INTEGRATED STRESS AND ANISOTROPY ANALYSIS USING MULTI-WELL BOREHOLE SONIC AND IMAGE DATA IN THE KINABALU FIELD, MALAYSIA

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ABSTRACT
The Kinabalu field, located offshore East Malaysia and operated by Talisman, is presently in a phase of rejuvenation with multiple deviated infill wells drilled from the same platform. Inclinations range from about 30° to 60° and trajectories are along main fault. Some of the reservoirs in the field show signs of depletion due to previous production. These reservoir sands were found prone to sanding. This is evidenced from the early producing wells that have been producing sands at surface.

With the current well completions, the operator is constrained to produce the field at economic rates. Uncertainties associated with sand failure are constraining them from implementing a more efficient completion design capable of delivering the required production. To make a decision for an alternative completion, geomechanical risks associated to formation stresses and rock strength need to be addressed as the reservoir conditions have changed from initial pre-production conditions. An alternative completion strategy such as perforated cemented liner was considered as it would deliver higher production rates with significantly reduced cost, however there were risks associated. Due to lack of data and confidence, uncertainties in rock strength and stress characterization with regard to faulting and historical production were to be reduced; emphasis on measurements was needed. Objectives were to quantify rock strength and stress anisotropy to improve the reservoir characterization while minimizing assumptions and analogue field experience.

To meet both geomechanical characterization and near-wellbore integrity evaluation objectives, the operator decided to acquire advanced wireline sonic and image tools. The advanced sonic processing provides azimuthal dipole measurements, shear anisotropy, slowness radial profiling and horizontal stress magnitudes. As technical difficulty arises in single-well data interpretation of borehole failure and acoustics, principally because of high inclination of the considered wells, a multi-well approach with advanced acoustics and image interpretations was proposed to overcome these limitations. The maximum stress direction was found more oblique to the fault than initially anticipated and the horizontal stress anisotropy was found to be higher that initially assumed. Most of the reservoir sands exhibit stress-sensitivity and near wellbore alteration. These together constrain the perforation and coring strategies in the final well of the rejuvenation drilling campaign. The sensitivity of sand failure and critical drawdown pressure to stresses and perforation design could then be better assessed.

Given a development strategy with high angle wells and a pressing need to pin parameters down to improve sand failure prediction, acquiring monopole and dipole sonic in stress sensitive formations together with borehole image prove to be an important piece of information. The integrated stress analysis provides valuable information regarding the field stress state. It also provides information on location, extension and orientation of near wellbore alteration. Both play critical roles in sanding management and completion design. The operator integrated this information in their geomechanical model to mitigate sanding risk and optimized their completion strategy. The near wellbore alteration assessment complements the change of perforation design to lower density and deeper penetration. As a result, the operator increased production with faster clean up in the final well of the campaign.
INTRODUCTION AND OBJECTIVES

The Kinabalu field, located offshore East Malaysia and operated by Talisman, is presently in a phase of rejuvenation with multiple deviated infill wells drilled from the same platform. Inclinations range from about 30° to 60° and trajectories are along main fault. Some of the reservoirs in the field show signs of depletion due to previous production. These reservoir sands were found prone to sanding. This is evidenced from the early producing wells that have been producing sands at surface (McPhee et al., 2014a, McPhee et al., 2014b). With the current well completions, the operator is constrained to produce the field at economic rates. Uncertainties associated with sand failure are constraining them from implementing a more efficient completion design capable of delivering the required production. Due to lack of data and confidence, uncertainties in rock strength and stress characterization were to be reduced and therefore an emphasis on measurements was needed. Objectives were to quantify formations strength, stress directions and stress anisotropy in the in the Kinabalu field to improve the reservoir characterization while minimizing assumptions and analogue field experience. Assessment of near wellbore alteration complements also the objectives for perforation design and for coring strategy.

BOREHOLES STRESS MEASUREMENTS AND INTERPRETATION METHODS

Stress directions and magnitudes are important input parameters for field geomechanical analysis. They are input to drilling design for mud weight determination and critical drawdown pressures for production in weak sand formations. While drilling, besides the formation mechanical rock properties, the stress directions and magnitudes will control whether shear or tensile borehole failure occurs or not and will also determine the severity and extension of the borehole damage. Thus having a good knowledge of the field stress state is required to design a proper drilling mud weight profile. With regard to sand production, the stress state around wellbores or around perforations is largely influenced by the far-field stress directions and magnitudes; with an accurate stress state estimation, predictions of allowed critical drawdown pressures and critical reservoir pressure before sanding occurrence will be far more reliable; it will help to optimize the type of completion and will be critical for correctly designing oriented perforations.

