Empirical and Numerical Geomechanical Approaches to Unconventional Resources*

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Abstract

A geomechanical model is a fundamental requirement for considering any unconventional related geomechanical application such as fracture permeability, hydraulic fracture placement or wellbore stability. These models are the cumulative understanding of the distribution of physical rock properties, pore pressure and stress magnitudes. Each of these three elements is interdependent and a change in any one affects the other two. Therefore, robust assessment is required across multiple disciplines to ensure a valid predictive model. Geomechanical models can be 1D, 3D or 4D representations and can be derived from empirical observations or calculated numerically. The available dataset or project objectives can affect the approach taken to assemble a geomechanical model and substitutions can be made utilising data sources with differing resolutions such as seismic data for log data. In some cases, a combination of empirical and numerical elements may be appropriate. This presentation summarises a range of workflows that can be implemented to create a geomechanical model based on typical unconventional datasets and objectives. An unconventional borehole-centric dataset is used to demonstrate these concepts in conjunction with 1D numerical models to illustrate the impact of high and low lateral stresses on stress distribution within a stratigraphy characterised by varying rock properties. An empirical 1D geomechanical model is presented for Cow Lagoon-1 located within the McArthur Basin, Northern Territory, Australia, which was drilled by Armour Energy in 2012 to assess the unconventional prospectivity of the Batten Trough. This model is used in conjunction with image log data to determine fracture orientations and formation properties conducive to permeable fracture networks. Contemporary stress magnitudes vary considerably ranging between strike-slip and extension between formations with differing elastic properties. Fracture density and permeability also varies between formations and is related to the geomechanical model. Target horizons in the Batten Trough are characterised by low Young's Modulus, low differential and low effective stresses.

Introduction

A geomechanical model is a fundamental requirement for considering any unconventional related geomechanical application such as fracture permeability, hydraulic fracture placement or wellbore stability. These models are the cumulative understanding of the distribution of physical rock properties, pore pressure and stress magnitudes. Each of these three elements is interdependent and a change in any one affects the other two.

The stress distribution within a formation is intrinsically linked to its elastic properties and the poroelastic equations, which take into account estimates for tectonic strain, demonstrate this relationship (Blanton and Olson, 1999). In a high strain environment, such as the Australian continent, lateral stresses are partitioned within high Young's Modulus units relative to low Young's Modulus units. Conversely, in a low strain environment, stress distribution is governed by Poisson's Ratio and stresses are preferentially distributed within high Poisson's Ratio units. Depending on the regional tectonic context, an identical stratigraphic section would have an inverted stress distribution dependent upon the applied strain. Additionally, considerable variation in mechanical stratigraphy can result in contrasting stress magnitudes and stress regimes in adjacent formations. The implications of this for unconventional assets are far reaching ranging from variability in suitability for stimulation operations to designing optimal wellbore trajectories to intersect permeable fracture sets.

Brittleness index (BI) is a commonly used property when assessing unconventional resources and is generally defined as a measure of the ease by which the rock can be fractured based on its organic content i.e. less organic content implies a more brittle material and therefore greater ability to be fractured. In this manner, it has been used as an indicator of suitability for hydraulic stimulation and a tool to map permeability "sweetspots". There exist multiple ways to define brittleness index and most commonly include a term for compressive (σ_C) and tensile (σ_T) strength (Altindag, 2003). These algorithms are indicative of the "shape" or slope of a failure envelope and are related to rock strength, rather than the preference for brittle deformation. More importantly, this measurement remains independent of the stress distribution and therefore not necessarily a clear indicator of fracture likelihood.

A Mohr-Coulomb diagram is a visual representation of a stress (Mohr circle) and strength (failure envelope) scenario. It is the relationship between the Mohr Circle and the failure envelope that describes brittle failure occurrence, the orientation of failure and the mode of failure (tensile, shear or mixed-mode). The likelihood of failure/fracturing can be the same independent of the Brittleness Index if the stress distribution is appropriate (Figure 1). Used in isolation independent of the stress conditions, brittleness itself is unreliable. Improved criteria can be derived from evaluating the relationship between strength and stress, which is more indicative of failure and therefore more closely related to natural permeability and improved production. Furthermore, an independent means of estimating organic content should be used to consider the likelihood of brittle or ductile deformation.

