Full waveform acoustic data as an aid in reducing uncertainty of mud window design in the absence of leak-off test

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Abstract

Creating a mechanical earth model (MEM) during planning the well and real-time revision has proven to be extremely valuable to reach the total depth of well safely with least instability problems. One of the major components of MEM is determining horizontal stresses with reasonable accuracy. Leak-off and minifrac tests are commonly used for calibrating horizontal stresses. However, these tests are not performed in many oil and gas wellbores since the execution of such tests is expensive, time-consuming and may adversely impact the integrity of the wellbore.

In this study, we presented a methodology to accurately estimate the magnitudes and directions of horizontal stresses without using any leak-off test data. In this methodology, full waveform acoustic data is acquired after drilling and utilized in order to calibrate maximum horizontal stress. The presented methodology was applied to develop an MEM in a wellbore with no leak-off test data. Processing of full waveform acoustic data resulted in three far-field shear moduli. Then based on the acoustoelastic effect maximum horizontal stress was calibrated. Moreover, maximum horizontal stress direction was detected using this methodology through the whole wellbore path. The application of this methodology resulted in constraining the MEM and increasing the accuracy of the calculated horizontal stresses, accordingly a more reliable safe mud weight window was predicted. This demonstrates that the presented methodology is a reliable approach to analyze wellbore stability in the absence of leak-off test.

Keywords: Mechanical Earth Model; Horizontal Stresses; Leak-Off Test; Full Waveform Acoustic Data; Safe Mud Weight Window

1. Introduction

During drilling, borehole breakouts and drilling-induced fractures (breakdowns) are known as two main instability challenges which may lead to tight holes, stuck pipe, sidetracking, and loss circulation (McLean and Addis, 1990; Gholami et al., 2014). Such challenges can be often tackled by selecting a safe mud weight window for drilling as an output of developing an MEM (Bell, 2003; Zhang et al., 2003). Estimation of in-situ stresses plays an important role in MEM construction (Sengupt et al., 2011). A comprehensive explanation of all existing stress measurement methods could be found in Amadei and Stephansson (1997), and Haimson and Cornet (2003).

For estimating the in-situ stress magnitudes, vertical stress is obtained by integrating the formation density from top to bottom of a wellbore. The minimum horizontal stress magnitude is obtained directly from well tests such as leak-off test (LOT), extended leak-off test (XLOT), formation integrity test (FIT), minifrac test (Zoback, 2010; Fjar et al., 2008; Immerstein, 2013), and analysis of mud losses (Hareland and Hoberock, 1993). Performing the LOT/XLOT may weaken the formation and causes problems during drilling the rest of the well (Wang et al, 2011). Moreover, such tests are not run in all sections of a well and are also not available in all wells within a field. In addition, there is not any direct measurement of maximum horizontal stress magnitude. Such issues led to use indirect measurements for horizontal stresses estimation (Zoback, 2010).

Breckels and Van Eekelen (1982) used a set of worldwide hydraulic fracturing data to develop empirical correlations for estimating minimum horizontal stress as a function of depth. Also, Zoback et al. (1987) proposed a stress polygon which merely constrained the range of possible stress state using E. M. Anderson's stress and faulting classification system (Anderson, 1951). Then, Aadnoy (1990) proposed inversion of leak-off test data of nearby wells for back calculating the minimum horizontal stress in a new well with the lack of LOT. However, this method might not be valid for complex structures in the presence of faults, fractures as well as heterogeneities (Gjonnes et al., 1998).

To predict the other horizontal stress, Vernik and Zoback (1992), and Peska and Zoback (1995) described two methods of obtaining maximum horizontal stress magnitude based on the indication of wellbore tensile fissures and breakouts using borehole image logs and caliper data. These methods are sensitive to the accuracy of breakout width measurement (Kadyrov, 2007). Also, Blanton and Olson (1997) developed poroelastic horizontal strain model to predict the magnitude of horizontal stresses simultaneously by assuming anisotropic horizontal stresses. This model takes tectonic strains into account along with vertical stress, pore pressure and some properties of rock to estimate the horizontal stresses. Results should be calibrated with available data such as LOT/XLOT, minifrac tests and observed drilling events. However, LOT/XLOT, minifrac tests are not performed in many oil and gas wellbores since running these tests is expensive, time-consuming and may negatively impact the integrity of the wellbore.

In this study, we present a methodology to accurately estimate the magnitudes and directions of horizontal stresses without using any LOT/XLOT, and minifrac tests data. In this methodology, we apply the full waveform acoustic data to develop an approach for estimating horizontal stresses. This is based on the assumption that the difference in shear waves velocities in anisotropic formations are related to changes in the principal stresses (Sinha, 1982; Norris et al., 1994).

Considering this assumption, it is possible to accurately estimate horizontal stresses by using sonic waves velocities at any specific depth (Sinha and Kostek, 1996; Sinha et al., 2000). Having an accurate estimation of horizontal stresses, it is then possible to build a consistent MEM and have precise mud window estimation.

In this paper, we develop the various steps of this methodology using a set of data from a wellbore with lots of instability related challenges during drilling, while no LOT/XLOT and minifrac tests were conducted in this wellbore. In this way, the accuracy of stress estimation and mud weight window, which is calculated using the developed model in this paper, is then validated against the actual instability data of the wellbore.

Herein, minimum horizontal stress magnitude is computed with poroelastic horizontal strain model and calibrated with complete mud losses. Then, the calibrated minimum horizontal stress along with shear moduli, which are obtained from processing of full waveform acoustic data, are used to calibrate maximum horizontal stress. This is done along the wellbore path in order to refine mud weight window. Accordingly, an MEM is developed. The constructed MEM is able to predict observed wellbore instabilities using Mohr-Coulomb failure criterion, which shows the validity of the applied methodology. Moreover, maximum horizontal stress direction is also extracted from full waveform acoustic data through the entire wellbore, which is in good agreement with formation microimager (FMI) log result. This demonstrates that an accurate MEM could be developed using full waveform acoustic data, while no LOT or minifrac tests are available.

2. Model Development

In order to develop the methodology of using full waveform acoustic data for creating a validated MEM, available data of an offshore wellbore was used in this study. Accordingly, the results of MEM was then compared with the actual instabilities of the wellbore for validation purposes. Well No-1 is a vertical offshore well located in one of the southern gas fields of Iran. Based on geology and geophysics reports, the structure of this field is an asymmetrical salt dome. Interpreted faults in the area are normally associated with extensional tectonics which mostly have near vertical fault planes. The main fault trend in the field is NW-SE (Hassanzadeh and Khatibi, 2015).

Further geological and geomechanical data were interpreted for estimating rock properties and predicting the in-situ stresses. Drilling events and image log were analyzed, and rock properties and pore pressure were estimated. In the next step, in-situ stresses were calculated and calibrated through different steps including the full waveform acoustic data analysis and then safe mud weight window was determined. These steps are presented in the following sections.

In addition, in a subsequent study (Hassanzadeh and Khatibi, 2015), 3D MEM of the field, including all wells, was constructed. This was carried out in order to optimize well placement and also reduce wellbore instabilities in future wells. This 3D model was also used to validate the results of the current paper. To do so, firstly, pore pressure prediction was performed by high resolution velocity data in the field using Bower’s method. Elastic properties were also derived from Pre-stack inversion of seismic data and then followed by 3D MEM construction. Then, 1D MEM Results were compared with 3D MEM at the final stage.

2.1. Drilling Events Analysis

Many types of drilling events may occur while drilling a well such as formation failure, breakdown, breakout, washout and kick. These events are encountered as a result of in-situ stresses contrast and possibly improper mud weight. These events could be extracted from daily drilling reports, image logs, caliper data and well summaries. Afterward, they should be compared with wellbore instabilities predicted by MEM for constraining the model and increasing the accuracy of the calculated in-situ stresses. Figure 1 shows drilling events observed in Well No-1.

As it can be seen from Figure 1, the main problem while drilling this wellbore occurred at a depth of 3122 m, where part of drill string was fished in the hole. In fact, mechanical borehole instability caused pipe sticking, and this made the drilling engineer to drill a sidetrack hole. It can also be perceived from the analysis of daily drilling reports that loss circulation occurred during drilling due to high drilling mud weight. Moreover, tight hole and pipe sticking occurred mostly due to mud type used while drilling and often observed in intervals containing high shale and siltstone. The analysis of these drilling events can be a good indicator of predictability of the created MEM and accordingly the validity of applying full waveform acoustic data for stress estimation.

