Paper No. 44
The 3rd Asia Pacific Coalbed Methane Symposium

APCBM 2011
May 3-6, 2011, Brisbane, Australia

A rock mechanical model developed for a Coal Seam Well

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Keywords: Coalbed methane; Rock mechanical model; In-situ stresses; Wellbore instability.

Abstract

Drilling operation in order to produce from Coalbed methane (CBM) is prone to various geomechanics related problems not only within the coal seam but also across the overburden layers. Wellbore instability in the form of shear failure (breakout) and washout in one hand and mud loss and fracturing in other hand are examples of failures which a wellbore may experience if a proper mud weight is not used for drilling. In order to conduct such an analysis the input data required includes mechanical properties of formations as well as the magnitude and direction of in-situ stresses and pore pressure.

It is well known that mechanical properties of formations are related to their physical characteristics. For example, the formation Young's Modulus or strength is expected to be higher in formations with larger sonic velocities or lesser porosities. Petrophysical logs reflect various rock physical properties from which continuous curves of rock mechanical properties could be estimated using several correlations developed in similar fields. Similarly, continuous logs of in-situ stresses (i.e. vertical as well as minimum and maximum horizontal stresses) could be estimated, for example from poroelastic formulae, in conjunction with rock physical properties. The estimated logs could be calibrated against lab tests on cores and field test data. For example, performing triaxial tests in the lab on cores obtained at different depths, the elastic and strength properties such as Young's Modulus, Poisson's ratio and uniaxial compressive strength (UCS) could be measured and this is used to correct the corresponding estimated logs. Similarly, the minimum horizontal stress log could be calibrated against any existing leak-off-test data whereas pore pressure curve can be calibrated if any MDT data is available. The direction of horizontal stress can be estimated from the image logs, for example FMI.

The combination of continuous curves of formation mechanical properties and magnitude of in-situ stresses together with stress directions is referred to as rock mechanical model (RMM). The RMM is constructed for a drilled well and then it is used for prediction of events in a new planned well in a nearby area. The RMM includes the input data for any geomechanics study such as wellbore instability analysis, fracturing design or sanding prediction.

In this study the RMM was constructed for data corresponding to Well Ridgwood 2 drilled in Surat basin in Queensland, Australia. The results indicate how the mechanical properties are changing across the coal seam comparing to other intervals and that the stress magnitudes experience significant changes accordingly. The results are used to predict the fraccability of the CBM for stimulation purposes using a hydraulic fracturing operation. Other applications of the constructed RMM will be discussed and the results interpreted.

1. Introduction

Coal seam gas (CSG) or coalbed methane (CBM) reservoirs are unconventional gas reservoirs which are different from the conventional ones in different aspects. First, despite of conventional reservoirs, in coal seams the gas is not in the pore space but adsorbed within the matrix. Second, in conventional gas reservoirs, gas flows to the well as a result of any pressure gradient between the well and the formation, but in CBM reservoirs the reservoir pressure should be under a threshold value in order to produce gas. Besides, in the CBM reservoirs, the main production procedure is to dewater coal layer so the gas molecules will desorb from the coal matrix and could flow within the cleats and also fractures made by hydraulic fracturing [Morad *et al.*, 2008]. For hydraulic fracturing to be effective, the stress state of the filed, which controls the hydraulic conductivity of the fracture networks [Barton *et al.*, 1995], should be precisely studied [Johnson *et al.*, 2010b]. In order to determine the stress regime of a field, the Rock Mechanical Model (RMM), which includes continuous logs of formation elastic and strength properties, in-situ stresses and pore pressure, should be constructed. Based on the RMM, hydraulic fracturing and wellbore stability analysis could be done and the stable mud weight windows could be determined.

This paper aims at constructing an RMM for Well Ridgewood 2 which is located at the Walloon Sub Group (WSG), in Surat Basin, Queensland, Australia. The first coal seam gas well was drilled in 1995 in Surat basin in order to investigate the gas content and saturation of the WSG, which is the main coal bearing formation in the Injune Creek Group. During late 2000 full evaluation of coal seam gas content, saturation and production rates in WSG was implemented [Scott *et al.*, 2007]. The WSG has 1000-1200 ft thickness containing a net coal of about 65-120 ft with gas content 0f 1 to 14 m^3 / ft. The Walloon Sub Group is of Middle Jurassic age and is divided into the Juandah Coal Measures, Tangalooma Sandstone and Taroom Coal Measures (Figure 1). There are up to ten named coal seams within the Juandah and Taroom Coal Measures in which the average ply thickness is 1-2 ft to a maximum of 7-10 ft [Scott *et al.*, 2007; Johnson *et al.*, 2010a].

Petrophysical logs, along with the core data, are the most important input data for geomechanical analysis and construction of the RMM. The log data is used to estimate and construct continuous logs of formations mechanical properties, whereas core data is used to calibrate the model. To identify the depth and thickness of coal seams the petrophysical data can be used, since these beds have different physical responses to the electrical logs in comparison to surrounding layers.

The physical response of coal layers is illustrated in Figure 2 and listed in Table 1. Coals normally show low values on Natural Gamma-Ray log. However, since clean sandstones also show a similar response, Gamma log should be used along with other logs in order to identify coal seams. The density of coals is very low, therefore the density log is one of the most important logs in distinguishing coals from other layers. Coals have high porosity values and high sonic transit times. The resistivity of coals is also high, but since tight sandstones and limestones show similar resistivities, this log cannot be used without considering other logs as an indicator of coal seams.

