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Correcting sonic logs for shale anisotropy: a case study in the Forties field

Donald Keir,1 Brett McIntyre,1 Ted Hibbert,1 Rachael Dixon,1 Klaas Koster,1 Farid Mohamed,2* Adam Donald,2 Anzar Syed,2 Chang Liu,2 Tom O’Rourke,2 Andrea Paxton,2 Steve Horne,2 Ed Knight,2 Colin Sayers and Paolo Primiero2 describe how a method employed to quantify anisotropy and correct sonic logs across the Forties field led to modifications of drilling parameters and practices and ultimately to significantly improved efficiency/productivity.

Investigation and comparison of field-wide sonic logs acquired in the Forties field led to the discovery of significant anisotropy in the overburden Sele Shale formation due to strong layering. Propagation of compressional and shear waves at different velocities through anisotropic shales can have a pronounced impact on sonic log readings and their interpretation. These, in turn, can impact geomechanical models used for wellbore stability predictions, as well as completion design and seismic imaging. Neglect of shale anisotropy can contribute to drilling and completion failures, poor well-seismic ties, and incorrect well placements. To characterize anisotropy in the Forties field, Apache and Schlumberger formed a joint team and carried out an integrated geomechanical and geophysical study. This article presents an overview of the challenges, the methodology used to quantify anisotropy and correct sonic logs across the field, and results achieved through well-informed modifications to drilling parameters and practices.

Drilling, completion and wellbore instability issues

The Forties field was discovered in the UK sector of the Central North Sea in 1970. Since 1974, it has been developed and produced from five platforms. Oil production rose as high as 500,000 bopd, and then declined steadily throughout the 1980s and 1990s. Since Apache acquired an approximate 97% working interest in 2003, more than 30 additional producing wells have been added to the field and production doubled. At present, there are more than 300 boreholes in the area, and the Forties field ranks as the UK’s second largest oil producer. Nevertheless, Apache has faced a number of drilling and completion challenges.

In recent years, drilling activities have focused primarily on in-fill and step-out targets sidetracked from existing wellbores. Although drilling parameters had become fairly well established after years of experience, when more complicated drilling scenarios – such as extended reach wells – pushed targets farther from the platforms, mud weights tended to creep upward to prevent collapse of overburden shales. At times, however, the potential for fluid losses became an even greater concern due to declining reservoir pressures, so mud weights crept downward again. As fields mature, the safe mud weight window becomes progressively narrower. Threading the needle between hole collapse and losses turns mud weight selection into a compromise, and drilling inevitably becomes more difficult.

For example, of the 94 boreholes drilled in the Forties field over the five-year period from 2002 to 2007, 45% were lost due to drilling or completion problems. Thirty-two percent never reached the target reservoir, and 13% reached it but were unable to complete. A bottom hole assembly (BHA) was lost in 40% of these failures. Even successful wells encountered drilling problems. When those were taken into account, fully 65% of the wells drilled during that period experienced incidents due to wellbore instability – cavings, holdups, stuck pipe, packoffs, and losses. As a result, production began to decline and the field’s economic viability was threatened (McIntyre et al., 2009).

A step-change in performance was required, but unanswered questions persisted. Why were some wellbores a complete failure, while others – drilled under roughly the same conditions and parameters – encountered no problems whatsoever? Which incidents were caused by wellbore instability due to incorrect mud weights, and which were the result of inappropriate drilling practices and hole cleaning? To improve drilling practices and develop proper operational contingencies and remedial actions, it was essential to identify the cause or causes of these problems. Without a correct diagnosis, an inappropriate solution could exacerbate the problem and result in further damage.

Challenges of shale anisotropy

In the course of data review for field development and well planning, Apache geoscientists observed an anomaly that ultimately led to resolving one source of drilling problems in the field. It also led to improvement in the well-seismic tie. Plotting

1Apache Corporation.
2Schlumberger
*Corresponding author, E-mail: fmohamed3@slb.com
measured compressional slowness from nine sonic logs against borehole deviation in the Sele Shale formation – a weak shale that directly overlies the reservoir – revealed a clear decrease in slowness at inclinations greater than 30° (Figure 1). Since wellbore stability and completion challenges were often encountered in such deviated wellbores, Apache and Schlumberger formed a joint team to understand this phenomenon and its impact on the field’s drilling and completion challenges.