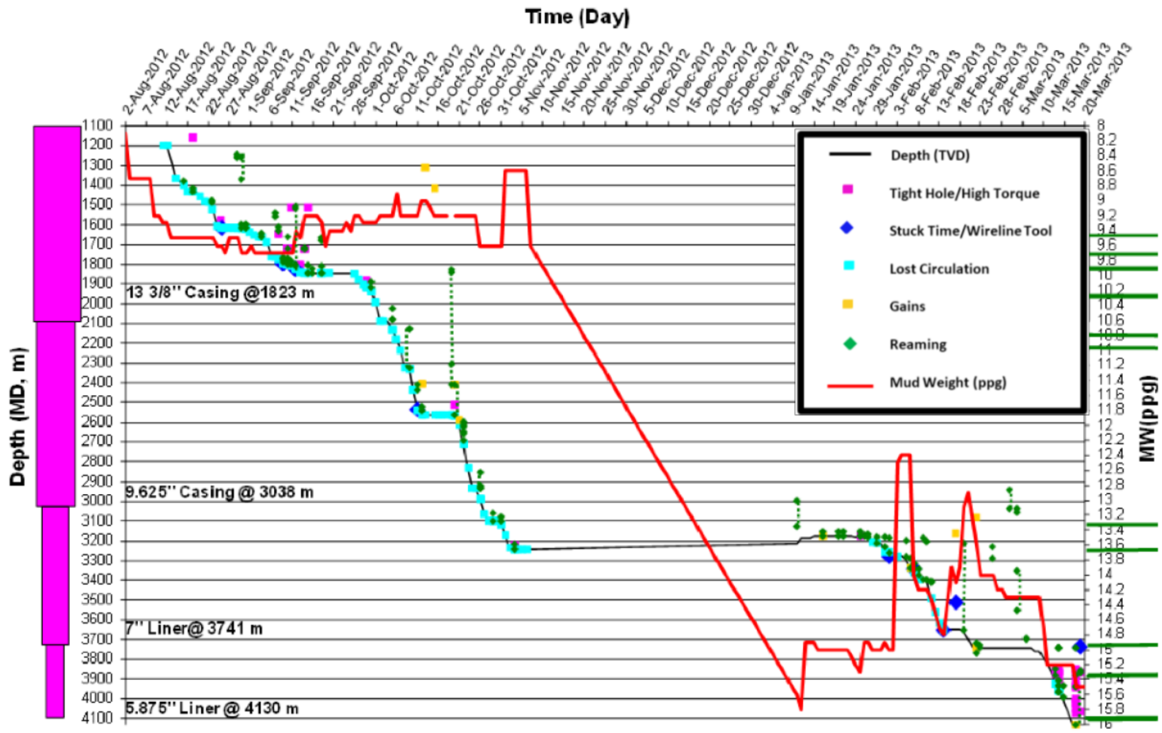

Figure 1. Drilling events extracted from daily drilling reports for Well No-1; The green lines illustrate top of the formations crossing this vertival well.

2.2. Image Log Analysis

Determination of horizontal stresses directions is of importance in designing the optimum trajectory of future wells in the field. Horizontal stress directions can be detected by analyzing the direction of breakouts and breakdowns.

Wellbore breakout orientation can be conventionally recognized from image logs, or from evaluating the oriented multi-arm caliper data (Plumb and Hickman, 1985). Wellbore breakout normally occurs in the direction of minimum principal stress around the wellbore. In a vertical well with normal or strike-slip dominant stress regime, the direction of minimum principal stress is basically the minimum horizontal stress direction. Therefore, breakout orientation in a vertical well identifies the minimum horizontal stress direction.

On the other hand, natural and induced fractures (breakdown) directions can also be identified from image logs which correspond to the direction of the maximum horizontal stress (Zoback, 2010). In addition, the direction of maximum horizontal stress can be detected from fast shear azimuth obtained by processing of full waveform acoustic data (discussed in Section 2.5).

In this study, horizontal stress directions were detected using caliper, FMI log and full waveform acoustic data. Figure 2 shows the FMI log result which was ran merely in reservoir section of Well No-1. This indicates a NW-SE (285˚) direction for the maximum horizontal stress.

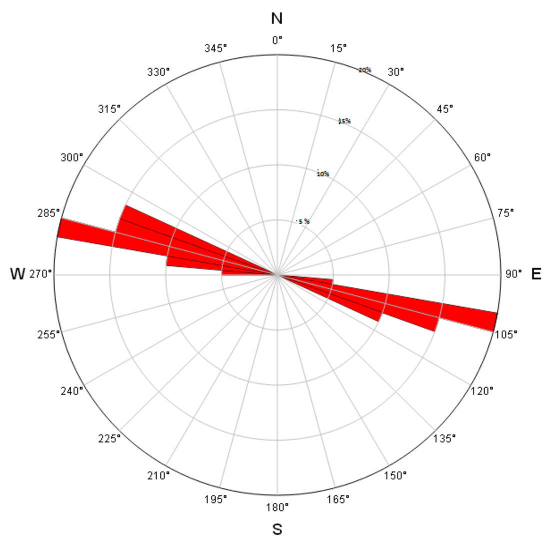

Figure 2. Maximum horizontal stress direction in reservoir section obtained from FMI log in Well No-1.

2.3. Rock Properties Estimation

Rock elastic properties are essential for estimating in-situ stresses and rock strength parameters, which should be later refined and calibrated with core laboratory measurements (Zoback, 2010). Assuming elastic isotropy, dynamic elastic moduli such as Young's modulus and Poisson's ratio were calculated using the subsequent equations (Fjar et al., 2008),

$$\nu_{dyn} = \frac{\frac{1}{2}({}^{\Delta t_s}/_{\Delta t_c})^2 - 1}{({}^{\Delta t_s}/_{\Delta t_c})^2 - 1} \quad (1)$$

$$E_{dyn} = \rho(\frac{1}{\Delta t_s})^2 \frac{3({}^{\Delta t_s}/_{\Delta t_c})^2 - 4}{({}^{\Delta t_s}/_{\Delta t_c})^2 - 1} \quad (2)$$

where ρ, ν_{dyn}, E_{dyn}, Δt_c, and Δt_s represent bulk density, dynamic Poisson's ratio, dynamic Young's modulus, compressional wave slowness and shear wave slowness, respectively. It should be noted that dynamic results were converted to static properties to better represent the elastic properties of rocks. The static and dynamic Poisson's ratios were considered the same, but dynamic Young's modulus was converted to the static one (E_{sta}) using the correlation proposed by Wang (2000),

$$E_{sta} = 0.4145\, E_{dyn} - 1.0593 \quad (3)$$

where E_{sta} and E_{dyn} are in GPa. The static elastic parameters were used then to estimate rock strength and horizontal stresses presented in the following sections.

Rock mechanical properties such as unconfined compressive strength (UCS), tensile strength and friction angle must also be calculated. Different empirical correlations are given in the literature for estimating these properties (Plumb, 1994; Chang et. al, 2006; Zoback, 2010; Oyeneyin, 2015). The ones which were more consistent with available core data were used here. UCS and friction angle were estimated based on correlations proposed by Plumb (1994). Since tensile strength of a rock is usually in the order of 1/12 to 1/8 of its UCS (Zoback, 2010), in the current study, the tensile strength was assumed to be 1/10 of UCS. Then, all rock mechanical properties were calibrated with their core measurements from laboratory tests.

Gamma Ray, density log, sonic data and all calculated properties including dynamic/static elastic moduli and rock mechanical properties are plotted in Figure 3 using PETRL software. Also, in this figure, the static properties are compared with core data, where available, in order to depict the accuracy of log-derived properties.

