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Calibration of Wire-Line Mechanical Properties Using Core Measurements Results for Heglig Oilfield - Case Study

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مشروع تخرج مقدم إلي كلية هندسة وتكنولوجيا النفط- جامعة السودان للعلوم والتكنولوجيا

إنجاز جزئي لأحد المتطلبات للحصول على درجة البكالريوس في الهندسة

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الإستهلال

بسم الله الرحمن الرحيم

قال تعالى:

(اللَّهُ نُورُ السَّمَاوَاتِ وَالأَرْضِ مَثَلُ نُورِهِ كَمِشْكَاةٍ فِيهَا مِصْبَاحٌ الْمِصْبَاحُ فِي زُجَاجَةٍ الزُّجَاجَةُ كَأَنَّهَا كَوْكَبٌ دُرِّيٌّ يُوقَدُ مِن شَجَرَةٍ مُّبَارَكَةٍ زَيْتُونَةٍ لّا شَرْقِيَّةٍ وَلا غَرْبِيَّةٍ يَكَادُ زَيْتُهَا يُضِيءُ وَلَوْ لَمْ تَمْسَسْهُ نَارٌ نُّورٌ عَلَى نُورٍ يَهْدِي اللَّهُ لِنُورِهِ مَن يَشَاء وَيَضْرِبُ اللَّهُ الأَمْثَالَ لِلنَّاسِ وَاللَّهُ بِكُلِّ شَيْءٍ عَلِيمٌ)

سورة النور35

الاهداء

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ونخص بجزيل الشكر ملهمتنا الفاضلـــــــــة:

دكتورة / الهام محمد محمد خير

علي كل ما تكبدتة من عناء من أجل انجاز هذا

المشروع في أفضل صـــــــــــــــــــورة

Abstract

The most direct way of determining the rock mechanical data is from laboratory tests on plugs; wire-Line can also be used as an indicator, In order to avoid the disadvantage of the two methods calibration are required. In This study, Wire-Line Mechanical Properties was calibrated with static one measurement at different depths in well case 38 in Hegig oilfield - Muglad basin which is located in the south of Sudan.

Rock mechanical properties (Shear modulus and Young's modulus and Bulk modulus) have been calculated with the absence of shear wave for unconsolidated sandstone based on Poisson's ratio. Anderson's equation was used to calculate Poisson's ratio as a function of the shale index which is mainly depend on the compressional wave only.

The static rock mechanics parameters have been calibrated with the dynamic one using different correlations; finally the best fitting equation were selected based on the correlation coefficient (R^2). It was found that the polynomial equations are the best correlations that minimize the error between estimated and measured values for all parameters.

التجريد

إن الطريقة المباشرة لتحديد الخواص الميكانيكية للصخور هي الاختبارات المعملية على العينات من تلك الصخور . كما يمكن أيضا استخدام قياسات وتسجيلات الابار السلكيه كمؤشر لهذه الخواص، من أجل تجنب مساوئ الطريقتين هناك حاجة للمعايرة. وفي هذه الدراسة، تم معايرة الخواص الميكانيكية المحسبة رياضياً مع الخواص الاستاتيكية المقاسة في المعمل علي عينات في أعماق مختلفة تم أخذها من البئر 38 في حقل هجليج بحوض المجلد الذي يقع في جنوب السودان. حيث ان الخصائص الميكانيكية للصخور (معامل القص ومعامل يونغ والمعامل الكلي) تم حسابها مع غياب موجة القص اعتماداُ علي نسبة بويسون. وقد تم استخدام معادلة أندرسون لحساب نسبة بويسون المرتبطة بمحتوي الطين الذي يعتمد أساساً على موجة الانضغاط فقط.

تم معايرة الخواص المقدرة (الديناميكية) والمقاسة (الاستاتيكية) للصخور باستخدام الارتباطات المختلفة؛ ثم تم اختيار المعادلة المناسبة بناءً على معامل الارتباط (R^2) وقد وجد أن المعادلات متعددة الحدود هي أفضل الارتباطات التي تقلل من الخطأ بين القيم المقدرة (الديناميكية) والمقاسة (الاستاتيكية).

Key words :

1. Rock mechanic properities
2. Shear waves
3. Presure waves
4. Poisson's ratio

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Introduction

Acoustic logs have become a widely used porosity tool in formation evaluation. In addition, there is a growing application of acoustic logs in cement bond evaluation and fracture detection. These applications have mainly involved the use of logs of first-arrival transit times and amplitudes and have not included detailed studies of the complete signal.

Rock mechanics is a vital decision-making tool for insuring economic benefits in all phases of petroleum reservoir development. Lithology and physical rock properties of formations can be derived by utilizing acoustic logging systems. Predictive tools for rock mechanical parameters are essential for reservoir development, management, and prospect evaluation in exploration areas with very sparse or no borehole-based rock mechanical data. The need for such predicative methods is particularly critical in carbonate reservoirs which are not as well understood or studied as clastic reservoirs.

The most direct way of determining the rock mechanical data is from laboratory tests on plugs. A core-based test for the whole reservoir interval in each well is expensive, and requires extensive coring. Furthermore, direct plug measurements cannot provide a continuous strength estimate as the plugs are taken from discrete points, every few feet, over a small section of the well in question. Therefore, there is a need to develop a quick and cost effective approach for rock mechanical characterization. As rock mechanical properties cannot be determined directly from logging tools, an indirect method must be introduced. Such method correlates the widely available Vp (P-wave velocity) log, with the laboratory derived rock mechanical parameters, from representative core samples to produce a set of pseudo-logs.

This study discusses how well logs are used to determine the mechanical properties of rocks. These properties are often called the elastic properties or elastic constants of rocks. The best known elastic constants are the bulk modulus of compressibility, Young's Modulus (elastic modulus), and Poisson's Ratio.

Problem statement:

Some Sudanese oilfield consist of unconsolidated formation, that rock failure can occur during drilling and production; as it difficult to measure the shear wave in these type of formation, an alternative approach to the conventional methods is necessary to calculate rock mechanics properties for this type of rocks. Few models were presented in the literature to estimate these properties; this study addresses the possible and the available tool to estimate rock mechanical for unconsolidated sandstone.

The Objective:

The main objective of this study is to provide the possible for estimating rock mechanical properties, with the absence of shear wave for unconsolidated sandstone. This include:-

1) Estimation of Poisson's ratio, Shear and Young's, modulus and Bulk modulus using the conventional dynamic.
2) Compare the estimated results with the conventional dynamic calculation methods.
3) To calibrate the static properties measured at core plugs with the dynamic one.

Methodology:

1) Density porosities were computed using a sandstone matrix and sonic porosity was calculated with Wyllie equation.
2) Using conventional mathematical dynamic Models and Microsoft Excel for the calculation of the rock mechanics properties for some formations.
3) Using Anderson's Model for unconsolidated sandstone and Microsoft Excel for recalculating the dynamic properties of the same formations.
4) Using measured core properties to calibrate the dynamic properties with the static one.

Chapter 1

General Background

Geophysical well log measurements are the major key for the development of oil and gas reservoirs. Formation evaluation is basically relies on characterizing the variation of petro-physical properties throughout the reservoirs; in this way, core measurements and well logs interpretation provide valuable estimates of these physical properties. By the same way, drilling optimization and bit type selection are substantially be based on rock mechanics calculation, where the only way for these calculations is the measurement of dipole sonic and density logs, or direct measurements on core. On the other hand, the prediction of sand production and wellbore stability depends on the measured well logging parameters.

In general, mechanical behavior of porous rocks depends on the elastic parameters, which correlated directly with well log measurements. Recently, different techniques were applied for correlating the log-derived parameters with rocks mechanical properties for different applications in petroleum industries.

Geophysical well log measurements have been used for many years with calibration of the core measurement to estimate several rock properties, the calibration purpose is to avoid the drawbacks of the both the core and well logging measurements. As the core testing methods are expensive, a very limited number of samples are generally tested; this is resulting in discontinuous profile for the cored well. Petrophysical data volumes generated from well information allow the geologist to integrate information from thousands of wells using standard interpretation systems. So far, the technique seems to be more suited to regional analysis rather than to prospect development. Elastic constants are needed by five distinct disciplines in the petroleum industry this include: the processed seismic sections, geophysicists interested in using logs to improve synthetic seismograms, seismic models, and interpretation of seismic attributes, and seismic inversion. Production or completion engineers who want to determine if sanding or fines migration might be possible, requiring special completion operations, such as gravel packs.

Hydraulic fracture design engineers, who need to know rock strength and pressure environments to optimize fracture treatments .Geologists and engineers interested in in-situ stress regimes in naturally fractured reservoirs. Drilling engineers who wish to prevent accidentally fracturing a reservoir with too high a mud weight, or who wish to predict over pressured formations to reduce the risk of a blowout.

The rock strength parameters can be derived at specific depths directly from core measurements. Although this is the most accurate method for estimation of rock properties, it is generally expensive and covers small part of the interval while a measurement through the entire section of the reservoir is required to get continuous profiles of rock strength against depth. The geo-mechanical properties can be modeled based on well logging tools such as density and acoustic velocities Gamma Ray, Neutron. Wireline measurements were converted to mechanical properties using the equations for homogeneous isotropic and elastic rock as follows.

1.1. Static Measurement of Rock Mechanical Properties:

When a stretching force (tensile force) is applied to an object, it will extend. We can draw its force - extension graph to show how it will extend. *Note:* that this graph is true only for the object for which it was experimentally obtained. We cannot use it to deduce the behavior of another object even if it is made of the same material. This is because extension of an object is not only dependent on the material but also on other factors like dimensions of the object (e.g. length, thickness etc.) It is therefore more useful to find out about the characteristic extension property of the material itself. This can be done if we draw a graph in which deformation is independent of dimensions of the object under test. This kind of graph is called stress- strain curve.

