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Safe mud weight window design using geomechanical model for existing and new wells

Case study (Abu Gabra South west-1)

تصميم النافذة الآمنة لكثافة الطين بإستخدام النموذج

الجيوميكانيكي للآبار الحالية و الجديدة

دراسة الحالة (بئر ابوجابرة جنوب غرب1)

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الإستهــلال

قَالَ تَعَالَىٰ:

﴿ وَيَرَى ٱلَّذِينَ أُوتُواْ ٱلْعِلْمَ ٱلَّذِىٓ أُنزِلَ إِلَيْكَ مِن رَّبِّكَ هُوَ ٱلْحَقَّ
وَيَهْدِىٓ إِلَىٰ صِرَٰطِ ٱلْعَزِيزِ ٱلْحَمِيدِ ٦ ﴾

[سورة سبأ: ٦]

Dedication

We are dedicating this thesis to our beloved friends, who have meant and continue to mean so much to us

To our great parents, who never stop giving of themselves in countless ways

To all the people in our life who touch our hearts.

Acknowledgment

We would like to express our sincere gratitude to several individuals and groups for supporting me throughout our Graduate study.

First, we wish to express our sincere gratitude to our supervisors, E&P consultant **Eng.Osman Suliman** and **PG.Abdullwahb** , for their enthusiasm, patience, insightful comments, helpful information, practical advice and unceasing ideas that have helped us tremendously at all times in my research and writing of this thesis.

their immense knowledge, profound experience and professional expertise in Data Quality Control has enabled us to complete this research successfully.

Without this support and guidance, this project would not have been possible.
We could not have imagined having a better supervisor our study.

Abstract

Wellbore stability analysis and efficient hole cleaning are highly recommended, which impact drilling cost, instability-related problems are some of the most costly issues that can happen in a drilling operation. Over the years, various studies have been conducted in this area.

The objectives of this study are first to build a geomechanical model for the Abu Gabra SW-1 using wireline logging data, second to utilize a geomechanical model and perform a wellbore stability analysis for the next development well.

One of the most critical factors that to be considered and controlled while drilling operation is the mud weight, this parameter is commonly used to determine the stability of the well, the graphical representation of its safe mud weight window is provided.

The model for the geomechanics is based on the in-situ stresses and rock properties that were obtained from wireline logging data. The mud pressure window and the mud weight are then calculated using the results of the study. The results of the exercise are then used to predict the mud weight window for the next development well.

Hence, we can minimize non-productive time NPT and the cost of drilling significantly by preventing some drilling problems. Based on the IP results, the mud pressure window is calculated and a mud weight is recommended for the Abu Gabra SW-1 , and can be calibrated for the next development well.

Based on the field geomechanical model, wellbore stability analysis was applied to find the mud weight in which a well is stable when having no safe mud weight window.

التجريد

تحليل استقرارية البئر و عملية استخراج الفتات الصخري المثلى مطلوبة بشده، والتي بدوها تؤثر على تكاليف الحفر و المشاكل المتعلقة بعدم استقرارية البئر. و تعد من أكثر المشكلات تكلفة التي يمكن أن تحدث في عملية الحفر. على مر السنين ، أجريت دراسات مختلفة في هذا المجال.تتمثل أهداف هذه الدراسة اولا في بناء نموذج جيوميكانيكي لبئر أبو جابره جنوب غرب 1 بإستخدام بيانات تسجيل الأبار، ثانيا إستخدام نموذج جيوميكانيكي و إجراء تحليل الإستقرارية للبئر الجديد.

تعتبر كثافة طين الحفر من أهم العوامل التي يحب التحكم فيها أثناء عملية الحفر، و يستخدم هذا المعامل لتحديد ثبات و إستقرارية البئر، يتم توفير التمثيل البياني لحدود كثافة الطين المثلى و الامنة.

يعتمد النموذج الجيوميكانيكي على الضغوط في الموقع وخصائص الصخور التي يتم الحصول عليها من بيانات تسجيل الابار حيث يتم حساب حدود كثافة الطين باستخدام نتائج الدراسة ثم يتم استخدام النتائج للتنبؤ بحدود كثافة الطين للبئر الذي سيتم حفره تاليا.

بالتالي ، يمكننا تقليل الوقت غير المنتج و تكلفة الحفر بشكل كبير عن طريق منع بعض مشاكل الحفر و بناءً على نتائج الدراسة يتم حساب حدود كثافة الطين و يوصى باستخدام حدود كثافة الطين لـ أبو جابرة جنوب غرب 1 و يمكن معايرته من أجل عمليات التطوير لحفر البئر التالي.

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Abbreviations:

BHA	Bottom Hole Assembly
NPT	Non-Productive Time
MW	Mud Weight (ppg)
WBM	Water Based Mud
OBM	Oil Based Mud
LOT	Leak Off Test
IFT	Integrity Formation Test
ROP	Rate Of Penetration
YP	Yield Point
HPHT	High Pressure High Temperature
ABM	Air Based Mud
UBD	Under Balance Drilling
WOB	Weight On Bit
RPM	Revolution Per Minuet
AV	Apparent Viscosity
ECD	Equivalent Circulating Density
IP	Interactive Petrophysics
UCS	Unconfined Compressive Strength
PPG	Pore Pressure Gradient
OBG	Overburden Gradient

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Chapter 1
Introduction

1.1. Introduction

1.1.1. Wellbore stability

Maintaining a stable wellbore is of primary importance during drilling and production of oil and gas wells. The shape and direction of the hole must be controlled during drilling. Wellbore stability requires a proper balance between the uncontrollable factors of earth stresses, rock strength, and pore pressure, and the controllable factors of wellbore fluid pore pressure, and the controllable factors of wellbore fluid pressure and mud chemical composition.

Hole size reduction can occur when plastic rock is squeezed into the hole, and hole enlargement can be caused by caving shales or hard rock spalling. If the wellbore fluid pressure is too high, lost circulation can occur as a result of unintentional hydraulic fracturing of the formation; if it is too low, the hole may collapse. Also hole instabilities can cause stuck drill pipe as well as casing or liner collapse. These problems can result inside tracked holes and abandoned wells. Since 1940 considerable effort has been directed toward solving rock mechanics problems associated with wellbore instabilities, and much progress has been made during the past 10 years toward providing predictive analytical methods. (J.B. Cheatham, 1940)

1.1.2. Hole cleaning

Hole cleaning is the ability of a drilling fluid to transport and suspend drilled cuttings, it is a very important operation that requires careful procedures. Despite recent improvements in hole cleaning procedures, debris continues to remain in the wells, which makes operations difficult to perform during drilling. When cuttings are not removed from the borehole, they accumulate in the well bottom and form a cuttings bed around the Bottom Hole Assembly (BHA). This result in pack off which are responsible for a NPT’s (Non-Productive Time) such as stuck pipes, hole instability, BHA lost issues or problems etc. (Jorg, 2012).

There are many parameters which help determine hole cleaning conditions, but a proper selection of the key parameters will facilitate monitoring hole cleaning conditions and interventions. The aim of hole cleaning monitoring is to keep track of borehole conditions including hole cleaning efficiency and wellbore stability issues during drilling operations.Adequate hole cleaning is the one of the main concerns in the underbalanced drilling operations especially for directional and horizontal wells.

Drilling fluid systems are designed and formulated to perform efficiently in hole cleaning. the active drilling-fluid system comprises a volume of fluid that is pumped with specially designed mud pumps from the pits, through the drilling string and the bit, up the annular in the wellbore, and back to the surface for solids removal and treatments as needed.

Drilled cutting transportation from the bottom hole to the surface to maintain efficient hole cleaning is a challenging issue while drilling vertical, deviated, high angle and extended reach wells, this is attributed to the huge number of parameters affecting the ability of drilling fluid to get rid of the drilled solids or chips, these parameters include:

- Wellbore parameters:
    - Flow rate and flow regimes.
    - Hole size.
    - Drill pipe size
    - Hole inclination.
    - Rate of penetration.
    - Washout.
    - Wellbore stability.
- Cutting parameters
    - Cutting size.
    - Cutting shape.
    - Cutting density.
    - Cutting dispersion.
    - Cutting concentration.
- Drilling fluid parameters
    - Rheology
    - Mud density

All of the above parameters are experimentally confirmed to play an important role in the efficiency of the drilling mud to get rid of the chips and keep a clean hole. (Abdulahmid, et al., 2019).

1.2. Problem statement

Wellbore instability illustrates in masses of issues identical to ineffective and poor hole cleaning lead to several problem include stuck pipes, sticking, annular pack off, loss of circulation, formation damage and fracturing, excessive torque and drag, troubles in logging and cementing, difficulties in casings landing, slow drilling rate and unbalanced hydrostatic pressure. Also drill cuttings in the hole may cause wear and tear of the drill string and reduce the rate of penetration, thereby increase the drilling expenditure (cost and time); hence, there is need to handle the situation properly, consequently to all of the above operators lose the well.

In our research we use the geomechnical model which are description of rock mechanical properties, rock strength and in-situ stresses in the subsurface to come out with safe mud window which presents confers the optimum mud weight to be used to hold back the instability problems.

1.3. Objectives

Instability of wellbore can cause a large fraction of the non-productive time so reducing the number of instability events would lead to less non-productive time and therefore higher cost saving. Since most of these instability events stem from geomechanical reasons, analyzing the geomechanical condition can help increase knowledge about when and where instability could occur and how it can be prevented.

The objectives are :

- Build a geomechanical model for Abu Gabra SW-1 using available data from the well logging with structural information.
- Using geomechnical model to calculate optimum mud weight for drilling.
- Utilizing the geomechanical model and perform a wellbore stability analysis for the next development well.

1.4. Project layout:

Chapter one:

Represent a brief introduction related to our project

Chapter two:

Explains the literature review

Chpter three:

Customize our method and program used to mention the problems which called by methodology

Chapter four:

we analyzedthe collected data and make prediction calculations of optimum mud weight to drill the well and the way to calibrate the data and result for new wells

Chapter five:

We put conclusion and our recommendation and references helped us to understand these proplems

Chapter 2

LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1. Literature Review

M.R. Mclean and M.A Addis et al (1990) discussed the effect of strength criteria on mud weight . They proposed a Homogenous, Isotropic, Wellbore stability analysis for the prediction of the onset of failure and consequently the mud weights required to prevent hole instability.

Santarelli et al. (1996) presented wellbore instability problems occurring in a developed field in Italy. The problems were back analyzed in regard to the mud types, mud weights, azimuths, and stress regime. More drilling problems like reaming and stuck pipe happened in a particular azimuth. This evidenced the existence of anisotropic distribution of horizontal stresses, which was not known because of absence of any in-situ stress related data.

(Saasen and Løklingholm, 2002) as noted by cuttings transport efficiency is closely related to annular pressure loss. The cuttings transport efficiency of drilling fluids increases with increasing shear stress acting on the bed which in turn contributes to frictional pressure loss. Therefore, frictional pressure loss estimation is important to study the hole cleaning behavior of drilling fluids.

Rama Rao, S. Grandi, M.N. Toksov et al (2003) presented geomechanical modeling of in-situ stresses around a borehole. Authors present a modelling of the in-situ stress state associated with the severe hole enlargement of a wellbore. Geomechanical information is relevant to assure wellbore stability, i.e., to prevent damages in the formation and later on, the casing.

Mr. Shams Elfalah Ahmed Alblola from Sudan university (2009) studied greater Bamboo area block 2A of unity in southern Sudan, the study starts by collecting data, evaluating and analyzing, logical arrangement of daily information and the other running operations, run a correlation analyzing, designing, targeting and vice versa to get the optimum. The failure envelope stress, mud pressure and mud weight calculation were done to prevent hole collapse in Bamboo west field.

Baker Hughes (2009) The factors which affect the carrying capacity of the fluid includes: fluid density and rheology, annular velocity and flow regime, pipe rotation, cuttings density, size and shape of the cutting, and annulus size and eccentricity. An optimum drilling fluid is expected to lift cuttings from the wellbore and suspend them when circulation is stopped.

Ali Piroozian (2012) have experimentally investigated the influence of the drilling fluid viscosity, velocity and hole inclination on cuttings transport in horizontal and highly deviated wells.

Ayad A. Al-Haleem, Abd Al-Razzaq (2016) efficient cuttings transport and hole cleaning are very important factors for obtaining an effective drilling operation. In an inclined and horizontal drilling, hole cleaning issue is a common and complex problem. The results show that parameters for optimum hole cleaning were flow rate, yield point, mud weight, plastic viscosity and rotation of the drill string.