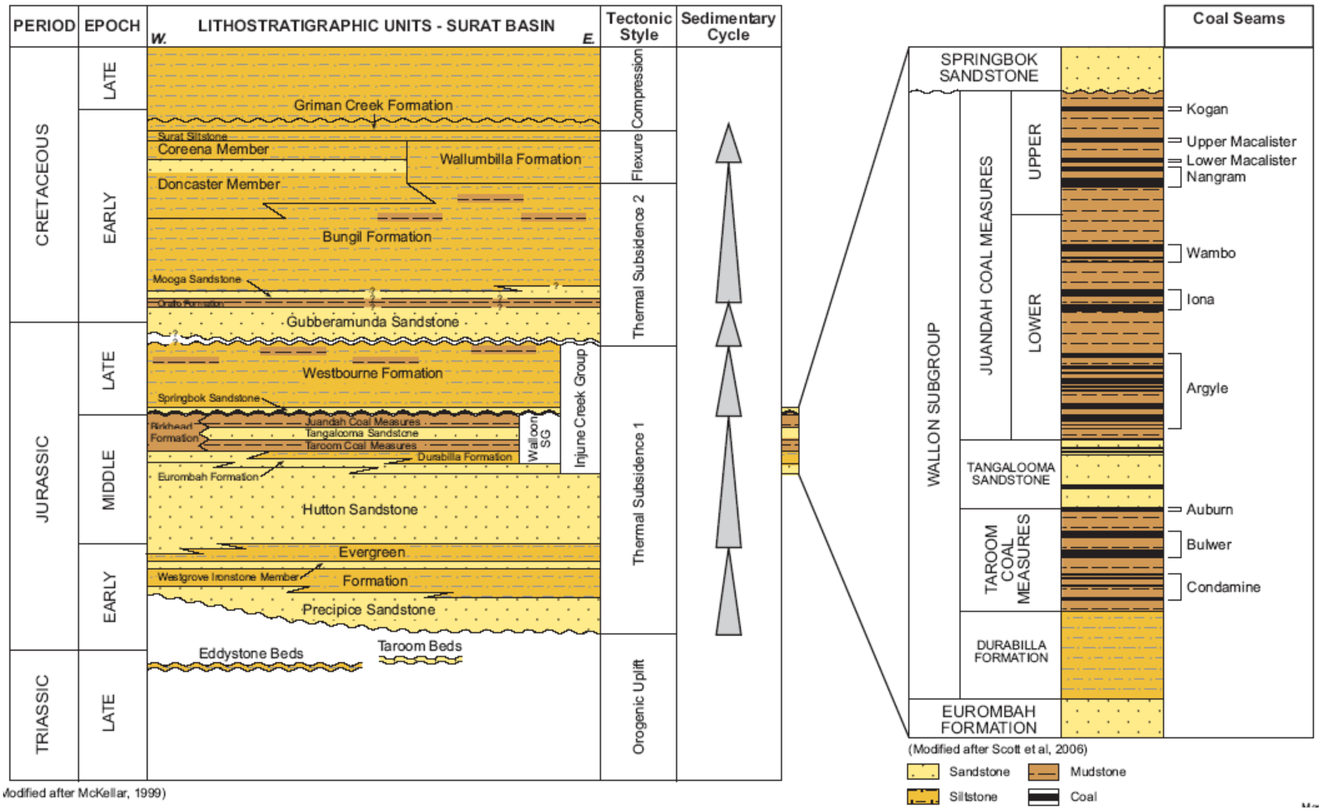

Figure 1: Litho-stratigraphy of Walloon Sub Group [Scott *et al.*, 2004].

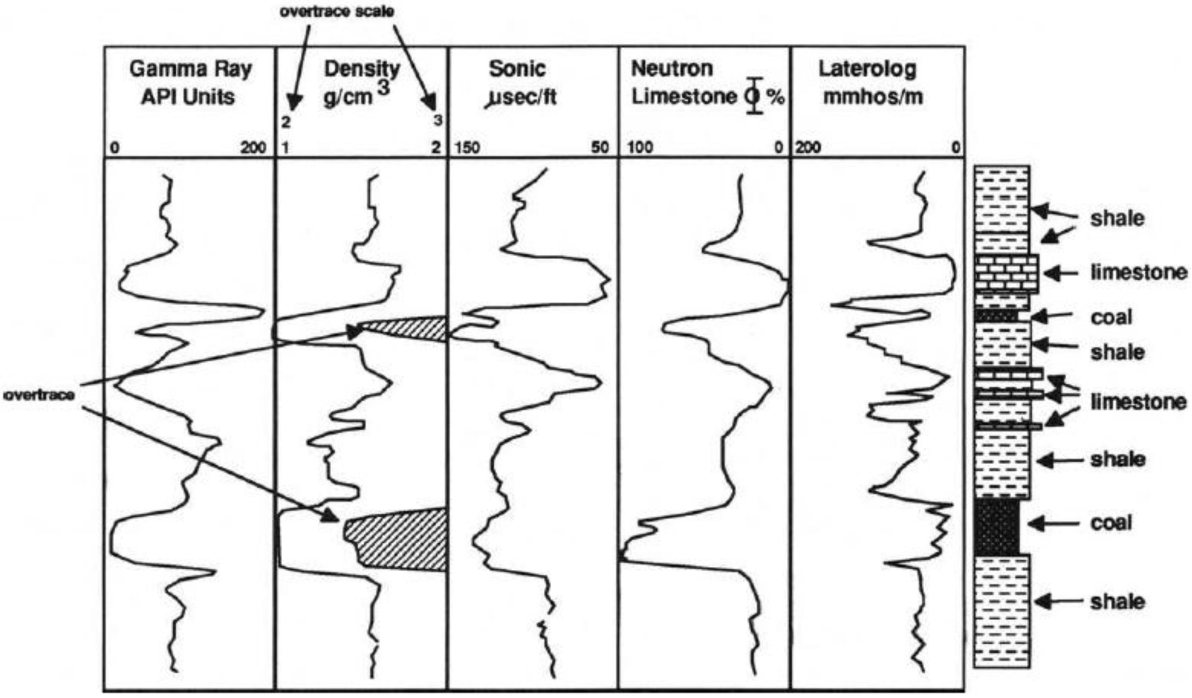

Figure 2: Typical physical responses of coals in comparison to other rock types [Luppens and Wilson, 1992].

Table 1: Logging characteristics of Coals [After Luppens and Wilson, 1992].

Log Type	Units	Response to Coal	Conditions which Invalidate Log or Make Interpretation More Difficult
Gamma Ray	API	Low natural Gamma	• Clean sand adjacent to Coal. • Coal bed containing Uranium-bearing minerals.
Density	g/cm^3	Low density	• Washout. • Caved shale adjacent to coal bed. • Fractured strata surrounding coal.
Neutron Porosity	%	High porosity	• Caving Shale next to coal bed. • Wet clay adjacent to coal bed. • Irregular hole diameter. • Fractured strata surrounding borehole.
Sonic	ft/ms or Interval transit time	Low velocity or High interval transit	• Loose, clean sand next to coal bed. • Irregular hole diameter. • Seam thinner than tool spacing. • Fractured strata surrounding borehole.
Resistivity	$ohm-m$	High resistivity	Highly resistant strata next to coal.

