Elastic anisotropy in the Haynesville Shale from dipole sonic data

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Abstract

Worldwide interest in shales as hydrocarbon resources has increased in recent years, driven mostly by the successful development of gas shales in North America. One of these gas shale plays is the Haynesville Shale located in Texas and Louisiana. In this paper we analyse dipole sonic log data acquired over the build section of a deviated well and show how these data can be used to estimate the elastic anisotropy of the formation. In this case the formation is relatively homogeneous over the build section and so the deviated well allows the sampling of well deviations from approximately 50° to horizontal. Using the compressional, fast-shear, and slow-shear data as a function of the well deviation angle, we estimated the anisotropy for the gas shale. These anisotropy estimates were then used to remove the anisotropy effects observed in the deviated well. Comparison of these 'corrected' sonic logs to sonic logs acquired in the vertical pilot well shows good agreement.

Introduction

Interest in natural gas production from shale formations has rapidly increased over the last decade in the United States. This interest has been driven primarily by technology advances, in particular by horizontal drilling and hydraulic fracturing technologies that allow natural gas to be recovered with favourable economic returns. This commercial success has stimulated worldwide interest by organizations wanting to exploit shale gas plays similar to those in the Barnett, Woodford, and Marcellus shales (Figure 1). The Haynesville Shale, sometimes referred to as the Bossier or Shreveport Shale, is one of these unconventional gas shale formations. It straddles the Louisiana–Texas border and extends over an area of approximately 15,000 km^2 at an approximate depth range of 10,000–13,000 ft. The formation is a relatively thick (200 ft), organic-rich shale that was deposited in a shallow marine environment during the Late Jurassic.

Shale formations are composed of thinly layered sequences of aligned microscopic clay platelets; therefore, it is not surprising that they exhibit anisotropic (directionally dependent) properties at larger scales. Because the layering is typically horizontal, the resulting effective anisotropy has a vertical symmetry axis about which the properties are invariant, known as vertical transverse isotropy (VTI). Knowledge of the anisotropic elasticity parameters is important for understanding the initiation of hydraulic fractures (Suárez-Rivera et al., 2006), for accurately locating the microseismic activity associated with hydraulic fractures (Warpinski et al., 2009), and for accurate seismic depth imaging. In this paper we show how it is possible to obtain all the elastic constants for a transverse isotropic (TI) medium from crossed-dipole sonic log data acquired in a single deviated well.

Anisotropy and dipole sonic logs

Five elastic constants are required to define VTI anisotropy: c_{11}, c_{33}, c_{44}, c_{66}, and c_{13}. An alternative set of parameters widely adopted within the geophysical industry are those of the Thomsen parameters: α_0, β_0, ε, γ, and δ (Thomsen, 1986). The α_0 and β_0 are the vertical P-wave and S-wave velocities, respectively. The Thomsen ε and γ parameters can be thought of as quantifying the difference between the vertical and horizontal velocities for the P-wave and the horizontally polarized S-waves (SH), respectively. The remaining Thomsen parameter δ is not easy to describe because its impact on the resulting anisotropy also depends on the ε parameter. However, if ε equals δ, the result is termed elliptical anisotropy because the P-wave velocity surface is ellipsoidal and the vertically polarized shear-wave (SV) velocity surface is spherical. The situation in which ε is greater than δ is known as positive anellipticity and is the general case for most shales. Positive anelliptic solids are characterized by P and SV-wave velocities at oblique angles that are slower and faster, respectively, when compared with the elliptical situation.

Crossed-dipole sonic tools can excite various wave modes from which formation properties can be measured. In the context of anisotropy parameter characterization,

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the compressional mode, flexural wave (shear) modes, and Stoneley mode are of particular interest because they can be used to infer the Thomsen γ parameter, α_0, and β_0 in a vertical borehole intersecting a VTI formation. If the wellbore is deviated, then β_0, γ, and two other parameters that are a function of the remaining Thomsen parameters can be retrieved (Norris and Sinha, 1993).