Novriansyah, Rend (2021) from analyzing the wellbore stability are the failure types that happened when carried out the exploration drilling are breakout and shallow knockout, and from the safe mud window that was obtained, recommendations of the optimum mud weight was given to carried out the next drilling activity.

2.2. Theoretical Background

2.2.1. Wellbore stability

Wellbore stability is primarily a function of how rocks respond to the induced stress concentration about the wellbore during several drilling activities, such as drill string movement. In such cases, wellbore stability is impacted by the surge/swab pressure variations from such movement.

2.2.1.1. Vertical stress

Is one of the principle stresses experienced by confined underground formations. The other stresses are minimum and maximum horizontal stresses. The magnitude and direction of these stresses depend on tectonic conditions and influence rock failure. Stresses in underground formations are not uniform and change in magnitude based on direction.

The stresses are generally compressive, anisotropic, and non-homogenous. Stresses increase as depth increases. The principle vertical stress also known as overburden stress is a result of the weight of rock overlying a certain point of measurement. Fractures always form perpendicular to the minimum in-situ stress and in almost all cases, the vertical stress equals the weight of the overburden per unit area. (Wardle & Gerrard, 1973).

2.2.1.2. Horizontal stress

Vertical effective stress is not enough to define the state of stress in a solid. Stresses in horizontal direction are very often different to the stress in vertical direction. The state of stress can be fully defined by the “principal stresses”. These are three independent normal stresses in directions all perpendicular to each other. A stress is a principal stress if there is no shear stress on the plane in which it is applied. Total vertical stress may not be a principal stress, although in most cases it is. If vertical stress is a principal stress, then the two other principal stresses are horizontal. The maximum principal stress in the horizontal case and the minimum horizontal stress.

2.2.1.3. Pore pressure

The pressure of fluids within the pores of a reservoir, usually hydrostatic pressure, or the pressure exerted by a column of water from the formation's depth to sea level. When impermeable rocks such as shales form as sediments are compacted, their pore fluids cannot always escape and must then support the total overlying rock column, leading to anomalously high formation pressures. Because reservoir pressure changes as fluids are produced from a reservoir, the pressure should be described as measured at a specific time, such as initial reservoir pressure.

The lithostatic pressure gradient described by the stress exerted on body of the rock by surrounding rock, it increases with depth below earth surface.

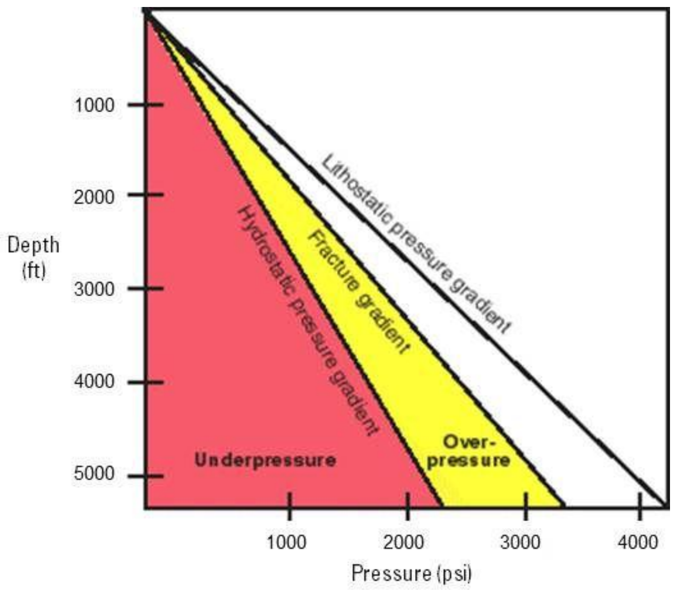


Figure 1: Pressure versus depth plot. (Oilfield Glossary slb.com)

2.2.1.4. Formation fracture pressure

Pressure above which injection of fluids will cause the rock formation to fracture hydraulically. For drilling in the oil and gas industry and geothermal exploration and production, fracture pressure is the pressure required to fracture the formation and to cause mud losses form a wellbore into the induced fractures. Fractures gradient is obtained by dividing the true vertical depth into the fracture pressure. The facture gradient is he upper bound of the mud weight; therefore, the fracture gradient is an important parameter for mud weight design in both stages of drilling planning and operations. If the downhole mud wight is higher than the formation fracture gradient, then the wellbore will have tensile failures (i.e., the formation will be fractured), causing losses of drilling mud or even lost circulation (total losses of the mud). Therefore, fracture gradient prediction is directly related to drilling safety.

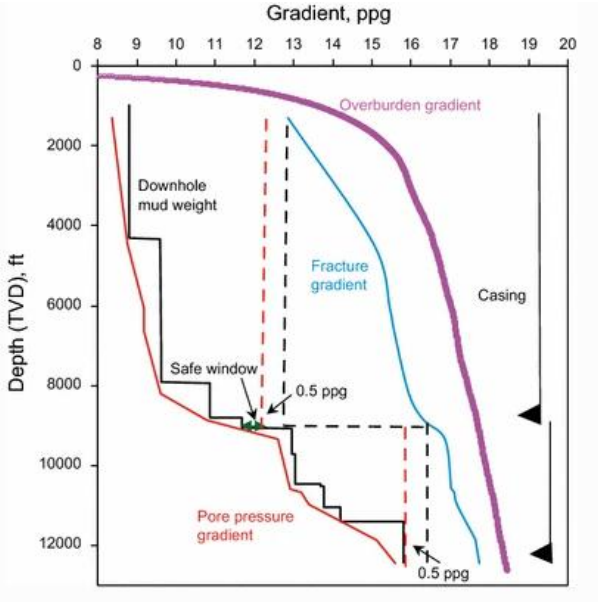


Figure 2: Gradient (ppg) Versus Depth (TVD). (Oilfield Glossary slb.com)

Pore pressure gradient, fracture gradient, overburden stress gradient, downhole mud weight, and casing shoes versus depth. TVD presents the true vertical depth. Unit conversion: 1 ft = 0.3048 m, 1 ppg = 0.12 g/cm3 (Zhang & Yin, 2017).

2.2.2. Drilling Fluids

Cuttings are transported to the surface by circulating a drilling fluid and it is vital for the drilling operator to be able to select an appropriate fluid for each individual well, including the decision of using oil-based or water-based fluids or "muds" (OBM or WBM).

Drilling fluid or drilling mud is one of the most important elements for drilling, DF helps us to avoid many hazard associated with drilling, therefore the properties of the DF must be analyzed and monitored very carefully to fulfill all the necessary requirements to have a good drilling performance. (HERIOT WATT UNIVERSITY, 2005).

2.2.2.1. Functions of drilling fluid:

- To remove and suspend cuttings.
- To prevent formation fluids flowing into the wellbore.
- Maintain wellbore stability.
- Cooling and lubricate the bit.
- Transmit hydraulic horsepower to bit.

- Transport drilling cuttings to surface.
- Gathering information about the formations.
- Provide Buoyancy to the drill string or hold the drilling pipes in suspension.

2.2.2.2. Drilling fluid properties

Density: The main functions of density are mechanical borehole stabilization and the prevention of formation-fluid intrusion into the annulus. Any unnecessary increase in mud density beyond fulfilling these functions will have an adverse effect on the ROP and, under the given in-situ stresses, may cause fracturing of the formation. Mud density should not be used as a criterion to enhance hole cleaning.

Rheology: There are three important criteria when discussing drilling fluid rheology which include:

Gel Strength: It is the strength of the drilling mud body and its internal structures when mud is static namely provide the ability of drilling fluid to keep the cuttings in suspension when mud is static in drilling pipes connection or other reason. Provide the indication of the pressure necessary to restart the flow after stationary condition.

Viscosity: Viscosity has the primary function of the suspension of added desired weighting materials, such as barite. Only in vertical-well drilling and high-viscosity pill sweep is viscosity used as a remedy in hole cleaning.

Yield Point (YP): The yield point is a measure of electro–chemical attractive forces in the mud.

Filtration: occurs when the mud hydrostatic pressure is higher than the pore pressure consequently mud filtrate penetrates the pores of the formation. The infiltration should be controlled to avoid damage of the formation meaning the hydrostatic pressure should be at a threshold already calculated using geomechanical modules. It can be allowed to invade the formation up to a certain distance and a mud cake will be built as a result. Mud cake slows down and stops invasion. The mud cake building properties is connected to the chemistry of the mud and can be measured by means of a filter press which reflects both the efficiency with which the solids in the mud are creating an impermeable mud cake and the efficiency thickness of the mud cake that will be created in the wellbore wall (driller, 2007).

Table 1: Function and physical properties of drilling fluid.

Physical/Chemical property	Function
Density	Maintain wellbore stability Prevent formation fluid flowing into the Wellbore
YP, apparent viscosity, velocity, gel Strength	Capability to transport cuttings from wellbore
Velocity	Cool and lubricate the bit
Velocity, density and viscosity	Transmit hydraulic horsepower to bit

2.2.2.3. Main types of drilling fluids:

- **Water Based Mud (WBM)**

Water-based mud is most common used to drill wells, The base fluid may be fresh water, seawater, brine, saturated brine, or a format brine. The type of fluid selected depends on anticipated well conditions or on the specific interval of the well being drilled.

- **Oil Based Mud (OBM)**

Consists of a composite of WBM, but the continuous phase is oil instead of water. In an invert oil emulsion (a mix of water with the oil in the continuous phase), mud water may increase to a large percentage of the volume, but oil is still in continuous phase. OBM does not contain free water which can react with clays.

2.2.2.4. Drilling Fluid Additives

Drilling fluid requires materials which called drilling fluid additives to drilling fluid functions

Materials that control the functions of drilling fluid

Table 2: Fluid additives.

Chemical	Common Name	Applications
BENTONITE	GEL	Increase Viscosity, Decrease FL
BARITE (Barium Sulfate) ($BaSO_4$)	BAR	Increase Mud Density
HEMATITE (Ferris Oxide) (Fe_2O_3)	-----	Increase Mud Density
CALCIUM CARBONATE ($CaCO_3$)	Calcium carb	Increase Mud Density, LCM
Caustic Soda (NaOH)	Caustic Soda	Increase pH
Lime ($CaOH_2$)	Lime	Increase pH & treat CO_3
Soda Ash (Na_2CO_3)	Soda Ash	Treat Hardness
Citric Acid	Citric Acid	Decrease Ph
Lignite	LIGNITE	Decrease FL
PAC LV ((Poly Anionic Cellulose)	PAC Low vis	Decrease FL
CMC (Carboxy Methyl Cellulose)	CMC	Decrease FL & increase viscosity
Ground Mica	------	Cure lost Circulation
Ground nut hulls	NUT PLUG	Cure lost Circulation

2.2.3. Mud system

Mud system consist of many processes which responsible for cleaning the drilling fluid from contamination due to cuttings, minerals, and formation fluids

Solids control

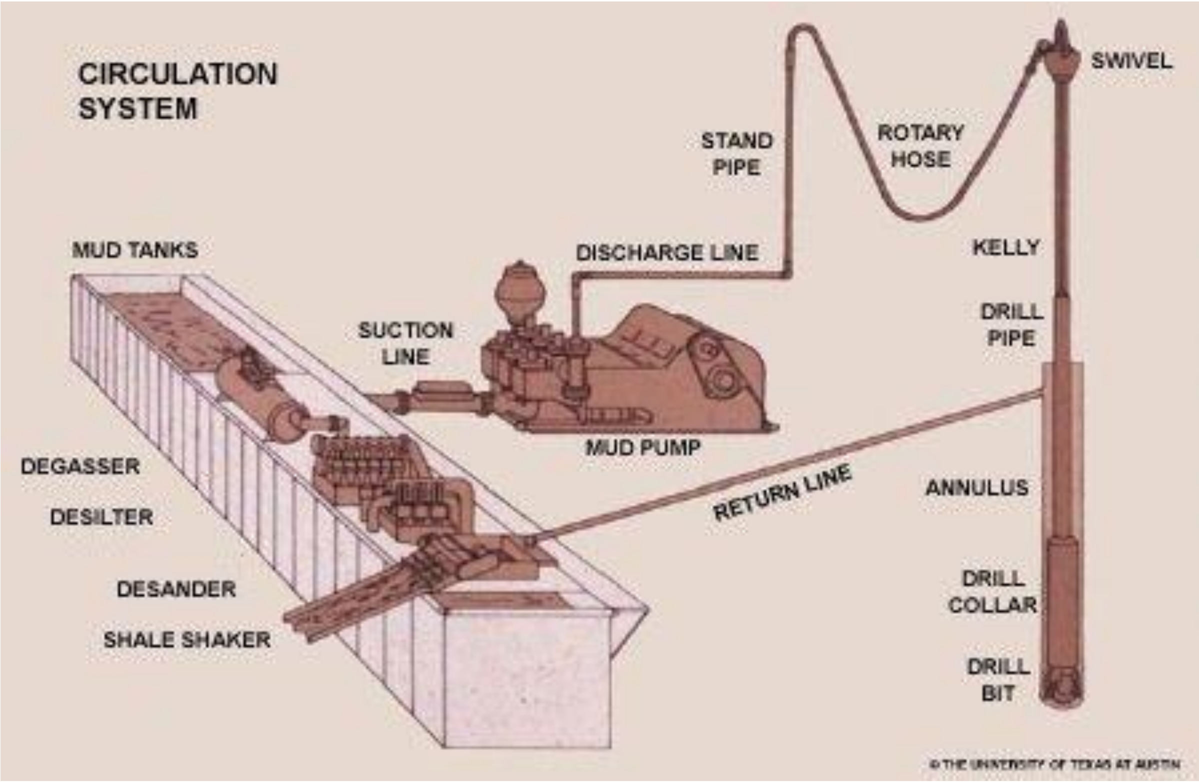


Figure 3: Solid control system (drillingfluid.org, n.d.).