Geomechanical Models

Geomechanical models can be 1D, 3D or 4D representations and can be derived from empirical observations or calculated numerically. In addition, the available dataset and project objectives can affect the approach taken to assemble a geomechanical model. In some cases, a combination of empirical and numerical elements may be appropriate. This presentation summarises a range of workflows that can be implemented to create a geomechanical model based on typical unconventional datasets and objectives.

1D geomechanical models are commonly borehole-centric creations based on empirical data. Where additional offset data are available, a wireline based rock physics model can be used to generate compressional and shear velocities where none exist. Similarly, input properties could also be generated from seismic for model construction. Once offset 1D mechanical earth models have been constructed, spatial interpolation for predictive geomechanical assessment can be performed using a range of methods that fall within three categories; non-geostatistical methods, geostatistical methods and combined methods (Li and Heap, 2008). Seismic data can be used to guide interpolation of wireline data or, through inversion for density, shear and compressional velocities, form the basis for calculating stress magnitudes to create a 3D geomechanical model. Static property models derived through these methods can be used to construct property models for dynamic modelling of stresses and fluid pressures using numerical methods, which can be projected through time. In all cases, stress, strength and elastic property based criteria can be applied to these models to identify permeability sweetspots.

Case Study

An unconventional borehole-centric dataset is used to demonstrate the use of multiple criteria to identify permeability zones. Figure 2 illustrates an empirical 1D geomechanical model for Cow Lagoon-1 located within the McArthur Basin, Northern Territory, Australia, which was drilled by Armour Energy in 2012 to assess the unconventional prospectivity of the Batten Trough. Contemporary horizontal stress magnitudes vary considerably with depth and stress regimes range between strike-slip and extension within formations with differing elastic properties. This distribution of stress demonstrates the poroelastic effect expected in a high strain environment with low Youngs Modulus units correlating with low differential stress and high differential stress associated with high Youngs Modulus units. Stress, strength and elastic properties were analysed to identify relationships that correlate with natural fractures and documented hydrocarbon shows (Figure 3). Target horizons in the Batten Trough are characterised by low Young's Modulus, low differential and low effective stresses and correspond with the following criteria: differential stress between 5 and 13.5 MPa, Youngs Modulus between 25 and 74 GPa and strength ratio (So/T) less than 3 (Figure 4). These criteria can be applied to a 3D mechanical earth model to map locations with matching characteristics that includes a greater potential for production based on the presence of permeable natural fracture populations with stress and strength conditions conducive to stimulation.

Conclusions

A mechanical earth model is a fundamental tool for considering the relationships between stress, strength and elastic properties of unconventional resources. Methods that focus on a single parameter such as Brittleness Index ignore these relationships and may not necessarily yield useful results. There exist many different methods to create empirical and numerical mechanical earth models, however, empirical well-centric analyses are key to constraining interrelated criteria that can be used to map permeability sweetspots across 3D and 4D models.