Multi-well and single-well methods

If sonic logs are available in the same formation from multiple wells at different deviations, it is possible to compute an averaged α_0, ε, and δ (Hornby et. al., 2003). This concept is illustrated in Figure 2 and is sometimes referred to as the multi-well method. The formation is assumed to be laterally homogeneous so that any variation observed in the sonic

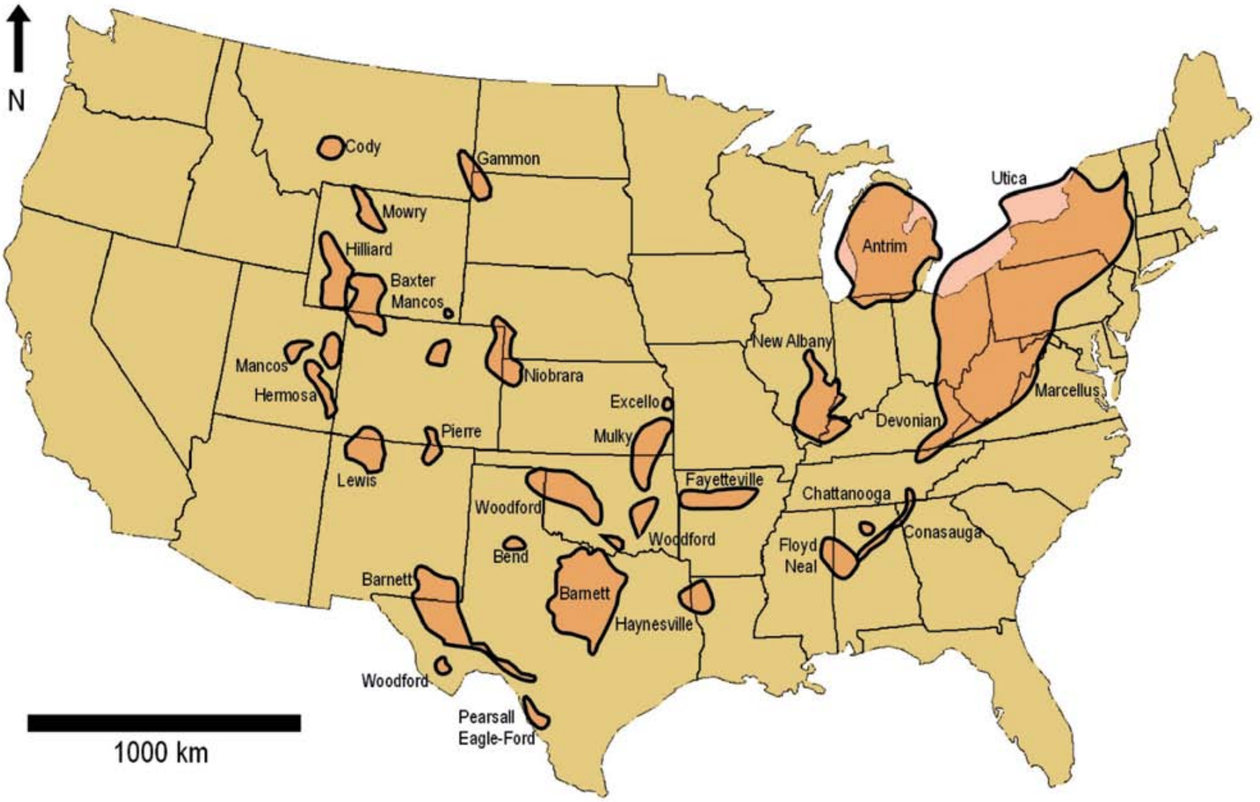

Figure 1 *Selected USA gas shale plays. The Haynesville Shale is located in eastern Texas and north-western Louisiana.*

