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A 3D GEOMECHANICAL MODEL OF BLUE BUTTES FIELD IN WILLISTON BASIN, NORTH DAKOTA

by

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Bachelor of Science in Petroleum Engineering, Jawaharlal Nehru
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Submitted to the Graduate Faculty

of the

University of North Dakota

In partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota
August
2018

This thesis, submitted by Rehan Ali Mohammed in partial fulfillment of the requirements for the Degree of Master of Science in Petroleum Engineering from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

Dr. Mehdi Ostadhassan

Hui Pu

Dr. Hui Pu

Dr. Vamegh Rasouli

This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Dr. Grant Mc Gimpsey
Dean of the School of Graduate Studies

Date July 24, 2018

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Title	3D GEOMECHANICAL MODEL OF BLUE BUTES FIELD, WILLISTON BASIN NORTH DAKOTA
Department	Petroleum Engineering
Degree	Master of Science

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Rehan Ali Mohammed

July 2, 2018

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Rehan Ali Mohammed

To my mom **Nuhi Fatima** and my dad **Mohammed Ali**

ABSTRACT

Minimizing the costs and risks of drilling and achieving a maximum production rate are technically and economically challenging, this becomes more crucial when drilling in tight shale formations, an in-depth investigation of geomechanical behavior of the reservoir, including elastic properties, and the in-situ stresses also known as Mechanical Earth Model (MEM) is inevitable, which is studied by concept of Mechanical Earth Model (MEM). In this thesis, the concept of the MEM is used to determine rock strength and elastic properties of the wells in the Blue Buttes Field, Williston Basin, North Dakota. Blue Buttes is one of the major oil producing fields from the Bakken Formation.

For this study, a 3-D MEM is constructed for the field. The input data includes wireline logs, core, drilling reports and, geological properties of the field. For the study, analysis was done on state of In-situ stresses, formation properties, and type of instabilities that occur around the trajectory of the wellbore specifically in the Bakken Shale Formation by acquiring anisotropic poro-elastic relationships to incorporate pore pressure and stresses in the field more accurately. In the next step, safe mud weight window was determined the to avoid shear and tensile failure during drilling, and mitigating other wellbore instabilities issues by controlling the sub surface parameters and considering chemical properties of the shales and mud activities. The constructed MEM model revealed how changes in pore pressure, stresses, and the overall properties physiochemical of the shale can hugely impact the drilling process and production from the field. which will minimize the unplanned well maintenance cost. Further it is helpful in studies such as drilling in the deviated holes, hydraulic fracturing, sanding analysis and perforation stability analysis.

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CHAPTER I

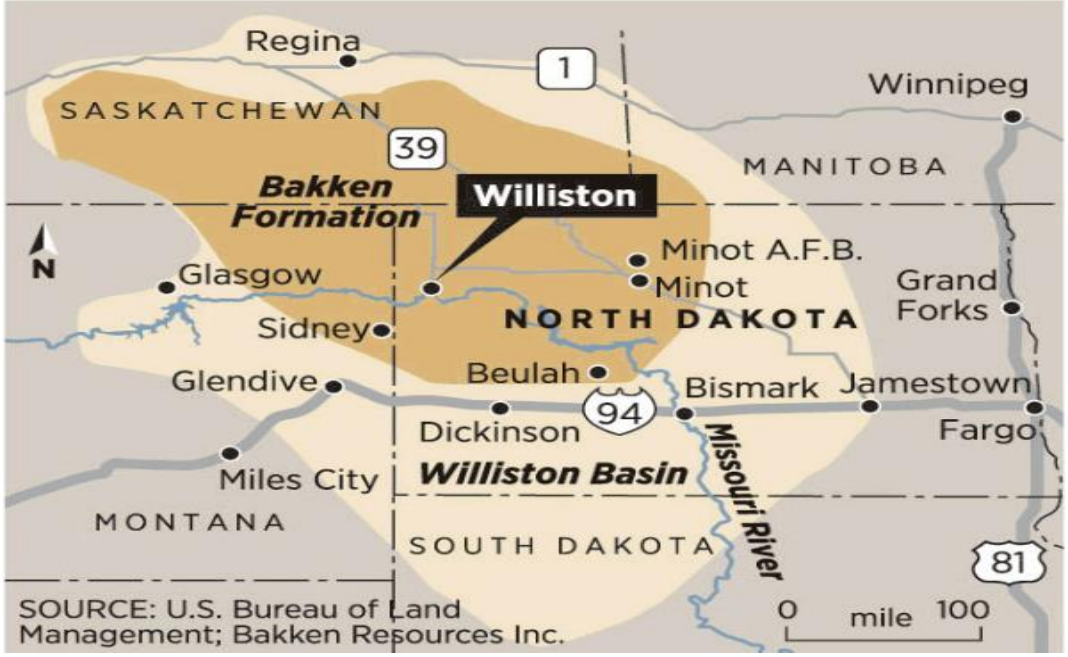
INTRODUCTION

Recent advancements in hydraulic fracturing and horizontal drilling enabled production from the low porosity, low permeability bakken reservoir. For this study, bakken formation in Blue buttes field, North Dakota is used which will give in depth insights geomechanical behavior of the formation. The aim of this study is to add to a pool of information on the bakken formation in geomechanical aspects by creating a field scale 3d-Geomechanical model. Major focus of this study will be middle bakken layer which has been the attention of many geologists and reservoir engineers. Knowing these properties is important as they are used in the beginning of the oilfield development for reservoir simulation and geomodelling purposes. Well log based modeling is the efficient way of getting different reservoir properties in the absence of actual core measurements, and it is considered more cost effective to acquire the data compared with conventional core measurements. The work started with well logs gathering from the designated field. The reservoir properties to identify were: porosity, permeability, effective permeability, water saturation, shale volume, lithology, and mineralogy. Various methods and approaches were used to acquire those properties. The next step is constructing 1D mechanical earth model (MEM), which is a numerical representation of the state of stress and rock mechanical properties for a specific stratigraphic section in a field or basin [2]. Developed after the drilling operations. The results from MEM can be linked with core data to provide localized stress conditions and predictive breakdown and breakout pressures.

Most importantly, the MEM can predict the Mud Weight Window (MWW) applicable to the well, minimizing the risk of kick and breakouts. Many drilling problems relating to wellbore stability or pore pressure can often be avoided if proper investigations and understanding of local geomechanics is undertaken. The practice of wellbore stability was developed throughout the 1980s, where geophysical logs were becoming the basis of well bore stability models. Results from 1D MEM will be used as an input to construct 3D MEM by populating the log properties over the geologic model of the field.

General Geology of Bakken Formation

The Mississippian Devonian Bakken including Three forks is largest and continuous oil accumulation in the United States that is located in the Williston basin spread across North Dakota and Montana in the United States and extends to Saskatchewan in Canada. Williston basin is highly intracratonic sedimentary basin. Recent advancements in multi-lateral drilling and multi stage hydraulic fracturing had led to North Dakota being the second most producing state in U.S. The bakken formation is subdivided into upper, lower and the middle member which is overlain by lodgepole formation, and nisku formation underlies three forks. Upper and lower bakken are potential source rocks abundant in organic black shales while middle bakken is the reservoir rock, which contains dolostone sandstone and limestone deposits. Middle bakken is highly heterogeneous with significantly varying lithology which is sandwiched between the shale formations. Oil generated in upper and lower bakken migrated to middle member [1]. Middle member is the major source of hydrocarbon recovery with ultra-low porosity and permeability ranging from 5-8% and 0.1 to 0.2 MD. The upper and lower bakken have similar lithology throughout the basin. Three forks is the shaly dolomitic layer which is proven to have abundant resources and possibly the future focus of drilling activity. The total estimated OIP in the range of 160 -900 BBL of oil. Due to declining productivity rates, bakken is currently the center of research for enhanced oil recovery. A study done by Sonnenberg say that. Center of basin middle Bakken consists of highly argillaceous, greenish-gray, highly fossiliferous and pyritic siltstones [2], Pitman et al. 2001 state that Bakken is over pressured formation due to Hydrocarbon generation which initiates fractures [3]. The depth of Bakken formation ranges from 140-170 ft. The maximum thickness of the middle member in North Dakota east of nelson anticline is 160 ft. [3]. In the deeper part of the basin, the shale contains calcite, dolomite and organic matter rich in kerogen.



SOURCE: U.S. Bureau of Land Management; Bakken Resources Inc.

Fig (1). Geophysical map of Williston Basin.

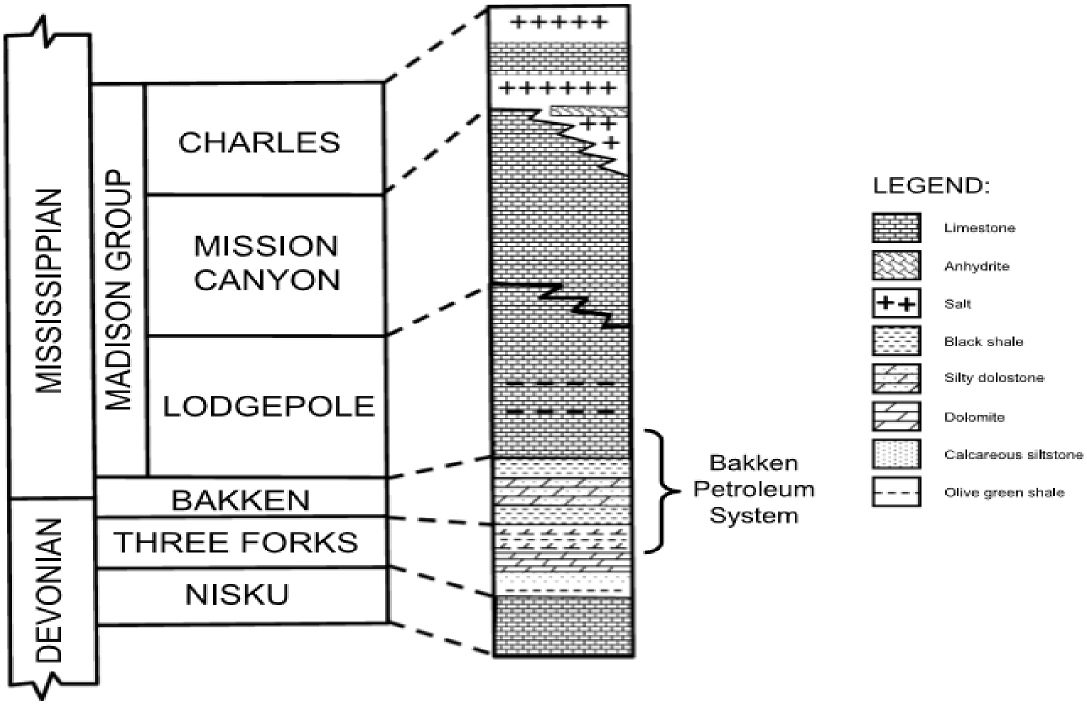


Fig (2). Stratigraphic Chart of Williston Basin showing the Bakken formation.

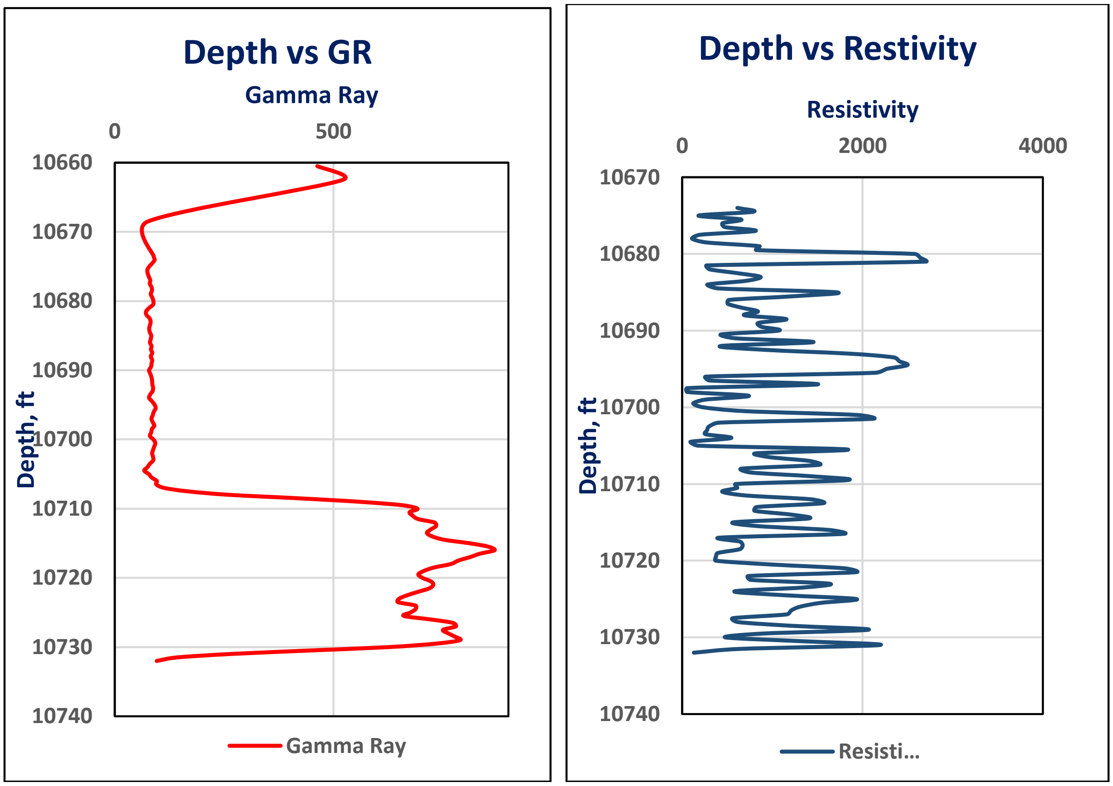


Fig (2). Gamma Ray and resistivity log of Bakken formation of middle Bakken member.

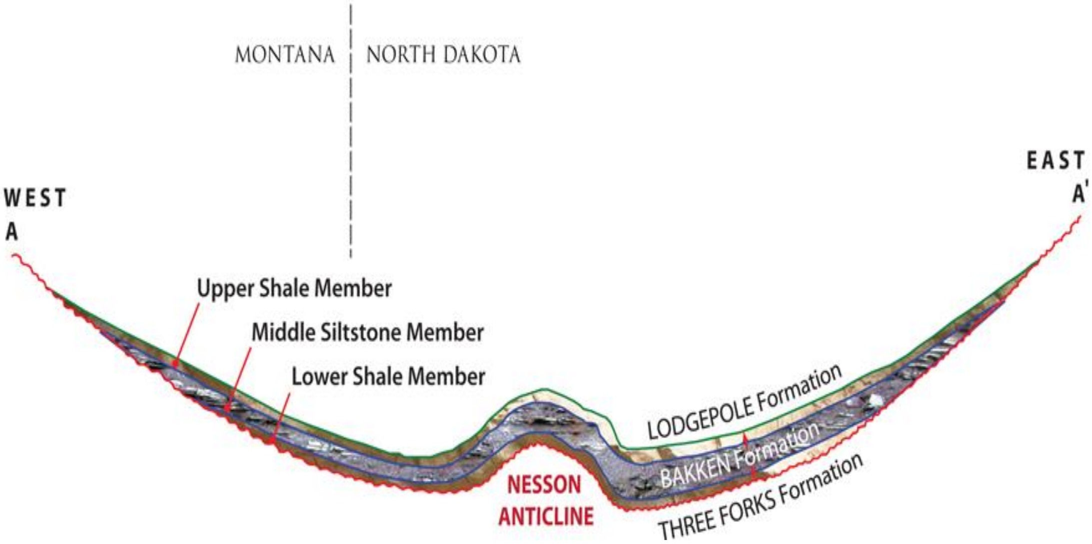


Fig (4). Depositional environment of Bakken formation in Williston basin, Montana & North Dakota [EERC].

Blue Buttes Field area

Blue Buttes is among major producing fields in North Dakota. The geographic location of blue buttes field is in McKenzie county in Williston basin, North Dakota. Blue buttes is one of the major producing fields with high drilling activity. All the wells for this study are from McKenzie County. For this study 22 wells of blue buttes field were studied, of all the wells used 19 are vertical and 2 are horizontal wells. The well data was acquired from North Dakota Industrial Commission Website (NDIC). The 1D & 3D Geomechanical model is constructed using Baker Hughes Jewel suit Geomechanics Software. Fig () Map of Blue Buttes Field on GIS Map Server.

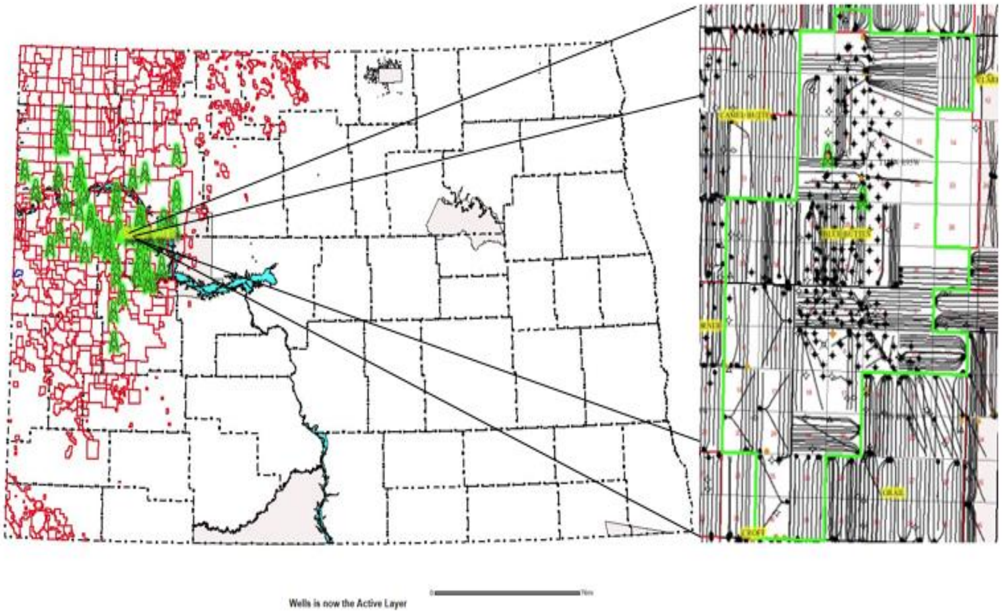


Fig (5). Blue Buttes Field on GIS Map of North Dakota (NDIC).

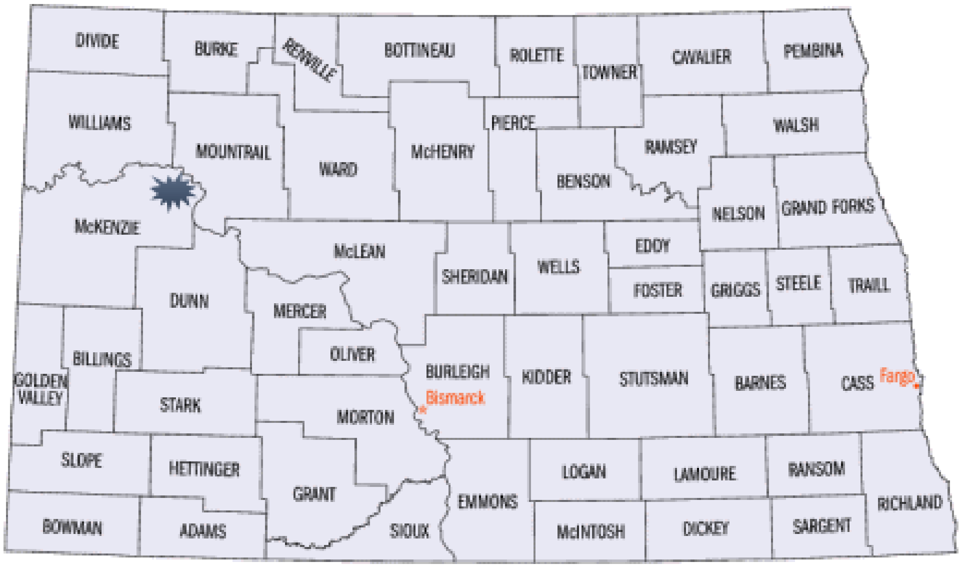


Fig (6). Map showing the location of blue buttes field in Mc Kenzie County, on county map of North Dakota

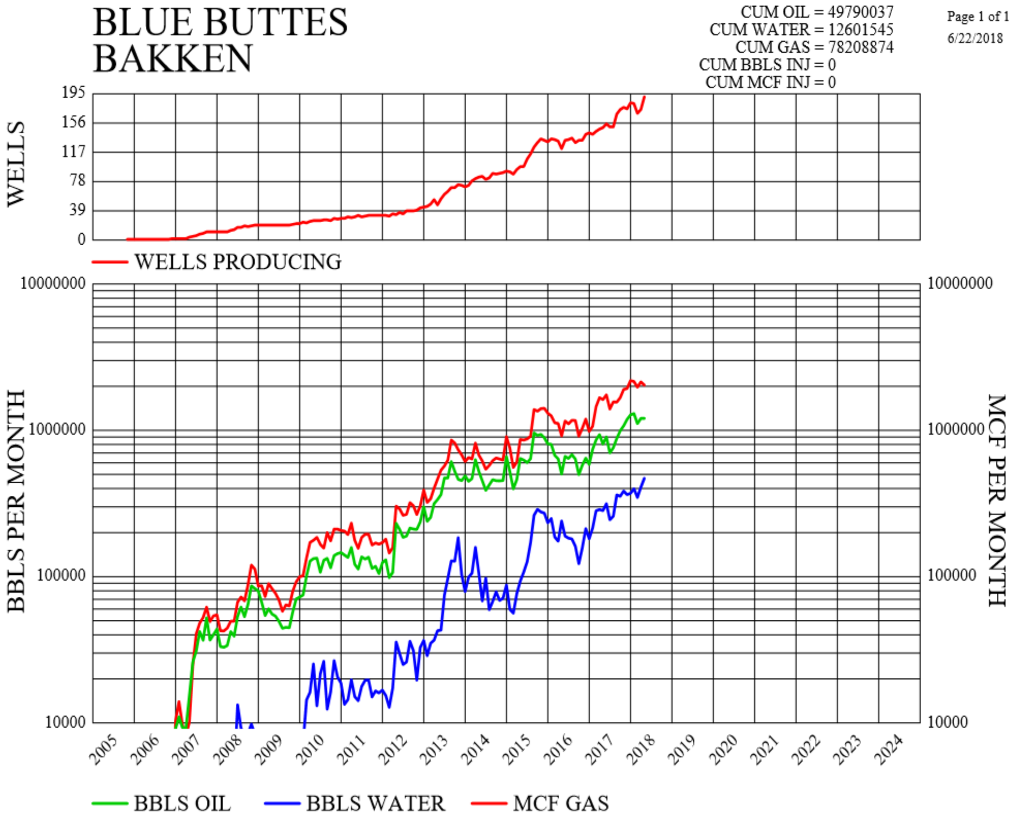


Fig (7). Inflow performance Curve of Bakken Formation in Williston Basin, North Dakota (NDIC)

1D-Mechanical Earth Model

The advancements in hydraulic fracturing and horizontal drilling enabled production from the low porosity, low permeability Middle Bakken reservoir. The focus of this study is to add to the pool of information on the Bakken that will help with the understanding of the properties and create a methodology for future similar studies. This case study will help with getting additional information on the Bakken Formation. For this study, we consider middle Bakken layer which has been the attention of many geologists and reservoir engineers to characterize it in great details. Knowing these properties is essential as they are used at the beginning of the oilfield development for reservoir simulation and geomodelling purposes as well as the Geomechanical and Mechanical Earth Modelling (MEM). Well log based modeling is the log based methodology to efficiently evaluate sub surface reservoir rock properties in the absence of core data [4], and it is considered more cost effective to get the data compared to core measurements. This study requires gathering well log data from the field including the reservoir rock properties. The reservoir properties such as porosity, permeability, effective permeability, shale volume, lithology, and mineralogy was studied. Various methods and approaches were used to acquire those properties. Mechanical Earth Model (MEM) is a numerical representation of the state of stress and mechanical rock properties for a specific stratigraphic section in a field or basin [5]. Developed after the drilling operations, the MEM can be linked with core data to provide localized stress conditions and predictive breakdown and breakout pressures. Most importantly, the MEM can predict the Mud Weight Window (MWW) applicable to the well, minimizing the risk of kick and breakouts. Geomechanical properties once populated over the 3D grid of the geological model can give insights into field scale variation of anisotropy. Use of MEM helps to efficiently predict and evaluate the well bore instability issues to avoid un planned well maintenance cost. [6] Many drilling problems relating to wellbore stability or pore pressure can often be avoided if proper investigations and understanding of local geomechanics is undertaken. The practice of wellbore stability was developed throughout the 1980s, where geophysical logs were becoming the basis of wellbore stability models.