Subsequent investigation showed that the correlation between hole angle and acoustic slowness was due to strong alignment of the rock fabric of the Sele Shale. However, during examination of slabbed cores from several wells, it became apparent that the shale characteristics varied from homogeneous and competent in some areas to highly layered or fractured, thereby weakening the rock fabric, in other areas (Figure 2). Such significant variations, which appear to occur unpredictably from well to well, help explain why some wellbores in the field experienced severe stability issues and failures while others encountered no problems at all.

Although it is known that overburden shales may exhibit elastic anisotropic behaviour, prior to this study it had not been widely understood how this behaviour would affect wellbore stability models and related drilling practices. Because the constituent plate-shaped clay particles are often oriented parallel to one another and to the bedding plane, a common form of anisotropy present in shales is transverse isotropy (TI), in which elastic (dynamic and static) and strength properties vary with respect to the direction of measurement. For example, compressional and shear waves propagate at different magnitudes parallel and perpendicular to bedding planes.

Obviously, shale anisotropy due to strong layering can have a pronounced impact on sonic log readings, which are critical to various disciplines. However, many technical professionals are not fully aware of this phenomenon. Those who are aware may not know how to properly interpret and correct for anisotropy in sonic log data, or how to incorporate the results into geomechanical and geophysical models.

Compressional and shear borehole sonic data are traditionally used for both geomechanical modelling and seismic calibration. Neglect of anisotropy can contribute to both drilling and completion failures due to imprecise understanding of its geomechanical effects. Just as significantly, failure to account for elastic anisotropy can lead to inaccurate AVO processing, low confidence in well-seismic ties, and poor seismic images, which, in turn, can lead to incorrect well placements. On the other hand, clear understanding and quantification of anisotropy can reduce uncertainty in wellbore stability models and substantially improve seismic calibration.

To properly address shale anisotropy in geophysics, it is essential to acquire accurate estimates of the Thomsen parameters $\varepsilon$, $\delta$, and $\gamma$ (Thomsen, 1986), which are commonly used to describe compressional and shear wave propagation within a TI anisotropic medium. However, in geomechanics, it is common to describe rock stiffness in terms of the directional Young’s modulus ($E$) and Poisson’s ratio, which are commonly used to describe compressional and shear wave propagation within a TI.

To characterize these anisotropy parameters within the Sele formation, the team developed an integrated geomechanics and geophysics workflow (Donald et al., 2009) that combined measurements from three different sources: cores, sonic logs, and borehole seismic (VSP) surveys. Although core analysis can provide all the required geophysical and geomechanical parameters (Figure 3), core samples are expensive to obtain, provide limited coverage across a formation, and most operators only core the reservoir, not the overburden shales. This is unfortunate, since they are focused mainly on obtaining
measurements. As a field evolves, changes within the reservoir due to depletion require any existing geomechanical model to evolve as well. Rock properties and the in-situ stress state were estimated from logs, calibrated with core measurements and validated against drilling experience. However, significant uncertainties remained due to conventional modeling assumptions (i.e., that the rock medium is continuous, homogeneous, isotropic, linear, and elastic), and the effects of shale anisotropy. The integrated workflow described below aimed to address these uncertainties.

**Single-well analysis**

To obtain the Thomsen parameters necessary to characterize anisotropy, the team decided to acquire the following data in a single well on the Bravo platform at a deviation angle of 40 degrees: full core over the Sele Shale formation, a walk-away VSP survey, full waveform sonic logs (compressional, dipole, and Stoneley shear data), in addition to standard logging-while-drilling (LWD) density, neutron, resistivity, and gamma ray logs. Instead of running a conventional dipole sonic tool, the team selected the Schlumberger Sonic Scanner acoustic scanning platform. This provides advanced corrections that take into account the tool’s own presence in the well, yielding a continuous estimation of Thomsen’s $\epsilon$ and $\delta$ parameters (Figure 3).