To assess the horizontal stress directions, industry relies generally on wellbore failure observations of breakout or induced fractures on wellbore images or dual arm calipers in near vertical wellbores (Zoback et al., 1985, Plumb et al., 1985). More recently, using cross-dipole sonic tool measurement (Pistre et al., 2005), anisotropy analysis together with dispersion analysis can also be used to determine the stress direction. In near vertical wells, breakout direction is associated with the direction of minimum horizontal stress; drilling induced fractures and sonic fast shear azimuth (which can be obtained from rotation of dipole shear data (Alford, 1986) corresponds to the propagation of slowness in the fastest direction) can be associated with the direction of maximum horizontal stress (Sinha et al., 1996, Winkler et al., 1998, Plona et al., 1999, Plona et al., 2000, Donald et al., 2015).

However, for deviated wells, those measurements cannot be directly related to the horizontal stress directions. In such a case, the breakout direction and the sonic fast shear azimuth are both function of the borehole deviation and azimuth and also of the stress state which is defined by the directions and the magnitudes of all the stresses (overburden, minimum and maximum horizontal stresses). Given one measurement and the borehole trajectory, the solution for the horizontal stress direction is non-unique; different stress states lying in the normal, strike-slip or thrust fault stress regime (Etchecopar et al., 1981) can be responsible for the same breakout direction or result in the same fast shear azimuth (Pistre et al., 2009, Prioul et al., 2010).

Therefore for deviated wells, interpretation of stress directions based on single-well data becomes extremely challenging. In order to overcome this limitation, a multi-well data analysis is required. One must therefore combine data (breakouts directions, fractures directions, sonic fast shear azimuth) acquired in different nearby wells drilled preferentially with different deviations and azimuths and perform a multi-well stress analysis (Pistre et al., 2009, Prioul et al., 2010). Among all the possible solutions, the common stress state for all those data acquired in the different wells will be the valid stress state solution for the field. The multi-well analysis will allow to identify both the horizontal stress directions, the stress regime and the stress regime factor (Etchecopar et al., 1981); yet it will not allow to determine directly the magnitudes of the horizontal stresses as different sets of minimum and maximum horizontal stress magnitude can correspond the same stress regime factor.
When it comes to the horizontal stress magnitudes assessment, industry relies generally on performing well test at given depths such as mini-frac or extended leak-off test in order to determine the least principal stress through closure pressure. Depending on the type of test and the quality of its realization, uncertainty on the magnitude of minimum horizontal stress is generally quite significant. Therefore, one would like to get a more accurate value and possibly at many different depths in the well sections through log data. Until recently, in order to estimate the maximum horizontal stress magnitude, industry has to rely on the occurrence of borehole failure while drilling and further analysis of breakouts and drilling-induced tensile fractures [3]. Breakout width estimation, which is required for such analysis, can be difficult to assess precisely from borehole images and furthermore it can also be worsened by drilling practices. In the absence of breakout, it was necessary to postulate a horizontal anisotropy stress ratio and then constrain it further based on Wellbore Stability Analysis of different wells in the same field. But recently a new method was proposed to calculate directly the two horizontal stress magnitudes and also the horizontal stress direction from sonic dipole shear slowness radial profiling (Sinha et al., 2009, Lei et al., 2012). No borehole failure is required for this approach anymore. This method has also the advantage to be applicable in both vertical and deviated wells up to 45° without large uncertainties.