Acknowledgements

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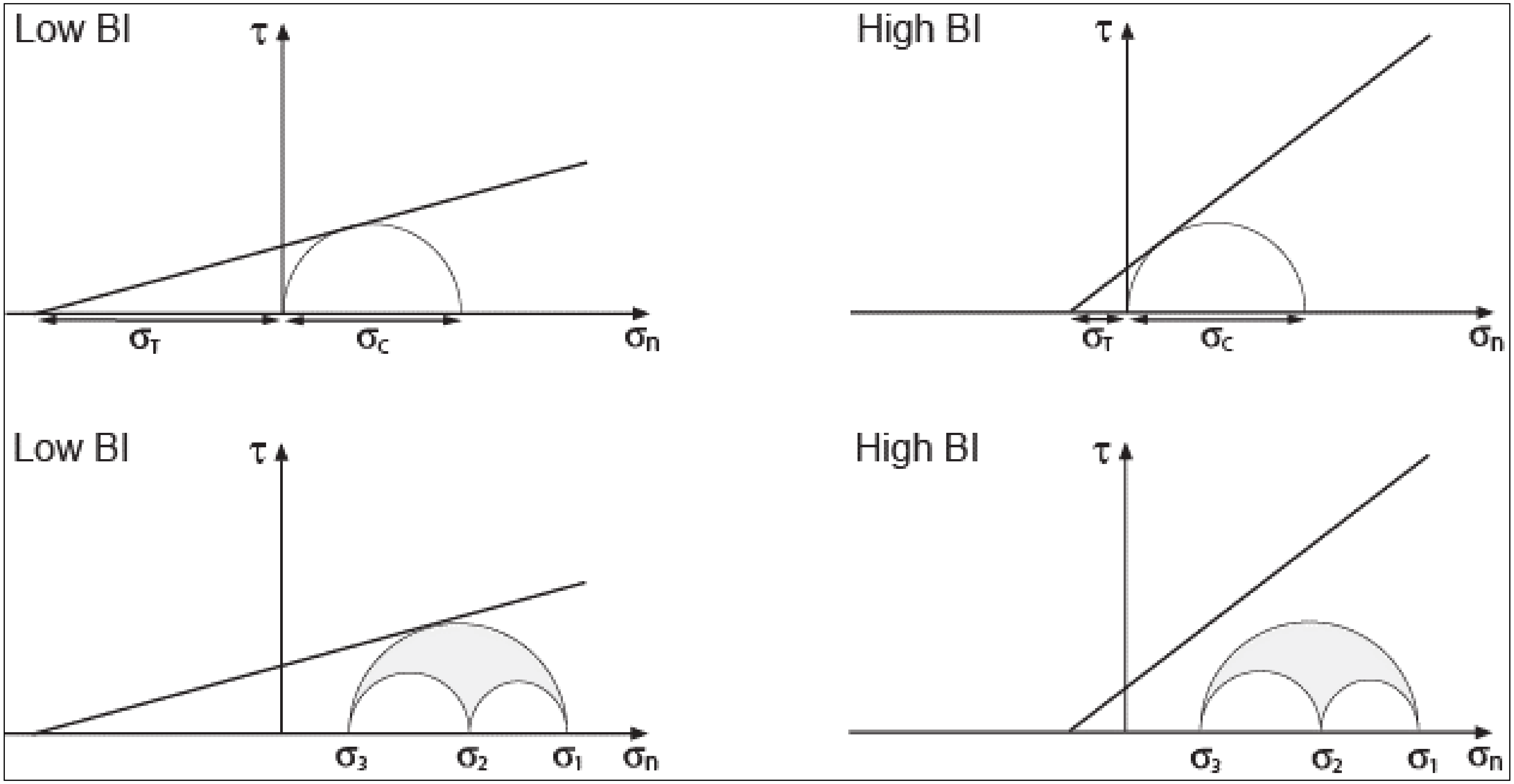

Figure 1. Mohr circle representation of low (a) and high (b) brittleness index (BI) assuming Coulomb failure criterion and BI = σ_T/σ_C where σ_T is the tensile strength and σ_C is the uniaxial compressive strength. Also shown are stress scenarios where (c) brittle failure would initiate with low BI and (d) failure is not associated with high BI.