2. Rock Mechanical Model (RMM) Constructed for Well Ridgewood 2

Figure 3 shows the workflow used for construction of a Rock Mechanical Model (RMM). This includes a thorough review of all available data (including seismic, drilling, geology, etc.) and the use of petrophysical logs to extract formations elastic and strength properties as well as in-situ stresses, pore pressure and the direction of the maximum horizontal stress. The estimated logs are calibrated against any available core or downhole test results. For example, rock elastic properties (Young's modulus, *E*) or formation strength (Uniaxial Compressive Strength, *UCS*) can be calibrated with the results of triaxial tests conducted on a core plug or the minimum horizontal stress log could be compared with the results of LOTs performed at specific depths. Rock Mechanical Model was constructed for Well Ridgewood 2. The details of the process are explained in this section and the results are presented.

Well Ridgewood 2 is one of a number of wells drilled in WSG in Surat Basin. The coal appears as thin layers of few metres thickness in Juandah and Taroom Coal Measures, which locate below a depth of 800 m. Figure 4 shows the Gamma Ray and porosity logs as well as generated Shale volume log from this formula [Serra *et al.*, 1980]:

$$V_{Shale} = \frac{(GR_{\log} - GR_{\min})}{(GR_{\max} - GR_{\min})}, \tag{1}$$

Where $GR_{\log}$ is the value of Gamma-Ray log, $GR_{\min}$ is the minimum value of Gamma-Ray log and $GR_{\max}$ is the maximum value on the Gamma-Ray log.

Figure 4 shows that most of the intervals (between 450 and 750 m) are Shale with interbeds of Sandstone and Coal seam. Figure 5 shows the compression (DTCO) sonic log together with the synthetically generated shear log, as no shear log was acquired in this well. We used the Castagna empirical correlations [Castagna *et al.*, 1993] for this purpose and applied correlation for Sand to extract shear sonic values for coal:

$$V_s = 0.8042V_c - 855.9 \quad \text{Sand,} \tag{2}$$

$$V_s = 0.7700V_c - 867.4 \quad \text{Shale.} \tag{3}$$

The velocity is in m/s in above correlations. We used GR and Shale volume logs together with other available logs to discriminate Shale, Sand and Coal interbeds.

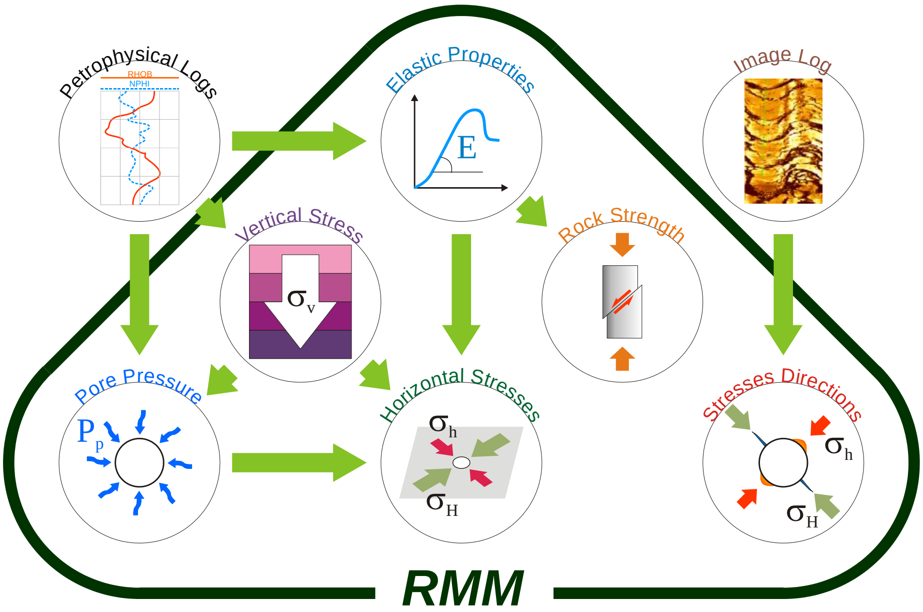

Figure 3: Workflow for construction of a RMM.

Elastic properties:

Dynamic elastic properties of rock including Young's modulus (E_{dyn}), Poisson's ratio (ν_{dyn}), Shear modulus (G_{dyn}) and Bulk modulus (K_{dyn}) can be estimated from shear and compressional sonic velocity through the following equations [Fjaer *et al.*, 2008]:

$$E_{dyn} = \frac{\rho V_s^2 (3V_c^2 - 4V_s^2)}{(V_c^2 - V_s^2)}, \tag{4}$$

$$\nu_{dyn} = \frac{V_c^2 - 2V_s^2}{2(V_c^2 - V_s^2)}, \tag{5}$$

$$G_{dyn} = \rho V_s^2, \tag{6}$$

$$K_{dyn} = \rho(V_c^2 - \frac{4}{3}V_s^2). \tag{7}$$

In above equations ρ is density (g/cm^3), V_c and V_s are compressional and shear sonic velocity (m/s), respectively. This shows the importance of acquiring shear sonic log data in any future planned wells in order to be able to perform a reliable rock mechanics study.

The dynamic properties obtained from above equations need to be changed to static properties. The dynamic elastic modules are higher than those under static load, known as static elastic modules [Fjaer *et al*., 2008]. The static Poisson's ratio was considered to be equal to the dynamic Poisson ratio. Also, the Biot coefficient of the formations was assumed to be 1 here, which is a conservative approached commonly used [Rasouli *et al.*, 2011].

The estimated static and dynamic Young's Modulus as well as Poisson's ratio and Biot factor corresponding to Well Ridgewood 2 are illustrated in Figure 6. The results show a range of static Young's modulus of 5 – 25 GPa within the studied interval with lower limits being corresponding to Coal seams. The Poisson's ratio has an average value of 0.30 for the whole interval with slightly lower values for Coal seams. Also the core test data available [Johnson *et al.*, 2010b] was used to calibrate the constructed Young's modulus log. The results show a good match in general (Figure 6).