The latest generation of dipole sonic tool (Pistre et al., 2005) with sources emitting a broadband frequency range allows to measure dispersion of dipole shear sonic slowness from low to high frequency; those dispersion curves can then be interpreted as shear slowness variation from far-field to near wellbore. Variation of elastic wave velocities (for instance shear slowness) radially can have for origin change of pre-stress of the propagating rock formations as can be demonstrated by acousto-elasticity theory (Sayers, 2010). Such rock can be qualified as stress-sensitive formations given that their elastic properties (moduli or slownesses) are responding to stress variations. The Acousto-Elastic parameter (AE) of the formations represent the formation shear stiffness sensitivity to applied stresses in the isotropic reference state. In the stress sensitive formations, the stress concentrations existing near wellbore will influence the slowness of fast & slow dipole flexural waveforms given its acousto-elastic constant AE. The acousto-elastic constant, which is at first an unknown formation property, can be solved independently with the formations three orthogonal shear moduli and the processed fast and slow shear radial variation profiles; AE being known, it is then possible to compute both minimum and maximum horizontal stress magnitudes. The far field stress field is rotated to borehole coordinate and combined to measured borehole radial profiles for stress estimation in deviated wells. Assumption here is that the incremental stresses above the reference state do not induce any plastic deformation and therefore the radial profiles are only interpreted out of to the near wellbore alteration region if present.

In this case study in Malaysia, we present how combination of advanced interpretation of dipole shear sonic data (such as fast shear azimuth and shear radial profiles) and borehole images were successfully utilized in deviated wells in Kinabalu field to help Talisman determine the stress state in the reservoirs and assess the local stress directions influenced by the presence of faults. Those were critical inputs required for the completion and perforation designs.

**Fig. 1:** Trajectories of the three considered deviated wells KN-A (blue), KN-B (red) and KN-C (green) in which borehole images and sonic data were acquired in the 8.5 in OH section; deviation range is ~32° to ~60° for KN-A, ~49° to ~59° for KN-B and ~41° for KN-C; KN-B well is drilled towards NNE while KN-A and KN-C are drilled in opposite direction towards SSW.
ULTRASONIC BOREHOLE AND DIPOLE SONIC CHARACTERIZATIONS

The Kinabalu Field is located Offshore Sabah in Malaysia; it presents a slightly dipping structure toward NW with a main fault dipping also in the same direction. The lateral continuity of the sand/shale formations is fairly good allowing correlation between the wells for the multi-well analysis. The recent rejuvenation phase consisted in drilling multiple deviated infill wells from the same platform. Inclinations range from about 30° to 60° with trajectories along main fault. This study focuses on three recently drilled nearby deviated wells, KN-A (~32° to ~60° inclination), KN-B (~49° to ~59°) and KN-C (~41°) having different azimuths (Fig. 1). To meet both geomechanical characterization and near-wellbore integrity evaluation objectives, Talisman decided to acquire advanced wireline sonic and image tools.

Ultrasonic Borehole Imager (UBI) tool provides a measurement of attributes of ultrasonic waves (amplitude and transit times) with high circumferential coverage; the waves are reflected at the borehole wall whose rugosity influences the reflection amplitude. Such images are strongly sensitive to surface variations at the borehole wall and not so much to variations in lithology. This make this type of tool very useful for analyzing hole shape, to identify borehole breakouts and drilling-induced fractures. UBI images from KN-A well were of good quality with geological features identifiable throughout most of the section. Dipole sonic tool provides high quality monopole and dipole measurements to determine formation slownesses and assess type and amount of anisotropy; it was logged in all three wells KN-A, KN-B and KN-C.

DIPOLE SHEAR ANISOTROPY ANALYSIS

Anisotropy analysis of dipole sonic data using Both Cross-Dipole Rotation (BCR) (Fig. 2) and dispersion analysis (Fig. 3) can be used to quantify the shear anisotropy of formations and to identify the mechanisms responsible for the anisotropy (intrinsic, stress induced, fractures induced).

Shear anisotropy analysis of KN-A and KN-B wells showed that most of the formations encountered in the two wells present shear anisotropy, in sands (Fig. 2(c,d)) and in some shales (Fig. 2(e,f)) formations. Overall, good correlation is observed between the shear anisotropy in the two wells and the anisotropy amount is higher in KN-B well having higher deviation. When well inclination is increasing (relatively to the structure) the dipoles measurements will be responding to components of the vertical and horizontal shear slownesses depending locally on the tool orientation.

