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Formation Compressive Strength Estimates for Predicting Drillability and PDC Bit Selection

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Abstract

Various indirect measuring techniques are presently employed for estimating formation strength, which in turn is correlated to drillability and polycrystalline diamond compact (PDC) bit selection. Formation mechanical properties derived from conventional open-hole logs in combination with a rigorous assessment of formation shear wave velocities can be used successfully to determine drillability as it pertains to bit selection. Formation drillability is best determined from unconfined compressive strength and the angle of internal friction assessment. Rock strength is found to correlate well with the overall measures of bit effectiveness.

Further, the angle of internal friction, which is a subsidiary rock strength parameter, correlates with PDC bit wear rates.

Compressive strength and drillability have been linked in the laboratory and observed in the field since the early 1960's. Compressive strengths, however, need to be qualified as a function of confinement stress. The concept that compressive strength increases with confinement stress is well-understood and can be easily explained with Mohr's failure criteria. With the Mohr's failure technique, it is important to understand that inherent rock strength properties (cohesion and angle of internal friction) must be known before compressive strengths can be estimated.

This paper also presents case histories from Gulf of Mexico wells that illustrate how unconfined compressive strength and angle of internal friction can be employed to indicate drillability as it pertains to optimized bit selection.

Introduction

Aggressiveness and wear resistance are two fundamental properties that must be considered when selecting a bit for a specific application. For simplicity's sake, these two bit properties, while not totally independent, may be considered separately.

The aggressiveness of the bit is determined by the depth of cut it is designed to take. In roller cone bits, aggressiveness is determined by projection, pitch of the teeth, and cone offset. In PDC bits, aggressiveness is determined by the exposure of the cutters and the cutter angle (backrake).

Wear resistance, on the other hand, is determined by the density of the cutters, especially those on and near the gauge.

In roller cone bits, increasing wear resistance is accomplished by adding more gauge cutters; more durable shapes of cutters; applying diamond to the cutters that contact gauge; and modifying carbide grade (at the expense of making cutters more brittle) or increasing the number of carbide inserts on the shirrtail.

The wear resistance of PDC bits is improved by increasing the length of the gauge so that more cutters can be placed on and near gauge and increasing the carbide or diamond content

References and figures at end of paper

of the gauge pad. Some of the trade-offs that make a bit more wear resistant also make it more susceptible to cutter breakage and whirl. It is generally accepted that a flat profile is more resistant to off-center bit whirl than a tapered profile, which is more resistant to wear. Typically, bits designed with a specific degree of aggressiveness are available with or without gauge wear enhancement.

When the selected bit is too aggressive for the targeted application, it is likely to sustain cutter breakage. Conversely, when a bit with low wear resistance is selected for an application requiring maximum durability, severe cutter wear typically results. In selecting bits that have the best opportunity for optimum performance in a specific application, it is vital to identify those rock properties that govern the aggressiveness and wear resistance of a particular bit.

For any application, the primary goal is to select a bit that will drill more hole at a maximum rate of penetration to produce the lowest cost per meter. Relying solely on trial and error and knowledge of a particular region all too often produces excessive trip time and can result in an overall higher well cost.

Rock Strength Measures for Selection of Bit Aggressiveness

Historically, measures of rock compressive strength have been used to aid in bit selection.^{1,2} However, rock compressive strength that is measured on cores or estimated from open hole logs is very much a function of the state of stress under which the measurement is made. Consequently, a brief summary of rock mechanical concepts typically used when measuring compressive strength is in order.

Compressive strength tests performed in the laboratory on cylindrical core specimens exhibit a common mode of diagonal (shear) failure (Fig. 1). The Mohr-Coulomb theory of failure postulates that failure will occur when the maximum shear stress exceeds the shear strength of the rock. The theory also holds that the normal stress acting across the plane of failure increases the shear resistance of the rock by an amount proportional to the magnitude of the normal stress. The normal and shear stresses at the failure plane can be derived as follows:

In Fig. 1, assume that stresses σ_x , σ_y , τ_{xy} and τ_{yx} are known and σ_θ and τ_θ acting on the failure plane whose normal makes angle θ with respect to the horizontal axis are desired. Summing forces leads to:

$$1) \quad \sigma_\theta = \sigma_x \cos^2 \theta + \sigma_y \sin^2 \theta + 2 \tau_{xy} \sin \theta \cos \theta$$

$$2) \quad \tau_\theta = \tau_{xy} (\cos^2 \theta - \sin^2 \theta) - (\sigma_x - \sigma_y) \sin \theta \cos \theta$$