Strength properties:

The formation fails as the stresses exceed the rock strength. Based on the Mohr-Coulomb criteria, the rock strength parameter can be defined as uni-axial compressive strength (*UCS*), internal friction angle (ϕ) and tensile strength of the rock (T_0). The Mohr-Coulomb failure criteria in the form of principal stresses expressed as:

$$\sigma_1 = UCS + \sigma_3 \frac{1+\sin\phi}{1-\sin\phi}, \tag{8}$$

where σ_1 and σ_3 are the maximum and minimum stresses, respectively. The strength parameters are generally obtained from core tests in the rock mechanics laboratory. Correlations developed based on lab experiments are used in a specific field to derive the *UCS* log. Several such correlations have been developed in Coal seams [Sharma and Singh, 2008; McNally, 1987]. Here we used correlation below for Sand and Coal intervals [McNally, 1987]:

$$UCS = 1277\exp(-0.0367\ \mathrm{DTCO}), \tag{9}$$

where *UCS* is in MPa and DTCO is in terms of μs/ft.

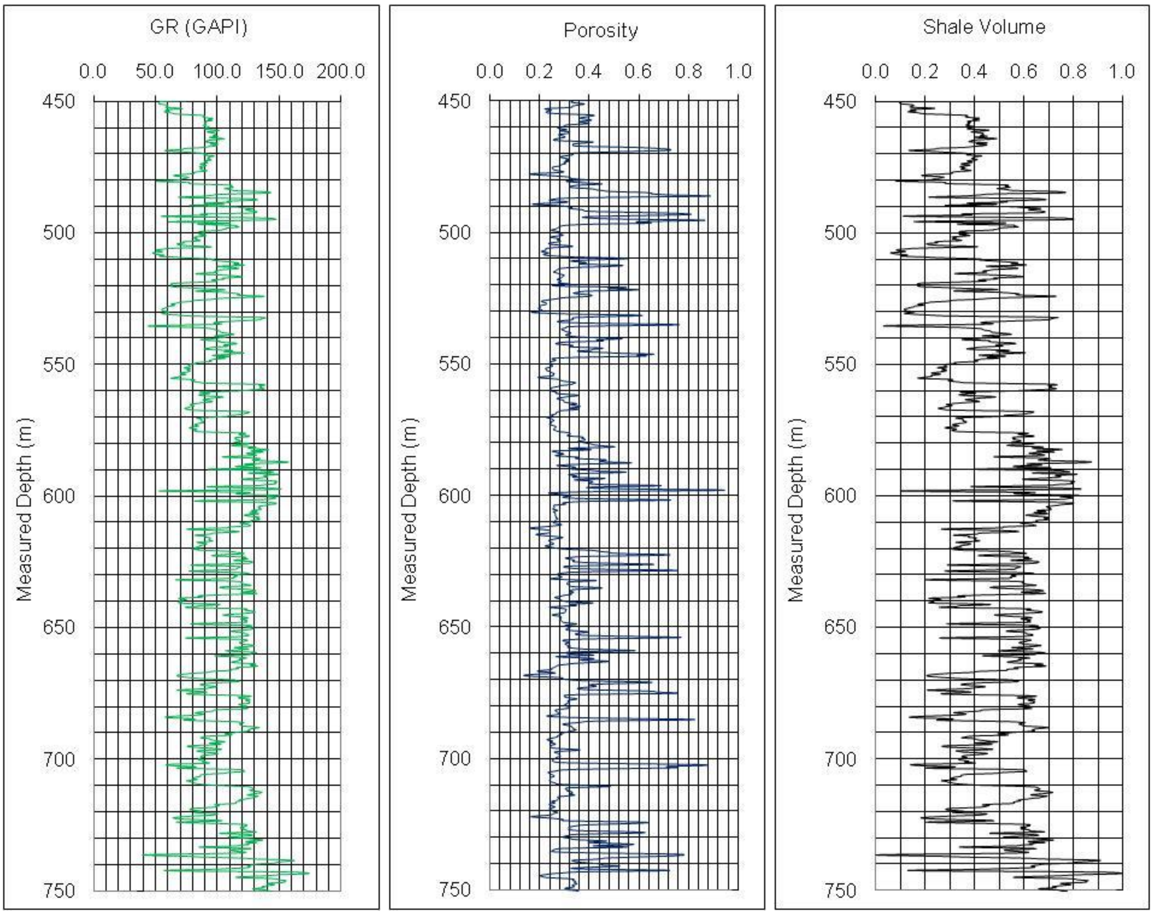

Figure 4: GR, porosity and generated Shale volume logs for Well Ridgewood 2.

For Shale intervals we found a linear correlation developed between *UCS* and static Young's Modulus based on previous experiences to be more appropriate. The modified correlation used for this interval is:

$$UCS = 0.8E_{sta} + 20\,. \tag{10}$$

In above equations *UCS* is in MPa, Young's modulus is in GPa and compression sonic is in μs/ft. The lab UCS results on cores [Johnson *et al.*, 2010b] was used to calibrate the UCS log, which shows a relatively good match as is shown in Figure 7.

Tensile strength of the rock (T_0) is usually estimated as 1/8 to 1/12 of its *UCS*. In this study the tensile strength was estimated to be approximately 1/10 of the *UCS* for Well Ridgewood 2.

The internal friction angle (FANG) values shown in Figure 7 were estimated from Plumb (1994) correlation:

$$\phi = 26.5 - 37.4(1 - Porosity - V_{shale}) + 62.1(1 - Porosity - V_{shale})^2 . \tag{11}$$

The friction angle shows an average value of 25 deg with lager values of up to 40 deg.

The rock strength properties of Well Ridgewood 2, obtained from the procedure explained above, are shown in Figure 7. No rock mechanical laboratory tests were available to calibrate and validate the *UCS*, tensile strength and the internal friction angle profile.

The results show the *UCS* changing between 20 and 55 MPa with the lowest values belonging to Coal seams. The tensile strength follows a similar trend as *UCS* profile.

