth relation. Additional applications include the use of the inversion workflow results as inputs into anisotropic seismic velocity models and AVOs.

Acknowledgements

The authors thank the management of Eni e&p division and Schlumberger for permission to publish this work, Marco Mantovani and Sandro Tommi (Eni e&p), Prince Abangwu, and Pereira Miranda (Schlumberger) for the support of the processing work involved and Ted Ter Burg (Schlumberger Borehole Geophysics Europe) for his help with generating the synthetic seismograms.

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