And using trigonometric identities, these equations can be rewritten as:

$$3) \quad \sigma_\theta = 1/2 (\sigma_x + \sigma_y) + 1/2 (\sigma_x - \sigma_y) \cos 2\theta + \tau_{xy} \sin 2\theta$$

$$4) \quad \tau_\theta = \tau_{xy} \cos 2\theta - 1/2 (\sigma_x - \sigma_y) \sin 2\theta$$

When stresses acting on the core specimen σ_x and σ_y are normal to the extent that shear stresses τ_{xy} and τ_{yx} vanish, these normal stresses are called principle stresses and are renamed σ_1 and σ_3 respectively. This convention is similar to that used in structural geology where σ_1 is the maximum principle stress and σ_3 is the minimum principle stress. The intermediate stress, not considered in this two-dimensional analysis, is σ_2 .

During core testing, the compressive load at failure (compressive strength) is σ_1 . The confining stress applied circumferentially around the specimen is σ_3 . When the confining stress is zero ($\sigma_3 = 0$), σ_1 is the unconfined compressive strength. Furthermore, as the confining stress σ_3 is increased, the compressive strength σ_1 increases. In other words, as confinement stresses increase, compressive strength also increases. Using the σ_1 and σ_3 notation, the following equations define stresses at the core specimen's plane of failure:

$$5) \quad \sigma_\theta = 1/2 (\sigma_1 + \sigma_3) + 1/2 (\sigma_1 - \sigma_3) \cos 2\theta$$

$$6) \quad \tau_\theta = 1/2 (\sigma_1 - \sigma_3) \sin 2\theta$$

Mohr's Circle

A convenient graphical representation of these relationships uses Mohr's circles (Fig. 2), which are constructed from destructive core tests. These analysis, (known as triaxial tests), are performed on cores from similar rock (i.e., comparable lithology, porosity, etc.), which are cut and prepared under standard conditions and loaded to failure σ_1 at selected confining stresses σ_3 .³

The line drawn tangent to at least two Mohr's circles defines Mohr's failure envelope. Mohr's envelope can be defined by a linear equation representing shear failure when the applied shear stress exceeds both the cohesive strength of the rock and the frictional shear resistance. Thus:

$$7) \quad \tau_\theta = S_0 + \sigma_\theta \tan \beta$$

The unconfined compressive strength C_0 expressed in terms of cohesion S_0 and angle of internal friction β is:

$$8) \quad C_0 = (2 S_0 \cos \beta) / (1 - \sin \beta)$$

As shown in Fig. 2, the Mohr's circle intercept required for failure expressed as $(\sigma_1 - \sigma_3) / 2$ increases as the angle of internal friction increases and the shear strength of the rock increases, i.e., for a given loading condition in terms of σ_1 and σ_3 . The angle of internal friction is dependent on the lithology. For example, sandstones generally have relatively large angles of internal friction compared to shales and even some limestones and dolostones.

Usually, the larger values of angle of internal friction are associated with angular, rather than rounded formation grain geometry, causing higher degrees of grain interlockment and reduced sorting coefficients.⁵

Stresses at TD

Previous investigations have shown that confinement due to geologic overburden stress is negligible as far as drilling strength is concerned.⁴ A strengthening of the rock, which affects drilling, is caused almost entirely by the differential pressure between the mud column and the pore pressure.⁸ Confinement stresses at the bottom are negligible when drilling at or near balanced conditions.

Thus, according to Sellami et al¹¹, the Mohr-Coulomb failure model adequately describes the decline in penetration rates experienced in the field and laboratory when mud pressure overbalance is increased. Conversely, if the mud weights are balanced, the rock is drilled effectively, according to its unconfined compressive strength.

Compressive Strength According to Acoustic Wave Velocities

Compressive strength has been successfully related to drillability since the early 1960's. Gstalder measured rock hardness from cores and compressional velocities for two wells, comprising shale and oolitic limestones, that were drilled in the Paris Basin.⁵ Gstalder's study concluded that rock hardness increases as compressional velocities increase.