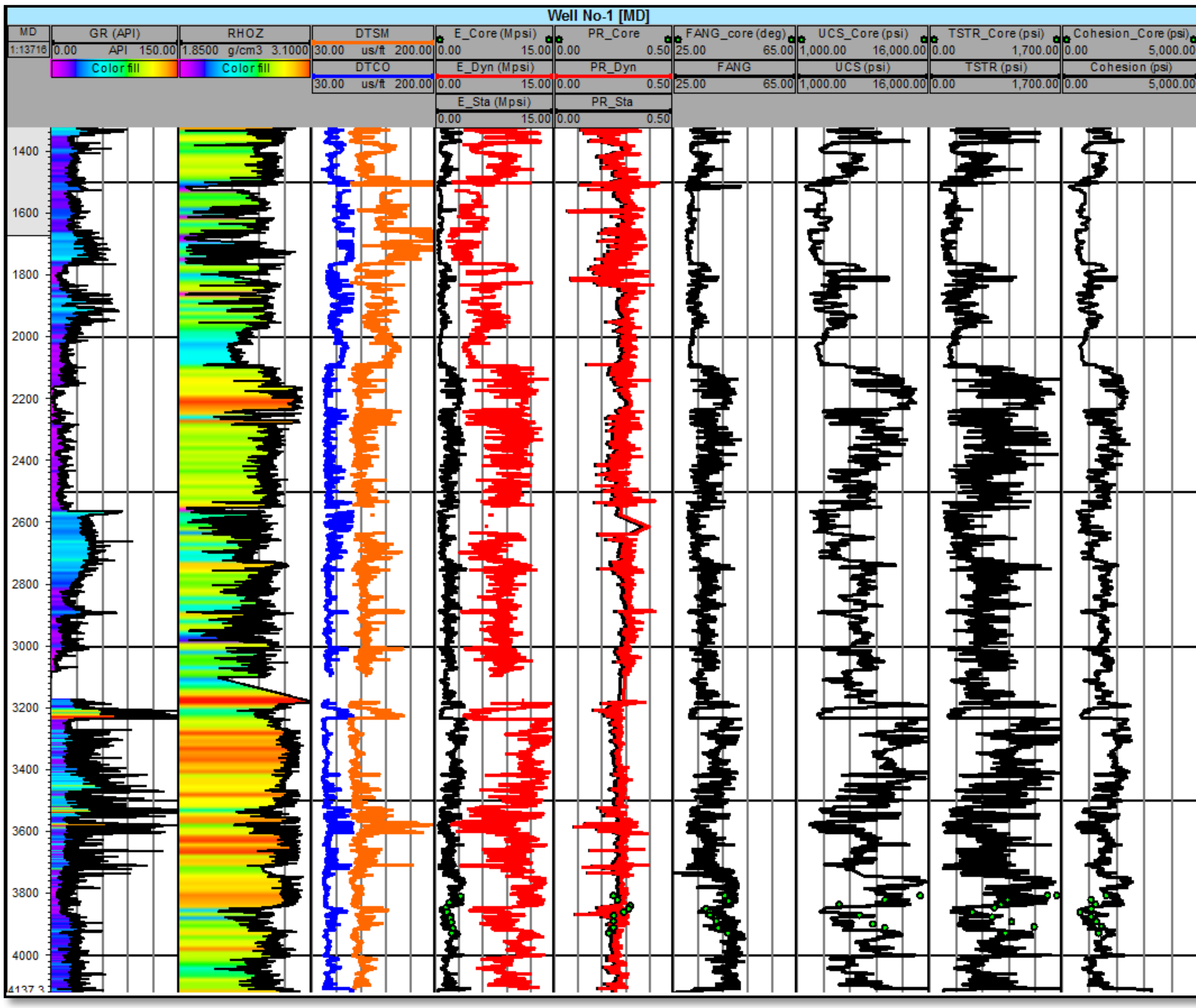

Figure 3. Rock properties with core measurement results for calibration. GR: gamma ray, RHOZ: bulk density, DTSM: shear wave transit time, DTCO: compressional wave transit time, Core: core samples, Dyn: dynamic moduli, Sta: static moduli, E: Young's modulus, PR: Poisson's ratio, FANG: friction angle, UCS: unconfined compressive strength, TSTR: tensile strength.

2.4. Pore Pressure Prediction

Pore pressure is one of the most noteworthy parameters in analyzing wellbore stability issues. Pore pressure might be determined through direct measurements such as modular dynamic tester (MDT), repeat formation tester (RFT), drill-stem tests (DST), build-up tests, and mud weight. Also, it can be predicted indirectly by log and seismic-based methods (Rezaee, 2015). Zhang (2011) reviewed different log-based methods of pore pressure prediction. In the current study, pressure gradient from MDT tool was used to estimate pore pressure in the reservoir section. For non-reservoir sections, Eaton method was used to predict the pore pressure profile in the clay-rich intervals. Herein, gamma ray and density values were cross-plotted and thresholds were defined for them to identify clay-rich intervals as seen in Figure 4. Gamma-ray values over 100 API represent clay-rich intervals used for pore pressure prediction by Eaton method.

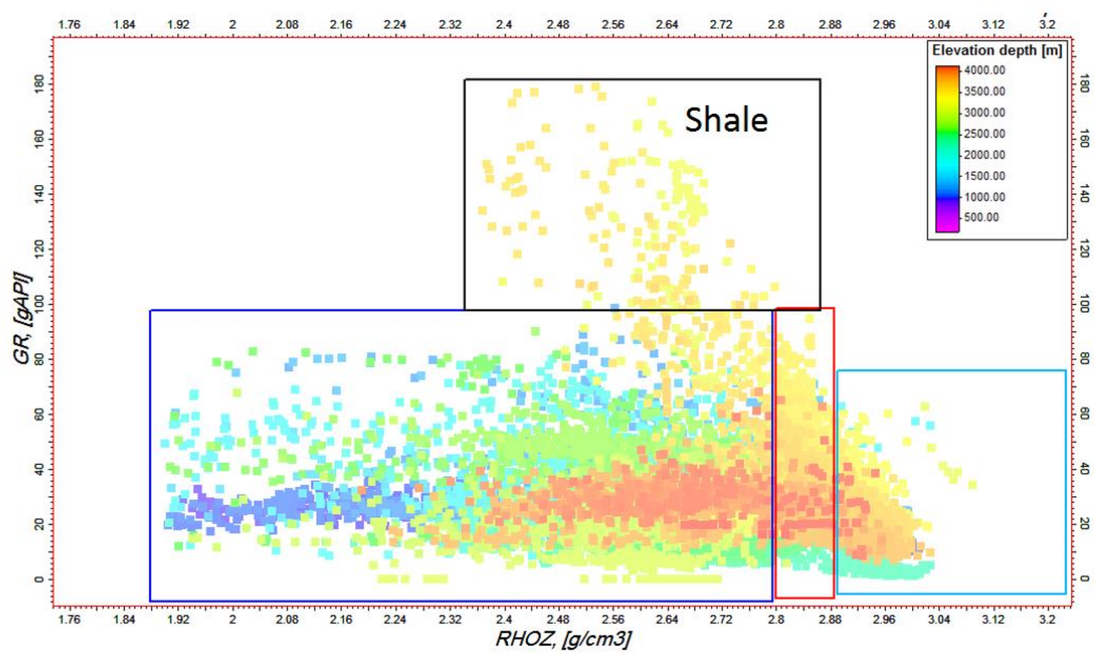

Figure 4. A classification of rocks using gamma ray (GR) and density (RHOZ) values; light blue box: anhydrate, red box: dolomite, dark blue box: limestone, and black box: Shale.

The Eaton equation is presented as below (Eaton, 1975),

$$P_{pg} = OBG - (OBG - P_{pn})(\frac{\Delta t_{cn}}{\Delta t_c})^3 \quad (4)$$

where P_{pg} is pore pressure gradient, OBG is overburden gradient, P_{pn} is normal pore pressure gradient or hydrostatic pressure gradient, Δt_c is compressional wave transient time and Δt_{cn} is compressional wave transient time in the normal compaction zone.

Due to lack of clay-rich intervals in some depth of the borehole, calculated pore pressure was future calibrated against applied mud weight utilized for drilling the well. In addition, observed drilling events such as loss and kick were used for further calibration. The calibrated pore pressure derived from Eaton method along with MDT results are shown in Figure 9.

2.5 Full Waveform Acoustic Data Analysis

An accurate knowledge of in situ stresses is essential for every wellbore stability analysis. In this study, vertical stress was calculated using the density log of the well. However, since there was no LOT data available in this wellbore, full waveform acoustic data was used to evaluate horizontal stresses. Herein, vertical stress (σ_v), as one of the principal stresses, was calculated based on the weight of overburden layers through the following equation (Song, 2012),

$$\sigma_v = g \int_0^{z_{TVD}} \rho \, dz \quad (5)$$

where ρ represents the density of the overlying layers, g is the gravitational acceleration, and z refers to depth. Since in Well No.1 density log was run from top to bottom, the estimated vertical stress is reasonably accurate which is shown in Figure 9.

