# Improving seismic calibration and geomechanical models through characterization of anisotropy using single and multi well data: Case Study in Forties Field, UK

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## Summary

Extending the life of mature fields is dependant on reducing cost of operations (drilling & completions) and choosing locations for optimized production. Understanding the implications of anisotropy helps in reducing the uncertainty of wellbore stability models and improving seismic calibration.

A major difficulty in extending seismic and sonic processing for geomechanical and geophysical applications within anisotropic media is the determination of an anisotropic velocity model. However, mature fields, where multiple wells are drilled at various deviations, represent optimum conditions for acquiring sonic data to determine anisotropy parameters.

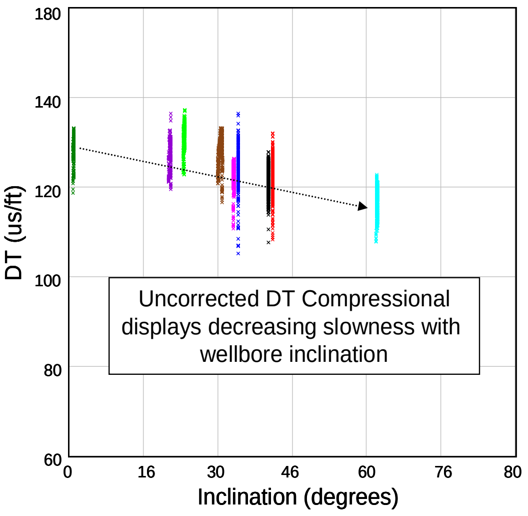
A case study is presented in the Forties Field, UK where the anisotropy parameters were studied at one well location from full waveform sonic logs, borehole seismic and core analysis. The field wide sonic data was then integrated with the single well results and used for a field wide calibration of the sonic data to account for the effects of anisotropy caused by the shale layering in the overburden. Subsequently, the wellbore stability predictions and seismic interpretation were updated and showed improvement by utilizing the anisotropy results.

## Introduction

Compressional and shear borehole sonic data are traditionally used for both seismic calibration and geomechanical modeling. The complexity of the velocity models used for time to depth conversion or AVO analysis for seismic calibration has been dependant on the input data or current techniques available. Similarly, stress and rock strength modeling for completion design or wellbore stability analysis utilizes combinations of existing log and core data to make validated predictions of rock failure. In both cases, only when predictions do not satisfy field observations, models are updated with measurements that may go beyond traditional means for a given field or formation. In order to economically justify additional data acquisition and analysis, the implications of more complex models must be understood.

Similar multi-well studies have been performed by Hornby (1995, 1999) and Brevik (2007) to characterize shale with respect to the TI parameters for seismic processing (AVO and time to depth) applications. The completion community has been actively using anisotropy to characterize in-situ stress profiles using anisotropic moduli derived from core and sonic logs (Higgins et al., 2007, Theircelin and Plumb, 1994). This case study represents a combined geomechanics and geophysics workflow to address the TI anisotropy parameters for both disciplines and quantify its impact.

Slowness data measured in a number of wells shows a clear decrease of slowness with well-bore deviation. Figure 1 illustrates this variation for the Sele shale. Calibration of surface seismic, borehole seismic and well logs was of interest, to ensure a consistent interpretation of all available data. Wellbore stability and completion challenges were sometimes encountered in these sub-vertical wells. Since the well logs were not corrected for bed layering or in-situ stress, wellbore stability analysis was made and calibrated using empirical methods. Although these empirical methods have improved drilling success, more complicated scenarios such as extended reach wells and alternate completion strategies still have significant uncertainties that require more detailed analysis.



Uncorrected DT Compressional displays decreasing slowness with wellbore inclination

Figure 1: Compressional slowness versus wellbore deviation in the Sele formations in the Forties Field, UK across 9 wells. Note that the slownesses start to decrease at angles > 30 degrees indicating that Thomsen's δ is small.

A joint study was undertaken to obtain all possible elastic modulus data at various scales (frequency and wavelength), over the Sele formation to address anisotropy. A single well was chosen on the Bravo platform to acquire the following data at a deviation angle of 40 degrees:

- Full core over the Sele shale formation
- Full waveform sonic logs (compressional, dipole and Stoneley shear data)
- LWD logs (density, neutron, resistivity, gamma ray)
- Borehole seismic survey (walkaway VSP)

After the data was acquired on a single well, these results were then used with all other compressional and shear sonic data across the field to further calibrate the anisotropy parameters. The results may then be used to address a number of key issues in understanding the effects of anisotropy caused by the presence of bedding planes or micro-layering within shale, and in-situ stress.