The application of a force to an object is known as loading. Materials can be subjected to many different loading scenarios and a material's performance is dependent on the loading conditions. There are five fundamental loading conditions; tension, compression, bending, shear, and torsion. Tension is the type of loading in which the two sections of material on either side of a plane tend to be pulled apart or elongated. Compression is the reverse of tensile loading and involves pressing the material together.

Loading by bending involves applying a load in a manner that causes a material to curve and results in compressing the material on one side and stretching it on the other. Shear involves applying a load parallel to a plane which caused the material on one side of the plane to want to slide across the material on the other side of the plane. Torsion is the application of a force that causes twisting in a material.

If a material is subjected to a constant force, it is called static loading. If the loading of the material is not constant but instead fluctuates, it is called dynamic or cyclic loading. The way a material is loaded greatly affects its mechanical properties and largely determines how, or if, a component will fail; and whether it will show warning signs before failure actually occurs.

If a material is subjected to a constant force, it is called static loading. If the loading of the material is not constant but instead fluctuates, it is called dynamic or cyclic loading. The way a material is loaded greatly affects its mechanical properties and largely determines how, or if, a component will fail; and whether it will show warning signs before failure actually occurs. Stress is defined as the force per unit area of a material.

Stress = force / cross sectional area

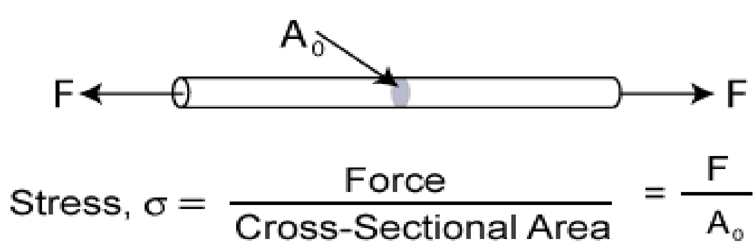
$$\sigma = \frac{F}{A} \qquad \text{……………….……. (1.1)}$$

Where:-

σ = stress

F = force applied, and

A= cross sectional area of the object.



Is the fractional deformation produced in a solid body when it is subjected to a load. Or is the ratio of the change in length to the initial length

$$\varepsilon = \frac{\Delta L}{L} \qquad \text{……………….……. (1.2)}$$

Strain is the response of a system to an applied stress. When a material is loaded with a force, it produces a stress, which then causes a material to deform. Engineering strain is defined as the amount of deformation in the direction of the applied force divided by the initial length of the material. This results in a unitless number, although it is often left in the unsimplified form, such as inches per inch or meters per meter. For example, the strain in a bar that is being stretched in tension is the amount of elongation or change in length divided by its original length. As in the case of stress, the strain distribution may or may not be uniform in a complex structural element, depending on the nature of the loading condition.

In a conventional triaxial compression test, a cylindrical core sample is loaded axially to failure, at constant confining pressure. Conceptually, the peak value of the axial stress is taken as the confined compressive strength of the sample. In addition to axial stress, axial and radial strains may be monitored during this test, to determine basic elastic constants (Young's Modulus, E, and Poisson's ratio, ν). In view of the variability of rock properties, when adequate samples are available, repeat testing may be merited to determine average values. If triaxial testing is performed at several confining pressures, and preferably if unconfined compression and tensile test data are available, a representative failure locus can be constructed. The selected confining pressures for triaxial testing are generally spread over a range from very low to beyond the maximum anticipated in-situ effective stress conditions. Measurements can be performed at in-situ temperature and pore pressure can be applied. Testing Equipment and Setup consist of a triaxial compression system which is used to perform this type of testing. Axial load is applied with a servo-controlled actuator. Confining pressure and pore pressure are hydraulically generated. Axial force up to 1.5 x 106 lbf can be applied to samples up to ten inches in diameter. Axial stress is monitored with a load cell. Confining pressure and pore pressure are monitored with conventional pressure transducers. Axial and radial strains are measured using cantilever type strain transducers. When a rock is brittle, or large deformation is expected, LVDTs may be used instead of cantilever devices. Occasionally, strain gages are attached directly to the sample. Tests can be conducted at temperatures up to 500° F. Inflow or outflow of pore fluid is measured with accumulators (or burettes with pressure transducers, if the test is drained to atmosphere). Triaxial test include the following steps:

In an unconfined compression test, a cylindrical core sample is loaded axially to failure, with no confinement (lateral support). Conceptually, the peak value of the axial stress is taken as the unconfined compressive strength of the sample. In addition to axial stress, axial and radial strains may be monitored during this test, to determine elastic constants (Young's Modulus, E, and Poisson's ratio, v). In view of the variability of rock properties, when adequate samples are available, repeat testing may be merited to determine average values. Testing Equipment and Setup consist of loading frames which and can be used to perform this type of testing. Axial load is applied with a servo-controlled hydraulic actuator. Available actuators can deliver up to 1.5 x 106 lbf. Axial stress is monitored with a load cell. Axial and radial strains are measured using cantilever type strain transducers. When a rock is brittle, or large deformation is expected, LVDTs may be used instead of cantilever devices. Occasionally, strain gages are attached directly to the sample. Tests can be conducted at representative reservoir temperatures.

Young's modulus is the ratio of the longitudinal stress to the longitudinal strain when a solid body is loaded by longitudinal stress within the elastic limit.

This is because stress is proportional to strain. The gradient of the straight-line graph is the Young's modulus, E

$$E = \frac{\text{Stress}(\sigma)}{\text{Strain}(\varepsilon)} \qquad \text{.........................} (1.3)$$

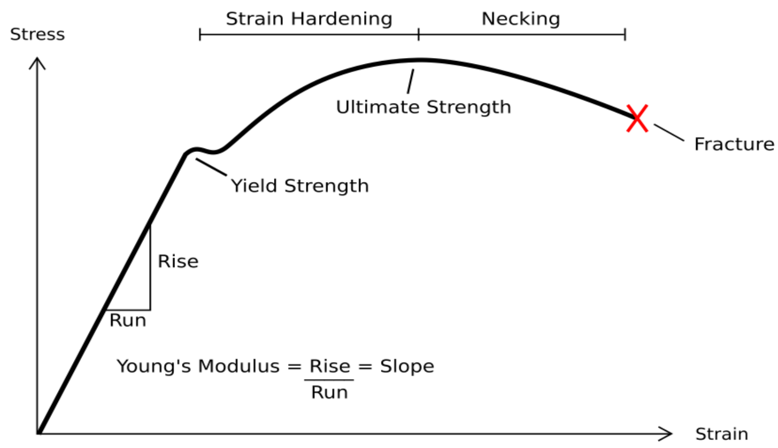


Figure (1.1) Strain VS Stress

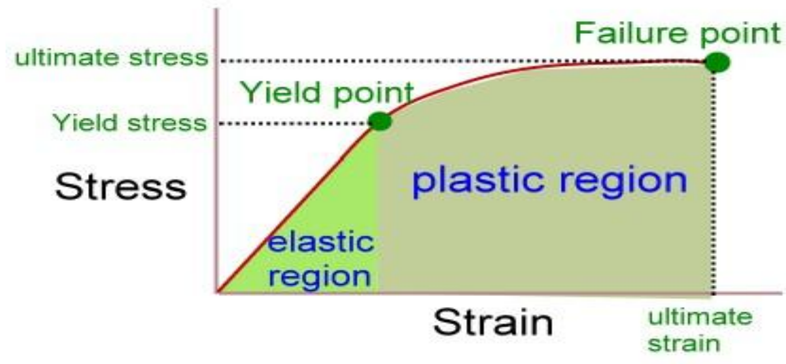


Figure (1.2) Strain VS Stress

Poisson's ratio is the ratio of lateral strain to axial strain, that is:

$$\mu = \frac{\text{lateral strain}}{\text{longitudinal strain}} \quad 0 \le \mu \le 0.5 \qquad \text{……………………. (1.4)}$$

Shear modulus is the ratio of shear stress to shear strain.

$$G = \frac{\text{shear stress}}{\text{shear strain}} \qquad \text{……………………. (1.5)}$$

On the other hand, Bulk modulus is the ratio of the applied stress to the volumetric strain when a solid body is subjected to uniform stress throughout its surface, that is:

$$K = \frac{E}{3(1-2\mu)} \qquad \text{……………………. (1.6)}$$

1.2. Dynamic Calculations of Rock Mechanical Properties:

The way to calculate the dynamic elastic modulus is to use the dual sonic log. A log that measures interval transit time (Δt) of a Compressional sound wave travelling through the Formation along the axis of the borehole. The acoustic pulse from transmitters detected at two or more receivers. The time of the first detection of the transmitted pulse at each receiver is processed to produce Δt. The rock strength parameters can be derived at specific depths directly from core measurements. Although this is the most accurate method for estimation of rock properties, it is generally expensive and covers small part of the interval while a measurement through the entire section of the reservoir is required to get continuous profiles of rock strength against depth.

