ROCK STRENGTH PARAMETERS FROM ANNULAR PRESSURE WHILE DRILLING AND DIPOLE SONIC DISPERSION ANALYSIS

T. Bratton, V. Bricout, R. Lam, T. Plona, B. Sinha, K. Tagbor, and A. Venkitaraman, Schlumberger, and T. Borbas, ConocoPhillips

ABSTRACT

The characterization of rock strength is perhaps the most important task in choosing the optimal type of completion in soft-sediment reservoirs. While two strategies have commonly been used to guide this decision, both have significant shortcomings. A new technique is presented that estimates formation strength parameters from annular pressure and dipole shear measurements.

The highest quality rock strength properties are normally determined in a rock mechanics laboratory by stress-loading actual formation material to yield and failure. Seldom will an operator dispense with this step in fields prone to sand production. However, fewer and fewer wells are cored, and the type of completion for different zones in different wells is increasingly based on a small number of laboratory measurements in a single well. Logging measurements yielding lithology, porosity, and elastic moduli are often transformed into rock-strength parameters and used to supplement the high quality but sparse laboratory data. However, while this strategy of log calibration to laboratory data can yield the correct trend over large porosity ranges, it generally fails in predicting the strength variations in high porosity (> 27%), soft-sediment reservoirs.

The new technique monitors and captures the drilling process for what it is, an in-situ stress test. As the driller penetrates each formation, the borehole magnifies the far-field stresses by an amount dependent on the wellbore pressure. This increase in loading near the wellbore causes soft-sediment reservoirs to yield and fail. The depth of this yielded material can be quantified using broadband dipole shear measurements. The magnitude of stress causing this radially varying damage can be estimated with a mechanical earth model and the variation in annular pressure measured between the time of drilling and logging. The methodology for this new technique is illustrated with a recent deepwater discovery.

INTRODUCTION

The best opportunity to observe formation behavior is while drilling, when the formation is subjected to stresses very similar to those expected during completion and production. These observations have the advantage of being continuous, quantifiable, and representative of in-situ conditions.

Historically, laboratory measurements on recovered core have been accepted as ground truth when determining mechanical properties. But while recovered core represents the actual formation material under consideration, it can be substantially altered during recovery and/or preparation for testing. In addition, in-situ stress conditions need to be reproduced in the laboratory, a task that is difficult if not impossible.

Today, drilling personnel gather increasing amounts of pertinent data, including azimuthally sensitive measurements, time-lapse observations of formation behavior, and the wellbore pressures that are associated with this behavior. In addition, broadband acoustic logging has shown to be an excellent measure of formation damage (Plona, et al., 2002).

This paper presents a method (patent pending) that capitalizes on this increase in relevant data to improve on log-derived strength correlations. It starts with an introduction into wellbore geomechanics and is followed by a discussion of borehole acoustics and wellbore hydraulics. A
case study illustrates this new method, and the paper concludes with the economic benefits that follow from this analysis.

GEOMECHANICS

Two sets of stresses are important in the analysis of wellbore rock mechanics, far-field stresses and wellbore stresses. Far-field stresses exist in the formation far away from the wellbore. By definition, far-field stresses are not influenced by the borehole. In contrast, wellbore stresses act on the formation at the mud/formation interface. The mud density as well as the far-field stresses controls the wellbore stresses. Fig. 1A illustrates these two sets of stresses. A Cartesian coordinate system describes the far-field stresses. One stress is vertical, $\sigma_v$, and the two orthogonal stresses are horizontal. If the magnitudes of the two horizontal stresses are different, then the minimum, $\sigma_h$, and the maximum, $\sigma_H$, horizontal stress. The direction of either horizontal stress completes the total description of the far-field stresses.

In a vertical well, a cylindrical coordinate system describes the wellbore stresses. Here, one stress is radial, $\sigma_r$, and the two orthogonal stresses are axial, $\sigma_a$, and tangential, $\sigma_t$. The axial stress is directed along the axis of the borehole whereas the tangential stress is directed around the circumference of the wellbore. The tangential stress is also called the hoop stress because of this geometry.