## Background

It is well understood that shales exhibit anisotropic behavior. This is due to the constituent plate-shaped clay particles oriented parallel to each other (Sayers, 2005). Shale can often be well-described by transverse isotropic models. Transverse isotropy characterizes a rock that has a vertical axis of symmetry (TIV), where the rock is isotropic in the bedding plane and is dissimilar in the direction perpendicular to the bedding plane (Walsh et al., 2006).

In geophysical terms, it is common to describe the TI anisotropy in terms of Thomsen's parameters $\varepsilon$, $\delta$ and $\gamma$. These parameters describe the compressional and shear wave propagation within TI material relative to the TI axis of symmetry (Thomsen, 1986). However in the geomechanics discipline, it is common to describe rock stiffness in terms of directional Young's modulus ($E$) and Poisson's ratio ($\nu$). In addition to rock stiffness, it is also required to quantify rock strength in terms of unconfined compressive strength (UCS) relative to bedding planes for wellbore stability applications (Jaeger et al., 2006).

## Methodology

Core acquired on the Bravo platform was plugged at three different depths within the Sele formation. The core plugs were taken at 0, 45 and 90 degrees to the bedding planes. In-situ stress conditions were applied, allowing the samples to be pseudo-fully drained. This was achieved by applying end and side drains to the core specimens while maintaining a very low strain rate ($10^{-7}$) while ramping to the in-situ stress conditions in order for the pore pressure to dissipate without creating micro-cracks. Both static and dynamic elastic moduli were acquired as a function of effective stress. At an additional depth location from core recovered on the Delta platform in the Sele formation, core plugs were taken at 0, 30, 45, 60 and 90 degrees to bedding where fast strain-rate unconfined compressive strength (UCS) tests were performed to assess rock strength as a function of bedding angle. This concise core program allowed for both geophysical and geomechanical parameters to be acquired.

Deviated wells represent the most difficult case for sonic log acquisition and interpretation of the parameters required for characterizing a TI medium. The axes of the TI medium (bedding planes) are not normal to the borehole-axis, thus wave propagation within the borehole is not axis-symmetric. This lack of symmetry introduces a case where the compressional and shear waves measured in the wellbore are a function of both horizontal and vertical stiffnesses. The borehole sonic data was processed to obtain elastic stiffnesses relative to bedding plane orientation (Norris and Sinha, 1993). The dynamic shear stiffnesses derived from the sonic logs correspond to the $S_V$ and $S_H$ velocities to obtain Thomsen's gamma ($\gamma$) parameter (Walsh et al., 2007).

Several techniques were used to estimate interval and effective anisotropy from walkaway VSP data. Thomsen's epsilon ($\varepsilon$) and delta ($\delta$) parameters as well as effective compressional and shear stiffnesses for the interval were also evaluated. The two techniques which measure the interval anisotropy across the array are the slowness/polarization and the phase slowness inversion techniques. Of these two techniques, the slowness/polarization technique is considered superior because it relies entirely on the local homogeneity around the receiver array and is independent of structural complexities in the overburden.

The multi-well analysis used 125 compressional slowness logs and 9 shear wave slowness logs across 5 platforms in the Forties Field. For a more simplistic and pragmatic approach for assessing Thomsen's $\delta$ parameter, the multi-well analysis used the equations described by Norris and Sinha (1993).

The workflow for the multi-well approach is outlined below:

1. Audit of all processed shear and/or compressional sonic to determine quantity, quality, tool type and date of acquisition
2. Mean average compressional and shear slowness values were computed across the Sele formation
3. Mean slowness values were plotted against relative dip (hole deviation – stratigraphic dip) along with the phase slowness curves with Thomsen's parameters derived from the VSP and sonic analysis

4. Anisotropy parameters (ε, η~δ, γ) were calibrated and updated using the multi-well data for each platform
5. Corrections using the calibrated parameters were applied to the measured sonic logs resulting in the generation of vertical slowness logs

## Results

The core results in Table 1 represent the Thomsen parameters from the dynamic elastic moduli. From the 3 cored intervals there is evidence of significant heterogeneity with variations in the δ parameter.

| Depth (mD) | ε | γ | δ |
|---|---|---|---|
| 2696 | 0.11 | 0.13 | -0.216 |
| 2699 | 0.23 | 0.19 | -0.014 |
| 2702 | 0.27 | 0.14 | 0.320 |

Table 1: Thomsen parameters obtain from the core plugs at three intervals under effective in-situ stress conditions.