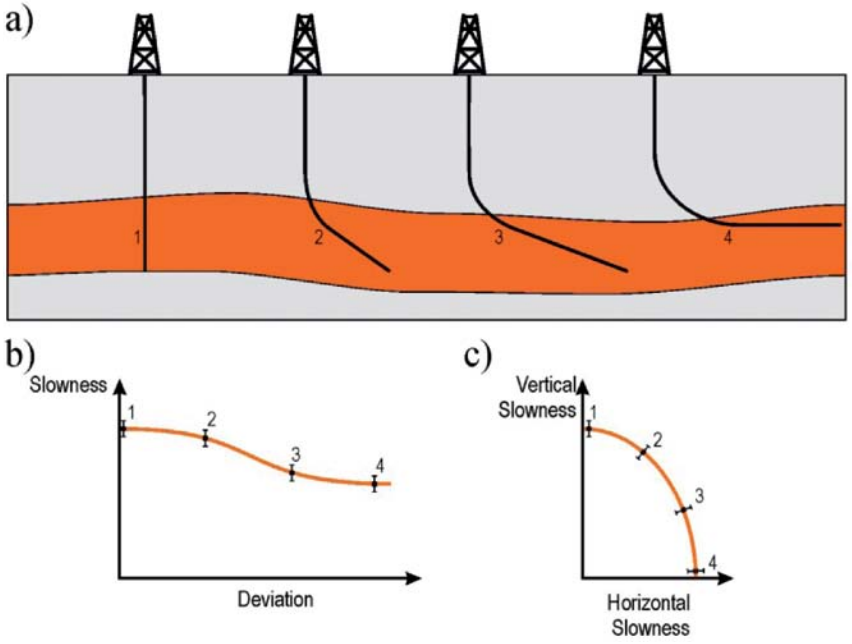

Figure 2 *Diagrams to show the sensitivity of sonic data in deviated wells to anisotropic effects. (a) The deviations of four wells increase from vertical to horizontal in the anisotropic formation (orange). (b) The plot of average formation slowness against well deviation shows that slowness decreases with increasing well deviation (i.e., velocity increases towards the horizontal direction). If the formation were isotropic, the data points 1 to 4 would lie on a straight line. (c) As an alternative to the plot in (b), this polar plot shows the effect of anisotropy as a decrease in slowness with increasing well deviation. Departure of the plotted points from the arc of a circle indicates anisotropy.*

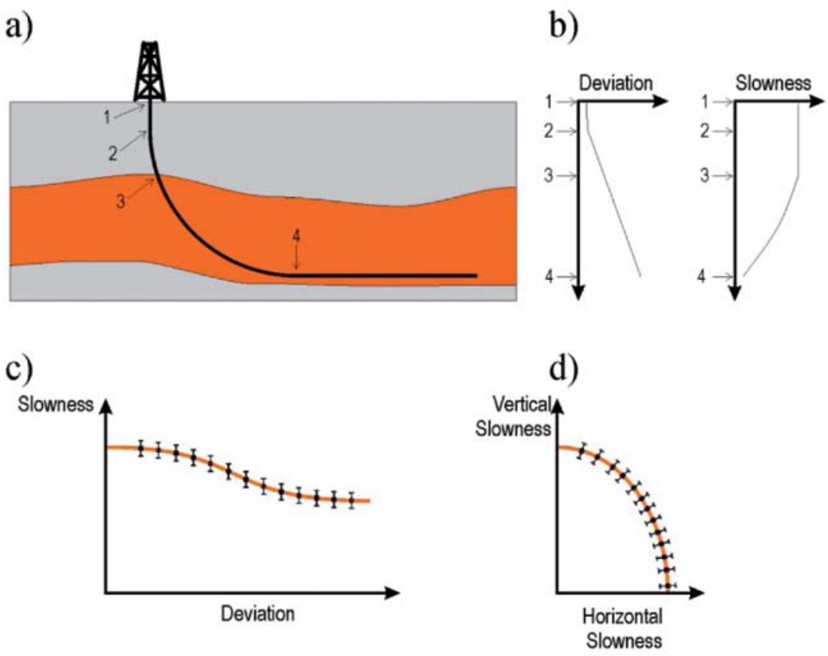

Figure 3 *Diagram to show the sensitivity of sonic data in a deviated well to anisotropic effects. (a) The deviated well is vertical from point 1 to point 2, begins to deviate from vertical in the isotropic formation (grey) between point 2 and point 3, enters the anisotropic formation (orange) at point 3, and becomes horizontal at point 4. (b) The deviation and sonic logs. Slowness decreases with depth from point 3 to point 4 as the well becomes horizontal (i.e., velocity increases with well deviation) whereas slowness is constant from point 2 to point 3 in the isotropic formation. (c) and (d) Crossplots of these logs in linear and polar representations. If the formation were isotropic, the lines would be horizontal in (c) and circular in (d).*

logs from the deviated wells can be entirely attributed to anisotropic effects. The estimation process then entails matching the averaged formation slowness as a function of angle to a modelled slowness as a function of the anisotropy parameters. If these sonic logs include dipole sources, then all five elastic parameters can be recovered (Walsh et al., 2007).