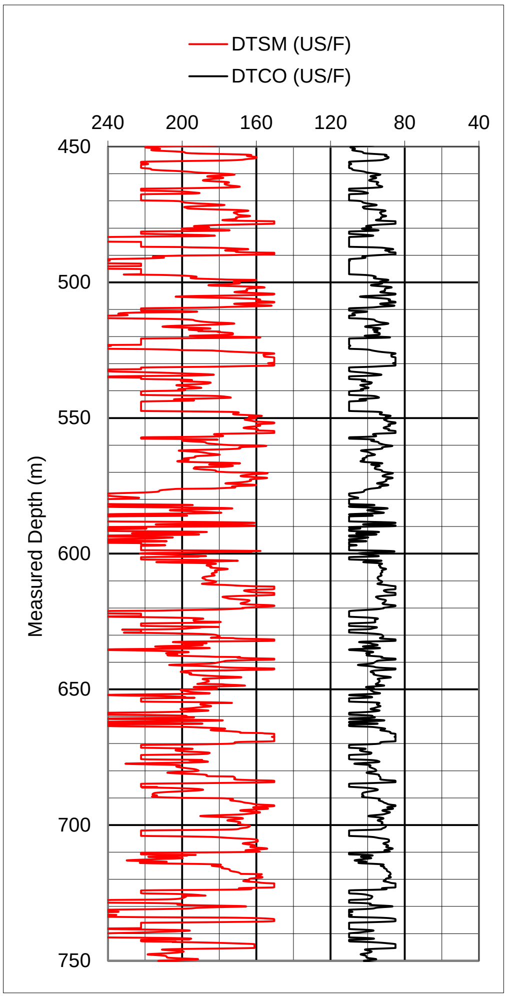

Figure 5: Compression and synthesised shear sonic logs for Well Ridgewood 2.

Vertical stress and pore pressure:

The principal stresses in a field are considered as a vertical stress (σ_v) and two horizontal stresses (σ_h and σ_H). The vertical stress is the result of the weight of the overburden rocks and is directly calculated from the density log as an integration of the density of different formations as [Rasouli *et al.*, 2011]:

$$\sigma_v = \int_{Surface}^{TVD} \rho g dh . \tag{12}$$

The density log can be extrapolated to the surface using the following equation:

$$RHOB_{Extrapolate} = \rho_0 + d \cdot TVD^f, \tag{13}$$

where ρ_0 is the surface density and d and f are constants derived from the density log. Figure 8 shows the extrapolated density log and the overburden stress estimated in Well Ridgewood 2.

The pore pressure is normal in the studied interval and an estimation of it is shown in Figure 8, which was obtained from available data from nearby wells [Johnson *et al.*, 2010a].

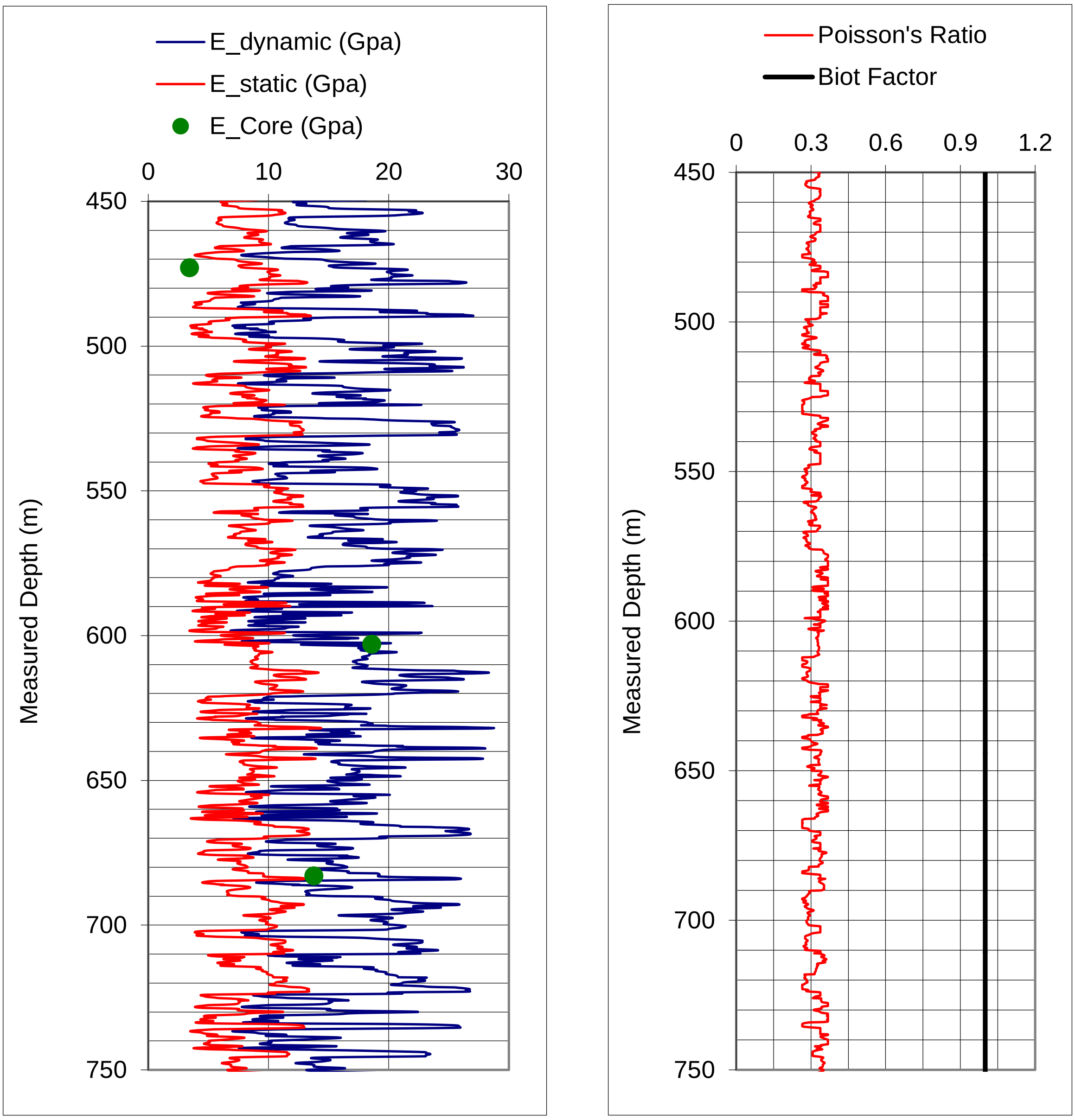

Figure 6: Dynamic and static Young's modulus, Poisson's ratio and Biot factor logs for Well Ridgewood 2.