The UCS values are plotted in Figure 2, illustrating the variations in rock strength relative to bedding plane orientation. There is an 85% reduction in strength at 45 degrees to bedding. Wellbores drilled at this angle (with flat bedding) have a higher likelihood of hole collapse than any other angle. It is interesting to note that the UCS parallel to bedding is nearly the same as it is perpendicular to bedding (0 and 90 degrees). In comparison, the dynamic and static stiffnesses (Young's modulus) does not exhibit the same character as both ε and γ are positive and thus the properties parallel to bedding are much higher than perpendicular to bedding. In the geomechanics discipline, it is common to relate stiffness to strength, but in the case of weak bedding planes, this type of correlation is not applicable as indicated by the UCS core tests.

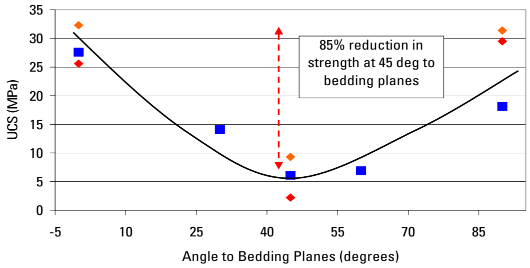


Figure 2: Rock strength (UCS) as a function of bedding planes show that the wellbore stability (collapse pressure) will be most affected at 45 degrees to bedding. Core data from Delta and Bravo platforms.

The sonic results are shown in Figure 3. The dynamic elastic moduli show that the horizontal shear (C66_TIV) is much higher than the vertical shear (C44_TIV) stiffness. The average Thomsen's γ parameter is ~0.7, much higher than the core results in Table 1.

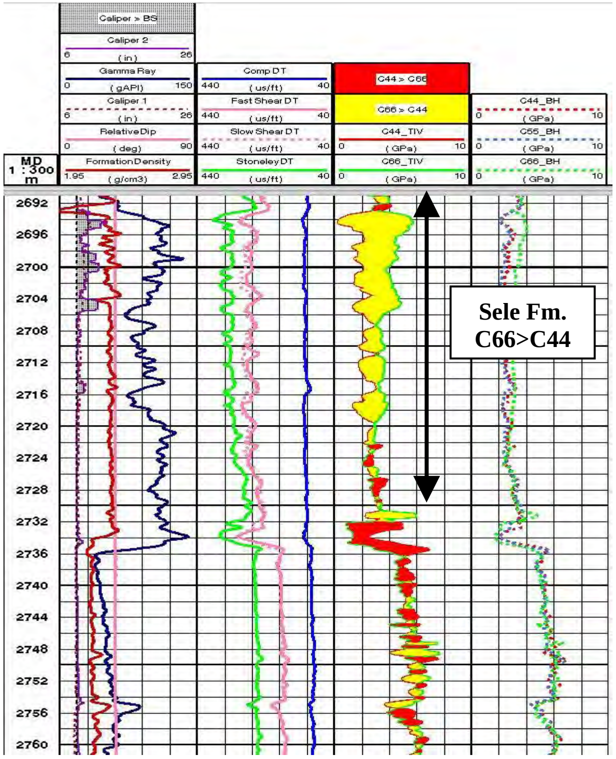


Figure 3: Composite plot of the sonic slownesses and dynamic stiffnesses C44_TIV and C66_TIV rotated relative to bedding planes (apparent dip was measured at 40 degrees),

We attribute this difference due to uncertainty in the borehole diameter and the extrinsic effects of bedding plane failure. As supported by the rock strength data above, there is a reduction in rock strength data relative dip between 40 and 55 degrees, which corresponds to the angle for this well. From observations in the shear and Stoneley radial profiling data, there appears to be significant alteration and evidence of stress induced anisotropy.

The multi offset VSP data was acquired using an eight level array spanning the Sele formation and provides a means to estimate the intrinsic anisotropy parameters at the seismic wavelength. Slowness and polarization angles are derived as a by-product of the elastic wavefield separation and these are cross plotted in Figure 4 for each of the constituent four planar wavefields for every shot. Inversion of these data points provides best estimates of ε = 0.254 and δ = 0.006.