Identifying horizontal stress directions and magnitudes is also crucial for well design and minimizing wellbore instability problems. Several methods can be used to identify horizontal stress directions including caliper data, image logs, microseismic monitoring, 3-component vertical seismic profile (Plona et al., 2002), and full waveform acoustic data (Sinha et al., 2008). In this study, processing of full waveform acoustic data along with FMI log and caliper data, as discussed in Section 2.2, were used for detection of horizontal stress directions.

Full waveform acoustic data provides slowness of shear waves measured with respect to the borehole axes (Franco et al., 2006). Full waveform acoustic log tool is a combination of 3 monopole and 2 orthogonally oriented dipole sources, and might have more than a hundred receivers.

At low frequencies the flexural mode is very little affected by the borehole and travels at the same speed as the shear wave (Pistre et. al, 2005). Moreover, dipole sources in the tool sweep through a frequency band, as shown schematically in Figure 5, from 300 Hz to 8 kHz. Such wide-frequency spectrum allows data capture, such as elastic wave velocities in the vicinity of the borehole. This is because it is sensitive to axial, azimuthal and radial variations, at high signal-to-noise ratios.

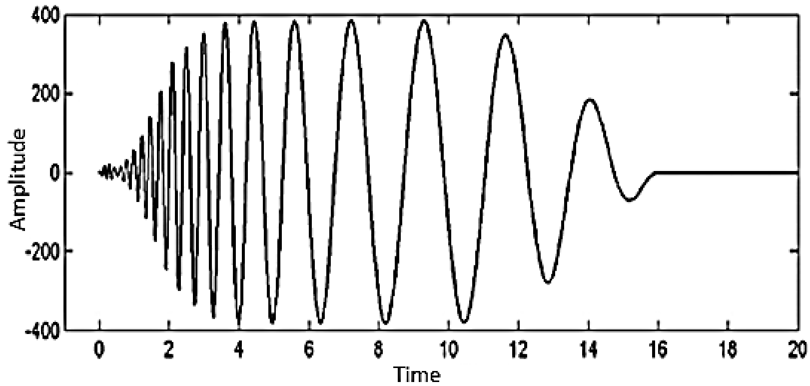

Figure 5. Frequency sweep of a dipole source (Pistre et. al, 2005). It covers wide range of frequencies.

In an isotropic formation, there is no shear wave splitting, however in a formation with stress-induced anisotropy, shear waves split into fast and slow components (Bratton et al., 2004). Franco et al. (2006) stated that "Shear waves travel fastest when polarized in the direction of maximum horizontal stress and slowest when polarized in the direction of minimum horizontal stress. This is because additional stress stiffens the formation, increasing velocity, and reduced stress conversely decreases velocity". Thus, determining the direction of fast shear wave propagation by processing of full waveform acoustic data yields the direction of maximum horizontal stress (Sinha, 2013; Franco et al., 2006).

In this study, full waveform acoustic data were analyzed from top to bottom of the wellbore. Figure 6 shows the maximum horizontal stress direction extracted from the processing of full waveform acoustic data in each section of the well. As it can be seen, the stress direction changes from top to bottom of the well. This is due to the existence of some faults near the well which were also found in seismic data (Hassanzadeh and Khatibi, 2015).

In the reservoir section of the well, the result of full waveform acoustic data (the borehole size of 5.875 inches in Figure 6) is in good agreement with FMI log result shown in Figure 2. FMI indicated a maximum horizontal stress direction of 285˚, and full waveform acoustic data specified a direction of 298˚. This validates the accuracy of the full waveform acoustic data analysis in predicting the horizontal stress direction with an error of less than 4.4%.

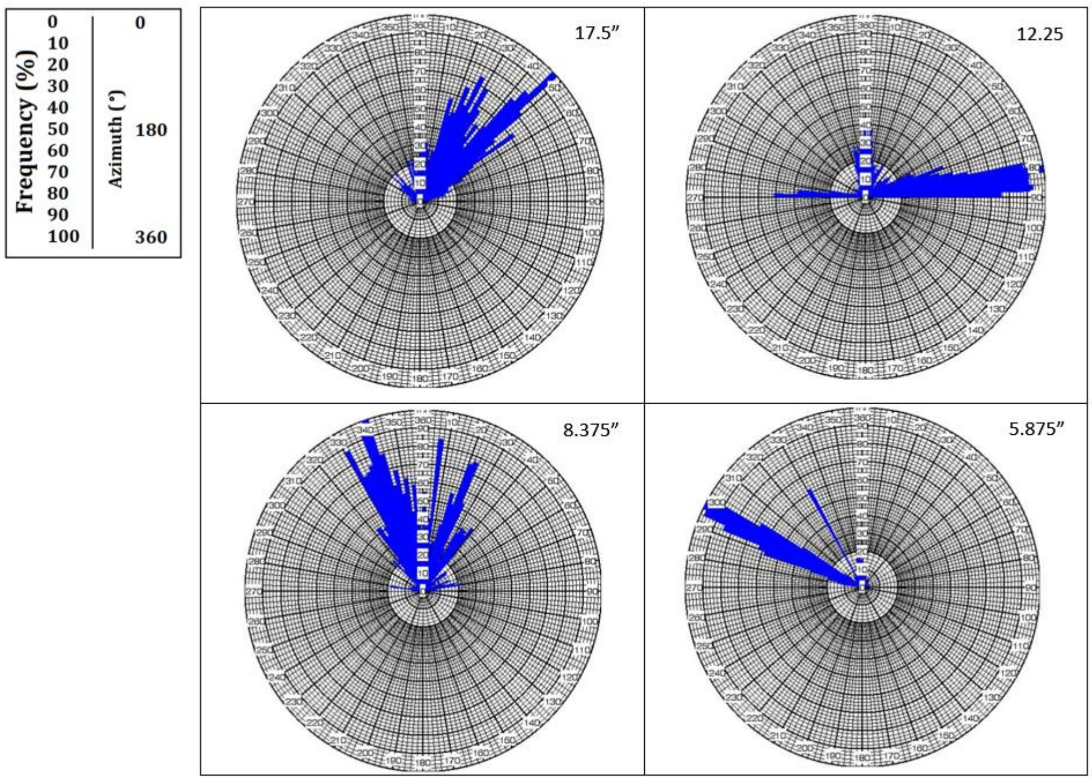

Figure 6. Maximum horizontal stress direction obtained from processing of full waveform acoustic data in different sections (different borehole sizes) of the well.

For horizontal stress magnitudes, direct measurements such as LOT/XLOT, minifrac test and hydraulic fracturing can be used to determine minimum horizontal stress. Conversely, maximum horizontal stress magnitude cannot be determined directly. However, both of them can be estimated with reasonable accuracy using indirect methods.

In an isotropic medium, the magnitude of two horizontal stresses are equal and can be estimated using uniaxial strain poroelastic equation discussed in Zoback (2010), however, it is not the case, when there is stress anisotropy (i.e. in tectonically active basins). One of the applications of full waveform acoustic data is the investigation of stress anisotropy. In a formation with stress-induced anisotropy, shear wave splits into fast and slow components and consequently their corresponding shear moduli diverge (Walsh et al., 2006; Sinha et al., 2008; Pistre et al., 2009). The more anisotropy in medium, the greater the difference between shear moduli.

Figure 7 shows the slow and fast shear moduli, C_{44} and C_{55}, in the reservoir section of the well. As it is shown in this figure, shear moduli diverge from each other due to stress anisotropy in this section of the well. The yellow area shows the separation of the two shear moduli. Large separations of C_{44} and C_{55} means that the horizontal stresses have also large difference. Therefore, as there is shear wave splitting in this wellbore, it is required to apply a method for determining horizontal stresses in such anisotropic medium.