A surface installation of several solid-liquid separators in series that drilling mud passes through after leaving the well (with cuttings) and before it injected back to the well (without cuttings). Solids control is an important mechanical process to keep the drilling fluids in their optimum parameters to perform operations safely and effectively.

The solid control can be classified according to the applied method as follows:

- Screen separation using for example shale shakers.
- Settling separation in sand traps and settling mud pits.
- Gas separation inside the degassers and surface vacuum.
- Forced separation by applying a centrifugal force in desanders, desilters and centrifuges.

The shale shaker is a screen device, and it contains one or more vibrating screens which mud passes through. During operations, mud comes out from the well through the flow line to the mud box, then the mud is distributed to the vibrating shale shakers. Normally, the mud pass through the screens and the drill cuttings are segregated out of the drilling fluids system. If the shakers work effectively and screens are the correct type and size, up to 80% of drill cuttings can be separated. According to the vibration motion, the shakers are categorized in two types: elliptical and linear motion.

Forced Settling (Desander and Desilter):

This process is performed by creating centrifugal forces which force the solids to separate from the drilling fluids. Both, desanders and desilters use the same principle. The mud is injected inside the hydrocyclones tangentially leading to the creation of centrifugal forces which drive the solids to the wall of the cones. Then, the solids with small amount of fluids are discharged from the bottom of the hydrocyclones and the processed drilling fluids flow from the top of hydrocyclones to drilling fluid active system.

Desanders are hydrocyclones with 6 inches diameters or larger. They are used mostly for the top hole drilling with water based muds in order to maintain low mud weights. The use of desanders helps to avoid overloading the desilters cones and improve their efficiency by reducing the solids content at the desilter inlet. Desanders should not be used with oil-based mud. Desilters are hydrocyclones with diameters less than 6 inches and they are designed to remove the silt sized particles.

Settling Separation:

This type of separation is based on the settling process where the solids are allowed to settle down inside mud pits forced by the gravity force. These control method works on an over flow principle. The solids can settle first at the sand trap which is fed by the segregated mud from shale shakers. The large heavy solids normally settle down at the sand trap. Medium size cuttings require more time to settle in slow condition, however smaller solids needs longer time to be separated for instance silt particles can take days. There are some conditions which can improve the settling process such as drilling with low viscosity drilling mud, using mechanical means to improve the gravitational impact.

Degasser (Gas Removal):

Under some circumstances such as well control situation, gas can come into the wellbore and can affect the mud density. In order to avoid losing the applied hydrostatic pressure, the drilling fluids are allowed to flow through surface degasser to separate the gas from the drilling fluids system. The poor boy is a gas separator that is used when circulating through the choke. The separated gas is vented away from the rig using the vent line. A vacuum degasser is used when the mud logging unit detects a certain percentage of gas in the mud. The gas is separated when the drilling fluids flow over internal baffle plates inside the degasser.

Mud cleaner:

Is a combination of fine screened shale shakers and desilter which is installed above the screens. This combination helps to recover the barite and reused it. They are used when it becomes difficult to keep low mud weight. Processing with the mud cleaner should be minimized because surface mud losses are not uncommon.

2.2.4. Flow regimes

Flow regimes describe the nature of fluid flow. There are two basic flow regimes for flow of a single-phase fluid: laminar flow and turbulent flow. Laminar flow is characterized by little mixing of the flowing fluid and velocity profile. Turbulent flow involves complete mixing of the fluid and a more uniform velocity profile.

The hole cleaning methodology focuses on managing a turbulent flow regime, contrary to the preference of many experienced drilling fluid specialist. Conventional practices suggest elevated low-end rheology promoting laminar flow, but experience throughout numerous wells has demonstrated this practice compromises hole cleaning efficiency.

Flow regime is characterized by the Reynolds number, which is a ratio of inertial to viscous forces. Lower Reynolds numbers correlate with laminar flow and higher numbers correlate with turbulent flow, with a transitional flow state in between.

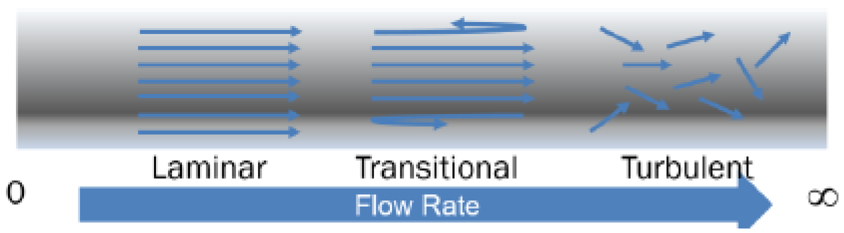


Figure 4: Flow regimes

API equations use power law calculations for flow regime. Because flow regime is a function of annular velocity, the low side of an extended lateral will have lower Reynolds number than the primary flow area. A typical response is to provide excess viscosity to ensure suspension; however, the increased viscosity ultimately reduces the region of turbulence. (Parsons & Strickland, 2018).

In laminar flow cuttings stay on low side of hole, fluid flow on high side of hole and needs to manage operation parameters such as RPM, annular velocity, fluid rheology to maintain laminar flow. It is easier to stay in turbulent flow, by adding additives and even sweeps, but we have to be aware of downhole and vertical annular velocity. (Houston, 2017).

2.2.5. Hole angle

Hole angle is one of the main reasons for wellbore stability. Generally, as the inclination increases, drilling fluid weight does not need to vary greatly because in many cases we are crossing the same formation. Otherwise, high angles result in longer intervals of troublesome formations being open, which can lead to an increase of problems related to hole stability.

2.2.6. Annular velocity

Annular velocity (AV) is one of the most important factors in achieving good hole cleaning in low angle and vertical situations. It is defined, as the speed that the fluid moves in the annulus region of the borehole (Barker, 2007).

2.2.7. Pipe Eccentricity

It is the term used to describe how off- centered a pipe is within another pipe or the open hole. It is usually expressed as a percentage. A pipe would be considered to be fully (100%) eccentric if it were lying against the inside diameter of the enclosing pipe or hole and concentric (0% eccentric) if it were perfectly centered in the outer pipe or hole (Hemphill, 2006).

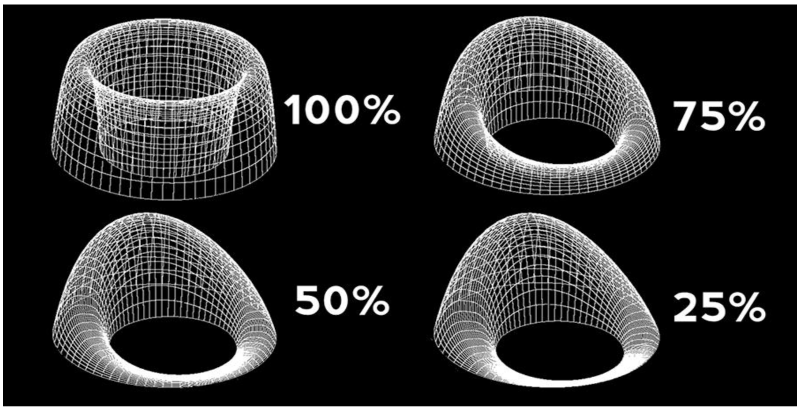


Figure 5: Fluid velocity profile in eccentric annulus.

(Hemphill, 2006)

2.2.8. Flow rate

Flow rate is the dominant factor in cuttings removal while drilling directional wells. An increase in flow rate will result in more efficient cuttings removal under all conditions. However, how high a flow rate can be increased may be limited by:

- The maximum allowed ECD.
- The susceptibility of the open hole section to hydraulic erosion.
- The availability of rig hydraulic power.

2.2.9. Rate of penetration

Under similar conditions, an increase in the drilling rate always results in an increase in the amount of cuttings in the annulus. To ensure good hole cleaning during high ROP drilling, the flow rate and/or pipe rotation have to be adjusted. If the limits of these two variables are exceeded, the only alternative is to reduce the ROP. Although a decrease in ROP may have a detrimental impact on drilling costs, the benefit of avoiding other drilling problems, such as mechanical pipe sticking or excessive torque and drag, can outweigh the loss in ROP.

2.2.10. Drill pipe Rotation

Under similar conditions, an increase in the drilling rate always results in an increase in the amount of cuttings in the annulus. To ensure good hole cleaning during high ROP drilling, the flow rate and/or pipe rotation have to be adjusted. If the limits of these two variables are exceeded, the only alternative is to reduce the ROP. Although a decrease in ROP may have a detrimental impact on drilling costs, the benefit of avoiding other drilling problems, such as mechanical pipe sticking or excessive torque and drag, can outweigh the loss in ROP.

2.2.11. Hole Cleaning Indicators:

- **Transport Ratio**

Transport ratio is defined as the transport velocity (difference between the mean annular velocity and the particle slip velocity) divided by the mean annular velocity. A positive value indicates that some of the cuttings will be transported, and 100% indicates no cuttings remain in the hole to optimize drill-cutting transport, the transport ratio should be maintained as high as possible, though 100% in practice is not possible (Vinod, 1994).

- **Carrying Capacity Index (CCI)**

The three-hole cleaning variables that can be controlled at the rig (mud weight, drilling fluid viscosity, and annular velocity) improve hole cleaning when increased. Good hole cleaning is indicated when the cuttings arrive at the surface with sharp edges.

$$CCI = (K \times AV \times MW) \div (400{,}000)$$

$$K = (511)^{1-n}(PV + YP)$$

$$n = 3.32log\frac{(2PV + YP)}{(PV + YP)}$$

Where:

PV: Plastic Viscosity

YP: yield point

AV: Annular Velpcity

MW: Mud weight ppg

(Mechanical, 2005)

- **Cutting Behavior in Downhole**

As inclination increase the difficult to bring the cuttings to surface increase as well. Hole cleaning in the vertical phase depends on the Annular Velocity (AV). In vertical wells the cuttings move around the drill pipe through flow path. On the other hand, in the high inclinations the fluid path is essential moving above drill pipe, the problem is that cuttings fall quickly to the low side of the hole, where the flow path is very slow. Figure bellow shows how cuttings move in low and high inclination and annulus.