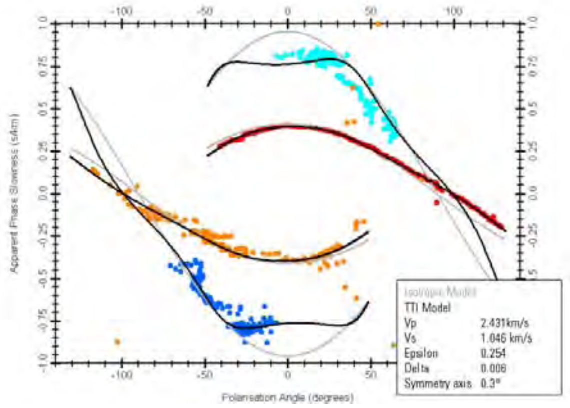


Figure 4: Slowness-polarisation inversion technique used on the walkaway VSP data.

The multi-well analysis is summarized in Figure 5. Calibration of the phase slowness curves with borehole sonic log data enabled Thomsen parameters (ε, δ, γ) to be estimated. The ε parameter varies between 0.20 and 0.28 across the field. The best fit value determined for δ is 0 and γ is ~ 0.7. The estimation of epsilon and delta parameters are consistent with anisotropy observations from VSP and core measurements. There is a higher uncertainty associated with the estimation of gamma, as a result of limited shear data, particularly for wellbore deviations > 40°.

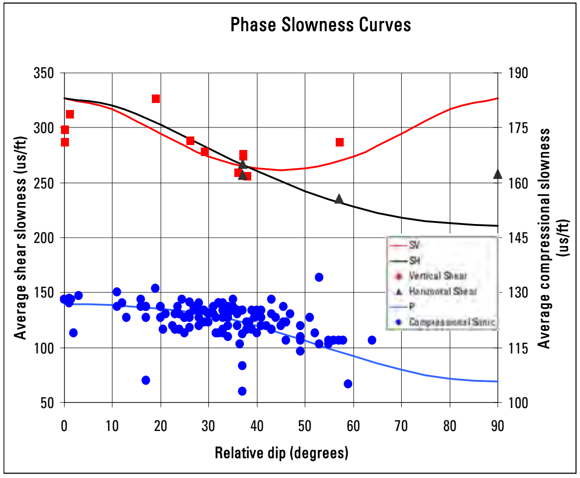
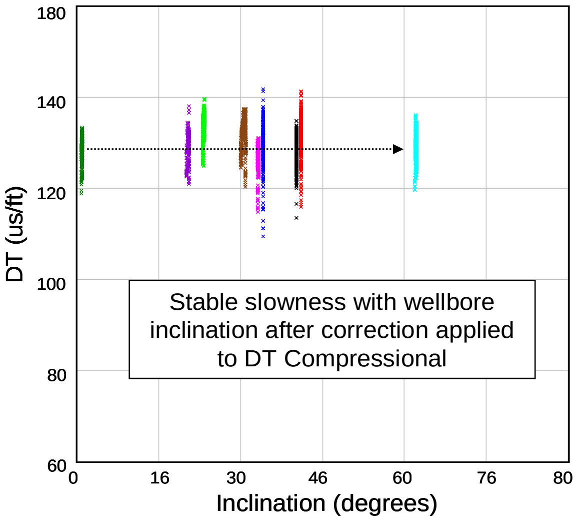


Figure 5: Phase slowness curves for all wells in the Forties field.

Vertical sonic data computed using the calibrated parameters are displayed in Figure 6.



Stable slowness with wellbore inclination after correction applied to DT Compressional

Figure 6: Verticalised compressional slowness vs. well bore inclination in the Sele formations in the Forties Field, UK across 9 wells.

## Conclusion:

Anisotropy parameters were computed using an integrated workflow using ultrasonic, sonic and VSP data. The anisotropy results indicated that the compressional data was well constrained throughout the field, however the shear ($S_V$ and $S_H$) had more uncertainty. Extrinsic effects such as bedding plane failure as supported by the anisotropic rock strength testing performed has a high impact on the shear wave data. The sonic logs acquired in significantly deviated wellbores were corrected to vertical slowness using these anisotropy parameters enabling calibration of the seismic data to these wells. Wellbore stability predictions were also improved through understanding rock strength as a function of bedding plane angle as well as static rock stiffnesses.

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## EDITED REFERENCES

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