Most of the reservoir sands exhibits shear anisotropy and stress-sensitivity (Fig. 2(c,d)) which are required conditions for the subsequent stress analysis. In KN-A well, shear slowness anisotropy is in the magnitude of 3 to 4 % while in KN-B it is a bit higher of the order of well 4 to 5%. In both wells, the sands at the top of the open hole section show typical cross-over of fast and slow dipole shear dispersion curves (Fig. 3) which classify them as stress-sensitive formations. After rotation of the dipole shear waveforms to the fast and slow propagating direction, the Fast Shear Azimuth (FSA) measured in different sands in the 3 wells point to ~ +17° to TOH in KN-A well [4], ~ -5° to TOH in KN-B well and ~ N50° to P1NO in KN-C well (Table 1). Because those wells are deviated (Table 1), none of those FSA can be directly associated to the maximum horizontal stress direction. Those azimuth data will be used all together to derive the field stress state solution using the multi-well stress analysis method.

Some of the shale layers also present dipole shear anisotropy, with typical parallel fast and slow dipole shear dispersion curves pattern (Fig. 3(c,d)) resulting from their intrinsic TI anisotropy (Transverse Isotropy type) combined with relative tilt to the borehole. This TI dispersion characteristic is more pronounced in KN-B well having higher deviation.

Table 1: Well deviation / azimuth and borehole image / sonic measurements data.

<table>
<thead>
<tr>
<th>Well</th>
<th>Deviation / Azimuth (deg)</th>
<th>Breakout Azimuth (deg)</th>
<th>Deviation / Azimuth (deg)</th>
<th>Fast Shear Azimuth (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KN-A</td>
<td>60° / 219°</td>
<td>N105°</td>
<td>31° / 258°</td>
<td>+17° TOH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>31° / 257°</td>
<td>+15° TOH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>37° / 252°</td>
<td>+20° TOH</td>
</tr>
<tr>
<td>KN-B</td>
<td>No Borehole Image Log</td>
<td>-</td>
<td>49.5° / 3.5°</td>
<td>-4° TOH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50.0° / 2.5°</td>
<td>-5° TOH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>59.0° / 13.5°</td>
<td>-5° TOH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>59.5° / 11.5°</td>
<td>-7° TOH</td>
</tr>
<tr>
<td>KN-C</td>
<td>No Borehole Image Log</td>
<td>-</td>
<td>41.0° / 234°</td>
<td>N50°</td>
</tr>
</tbody>
</table>
ULTRASONIC BOREHOLE IMAGE INTERPRETATION

In KN-A well, interpretation of borehole images from the open-hole section has been performed (Fig. 4(a)); features of shearing rock failure appear at the bottom of the section and were classified as incipient breakouts. On the UBI images (Fig. 4(a)) it appears as high amplitude/ high radius scars on the borehole wall that are also identifiable on hole shape analysis (Fig. 4(b)); the strike of the identified breakout points to the azimuth N105° (Fig. 4(c) and Table 1) which is not the minimum horizontal stress direction due to the deviation of the well. This azimuth data will be integrated to the sonic ones to derive the field stress state solution using the multi-well stress analysis method.
multi-well stress analysis, the FSA measurements must be very accurate in order to quantify correctly the influence of the horizontal stresses. By integrating to the stress analysis, FSA measurements in different stress-sensitive sands in the 3 wells (Fig. 5 (a,b,c)), plus the breakout direction identified from borehole images (Fig. 5(a)), we are able to find a common solution for the stress state that is compatible with all the measured/interpreted sonic and images data (Fig. 5(c)). The maximum horizontal stress direction $\theta_{\text{OH}}$ is found to lie in the range [N155° - N175°] (i.e. SSE) and the stress regime was determined as normal with a stress regime factor $Q$ belonging to the range [0.20 - 0.45] (Fig. 5(c) and Table 2).

As the stress state lie in the normal stress regime, the $Q$ factor is defined as $(\sigma_{\text{H}} - \sigma_{0})/(\sigma_{V} - \sigma_{0})$ (Etchecopar et al., 1981); therefore if one had a good knowledge of the minimum horizontal stress magnitude, knowing the overburden stress from integration of density logs, one could calculate directly the maximum horizontal stress magnitude and thus the horizontal stress anisotropy ratio. Unless one conduct a proper Extended Leak-Off Test to obtain the closure pressure, FIT / LOT data can only be considered as constrain or estimation of the minimum horizontal stress $\sigma_{h}$.