Introduction to Mechanical earth model

Mechanical Earth Modelling is a log-based Methodology to predict mechanical behavior, In-situ stresses and safe mud weight window. Input data needed to build MEM includes wireline logs, seismic data, image log data, Pore pressure, stresses, and laboratory test data from experiments on core samples. A series of empirical correlations were used to extract geomechanical properties from log data.

Mechanical earth modeling workflow is as follow:

1. Study the formation lithology, and calculate shale volume (V-shale) using Gamma Ray logs.

2. Calculating rock strength, elastic and mechanical properties such as Young's Modulus, Poisson's Ratio, UCS (Uniaxial compressive strength), Biot's Coefficient, Tensile Strength, Friction Angle using log data.

3. Estimating Vertical stress (S_V) using Density logs.

4. Estimating Pore pressure from Acoustic slowness logs and calibrating with (Modular Dynamic Tester) MDT data.

5. Determining the maximum and minimum horizontal stresses using empirical correlations, which can be calibrated to leak off test (LOT) Data, if available.

6. Finally calculating Kick Mud weight, Break Out mud weight, Loss Mud weight and Break down Mud weight to predict Safe mud weight window.

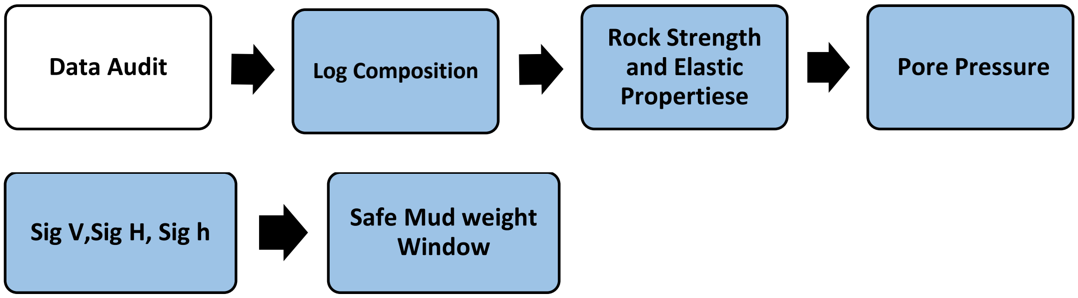


Fig (8). 1D Mechanical Earth Model work flow.

Data Audit: To begin with MEM Modelling the first step is data auditing. Blue Buttes field of Mc Kenzie County was selected. The Input data used includes petro physical well logs (DT, DTSM, ROHZ, NPHI, GR, core data, regional data, and well data from the well file. The well data was available from North Dakota Industrial Commission (NDIC) website. The logs images were digitized in Neura Log software. The data from logs was verified and checked for missing, –ve values. Elastic and geomechanical properties were then calculated by use of empirical correlations, which is discussed later. Well log analysis was mostly done in excel software. This Study uses Jewel Suite Geomechanics 6.2 version to calculate 1d and 3D Geomechanical model. Petrel software and Jewel suit subsurface modelling software is used to create a geological model of Blue Buttes Field.

Elastic and Mechanical Properties

The next step is the calculation of Geomechanical properties of the formation from well log data, which includes elastic properties, rock strength properties, in-situ Stresses and pore Pressure.

Elastic Properties: Elastic properties of rocks is divided into Static and Dynamic. Dynamic Properties such as Poisson's Ratio and Dynamic Young's Modulus are calculated from Wang's [7] empirical correlations related to Acoustic, shear wave velocities obtained from Compressional sonic, and Shear.

$$E_{dynamic} = \left[\frac{\rho}{\Delta t_s^2}\right]\left[\frac{3\Delta t_s^2 - 4\Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2}\right] \tag{1}$$

Where Δt_p and Δt_s is Acoustic and Shear slowness, ρ is Bulk Density.

Young's Modulus, Static:

$$E_{static} = 0.414 * E_{dyn} - 1.05 \tag{2}$$

Poisson's Ratio:

$$(\nu) = 0.5\left[\frac{\Delta t_s^2 - 2\Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2}\right] \tag{3}$$

Where $\Delta t_p and\ \Delta t_s$are compressional and shear sonic logs (us/ft).

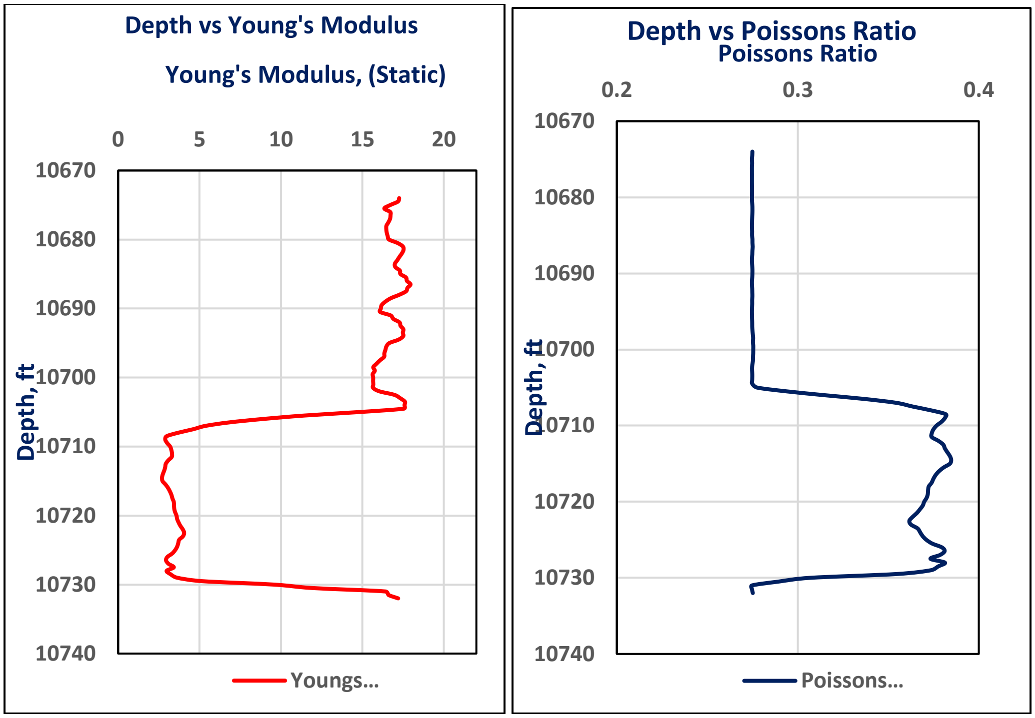


Fig (9). Gamma Ray and resistivity log of Bakken middle member.

Shear modulus: also known as rigidity modulus; it shows the resistance to stress deformations.

$$G_{dyn} = \frac{E_{dyn}}{2(1+\nu)} \tag{4}$$

Bulk modulus and shear modulus is used when dealing with low-frequency data.

$$K_{dyn} = \frac{E_{dyn}}{3(1-2\nu)} \tag{5}$$

Rock strength Properties: Log Based Modelling is the efficient way to extract reservoir properties in the absence of core data (Azadeh et al.). As core samples were not available for rock strength measurement, UCS was calculated from empirical correlation, which uses Acoustic slowness (DT), as the well was from shale formation we use empirical correlation by Vernik[8].

$$UCS = 2.28 + 4.1089 * E_{stat} \tag{6}$$

Where UCS is Unconfined Compressive Strength (MPa), E_{stat} is static Young's Modulus calculated using Equation (2).

Tensile Strength is 1/10th of UCS.

Friction Angle (FANG): FANG is calculated using Plumb's empirical correlations, which is related to porosity and shale volume.

$$\varphi = 26.5 - 37.4(1 - \phi - V_{shale}) + 62.1(1 - \phi - V_{shale})^2 \tag{7}$$

Where ϕ is the Neutron Porosity, $V_{shale}\ is$ the shale volume calculated using equation (8).

V_{shale}: Volume of shale is calculated using maximum and minimum values of Gamma-ray.

$$V_{SHALE} = (GR - GR_{MIN})/(GR_{MAX} - GR_{MIN)} \tag{8}$$

Where GR_{MIN} and GR_{MAX} are minimum and maximum values of Gamma Ray Log.

Geomechanical Properties

Overburden stress: Overburden Stress is the vertical integration of density log data.

Pore Pressure: To calculate pore pressure we use Eaton's method [9], which uses acoustic slowness log.

$$P_p = OBG - (OBG - P_{hyd})(\frac{\Delta T_n}{\Delta T_{log}})^3 \tag{9}$$

Where *OBG* is overburden stress gradient, P_{hyd} is hydrostatic pore pressure gradient and log refer to normal and measured values of ΔT at each depth. ΔT_n is the Normal Compaction Trend plotted against ΔT.

Horizontal stresses: In-situ stresses are categorized as S_V (Overburden stress) S_H and S_h (Maximum and Minimum Horizontal Stresses). Direction of Horizontal stresses can be determined from Formation Micro Imager Log. Poroelastic theory can be used to find the magnitude which can be calibrated with Leak off test and Mini Frack test data.

$$S_V = \rho g h \tag{10}$$

$$S_h = \frac{\upsilon}{1-\upsilon}(S_\upsilon - \alpha P_P) + \alpha P_P + \frac{E\varepsilon_x}{1-\upsilon^2} + \frac{\upsilon E\varepsilon_y}{1-\upsilon^2} \qquad (11)$$

$$S_H = \frac{\upsilon}{1-\upsilon}(S_\upsilon - \alpha P_P) + \alpha P_P + \frac{E\varepsilon_y}{1-\upsilon^2} + \frac{\upsilon E\varepsilon_x}{1-\upsilon^2} \qquad (12)$$

Where ρ is density, g is acceleration due to Gravity, υ is Poisson's ratio, P_P is the Pore pressure, ε_x and ε_y are parameters corresponding to tectonic strains coefficients in the field. The Biot's coefficient α is assumed as 1.

1D Geomechanical Model workflow.

1D Geomechanical Model: The crucial aspects in 1D Geomechanical modelling is composing the petrophysical well logs, identifying the lithology of subsurface and calculating shale volume. Estimating the overburden density profile to calculate overburden stress. The next step deals with predicting pore pressure using Eaton's method of normal compaction technique. Keeping in view of tectonic strain in the basin the maximum and minimum horizontal stress. The above data then will be used to calculate fracture Gradient profile.

Log Composition: Creating a composite of raw logs used in MEM is essential task. Pore pressure prediction requires a complete set of log data. Log composition removes the overlapping log values and creates a single log of data. Compositor tracks creates composite of the missing log data. Composite tracks are created adjacent to logs Tracks that will be used in the subsequent steps of calculating Geomechanical Properties. Composite tracks allow confining a particular section of log. Fig composite logs of well 8163**.**

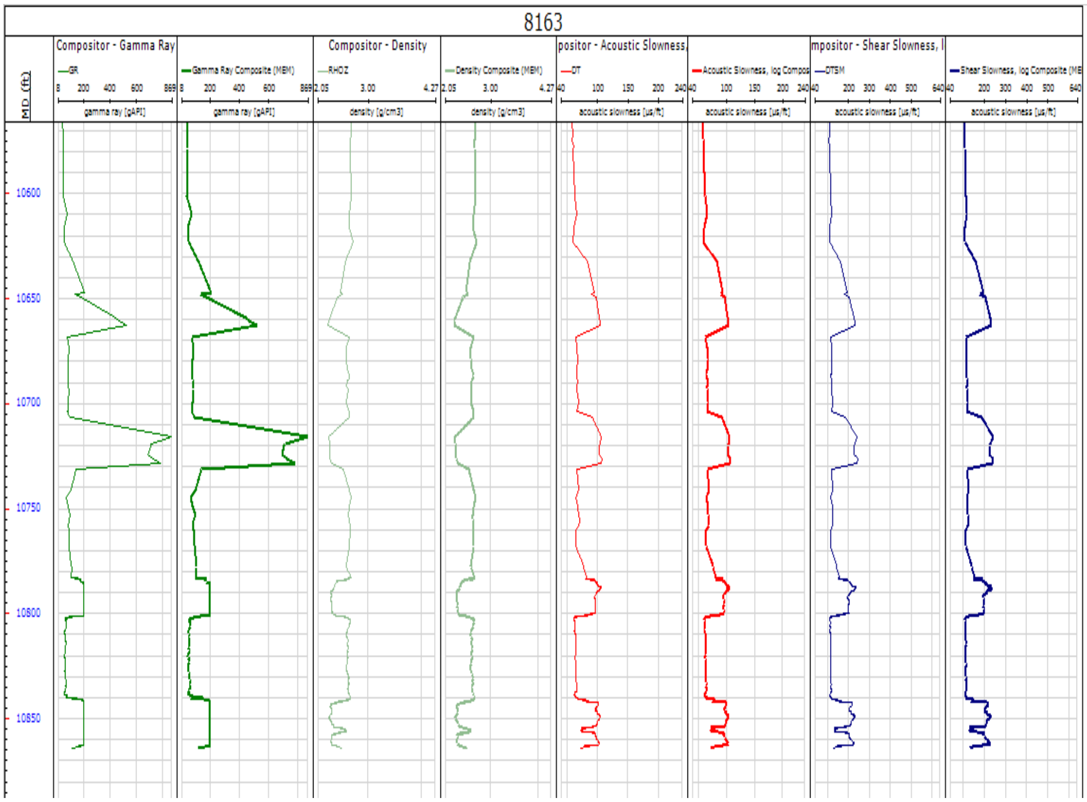


Fig (10). Composite logs of well 8163**.**

Zonation Model and Lithology: Zonation model calculates the zonation and lithology of the formation from Logs. Formation rock types was imported. Mostly gamma ray log is used to shows zonation and lithology. Track 4 shows Gamma Ray log, which shows. Pore pressure is usually calculated for zones with high gamma ray count. High gamma ray count indicated shale while low indicates sandstone. Track 6 shows lithology calculated from gamma-ray log. Track 7 shows Shale volume.

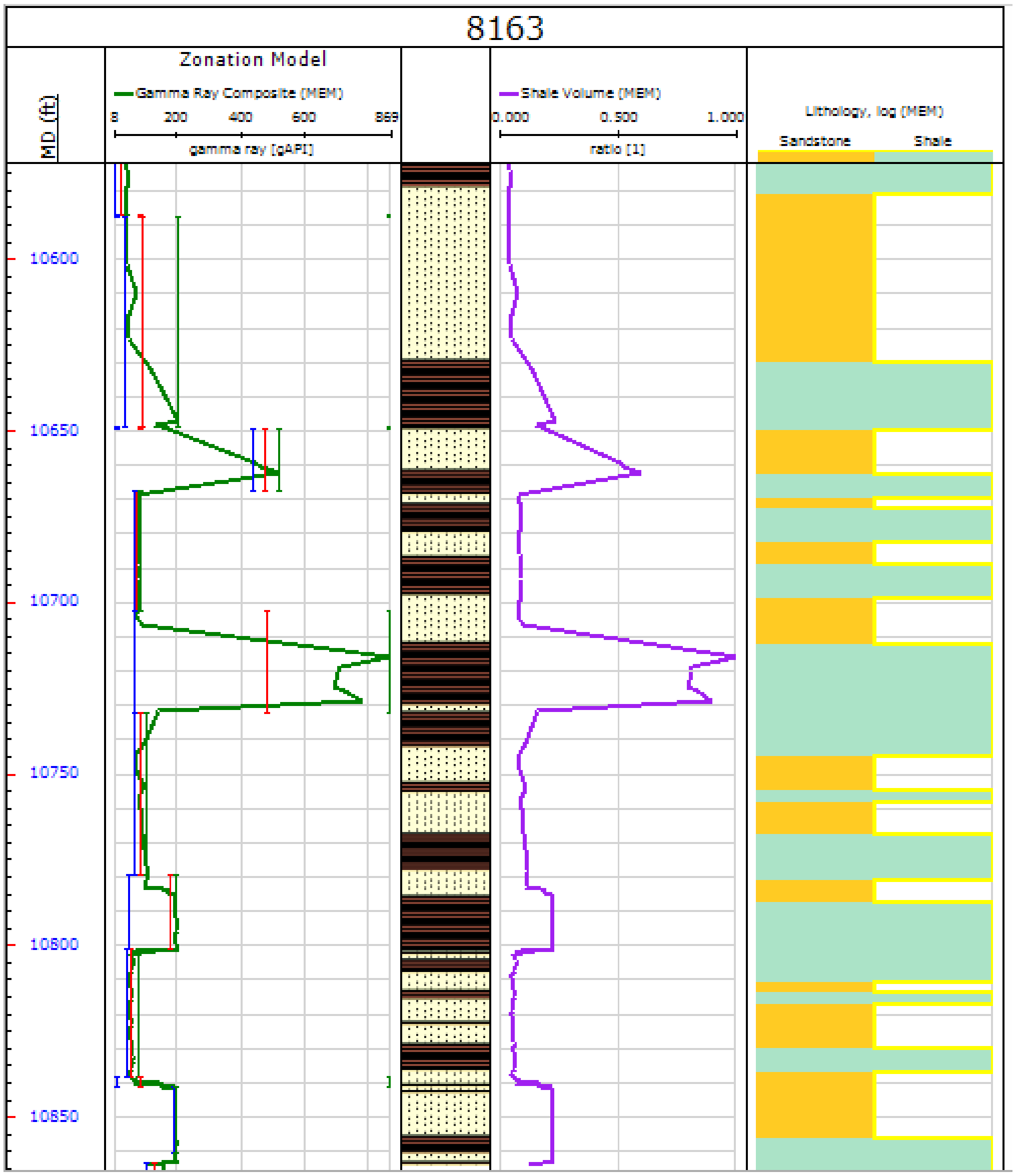


Fig (11). Zonation and lithology Model of 8163 extracted from Gamma ray log.

In-situ stresses: In-situ stresses are categorized as S_V (Overburden stress) S_H and S_h (Maximum and Minimum Horizontal Stresses).