The geo-mechanical properties can be modeled based on well logging tools such as density and acoustic velocities Gamma Ray, Neutron. Wireline measurements were converted to mechanical properties using the equations for homogeneous isotropic and elastic rock as follows:

Poisson's Ratio

For homogeneous isotropic and elastic rock, physical rock, Poisson's Ratio is given as:

$$\mu = 0.5\left(\frac{\left(\frac{\Delta t_s}{\Delta t_c}\right)^2 - 2}{\left(\frac{\Delta t_s}{\Delta t_c}\right)^2 - 1}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.7)$$

Shear Modulus:

For homogeneous isotropic and elastic rock, physical rock, Poisson's Ratio is given as:

$$G\ (\text{psi}) = 1.34 * 10^{10}\,\frac{\rho_B}{\Delta t_s^{\,2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.8)$$

Young's Modulus:

For homogeneous isotropic and elastic rock, physical rock, Poisson's Ratio is given as:

$$E\ (\text{psi}) = 1.34 * 10^{10}\left(\frac{\rho_B V_s^2 (3V_c^2 - 4V_s^2)}{V_c^{\,2} - V_s^2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.9)$$

Bulks Modulus:

For homogeneous isotropic and elastic rock, physical rock, Poisson's Ratio is given as:

$$K_B\ (\text{Psi}) = \frac{1}{C_b} = 1.348 * 10^{10}\rho_B\left(\frac{1}{\Delta t_c^2} - \frac{4}{3\Delta t_s^2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.10)$$

Where:-

V_s =Travel time of shear (Msec/ft)

V_c =Travel time of compressive (Msec/ft)

ρ_b =Bulk density

For unconsolidated sandstone, estimation of the dynamic rock mechanics properties is difficult as it is difficult to measure the shear wave in this type of formation, then alternative approach is necessary calculate these parameters. All though many Sudanese oilfield has unconsolidated formation; however, few models was presented to estimate rock mechanics properties; this study however address the possible models which can be used.

Chapter 2

Literature Review

It was presented in the literature that sonic measurements are conveniently used to determine the elastic properties, which are called dynamic elastic properties. Logging models are typically too high and have a very little success; hence calibration to static measurements on selected core samples is required. The calibrated log properties can be used with some correlations to estimate formation strength and failure conditions. Shear velocity is important in seismic inversion and petrophysical evaluation, particularly for evaluation of formation geomechanical properties. The shear (S-wave) velocity, compressional (P-wave) velocity and density can be used to estimate the Young's modulus, Poisson Ratio in a petrophysical evaluation, which are helpful in determination of maximum and minimum horizontal stresses. However the absence of the dipole shear sonic logs imposes severe limitations to such applications. Fortunately the S-wave velocity, P-wave velocity and density can be inverted using current advanced pre-stack seismic inversion technique from seismic AVO angle gathers (Russell et al. 2005).

Additional rock properties can be computed from the fundamental properties using standard procedures such as the Greenberg-Castagna technique (Greenberg and Castagna, 1992) for computing shear wave velocities, inverse Gassmann's equation (Gassmann, 1951) for computing dry-rock properties, and Gassmann's equation along with the dry rock properties to compute the properties of hydrocarbon-filled sands (Hilterman et al., 1999, Hilterman, 1990; Hilterman et al., 1998).

Like the petrophysical evaluations, the vertical stress, minimum and maximum horizontal stresses can also be estimated from the seismic inversion if the shear velocity is available. Gray (2010) has proposed method of estimating horizontal stresses for optimizing hydraulic fracturing locations using seismic data in their stress estimations; however no consideration was made to corporate petrophysical data.

Several methods have been proposed to evaluate rock mechanics dealing with sandstones with variable shale and hydrocarbon contents. Parameters for characterizing rock mechanical properties, such as Poisson Ratio, pore pressure; minimum and maximum horizontal stress can be estimated for each borehole with proper well logs.

The way to calculate the dynamic elastic modulus is to use the dipole sonic and density log; when these variables are available, the solution is at hand; however share velocity is difficult to evaluate in unconsolidated sand and an alternative approach is necessary to estimate rock properties. Historically many methods are available for calculating share velocity depending on compressional velocity [Pickett et al, 1963; Castagna et al., 1985, 1993; Mavko et al, 1998; Brocher et al, 2005, 2008].

It is clear that the only tool that responds to the elastic properties of the formation is the dipole sonic log, unfortunately the share wave is not available for most of the friable sediments, hence alternate approach has been to determine indirectly by a correlation of other parameter.

Experimental methods were presented in literature for modeling rock strength with the empirical core loge correlations [Henry et al, 2003; Morales et al, 1993]. Unfortunately the application of those models is only valid on the conditions in which they are derived. Application for any other conditions need verified before it used

Porosity has long been assumed to be a major factor influencing the elasticity and strength of many rock types; historically many experimental methods are available for utilizing of porosity as a geo-mechanical index. The strength of sandstones has been observed to decrease in a nonlinear manner with increasing porosity as reported by Hoshino (1972 and 1974). Howarth (1987) has shown that drilling penetration rate in sandstones increases linearly with decreasing compressive strength and increasing porosity. Kamel et al. (1991) found very good correlations between porosity determined from neutron and density logs with dynamic elastic modulus and acoustic velocities. Porosity also has been observed to be the best single primary indicator of strength in sedimentary rocks as set out by Vernik et al. (1993). Sarda et al. (1993) presented a direct correlation between the porosity and uniaxial compressive strength (UCS) to be used when no direct core measurements are available as follows:

Using the data published in the literature and the relationships exist between porosity and the mechanical properties of sandstones and carbonates measured under uniaxial loading conditions, Farquhar et al. (1994) derived a geo-mechanical index that enabled rock mechanical properties to be estimated porosity and field specific correlations. A general form for exponential functions of porosity was found as follows:

$$R = X \exp^{Y} \qquad \text{.......................... (2.1)}$$

Where R is the rock property and X and Y are constants have been favored by many researchers to describe this type of experimental data. The constant and correlation coefficient for such expressions can be found through Table (2.1).

Another approach was presented by Edlmann et al. (1998) using laboratory measured porosity and rock mechanical parameters for North Sea reservoirs to establish direct linear correlations between the porosity and the rock mechanical parameters and to produce continuous rock mechanical logs. All of these works showed a relatively good correlation between strength and porosity. Eissa and Kazi,(1988) present a linear relation between static and dynamic modulus that reflect the behavior of consolidated samples (<15% porosity). Morales and Marcinew (1993) found that Eissa and Kazi's relation is not applicable to the prediction of static modulus of weakly consolidated rocks (>25% porosity). Their laboratory observations indicate that the difference between static and dynamic modulus increases with increase in porosity, while no apparent correlation between static and dynamic Poisson's ratio was observed. Unfortunately the application of those models is only valid on the conditions in which is derived, application for any other conditions need verified before they used.

Table (2.1) Constants for simple exponential curve fits to porosity - mechanical properties relationships for sandstone and carbonates after Farquhar et al

Property (units)	Rock Type	Constants		Correlation Coefficient
		A	B	
σ_{UCS} (MPa)	Sandstone	208.08	0.074	0.71
	Carbonate	174.8	0.093	0.83
E_{Static} (GPa)	Sandstone	56.4	0.112	0.94
	Carbonate	69.05	0.06	0.87
$E_{Dynamic}$ (GPa)	Sandstone	55.39	0.146	0.96
	Carbonate	66.98	0.042	

Where: P_c, P_w, P_e are the critical pressure, working bottom hole pressure and reservoir pressure respectively; r_e, r_w and R_s are the reservoir, wellbore and sanding radius respectively.

Recently Mullen et al 2007 presented method to use petrophysical relationships and artificial neural networks (ANN) to estimate mechanical rock properties if dipole sonic information is not available.

Castagno et al.(1984) establish general VP/Vs relationships for elastic silicate rocks by comparing in-situ and laboratory data with theoretical model data. Available velocity information was examined for data from water-saturated mud rocks and sandstones. They examine laboratory data from dry sandstone and compare with simple sphere pack and cracked media theoretical model data. Data from water-saturated rocks were similarly investigated. The results of the relationships established between VP and V, are then applied to calculations of rock dynamic moduli. Finally, the general VP- Vs trends versus depth were estimated for Gulf Coast elastics.

Widarsono et al (2001) presented a new approach for estimating rock elastic properties in wells, especially for wells with limited log suites. The approach is basically a combination of efforts that are put is a series of steps. Firstly, is to model a synthetic S-wave velocity profile for a key well, with support from laboratory acoustic measurement on core samples, enabling the establishment of profiles of elastic properties through the theory of elasticity. Secondly, the modeling and validating of relationship between P-wave velocity, Poisson ratio (as an example in this paper), porosity, water saturation, shale contents, and matrix density based on the log data available for the key well. Thirdly, prediction of all missing log suites (if any) for other wells using soft computing (artificial intelligence/neural network) that has been 'trained' using data from the key well and other wells that have more or less complete log data. Fourthly, estimation of rock elastic properties for all wells (except the key well) using soft computing. Finally, evaluation of results using comparison with the model validated in the key well. The method has been applied on 14 wells of an active oil reservoir in Java, Indonesia. Comparisons of porosity and water saturation values between results from standard log interpretation and results from the validated model serve as indicators for the success of the method. The reasonably good comparisons achieved have proved that the new approach is applicable, and the use of the model relationship avoids 'blind' estimation often practiced in reservoir characterization.

Other studies have offered many methods and abundant investigation data that range from well survey to laboratory measurement on samples, from fully empirical to models, and from analysis on single source to combination of approaches. For instance Charlez et al (1987) proposed an inversion method to estimate the properties from fracmeter survey in wells, Harrison et al (1990) presented a method to extract shear wave velocity from a combination of monopole and dipole sonic logs from which elastic/mechanical properties can be estimated, whilst direct investigations on rock samples are best presented by extensive data (Gebrande et al 1982; Ellis et al 1987) Empirical relationships have also been taken as an approach5,4 as well as a combination with application of acoustic velocity models.6 As commonly accepted, none of empirical relations appears to have no general validity.

Santarelli et al. (1991) suggested that rock strength can sometimes be virtually independent of the sonic velocity, particularly in high porosity intervals. This implies that a method that relies on the traditional sonic log method would not produce satisfactory results in general. Strength estimates from sonic logs have never come close to the rock mechanical tests performed in the laboratory. An alternative approach for estimating rock mechanical properties would be to use the porosity as the primary parameter.

Bastos et al. (1998) established relationship between compressional and shear wave velocity and petrophysical properties for an offshore Brazilian field using laboratory tests on limestone samples.