The multi-well stress analysis (Pistre et al., 2009, Prioul et al., 2010) is a powerful tool that can integrate many types of log data coming from vertical to highly inclined wells (given the accuracy of the measurements) in order to assess the field stress state. To quantify the minimum and maximum horizontal stress magnitudes beyond the $Q$ factor, more sophisticated stress calculation has to be carried out based on advanced dipole sonic processing in addition to anisotropy processing. By implementing this second level of sonic and stress interpretation, we will be able to perform a consistency check of both methods from the determined $Q$ factor standpoint and stresses magnitudes directions.

**Table 2**: Stress state solution from multi deviated wells stress analysis.

<table>
<thead>
<tr>
<th>Solution of Multi Deviated Wells Stress Analysis</th>
<th>Maximum Stress Direction $\theta_{\text{OH}}$ (deg)</th>
<th>Stress Regime</th>
<th>Stress Regime Factor $Q$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N155° - N175°</td>
<td>Normal</td>
<td>0.20 - 0.45</td>
<td></td>
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</table>
formations sensitive to the model parameters and those higher than initially assumed image data: minimizing the hear. Wide bandwidth cross-exural wave independent method, Q factor was belonging to the range [0.20–0.45] (x-intersection). The maximum horizontal stress direction \( \theta_{H1} \) (x-axis) belongs to the range [1155°–1175°] (i.e. SSW); the stress regime is normal with a stress regime factor Q (y-axis) belonging to the range [0.20–0.45].

**HORIZONTAL STRESS MAGNITUDES FROM SHEAR SLOWNESS RADIAL PROFILES**

In this study, to obtain the horizontal stress magnitudes, because of deviation of the wells, a more advanced algorithm is required (Sinha et al., 2009, Lei et al., 2011, Lei et al., 2012) than the three shear moduli method (Sinha et al., 2008) which is only applicable in close to vertical wells. Wide bandwidth cross-dipole transmitter in the sonic logging tool generates dispersive dipole flexural waves that probe the near-wellbore formation at high frequencies and far-field formation at low frequencies. The flexural wave velocity at various frequencies can be inverted to obtain radial variations of shear moduli away from the borehole surface (i.e shear radial profiles \( C_{44} \)) and \( C_{55} \). The model parameters and of those radial functions can be estimated by minimizing the differences between the modeled radial profiles and the dispersion-inverted radial profiles which allow to solve for the acousto-elastic parameter \( AE=1/(3+(C_{155}+C_{144})/\mu_{ref}) \). \( C_{144} \) and \( C_{155} \) being the non-linear elastic constants of the stress sensitive formations (Sinha et al., 2009, Lei et al., 2011, Lei et al., 2012); once known, the minimum and maximum horizontal stress magnitudes can be calculated given the effective overburden stress and pore pressure. This method was applied successfully recently for other cases study (Donald et et., 2013, Jones et al., 2014, Donald et al., 2015, Sinha et al., 2014).

This single well shear radial profiles method was applied to KN-A well in the upper section (Fig. 7(a,b)) where the deviation remains below 45°. Given the advanced sonic input data together with overburden stress, pore pressure and Biot’s coefficient, the horizontal stress magnitudes and directions were solved in a set of stress-sensitive intervals (green shaded zones) meeting the method criterion: they are shown as light and dark green diamonds symbols in Track 6 and pink diamond symbol in Track 11 respectively. Corresponding stress regime factor and horizontal stress anisotropy are shown in Tracks 8 and 9. Through this independent method, Q factor was found to lie in the range [0.3–0.5], horizontal stress anisotropy in the range [1.11–1.14] and maximum horizontal stress direction in the range [155°–175°] (Fig. 6(a) and Table 3). Consistency check (Fig. 6(a)) and Fig. 6(b) with the multi-well stress analysis method has been performed; the two methods give consistent result for the stress state of the Kinabalu field. A summary of the integrated stress analysis of the Kinabalu field is presented in Fig. 8; it shows the maximum horizontal stress azimuth, the stress regime, the Q factor and the horizontal stress anisotropy determined for the Kinabalu field. The maximum horizontal stress direction was found more oblique to the fault than initially anticipated and the horizontal stress anisotropy was found to be higher that initially assumed (McPhee et al., 2014a, McPhee et al., 2014b).
Fig. 6: Consistency checks of the horizontal stresses magnitudes and azimuths obtained from the single well shear radial profiles method applied to stress-sensitive formations in well KN-A with the previous result obtained from the multi-well stress analysis including UBI and FSA data of wells KN-A, KN-B and KN-C; (a) Q factor and maximum horizontal stress azimuth is consistent with the previous determined values; (b) stress state lies in the normal stress regime in agreement with previously determined stress state.