Overburden stress: Overburden Stress or Vertical stress is the weight of the overlying rock. Overburden density logs (ROHZ) is used to calculate overburden stress with starting ground density as 1.89g/cc. Track 5 shows Overburden stress.46

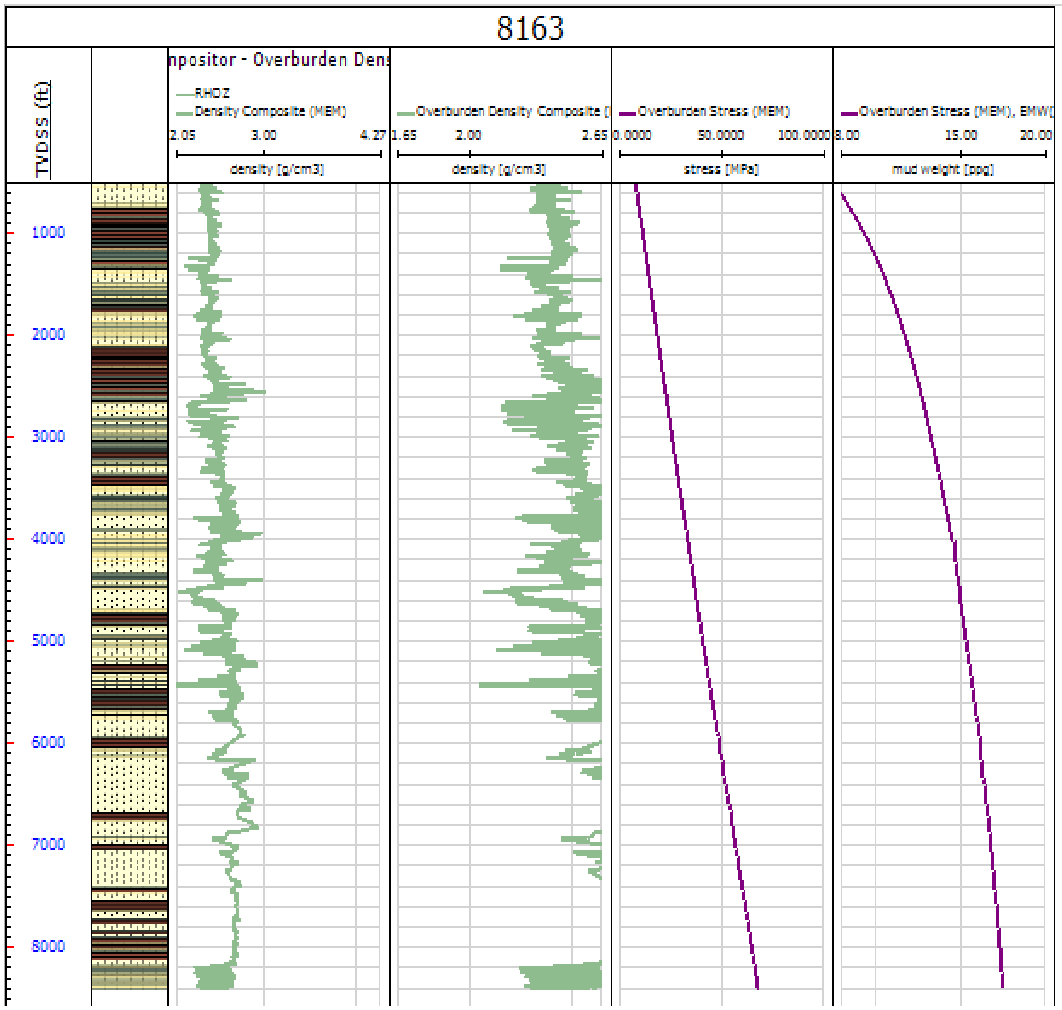


Fig (12). Overburden Calculation from vertical integration of density log data of well 8163.

Pore pressure Prediction: Pore pressure is pressure acting in the pore space of rock. At specific depths, pore pressure exceeds hydrostatic pressure, which is called overpressure. Overpressure is a cause of compaction, buoyancy and fluid migration. Eaton's method of Normal Compaction Technique (NCT) to calculate Pore Pressure. Compressional sonic and density logs are used on which a trend line is plotted against normal compaction and boxcar's values to show the pore pressure values. Again, pore pressure interpretation is made to match the exact values of pore pressure. Track 7 shows Final Pore pressure.

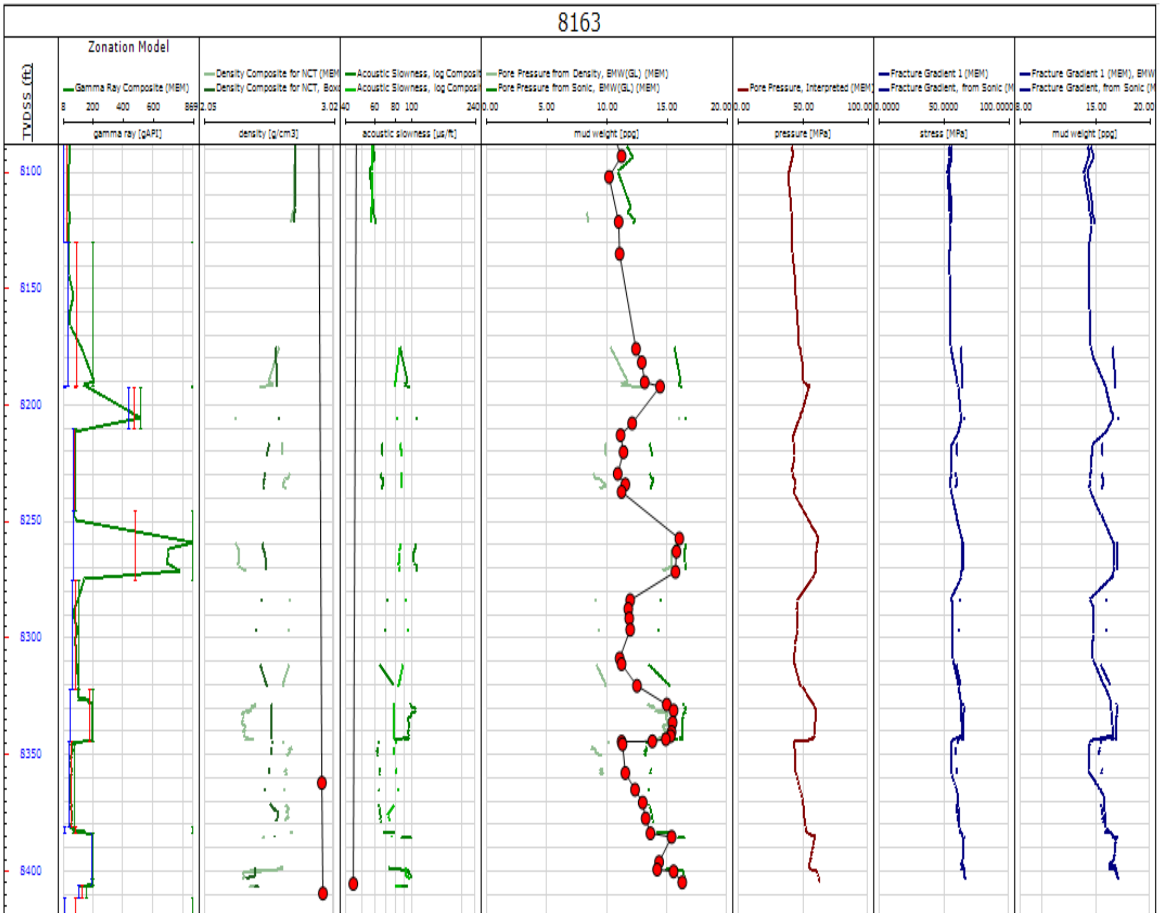


Fig (13). Pore Pressure Prediction of well 8163

Horizontal stresses: Direction of horizontal stresses can be determined from formation Micro imager log. Poro-elastic theory can be used to find the magnitude of stresses, which can be calibrated with leak off test and mini frack test data. The horizontal stresses we calculated by stress contrast method. ε_x and ε_y are parameters corresponding to tectonic strains coefficients in the field. Track 3 in fig () shows the stresses in MPa. The magnitude of stresses can be matched to calibration data based on iteration of tectonic stress coefficients ε_x and ε_y.

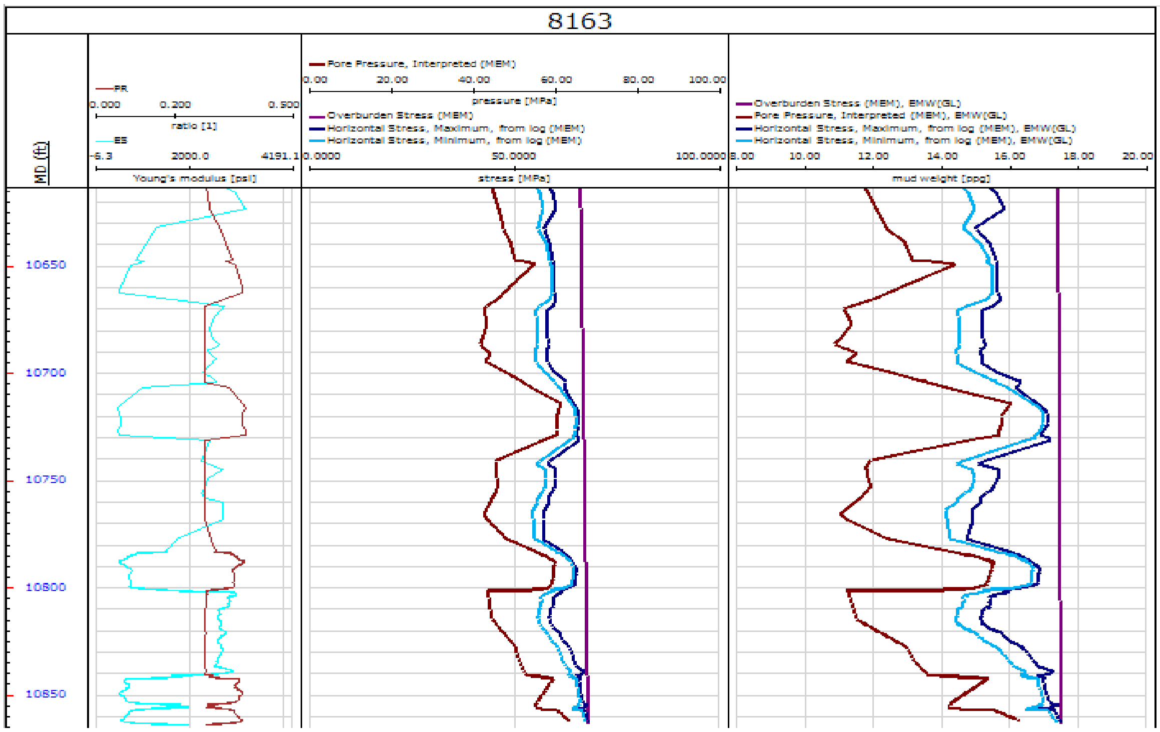


Fig (14). Maximum and minimum horizontal stresses calculate from stress ratio method.

The workflow discussed earlier was used to construct MEM. Fig. 2 shows MEM of a well in Bakken Shale of Williston Basin. The First Track Shows Depth in (ft.). Track 2 shows the well

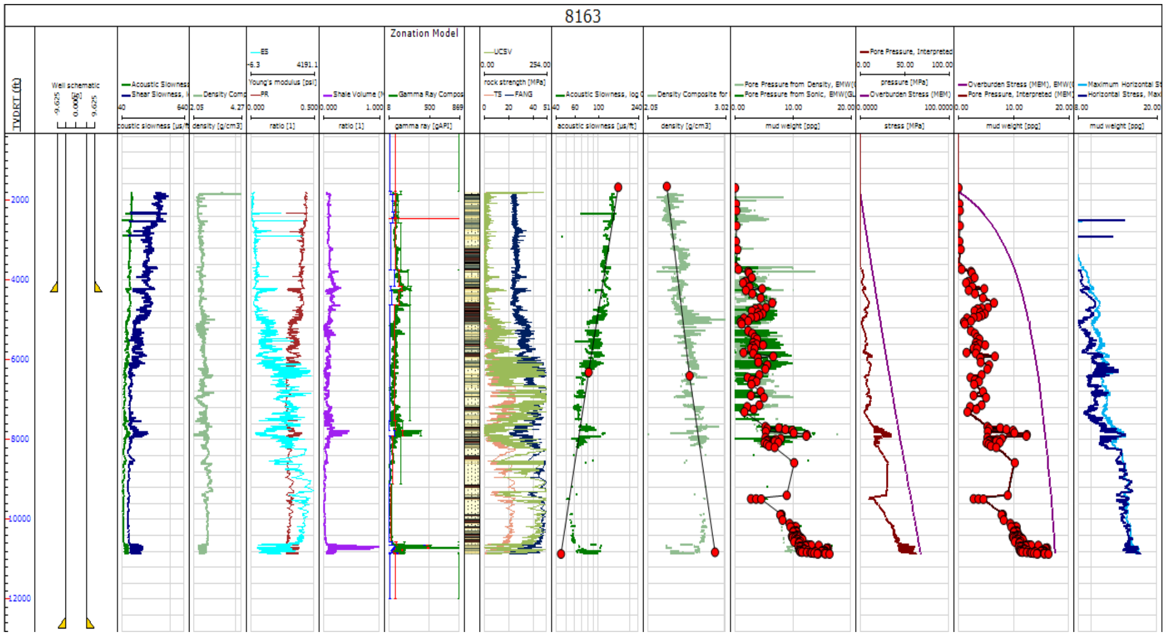


Fig (15). Complete view of 1-D Mechanical Earth Model of well in Blue Buttes Field.

schematic. Track 3 shows the compressional and sonic slowness logs (us/ft). Track 4 Shows the density (ROHZ) in (gm/cc). Track 5 shows the static Young's Modulus and Poisson's Ratio. Track 6 shows the shale volume. Track 7 shows the Gamma Ray Log (GAPI) used to extract zonation and lithology. Track 8 represents Rock strength properties such as Friction Angle (Degrees), Rock Strength (UCS) MPa, calculated from vernik's Equation (6), Track 9 shows the normal compaction trend plotted against the compressional slowness log. Track 10 shows the normal compaction trend plotted along density log. Track 11 shows the pore pressure interpreted from curves obtained by plotting normal trend over compressional sonic and Density logs. Track 12 shows the pore pressure with overburden stress in (MPa). Track 13 shows the interpreted pore pressure with overburden calculated from density log. Track 14 shows the Maximum and Minimum horizontal stresses (ppg) and Tensile Strength. UCS values obtained from log based empirical correlation can be calibrated with UCS from core test data to get better results. Track 8 shows Pore pressure estimated from Eaton's Method, Maximum and Minimum Horizontal Stresses (MPa) and Vertical Overburden stress (MPa). It can be seen that the magnitude of stress is in the order of ($S_V > S_H > S_h$) which is a normal stress regime.

CHAPTER-II

Safe Mud Weight Window (SMWW) determination.

Wellbore instability is one of the significant issues of drilling. Predicting SMWW in the planning phases of well helps to reduce instability and unplanned well maintenance cost. Safe MWW determination requires a complete analysis of elastic and mechanical properties coupled with geomechanical properties and state of stresses such as vertical overburden stress, maximum and minimum horizontal stresses. The main parameter to control borehole instability issues is proper mud weight. The concept of mud weight is understood by Mohr's coulombs failure criteria. Excess mud weight leads to fracture initiation, which leads to tensile failure of the formation being drilled while less mud weight results in borehole break out which results in shear failure. In this study, Analysis of Safe MWW in Bakken formation is done by using the state of stresses considering tectonic strains coefficients. During drilling If the MW used for drilling is below the pore pressure gradient, then a kick is expected (Kick MW). A low MW but not below the pore pressure may result in shear failures of the rock, which results in instability in the form of breakouts (BO_MW). On the other hand, increasing the MW beyond will result in mud loss (LOSS_MW) but increasing it further may result in fracturing the formation in the form of tensile or breakdown failure (BD_MW). Fig () shows the concept of safe Mud weight window.

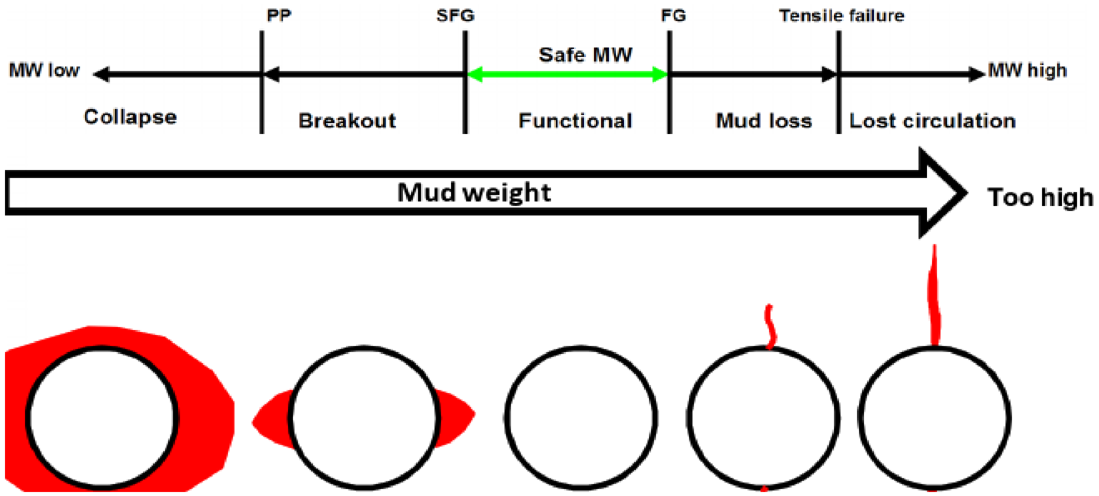
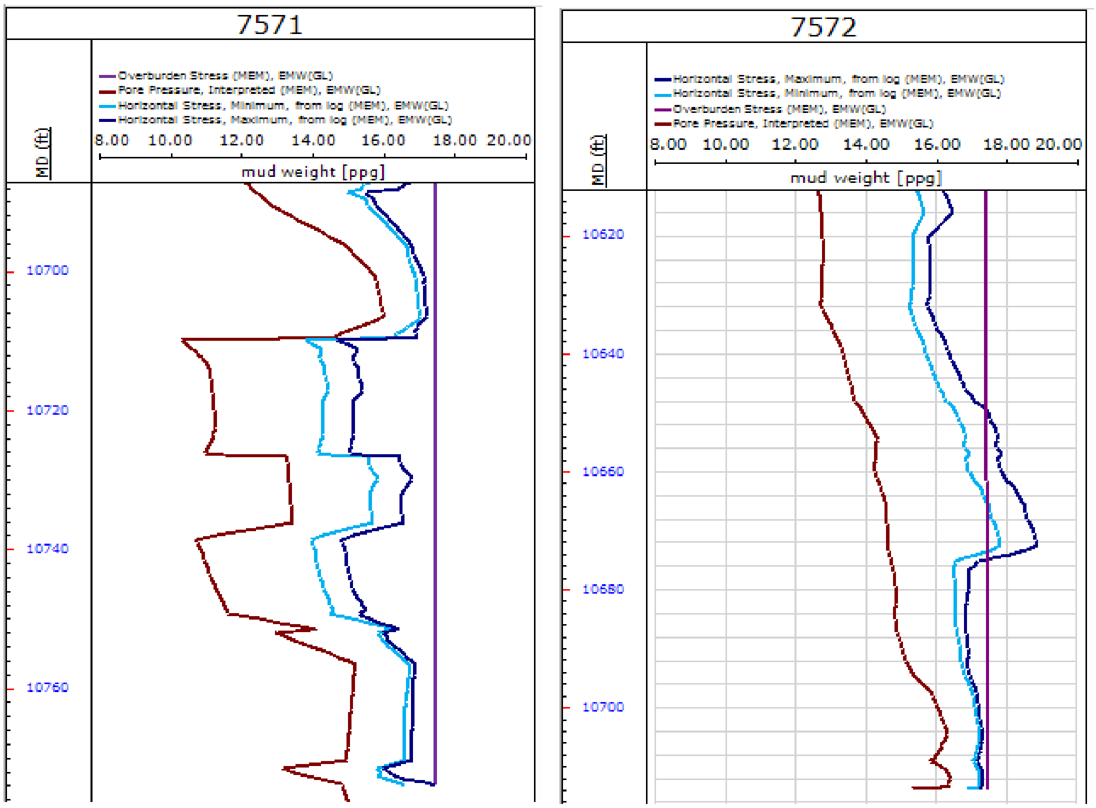
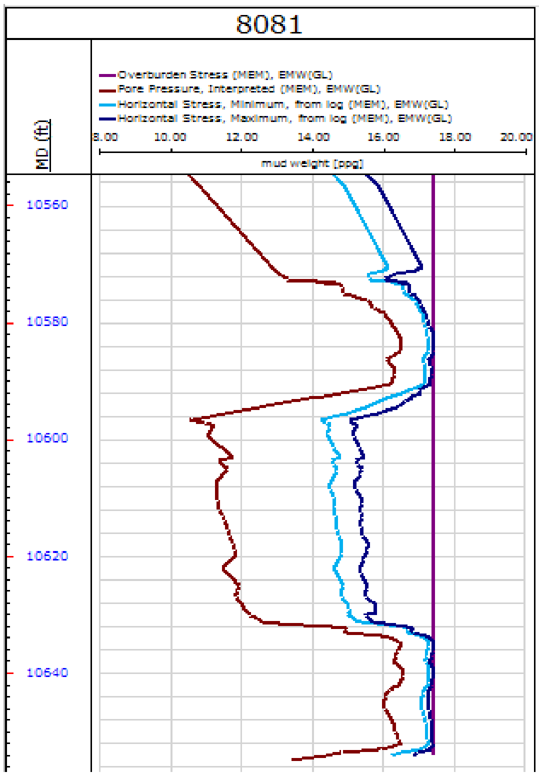
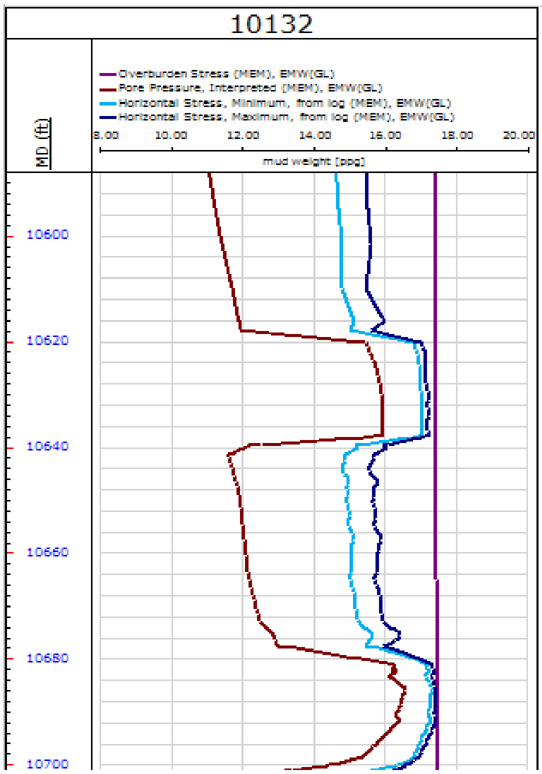


Fig (16). Schematic explaining the safe mud weight window concept.