Fig. 1B illustrates how the principal stresses change in magnitude as they approach a vertical wellbore. The stresses are plotted as a function of dimensionless radius ($r/a$), the radial distance into the formation (r) normalized to the wellbore radius (a). However, during drilling, the wellbore pressure can vary significantly from this ideal scenario. Fig. 1C illustrates how the wellbore stresses vary with wellbore pressure. Large variations in wellbore pressure are the primary cause of the failure observed in formation images (Bratton et al., 1999; Rezmer-Cooper et al., 2000).

Stresses in the earth are generally compressive. For example, the overburden loads (compresses) the formation grains together vertically. Shear failure is initiated when sufficiently different orthogonal stresses exceed the compressive strength of the formation. When a formation is subjected to such a stress field, the grains will be sheared apart at an angle, $\alpha$. This angle is measured between the direction of minimum stress, $\sigma_3$, and the failure plane (Fig. 1D). For small shear stresses, the formation behaves elastically. This means when the stress is released, the grains return to their original position. However, as the difference in these orthogonal stresses increase in magnitude, and the yield strength of the formation is exceeded, the grains begin to re-orient and can no longer return to their original position. Even so, most formations can support an increasing load even though yielding has begun. Eventually, however, the formation will fail and create a volume of disaggregated material. A common criterion of shear failure is known as Mohr-Coulomb, and is given by

$$
\sigma_1 = C_0 + \sigma_3 \tan^2 \alpha 
$$

(1)

It states that the rock will fail if the maximum compressive stress overcomes two material properties that resist deformation. These are the unconfined compressive strength, $C_0$ (also noted as UCS), and the angle of internal friction, $\phi$, which is related to $\alpha$ by the following equation:

$$
\alpha = 45^\circ + \frac{\phi}{2}
$$

(2)

While the Mohr-Coulomb criterion is generally used to describe failure, it can also be used to describe yield. The two material properties corresponding to $C_0$ and $\phi$ would be more appropriately called the unconfined yield strength, $Y_0$, and the friction angle controlling the yielding process, $\phi$.

$$
\sigma_1 = Y_0 + \sigma_3 \tan \left(45^\circ + \frac{\phi}{2}\right)
$$

(3)
Formation yield can be observed and quantified using broadband dipole measurements. Future work will address the consequences of formation yield, including the reduction of both porosity and permeability in this yielded, mechanically damaged annulus.

BOREHOLE ACOUSTICS

Most of the existing analyses of borehole propagation assume the surrounding formation to be radially homogeneous. However, the stress concentration surrounding the borehole causes near-wellbore yielding when soft-sediment reservoirs are subjected to tectonic stresses. These damaged formations often exhibit radially varying acoustic properties (Gnirk, 1972; Blakeman, 1982).

Fig. 2A shows a schematic diagram of a borehole of radius $a$, in the presence of radially varying annulus of thickness $(b-a)$. Generally, the radial damage extends from 1 to 3 borehole radii. A new technique was recently proposed to estimate both increasing and decreasing shear slowness profiles using the Backus-Gilbert (B-G) inversion of measured cross-dipole dispersions (Backus and Gilbert, 1970; Burridge and Sinha, 1996). Fig. 2B shows a typical dipole shear slowness profile (and the equivalent shear modulus profile) using this new technique.

The dipole radial profiling (DRP) of shear slowness (or equivalently, shear modulus) is based on the B-G inversion of a set of discrete slownesses over a wide bandwidth on the measured flexural dispersion (Burridge and Sinha, 1996; Sinha et al., 2000; Sinha and Burridge, 2001). The B-G inversion technique consists of a perturbation model that relates changes in the flexural dispersion caused by perturbations in formation properties. From measured flexural wave slownesses (or velocities) at a few discrete frequencies, a reasonable initial guess of the formation parameters is made. These initial parameters for an assumed homogeneous and isotropic formation yield the flexural dispersion in the reference state. Differences between the measured and reference slownesses at several chosen frequencies constitute the input to the B-G procedure. In addition, the kernels are calculated at various frequencies from the flexural mode eigenfunctions in the reference state. These kernels $G_i$ at frequencies $i=1,2,3,...,8$ indicate sensitivity of the measured slownesses to changes in the formation shear modulus at various radial positions. Fig. 2C displays radial variations of the kernel $G_i$ at eight frequencies that are indicators of the radial depth of investigation of the dipole signal as a function of frequency. The sum of the inverted perturbation and the background profile yields the actual shear slowness (or shear modulus) profile.