Fig. 7: (a) Minimum and maximum horizontal stresses magnitudes (light and dark green diamond symbols respectively in Track 6) calculated using the N-Points method based on shear radial profiles in the stress-sensitive formations in the well KN-A; corresponding stress regime factor Q and horizontal stress anisotropy are shown respectively in Tracks 8 and 9; maximum horizontal stress azimuth determined concomitant with the magnitude is showed in Track 11; (b) zoom on two analyzed sand intervals in the upper section.
### Table 3: Stress state solution of single well method using shear slownesses radial profiles.

<table>
<thead>
<tr>
<th>Stress State Solution of Single Well Method using Shear Radial Profiling in KN-A</th>
<th>Maximum Stress Direction ( \theta_{\text{eff}} ) (deg.)</th>
<th>Stress Regime / Q factor (+)</th>
<th>Horizontal Stress Anisotropy ( \sigma_H/\sigma_h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>Normal ( Q \approx 0.3-0.5 )</td>
<td>~ 1.11 – 1.14</td>
<td></td>
</tr>
<tr>
<td>~ N162°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### KN-A

**Integrated Stress Analysis summary**

<table>
<thead>
<tr>
<th>Stress regime</th>
<th>Stress regime factor ( Q ):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Fault</td>
<td>0.4</td>
</tr>
</tbody>
</table>

**Fig. 8:** Integrated Stress Analysis summary; the maximum horizontal stress direction is ~N162° (SSW), with a normal stress regime characterized by a Q factor ~0.4.

## IMPROVEMENT OF WELLBORE STABILITY AND SANDING ANALYSIS USING THE INTEGRATED STRESS ANALYSIS

The objectives of the study were to improve the rock properties and stress characterization of the formations in the Kinabalu field. For each well KN-A and KN-B, a Mechanical Earth Model (MEM) (Fig. 9, for KN-A) was constructed; it consists in calculation of rocks mechanical properties (static Young’s modulus and static Poisson’s ratio), rock strengths (Unconfined Compressive Strength, friction angle and tensile strength), the formation pressure and the three principal stresses. Rock elastic and strength properties were calibrated based on mechanical core test data from exploration well KN-D (Fig. 9, Tracks 4, 5, 6). Pore pressure and overburden stress were calculated respectively based on compressional slowness and density logs (Fig. 9, Track 7).

For the horizontal stress magnitudes, the poro-elastic strain model (Thiercelin et al., 1994) was used; magnitudes of \( \sigma_H \) and \( \sigma_h \) in stress sensitive formations of KN-A well obtained with the shear radial profiling method were used to calibrate the strains that represent the response to the regional tectonic forcing; those calibrated regional strains were then used for the other well KN-B; the calibrated horizontal stress magnitudes are shown in Fig. 9, on track 7. Wellbore stability analysis was then conducted using the MEM inputs. Post-drill Mud Weight Window of KN-A well is shown in Fig. 9 on Track 8, with the calibrated loss gradient;
for final model refinement, synthetic images (Fig. 9, Track 9) derived from the breakout boundary and the mud weight profile were compared to the wellbore damage from calipers and images logs.

The stress calibrated Mechanical Earth Models of KN-A and KN-B wells can then be used for sanding analysis for completion and oriented perforation designs. Sanding prediction and management require a good accuracy, not only of the mechanical properties, but also of the stress state. The Integrated Stress Analysis performed for Kinabalu field, led to an improvement of the accuracy of the constructed MEM and finally to a higher confidence in the sanding prediction. Talisman used a coupled geomechanical failure model to assess sand failure and to evaluate alternatives to sand exclusion completion. In addition Talisman integrated the new stress state information in their established base cased model (McPhee et al., 2014a, McPhee et al., 2014b), in order to mitigate sanding risk and optimize their completion strategy.

ASSESSMENT OF NEAR WELLBORE ALTERATION FOR PERFORATION DESIGN AND CORING STRATEGIES

Most of the reservoir sands encountered in the wells KN-A and KN-B exhibits cross-over of fast and slow shear slowness dispersion curves which is the typical signature of stress-sensitivity; they also present near wellbore alteration characteristics; the shear slowness radial profiling performed for the two wells clearly show shear slowness increase near wellbore starting from about two and half times of the well radius. Fig. 10(a,b) shows radial profiling processing of fast dipole data for two sand intervals in KN-B well; shear dispersion and slowness radial profiling are also shown for fast and slow dipole data at two specific depths (Fig. 10(c,d)).