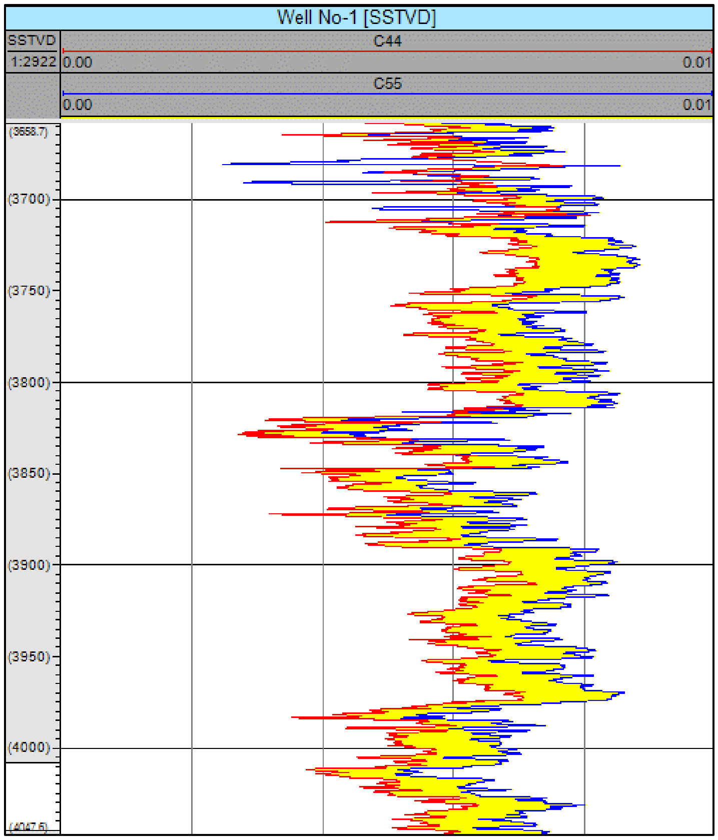

Figure 7. Separation of slow and fast shear moduli due to the presence of anisotropy in reservoir section of the wellbore. C_{44}: slow shear modulus (red), C_{55}: fast shear modulus (blue).

One of the indirect methods for estimating horizontal stress magnitudes in an anisotropic medium is poroelastic horizontal strain model, which is discussed by Blanton and Olson (1997). This method, which was used in this study, takes tectonic strains into account, and therefore evaluates anisotropic horizontal stresses as below,

$$\sigma_h = \frac{\upsilon}{1-\upsilon}\sigma_v + \frac{1-2\upsilon}{1-\upsilon}\alpha P_p + \frac{E}{1-\upsilon^2}\varepsilon_x + \frac{\upsilon E}{1-\upsilon^2}\varepsilon_y \quad (6)$$

$$\sigma_H = \frac{\upsilon}{1-\upsilon}\sigma_v + \frac{1-2\upsilon}{1-\upsilon}\alpha P_p + \frac{E}{1-\upsilon^2}\varepsilon_y + \frac{\upsilon E}{1-\upsilon^2}\varepsilon_x \quad (7)$$

where ν, E, σ_v, P_p are Poisson's ratio, Young's modulus, vertical stress and pore pressure, respectively. Biot's coefficient, α, is assumed to be 1.0 for all formations, and ε_x and ε_y are two horizontal strains which might be compressional or extensional. They can be treated simply as calibration factors. ε_x (strain in the minimum horizontal stress direction) is considered as a tool to predict losses, and ε_y (strain in the maximum horizontal stress direction) is to predict breakouts in order to satisfy the observed drilling events. In this study, due to lack of LOT/XLOT, the minimum and maximum horizontal stresses were estimated by poroelastic horizontal strain model, and then they were calibrated with complete mud losses and full waveform acoustic data, respectively.

The underlying theory behind the calibration of maximum horizontal stress using full waveform acoustic data is based on acoustoelastic effect in rock. This concept assumes difference in the shear waves slowness are primarily caused by difference in the three principal stresses (Sinha, 1982; Norris et al., 1994; Sinha and Kostek, 1996; Eldevik, 2014).

In addition to shear waves slowness, the full waveform acoustic data acquisition provides compressional and Stoneley waves slowness at multiple depths of investigation (Pistre et al., 2005; Franco et al., 2006; Wendt et al., 2007). 3D anisotropy processing of full waveform acoustic data results in three far-field shear moduli, two vertical shear moduli C_{55} and C_{44} with respect to fast and slow shear waves slowness, and a horizontal shear modulus C_{66} estimated from Stoneley wave slowness (Sinha, 2002; Liu and Sinha, 2003; Bratton et al., 2004). C_{44}, C_{55} and C_{66} denote shear rigidity in the three orthogonal planes. C_{44}, C_{55} are measured in the two orthogonal planes containing borehole axis, and C_{66} is measured in the borehole cross-sectional plane as shown in Figure 8 .

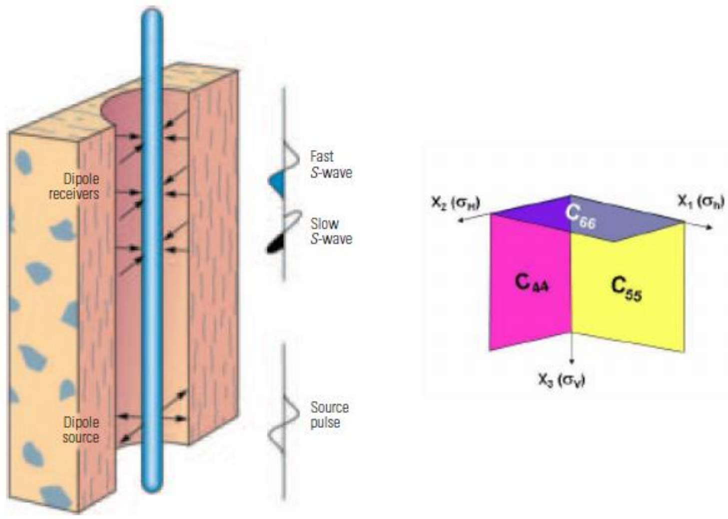

Figure 8. **(Left) Full waveform acoustic data measurement and (Right) planes of measuring three shear moduli (Haldorsen et al., 2006; Pistre et al., 2009).**

The following equations relate variations in the three shear moduli to relative variations in the principal stresses in terms of an acoustoelastic coefficient (Sinha et al., 2008),

$$C_{44} - C_{66} = A_E(\sigma_V - \sigma_H) \tag{8}$$

$$C_{55} - C_{66} = A_E(\sigma_V - \sigma_h) \tag{9}$$

$$C_{55} - C_{44} = A_E(\sigma_H - \sigma_h) \tag{10}$$

where A_E is the acoustoelastic coefficient indicating the dependency of wave slowness to difference of stresses in the sonic wave propagating medium. σ_V, σ_h and σ_H are the vertical, minimum and maximum horizontal stresses, respectively. And C_{44}, C_{55}, and C_{66} are the three shear moduli obtained from the subsequent equations (Sinha, 2013),

$$C_{44} = \rho(\frac{1}{\Delta t_{s\,(slow)}})^2 \tag{11}$$

$$C_{55} = \rho(\frac{1}{\Delta t_{s\,(fast)}})^2 \tag{12}$$

$$C_{66} = \rho(\frac{1}{\Delta t_{Stoneley}})^2 \tag{13}$$

where $\Delta t_{s\,(slow)}$ and $\Delta t_{s\,(fast)}$ are slow and fast shear wave transit times, and $\Delta t_{Stoneley}$ is Stoneley wave transit time. As we had estimates of the shear moduli, vertical and the minimum horizontal stresses, acoustoelastic coefficient, A_E, was calculated from the following equation,

$$A_E = \frac{C_{55} - C_{66}}{\sigma_V - \sigma_h} \tag{14}$$

Once we determined the acoustoelastic coefficient, we can estimate the maximum horizontal stress magnitude as a function of depth from the rearranged form of Equation 10,

$$\sigma_H = \sigma_h + \frac{(C_{55} - C_{44})}{A_E} \tag{15}$$

The result from Equation 15 was used to calibrate the maximum horizontal stress obtained by Equation 7. The final result of principal stresses calculation is shown in Figure 9. As it can be seen from the order of principal stresses, the normal tectonic system seemed to be the dominant regime. Maximum horizontal stress calculated here along with other obtained data from previous sections were then used to determine the safe mud weight window using Mohr-Coulomb failure criterion.

3. Results and discussion

The most effective approach to validate the accuracy of the presented full waveform acoustic methodology is to verify the predictability of the wellbore instabilities by building a MEM. Using the estimated rock properties and principal stresses, wellbore stability analysis shows how robust the presented full waveform acoustic methodology is. This is done by comparing the predicted wellbore stability/instability with the drilling events, image logs, and caliper data. To do so, after estimating the principal stress magnitudes, a safe mud weight window was determined by means of rock shear and tensile failure criteria.

There are generally four limits of mud weight by which different conditions are defined. These limits are pore (formation) pressure, breakout mud weight, minimum horizontal stress and breakdown mud weight. If drilling mud pressure is less than formation pressure, wellbore washout and/or kick might be expected. When the mud weight is less than the breakout mud weight, rock shearing and wellbore enlargement may occur.