Poisson's ratio was related to shale index by Anderson's equation et al.(1973) . The other properties can be calculated from equations depending on Poisson's ratio. Anderson method lends more insight into Poisson's Ratio increasing with shale. This widely used method is that presented by Anderson which related Poisson's Ratio to shaleness as follows:

Poisson's Ratio was calculated as:

$$\mu = \mathrm{A}q + \mathrm{B} \qquad \text{……………………..……. (2.2)}$$

Where q is the shale index given by:

$$q = \frac{\phi_S - \phi_D}{\phi_S} \qquad \text{……………………..……. (2.3)}$$

Where:

q = shale index.

$\emptyset_s$ =sonic-derived porosity.

$\emptyset_D$ =density derived porosity.

(A) and (B) are constant found by Anderson for Gulf Mexico as 0.125 and 0.27 respectively.

Sonic and density porosity can be calculated using Wyllie time average equation (Wyllie, 1958) as follows:

Sonic porosity:

$$\phi_S = \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}} \quad \text{.......................... (2.4)}$$

Where:

$\emptyset_s$ =sonic-derived porosity.

Δt_{log} =interval transit time in the formation (from sonic log) (µsec/ft).

Δt_{fl} = interval transit time of interstitial fluids (µsec/ft).

Δt_{ma} = interval transit time of the rock matrix (µsec/ft).

Density porosity:-

$$\phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}} \quad \text{......................... (2.5)}$$

Where:

$\emptyset_D$ =density derived porosity.

ρ_b =formation bulk density (the log reading).

ρ_{ma} =matrix density.

ρ_{fl} =fluid density.

Where Δt is the sonic transit time (µs/ft), Δtma is the sonic transit time of matrix (µs/ft), Δtf is the sonic transit time of a fluid (µs/ft), and Cp is a correction factor equal to 1 in hard rocks, but in unconsolidated formations better results are found by using Cp=(Δtsh/ 100) as proposed by Hilchie (1978). Typical constants values used in above mensioned equations were: matrix density for sandstone was 2.65 g/cm, density of the mud filtrate is 1.0 g/cm3, matrix acoustic value 54.8µs/ft, fluid acoustic value 189µs/ft, and acoustic value of shale is 115µs/ft.

The values of the Matrix sonic velocity and Matrix interval time which presented through for different formation types were presented in table (2.2), while the values of the matrix densities for different formation types are presented in table (2.3).

Table (2.2) sonic velocities and interval times for different matrixes:

Lithology	Matrix velocity (V_{ma})(ft/sec)	Δt_{ma} µsec/ft
Sandstone	18000 to 19500	55.5 to 51
Limestone	21000 to 23000	47.6
Dolomite	23000 to 26000	43.5
Anhydrite	20000	50
Salt	15000	66.7
Casing	17500	57

Table (2.3) Matrix densities values of common lithologies :

Lithology	ρ_{ma} **g/cm^3 [kg/m^3]**
Sandstone	2.644 [2644]
Limestone	2.710 [2710]
Dolomite	2.877 [2877]
Anhydrite	2.960 [2960]
Salt water	1.15 [1150]
Barite (mud additive)	

After Poisson's ratio have been calculated, the other properties (Shear modulus, Young's modulus and Bulk modulus) can be calculated as follows:

Young's modulus:

$$E = 3k(1-2\mu) \qquad \text{……………………. (2.6)}$$

Shear modulus:

$$G = 1.34*10^{10} \frac{A\rho_B}{\Delta t_c^{\ 2}} \qquad \text{(2.7)}$$

Bulk modulus:

$$K = \frac{1}{Cb} = 1.34*10^{10} \frac{B\rho_B}{\Delta t_c^{\ 2}} \qquad \text{(2.8)}$$

Where:

$$A = \frac{1-2\mu}{2(1-\mu)} \qquad \text{(2.9)}$$

$$B = \frac{1+\mu}{3(1-\mu)} \qquad \text{(2.10)}$$

The empirical correlation of Anderson is valid only for un-compacted Gulf Mexico sand, more studies are required to confirm the applicability of this method in other area, however the equation was widely used to calculate the formation strength and predicting sanding in Gulf of Mexico sands (Tixier el At (1975), Ghalambor (2002)), it was also used in Gulf of Suez Basin in Egypt (Walid et al (2006)).

Elham et al, (2010) presented that the empirical correlation of Anderson is valid in fulla oilfield in Muglad basin and can be used with high confidence with small different in the constants; Elham presented that the constant of 0.125 and 0.27 can be changed to 0.313 and 0.255 respectively. Using this values a calibration between static and Dynamic mechanical rock properties were done the result were presented through Fig (2.1) to (2.4).

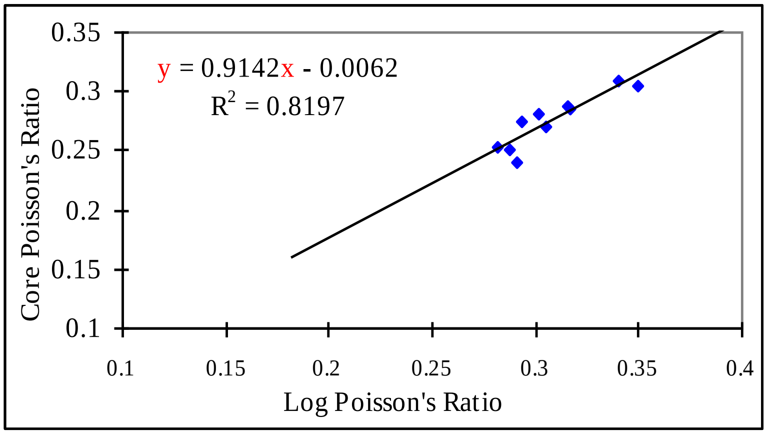


Fig (2.1) Core Poisson's Ratio vs. Log Poisson's Ratio for Fulla Oilfield (Elham et al -2010)

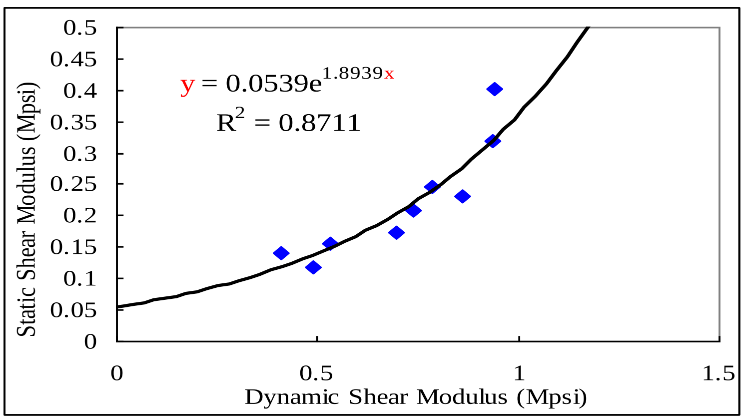


Fig (2.2) Core Shear Modulus vs. Log Shear Modulus for Fulla Oilfield (Elham et al -2010)

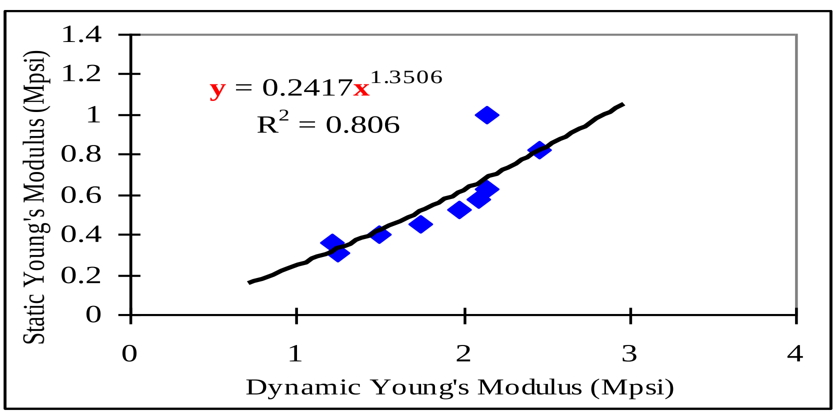


Fig (2.3) Core Young's Modulus vs. Log Young's Modulus for Fulla Oilfield (Elham et al -2010)

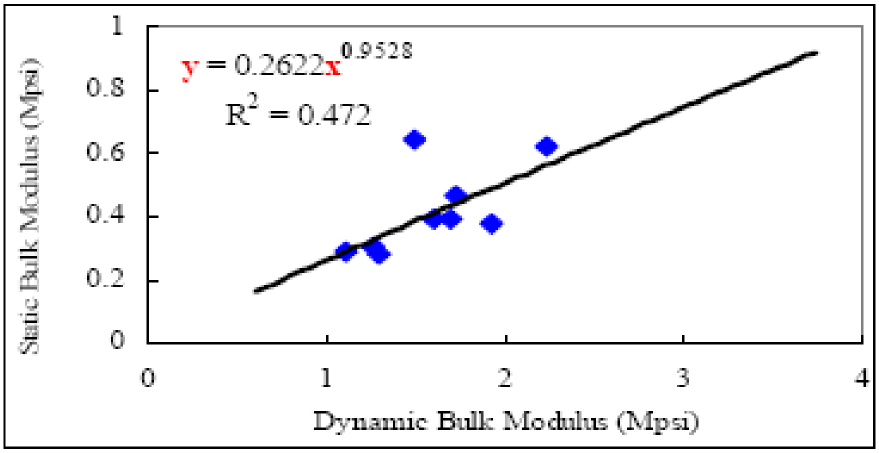


Fig (2.4) Core Bulk Modulus vs. Log Bulk Modulus for Fulla Oilfield (Elham et al **-2010)**

Ning et al (2013) estimated mechanical properties of gas-hydrate-bearing sediments in ocean and permafrost taking Well SH7 in South China Sea and Well Mount Elbert in Alaska North Slope permafrost as examples, based on the method used in conventional oil and gas reservoirs with log data, and the results were compared with other tests or calculations.