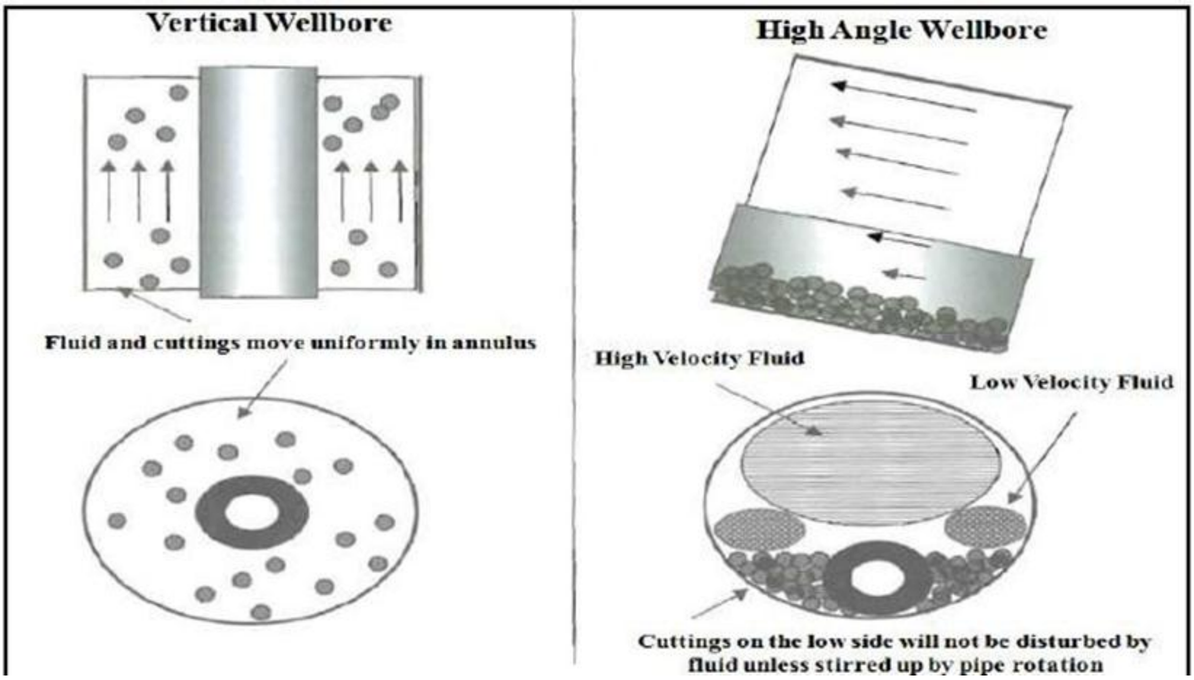


Figure 6: Fluid Movement in the Annulus *(Krepp, 2007).*

The annular space increases after the BHA, which leads to a decrease in AV. With these decreases, the cuttings quickly fall to the low side of the well and will accumulate to form dunes. If the dunes reach a critical height, it is possible to pack off the hole with cuttings once rotation starts. It is essential to prevent the dunes from reaching a critical height, and is important to take this phenomenon into account before start the rotation (Krepp, 2007).

Chapter 3
Methodology

3.1. Introduction

Geomechanics comes into play when we talk about mud and it provides the means to develop and calibrate a geomechanical model based on a well under study and an offset well, then apply that model to new wells or study wells with problem for predicting the safe drilling mud weight or finding out the difference between actual and calculated mud weights (Wellbore Stability workflow) for the already drilled wells to be capable of diagnosing the drilling issues encountered.

The Geomechanics module provides the means to develop and calibrate a geomechanical model based on a offset well, then apply that model to new wells for predicting the safe drilling mud weight (Wellbore Stability workflow) and potential sand failure issues.

The geotechnical model is defined by three primary quantities:

- rock strength.
- rock stress.
- pore pressure.

Calibration data can be specified for offset wells as core data, LOT/FIT/Formation Test points and actual drilling mud weight.

The Mechanical Properties, Horizontal Stress and Wellbore Stability Multi Depth are provided as a multi-well interpretation, whilst Density Estimation, Vertical Stress, Pore Pressure and Multi Depth and Discrete Depth are currently single-well interpretations.

3.2. Interactive Petrophysics

Interactive Petrophysics (IP) is the best-in-class tool for robust subsurface interpretations. It is stable, and minimises user errors through its interactive graphical interface. Whatever your experience level, IP offers a complete, cost-effective solution enabling thorough analysis for making geological and petrophysical and engineering decisions. IP provides you and your team with seamlessly integrated workflows across subsurface disciplines and supports improved reservoir performance throughout the entire assets' lifecycle.

IP Assure your well's stability and maximize production lifetime with IP Geomechanics. Calculate reservoir rock strengths and wellbore stresses from proven models. Save your well from rock-face failures and analyze for potential sand production. Predict pore pressure and mud weight to optimize drilling speed and to a void extra material to transport which will affect the transportation capability so mud weight has to be optimized.

3.2.1. The Advantages of using Interactive Petrophysics

Interactive Petrophysics; IP is an innovative, comprehensive, flexible, specialized and fast software that different students can use from different fields such as geologists and reservoir engineers and petrophysicists. The user-friendly interface of this software makes it easy for different people to work with and enhances the potential of using the program. In the new version of the program, various features have been optimized and modified. This software helps you to make the desired decisions based on the wall and the wall of the holes that deal with the drilling

IP is a fast, scalable software solution for Geoscientists tasked with maximizing the value of subsurface data. Using IP this analysis can be done with an interactive interface, which enhances efficiency and productivity for Geoscientists. IP is a mathematically robust software for Geoscientists seeking a stable, powerful interface that enables them to customize workflows to their needs. Its interactive parameters enable fast analysis and interpretation for geological and petrophysical decisions. User proficiency is crucial to maintaining a competitive edge and giving your team the latest skills that they need to make expert analysis of their wellbore data. Using IP provides you and your team seamlessly integrated workflows across subsurface disciplines and supports improved reservoir performance throughout the entire assets' lifecycle.

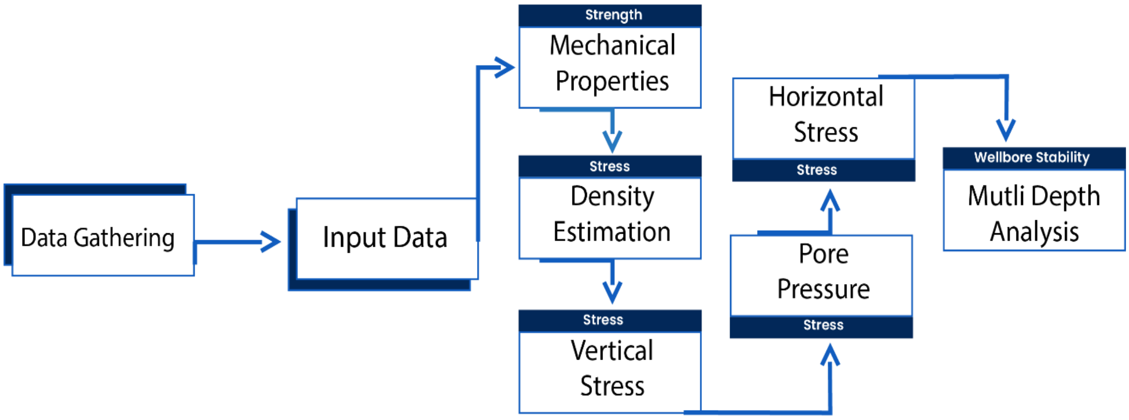


Figure 7: Geomechanical work flow

3.3. Mechanical Properties

Log based models run to produce rock strength indicators for Shales, Carbonates and Dolomite appropriate for a Wellbore Stability workflow, and rock strength.

These can then be calibrated using core data where available through well events (Wellbore Stability workflow).

The following equations can be used to derive dynamic properties from sonic log data:

$$Vs = 0.7858 - 1.2344 * Vp + 0.7949 * Vp^2 - 0.1238 * Vp^3 + 0.0064 * Vp^4 \quad \text{Eq(1)}$$

Where:

Vs: Vertical stress.

Poisson Ratio Calculations:

$$\mu = 0.5\left(\frac{\left(\frac{\Delta Ts}{\Delta Tc}\right)^2 - 2}{\left(\frac{\Delta Ts}{\Delta Tc}\right)^2 - 1}\right) \quad \text{Eq (2)}$$

Shear Modulus Calculations:

$$G = \rho * 1000 * v_s^2$$

$$G = 1.34 * 10^{10} \frac{A\rho_b}{\Delta Tc^2}$$

$$A = \frac{1-2\mu}{2(1-\mu)} \quad \text{Eq (3)}$$

Young's Modulus Calculations:

$$E(psi) = 2G(1 + \mu)$$

Eq (4)

In all above equations Vp and Vs represent compression and shear wave velocity (ft/s) respectively. All elastic module used in this research are dynamically calculated.

(khair, et al., 2015).

3.4. Rock Strength Parameters

The unconfined compressive strength (UCS) and angle of internal friction (φ) of sedimentary rocks are key parameters needed to address a range of geomechanical problems ranging from limiting wellbore instabilities during drilling, to assessing sanding potential and quantitatively constraining stress magnitudes using observations of wellbore failure.

Due to the absence of laboratory core measurements, UCS is determined using empirical relationships based on wireline logging measurements. For sandstone reservoirs.

$$UCS(MPa) = 258exp^{-9\emptyset}$$

Eq (5)

The basic equation for calculating porosity from measured logs were as follows: Porosity from density log:

$$\emptyset_D = \frac{\rho_{ma-\rho_b}}{\rho_{ma-\rho_b}}$$

Eq (6)

For formation containing shale, the porosity has to be corrected for shale as follows:

$$\emptyset_D = \frac{\rho_{ma-\rho_b}}{\rho_{ma-\rho_b}} - Vsh\left(\frac{\rho_{ma-\rho_b}}{\rho_{ma-\rho_b}}\right)$$

Eq (7)

Porosity from sonic log the general equation for the porosity calculation from sonic transit time is the relationship proposed by (khair et al., 2015).

$$\emptyset_s = \left(\frac{\Delta T_{log} - \Delta T_{ma}}{\Delta T_f - \Delta T_{ma}}\right)$$

Eq (8)

3.5. Rock Stress

Wellbore Stability requires that values for in-situ Rock Stresses are specified as part of the input data. Three stress estimations are available:

3.5.1. Vertical Stress

estimated using the existing IP Density Estimation and Overburden Gradient Calculation, which are available as part of Geomechanics.

The overburden stress or vertical stress is induced by the weight of the overlying formations. The typical source to determine it is the density log data. The bulk density is integrated over the overburden depth and multiplied by the gravitational constant to receive the resulting vertical stress. This can be expressed by Eq (9). If a formation is not logged exponential extrapolation is sometimes used to model the unlogged region (H.Rabia, 2002).

$$\sigma v = \int \rho(z)\, g\, dz$$

Eq (9)

3.5.2. Minimum Horizontal Stress

Estimated using log-based models and calibrated using LOT/FIT points. There are many available techniques for measuring in stress at depth in a wellbore, but all of the methods suffer disadvantages. Core-based methods, including an elastic strain recovery, differential strain curve analysis, shear acoustic anisotropy, acoustic emissions, and others, all require the taking of core and detailed analysis. Furthermore, problems with core quality, rock fabric, and other factors may degrade the accuracy of the stress estimate. Direct measurements using small volume hydraulic fractures have fewer analysis problems, but they are expensive and may not be compatible with the well completion scheme, particularly if measurements will be made in layers above the pay zone. The ideal situation would be to measure stress directly from logs, core or drilling data. Attempts to use sonic logs have in some cases given poor results, primarily because of the questionable assumption of elastic uniaxial strain behavior and an uncertain pore-elastic parameter. However, we will be using the normalized Mohr failure envelope approach for different lithologies. The Mohr failure envelope can be obtained from the following normalized equation fit to different lithologies:

$$\sigma_h = k_o(\sigma_{ob} - \mathrm{Pp}) + \mathrm{Pp}$$

Eq (10)

(McLean & , 1990)

3.5.3. Maximum Horizontal Stress

Estimated by applying a multiplication factor to the despite the importance of the determination of SHmax in geomechanics, it has long been recognized that this is the most difficult component of the stress tensor to accurately estimate, particularly as it cannot be measured directly. Because making stress measurements at great depth offers a unique set of challenges.

Maximum horizontal stress from in stress configuration: It is commonly accepted that in stress of subsurface formations includes three mutually orthogonal vertical stress, maximum horizontal stress, and minimum horizontal stress. The three principal stresses should satisfy to Hooke's law in order to keep the stress-strain equilibrium. According to Hooke's Law, the minimum horizontal strain can be written as the following formula, when the stresses are expressed in effective stress forms:

$$\varepsilon_h = \frac{\sigma'_h - v(\sigma'_v + \sigma'_H)}{E}$$

Eq (11)

We have:

$$\sigma'_H = \frac{\sigma'_h - E\varepsilon_h}{v} - \sigma'_v$$

Eq (12)

Normally the formations extend very long in horizontal directions, therefore, the strain in the minimum horizonal direction is much smaller than the strains in vertical and maximum horizontal stress directions. particularly, when the formations of interest are constrained by stiffer formations, the stress state is similar as the condition of uniaxial strain loading is close to zero. Therefore, the upper bound maximum horizontal stress can be expressed as:

$$\sigma'_H \le \frac{\sigma'_h}{v} - \sigma'_v$$

Eq (13)

In porous media, the effective stress and total stress have the following relationship:

$$\sigma' = \sigma - \alpha_B Pp$$

Eq (14)

Combine above equations, we have the maximum horizontal stress as follows:

$$\sigma_H \le \frac{(\sigma_h - \alpha_B Pp)}{v} - \sigma_v + 2\alpha_B Pp$$

Eq (15)

We can obtain the upper bound maximum horizontal stress as follows:

$$\sigma_H = \frac{(\sigma_h - Pp)}{v} - \sigma_v + 2Pp$$

Eq (16)

maximum horizontal stress can be estimated when we know the minimum horizontal stress, vertical stress, pore pressure and poisson’s ratio (Engineers, 2016).