8081
Overburden Stress (MEM), EMW(GL)
Pore Pressure, Interpreted (MEM), EMW(GL)
Horizontal Stress, Minimum, from log (MEM), EMW(GL)
Horizontal Stress, Maximum, from log (MEM), EMW(GL)
8.00
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
MD (ft)
10560
10580
10600
10620
10640


10132
Overburden Stress (MEM), EMW(GL)
Pore Pressure, Interpreted (MEM), EMW(GL)
Horizontal Stress, Minimum, from log (MEM), EMW(GL)
Horizontal Stress, Maximum, from log (MEM), EMW(GL)
8.00
10.00
12.00
14.00
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18.00
20.00
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MD (ft)
10600
10620
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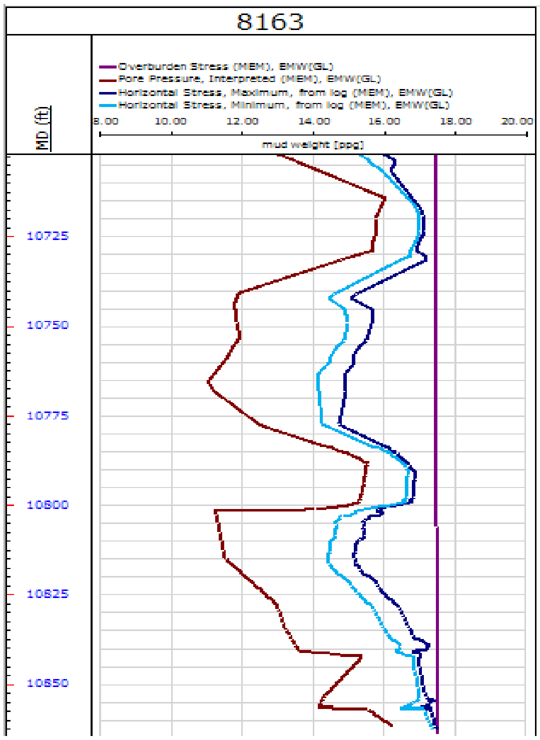
10660
10680
10700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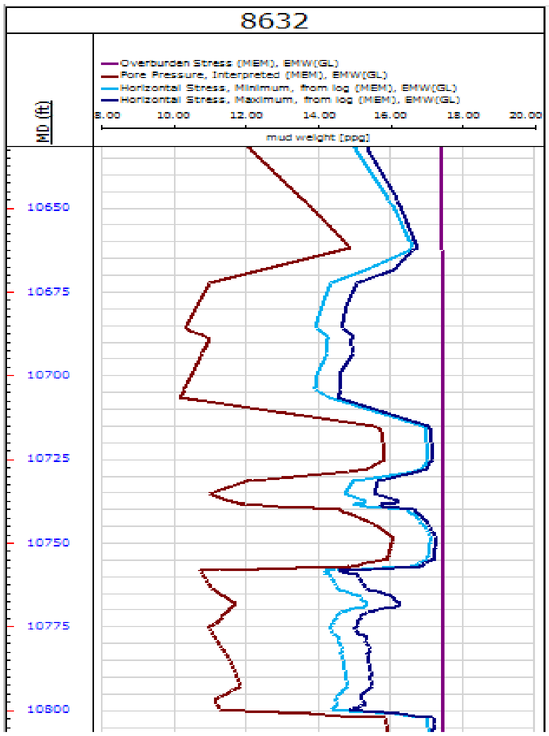
Overburden Stress (MEM), EMW(GL)
Pore Pressure, Interpreted (MEM), EMW(GL)
Horizontal Stress, Maximum, from log (MEM), EMW(GL)
Horizontal Stress, Minimum, from log (MEM), EMW(GL)
8.00
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
MD (ft)
10725
10750
10775
10800
10825
10850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8.00
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
MD (ft)
10650
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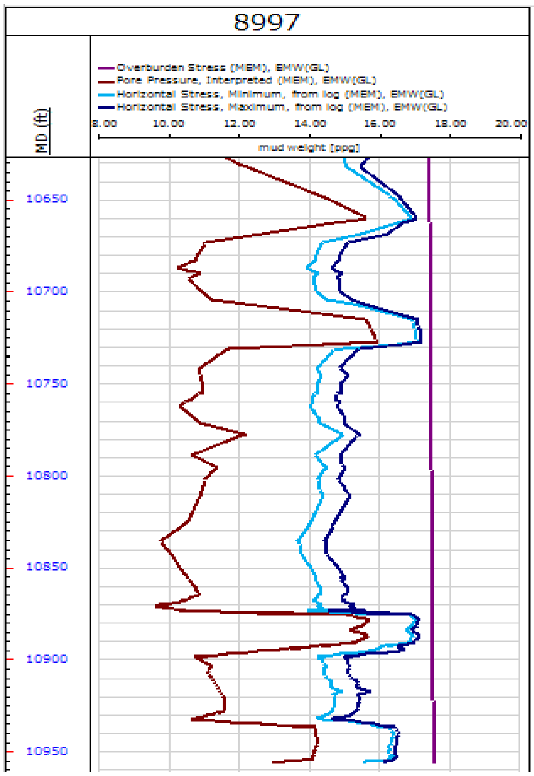
10700
10725
10750
10775
10800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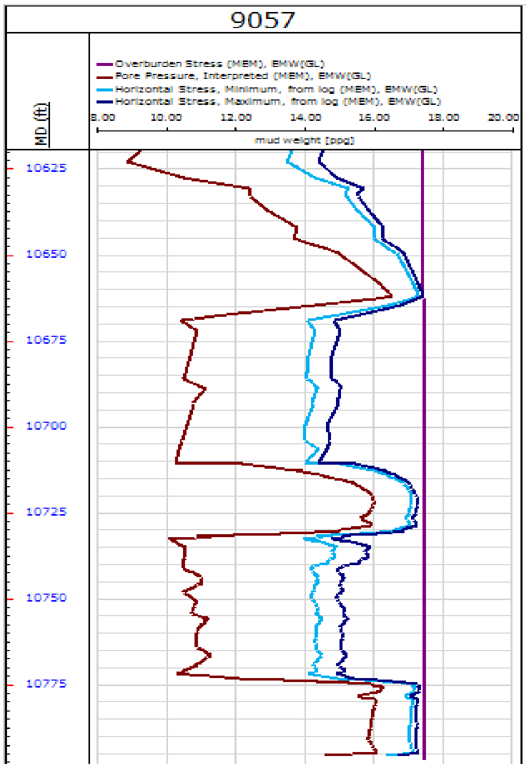
8.00
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
MD (ft)
10650
10700
10750
10800
10850
10900
10950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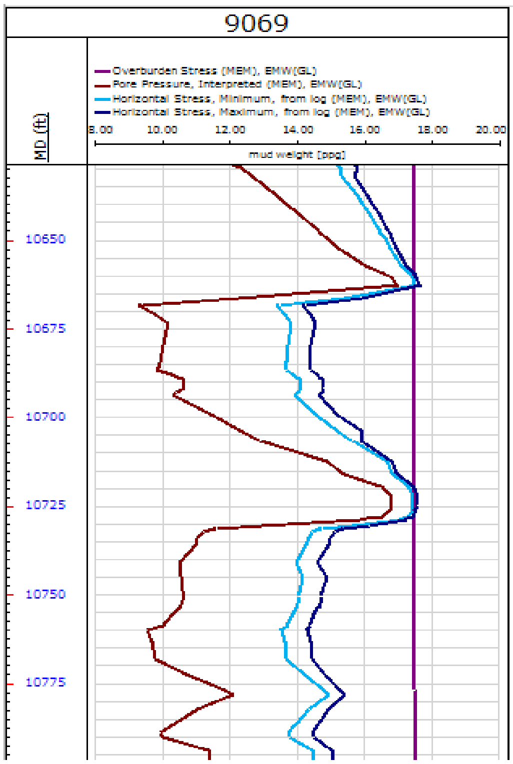
Horizontal Stress, Maximum, from log (MEM), EMW(GL)
8.00
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
MD (ft)
10625
10650
10675
10700
10725
10750
10775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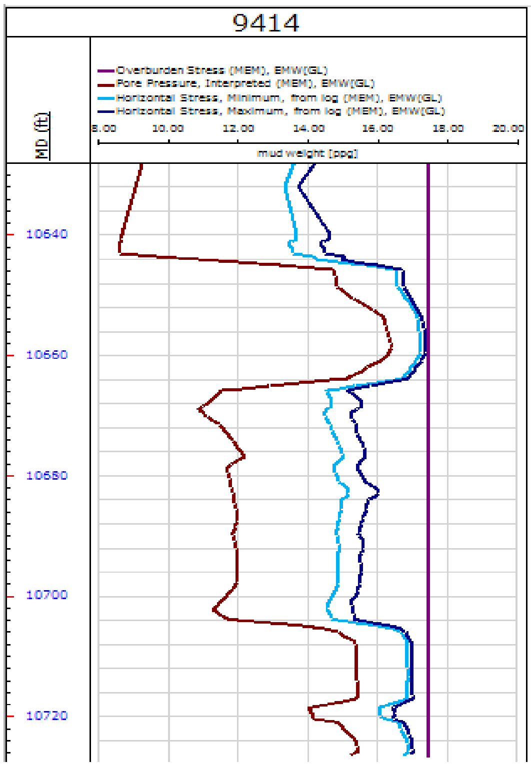
8.00
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
MD (ft)
10650
10675
10700
10725
10750
10775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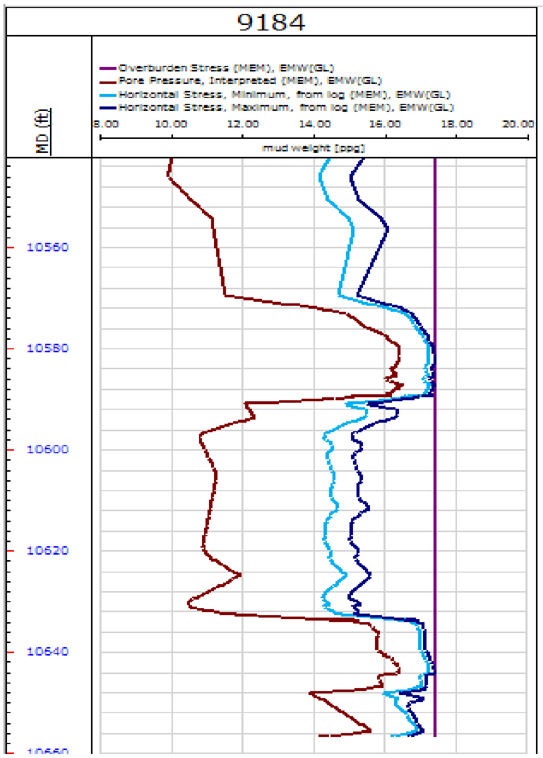
Horizontal Stress, Minimum, from log (MEM), EMW(GL)
Horizontal Stress, Maximum, from log (MEM), EMW(GL)
8.00
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
MD (ft)
10640
10660
10680
10700
10720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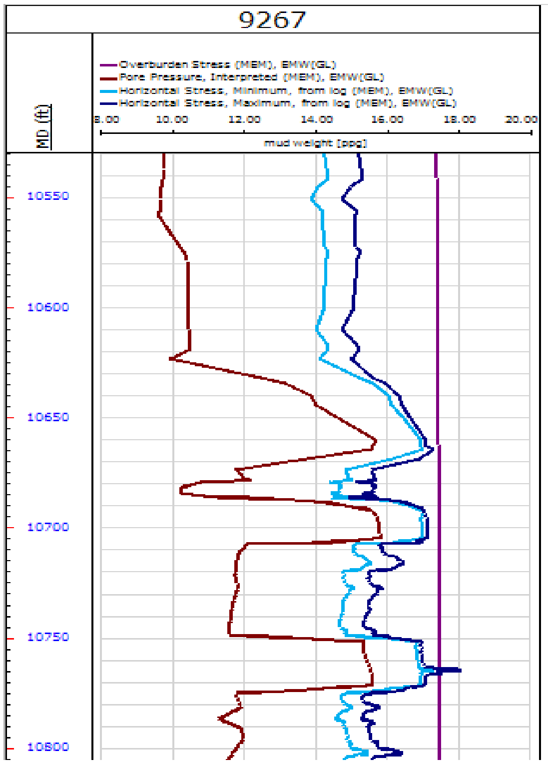
8.00
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
10560
10580
10600
10620
10640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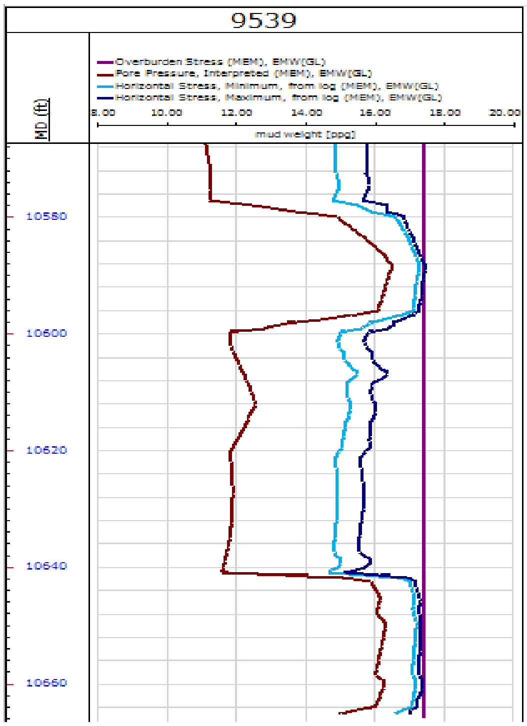
8.00
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
10550
10600
10650
10700
10750
10800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Horizontal Stress, Minimum, from log (MEM), EMW(GL)
Horizontal Stress, Maximum, from log (MEM), EMW(GL)
8.00
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
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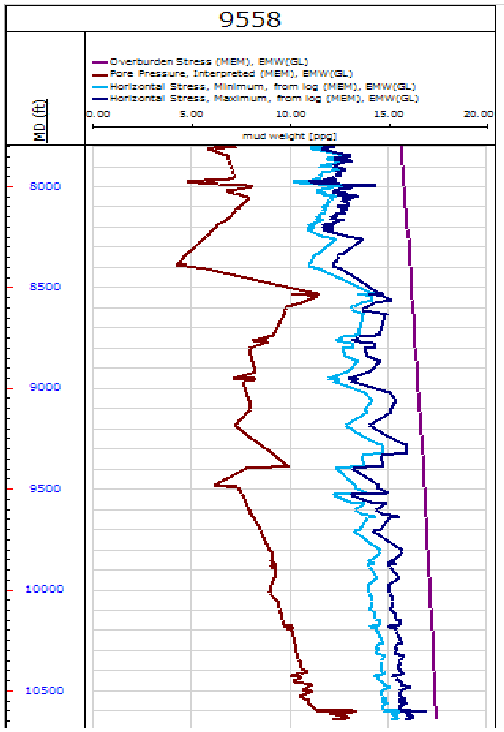
10600
10620
10640
10660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Horizontal Stress, Minimum, from log (MEM), EMW(GL)
Horizontal Stress, Maximum, from log (MEM), EMW(GL)
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10.00
15.00
20.00
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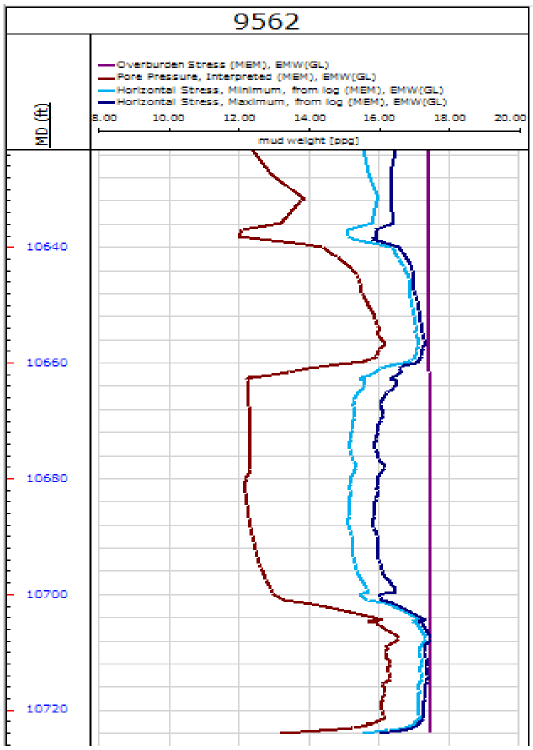
8500
9000
9500
10000
10500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Horizontal Stress, Maximum, from log (MEM), EMW(GL)
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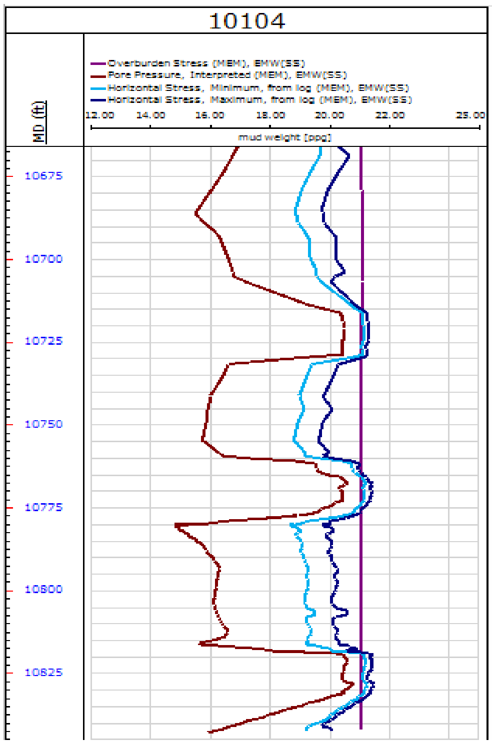
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
10640
10660
10680
10700
10720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Overburden Stress (MEM), EMW(SS)
Pore Pressure, Interpreted (MEM), EMW(SS)
Horizontal Stress, Minimum, from log (MEM), EMW(SS)
Horizontal Stress, Maximum, from log (MEM), EMW(SS)
12.00
14.00
16.00
18.00
20.00
22.00
25.00
mud weight [ppg]
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10700
10725
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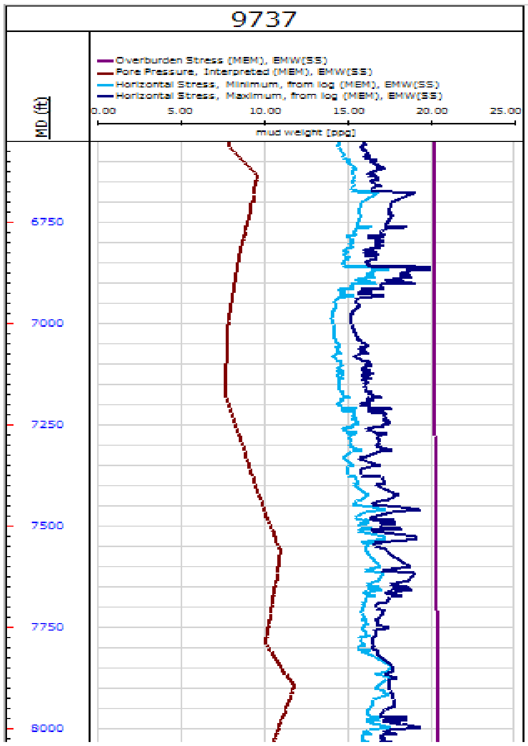
10775
10800
10825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Horizontal Stress, Maximum, from log (MEM), EMW(SS)
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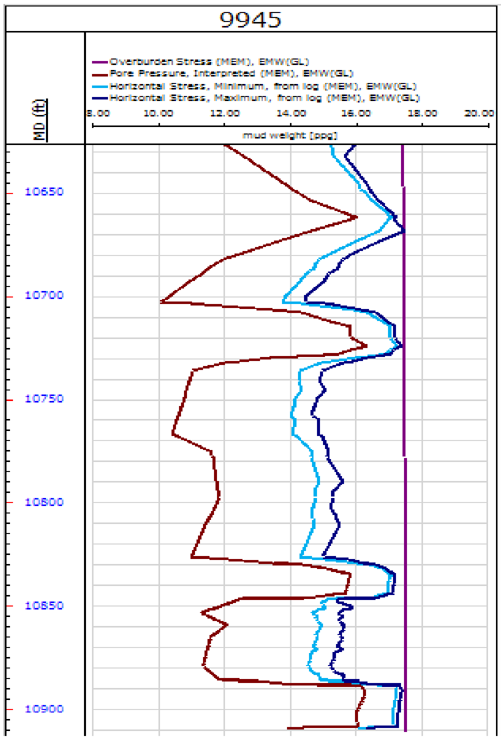
10.00
15.00
20.00
25.00
mud weight [ppg]
6750
7000
7250
7500
7750
8000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Pore Pressure, Interpreted (MEM), EMW(GL)
Horizontal Stress, Minimum, from log (MEM), EMW(GL)
Horizontal Stress, Maximum, from log (MEM), EMW(GL)
8.00
10.00
12.00
14.00
16.00
18.00
20.00
mud weight [ppg]
10650
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10750
10800
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10900

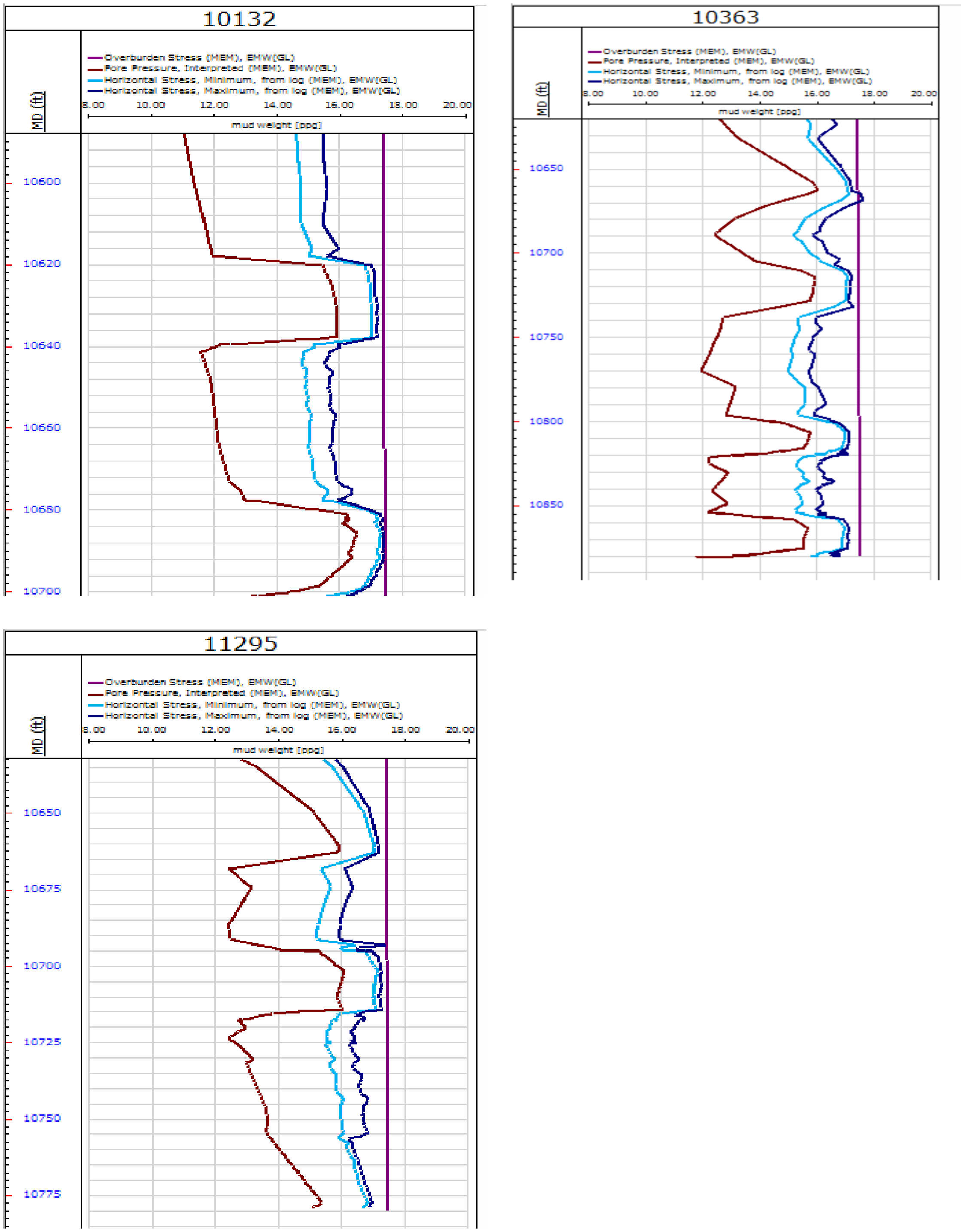

Fig (17). The Figures above illustrates the mud weight window across upper, middle and lower Bakken of 22 wells in Blue Buttes Field, North Dakota. MMW varies for middle bakken formation with loss circulation zones at certain depths. From the pore pressure profile, it observed that upper and lower bakken members are over pressured due to presence of kerogen, Middle member is less pressured which is reservoir. Over all the blue buttes field has a normal stress regime.