The technique described in this paper uses sonic data from a single deviated well to fully characterize the VTI anisotropy. For this reason we call this the 'single-well' method. In the single-well method, we make use of crossed-dipole or logging-while-drilling (LWD) sonic logs recorded in wells with deviations that span a wide range of angles over a single homogeneous formation (Figure 3). Suitable well profiles are encountered in gas shale plays because production is maximized through long horizontal sections and drilling costs are minimized by drilling vertically through the overburden to reach the target formations. The resulting wells comprise an essentially vertical section that rapidly changes to the horizontal direction over a relatively short depth range in the formation of interest. Because the well deviation changes rapidly over a relatively small depth range in the target gas shale, a wide range of angles can be sampled with borehole log measurements. Such data are ideal for anisotropy analysis because the rapid change from vertical to horizontal over a small depth range minimizes lateral variability effects, and the resulting wide angular aperture exposes any anisotropy effects. However, logging in such environments is non-trivial because logging tools may require the use of downhole tractors to position the tools in the near-horizontal well sections. An alternative is to use LWD measurements, which record the sonic data as the well is being drilled or as the drill bit is removed from the formation after drilling is completed.

Field example

The crossed-dipole sonic log data that we use to demonstrate the technique are shown in Figure 4. Anisotropy effects can be clearly observed in the data. First, the P-wave and the SH (fast) sonic data show a clear velocity increase as the well becomes more horizontal. Secondly, the phenomenon of shear-wave splitting can be clearly observed as the well deviation increases beyond 50° (below relative measured

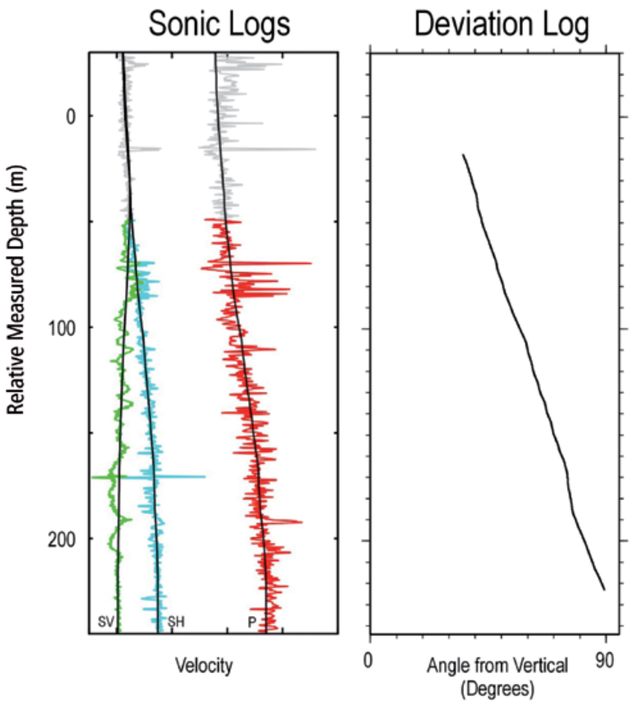

Figure 4 *Left: Dipole sonic logs showing P-wave velocity (red) and the fast (green) and slow (blue) S-waves over the shale section. Right: Well deviation log. The modelled sonic data determined from the inversion results are overlain. The axes are unnumbered for confidentiality.*

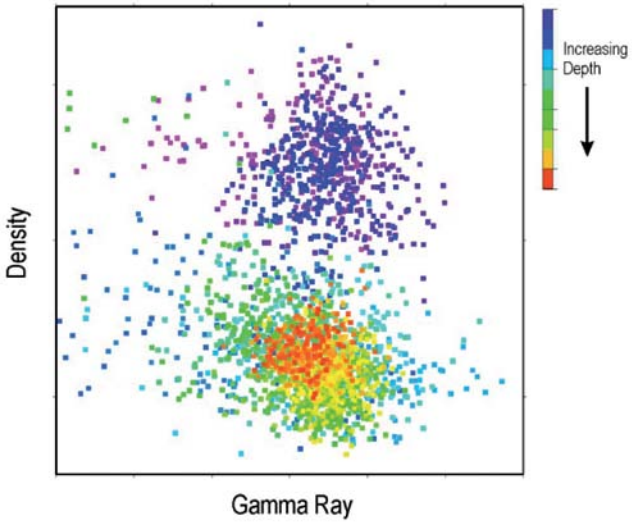

Figure 5 *Crossplot of gamma ray and density log data colour-coded according to depth. Two distinct formations corresponding to the shallower Bossier Shale (blue and purple) and deeper Haynesville Shale (red, yellow, green) can be identified. The axes are unnumbered for confidentiality.*