Sommerton measured compressional velocity and drilling strength at laboratory conditions⁶ and found that drilling strength increased with an increase in compressional velocities.

Thus, it is clear that a strong correlation exists between rock hardness and compressional travel times. Essentially, as travel times become faster, the rocks harder. However,

compressional wave velocity can be very sensitive to formation fluid. This can be especially problematic when gas, even in concentrations as low as 5%, is present in the formation. Even small concentrations of formation gas can greatly reduce the P wave velocities. Therefore, if one only considered compressional wave velocities, rocks strongly saturated with gas would appear to be "weak."

Formation fluid, on the other hand, has little or no effect on shear wave velocity. Therefore, correlations between formation strength and shear wave velocity represent a significant improvement over compressional wave techniques.

Data sets generated by Mason⁷ indicate the strong tendency of rock strength to increase with increasing shear wave velocities. Although a very simplistic method of estimating crucial shear wave velocities from lithologies, the Mason technique is being used with some success for bit selection purposes.

A hypothetical example follows illustrating how unconfined compressive strength can be used for optimum bit selection.

A well is to be drilled in near-balanced conditions in a low permeable sand that has an unconfined compressive strength of 10,000 psi. An IADC Class 437 roller cone bit is to be run on 9 ppg mud with a targeted penetration rate of 9 m/hr (30 ft/hr). Later, the mud weight is increased to 16 ppg, whereupon the increased differential pressure strengthens the rock to 17,000 psi, causing the ROP to drop to 3 m/hr (10 ft/hr).

At this point, some consideration may be given to pulling the 437 class bit in favor of a less-aggressive IADC 517 type. However, the wisest course would be to keep the 437 type bit in the hole. Even though plastic rock strength has increased by 7000 psi, it would be insufficient to break the 437-class teeth. The use of a less aggressive bit, therefore, is not only unnecessary, but would further lower the penetration rate.

While unrelated to aggressiveness, it must be pointed out that the plastic strengthening of the rock conceivably could aggravate cutter wear, since the lower depth of cut would require the bit to complete more revolutions to drill a given section. In such a case, the 437 class bit would still be recommended, providing it incorporated enhanced gauge wear features.

Using confined compressive strength to determine bit aggressiveness results in the selection of a bit that is too conservative for the targeted formation. The end result is lower penetration rates.

This phenomenon holds true when drilling in normally pressured rocks, but in depleted sands, where the overbalance typically exceeds 2,000-3,000 psi (4-6 ppg at 3,048m), a less aggressive bit may be in order. When overbalance becomes the overriding mechanism for bit selection, it is impossible to assign a hard and fast value to the cutoff point. This will not be addressed in this presentation. However, it should be noted that drilling very overbalanced sands, such as those encountered in the Gulf of Mexico, negatively impacts bit wear and penetration rate to the point that natural diamond or TSP bits may be required.

For bit selection purposes, a logical explanation as to why unconfined compressive strength is superior to confined compressive strength is the fact that unconfined compressive strength is a property of the rock. As such, it remains constant with drilling conditions, assuming the conditions are balanced.

Confined compressive strength, on the other hand, is greatly influenced by the drilling environment. Since it is not a constant, confined compressive strength cannot be compared from well to well. For example, a well drilled with a unique casing and mud program will have a particular confined state of stress. For that reason, it would be imprudent to use the confined compressive strengths of this well in the planning of a future well having different casing and mud programs.

Another data analysis technique that may be exploited by means of unconfined compressive strength is the use of specific drilling energy to calculate drilling efficiency.

Specific energy, which is the energy expended in drilling a unit volume of rock, has units of force per square length:

$$E_s = \frac{W}{A_B} + \frac{120\pi NT}{A_B R}$$

It has been observed that the lowest specific energy with which a rock may be drilled happens to be numerically equal to the unconfined compressive strength of the rock.^{8,9,10} Such unfavorable drilling parameters as improper bit selection, poor hole cleaning, poor solids control and high differential pressure, to name a few, can result in the expending of specific energy that is higher than the unconfined compressive strength.

Improving the drilling parameters can lower specific energy. Ideally, the specific energy may approach a minimum, the magnitude of which will be close to the unconfined compressive strength. The ratio of unconfined compressive strength divided by specific energy produces a number between zero and one that is defined as the drilling efficiency.

The optimum drilling efficiency is reached when it approaches one.