Data Calibration

Calibration Data: Before concluding the 1D model, results obtained were calibrated from experimental laboratory data and the data available from the literature. The modelling parameters such as stresses and pressures were good fit and matched Eaton's method of normal compaction technique was used to calculate pore pressure. As Bakken formation is less prone to tectonic activity, Iterative tectonic strain coefficient method was used to calculate the magnitude of stresses across the field. Based on iterative method stresses from the model were calibrated against the data from the field best fit was achieved with strain coefficients ε_x and ε_y as 0.10 and 0.30. Fig () shows the mud weight window plotted against calibration data. Azimuth values available in the literature as listed in the table were proven accurate. The data was calibrated to one of the wells in the field. The calibration data extracted from research work of Kegang Ling and Zhengwen Zeng [10].

Table (1). Wells used in data Calibration [10]

Well #	NDIC file #	Assessment Unit (USGS 2008)	Assessment Unit #	Top of Formation (ft)
96	16771	Nesson-Little Knife Structural AU	2	Upper Bakken (UB):10288 Middle Bakken (MB):10307 Lower Bakken (LB):10378
70	16862	Eastern Expulsion	3	Upper Bakken:8803

		Threshold AU		Middle Bakken:8820 Lower Bakken:8850
20	16174	Elm Coulee-Billings Nose AU	1	Upper Bakken:10673 Middle Bakken:10683 Lower Bakken:10712
13	15923	Central Basin-Poplar Dome AU	4	Upper Bakken:10985 Middle Bakken:11005 Lower Bakken:11050
86	17450	Northwest Expulsion Threshold AU	5	Upper Bakken:7300 Middle Bakken:7355 Lower Bakken:7415
18	16089	Northwest Expulsion Threshold AU	5	Upper Bakken:8595 Middle Bakken:8610 Lower Bakken:8675
72	16985	Central Basin-Poplar Dome AU	4	Upper Bakken:10486 Middle Bakken:10510 Lower Bakken:10550
2	11617	Nesson-Little Knife Structural AU	2	Upper Bakken:10310 Middle Bakken:10330 Lower Bakken:10380

Table (2). Laboratory experimental Geomechanical data extracted from [10]

Sample No.	Depth (ft.)	Overburden Stress (MPa)	Pore Pressure (MPa)	Min Horizontal Stress (MPa)
1V	5844	58.90881	30.63341	44.36776
2V	8586.2	59.19840936	30.7851034	45.89841732
3V	8629.6	59.5017788	30.93678812	42.9888286

4V	8631.4	59.50867356	30.94368288	43.09225
5V	8639.3	59.56383164	30.97126192	42.058036
6V	8715.5	60.0878334	31.24705232	43.68519936
7V	8720.1	60.1223072	31.26084184	44.94694044
8V	8729	60.18436004	31.29531564	44.63667624
9V	8737.5	60.23949	31.32978	44.23676

Table (3). (left) Laboratory experimental Uni/Triaxial stress data extracted from [10].

Well#	NDIC file	Depth	Formation	Uni/Triaxial stress,(MPa)
96	16771	10705.9	MB	185.3
		10733.3	LB	125.5
70	16862	8841.4	MB	186.2
		8850.3	LB	154.4
20	16174	10687	MB	172.1
		10718.7	LB	125.1
13	15923	11007	MB	232.3
86	17450	7321	UB	64.5
		7379	MB	155.5
		7373	LB	198.5
18	16089	8655	MB	171.2
72	16985	11008	MB	148.3
2	11617	10372	MB	109.8

Table (4). (Right) Laboratory experimental Poisson ratio extracted from [10].

Well#	**NDIC file#**	**Depth**	**Formation**	**Poisson's Ratio**
96	16771	10321	MB	0.194
		10452	LB	0.465
70	16862	8837.8	MB	0.486
		8850.3	LB	0.156
20	16174	10673.6	UB	0.393
		1068.3.5	MB	0.234
		10731.4	LB	0.413
13	15923	11007	MB	0.243
86	17450	7353	UB	0.186
		7405	MB	0.167
		7373	LB	0.149
18	16089	8655	MB	0.182
72	16985	10498	UB	0.25
		10512.7	MB	0.44
2	11617	10367	MB	0.165
		10419	LB	0.182

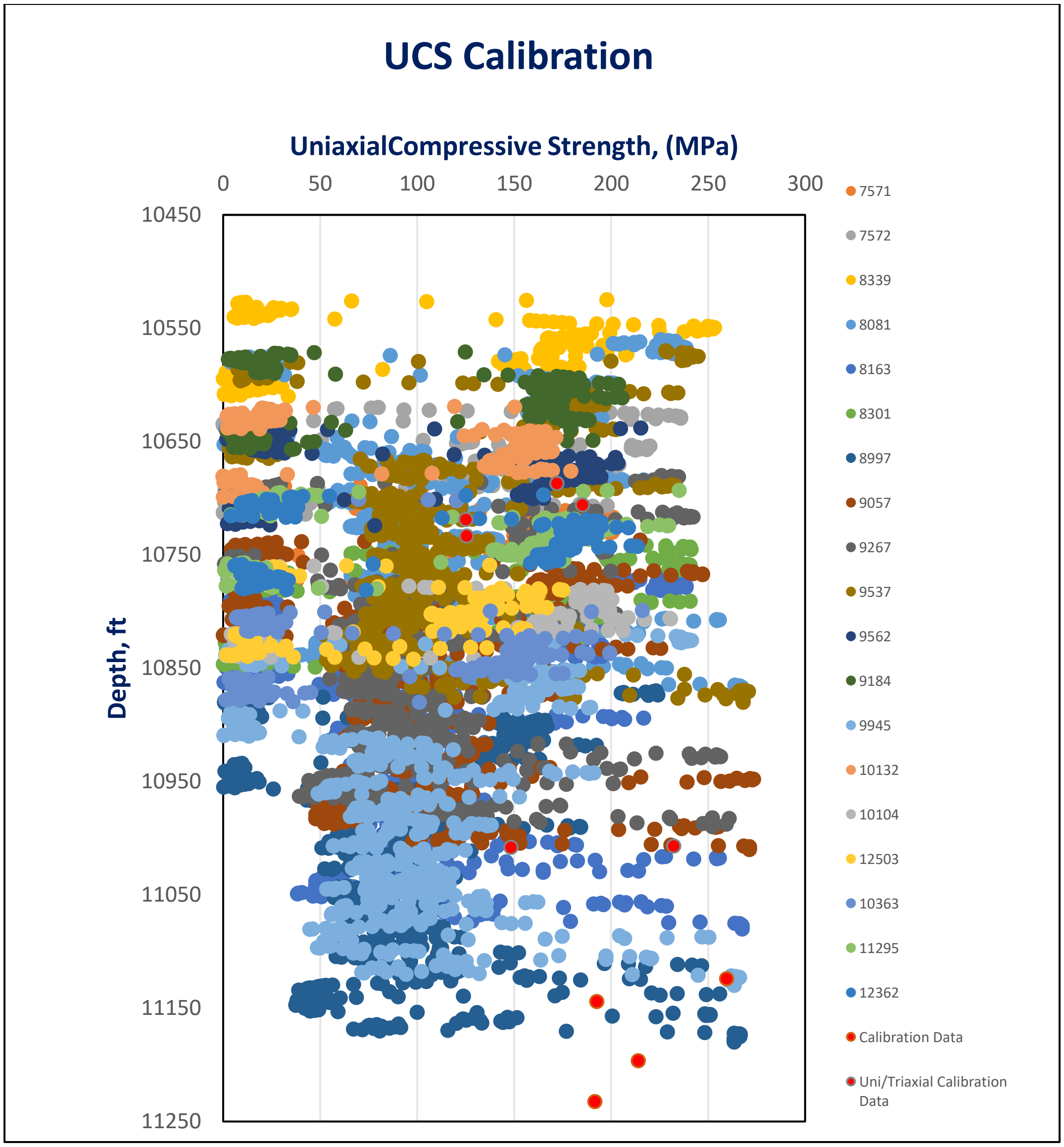

Fig (18). Uniaxial and Trixial data extracted from [10] is calibrated to log obtained UCS Data.

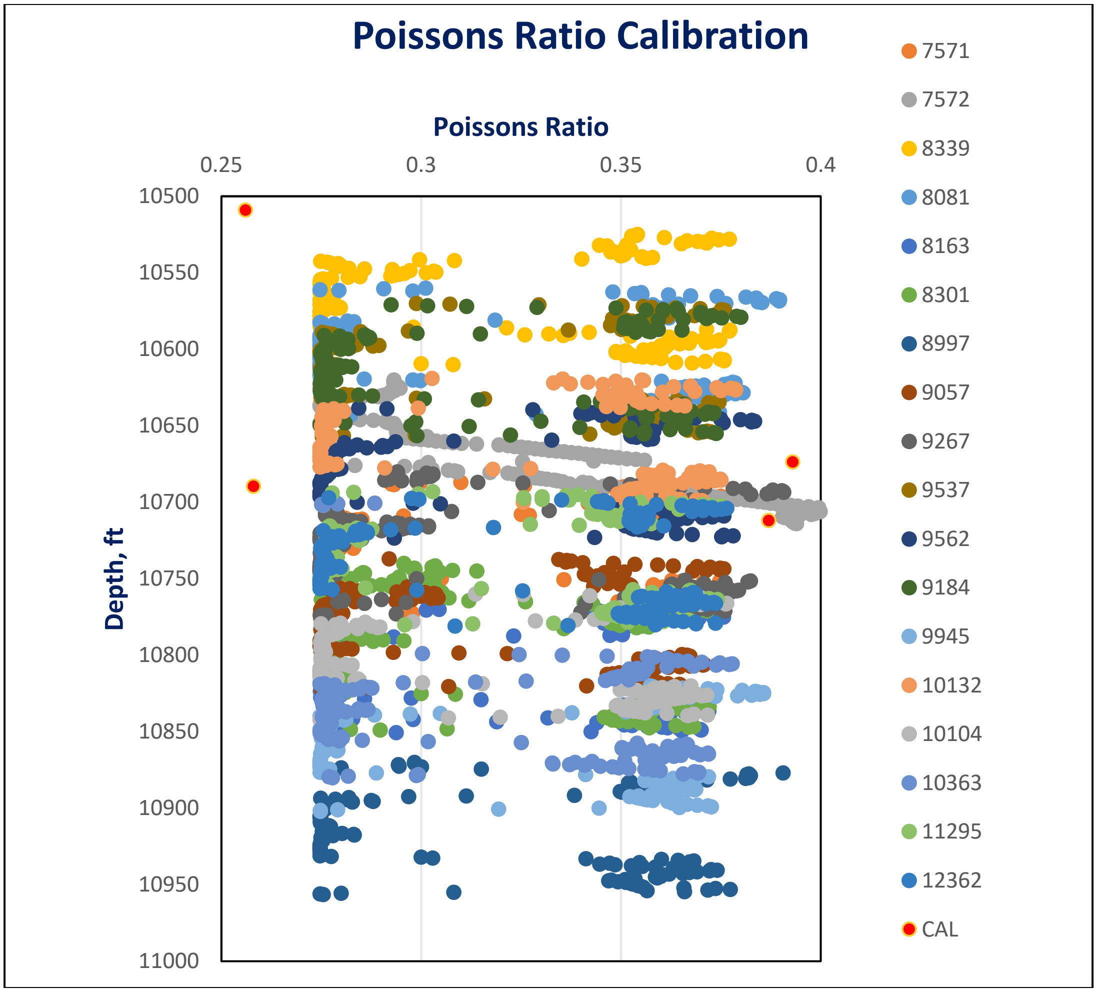

Fig (19). Poisson’s Ratio data extracted from [10] is calibrated to log obtained UCS Data

Table (5). Sig H Azimuth data extracted from [10] for calibrating Maximum Horizontal stresses.

NDIC Well No.	Well Name	Depth, ft.	σH Orientation	Formation
12072	MOI-ELKHORN 33-1H	10388-10418.64	275°; 270-285°	Bakken
16405	PEGASUS 2-17H	10088.70-10209	330°	Bakken, Three Forks
12772	AHEL ET ALGRASSEY BUTTE 12-13H3	11242-11284	335-340°, 290-300°	Bakken
15845	NELSON FARMS	9637-9675.85	300°	Bakken

Stress Calibration

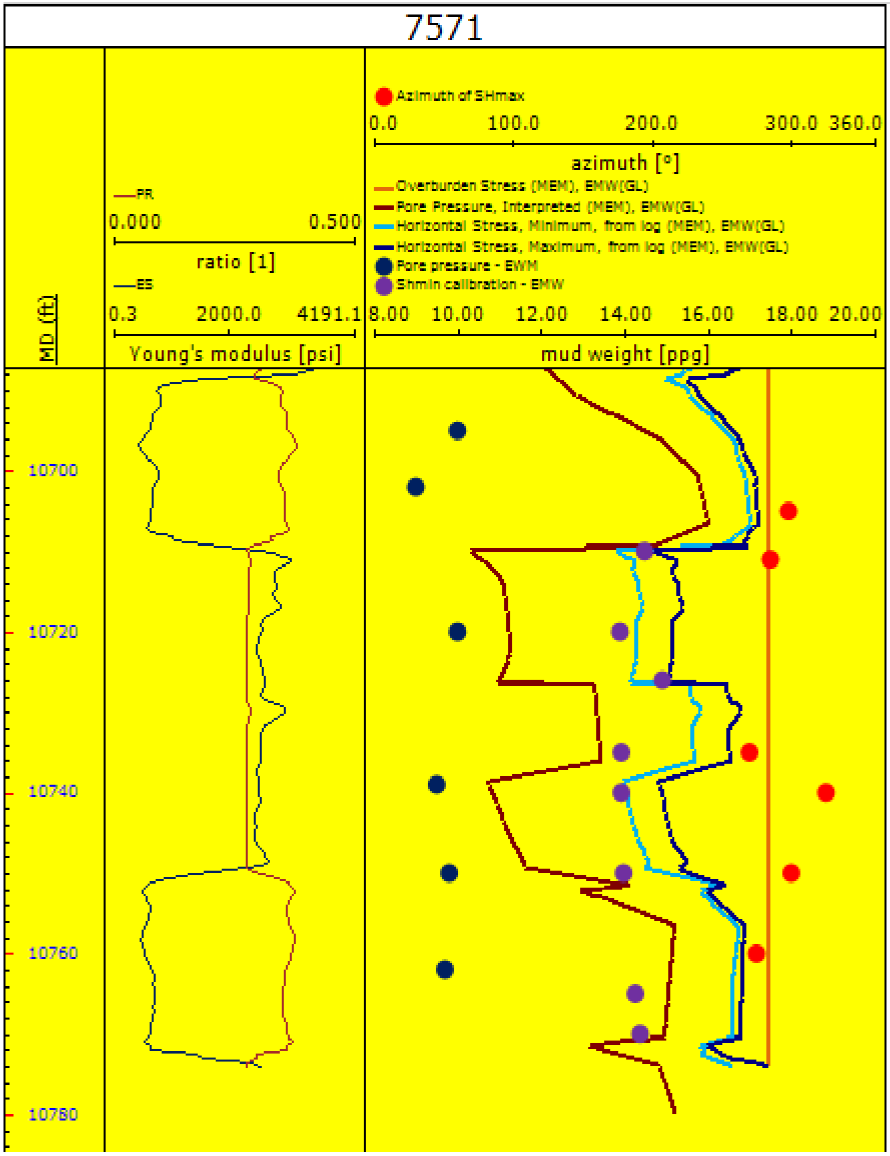

Fig (20). Track 3 shows calibration data plotted against the Mud weight window (Pore pressure Sig H max, Sig h min and Overburden).

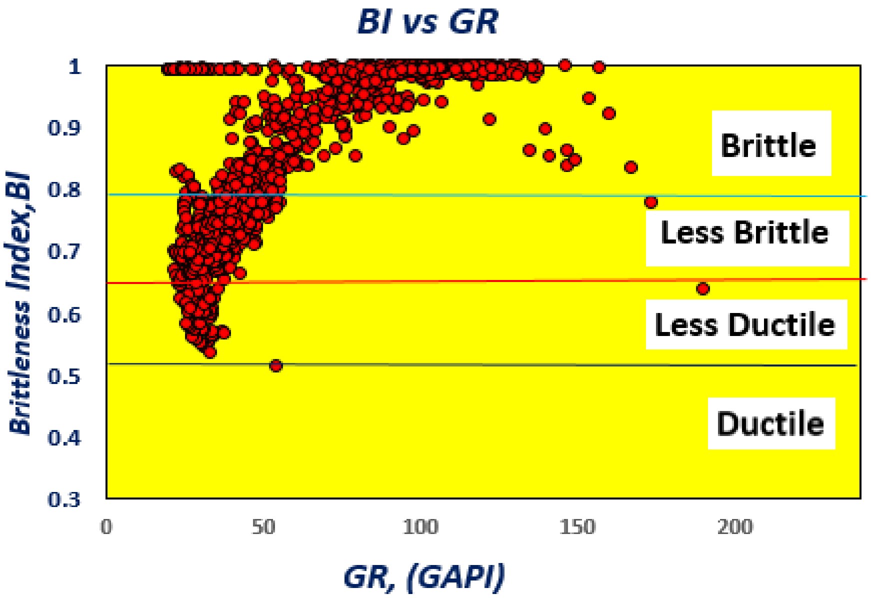

Fig (21). The log plots of brittleness estimated from geomechanical and elastic properties plotted against gamma ray log of Bakken formation.

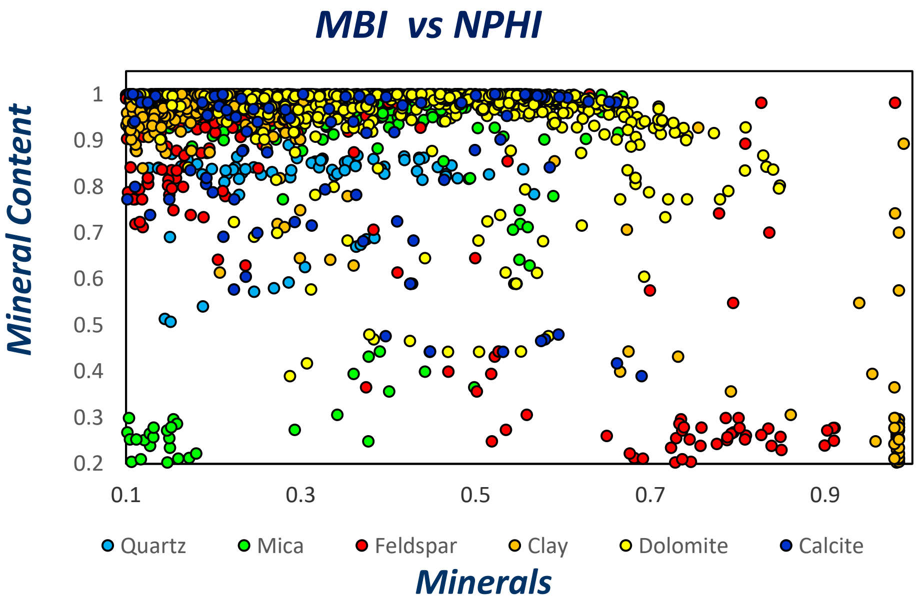

Fig (22). Cross plot of Mineral content versus Neutron Porosity.