Fig. 2D compares the inverted radial profile of the shear slowness using synthetic dipole waveform data for an actual staircase profile. Good agreement between the inverted and actual profiles validates the DRP algorithm for obtaining radial profiles of shear slownesses from measured wideband dipole dispersions.

To avoid obtaining false indicators of near-wellbore alteration, it is important to have accurate estimates of mud compressional slowness and borehole diameter while computing the reference dipole dispersion for an isotropic and homogeneous formation. A combination of methods is used to estimate these inputs. Generally, the mud compressional slowness can be estimated from the Stoneley and dipole dispersions in an isotropic and homogeneous section of the formation. The mud slowness is varied until both the measured Stoneley and dipole dispersions agree with the corresponding theoretical dispersions for a homogeneous and isotropic formation. A look-up table can provide estimates of the mud compressional slowness based on mud properties and in-situ conditions.

Consequently, we suggest the sonic tool be run in all modes to acquire a complete set of data to enable unambiguous interpretation of near-wellbore and far-field formation parameters. In addition we recommend that 4- or 6-arm caliper data be recorded to accurately measure the borehole size.

WELLBORE HYDRAULICS

Near-wellbore yielding is caused by variations in wellbore pressure. Fig. 3 shows a typical sequence of events, and the accompanying wellbore stresses, from the time when a formation
is penetrated by a vertical wellbore until a high-bandwidth wireline acoustic tool logs it.

Initially, a formation is only subjected to the far-field effective stresses. In this example, the minimum horizontal stress is just below 1,300 psi while the maximum horizontal stress is just greater than 1,300 psi. The vertical stress is just over 1,800 psi. When the drill bit penetrates the formation, these far-field stresses are transformed into wellbore stresses. The wellbore pressure, a choice made by the drilling engineer, determines the magnitude of these wellbore stresses. In this figure, the wellbore pressure gives rise to a radial stress just over 500 psi. The tangential stress is just under 2,000 psi, while the axial stress is nearly 1,800 psi. Observe that the difference in stress between the maximum stress, the tangential stress, and the minimum stress, the radial stress, is more than double the far-field conditions. This could easily induce yielding near the wellbore. The next change occurs when the driller turns off the mud pumps to make a connection. This change lowers the radial stress and increases the tangential stress, representing the most aggressive stress yet applied to the formation. However, the drillstring has yet to be extracted from the wellbore. When the drillstring is raised, the pressure above the drill bit is increased while the pressure below the drill bit is lowered. These variations in wellbore pressure caused by the motion of the drillstring are called surge and swab. Surge pressures are normally less aggressive to the formation than swab pressures.

The radial depth of yielding is dependent on both the yield strength of the formation and the maximum shear stress applied until the formation is logged. Thus, to invert for the mechanical strength of the formation, the stress history caused by wellbore pressure variations must be determined.

Wellbore pressure, or annular pressure while drilling, is routinely available. In fact, few offshore wells are drilled without this basic measurement. However, it measures the wellbore pressure at only one point in the wellbore, the point adjacent to the pressure sensor. Because the most aggressive stresses are likely to be caused by surge and swab pressures, an accurate hydraulics-modeling program must be used to estimate the wellbore pressure above and below the pressure sensor.

The hydraulics analysis software must output the minimum and maximum wellbore pressure applied to the formation from the time the formation was drilled until the time the formation was logged by the acoustic logging tool.

**INVERSION TECHNIQUE**

An inversion for the strength properties of soft-sediment reservoirs can now be attempted using the following method:

1. Compute the dipole radial profile: shear slowness vs. radial distance into the formation. Transform the shear slowness to shear modulus and observe the radial distance where yielding begins. A significant drop in shear modulus diagnoses yielding.