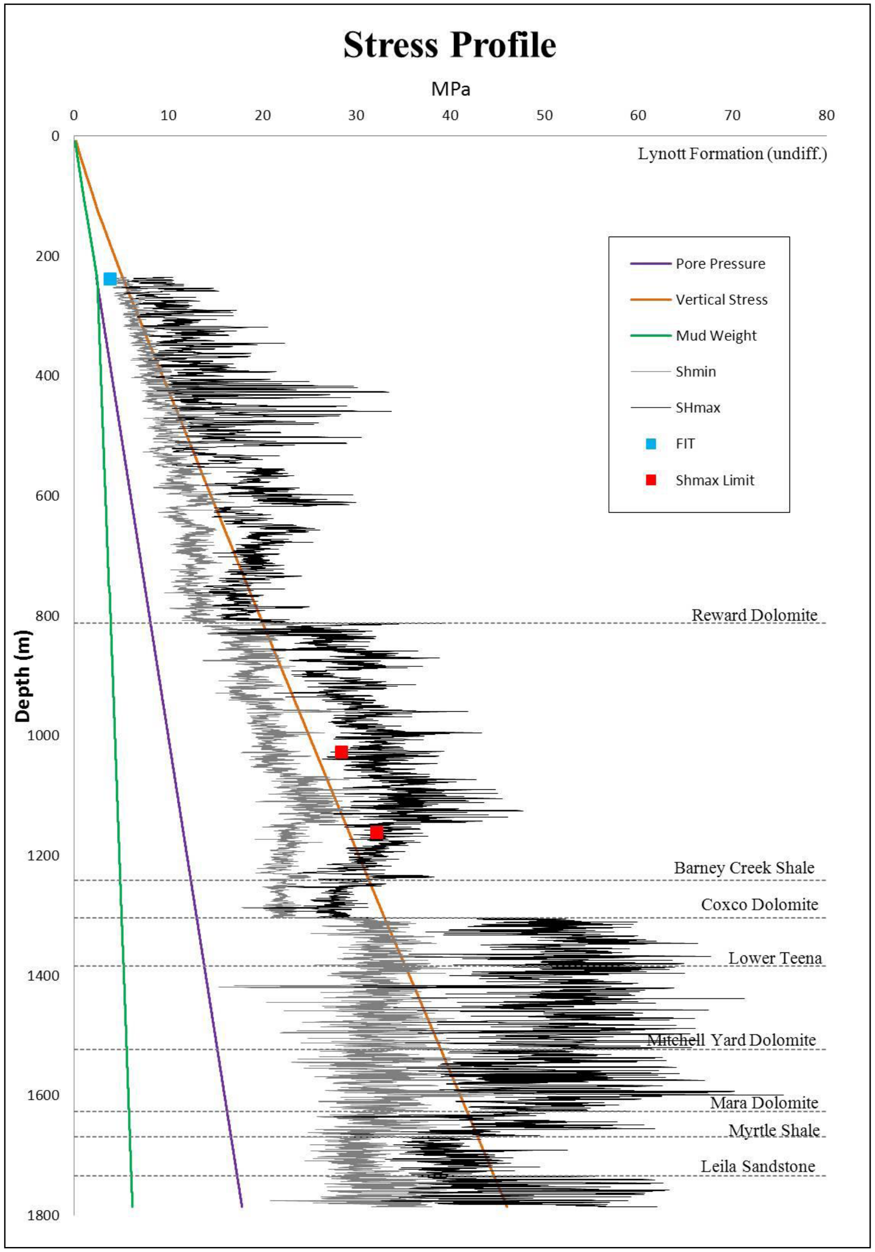

Figure 2. Stress profile at Cow Lagoon-1 showing a predominantly strike-slip regime with intervals of extension such as the Barney Creek Shale.