depths of 50 m) where the SH (blue curve) and SV (green curve) velocities separate. Shear-wave splitting (sometimes referred to as shear-wave birefringence) can occur in a VTI medium and results in the SV and SH waves propagating with different velocities.

Measurement of the P, SV, and SH velocities in the horizontal section of the well allows a direct measurement of c_{11} (a function of α_0 and ε), c_{44} (related to β_0), and c_{66} (related to β_0 and γ), respectively. The remaining two elastic parameters, c_{33} (related to α_0), and c_{13} (a function of α_0, β_0, ε and δ), can be estimated from the P and SV velocities observed over the deviated section of the well.

A crossplot of the gamma ray and density log data was used to identify a homogeneous shale section in the deeper section of the well (Figure 5). The sonic data over the depth range corresponding to this cluster were then extracted and processed to yield P, SV, and SH velocities as a function of well deviation.

We used a non-linear optimization algorithm based on the neighbourhood algorithm (Sambridge, 1999) to invert the sonic data simultaneously for all five elastic constants and a dip parameter. A comparison between the velocity curves and the observed sonic log data is shown in a polar representation in Figure 6. There is very good agreement between the modelled velocities and observed sonic velocities, and the estimated model parameters are consistent with expectations for anisotropic shales. Although the solution is non-unique, the most probable model is much better than the auxiliary solutions for other local minima.

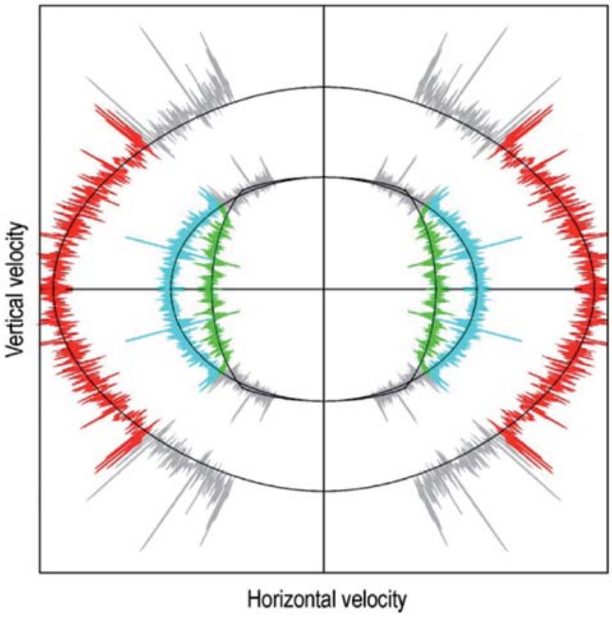

Figure 6 *Dipole sonic log data of Figure 4 shown in a polar velocity representation: P-wave – red; fast S-wave – blue; and slow S-wave – green. Grey lines show data that lie outside the Haynesville Shale. The modelled velocity curves for the best-fitting anisotropic model are overlain in black. Note that only data in one quadrant were actually acquired. The other three quadrants are shown for visual clarity and are generated based on symmetry assumptions. The axes are unnumbered for confidentiality.*

The inclusion of SV data reduced this non-uniqueness and improved the resolution of the anisotropy parameters (Figure 7). Although the P-wave data show a well defined minimum, the probability distribution trades off between the ε and δ parameters such that the δ parameter is not well resolved (Figure 7, left). The conditional probabilities for the SV data show that neither ε nor δ are resolved independently (Figure 7, middle). This lack of resolution was expected because the weak phase velocity expressions of Thomsen (1986) show that the SV velocity is primarily a function of the difference between ε and δ. Nonetheless, because the trade-offs in the ε and δ parameters for the P and SV data probabilities are not parallel, the combined data reduced the overall uncertainty on these estimated parameters (Figure 7, right).