Chapter 3

Case Study

3.1. About the Field

This Study presents the results of estimation of rock mechanical properties on the cored Bentiu Formation from Case-38 WELL, located in Muglad Basin in Heglig Main oil field. The Greater Heglig area encompasses some 380 km2. The area forms part of the Cretaceous-Tertiary Muglad Basin in south-central Sudan. The basin was initiated as an extensional graben to the immediate south of the Central African Shearzone. An early phase of extensional tectonics led to rapid subsidence and lacustrine basin fills comprising the rich source rocks of the Lower Cretaceous Barremian Neocomian Sharaf Formation and Albian-Aptian Abu Gabra Formation. The reservoir section in the Late Albian to Cenomanian Bentiu Formation accumulated as widespread sheet sandstones in response to a cessation of active extension and during a period of regional sag. It marks a fundamental change from an internally draining lake basin to larger scale sediment dispersal patterns transporting sediment out of the basin in the north and south.

Stratigraphically the successi on composed of sand/shale intercalations of continental or igin varying in sand and organic content upon the environment of deposition. The multiple phases of rifting lead to episodic variations in basin subsidence that influence the stratigraphic evolution of the study area. Eleven (11) lithostratigraphic units have been established in the Muglad basin: Abu Gabra Formation, Bentiu Formation, Darfur Group (Aradeiba Formation, Zarqa Formation, Ghazal Formation and Baraka Formation), Amal Formation and Kordofan Group (Nayil Formation, Tendi Formation, Adok Formation and Zeraf Formation) in ascending order. The oil is accumulated in the Lower Cretaceous Abu Gabra and Bentiu Formations (divided into two members) and the Upper Cretaceous Darfur Group (Aradeiba Formation). The Aradeiba Formation is divided into three members (Aradeiba upper shale, Aradeiba sand and Aradeiba lower shale).

3.1.1. Bentiu formation

Bentiu Formation is the main oil-bearing unit in the study area, with average thickness of 317 m. The Bentiu Sandstone consists of a series of sandstones interbedded with claystone. Sandstone are medium to coarse grained and less consolidated than the overlying Formations, generally deposited in a braided stream environment with high Rw (RRI, 1991). The reservoir qualities are good according to the petrophysical evaluation and adjacent productive field (Heglig Field). According to Mohammed (2003) the core analysis of Bentiu sandstone in Shelungo North_1 shows that the porosity ranges from 23% to 31.2%, averaged 29.4%

3.1.2. Aradeiba formation

Aradeiba Formation sandstone is the main secondary reservoirs in the study area, with average thickness about 43 m. The Upper Cretaceous Darfur Group is predominantly composed of claystones and thin interbeded sandstone. The claystone is reddish brown to dark brown and moderately hard. Sandstone from core description is light brow n-grey colour, massive to large trough cross-bedded. Core analysis of Aradeiba sand in Shelungo North_1 shows that the porosity of the Aradeiba E range from 21% to 27% averaged 26.2% (Mohammed, 2003). Generally Aradeiba sands are deposited in lower energy environment.

This study focuses on three cores from Case-38, which represent the depth intervals from 1632.12m to 1634.30m (Core #1), 1638.00m to 1649.00m (Core #2) and 1649.50m to 1658.85m (Core #3). The three cores cover a combined total length of 22.53m. The cored intervals are part of the Cretaceous Bentiu Formation of the Muglad Basin. The Bentiu Formation comprises the main reservoir interval in the study area and is characterized by stacked successions of thick, amalgamated cross-bedded sandstones and intervening laterally extensive, thinner mud rock intervals.

The models presented through chapter 2 were applied in a real data of well – 38, Wire-line log data include compressional and shear velocity and density, while shear velocity which can be used to calculate the elastic modulus was not available in the well under the study; therefore the dynamic elastic properties were calculated with the absence of sonic measurements based on Anderson’s equation.

3.2. Steps of Calibration:

1. Before start calibrations, borehole assessment and conditions were studied to present borehole environmental influence, which may be caused by pressure, temperature, mud weight, and logging speed. These influences often happened due to washouts in shale intervals, this may change log values and result in inaccurate properties. Caliper and drilling bit size were compared to insure the log quality.
2. Core measurements were adjusted to the correct log depth by comparing the core gamma with the open-hole log gamma to make it more representative of the reservoir. The depth errors were found and the log measurements were shifted according to the result.
3. Log porosity was calculated from density and sonic log using Wyllie equations which were presented through chapter 2. Note here the log porosity are not corrected for shale as required by Anderson
4. Poisson's Ratio and strength parameters were calculated using the previously presented Anderson's equation.
5. The dynamic properties were cross plotted vs. Core elastic modulus (static) and calibrated by different correlations. The equations of the best fit curve are the correlations necessary to apply to the log data.

3.3. Result and Dissection

3.3.1. Log Quality and Depth Correction:

Fig (3.1) presents the relationship between the bit size and the caliper with the depth; the figure can be divided into two regions:-

I. The first region is in the depth about (480 - 760) m, in this region it is clear that borehole conditions indicates that the log quality is very bad: fortunately this depth is not the desired depth.

II. The second region is in the depth about (760 – 1950) m, borehole conditions indicate that the logs are in good quality for Bentiu Formation. Hence this log can be used in high confidence for Bentiu Formation.

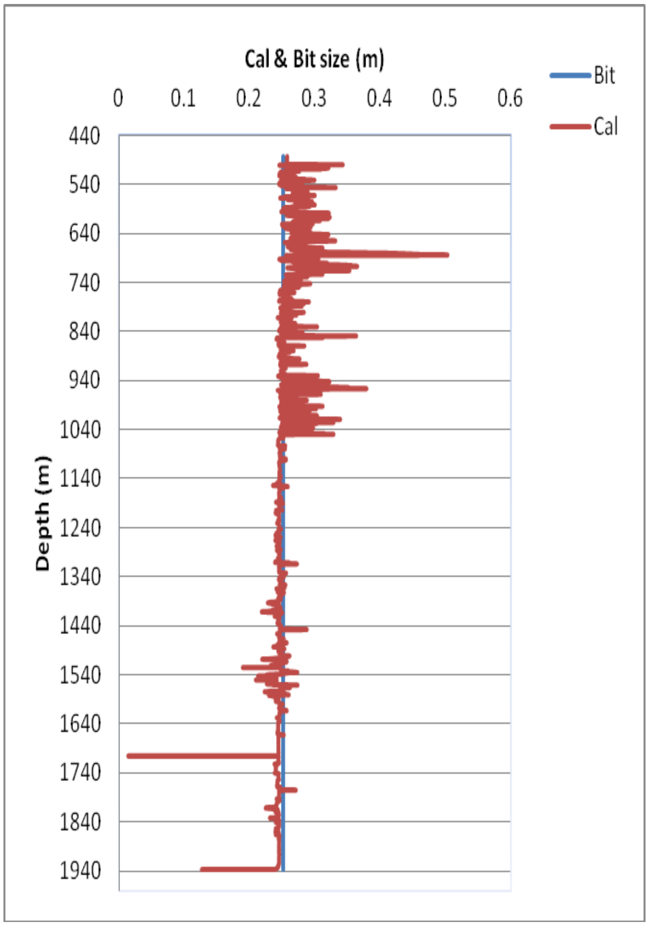


Fig (3.1) Comparison between Bit Size and Caliber Log for Different Interval

3.3.2. Core gamma and the open-hole Log Gamma

The core gamma and the open-hole log gamma were presented through Fig (3.2). The figure presented that a variation between core and log GR is occur, which indicate that depth errors is 0.5 meter hence the log data should be shifted up with 0.5 meter.

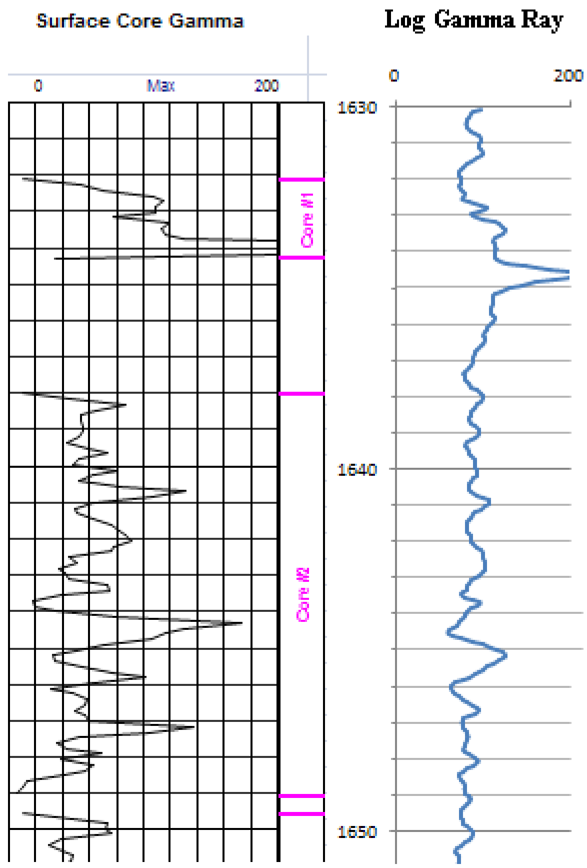


Fig (3.2) GR from Log vs. GR from Core

3.3.3. Dynamic Properties Calculations:

First, log porosity from sonic has been calculated using equation (2.4) while the density porosity $(\emptyset_D)$ has been calculated using equation (2.5). The shale index (q) was then evaluated using equation (2.3). And then Poisson's ratio was estimated using equation (2.2). Fig (3.3) shows the log porosities from sonic and density, it can be observed that the two porosities are in equivalent range for the cored interval while considerable different were observed in the interval of 1600 to 1640 m. this is also indicate that the cored interval are in good quality.