When unconfined compressive strength is used, a log of drilling efficiency may be plotted. On such a log, the sections showing low drilling efficiency indicate where the most improvement can be made. Improvement may come in the form of a new casing and mud program to lower differential pressure and increase penetration rates. Such an improvement will change the confined compressive strengths, which, as mentioned earlier, are products of the drilling environment and cannot be used to identify optimal opportunities.

Rock Abrasiveness Measures for Selection of Bit Wear Resistance - Angle of Internal Friction / Wear Correlation

The literature does not document the rock properties that may be used to determine the wear resistance of a bit. The authors propose that the angle of internal friction correlates with formation abrasiveness and, therefore, provides a measure of abrasiveness. Both field performance and laboratory testing support this theory. As mentioned earlier, the angle of internal friction is very dependent upon lithology with sandstones generally having a relatively large angle of internal friction when compared to shales, limestones, and dolostones.

This hypothesis has been tested empirically. Five sandstones having a wide degree of abrasiveness were selected for evaluation. The sandstones used were the Crab Orchard, Nugget, Berea, Salt Wash, and Navaho. In laboratory wear tests, a PDC core bit equipped with PDC cutter blanks without the diamond table was used to drill these rocks under atmospheric pressure.

The volumetric wear of the carbide cutter blanks was measured and divided by the volume of rock removed. This ratio of cutter wear to rock removed is considered the most realistic means of quantifying drill bit abrasion since it is a measure of how much a bit will wear while drilling a given section of rock.

Compressive strength tests under various confining pressures were conducted on samples taken from the same five rocks. The tests were done to quantify the internal angle of friction and the compressive strength of each rock. As suspected, the tests revealed there is a stronger correlation between the angle of internal friction and wear than there is between compressive strength and wear. The conjecture was confirmed when the ranking of rocks in terms of abrasiveness was shown to be identical to the ranking of rocks on internal angle of friction. The test data is shown in Table 1.

Rock Mechanics Algorithm (RMA)

Chevron Petroleum Technology Company's Rock Mechanics Algorithm (RMA) program estimates unconfined compressive strength and angle of internal friction from basic electric log data. The output from this algorithm consists of a log-like plot of unconfined compressive strength, angle of internal friction and related data.

In the past, making bit recommendations based solely on compressive rock strength frequently led to premature bit failure. All too often, this failure was a direct result of whirl-induced cutter breakage. Over the last several years, several methods have been used to reduce the effects of whirl. Improved bit designs have successfully addressed this problem. For example, some bits are now designed to resist whirl by directing load forces generated by the cutters during drilling through a low friction gauge pad. By designing the optimum resultant cutting load to be directed through the gauge pad, the bit self-stabilizes while drilling. As a result, the bit drills smoothly and is capable of penetrating a much wider variety of formations without the catastrophic cutter fracture sustained by conventional PDC bits. While the instances of cutter breakage have diminished, abrasion-induced wear has become a more critical factor in determining bit life.

The angle of internal friction has proven to be a good measure of abrasion. Experience has shown that when the average angle of internal friction consistently stays above 40°, formations are too abrasive for a conventional PDC bit.

Case Histories

Selected bit runs from two wells follow, illustrating the log-derived unconfined compressive strength and angle of internal friction estimates and their strong relationship to bit performance. Both wells were drilled east of the Mississippi River where offshore wells are generally deeper and encounter more carbonates and abrasive sands than do typical Gulf of Mexico wells.

Case History One - Well A

Two of the 6 1/2" PDC bits run in Well A had been very successful in drilling hard formations elsewhere in the U.S. The first bit effectively drilled hard formations in West Texas (below 6,095 m - 20,000 ft); however, the angle of internal friction was less than 40°. The second bit recorded good performance in the Rocky Mountains that possessed high compressive strengths (>15,000 psi.).

Both bits however, performed very poorly in Well A. Neither bit was able to drill a 27-meter (90 ft) stand and penetration rates dropped to as low as 1.5 m/hr (5 ft/hr).

When looking only at compressive strength, the bits should have been capable of drilling the formations. An evaluation of the angles of internal friction showed them to be a consistent 42° to 44° for both of the inefficient bit runs. When their performance fell short of expectations, natural diamond bits designed to drill such abrasive formations on turbines were eventually run. These natural diamond bits achieved longer runs at rates of penetration that were consistently more than 3 m/hr (10 ft/hr).