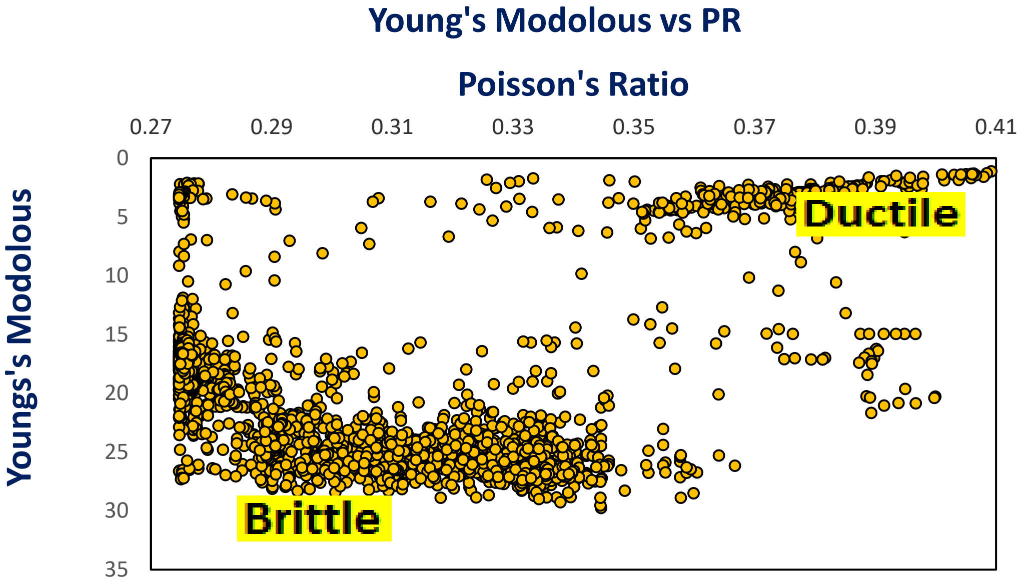

Fig (23). Cross plot of Young's modulus versus Poisson's Ratio showing the Brittle and Ductile regions.

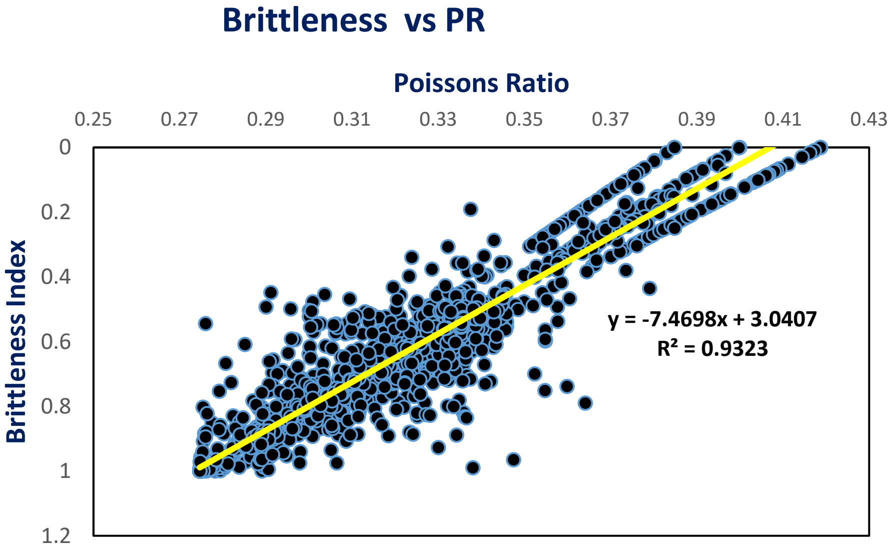

Fig (24). Illustrates the crossplot of mineralogical brittleness versus porosity, which shows formation is less porous and exhibit high brittleness. Fig. 6 high show high brittleness corresponds to low Poisson's ratio.

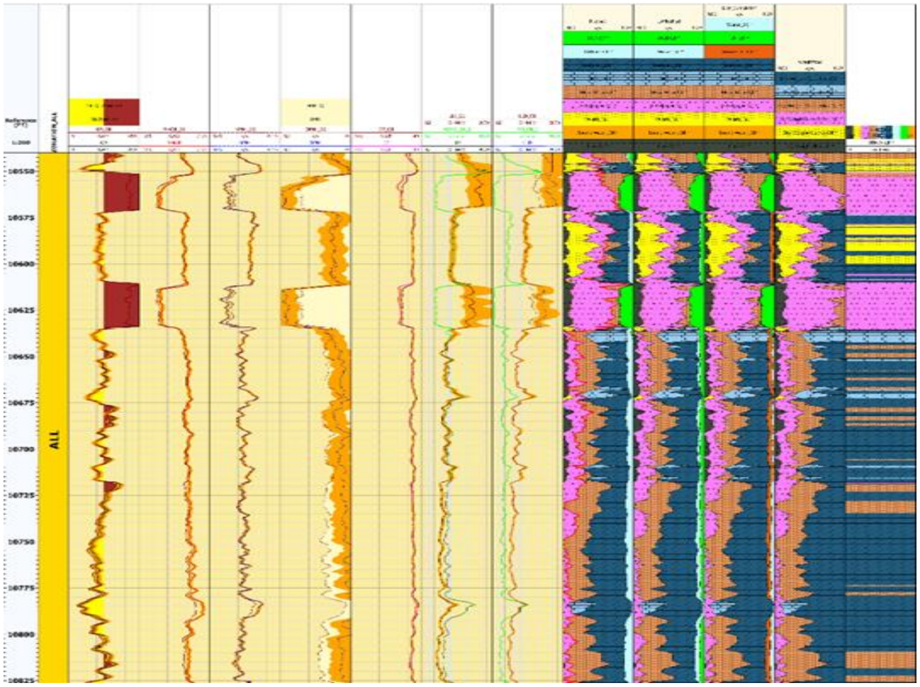

Fig (25). Mineralogical analysis of formation from Deep and Shallow Resistivity Logs.

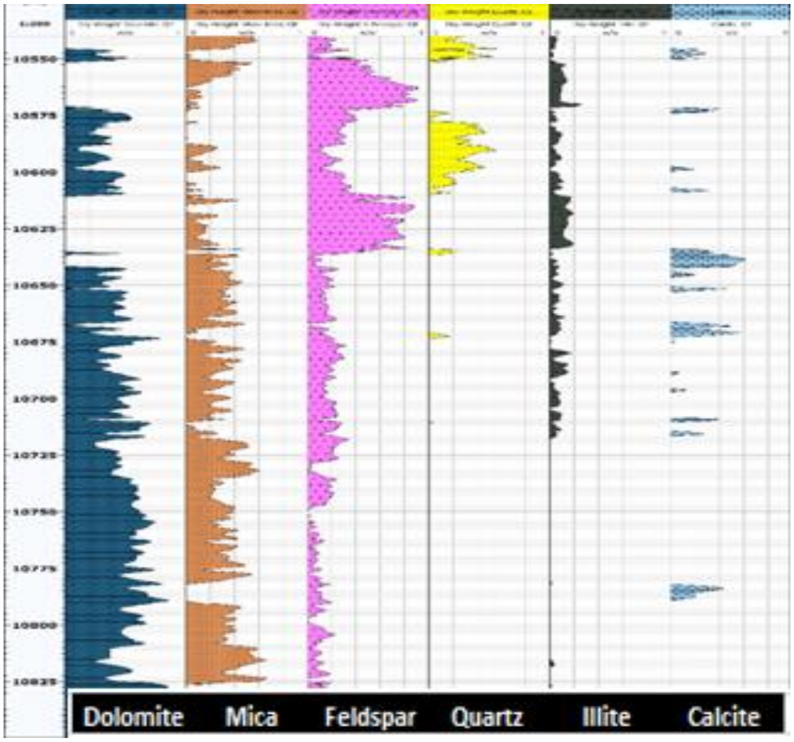

Fig (26). Minerological Analysis of a well in Blue Buttes Field.

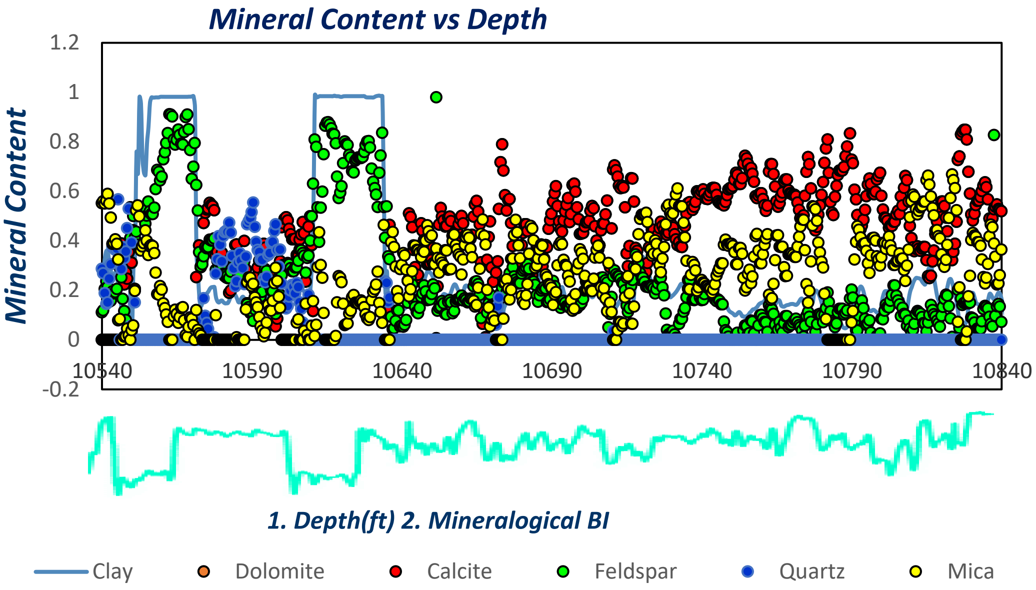

Fig (27). Mineral content versus depth

Table (7) Rock strength Properties obtained from MEM across the Blue Buttes Field

Formation	Depth, ft.	Lithology	E Static, GPa	Poisson's Ratio	UCS, MPa
Upper Bakken	8500-10500	Shale	3--5	0.34-0.38	2--30
Middle Bakken	10300-10800	Sandstone	18--20	0.26-0.28	150-170
Lower Bakken	10200-11300	Shale	3--5	0.34-0.38	1--20

CHAPTER IV

Field scale 3D Geomechanical Model

The objective of this study was to build a field scale Geomechanical model and identify the zones of instability of blue buttes field for Bakken formation in North Dakota. Rock elastic and mechanical properties including magnitude and stresses were determined by constructing 1-D Mechanical Earth Models of 21 wells in the field. Constructed mem is representation of elastic, mechanical, rock strength properties, stresses as a function of depth with Inyan Kara formation being the reference layer for the target reservoir buried at a depth of 10500ft.

The 3D Model workflow involves a series of modelling process, the first step in creating a 3D Geomechanical model is calculating the mud weight window from log based 1d MEM, the next step is creating geological model of the field followed by importing data such as surfaces (stratigraphic horizons and faults), wells, formation tops (Markers), creating the 3d structured of the area and generating grids overs the area of interest. The last step is population of Geomechanical properties on to the grid. The geological model of the field was created in Petrel and moved to Jewel suit software for population the Geomechanical properties. To populate the geomechanical properties obtained calculated from rock elastic and mechanical properties from 1D Geomechanical model. Logs of each well in the field were merged and populated by Baker Hughes team. Several populating techniques were available for populating the data into grids, Fig (33) shows the 3D MEM workflow

3d Geomechanical Model workflow.

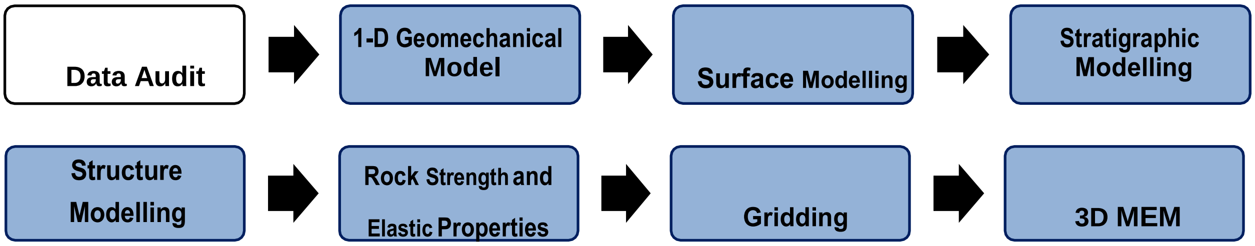

Fig (28). 3D MEM workflow.

Fig (34) shows the 3D view of wells which is plotted based on Bell Wire Center V&H Coordinates reference system. Out of 20 well 18 wells are vertical wells.

Table (): List of well details used for this study.

WELL No.	NDIC WELL No.	TYPE	Depth	KB
1	7571	VERTICAL	14893	2486
2	7572	HORIZONTAL	16141	2417
3	8081	VERTICAL	11392	2357
4	8163	VERTICAL	12704	2457
5	8269	VERTICAL	12675	2423
6	8301	VERTICAL	12863	2561
7	8632	VERTICAL	12721	2400
8	8997	VERTCAL	14300	2538
9	9057	VERTICAL	14164	2506
10	9184	VERTICAL	14060	2421
11	9267	VERTICAL	12707	2391
12	9414	VERTICAL	12685	2355
13	9539	VERTICAL	14047	2436
14	9558	VERTICAL	12635	2331
15	9562	VERTICAL	12624	2328
16	9737	VERTICAL	12604	2270
17	9945	VERTICAL	12900	2486
18	10104	VERTICAL	12870	2451
19	10132	VERTICAL	12525	2305
20	10363	VERTICAL	12715	2462
21	11295	VERTICAL	12827	2327
22	16829	HORIZONTAL	17217	2357

Fig (29). 3DView of Wells in Blue Buttes Field

Formation	Depth, ft.	Thickness, ft.	lithology
Upper Bakken	10600-10750	30	Shale
Middle Bakken	10700-10850	40	Sandstone, Dolomite, Siltstone, shale.
Lower Bakken	10800-11000	38	Shale

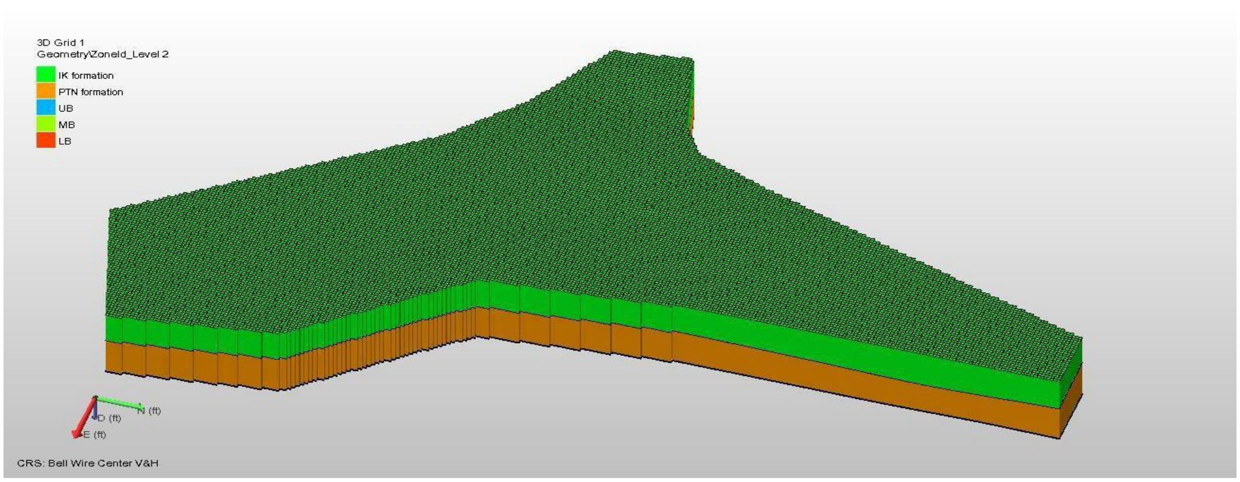

Fig (30). View of Stratigraphic formations of blue buttes field.

Surface Modelling:

Surface modeling involves importing surfaces to create a stack of layers and create 3D grids over the entire section. Figure shows the surfaces (Inyan Kara-IK, PTI, UP-Upper Bakken, MB-Middle Bakken, LB- Lower Bakken and TF-Three Forks). Fig () shows the stratigraphic surfaces with wells. The shallowest surface available as an overburden surface is Inyan Kara Formation, which is limestone, which is the primary source of saltwater disposal in Bakken.

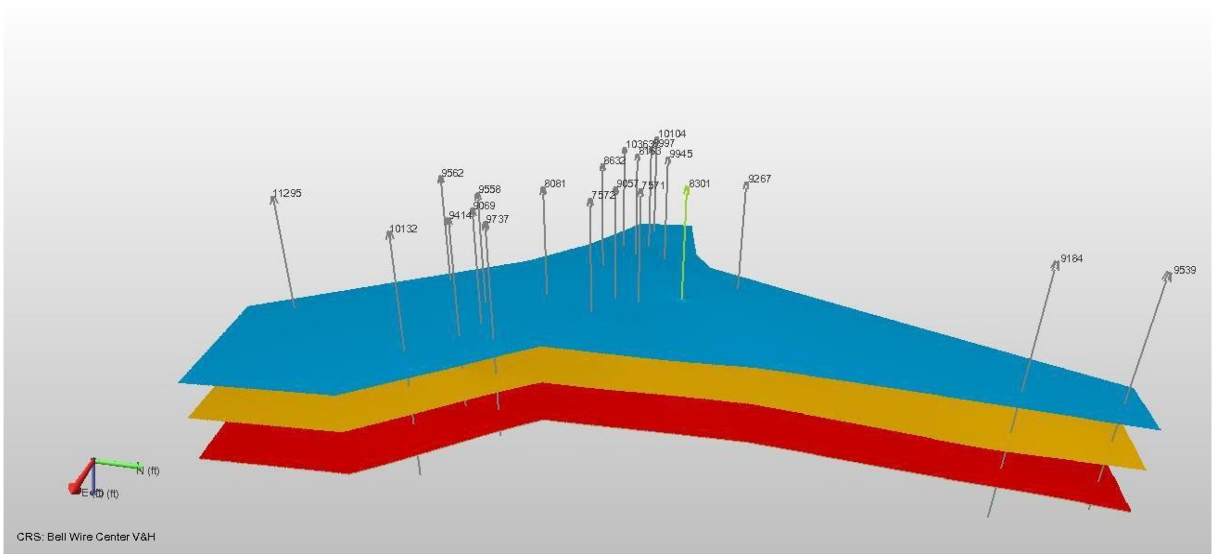

Fig (31). Surfaces with wells of Blue Buttes field.

Structure Modeling

Structure modelling deals with creating a 3d structure of field by utilizing the previously imported data (Horizons and Faults). The 3D structure is the base for the 3D grid on which Geomechanical properties are populated to show the lateral and vertical variation of anisotropy. The boundary polygon of the field with well locations is shown in the figure (), A 3D structure was constructed from stratigraphic layers. As Bakken is a quiet and continuous formation, with no faults and anticlines in blue buttes field. Fig () shows the 2D structural model.

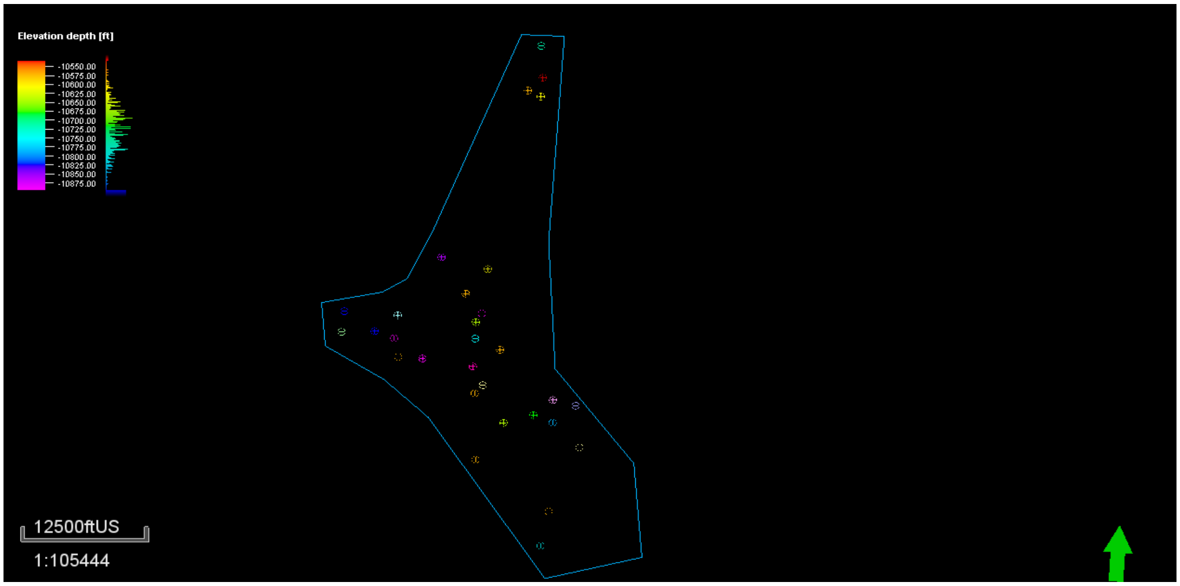

Fig (32). Polygon of Blue buttes field showing well locations.