However, if wellbore has natural fractures, conductive fissures and/or highly permeable thief zone, then any mud pressure above the minimum horizontal stress will tend to reopen the natural fractures/fissures. This would cause loss of drilling fluid to the formation. When the mud weight is higher than the breakdown mud weight, induced fractures are more likely to be created in the borehole. Therefore, a safe mud weight would be higher than the formation pressure and the breakout mud weight, but lower than the minimum horizontal stress and breakdown mud weight. The first step for establishing the safe mud weight window is determining the stresses around the borehole.

In this study, to determine the stresses around the borehole, we assumed a linear elastic behavior for formation rocks. In a linear elastic rock, the largest stress concentration occurs at the borehole wall. Therefore, the stress components on the borehole wall should be examined using rock failure criteria for wellbore stability analysis. On the borehole wall, the stress components are expressed by Kirsch's equations (Fjar et al., 2008; Al-Ajmi, 2012),

$$\sigma_r = P_w \tag{16}$$

$$\sigma_\theta = (\sigma_H + \sigma_h) - 2(\sigma_H - \sigma_h)\cos 2\theta - P_w \tag{17}$$

$$\sigma_z = \sigma_v - \nu[2(\sigma_H - \sigma_h)\cos 2\theta] \tag{18}$$

where σ_r, σ_θ, σ_z, P_w, θ and ν are radial stress, tangential stress, axial stress, wellbore pressure, angle clockwise from the σ_H direction, and Poisson's ratio, respectively. As it can be seen from Equations 17 and 18, the tangential and axial stresses around a vertical borehole are functions of the angle θ. The breakout is expected to happen at the point of maximum tangential stress and breakdown, however, is expected to occur at the point where minimum tangential stress is applied to the rock. These two equations show that both tangential and axial stresses reach their maximum value at $\theta = \pm\pi/2$, and their minimum values at $\theta = 0, \pi$. In order to find the safe mud weight window, we employed conventional Mohr-Coulomb failure criterion. The linearized form of the Mohr-Coulomb failure criterion is as below (Mohr, 1900),

$$\sigma_1 = UCS + tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)\sigma_3 \tag{19}$$

where σ_1, σ_3 and φ are maximum and minimum principal stresses, and friction angle, respectively. Depending on the magnitudes of σ_r, σ_θ and σ_z, the largest one is replaced with σ_1

and the smallest one with σ_3. In a normal tectonic system the most common cases for borehole breakout and breakdown are $\sigma_\theta > \sigma_z > \sigma_r$ and $\sigma_r > \sigma_z > \sigma_\theta$, respectively (Al-Ajmi and Zimmerman, 2006). Therefore, the limits of pressure to avoid breakout, p_w^{BO}, and breakdown, p_w^{BD}, are defined as below,

$$p_w^{BO} = \frac{3\sigma_H - \sigma_h - UCS}{1 + tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)} \tag{20}$$

$$p_w^{BD} = \frac{UCS + tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)(3\sigma_h - \sigma_H)}{1 + tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)} \tag{21}$$

Since Mohr–Coulomb failure criterion overestimates the breakdown pressure, a tensile cut-off should be considered for determining pressure required to avoid breakdown. The tensile cut-off is defined using the following equation (Al-Ajmi and Zimmerman, 2006),

$$P_{w(cut-off)} = 3\sigma_h - \sigma_H - T \tag{22}$$

where T is the tensile strength of rock. The mud pressure obtained from Equation 22 should be compared with calculated breakdown pressure using Equation 21. The smaller one is considered as the breakdown pressure. Results of Equations 20, 21 and 22 along with calculated pore pressure and minimum horizontal stress defined four limits of mud weight window. Figure 9 shows the generated safe mud weight window, the white area, for Well No.1. From the caliper data shown in this figure, breakouts are observed in the depth intervals of 800-1200 m, 1500-2100 m and 2450-3120 m. The latest breakout was so severe which led to pipe sticking. This problem made drilling engineers to drill a sidetrack. Two remarkable complete mud losses also occurred at 2550 m and 3260 m.

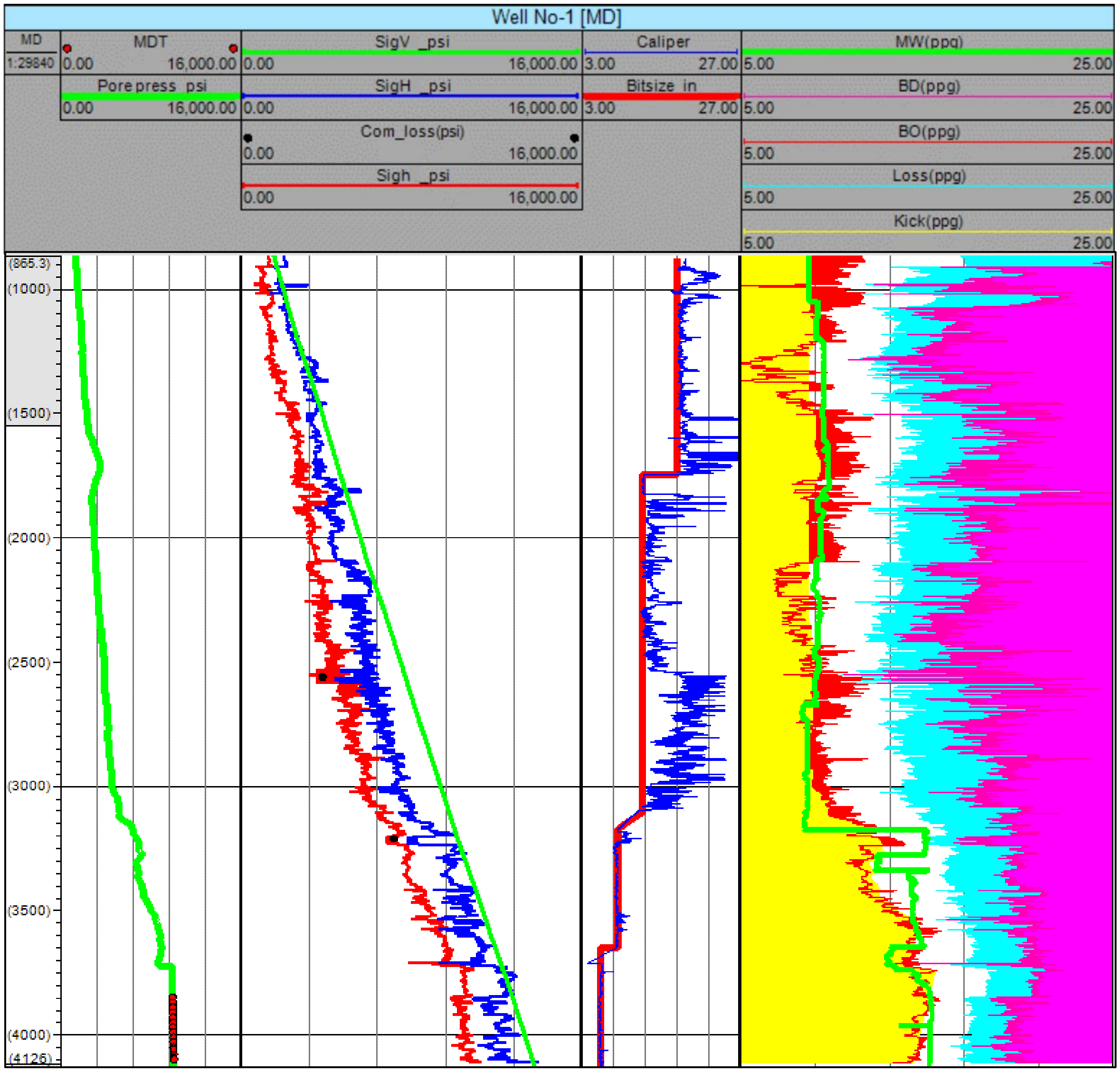

Figure 9. From Left: pore pressure profile derived from Eaton method and MDT results; principal stresses calculation results, Sig H: σ_H, Sig h:σ_h , Sig V:σ_V and Com_loss: points of complete mud losses; breakouts detected by comparison of caliper data with bit size; four limits of mud weight as well as applied drilling mud weight.

Figure 9 also shows that there is not a safe mud weight window at interval of 2510-2600 m. The observed breakouts and complete mud loss at this interval verify the reliability of the results. As it can be seen in this figure, drilling events were predicted very well by the developed methodology. This infers that the application of full waveform acoustic data for calibration of maximum horizontal stress is reliable and leads to a valid MEM. Therefore, even when the LOT/XLOT and minifrac tests are not available in a wellbore, satisfactory MEM and mud weight window could be developed using the full waveform acoustic data. Further validation was done by comparing the results of this 1D model with a 3D model.