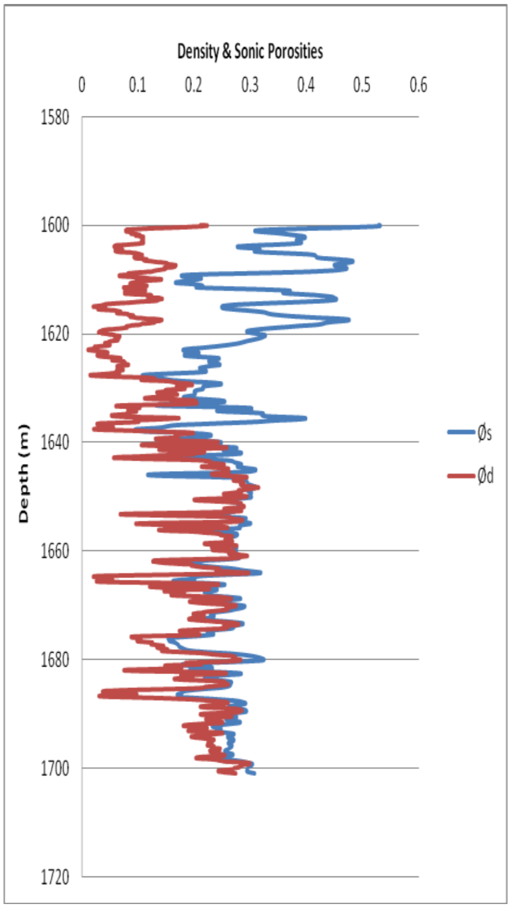
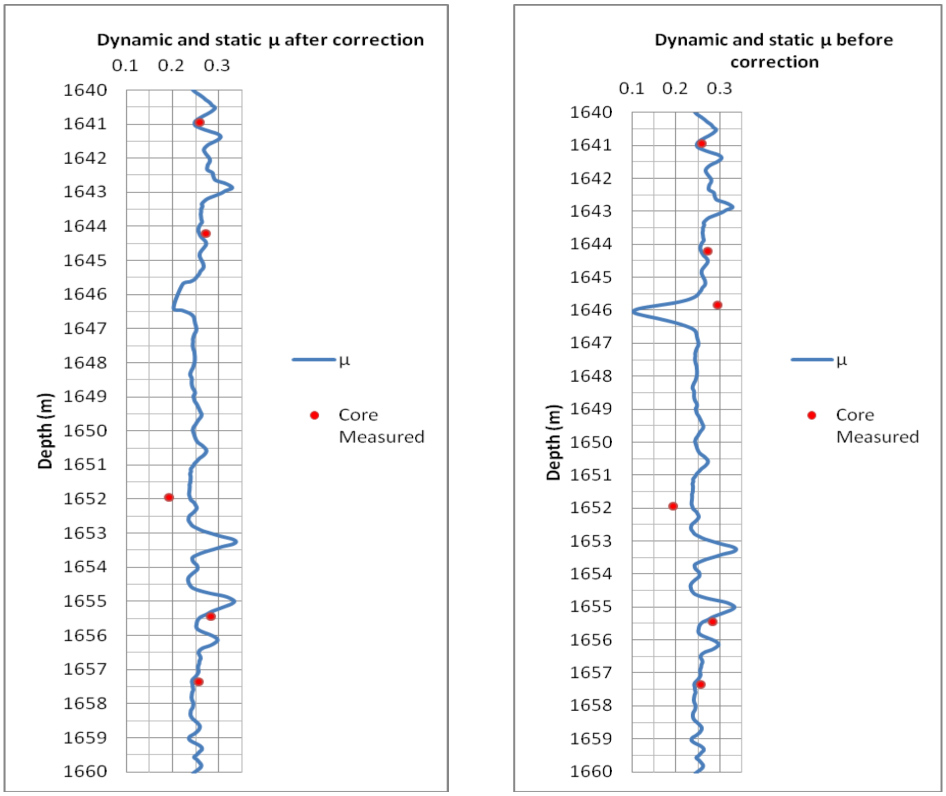


Fig (3.3) Density and Sonic Porosities V.s Depth

Core and log calculated Poisson's ratio were cross plotted for the cored interval, Fig (3.4.b), The figure presented that the core values are in good equivalent with the dynamic one, however an unacceptable value was observed for one point which was early presented as anomaly point, when this point was omitted, the curve has a good matching with the dynamic values, Fig (3.4.a), hence this point will be omitted for all other parameters.

Table (3.1): Static and Dynamic Poisson's ratio

Depth	Static Poisson's ratio	Dynamic Poisson's ratio
1640.95	0.2730666	0.258
1644.20	0.2730741	0.2665
1651.95	0.1934971	0.2727
1655.45	0.2830325	0.2708
1657.35	0.2581452	0.253



a **b**

Fig (3.4) Dynamic Poisson's Ratio and the Static Poisson's Ratio V.S Depth

Dynamic Poisson's ratio was cross plotted against the static one, and calibrated by different correlations, Fig (3.5). The equations of the best fitting curve were presented, as can be shown from the figure the polynomial equation is the best correlations that minimize the error between estimated and measured values with value of R^2 of 0.89. The value of R^2 in Fulla oilfield in Muglad basin that was found by Elham et.al was only R^2 = 0.819 which indicate that the equation can be used in Heglig with also high confidence. The obtained equation can be written as follows:

$$\mu\,(\text{Static}) = 5.8698\mu^2(\text{Dynamic}) - 2.511\mu(\text{Dynamic}) - 0.5038$$

After Poisson's ratio was calculated, the other rock mechanics properties (Shear modulus, Young modulus and Bulk modulus) have been estimated depending on Poisson's ratio on the base of Anderson, related on specific factors A from equation (2.9) and B from equation (2.10). After that the Bulk modulus have been calculated by using equation (2.8), the Shear modulus can be calculated by using equation (2.7) and the Young modulus have been calculated by using equation (2.6). The result was presented through table (3.1) to (3.4).

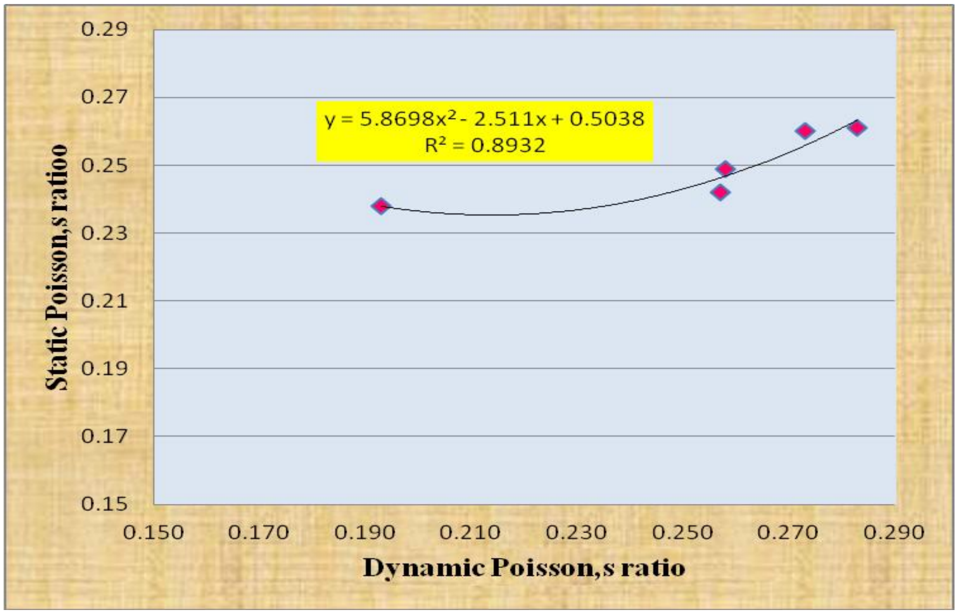


Fig (3.5) Static Poisson's Ratio Vs. Dynamic Poisson's Ratio

Using the data in table (3.2) across plot of the dynamic shear modulus and static shear modulus was presented in Fig (3.6). The correlation of the best fitting line was presented in the figure with R^2 of 0.99; while the value obtained Fulla oilfield in Muglad Basin by Elham et.al was only $R^2 = 0.8713$, which indicate that the equation can be used in Heglig oil Field with also high confidence. The polynomial equation is the best correlations that minimize the error between estimated and measured values as follows:

$$G\,(\text{Static}) = -248.98G^2(\text{Dynamic}) + 572.03G(\text{Dynamic}) - 327.88$$

Table (3.2): Static and Dynamic Shear Modulus

Depth	Static shear modulus	Dynamic shear modulus
1640.95	0.609582	1.164
1644.20	0.349281	1.113
1651.95	0.686806	1.154
1655.45	0.396006	1.114
1657.35	0.428447	1.181