3.6. Pore Pressure

Estimated using the existing IP Pore Pressure calculations, which are available as part of Geomechanics. Direct measurement of pore pressure in relatively permeable formations is straightforward using a variety of commercially available technologies conveyed either by wireline (samplers that isolate formation pressure from annular pressure in a small area at the wellbore wall) or pipe (packers and drill-stem testing tools that isolate sections intervals of a formation). Similarly, mud weights are sometimes used to estimate pore pressure in permeable formations as they tend to take drilling mud if the mud pressure is significantly in excess of the pore pressure and produce fluids into the well if the converse is true. The pore pressure is an important component in a Mechanical Earth Model and critical to the calculation of horizontal stresses, wellbore stability analysis and other geomechanics applications. Sonic and resistivity logs can be used to identify pore pressure trends which can be used to estimate the pore pressure. The estimated pore pressure needs to be calibrated by pore pressure data.

3.6.1. Eaton's method

Eaton's presented the following empirical equation for pore pressure prediction from sonic transient time:

$$Ppg = OBG - (OBG - Png)\left(\frac{\Delta t_n}{\Delta t}\right)^3$$

Eq (17)

Where Δtn is the sonic transient time or slowness in shales at the normal pressure; Δt is the sonic transient time in shales obtained from well logging and it can also be derived from seismic interval velocity

3.7. Wellbore Stability (multi-Depth mode)

currently available in multi-Depth mode only. This module provides an estimate of mud weight for no shear failure / some shear failure during drilling.

Chapter 4

Result and Discussion

4.1. Geomechanics calculations

Geomechanics interpretation comprises the following:

- Mechanical Properties.
- Density Estimation.
- Vertical Stress.
- Pore Pressure.
- Horizontal Stress (minimum and maximum).
- Wellbore Stability Multi Depth.

The process of analysis and calibration in wellbore stability is as follows:

4.1.1. Mechanical Properties

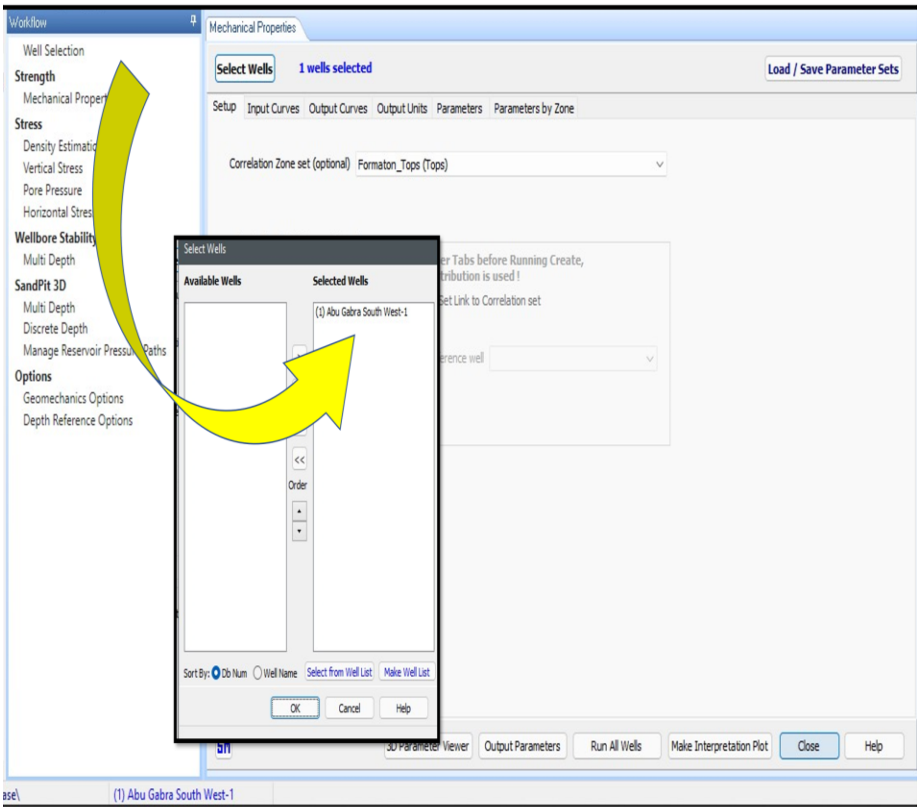


Figure 8: Well selection

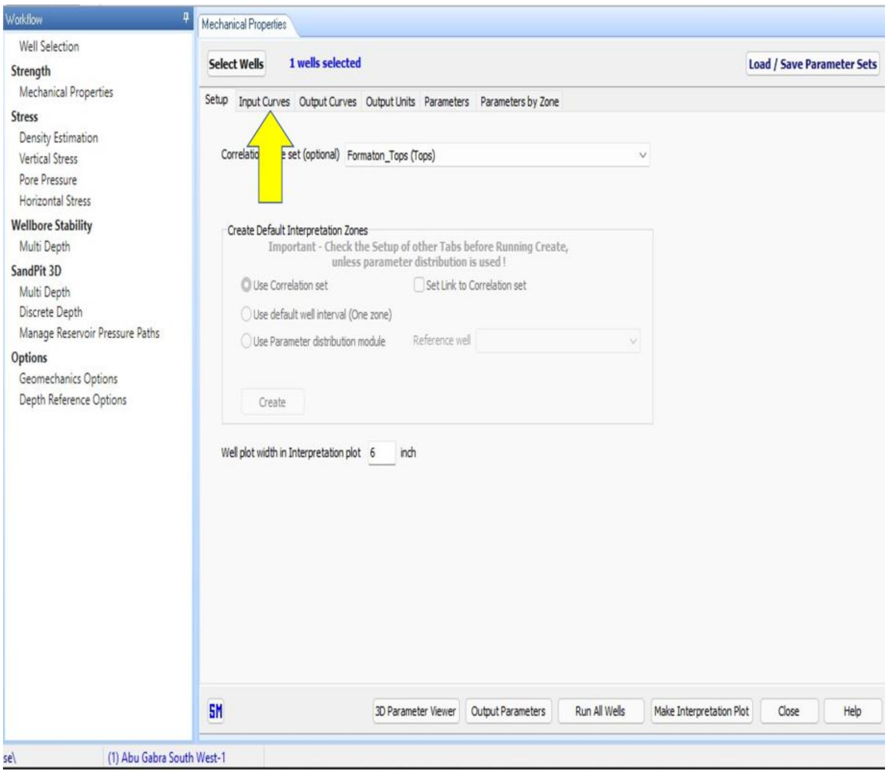


Figure 9: Inserting formation Tops

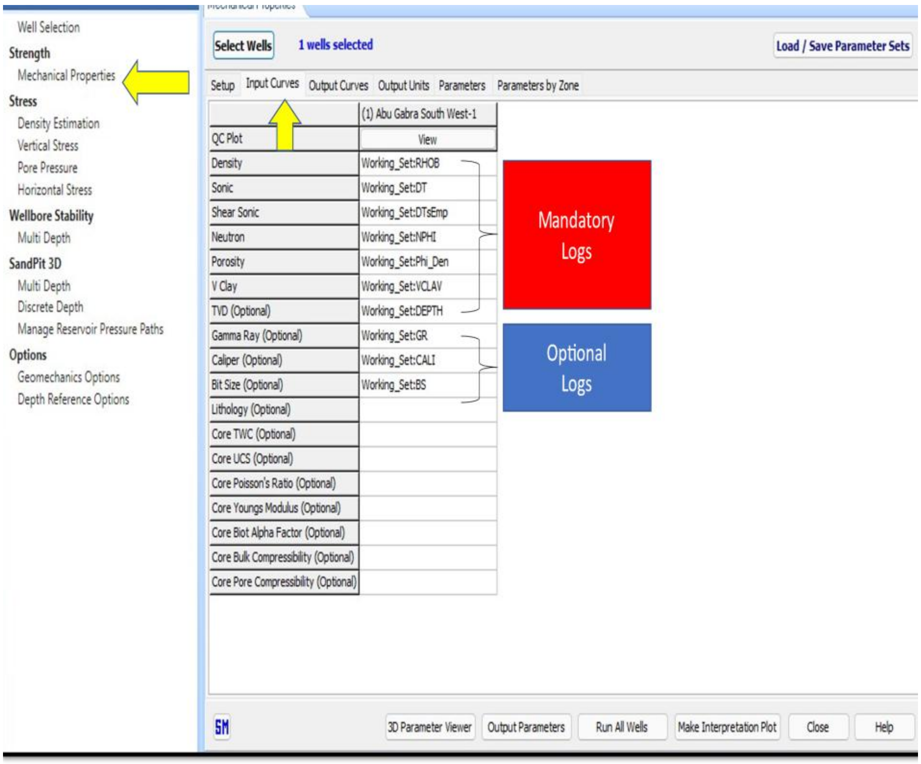


Figure 10: Input Curves

Calculate the mechanical properties, and check that the predicted rock strength (UCS) is reasonable against knowledge of the geology in the area. The calibration of the rock strength UCS is done as part of the calibration of the wellbore stability (shear failure) calculation.