2. Calibrate the drilling hydraulics using the while-drilling annular pressure measurement and determine the minimum and maximum well pressure for each depth.

3. Build a mechanical earth model including pore pressure, far-field stresses, elastic parameters and the normal material properties governing failure, $C_0$, and the angle of internal friction, $\phi$. These two properties are generally determined by correlation.

4. Compute the principal stresses as a function of radial distance into the formation using either linear-elastic theory or, alternatively, a more complex model. A 3D linear-elastic model was used in this paper. The far-field stresses and pore pressure come from the mechanical earth model while the minimum well pressure comes from the hydraulic modeling.

5. Solve Eq. 3 for $Y_0$, the unconfined yield strength, as a function of radial distance into the formation. The friction angle controlling the yielding process, $\phi$, was taken to be one-half the value of $\phi$.  

4
6. Overlay the computation of $Y_0$ vs. radial distance into the formation with the shear modulus vs. radial distance into the formation, and extract the unconfined yield strength at the radial distance where the shear modulus begins to decrease.

7. Compute the unconfined compressive strength based on the unconfined yield strength.

8. Compare the result with other estimates of unconfined compressive strength.

Fig. 4 shows the results from such a calculation. The three principal stresses of Step 4 are shown in blue, green, and brown. These curves show the variation in principal stress from the wellbore to the far-field. The radial stress is equal to the minimum wellbore pressure from the hydraulics modeling. The red curve is the dipole shear-radial profile. A significant drop in shear modulus begins at a radial distance of 18.7 in., indicated by the black vertical line. The unconfined yield strength is taken from the calculation (Eq. 3) at this radial distance.

CASE STUDY

A deepwater oil discovery was recently made in the Gulf of Mexico. A productive interval in the second well was cored to determine the appropriate petrophysical and mechanical properties needed for the development of this field. No other intervals have been cored in subsequent development wells.

The reservoir of interest consists of Pleistocene age stacked turbidite sand/shale sediment, deposited as a series of laterally and vertically amalgamated channels. The reservoir unit displays an overall fining upward trend, with increased structural shale present in the upper facies and more massive sand placement with ripple fabric in the lower interval. A log section of the reservoir showing the conventionally cored interval is shown as Figure 5A. Figure 5B depicts whole core photos comparing the upper and lower facies.

Deposited in a deep-water environment, the pore geometry is largely controlled by particle size, as moderate temperatures (160°F) and recent geologic deposition have inhibited development of authigenic cements. Higher quality flow units are comprised of very fine-grained sediment, with the poorer flow units dominated by medium silts. The average flow unit is comprised of coarse silt grains.

A number of different types of mechanical testing were conducted on the recovered core. However, only three depths were evaluated in the productive interval.

Fig. 6A shows a representative triaxial test from the productive interval. As the confining pressure increases, so does the peak strength. However, no peak strength was observed beyond 500 psi confining pressure. This limits the quantity of data required to compute the friction angle that governs peak strength. While friction angle is not normally needed to predict the onset of sanding, a variation of this property, the friction angle governing the increase in yield strength with confining pressure, is needed to estimate the unconfined yield strength, which is then used to estimate the unconfined compressive strength. Fig. 6B zooms in on the two tests corresponding to a confining pressure of 50 psi and a confining pressure of 500 psi.

Fig. 6C shows the stress/strain curve for a confining pressure of 50 psi. The confined compressive strength is seen to be 405 psi. The unconfined compressive strength is 280 psi. Also plotted is the static shear modulus. Note the slight increase in modulus until the sample begins to yield followed by a significant decrease. This decrease in shear modulus is explained by the sample losing its rigidity because of grain realignment and the breakage of cementation, a consequence of formation yielding. This laboratory behavior of static shear modulus supports the validity of using the radial variation of shear velocity to quantify in-situ yielding.

Fig. 6D plots the axial stress as a function of static shear modulus to determine the confined yield strength of 255 psi.