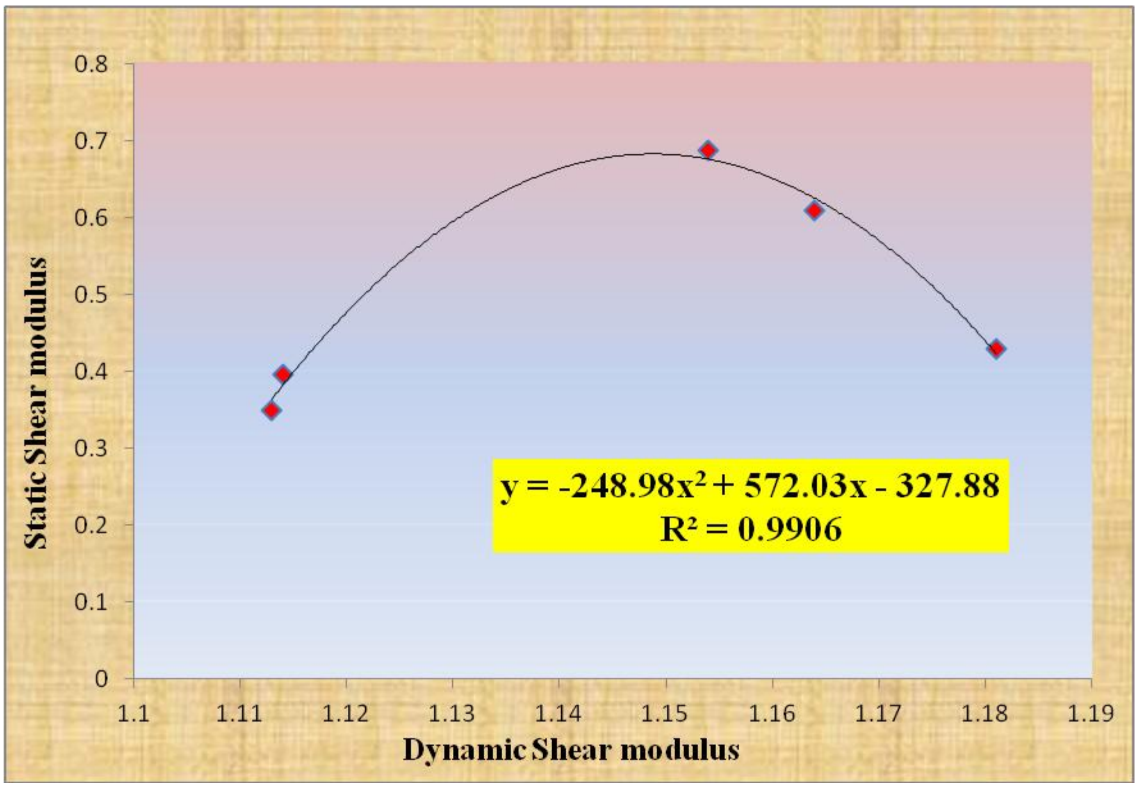


Fig (3.6) Dynamic Shear Modulus V.s Static Shear Modulus

By the same way; the data in table (3.3) across plot of the dynamic Young's modulus and static Young's modulus was presented in Fig (3.7). The correlation of the best fitting line was presented in the figure with R^2 of 0.995; while the value obtained in Fulla oilfield in Muglad Basin by Elham et.al was only $R^2 = 0.806$, which indicate that the equation can be used in Heglig oil Field with also high confidence. The polynomial equation is the best correlations that minimize the error between estimated and measured values as follows:

$$E\,(\text{Static}) = -150.48E^2(\text{Dynamic}) + 871.89E(\text{Dynamic}) - 1261.2$$

Table (3.3): Static and Dynamic Young's Modulus

Depth	Static young modulus	Dynamic young modulus
1640.95	1.5520779	2.93
1644.20	0.8893223	2.825
1651.95	1.639401	2.884
1655.45	1.0161775	2.829
1657.35	1.0780961	2.96

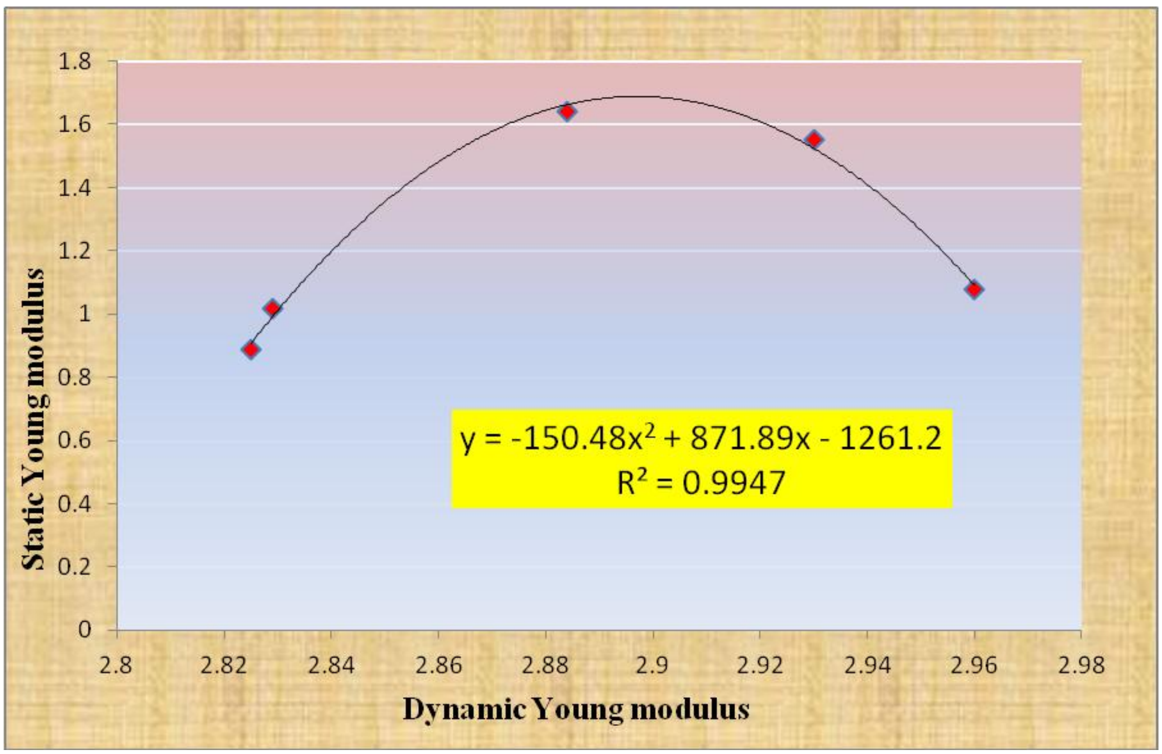


Fig (3.7) Dynamic Young's Modulus V.S Static Young's Modulus

Finally; the data in table (3.4) was cross-plotted to present the dynamic Bulk Modulus and static Bulk Modulus was presented in Fig (3.8). The correlation of the best fitting line was presented in the figure with R^2 of 0.995; while the value obtained in Fulla oilfield in Muglad Basin by Elham et.al was only R^2 = 0. 476, this indicates that the equation can be used in Heglig oil Field with higher confidence than Fulla oilfield. The polynomial equation is the best correlations that minimize the error between estimated and measured values as follows:

$$K\,(\text{Static}) = 47.069K^2(\text{Dynamic}) - 187.49K(\text{Dynamic}) + 187.35$$

Table (3.4): Static and Dynamic Bulk Modulus

Depth	Static bulk modulus	Dynamic bulk modulus
1640.95	1.1576782	2.09
1644.20	0.6634923	2.037
1651.95	0.9052309	1.915
1655.45	0.7927003	2.058
1657.35	0.7549058	2

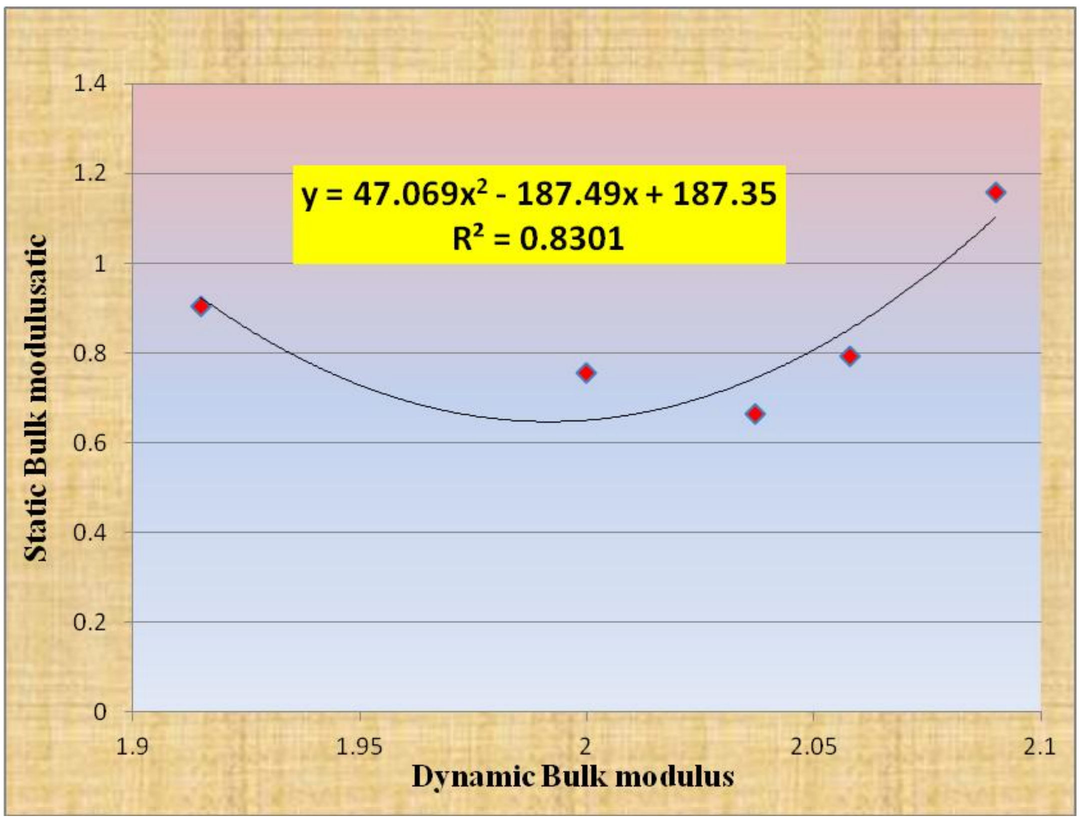


Fig (3.8) Dynamic Bulk Modulus V.S Static Bulk Modulus

Chapter 4

Conclusions and Recommendations

4.1. Conclusions:

In this study calibrations for the dynamic Rock mechanical properties and static properties of core were made for Bentiu formation in Heglig oilfield.