4.1.2. Density Estimation

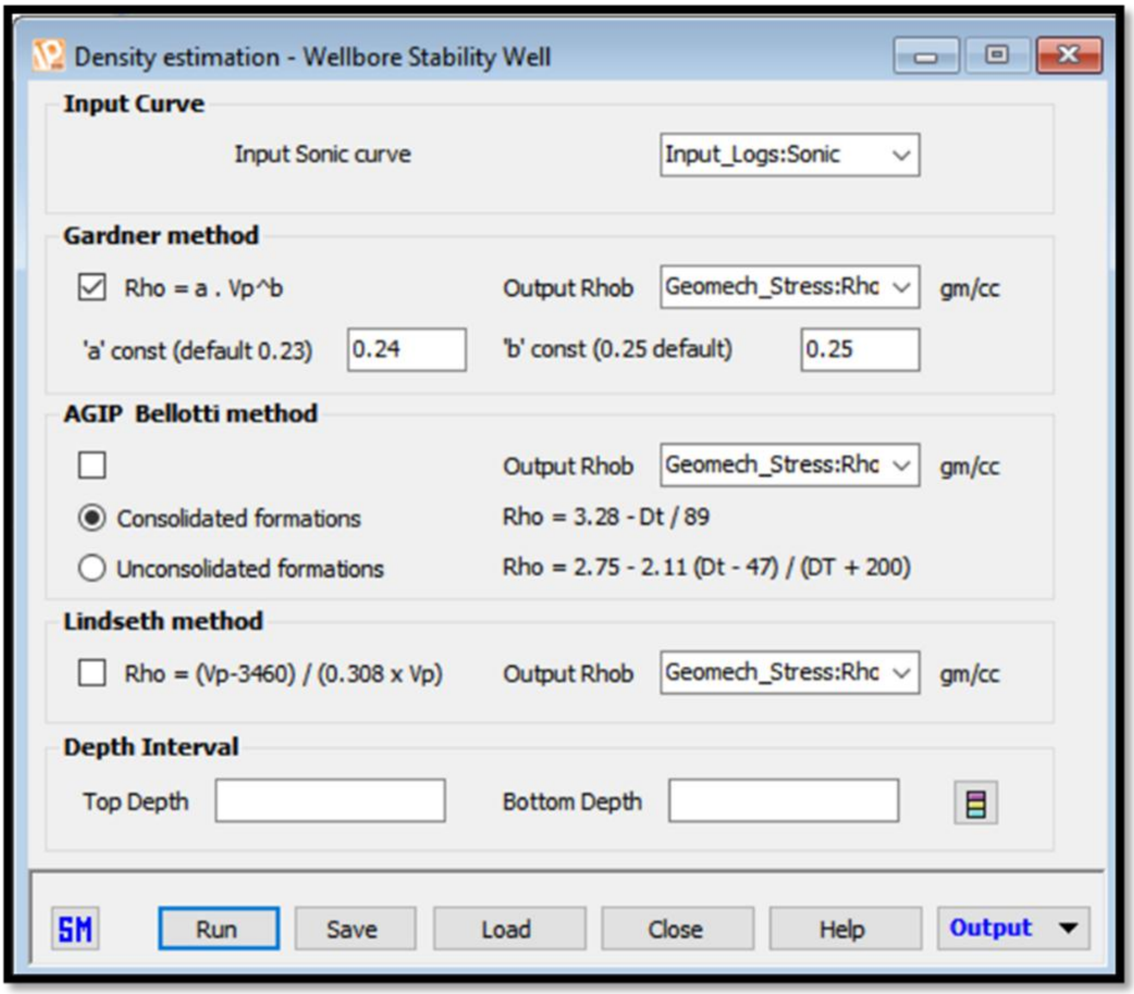


Figure 11: Density estimation

4.1.3. Vertical Stress

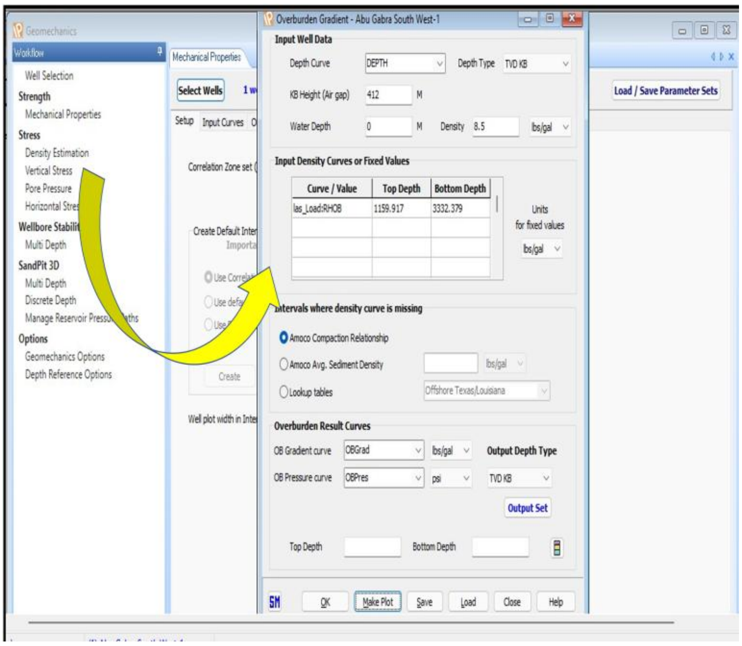


Figure 12: Vertical stress input data

Calculate the vertical stress, by estimating the density from compressional sonic (if density has only been logged part way down the well) then estimating the vertical (overburden) stress from surface to bottom of the well. No specific calibration is done of the vertical stress at this stage except to check that the general shape and magnitude is as expected. The calibration is implicitly done through the pore pressure and horizontal stress validation which take the vertical stress as an input.

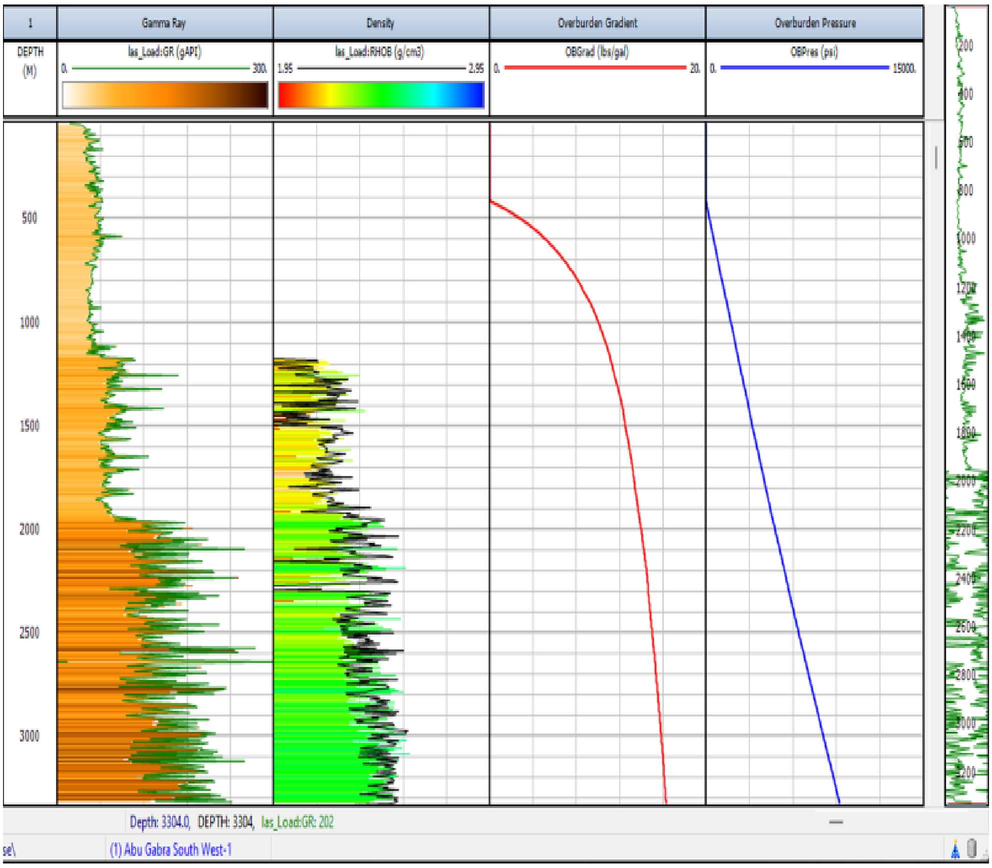


Figure 13: Density estimation.

4.1.4. Pore Pressures

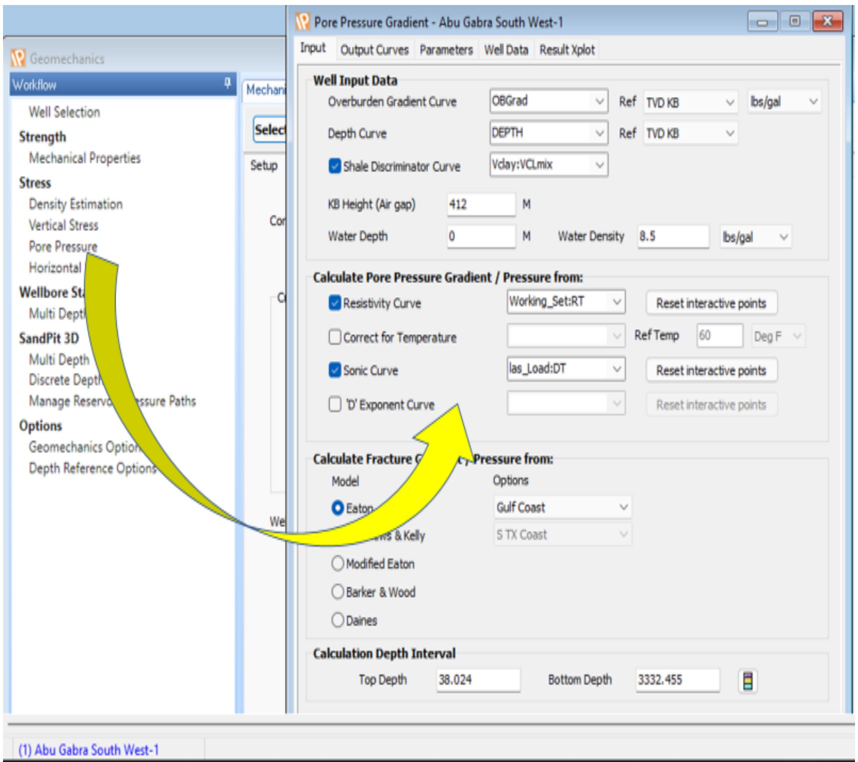


Figure 14: Pore pressure calculation

Calculate the pore pressure, and calibrate it against formation test points, the actual mud weight used during drilling and any relevant well events.

4.1.5. Horizontal Stress

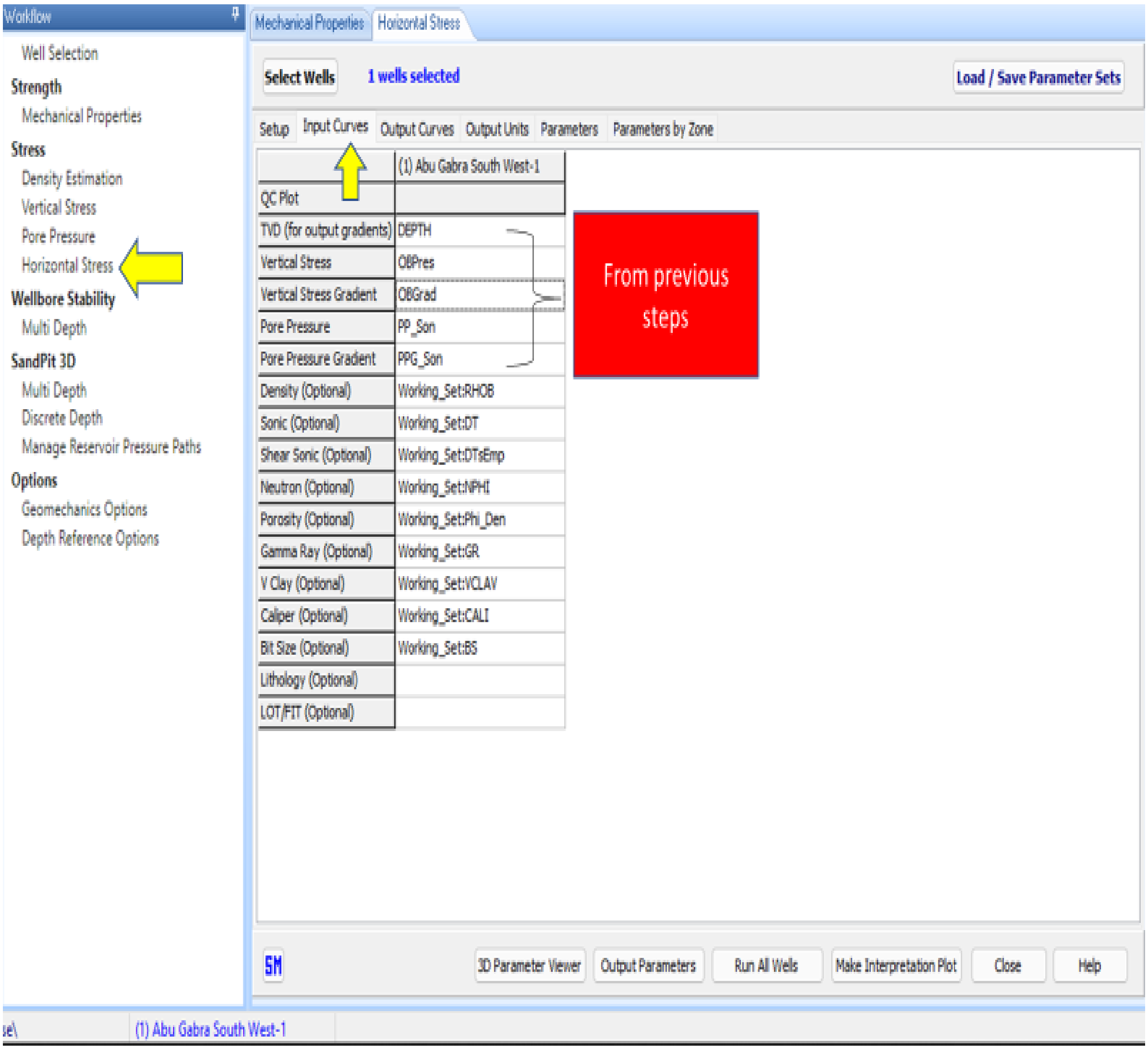


Figure 15: Horizontal stress Input

Calculate the horizontal stress and calibrate it against LOT / FIT data and any available well events. The calibration is done by selecting the model and adjusting its parameters so that it predicts the best fit to the LOT/FIT points. This is usually done by looking field wide across all the offset wells.