In a 3D modeling, pore pressure prediction was performed by high resolution velocity data in the field using Bower's method. Also, elastic properties were derived from Pre-stack inversion of seismic data and then followed by 3D MEM construction. Figure 10 compares the horizontal stresses profiles obtained from both modeling. As it can be seen from this figure, the results from full waveform acoustic tool (1D) match well with the results obtained from the 3D model.

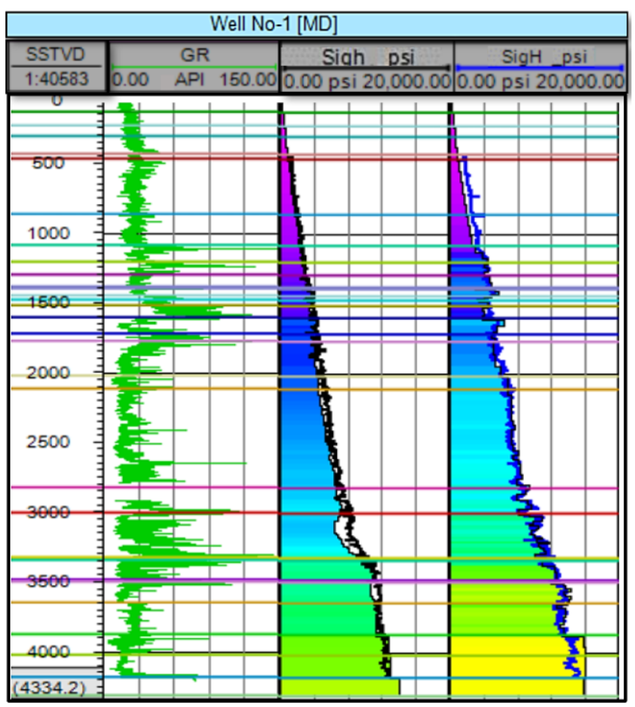

Figure 10. Log derived stresses 1D (curves) and modelled ones 3D (colored shading) for well No-1, left (GR), middle (σ_h), right (σ_H), and colored straight lines are well tops crossing the well.

In addition, in the 3D model, a well 8 Km from Well No-1 was used as a blind well to further confirm the full waveform acoustic results. In situ stresses and pore pressure results of the two wellbores are shown in Figure 11. As this figure demonstrates, both set of results correspond well to each other. This further approves that, while no LOT/XLOT and minifrac tests are available, accurate outcomes could be obtained from the analysis of the full waveform acoustic data according to the presented methodology in this study

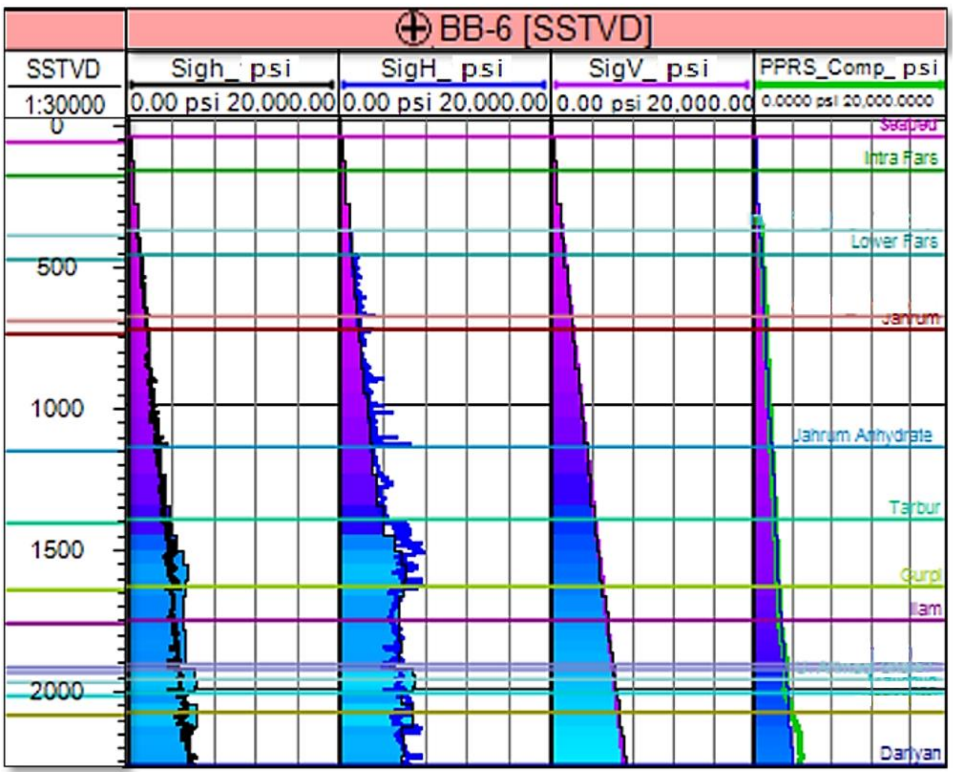

Figure 11. Log derived properties 1D (curves) and modelled ones 3D (colored shading) for a blind well 8 km away from Well No-1. Colored horizontal lines are well tops crossing the well.

4. Conclusions

In this study, we used full waveform acoustic data measurements after drilling to develop a methodology for analyzing wellbore stability in the absence of LOT/XLOT and minifrac tests. We employed the shear moduli extracted from the processing of full waveform acoustic data along with an analysis of mud losses to calibrate horizontal stresses. As FMI log was only available in the reservoir section, full waveform acoustic data were used to detect the maximum horizontal stress direction along the wellbore which was in accordance with FMI in the reservoir section. Drilling events such as wellbore breakouts were well predicted with the developed model. Also, a good match existed between the results of the developed 1D model and a 3D model. This confirmed the validity and reliability of the application of the full waveform acoustic data for calibration of maximum horizontal stress. Therefore, this study demonstrated that even when the LOT/XLOT and minifrac tests are not available in a wellbore, reliable MEM and safe mud weight window could be developed using the full waveform acoustic data.

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5. References

Aadnoy, B.S., "Inversion Technique to Determine the in-Situ Stress Field from Fracturing Data." *Journal of Petroleum Science and Engineering* 4, no. 2 (1990): 127-41.

Al-Ajmi, A.M., "Mechanical Stability of Horizontal Wellbore Implementing Mogi-Coulomb Law." *Advances in Petroleum Exploration and Development* 4, no. 2 (2012): 28-36.

Al-Ajmi, A.M., and Zimmerman, R.W., "Stability Analysis of Vertical Boreholes Using the Mogi–Coulomb Failure Criterion." *International Journal of Rock Mechanics and Mining Sciences* 43, no. 8 (2006): 1200-11.

Amadei, B., and Stephansson, O., *Rock Stress and Its Measurement*. Springer Science & Business Media, 1997.

Anderson, E.M., "*The Dynamics of Faulting and Dyke Formation with Applications to Britain*." Hafner Pub. Co., 1951.

Bell, JS., "Practical Methods for Estimating in Situ Stresses for Borehole Stability Applications in Sedimentary Basins." *Journal of Petroleum Science and Engineering* 38, no. 3 (2003): 111-19.

Blanton, T.L., and Olson, J.E., "Stress Magnitudes from Logs: Effects of Tectonic Strains and Temperature." Paper presented at the SPE Annual Technical Conference and Exhibition, 1997.

Bratton, T., Bricout, V., Lam, R., Plona, T., Sinha, B.K., Tagbor, K., Venkitaraman A., and Borbas, T., "Rock Strength Parameters from Annular Pressure While Drilling and Dipole Sonic Dispersion Analysis." Paper presented at the SPWLA 45th Annual Logging Symposium, 2004.

Breckels, I.M., and Van Eekelen, H., "Relationship between Horizontal Stress and Depth in Sedimentary Basins." *Journal of Petroleum Technology* 34, no. 09 (1982): 2,191-2,99.

Chang, C., Zoback, M.D., and Khaksar, A., "Empirical Relations between Rock Strength and Physical Properties in Sedimentary Rocks." *Journal of Petroleum Science and Engineering* 51, no. 3 (2006): 223-37.

Crain, E.R., "Crain's Petrophysical Handbook." *Spectrum* (2000).