The friction angle parameter controls the increase in strength with confinement. Fig. 6E shows the friction angle as determined from the peak strength data (25.4º) while Fig. 6F shows the friction angle based on formation yield (11.5º).
The friction angle for yield strength is significantly smaller than for peak strength.

Because the confinement is so low (50 psi) there is little difference between the unconfined (280 psi) and confined (405 psi) strengths. In addition, it could also be argued that considering the accuracy of rock strength measurements in soft-sediment reservoirs, little difference appears between the unconfined yield strength and the unconfined compressive strength. In fact, the estimated UCS from peak strength data and the yield strength data were identical (280 psi). However, it is always best to account for these differences even though they are small.

Fig. 7 shows the comparison of this new technique with two existing strength correlations, one based on porosity and the other based on shear modulus, and the measured values from the mechanical testing in the laboratory. Neither the UCS from the porosity correlation nor the shear modulus correlation captures the strength trend revealed by the laboratory measurements. However, the strength estimates from the dipole radial profiling captures both the absolute magnitude as well as the trend.

**COMPLETION OPTIMIZATION**

A commonly used method of completion optimization relies on a decision tree and a combination of predictive analytic tools (Venkitaraman et al., 2001). Fig. 8 shows some common completion options applicable for soft-sediment reservoirs. The choice of completion technique, especially the decision of sand exclusion versus screenless options, is critically dependent on the accurate quantification of sand prediction.

Most sand prediction techniques use the two-stage model of sand production: a) failure of the borehole or perforation tunnel, and b) transport of the failed material into the completion. These models predict the sanding tendency for varying reservoir conditions such as different drawdowns and depletion.

The accuracy of these models is profoundly dependent on the quality of the input rock data, especially the UCS of the formation. The following comparison illustrates this point.

Two scenarios of perforation stability are compared, holding all parameters constant except UCS. The results are presented in the popular “stability envelope” format (safe bottomhole flowing pressure vs. depleting reservoir pressure). A 3D semianalytic, elastic, perfectly plastic model was used. Corrections were made for scale effects. Fig. 9A shows the results assuming a uniform distribution of UCS between 1,500 and 2,500 psi. Fig. 9B shows the results of the same analysis when a more accurate UCS value is available (UCS between 2,000 and 2,100 psi).

More accurate estimates of UCS can have a significant economic impact. Conservative estimates of UCS lead to higher expenses for the initial completion and potential loss of productivity with some sand control options (for instance choosing sand exclusion over a screenless option). Liberal estimates of UCS lead to unexpected sand production. The methodology presented in this paper directly impacts completion optimization by significantly improving estimates of UCS.

**SUMMARY**

A new method to quantify rock strength parameters uses radial variations in dipole shear slownesses to determine the depth of mechanical damage. A mechanical earth model including the wellbore pressure history quantifies the stress that extended the mechanical damage to the observed depth. This in-situ stress test, captured from the drilling process, yields quantitative estimates of rock-strength parameters. A comparison between the unconfined compressive strength estimates from this new technique with those of standard correlations and laboratory testing on recovered core shows that this new technique is comparable with laboratory results and is superior to standard correlations.

**ACKNOWLEDGMENTS**

The authors thank ConocoPhillips for releasing the case study dataset.
REFERENCES


Sinha, B. K., and Burridge, R., 2001, Radial profiling of formation shear velocity from borehole flexural dispersions: Proc., 2001 IEEE International Ultrasonics Symposium, Atlanta, GA.


ABOUT THE AUTHORS

Tom R. Bratton is a scientific advisor for Schlumberger in Houston, Texas. He began his career in 1977 as a field engineer and has held various staff, management, and interpretation positions specializing in acoustic waveform analysis and rock mechanics. He received an MS degree in atomic physics from Kansas State University and is a member of SPE and SPWLA. He is currently developing solutions for geomechanical-related drilling and completion problems.

Vincent Bricout is a team manager for Schlumberger in Houston working on different aspects of drilling and hydraulics. He received his PhD degree in mechanical engineering from Cornell University in 2000. He sits on the Tulsa University Drilling Research Program advisory board and is currently involved with the API 13D - Section 9 (Pressure Losses) initiative.