4.1.6. Wellbore Stability

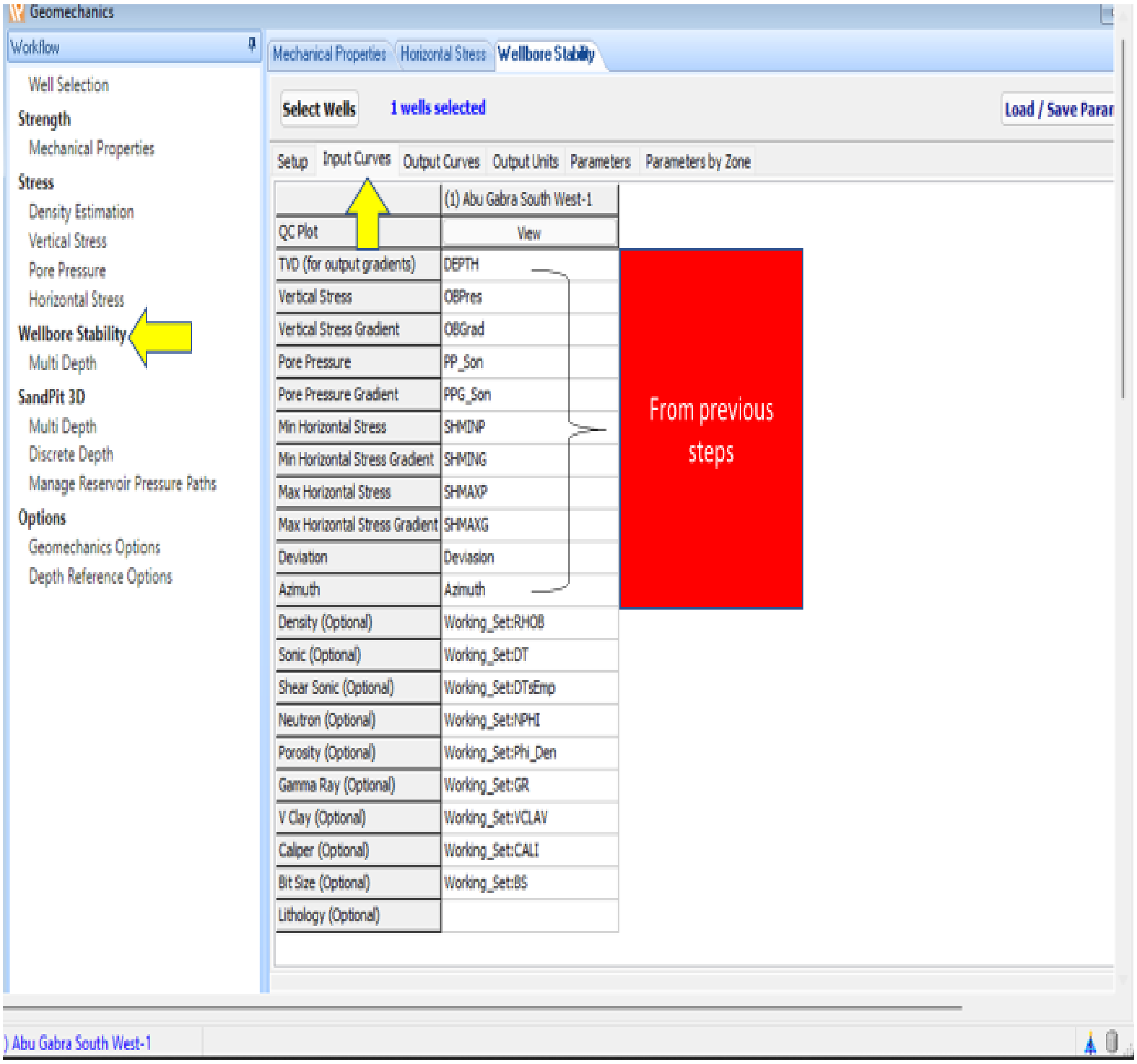


Figure 16: Wellbore Stability Input Data.

Calculate the shear failure and calibrate it against the actual mud weight used for drilling. Calibration usually involves adjusting the UCS values until the predicted shear failure matches the actual mud weight and the events that took places during drilling (i.e. any breakouts).

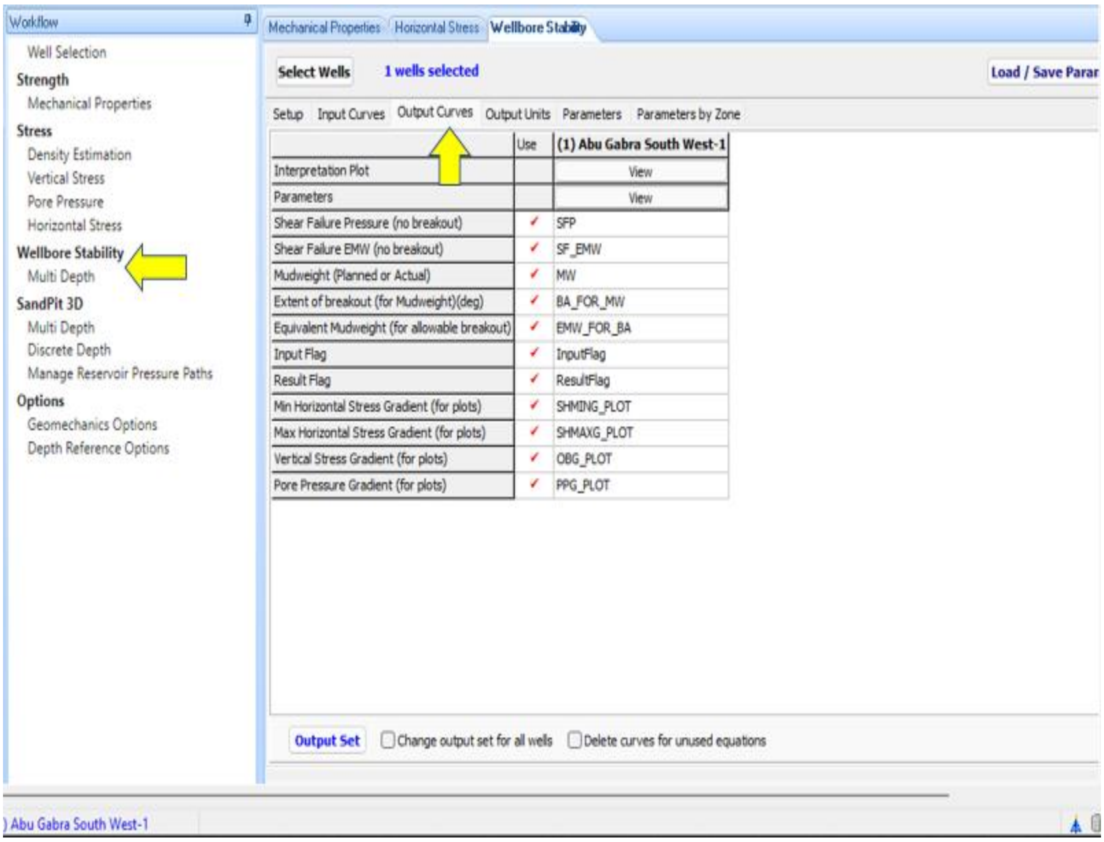


Figure 17 Wellbore Stability Output Data: Wellbore Stability Output Data.

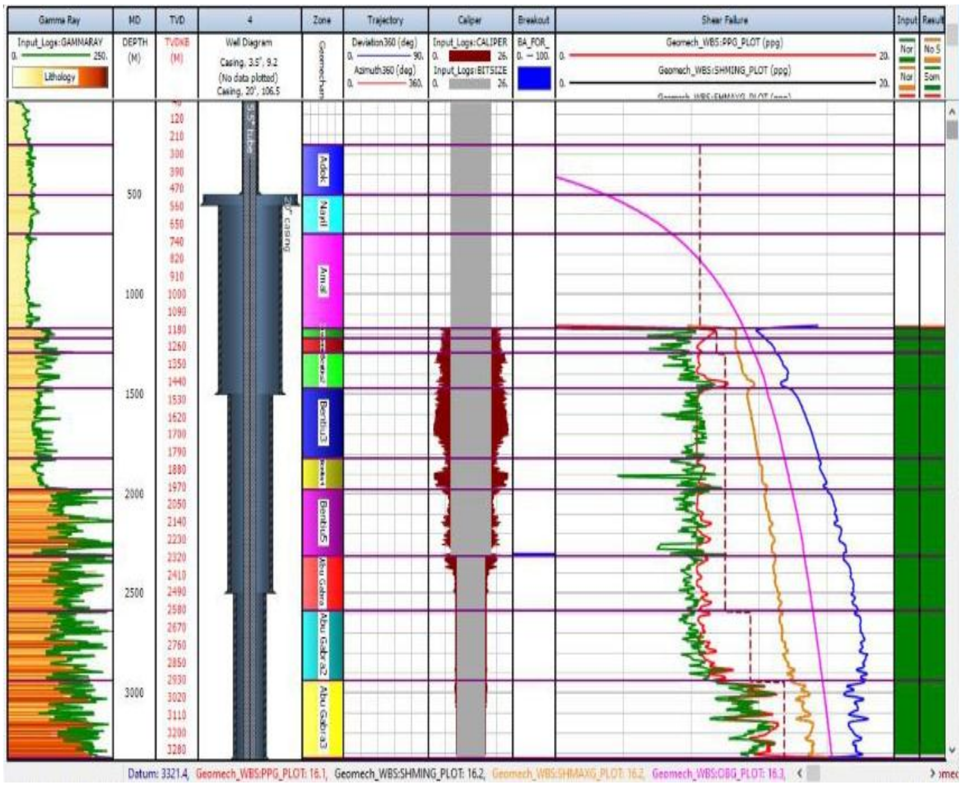


Figure 18: Final Result.

Table 3: Summary of final result

Formation	Interval (m)	Observation	Calculated optimum mud weight window(ppg)
Bentiu 1	1200 - 1310	Excessive wash out	8.2-9.1
Bentiu 2	1310 - 1484	Excessive wash out	8.2-9.1
Bentiu 3	1484 - 1819	Excessive wash out	8.2-9.1
Bentiu 4	1819 - 1976	Excessive wash out	8.2-9.1
Bentiu 5	1976 - 2320	—	8.2-9.1
Abu Gabra 1	2320 - 2550	—	8.2-9.1
Abu Gabra 2	2550 - 2933	—	8.2-9.1
Abu Gabra 3	2933 - 3280	—	11.8-12.6

4.2. Multi Depth Analysis

This is primarily designed to help develop and calibrate the geomechanical model (characterised by rock Strength, rock Stress and pore pressure) in offset wells, using existing log and drilling information. The model can then be applied to a new well, using logs from seismic or copied from an offset well and stretched and squeezes to the new well formation depths.

Predicting Wellbore Stability in a New Well

In an undrilled well, there may be some logs available from seismic survey, or as often is the case there will be no logs available. In order to run the Wellbore Stability model on a new well, some logs are required. A common approach in geomechanics is to copy logs for a representative offset well and stretch and squeeze the log data to the predicted formation depths for the new well.

IP has existing depth shift functionality that can be used to carry out this stretch and squeeze operation after the logs have been copied from the offset well. The steps to use are:

Copy required log data from offset (existing) well data into new (undrilled) well. The log data is unchanged at this stage and is still related to the depth in the offset well.

Create a formation tops curve holding the top depths for the planned formations in the new well.

Use "fill range" function to create a continuous top depth curve for the planned formations in the new well.

Apply the continuous top depth curve to copied log data using the 'Depth Shift Other Curves function. The result of this operation is that the copied log data is now stretched and squeezed to the formation tops in the new well.

For example, in the table 4, take an offset well and a new well with different formation top depth, as shown in the table.

Table 4: Example for the difference in formation tops.

Formation	**Offset Well Depth (m)**	**The Well Depth (m)**
A	500	600
B	800	790
C	150	1600
D	2200	2202
E	2800	2900
F	3000	3090
G	3200	3100
H	3500	3400
I	4700	4500

These formation depths are imported into IP using the Interval / Spreadsheet Loader (located under Input/Output → Load Data menu), Or they can be typed in manually directly into the Interval Loader form.