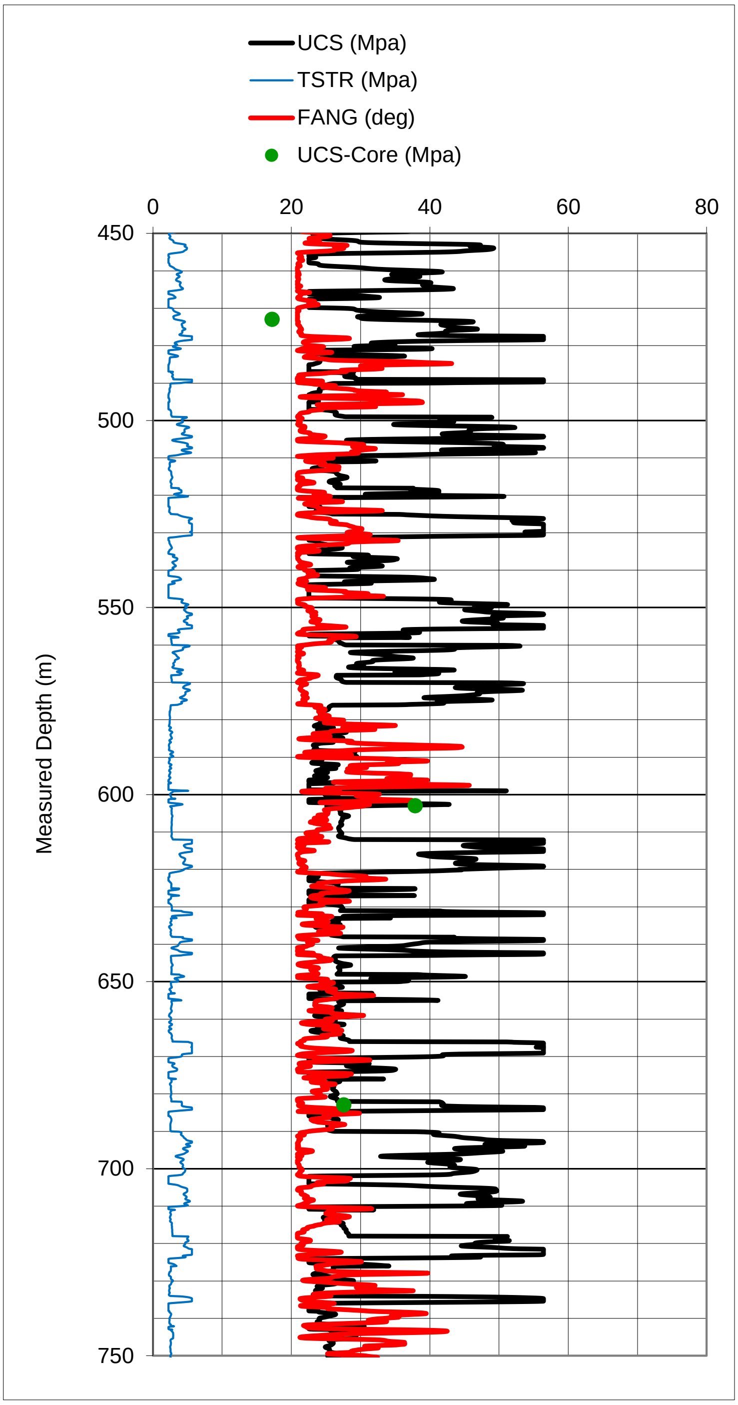

Figure 7: Estimated UCS, tensile strength and friction angle logs for Well Ridgewood 2.

Horizontal Stresses:

The regional principal tectonic directions can be estimated from the regional geology structure of the field and at local scales from the direction of breakouts in a drilled well. Usually faults are directed along the direction of maximum horizontal stress whereas the breakouts (borehole ovalisation) occur along the minimum horizontal stress direction.

In this study the direction of maximum horizontal stress was considered N7.5°E, which was obtained from the existing information from nearby wells [Johnson *et al.*, 2010b]. However, this is unimportant in wellbore stability analysis as the wellbore is vertical.

Poro-elastic formulae were used to extract the magnitude of horizontal stresses as below [Fjaer *et al.*, 2008]:

$$\sigma_h = \frac{\nu}{(1-\nu)} \cdot (\sigma_v - \alpha \cdot P_p) + \alpha \cdot P_p + \frac{E_{sta}}{(1-\nu^2)} \cdot (\varepsilon_x + \nu \cdot \varepsilon_y)\,, \tag{14}$$

$$\sigma_H = \frac{\nu}{(1-\nu)} \cdot (\sigma_v - \alpha \cdot P_p) + \alpha \cdot P_p + \frac{E_{sta}}{(1-\nu^2)} \cdot (\varepsilon_y + \nu \cdot \varepsilon_x)\,, \tag{15}$$

where ε_x and ε_y account for the horizontal stress anisotropy.

The horizontal stresses estimated for Well Ridgewood 2 using equations 14 and 15 are plotted in Figure 9. The closure pressure values measured in Ridgewood 5 and 6 were used to calibrate the minimum horizontal stress (Sigh) log in Sand, Shale and Coal layers [Johnson *et al*., 2010a]. It is seen that in general a strike-slip stress regime is dominant in this field as the order of stress magnitudes is SigH>SigV>Sigh.