Fig. 3 presents the RMA program output for the two PDC bit runs indicating the high angle of internal friction.

Case History Two - Well B

Multiple runs of identical 12 1/4" PDC bits were conducted in Well B. The two bits being presented were eight-bladed with spiral layouts and enhanced cutter configurations. Both bits were run on rotary.

Although the compressive strength remained relatively consistent for the runs, bit life was substantially reduced on those runs with a higher angle of internal friction.

Bit No. 1:	378 m (1242 ft) 5.3 m/hr (17.4 ft/hr) 24BTSXIOPR
Bit No. 2:	70 m (230 ft) 1.6 m/hr (5.4 ft/hr) 28ROSXIWTPR)

A review of the angle of internal friction indicates that for Bit No. 1, the angle of internal friction remained at 32°. On Bit No. 2, however, the angle of internal increased to a consistent 36° to 40°.

Bit No. 1 predominantly drilled limestone, while Bit No. 2 encountered sandstone and siltstone. The lithological impact on angle of internal friction determination cannot be overemphasized. An inspection of the mud log shows that Bit No. 2 commenced drilling at a reasonable rate of penetration (ROP), but slowed soon afterwards. The reduction in ROP is attributed to the high wear rate of the cutters in the more abrasive formation.

Compressive strength alone would not have indicated the greatly reduced bit run. Fig. 4 and 5 presents the RMA program output for the two bit runs indicating essentially no change in the compressive strength, but a substantial change in the angle of internal friction only.

Conclusions

Confined or unconfined compressive strengths by themselves are insufficient to determine optimum bit selection. While unconfined compressive strength provides a good measure of the required aggressiveness of a particular bit, the abrasiveness of a targeted formation also must be taken into consideration when selecting the optimum bit for a given situation.

The angle of internal friction, which can be estimated from basic electric logs, has been shown to be a good indicator of formation abrasiveness.

Confined compressive strength must account for pore pressure, mud weight, angle of internal friction and cohesion to be meaningful. Confined compressive strength estimates which do not take such contributing factors into account, are no more useful than using unconfined compressive strengths alone.

It is important to keep in mind that confined compressive strengths are required when drilling severely overbalanced, and full account must be made of all factors that influence confined compressive strength.

While bit wear is extremely difficult to evaluate, laboratory and field results support the use of the angle of internal friction for predicting wear. Often, the breaking of cutters caused by circumstances such as drillstring whirl, the presence of junk, and improper operating parameters, may mask the actual bit wear and lead to incorrect conclusions.

Nomenclature

τ	=	shear stress
σ	=	normal stress
τ_s	=	shear strength
S_0	=	cohesive shear strength (at zero confining stress)
β	=	angle of internal friction
θ	=	angular position of specimen failure plane
E_s	=	Specific Energy
W	=	Weight on Bit
A_B	=	Borehole diameter
T	=	Torque
N	=	RPM
R	=	rate of penetration

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Table 1 - Angle of Internal Friction Vs. Abrasive Wear

Sandstone Sample	Angle of Internal Friction (Degrees)	Phase II Cutter Wear Ratio (in ³ cutter / in ³ rock) (X 10 ⁻⁴)	Unconfined Compressive Strength (psi)
Crab Orchard	52.3	775	22,290
Nugget	49.5	100	1,780
Berea	40.3	5.4	10,110
Salt Wash	38.4	3.3	1,520
Navaho	37.7	0.094	10,360