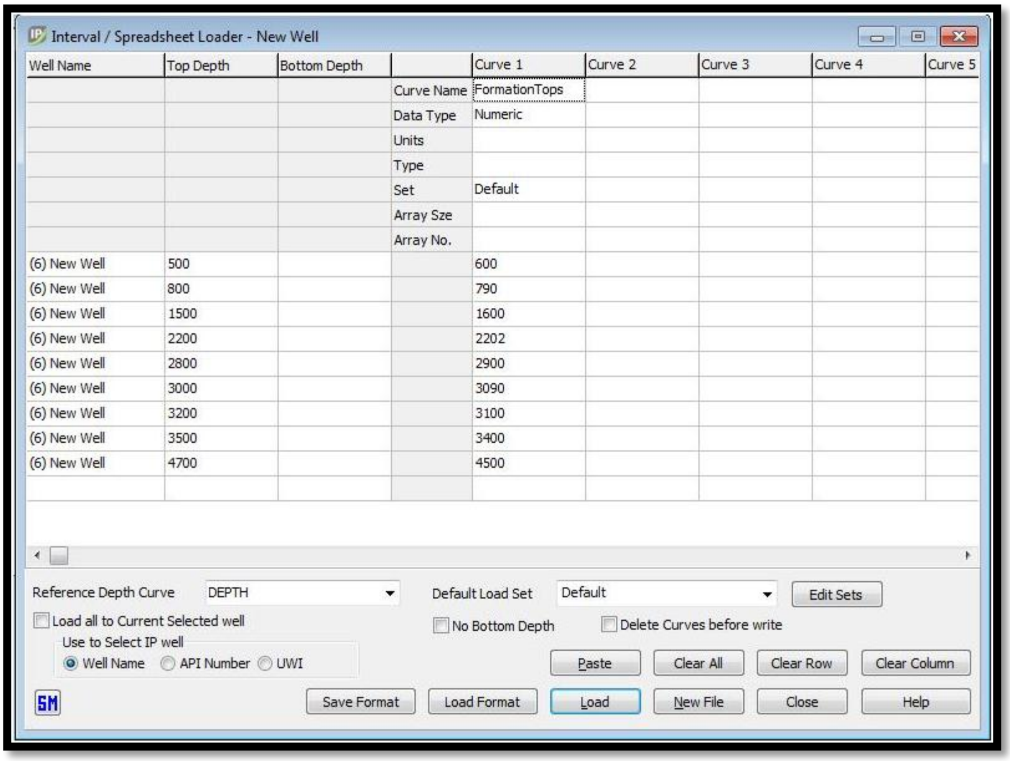
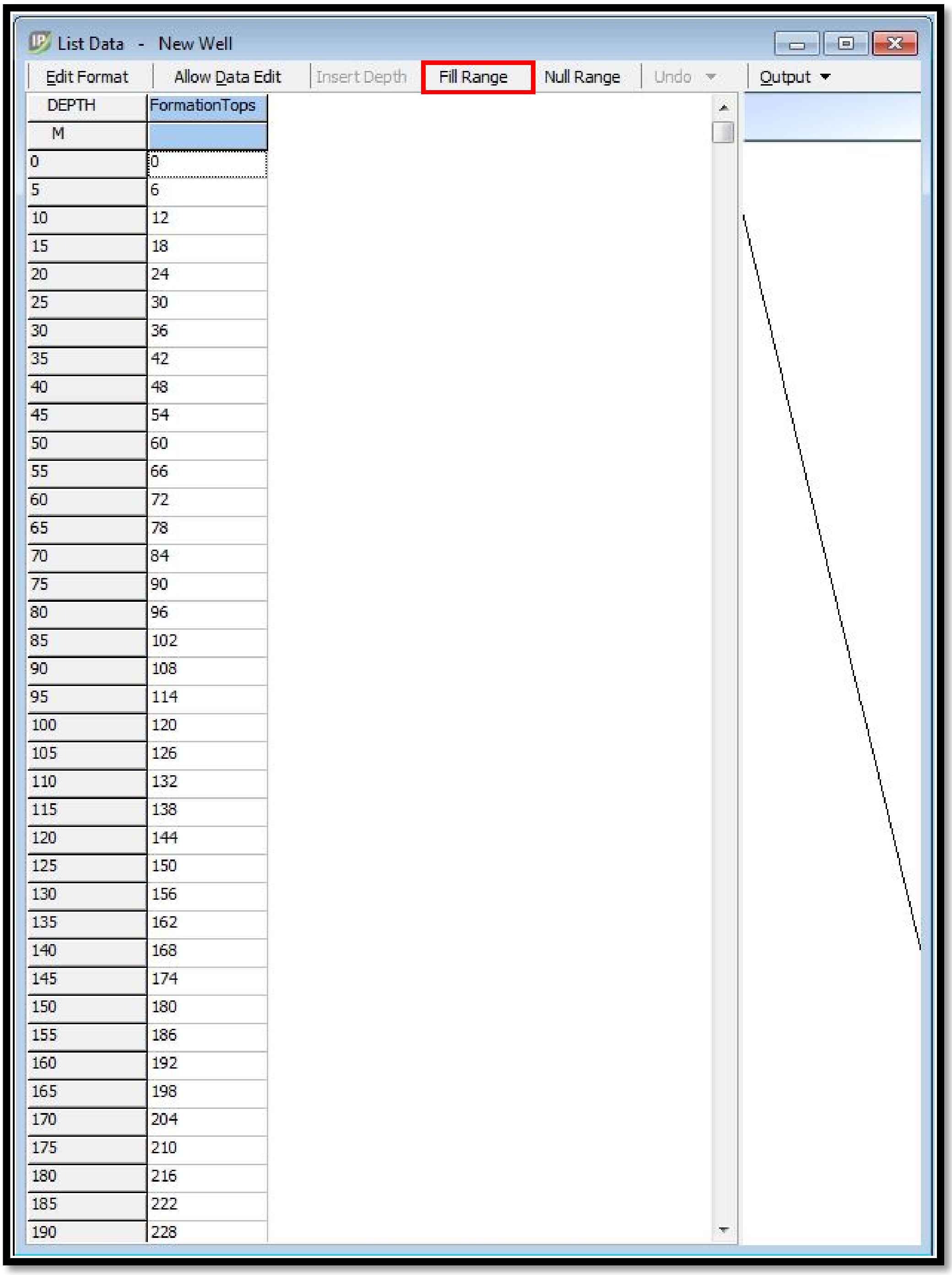


Figure 19: Interval / Spreadsheet Loader.

The new “FormationTops” curve is created containing only values at the depths specified in the Interval Loader form. In order to use the Depth Shift Curve facility in IP, a continuous depth curve is required. This is created by using the “Fill Range” facility of the curve editor to transform the “FormationTops” curve into a continuous curve.



DEPTH	FormationTops
M	
0	0
5	6
10	12
15	18
20	24
25	30
30	36
35	42
40	48
45	54
50	60
55	66
60	72
65	78
70	84
75	90
80	96
85	102
90	108
95	114
100	120
105	126
110	132
115	138
120	144
125	150
130	156
135	162
140	168
145	174
150	180
155	186
160	192
165	198
170	204
175	210
180	216
185	222
190	228

Figure 20: Depth Shift Curve.

Finally, to stretch and squeeze any log curve that has been copied from a representative offset well, use the “Depth Shift Other Curves” functionality in IP, located under menu: Edit -> Depth Shift Other Curves. Specify the copied curve, e.g., Density, and the continuous depth curve for the new formations, e.g. Formation Tops and run. A new Density curve stretched and squeezed to the formation depths in the new well is created.

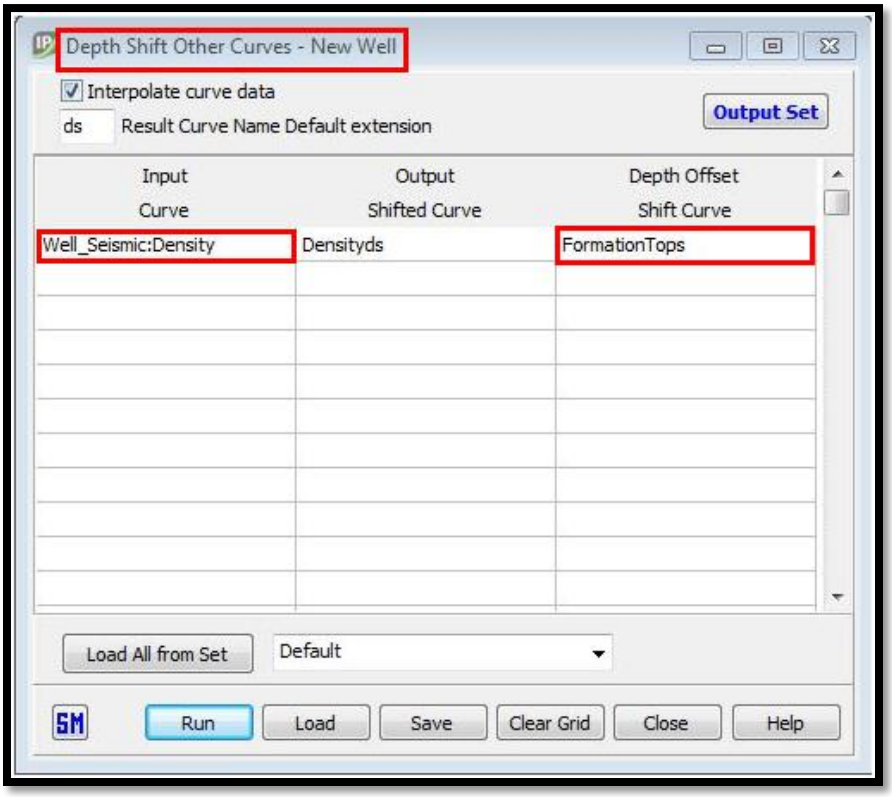


Figure 21: Depth Shift Other Curves

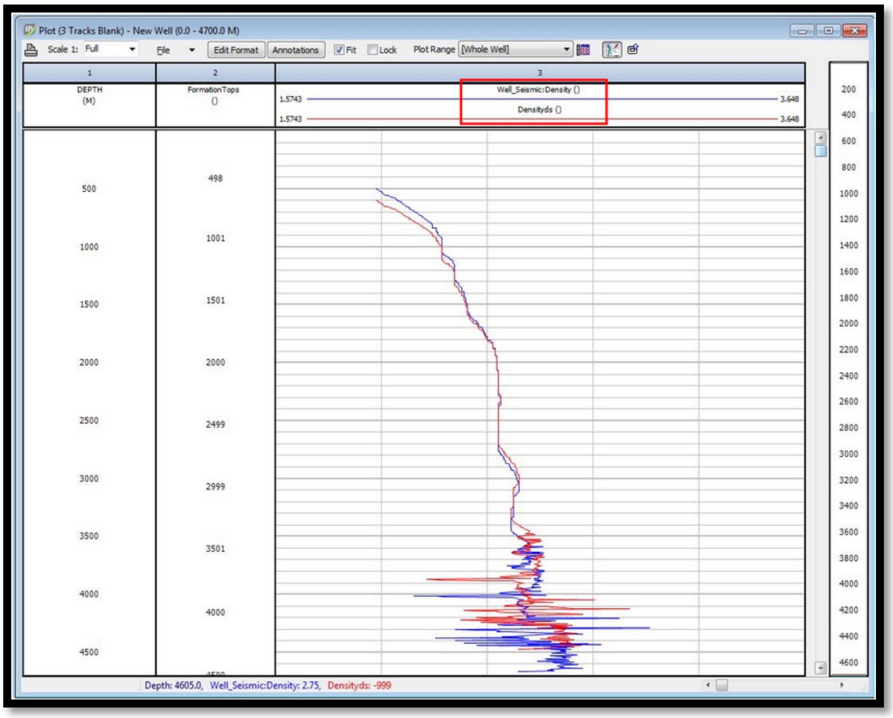


Figure 22: A new Density curve stretched and squeezed.

Chapter 5

Conclusion and Recommendation

5.1 Conclusion

The Geomechanics module provides the means to develop and calibrate a geomechanical model based on offset wells, geotechnical model plays a vital and important role at field development projects since field development decisions are aided by an accurate assessment of well design options that are closely tied to the existing geological and engineering data set using geomechanics modeling.

5.2 Recommendation

Based on the field geotechnical model, wellbore stability analysis was applied to find the mud weight in which a well is stable when having no safe mud weight window.

1. From IP results, an obvious change in the profiles of pore pressure, shear failure, and fracture gradients are visible for the interval between 2930m up to 3820m. The recommended mud weight window for drilling this interval is (12-13.5) ppg.
2. The interval from (1180m up to 2930m) wash out was observed. The recommended mud weight window for drilling this interval is (8.2-9.1) ppg.
3. Using Abu Gabra SW-1 logging data to design the mud weight window for the new development well by calibration formation tops of the new well with the logging data of Abu Gabra SW-1.

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