**Integrated geomechanics and geophysics workflow**

The joint company team’s integrated geomechanics and geophysics workflow involved construction of a geomechanical earth model, acquisition and analysis of additional data in a single well to calculate Thomsen parameters for the Sele Shale, multi-well analysis to calibrate anisotropy parameters and correct sonic logs across the field for the effects of anisotropy, refinement of the initial geomechanical model, and application of expanded knowledge to develop individual well plans and modify drilling practices.

**Geomechanical modelling**

Use of an up-to-date geomechanical model that incorporates the in-situ stress state and rock strength of both overburden and reservoir enables more accurate definition of mud weight windows and identifies zones of potential drilling problems along any proposed well path. Building on several vintages of previous geomechanical analysis, Schlumberger generated a comprehensive new geomechanical model from well data including logs, cores, leak-off tests, and reservoir pressure measurements. As a field evolves, changes within the reservoir due to depletion require any existing geomechanical model to evolve as well. Rock properties and the in-situ stress state were estimated from logs, calibrated with core measurements and validated against drilling experience. However, significant uncertainties remained due to conventional modeling assumptions (i.e., that the rock medium is continuous, homogeneous, isotropic, linear, and elastic), and the effects of shale anisotropy. The integrated workflow described below aimed to address these uncertainties.
hole collapse than at any other angle (Figure 2). Wellbores drilled at this angle would be more likely to suffer reduction in rock strength at 45–55° to bedding. As a result, data from both platforms indicated that there was an 85% rock strength as a function of bedding angle. Analysis of core addition, fast strain-rate UCS tests were performed to assess were used, due to the shale’s extremely low permeability. In pore pressure to the atmosphere – very slow strain rate tests platform. To perform triaxial tests in a drained state – venting wellbores drilled at this angle would be more likely to suffer hole collapse than at any other angle (Figure 2).

Full waveform borehole sonic logs from this single 40° well on the Bravo platform underwent advanced processing to obtain elastic stiffnesses relative to bedding plane orientation. Dynamic elastic moduli calculated from the sonic data showed a distinct difference between the horizontal and vertical shear stiffness within the Sele, but not in adjacent formations. However, the average Thomsen’s γ derived from dynamic shear stiffnesses was higher than the value derived from core analysis (Figure 3), possibly due to borehole break-out caused by bedding plane failure. Since the wellbore deviation was close to the critical angle at which rock strength is at a minimum, the mud weight was below the borehole collapse pressure. Examination of shear and Stoneley radial variation profiling data support an interpretation of shear borehole failure. As a result, a second set of Sonic Scanner measurements were acquired in a well on the nearby Delta platform that had a deviation of only 26° degrees. Advanced processing showed that differences between the sonic and ultrasonic data were negligible. Full waveform sonic analysis agreed well with the results of triaxial core measurements, clearly showing that the dynamic sonic and ultrasonic measurements were consistent with static measurements of shear stiffness, both parallel and perpendicular to bedding. By integrating anisotropic elastic properties with anisotropic rock strength behaviour, the team derived an improved wellbore stability model for the worst-case scenario of bedding plane failure in the Sele formation.

Multi-offset walkaway VSP data was acquired using an eight-level array spanning the Sele formation, providing a means of estimating anisotropy parameters at the seismic wavelength. This technique can provide even better estimates of anisotropy parameters than core lab measurements because it propagates waves through the rock medium at many more angles. In general, there are two methods of measuring interval anisotropy across the downhole receiver array: slowness-polarization and phase slowness inversion. Phase slowness requires a near horizontally layered overburden. Of the two techniques, slowness-polarization is considered superior because it relies entirely on local homogeneity around the receiver array, and does not require the overburden to be structurally simple. Apparent phase slowness and polarization angles were derived as a by-product of elastic wavefield separation, and cross-plotted against each other. Inversion of these data points provided best estimates of Thomsen’s ε and δ (Figure 4).

Sonic logs obtain high spatial resolution estimates of elastic properties around the wellbore using high-frequency seismic sources and receivers deployed inside the wellbore. On the other hand, walk-away VSPs obtain elastic anisotropy estimates using receivers within the well to measure lower frequency seismic waves generated by remote sources. As a result, VSP measurements are of a lower spatial resolution than sonic log measurements. This scale difference makes direct comparison of dipole sonic with VSP data difficult. One means of reconciling the two is through a process known as up-scaling. Using a seven step calibration algorithm (Horne et al., 2010), the team used anisotropy estimates derived from walkaway VSP data as a constraint on up-scaled sonic log data recorded in the single, deviated well on the Bravo platform to derive a calibration relationship with anisotropic parameters measured from sonic logs. This calibration was then applied to the dipole sonic log data to successfully extract all TI parameters at continuous sonic log scale.