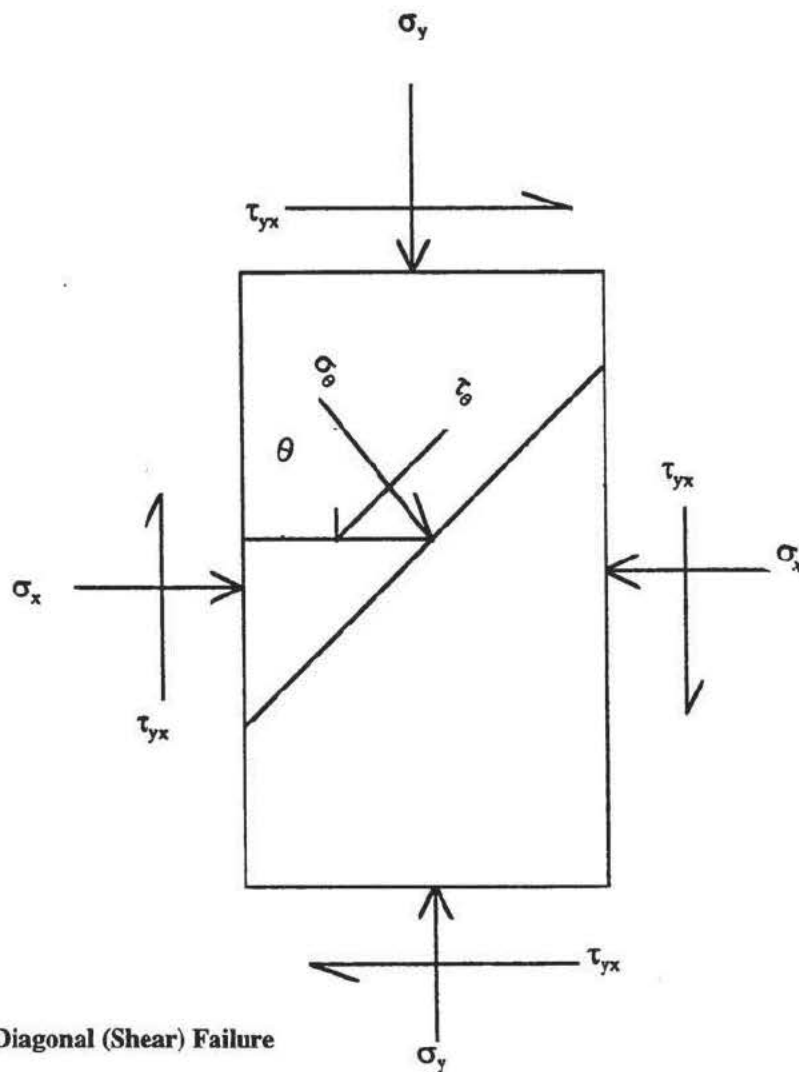


Figure 1 - Mode of Diagonal (Shear) Failure

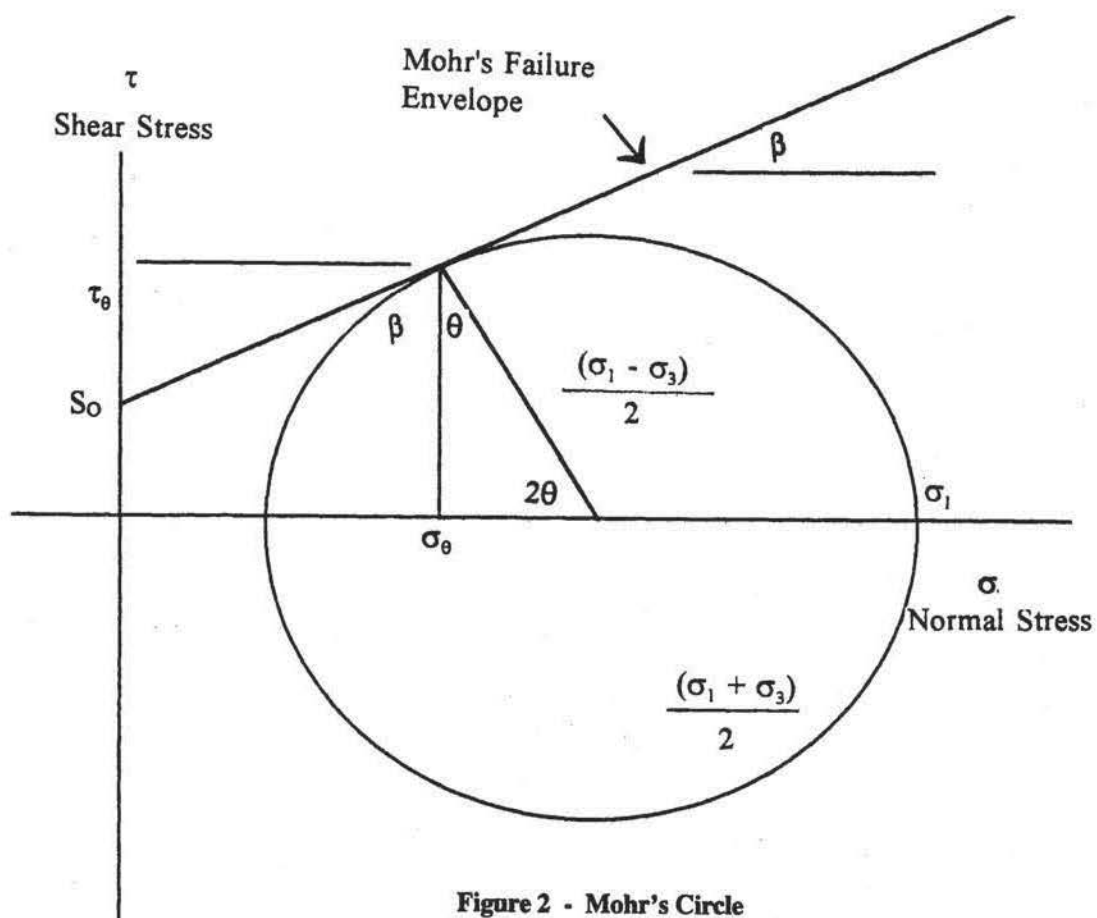