Rock mechanical properties (Shear modulus and Young's modulus and Bulk modulus) have been calculated with the absence of shear wave for unconsolidated sandstone based on Poisson's ratio.

Anderson's equation was used to calculate Poisson's ratio as a function of the shale index which is mainly depend on the compressional wave only.

The static rock mechanics parameters have been calibrated with the dynamic one using different correlations; finally the best fitting equation were selected based on the correlation coefficient (R^2).

It was found that the polynomial equations are the best correlations that minimize the error between estimated and measured values for all parameters, thus:

1. Poisson's Ratio:

$$\mu\,(\text{Static}) = 5.8698\mu^2(\text{Dynamic}) - 2.511\mu(\text{Dynamic}) - 0.5038$$

2. Bulk modulus:

$$K\,(\text{Static}) = 47.069K^2(\text{Dynamic}) - 187.49K(\text{Dynamic}) + 187.35$$

3. Shear modulus:

$$G\,(\text{Static}) = -248.98G^2(\text{Dynamic}) + 572.03G(\text{Dynamic}) - 327.88$$

4. Young modulus:

$$E\,(\text{Static}) = -150.48E^2(\text{Dynamic}) + 871.89E(\text{Dynamic}) - 1261.2$$

4.2. Recommendations:

Unfortunately the application of Anderson's equation is only valid on the conditions in which is derived, if and only if s-wave is available Anderson's equation can be accurate for the any condition .also if core data is available the equations can corrected

References

Brocher, T. M., 2008. "Key Elements of Regional Seismic Velocity Models for Long Period Ground Motion Simulations", J. Seismol. Doi. Vol. 10.-9061-3.

Castagna, J. P., Batzle, M. L., and R. L. Eastwood., 1985. Relationships between compressional-wave and shear-wave velocities in clastic silicate rocks, Geophysics, 50, 571-581.

Charlez, P., Saleh, K. and Despax, D,. (March 1987. "The Fracmeter: A New Numerical Method to Evaluate the State of Stress and the Elastic Properties of Rocks," SPE 15773, presented at 5th SPE Middle East Oil Show, Manama-Bahrain,).

Ghalambor, TE Martin. 2002. Comparative manipulation of predation risk in incubating birds reveals variability in the plasticity of responses Behavioral Ecology 13 (1), 101-108.

Harrison, A.R., Randall, C.J., Aron, J.B., Morris, C.F., Wignall, A.H., Dworak, R.A., Rutledge, L.L. and Perkins, J.L. September 1990. "Acquisition and Analysis of Sonic Waveforms from a Borehole Monopole and Dipole Source for the Determination of Compressional and Shear Speed and Their Relation to Rock Mechanical Properties and Surface Seismic Data," SPE 20557, 65th Annual technical Conference and Exhibition, New Orleans, .

Eissa and Kazi, A,. 1988Relation between static and dynamic young's modulus of rocks , Int Jounal of rock mechanics mining sciences and geomechanics abstract.vol 25,. .

Ellis, D.V, 1987. Well Logging for Earth Scientists. Elsevier Sc. Publ., New York, Amsterdam, London

Gebrande, H., Kern, H. and Rummel, F, 1982. "Elasticity and Inelasticity," In: Landolt-Bornstein Numerical Data and Functional Relationships in Science and Technology (K. H. Hellwedge, ed), New Series; Group V. Geophysics and Space Research, Vol. Physical Properties of Rocks, Subvolume b, 1 – 233. Springer-Verlag Berlin, Heidelberg, New York

Anderson, R., Coates, G.R., Denoo, S., Rsines, R., 1986. Formation collapse in a producing well. The Technical Review 34, 29–32.

Bastos, A.C., Dillon, L.D., Vasquez, G.F., Soares, J.A., 1998. Core derived acoustic, porosity and permeability correlations for computation pseudo-logs.

References

Edlmann, K., Somerville, J.M., Smart, B.G.D., Hamilton, S.A., Crawford, B.R., 1998. Predicting rock mechanical properties from wireline porosities. SPE paper 47344. In: Proceedings of the EUROCK 98 SPE/ISRM Rock Mechanics in Petroleum Engineering Meeting, vol. 2. Society of Petroleum Engineers, Richardson, Texas, pp. 169–175.

Farquhar, R.A., Somerville, J.M., Smart, B.G.D., 1994. Porosity as a geomechanical indicator: an application of core and log data and rock mechanics. SPE paper 28853. In: Proceedings of the European Petroleum Conference, London, England. Society of Petroleum Engineers, Richardson, Texas, pp. 481–489.

Gardner, G.H.F., Gardner, L.W., Gregory, A.R., 1974. Formation velocity and density – the diagnostic basics for stratigraphic traps. Geophysics 39, 770–780.

Santarelli, F.J., Dusseault, M.B., Yassir, N.A., 1991; Estimating Rock Mechanics Properties in Petroleum Engineering Practice: Problem Statement. Report of the ISRM/SPE Joint Commission on Rock Properties for Petroleum Engineers

Sarda, J.P., Kessler, N., Wicquart, E., Hannaford, K., Deflandre, J.P., 1993. Use of porosity as a strength indicator for sand production evaluation: SPE paper 26454. In: Proceedings of SPE Annual Technical Conference and Exhibition.Society of Petroleum Engineers, Richardson, Texas, pp. 381–388.

Tixier, M.P., Loveless, G.W.,Anderson, R.A.,1975. Estimation of formation strength from the mechanical properties log; Journal of Petroleum Technology 27 (3), 283–293

Widarsono, B., Wong, P.M., Saptono, F., 2001; Estimation of rock dynamic property profiles through the combination of soft computing, acoustic velocity modeling and laboratory dynamic test on core; SPE Paper 68712; Society of Petroleum Engineers, Richardson, Texas, pp. 1–10.

Wyllie, M.R.J., Gregory, A.R., Gardner, G.H.F., 1958. Elastic wave velocities in heterogeneous and porous material; Geophysics 23, 459–493

Ning, Jiang G.1, Sun C. Chen G. August 2013 ,.“Estimation of in-situ mechanical properties of gas hydrate-bearing sediments from well logging”; petroleum exploration and development volume 40, issue 4,

Greenberg and Castagna, 1992. Shear-wave velocity estimation in porous rocks: theoretical formulation, preliminary verification and applications. Volume 40, Issue 2, pages 195–209

References

Gassmann, F, 1951 . Elastic Waves Through Packing of Spheres , Geophysics .

Hilterman .J.T.Lapperme.T.S.Van Bree,L,Streerenberg.P.A Brahim.J.J sont.J.K Hilemstra P.Stolk J,1999.Free Radic Biol Med

Gray ,2010 . Show Sold Separately Promos Spoilevs and Other Media Paratexts

Pickett, G. R., 1963, Acoustic character logs and their application in formation evaluation, J. Petr. Tech.,659-667.

Morales,G.M..Hubbert.T.Brummeodorf.U.tereubert,A.tarnok.U.Schwarzand.E.G.Rathjen.1993.Induction of axonal groth by hetrophilic interactions between the cell surfase recognition proteins F11 and Cam/bravo.Neuron,11.1113-1122.

Elham et al, 2010.Calibration of wireline mechanical properties using core measurments results for fula oilfield case study.

Walid M. Mabrouk .2006 ., An Approach for Estimating Porosity from Sonic-Logs in Shaly Formations .

Hoshino ,K., Kiode inarni,S.,Lwamura,S. and Misui,S.1972. mechanical properties of japanese tertiary sedementry under high confining pressures. Geological survey of japan. report No .244.

Hoshino ,K.1974.Effect of porosity on the strain of elactic sedementary rocks , in,reports of current research vol.III,partA.themes1-2,proc.3rd cong.int.sot.rock mech.,denver,colorado,pp.511-516.

Howarth.D.F. 1987.the effect of pre-existing micro-cavities on mechanical rock performanse in sedementry and crystalline rocks.Int.J.rock mech geomech.abstr vol.24 (4).pp ,223-233.

Kamel, H. 1991.,porosity.mechanical properties cross plots,posible indicators of fracture intensity.spwl.A 32nd annual logging symposium.

Henry A. Ohen ,.1998. "Calibrated Wire line Mechanical Rock Properties Model for Predicting and Preventing Wellbore Collapse and Sanding", SPE 82236, SPE European Formation Damage Conference, Netherlands,13-14May2003

Mavko G., Mukerji T., Dyorkin J.", The Rock Physics Handbook: Tools for Seismic Analysis of Porous Media",CambridgeUniversityPress,NewYork,Pp339.

Mullen M., Roundtree R., Barree B., April 2007,. "A Composite Determination of Mechanical Rock Properties for Stimulation Design - What to Do When You Don't Have a

Sonic Log ", SPE 108139, Rocky Mountain Oil & Gas Technology Symposium, Denver Colorado U. S. A.

Russell, P., J. Livingston, B. Schmid, J. Eilers, R. Kolyer, J. Redemann, S. Ramirez, J-H. Yee,W. Swartz, R. Shetter, C. Trepte, A. Risley, Jr., B. Wenny, J. Zawodny, W. Chu, M. Pitts, J.Lumpe, M. Fromm,C. Randall, K. Hoppel, R. Bevilacqua , 2005. Aerosol optical depth measurements by airborne Sun photometer in SOLVE II: Comparisons to SAGE III, POAM III and airborne spectrometer measurements, Atmos. Chem. Phys., 5, 1311–1