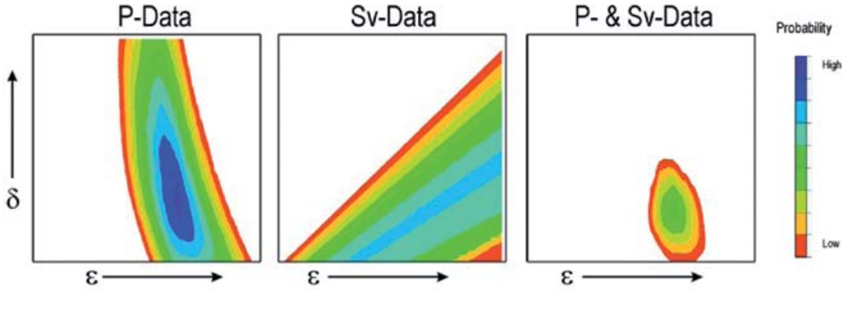

Figure 7 *Conditional posterior probabilities for the δ and ε parameters computed from the most probable solution. From left to right, plots show the contributions from the P-wave data and the SV-wave data, and the conditional probability arising from the combination of P and SV data. The axes are unnumbered for confidentiality.*

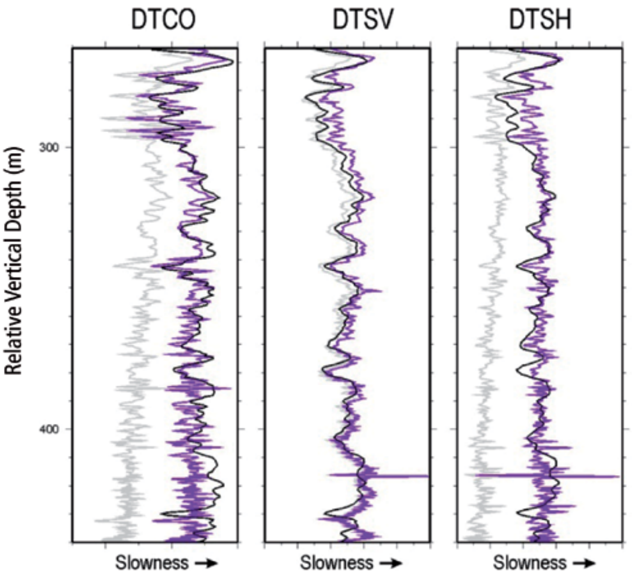

Figure 8 *Comparison of dipole sonic log data from the vertical pilot hole (black) and the deviated well (grey) and corrected data from the deviated well (purple). From left to right, the plots are for P, SV and SH-wave data. The axes are unnumbered for confidentiality.*

Fortunately, crossed-dipole sonic data were also acquired in a vertical pilot well through the same shale formation. These data enabled us to test the accuracy of the estimated anisotropy parameters because we could predict the vertical velocities from the deviated well data using the anisotropic model and compare them with those measured in the vertical pilot hole. We found that the difference between the predicted and measured average vertical velocities is less than 2%. Furthermore, we corrected the dipole sonic logs acquired in the deviated section of the well and compared them with the crossed-dipole sonic logs measured in the vertical pilot hole (Figure 8). The anisotropy-corrected logs clearly show a much better match to the vertical pilot-hole logs, especially for the P and SH log data.

Summary and conclusions

In this paper we show a successful application of single-well anisotropy estimation using crossed-dipole sonic data acquired in the Haynesville Shale. The estimated anisotropy parameters are consistent with a priori expectations. Furthermore, confirmation of the accuracy of the recovered anisotropy parameters was obtained by comparison with the crossed-dipole sonic log data acquired in the vertical pilot hole.

It might be expected that the extreme deviations of such horizontal wells reduce the applicability of this method because logging tools would need to be deployed using tractors. However, we have also successfully tested the single-well estimation technique with LWD sonic data from other unconventional gas reservoirs with good results.

These data also verified the conclusion of Hornby et al. (2003) that in fast formations sonic logs measure group slowness for propagation with the group angle equal to the borehole inclination angle (Miller et al., 2012).

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