Figure 2 - Mohr's Circle

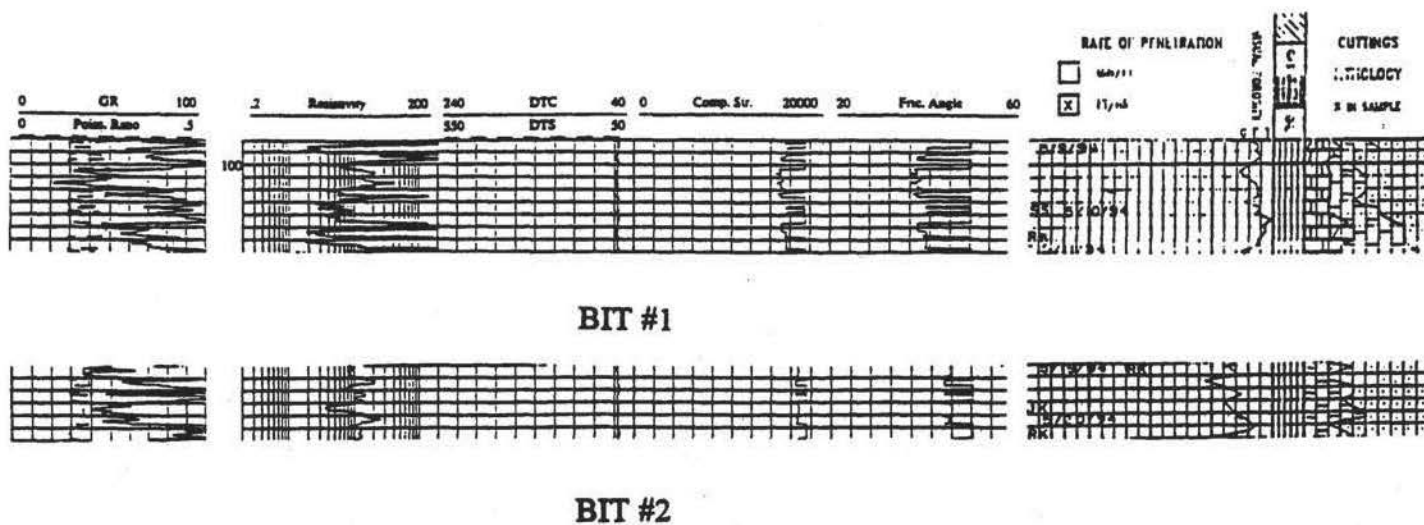


Figure 3 - RMA Output - Well A (2 PDC Bit Runs)