Roi Lam is a drilling engineering center manager for Schlumberger in the Gulf of Mexico based in Houston TX. He began his career in Well Services in 1996 providing cementing and drilling fluid services. He then cross-trained with Drilling & Measurements and since then provided execution and managerial support for PERFORM (Performance Through Risk Management) services.

Tom Plona is a Schlumberger scientific advisor working in research. He began his career in research in 1976 and has worked on both wireline and logging-while-drilling sonic issues. He received a PhD degree in physics from Georgetown University and is a member of SEG, SPWLA, IEEE, AGU, and ASA. His current interests are in expanding the use of sonic measurements in geophysics and geomechanics through the use of dispersion curves.

Bikash Sinha is a scientific advisor at Schlumberger-Doll Research. Since joining Schlumberger in 1979, he has contributed to many sonic logging innovations for geophysical
and geomechanical applications. He received a Ph.D. degree in applied mechanics from Rensselaer Polytechnic Institute. He is currently involved in near-wellbore characterization of mechanical damage and formation stress parameters using borehole sonic data.

Kwasi Tagbor is a senior petrophysicist with Schlumberger Data and Consulting Services in Houston. He began his career with Schlumberger as a wireline field engineer in 1980 and has held positions in operations, technique, and training. He holds a BS degree in electrical engineering from Kwame Nkrumah University of Science and Technology, Ghana, and a postgraduate diploma in computer science from University of Ghana, Legon, Ghana. His interests are primarily with borehole sonic logging, interpretation, and applications.

Adi Venkitaraman is sand management solution champion at Schlumberger. He holds a BS degree in mechanical engineering from University of Kerala, India, and an MS degree in petroleum engineering from University of Texas at Austin. In his 11 years with Schlumberger his work has been primarily formation damage research, especially perforation damage. His current focus is in sand management.

Tim Borbas received a BS degree in petroleum engineering from West Virginia University in 1984. He joined Conoco (now ConocoPhillips) the same year. He has previously worked in the Exploration Production Technology section in Houston, Texas and Gulf of Mexico Region office in Lafayette, Louisiana. Tim is currently a staff engineer with ConocoPhillips in the US Lower 48 organization. His duties include open and cased hole petrophysical support for Gulf of Mexico deep water projects.

Fig. 1A – Far-field and wellbore stresses.

Fig. 1B – Principal stresses near a wellbore with radius a.
Fig. 1C – Wellbore stresses vs. wellbore pressure.

Fig. 1D – Shear-failure geometry.

Fig. 2A – Damaged zone around a wellbore.

Fig. 2B – Variation of shear slowness (Dtsm) and shear modulus (G) with radial distance.

Fig. 2C – Radial distribution of the kernels $G_i$ at eight chosen frequencies $i = 1, 2, 3, \ldots 8$.

Fig. 2D – Comparison of the inverted shear slowness profile shown by the circles with the actual staircase profile used to generate the synthetic dipole dispersion.
Fig. 3 – Effective stresses as a function of standard drilling procedures.

Fig. 4 – Effective stress/strength as a function of radial distance.
Fig. 5A – Cored interval shown in yellow.

White and UV Photos of Cored Reservoir Section

Fig. 5B – Whole core photos comparing the upper and lower facies.
Fig. 6A – Triaxial test.

Fig. 6B – Peak strength behavior.

Fig. 6C – Stress and G vs. strain, confining pressure = 50 psi.

Fig. 6D – Yield strength from shear modulus.

Fig. 6E – Mohr circle for peak strength.

Fig. 6F – Mohr circle for yield strength.
Fig. 7 – Comparison of different rock-strength methods.
Fig. 8 – Completion options available for sand management.

Fig. 9A - Stability envelope for a case where the UCS is known to be somewhere between 1,500 and 2,500 psi.

Fig. 9B - Stability envelope for the same case when we can narrow the UCS to be between 2,000 and 2,100 psi.