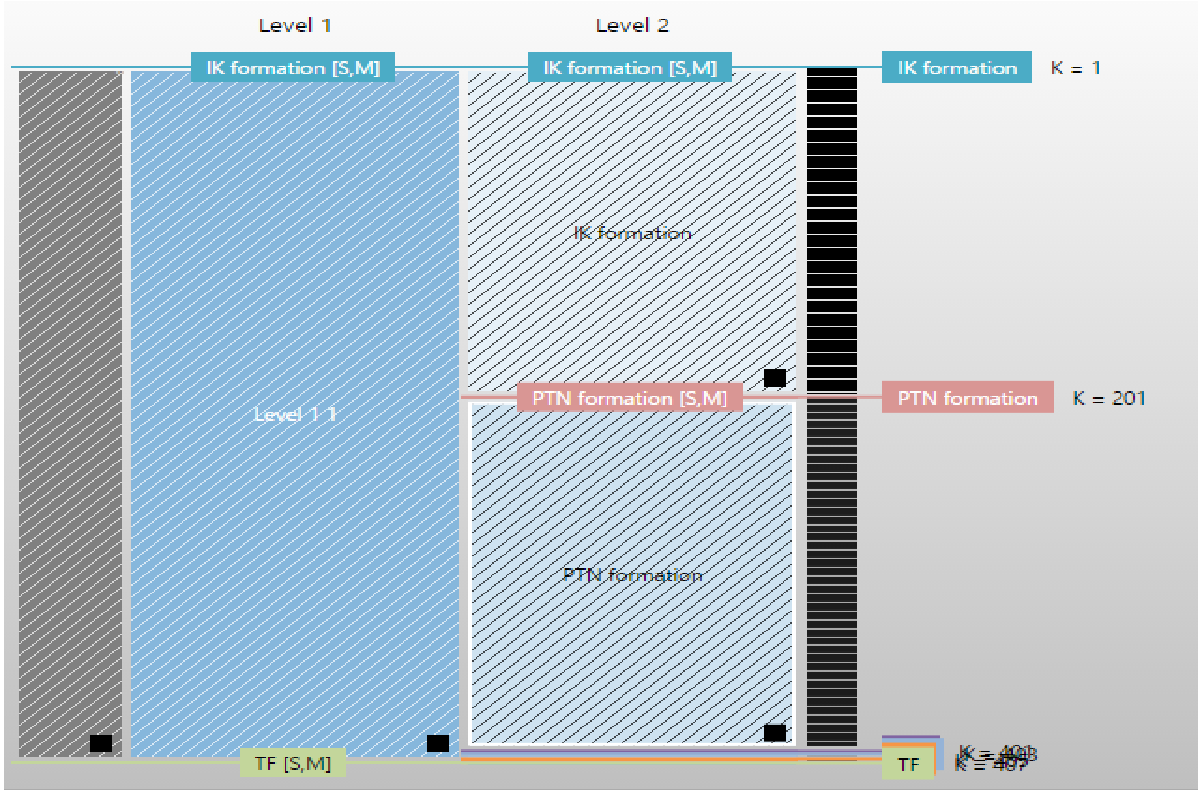

Fig (33). 1-D View of stratigraphic Surfaces

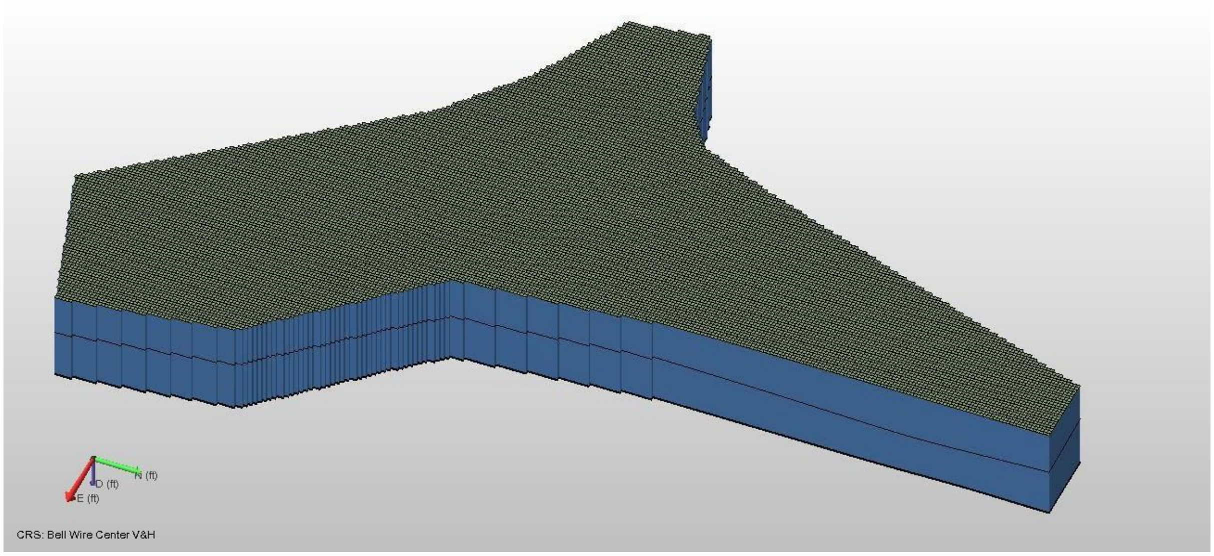

Fig (34). 3D Grid of Blue Buttes field.

Gridding: After creating structure model of the field, 3D Grid was generated to populate Geomechanical properties. The grid is constructed only for Upper, Middle and lower Bakken Layers. The horizons are constructed based on surfaces, and the target reservoir is located at a depth of 10600 ft. approximately. No faults were encountered in the Blue Buttes Field. Also, no seismic data was available for the field.

Easting	1399200 ft
Northing	1294600 ft
TVDSS	4800
I Step Length	200 ft
J Step Length	200 ft
I Step Dimension	33400 ft
J Step Dimension	57800 ft
Number of Steps I	167
Number of Steps J	289

Property modelling

Once the 3D structure for the target field is constructed the stress profiles of each well in the field is combined and propagated on to 3D grid by populating techniques. As Bakken formation is less prone to tectonic activity, the 3D model for the field was cake layer model. Inverse Distance Weighted Method was used to populate rock properties. Effective stress ratio method was used to for modelling the stresses. Pore pressure was calculated based on Eaton's method of Normal Compaction Technique (NCT), for this study pore pressure reference was taken from the Inyan Kara formation which is the shallowest surface data available. Fig () shows the field scale view of the grid populated with pore pressure.

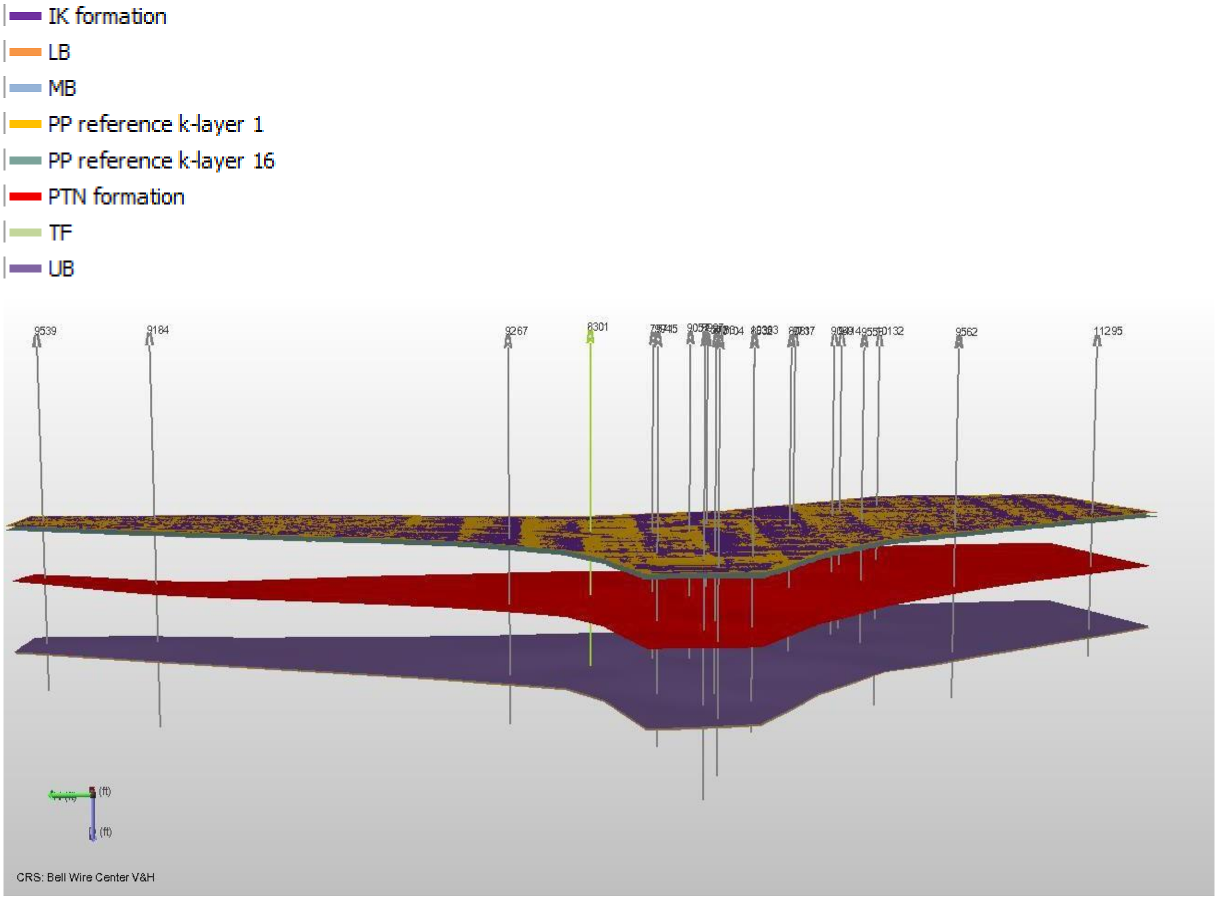

Fig (35). Pore pressure reference taken from Inyan Kara formation which is the shallow surface available

Pore Pressure

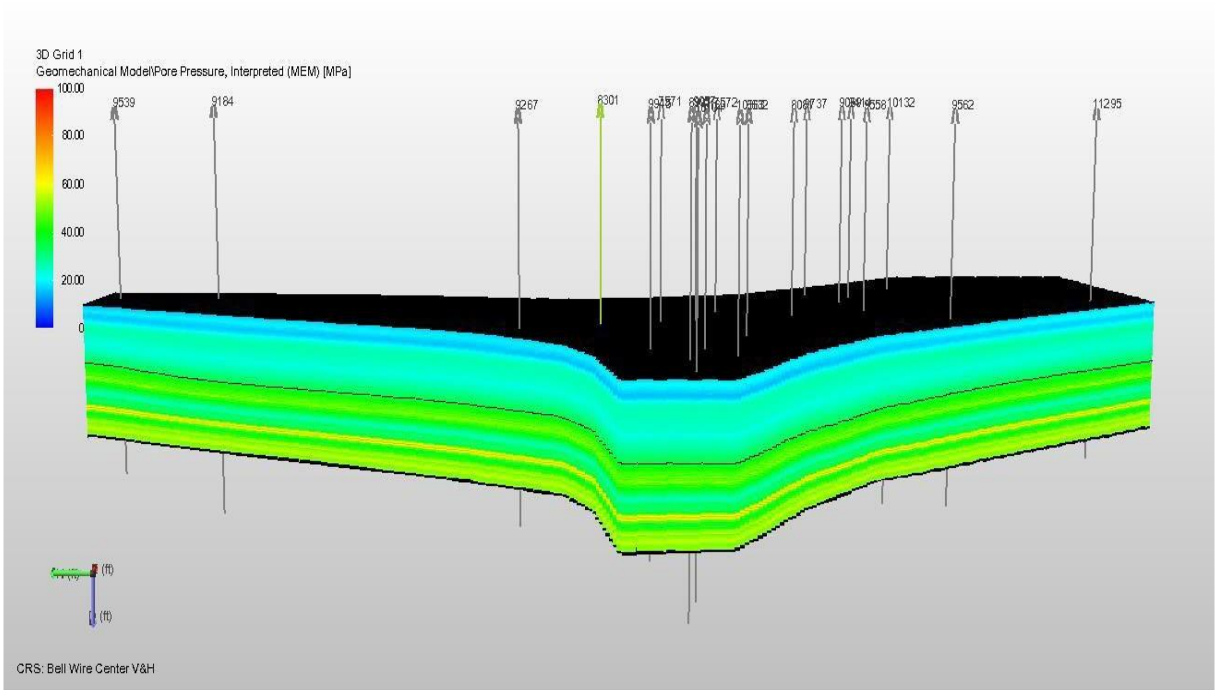

Fig (36). View of Blue Buttes grid populated with Interpreted Pore Pressure.

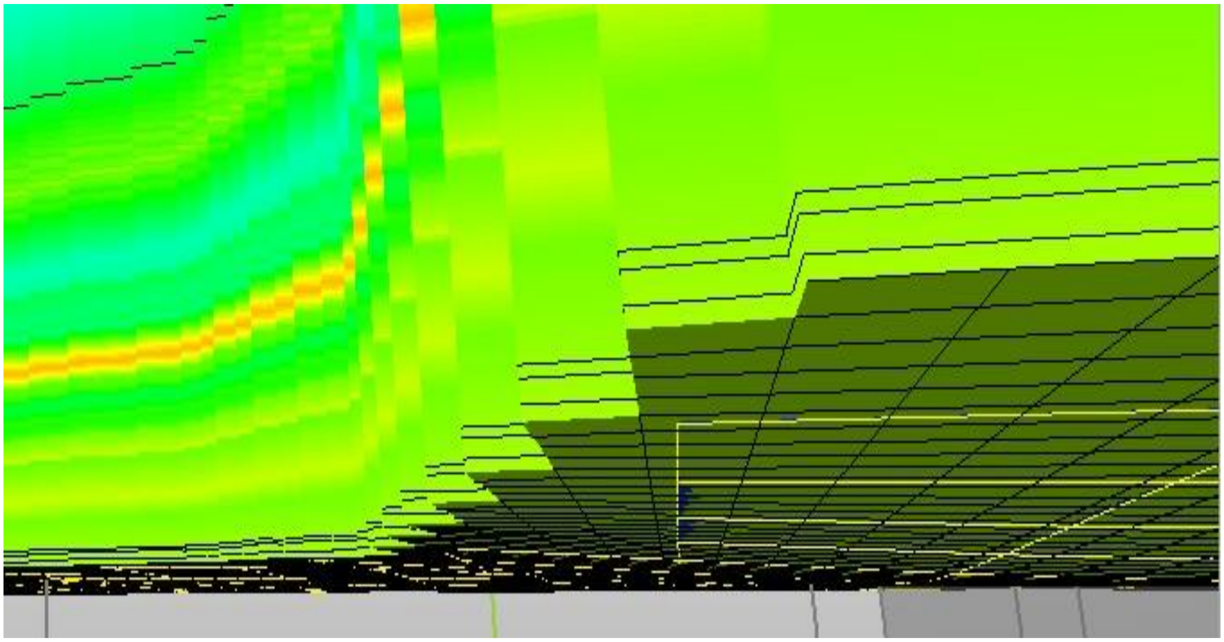

Fig (37). View of Interpreted Pore Pressure across Bakken Formation.

Overburden stress

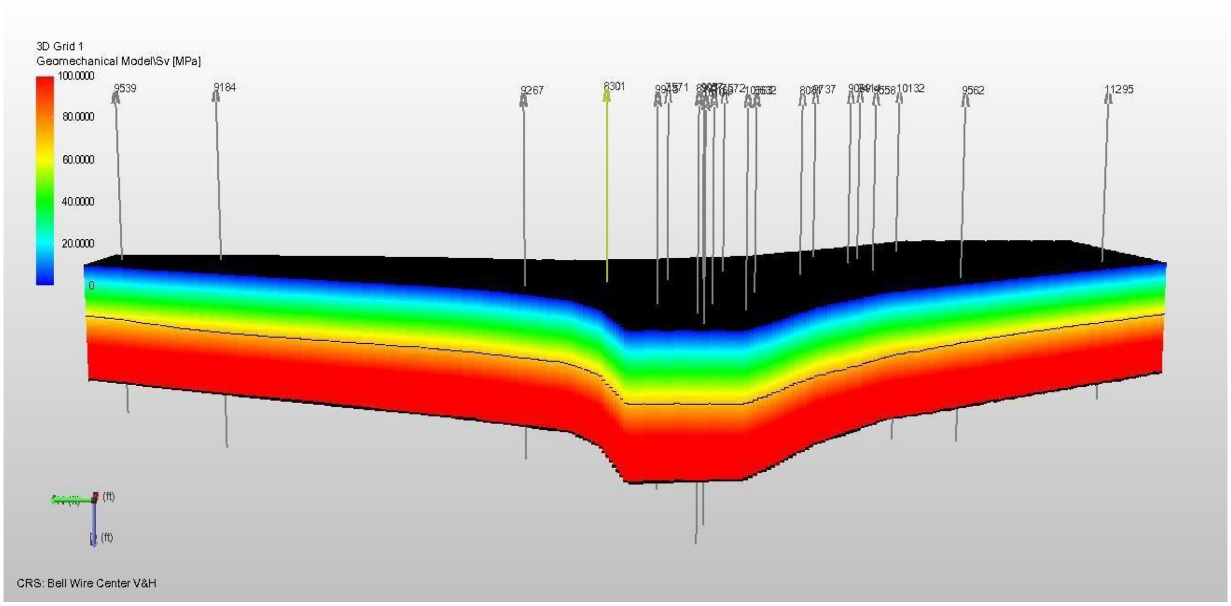

Fig (38). View of Blue Buttes grid populated with Overburden Stress.

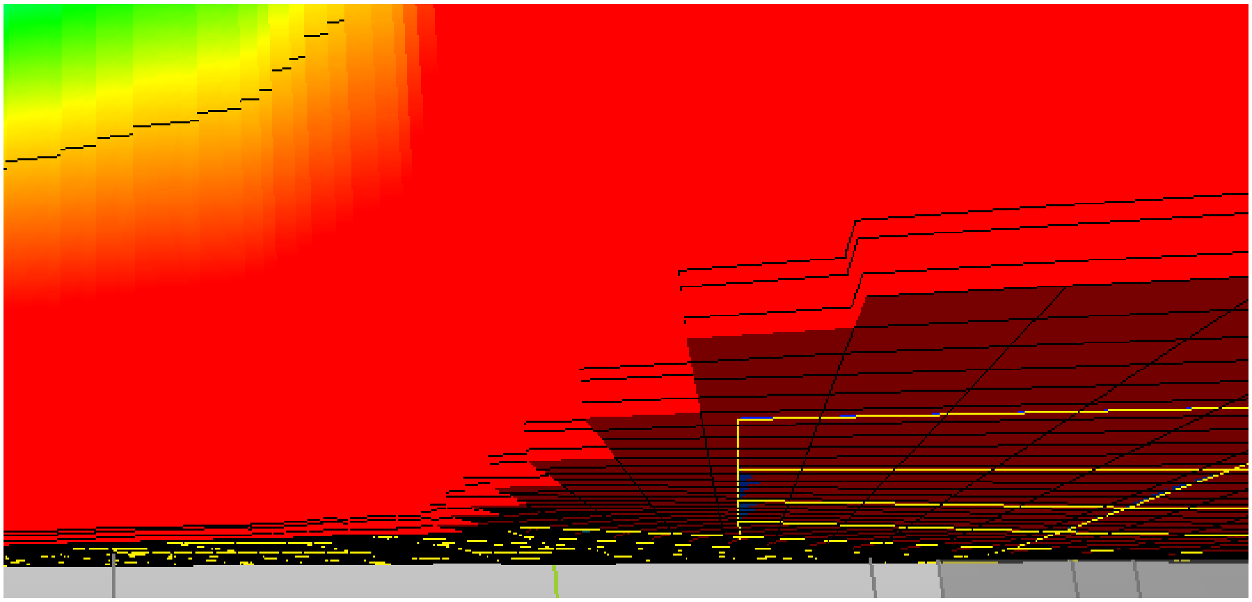

Fig (39). View of Overburden Stress across the Bakken formation in Blue Buttes Field.

Maximum and minimum stress in the field were calculated by considered tectonic strain coefficients based on stress ratio method. Based on the calibration data available for the field ε_s and ε_y are parameters corresponding to tectonic strains coefficients were 0.10 and 0.30 in the field.

Minimum Horizontal Stress

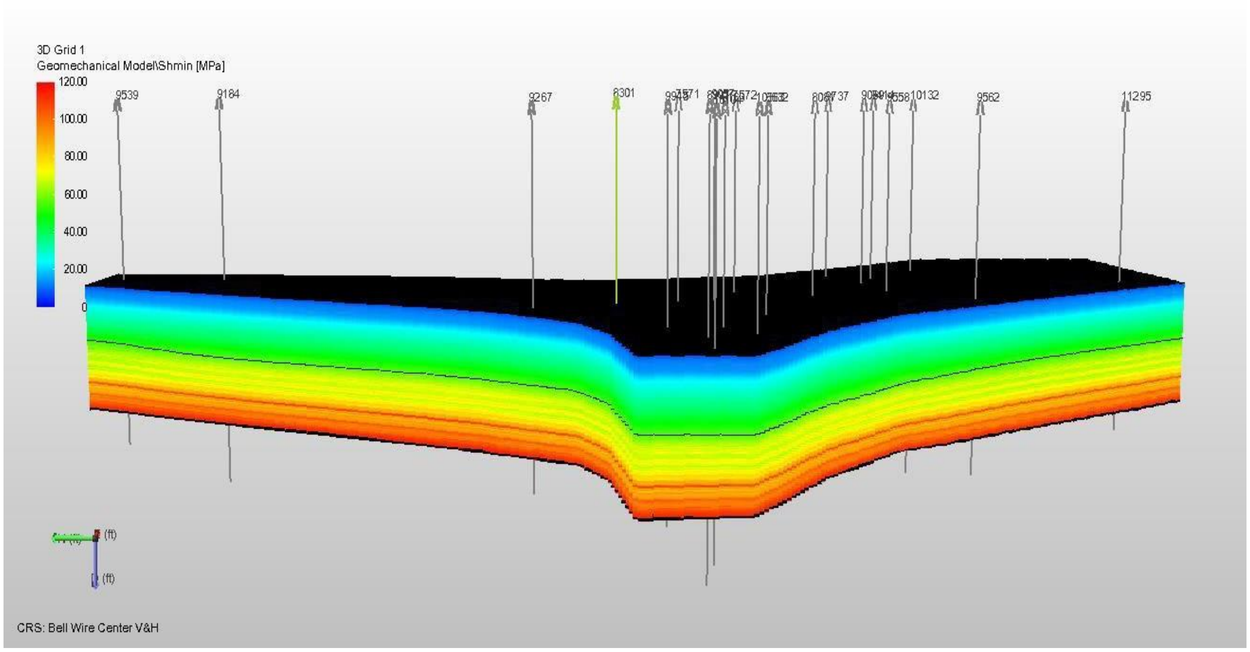

Fig (40). View of Blue Buttes grid populated with Minimum Horizontal Stress.