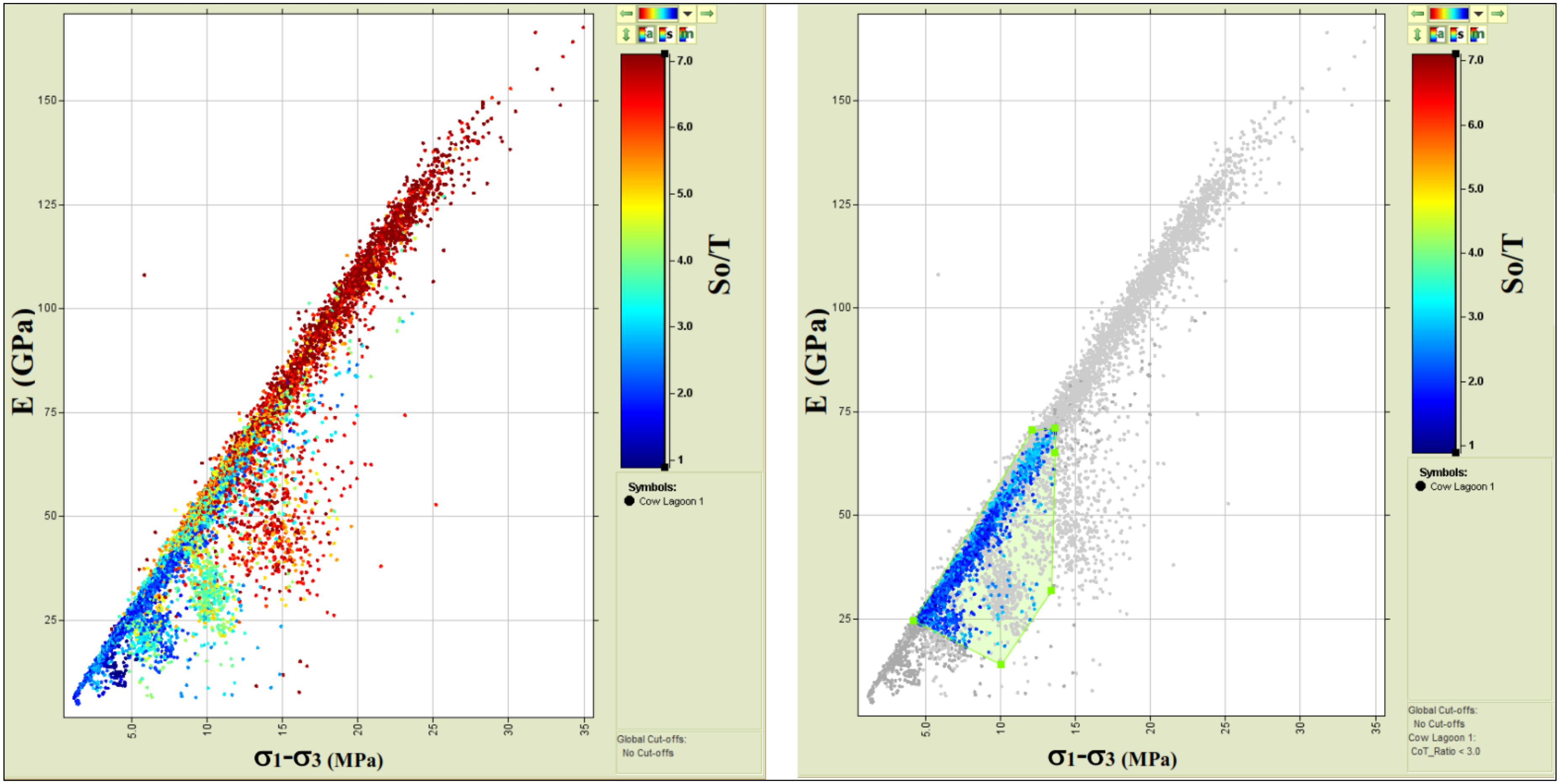

Figure 3. Cross-plots of differential stress (σ_1-σ_3) versus Youngs Modulus (E), coloured with respect to strength ratio (So/T) for (a) the complete data interval and (b) data that meets the criteria that match natural fracture occurrence and hydrocarbon shows (see text).