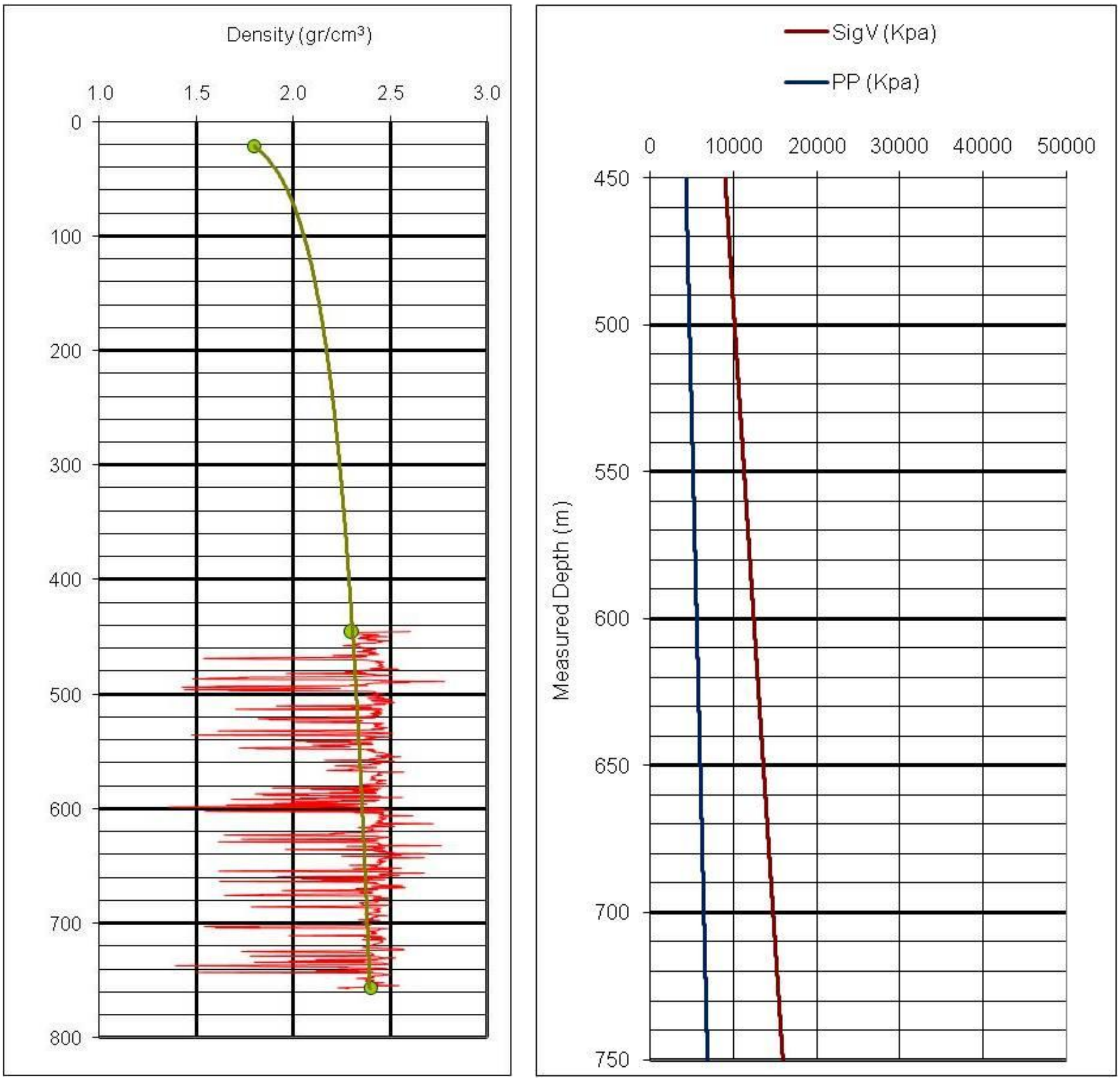

Figure 8: Estimated vertical stress and pore pressure for Well Ridgewood 2.

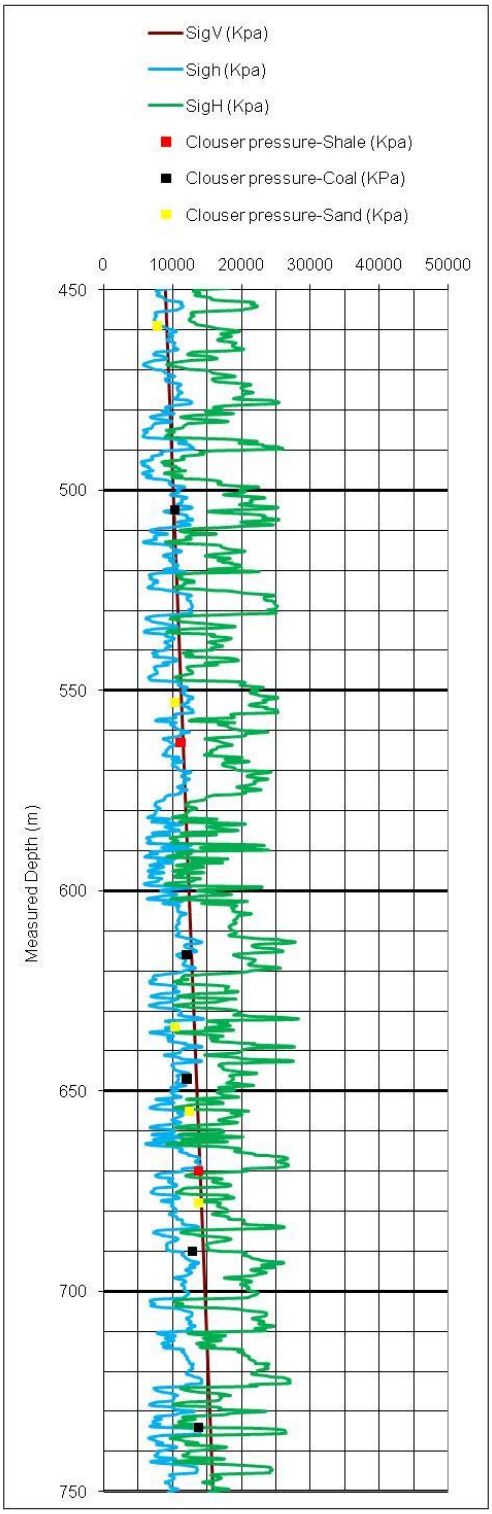

Figure 9: Estimated horizontal stresses for Well Ridgewood 2.

3. Mud weight windows determination

The stable mud weight windows concept is shown schematically in Figure 10 where it is seen how reduction of mud weight below the optimum mud weight windows could result in wellbore breakout and kick. On the other hand increasing the mud weight above the minimum stress gradient and fracture gradient will result in mud loss and fracturing of the formation, respectively.