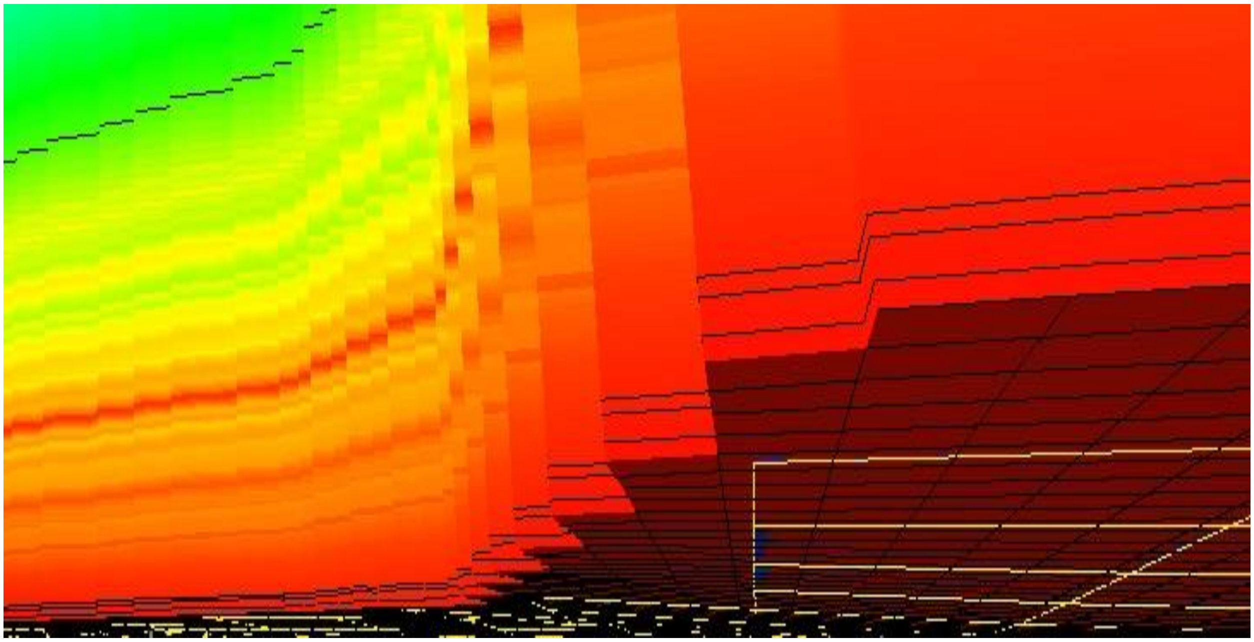

Fig (41). View of Minimum Horizontal Stress across the Bakken formation in Blue Buttes.

Field.

Maximum Horizontal Stress

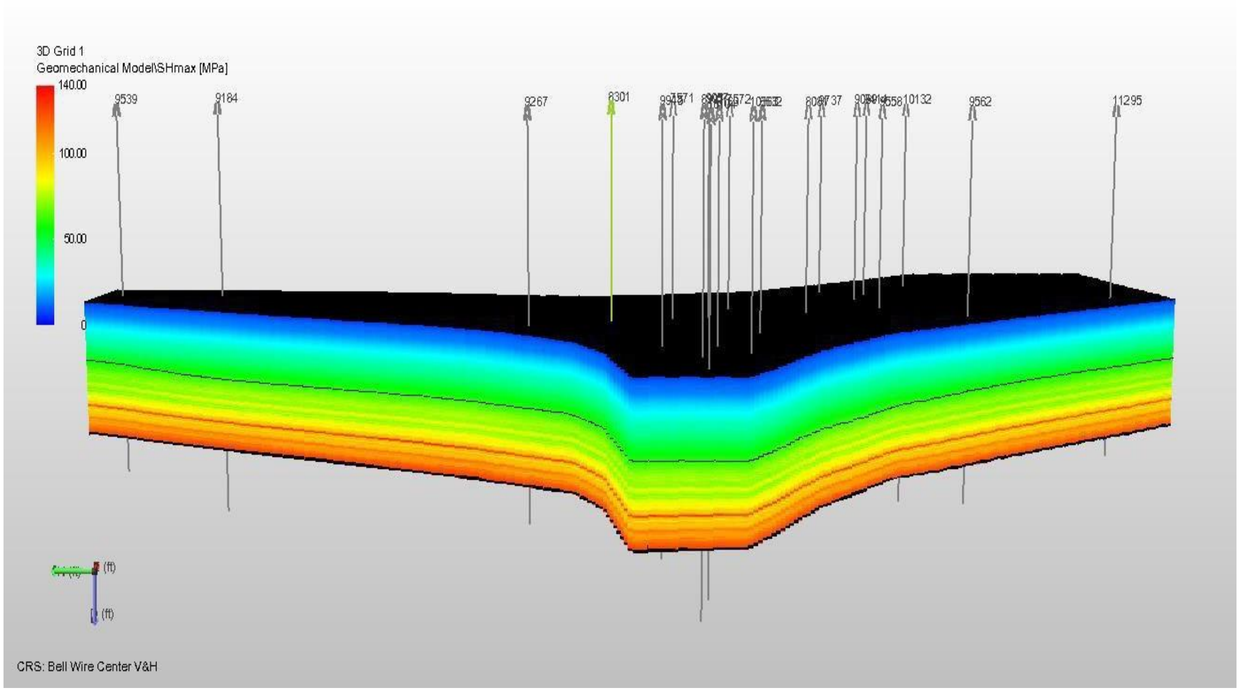

Fig (42). View of Blue Buttes field grid populated with maximum horizontal stress.

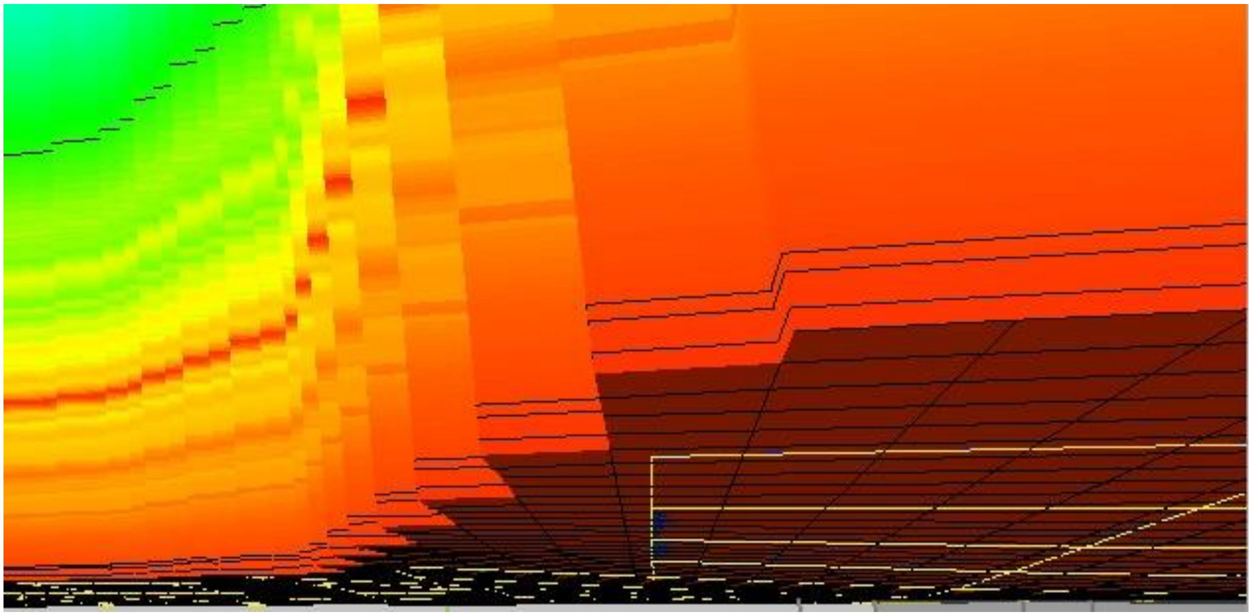

Fig (43). View of Maximum Horizontal Stress across the Bakken formation in Blue Buttes Field.

Minimum Fracture Gradient

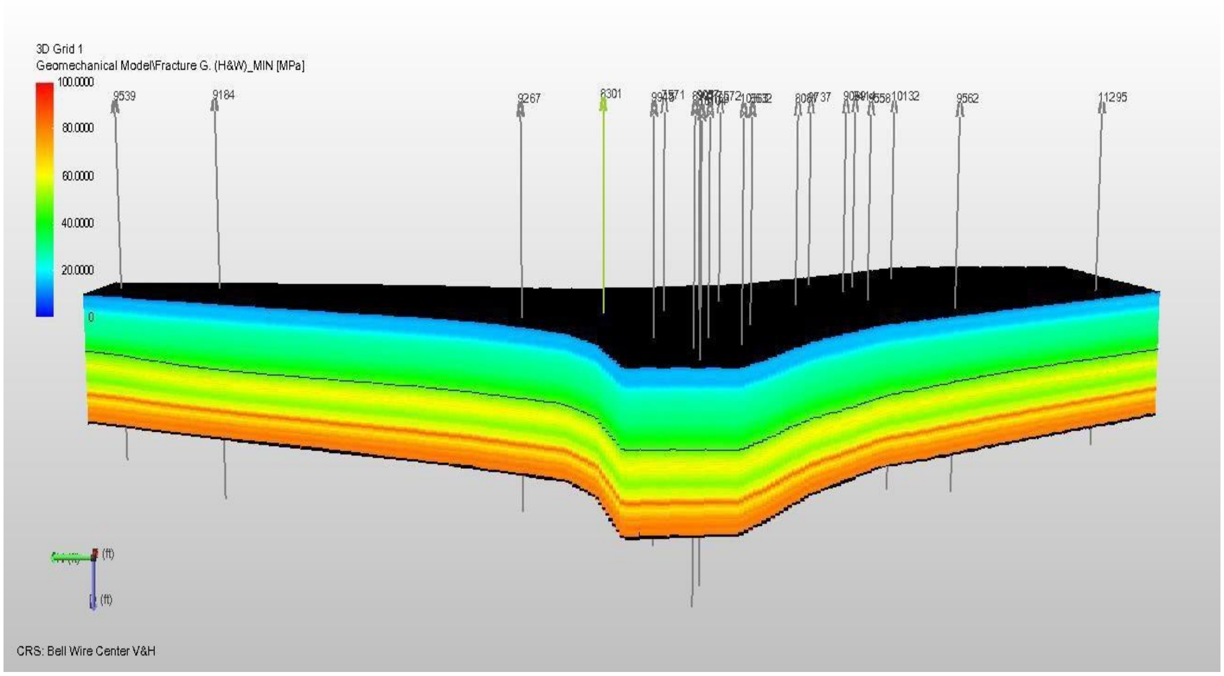

Fig (44). View of Blue Buttes grid populated with Minimum Fracture Gradient.

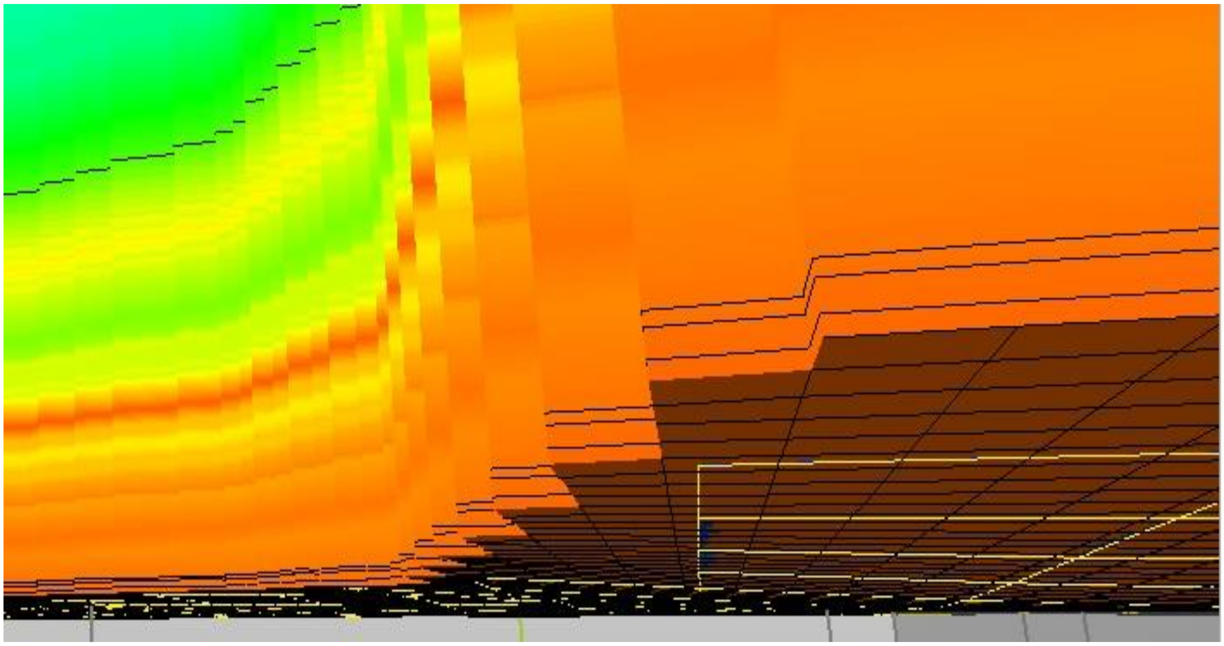

Fig (45). View of Minimum Fracture Gradient across the Bakken formation in Blue Buttes Field.

Density Composite

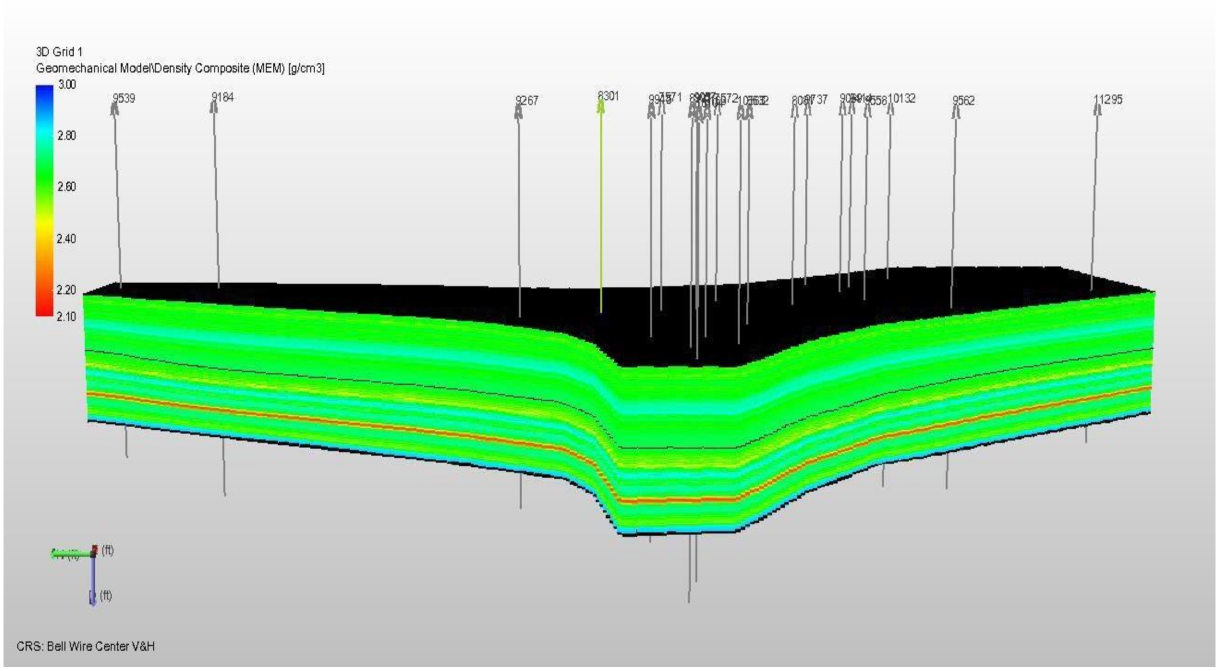

Fig (46). View of Density Composite across the Bakken formation in Blue Buttes Field

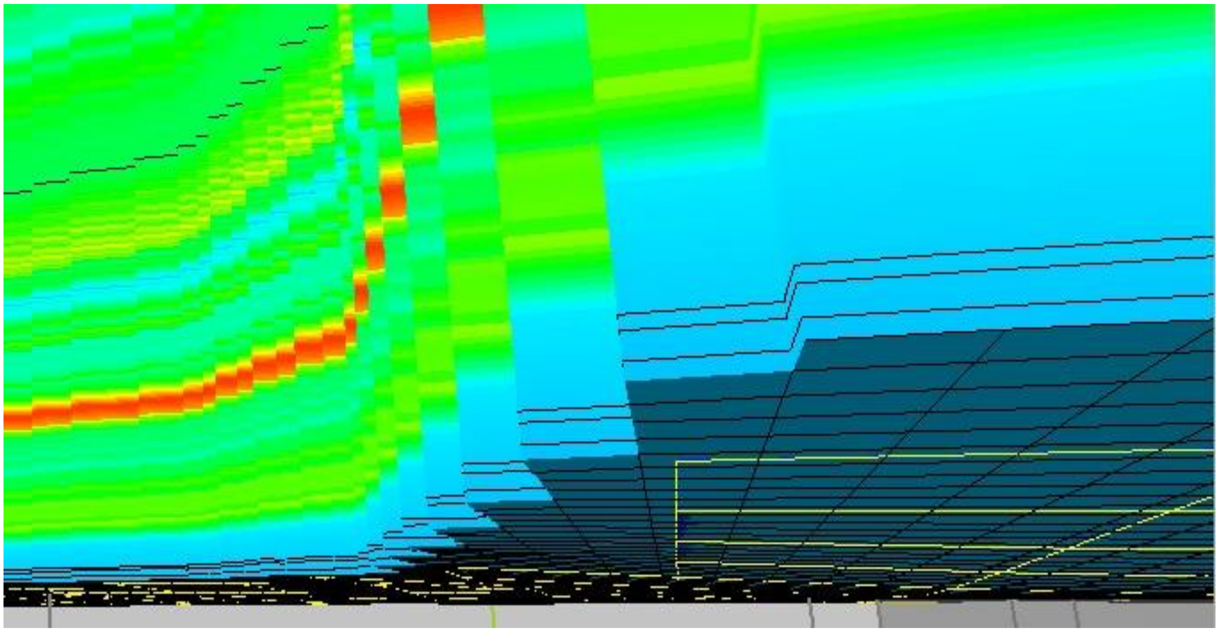

Fig (47). View of Density Composite across the Bakken formation in Blue Buttes Field.

V Conclusions

The mechanical earth model was constructed for Bakken formation in the blue buttes field in North Dakota. The results from 1D model showed the anisotropy as a function of depth. Elastic and rock mechanical properties and sate of in-situ stresses were studied. Although Bakken formation is quite and continuous formation, tectonic strain method was used to calculate the magnitude and orientation of horizontal stresses. The Mud weight window was then calibrated to laboratory experimental data and the data available in the literature. A safe mud weight for Bakken formation is seen in the mud weight window. pore pressure profile shows Upper and lower Bakken as over pressured, middle Bakken as less pressured. A normal stress Regime was observed, and in some wells with zones of mud loss along the middle Bakken layer. Rock elastic and geomechanical properties including mineralogy were investigated. Mineralogical analysis showed that the formation is highly dolomitic due to the presence of high dolomite content, which is the primary cause of high brittleness. Then results from 1D mem was used as an input to construct 3D geomechanical model. a geological model was constructed over the field area and propagated with geomechanical properties on to the grid. The results of state of in-situ stresses is helpful in planning of trajectories to prevent instability related issues. Prolific Bakken formation in Blue buttes field proved to be quite and continuous with absence of faults. The 3D Geomechanical model results can be more precisely characterized as Cake layer model due to similar layering trend across the field. Seismic survey data and image logs were not available, which would have been input of importance in calibration and accuracy.

REFERENCES

[1] Price, L.C. & Lefever, J. (1994). Dysfunctionalism in the Williston Basin: The Bakken/mid-Madison petroleum system. 42. 187-218. Pitman, Janet & C. Price, Leigh & Lefever, Julie. (2001). Diagenesis and Fracture Development in the Bakken Formation, Williston Basin: Implications for Reservoir Quality in the Middle Member. 1653.

[2] Sonnenberg, S.A., and A. Parmudito, 2009, Petroleum geology of the giant Elm Coulee Field, Williston Basin: AAPG Bulletin, v. 93/9, p. 1127-1153.

[3] Pitman, J. K., L. C. Price, and J. A. LeFever, 2001, Diagenesis and Fracture Development in the Bakken Formation, Williston Basin: Implications for Reservoir Quality in the Middle Member: U.S. Geological Survey Professional Paper 1653, 19 p.

[4] Well Log Based Geomechanical and Petrophysical Analysis of the Bakken Formation Alan Alexeyev, Mehdi Ostadhassan, Rehan Ali Mohammed, Bailey Bubach, Seyedalireza Khatibi, Chunxiao Li, Lingyun Kong This paper was prepared for presentation at the 51st US Rock Mechanics / Geomechanics Symposium held in San Francisco, California, USA, 25-28 June 2017.

[5] Plumb, Richard & Stephen, Edwards & Gary, Pidcock & Donald, Lee & Brian, Stacey. (2000). The Mechanical Earth Model Concept and Its Application to High-Risk Well Construction Projects. 10.2118/59128- MS.

[6] Aghajanpour, Azadeh, Seyed Hassan Fallahzadeh, Seyedalireza Khatibi, M. Mofazzal Hossain, and Ali Kadkhodaie. "Full waveform acoustic data as an aid in reducing uncertainty of mud window design in the absence of leak-off test." Journal of Natural Gas Science and Engineering 45 (2017): 786-796.

[7] Wang, Herbert. (2000). Theory of Linear Poroelasticity.

[8] Vernik, l & Bruno, m & Bovberg, c. (1993). Empirical relations between compressive strength and porosity of siliclastic rocks. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 30. 677-680. 10.1016/0148-9062(93)90004-W.

[9] Eaton, Ben. (1975). The Equation for Geopressure Prediction from Well Logs. 10.2523/5544-MS.

[10] Geomechanical Study of Bakken Formation for Improved Oil Recovery Kegang Ling (Principal Investigator, July 1, 2012-December 31, 2013) Zhengwen Zeng* (Principal Investigator, October 1, 2008- June 30, 2012).