Multi-well analysis

Once accurate shale anisotropy parameters were determined at this one well location, multi-well data from all five platforms was integrated and used to understand anisotropy variation across the field. Multi-well analysis generally assumes that sonic measurements are made in the same homogeneous formation at various wellbore deviations. Using the anisotropy parameters derived from the single well analysis as a starting point, the team compared information from other wells drilled through the Sele to the model, which described sonic slownesses as a function of bedding plane angle. The model was then updated and calibrated on each platform. Subsequently, it was used to correct sonic log readings for the effects of anisotropy in significantly deviated wellbores across the entire field.

The multi-well analysis incorporated 125 compressional slowness logs and nine shear wave slowness logs from throughout the field. The five step integrated multi-well workflow...
A revised mud weight window across critical formations was generated from the updated geomechanical model. Previous vintages of the model that had not accounted for the effects of shale anisotropy appeared to have over-estimated rock strength and under-estimated stress. Updating the anisotropic model improved the match with observed hole conditions (Figure 5).

To verify the geomechanical model and establish most likely root causes of wellbore instability incidents, a systematic review of drilling events in more than 90 boreholes over a five-year period was undertaken in conjunction with this study. As it turned out, wellbores drilled at incident angles between 40–55° to the bedding planes had been exposed to significantly higher risk of hole instability and caving events (Figure 6), confirming the effects of anisotropy within the layered Sele formation. Wellbores drilled outside of this range proved to be stable.

Well planning
Based on the joint team’s anisotropy characterization study, the initial geomechanical model was refined and updated. A revised mud weight window across critical formations was generated from the updated geomechanical model. Previous vintages of the model that had not accounted for the effects of shale anisotropy appeared to have over-estimated rock strength and under-estimated stress. Updating the anisotropic model improved the match with observed hole conditions (Figure 5).

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Wellbore stability results

- Over-estimate rock strength and under-estimate stress without correcting for anisotropy
- Drillers may use operations practices that do not consider excess cavings
initially, but often became destabilized by subsequent mechanical or hydraulic activity. For example, destabilizing fractured zones in the overburden appeared to be a significant source of instability. In fact, the majority of problems in the Forties field did not occur while drilling or making connections, but while pulling out of the hole. This implied that the mud weights selected for most wells had been nearly correct, and that improper drilling or hole cleaning practices had caused many wellbore stability incidents. In addition, many instability events were due not to a single factor alone, but to a combination of drilling parameters and practices.

To apply the team’s enhanced geomechanical knowledge to the drilling process, well plans were designed to identify optimal trajectories and hole angles while recommending appropriate drilling parameters and tripping practices that would minimize disturbance to fragile or damaged zones. In addition, recommendations were made to monitor both surface and downhole measurements during drilling to detect the onset of wellbore instability as early as possible. Contingency plans were established in advance. Then predictions from the geomechanical model were compared with actual conditions in the wellbore, and the field model was updated for the benefit of planning subsequent wells.

**Study results and implications**

Accurate understanding and characterization of TI anisotropy effectively resolved Apache’s wellbore instability problems in the Forties field related to the Sele Shale formation, along with implementation of fit-for-purpose drilling and hole cleaning practices identified in the course of the integrated geomechanical and geophysical study. Apache successfully reduced NPT costs by more than 60% the year following the study. Unlike the previous five-year period, no BHAs were lost.

In addition, the ability to correct sonic log readings for the effects of anisotropy throughout the field had significant implications beyond geomechanical modelling and wellbore stability prediction. Those same measurements are used, for example, in the analysis of completion design and fracture propagation, as well as AVO processing, time-depth conversion, seismic interpretation, and modelling. From a geophysical standpoint, the ability to correct for the impact of anisotropy on sonic log data enabled Apache to improve seismic imaging in the Forties field.

**References**