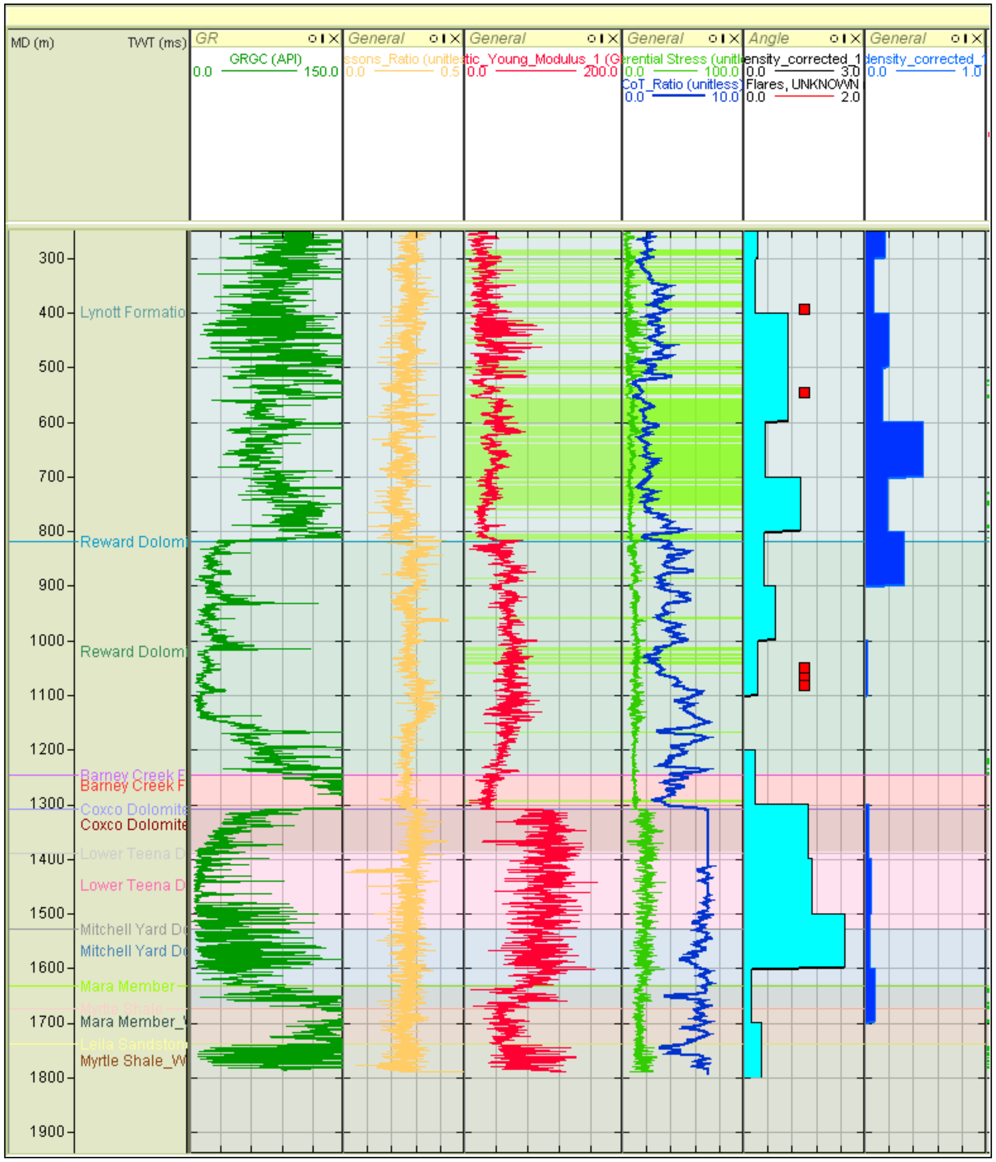

Figure 4. Depth intervals (in green) that correspond with data that matches elastic property, stress and strength criteria illustrated in Figure 3 cross plots. Note that intervals corresponding with natural fracturing and hydrocarbon shows (red squares) observed in the Lynott Formation and Reward Dolomite and do not correspond with drilling related fracturing within the Coxco, Teena and Mitchel Yard Dolomites.