The near wellbore alteration assessment complements and comforts the initial decision to change perforation design to a lower density but deeper penetration gun. As a result, Talisman increased production with faster clean up in the final well of the campaign KN-C. Coring strategy for the last well of the rejuvenation drilling campaign was also decided based on this near-wellbore alteration assessment of sands reservoirs; full coring was preferred to side wall coring due to the risk of getting mechanically altered samples.
CONCLUSIONS

During the rejuvenation of the Kinabalu Field, offshore East Malaysia, with a development strategy with high angle wells, to meet both geomechanical characterization and near-wellbore integrity evaluation objectives, Talisman decided to acquire advanced wireline sonic and image tools. Through this case study we have shown how borehole image logs and latest generation dipole sonic tool data acquired in only deviated wells can be combined in an Integrated Stress Analysis to reduce uncertainty on the Kinabalu field stress state.

First, we demonstrate how using common breakout information along with cross-dipole fast shear azimuth data measured in a couple of deviated wells, the multi-well stress analysis allows to determine the local stress state; although all the considered wells are deviated, it is possible to determine the horizontal stress directions, the stress regime and the stress regime factor which are critical input for geomechanical analysis. Then we present a further advanced interpretation of single well sonic dipole shear data that allows the inversion of both the horizontal stress magnitudes and directions; the stress state inferred from the shear radial profiles method is then checked for consistency with the former multi-well method.

Through the consistency of the solutions obtained by the multi-well method (azimuth based) and the single well method (shear radial profiles based), we prove that despite high inclination of the considered wells, an integrated stress analysis can be used successfully for accurate geomechanics characterization and increase level of prediction of wellbore stability and sanding analysis. Furthermore this case study qualifies the stress direction interpretation obtained using single deviated well cross dipole sonic data. Depending on well configurations, available logs data and level of interpretation, one or the other method can be used to better constrain a field stress state critical for all kind of geomechanical application studies.

The stress regime for the Kinabalu field is normal with a Q=[0.3-0.5] and a stress anisotropy $\sigma_{H}/\sigma_{R} \approx[1.11-1.14]$ higher that initially assumed in previous geomechanics field studies. The maximum stress direction $[155^\circ-175^\circ]$ was found more oblique to the fault (dipping towards N300°) than initially anticipated. Talisman integrated all those information in their geomechanical model to mitigate sanding risk and optimized their completion strategy.

Finally, we also showed that the reservoir sands in the field exhibit both stress-sensitivity and near wellbore alteration. Sonic shear radial profiling provides location, extension and orientation of near wellbore alteration. The perforation and coring strategies for the final well of the rejuvenation drilling campaign were defined based on those new formation characterizations.

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Shan Wang is a geophysicist in PetroTechnical Services Schlumberger based in Kuala Lumpur. She has been involved in various VSP, Hydraulic Fracture monitoring, LWD and Wireline acoustic data processing and interpretation for 8 years till now. She graduated with Master degree in Geophysics from Moscow State University in Mosocow, Russia.

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Michael Jones has worked for surface seismic companies in Europe and Canada, and for the last 25 years for Schlumberger Wireline in various roles. His interests and publications are on pushing the boundaries of seismic, microseismic and sonic data.

Adam Donald is the theme and technical director for Unconventional Resources, and is also responsible for global wellbore acoustics & geomechanics at Wireline Headquarters for Schlumberger in Paris, France. He joined Schlumberger in 1998 as a field engineer has held technical & management positions in Canada, US, Norway and Malaysia. His area of focus has been on rock mechanics and geophysical logs for applications with completions, wellbore stability, rock mechanics testing, sanding and drilling optimization. He received his Bachelors in Geological Engineering from University of Waterloo in Ontario, Canada (1998) and a Masters in Mining Engineering from Dalhousie University in Nova Scotia, Canada (2004). Adam holds 3 Patents in areas of borehole acoustics and geomechanics and is a registered Professional Engineer in Canada. He is an active publishing member of SPWLA, SPE, and SEG with over 30 industry and scientific articles.

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