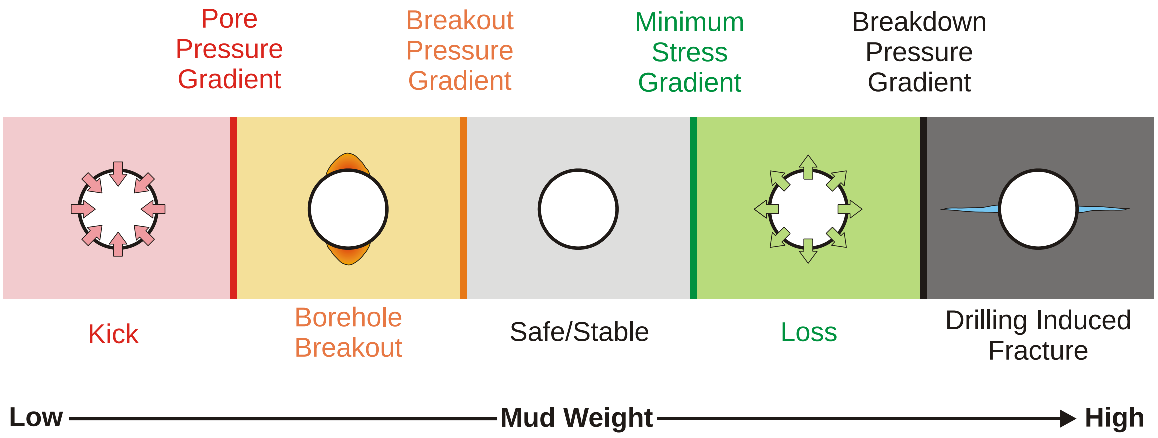

Figure 10: Stable mud weight windows for drilling.

Figure 11 shows the stable mud weight windows for Well Ridgewood 2. In this figure the mud weight associated with kicks, breakouts, losses and drilling induced fractures are plotted along the wellbore trajectory. A mud weight of 1.12 SG was used to drill this well and this is shown in the figure. It is seen that at number of depths this mud weight is lower than that of the breakout mud weight meaning that the wellbore is prone to instability. The caliper data plotted in the right track of Figure 11 used to calibrate the model and in overall, shows a close agreement with the predicted model. No image log was available to identify the potential for any induced fractures.

4. Conclusions

The rock mechanical model provides useful information during the life of a field for various design purposes. The RMM constructed for Well Ridgewood 2 indicated that mechanical properties, including Young's modulus and rock strength reduces across coal seam comparing to sandstone and shale formations. The horizontal stress anisotropy was found responsible for borehole enlargement at different intervals, in particular in lower depths. The lack of image logs made it difficult to calibrate the model but in overall the predicted model was in a good agreement with caliper data.

Acknowledgement: The Authors would like to acknowledge the Department of Employment, Economic Development and Innovation of Queensland for making available the log data used for this study.

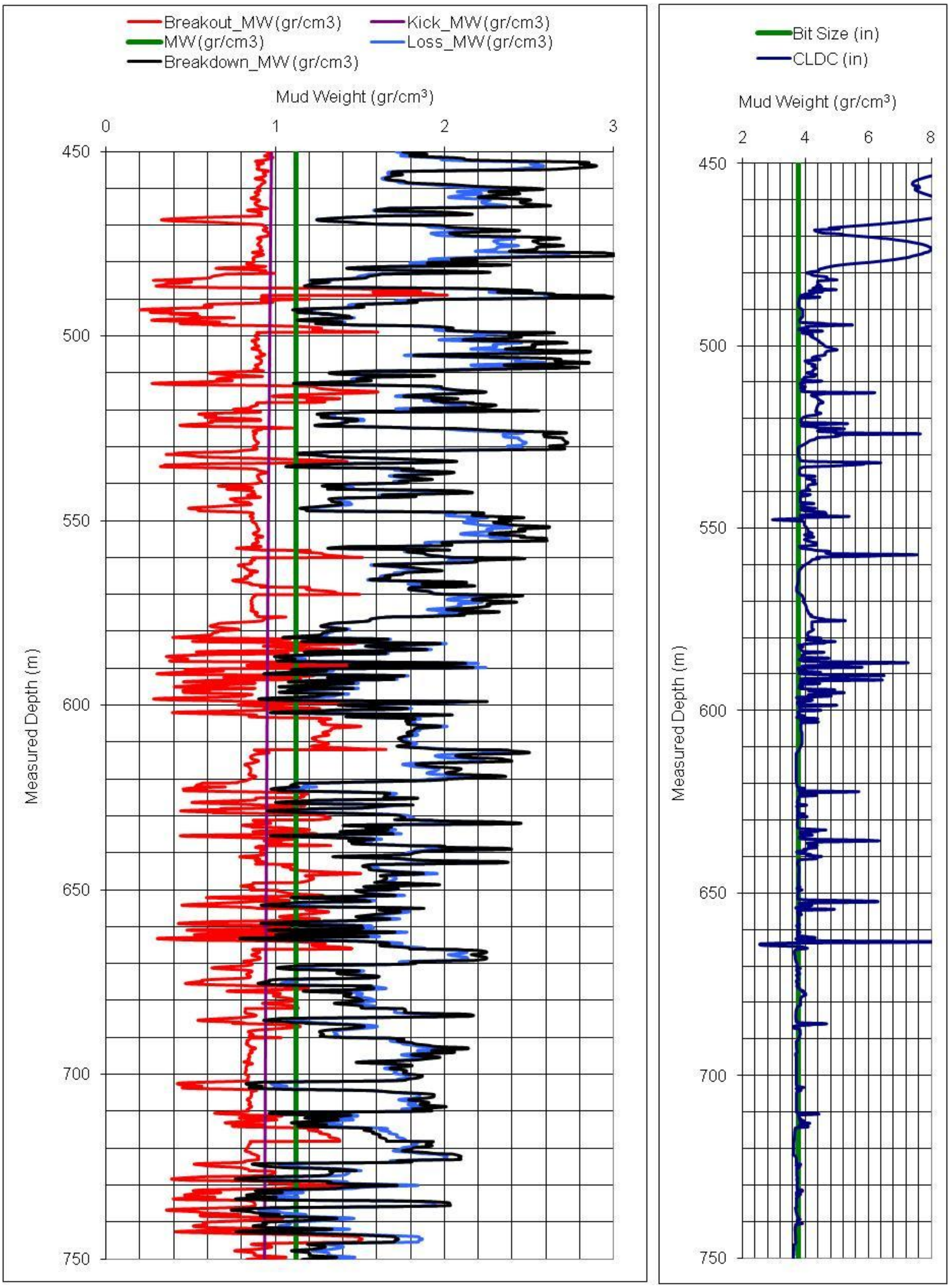

Figure 11: Mud weight windows for Well Ridgewood 2.

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