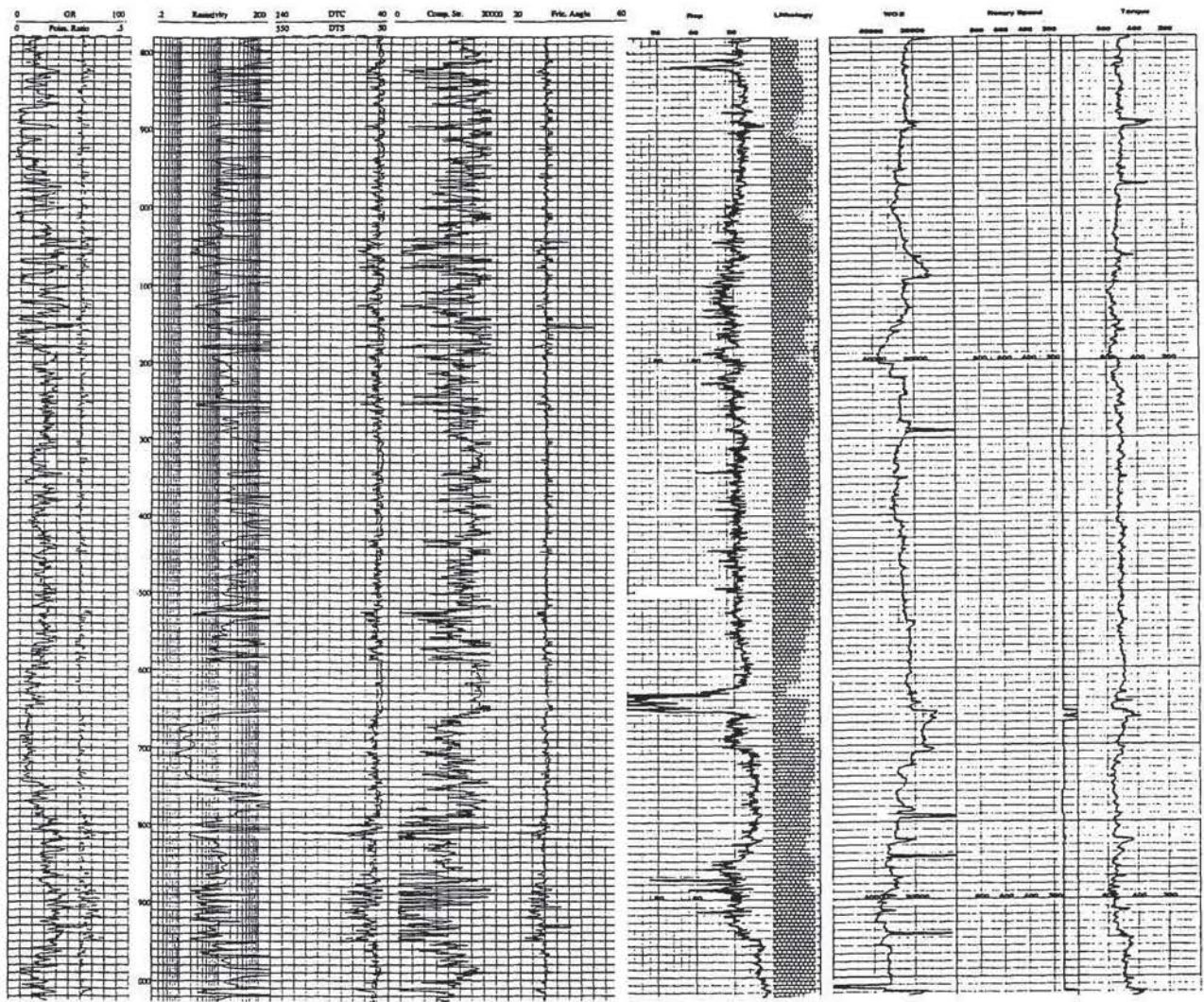


Fig. 4 - RMA output and drillability data for Bit No. 1 - Well B

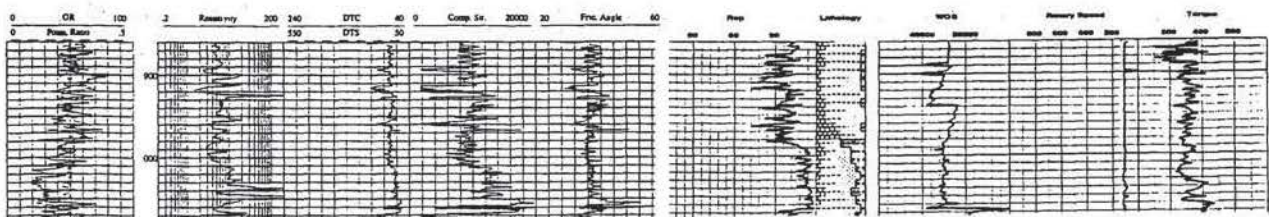


Fig. 5 - RMA output and drillability data for Bit No. 2 - Well B