Eaton, B.A., "The Equation for Geopressure Prediction from Well Logs." Paper presented at the Fall Meeting of the Society of Petroleum Engineers of AIME, 1975.

Eldevik, S., "Measurement of Non-Linear Acoustoelastic Effect in Steel Using Acoustic Resonance." (2014).

Fjar, E., Holt, R.M., Raaen, A.M., Risnes, R., Horsrud, P., "*Petroleum Related Rock Mechanics*." Vol. 53: Elsevier, 2008.

Franco, J.A., Ortiz, M.M., De, G.S., Renlie, L., Williams, S., "Sonic Investigation in and around the Borehole." *Oilfield Review* 18, no. 1 (2006): 14-31.

Gholami, R., Moradzadeh, A., Rasouli, V., Hanachi, J., "Practical Application of Failure Criteria in Determining Safe Mud Weight Windows in Drilling Operations." *Journal of Rock Mechanics and Geotechnical Engineering* 6, no. 1 (2014): 13-25.

Gjønnes, M., Cruz, A.M., Horsrud, P., Holt, R.M., "Leak-Off Tests for Horizontal Stress Determination?". *Journal of Petroleum Science and Engineering* 20, no. 1 (1998): 63-71.

Haimson, B.C., and Cornet, F.H., "Isrm Suggested Methods for Rock Stress Estimation—Part 3: Hydraulic Fracturing (Hf) and/or Hydraulic Testing of Pre-Existing Fractures (Htpf)." *International Journal of Rock Mechanics and Mining Sciences* 40, no. 7 (2003): 1011-20.

Haldorsen, J.B., Johnson, D.L., Plona, T., Sinha, B.K., Valero, H.P., Winkler, K., "Borehole Acoustic Waves." *Oilfield review* 18, no. 1 (2006): 34-43.

Hareland, G., and Hoberock, L.L., "Use of Drilling Parameters to Predict in-Situ Stress Bounds." Paper presented at the SPE/IADC Drilling Conference, 1993.

Hassanzadeh, J., and Khatibi, S.A., "3d Seimic Interpretation." Petropars Co., 2015.

Immerstein, T., "Wellbore Stability and Rock Mechanics Study on the Ula Field." (2013).

Kadyrov, T., "Integrated Wellbore Stability Analysis for Well Trajectory Optimization and Field Development: The West Kazakhstan Field." (2007).

Liu, Q.H., and Sinha, B.K., "A 3d Cylindrical Pml/Fdtd Method for Elastic Waves in Fluid-Filled Pressurized Boreholes in Triaxially Stressed Formations." *Geophysics* 68, no. 5 (2003): 1731-43.

Mavko, G., Mukerji, T., Dvorkin, J., "*The Rock Physics Handbook: Tools for Seismic Analysis of Porous Media*." Cambridge university press, 2009.

McLean, M.R., and Addis, M.A., "Wellbore Stability Analysis: A Review of Current Methods of Analysis and Their Field Application." Paper presented at the SPE/IADC Drilling Conference, 1990.

Norris, A.N., Sinha, B.K., Kostek, S., "Acoustoelasticity of Solid/Fluid Composite Systems." *Geophysical Journal International* 118, no. 2 (1994): 439-46.

Oyeneyin, B., "*Integrated Sand Management for Effective Hydrocarbon Flow Assurance*." Vol. 63: Newnes, 2015.

Peška, P., and Zoback, M.D., "Compressive and Tensile Failure of Inclined Well Bores and Determination of in Situ Stress and Rock Strength." *Journal of Geophysical Research: Solid Earth* 100, no. B7 (1995): 12791-811.

Pistre, V., GongRui, Y., Sinha, B.K., Prioul, R., "Determining Stress Regime and Formation Q Factor from Sonic Scanner: 50th Annual Logging Symposium." *Society of Petrophysicists and Well Log Analysts, Expanded Abstracts* (2009): 1-1.

Pistre, V., Kinoshita, T., Endo, T., Schilling, K., Pabon, J., "A Modular Wireline Sonic Tool for Measurements of 3d (Azimuthal, Radial, and Axial Formation Acoustic Properties." Paper presented at the SPWLA 46th Annual Logging Symposium, 2005.

Plona, T.J., Kane, M.R., Sinha, B.K., Walsh, J., "Evaluating Stress-Induced Anisotropy and Mechanical Damage from Cross-Dipole Sonic Data Using Dispersion Analysis." Paper presented at the SPE/ISRM Rock Mechanics Conference, 2002.

Plumb, R.A., "Influence of Composition and Texture on the Failure Properties of Clastic Rocks." Paper presented at the Rock Mechanics in Petroleum Engineering, 1994.

Plumb, R.A., and Hickman, S.H., "Stress-Induced Borehole Elongation: A Comparison between the Four-Arm Dipmeter and the Borehole Televiewer in the Auburn Geothermal Well." *Journal of Geophysical Research: Solid Earth* 90, no. B7 (1985): 5513-21.

Rezaee, R., *Fundamentals of Gas Shale Reservoirs*. John Wiley & Sons, 2015.

Sengupta, M., Dai, J., Volterrani, S., Dutta, N., Rao, N.S., Al-Qadeeri, B., Kidambi, V.K., "Building a Seismic-Driven 3d Geomechanical Model in a Deep Carbonate Reservoir." Paper presented at the 2011 SEG Annual Meeting, 2011.

Sinha, B.K., "Recent Advances in Borehole Sonic Technology." 2013.

Sinha, B.K., "Determining Stress Parameters of Formations from Multi-Mode Velocity Data." Google Patents, 2002.

Sinha, B.K., "Elastic Waves in Crystals under a Bias." *Ferroelectrics* 41, no. 1 (1982): 61-73.

Sinha, B.K., Kane, M.R., Brie, A., Burridg, R., "Radial Variations in Cross-Dipole Shear Slownesses in a Limestone Reservoir." Paper presented at the 2000 SEG Annual Meeting, 2000.

Sinha, B.K., and Kostek, S., "Stress-Induced Azimuthal Anisotropy in Borehole Flexural Waves." *Geophysics* 61, no. 6 (1996): 1899-907.

Sinha, B.K., Wang, J., Kisra, S., Li, J., Pistre, V., Bratton, T., Sanders, M., Jun, C., "Estimation of Formation Stresses Using Borehole Sonic Data." Paper presented at the 49th Annual Logging Symposium, 2008.

Song, L., "Measurement of Minimum Horizontal Stress from Logging and Drilling Data in Unconventional Oil and Gas." University of Calgary, 2012.

Vernik, L., and Zoback, M.D.,"Estimation of Maximum Horizontal Principal Stress Magnitude from Stress-Induced Well Bore Breakouts in the Cajon Pass Scientific Research Borehole." *Journal of Geophysical Research: Solid Earth* 97, no. B4 (1992): 5109-19.

Walsh, J., Sinha, B.K., Donald, A., "Formation Anisotropy Parameters Using Borehole Sonic Data." Paper presented at the SPWLA 47th Annual Logging Symposium, 2006.

Wang, H., Soliman, M.Y., Shan, Z., Meng, F., Towler, B.F., "Understanding the Effects of Leak-off Tests on Wellbore Strength." *SPE Drilling & Completion* 26, no. 04 (2011): 531-39.

Wang, Z., "Dynamic Versus Static Elastic Properties of Reservoir Rocks." *Seismic and acoustic velocities in reservoir rocks* 3 (2000): 531-39.

Wendt, A.S., Kongslien, M., Renlie, L., Pedersen, E.S., Vissapragada, B., Skomedal, E., Sinha, B.K., "Advanced Mechanical Earth Modelling and Wellbore-Stability Calculation Using Advanced Sonic Measurements: A Case Study on an Hp/Ht Field in the Norwegian North Sea." Paper presented at the SPE Annual Technical Conference and Exhibition, 2007.

Zhang, J. "Pore Pressure Prediction from Well Logs: Methods, Modifications, and New Approaches." *Earth-Science Reviews* 108, no. 1 (2011): 50-63.

Zhang, J., Bai, M., Roegiers, J.C., "Dual-Porosity Poroelastic Analyses of Wellbore Stability." *International journal of rock mechanics and mining sciences* 40, no. 4 (2003): 473-83.

Zoback, M.D., "*Reservoir Geomechanics*". Cambridge University Press, 2010.

Zoback, M.D., Zoback, M.L., Eaton, J.P., Mount, V., Suppe, J., "New Evidence on the State of Stress of the San Andreas Fault System." *Science* 238, no. 4830 (1987): 1105-11.