Feasibility Study of the Stability of Openhole Multilaterals, Cook Inlet, Alaska

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Summary

A study of in-situ stress, rock strength, and wellbore stability was initiated in the Hemlock sands of the McArthur River field, Cook Inlet, Alaska, to evaluate the potential of leaving the near-wellbore portions of multilaterals uncased. A northwest/southeast direction of maximum compression and a strike-slip faulting regime were predicted from analyses of leakoff test data and observations of failure (breakouts) in adjacent wells. Caliper, well-log, and core data indicated that cementation, and hence rock strength, is highly variable within the reservoir. Thus, it was decided to evaluate the stability of the lateral sections (i.e., the likelihood of wellbore failure during production) as a function of both stratigraphic position and well orientation. Laboratory rock-strength measurements were carried out on cores selected from target intervals in adjacent wells to provide sufficient precision to quantify the results. The results indicated that, while some reservoir intervals have high enough strengths to be left uncased when drilled in the most stable direction, these intervals are too thin to provide sufficient support at the point where the laterals leave the parent well. This justified the decision to case back the laterals to the parent well despite the cost.

Introduction

Drilling problems and sand production frequently result from severe mechanical failure of the wellbore wall; therefore, they depend on the interplay between the magnitude and orientation of in-situ stresses, the rock strength, the wellbore and reservoir fluid pressures, and the orientation of the wellbore. Using a new suite of software tools developed to study wellbore stability in a wide variety of geologic environments, we can accurately predict optimally stable wellbore trajectories during drilling and production. The analysis is a two-step process. We determine the stress from observing the failures in existing wells; then we apply this knowledge to predict the stability of proposed wells while drilling and during production. In this paper, we illustrate this approach with an example in which we first determine the stress field using information from pre-existing wells, and then apply that information to predict the stability during drawdown of a series of multilaterals drilled from an inclined parent well.

Background

The process of drilling a well results in the development of a stress concentration at the borehole wall.[1,2] The stress concentration occurs because after drilling, the rock surrounding the hole must support the stress previously supported by the removed material. Because the magnitudes of the in-situ principal stresses are generally different (that is, the vertical stress, σ, and the two horizontal stresses, $\sigma_{H\min}$ and σ_H, are all unequal),[3–5] the magnitude of the stress concentration varies markedly with azimuth around the well.[1,6,7] Furthermore, the wellbore stress concentration depends on both the wellbore deviations, azimuth, and the magnitudes and orientations of the in-situ stresses.[8-10]

When the wellbore stress concentration exceeds the rock strength, the rock will fail. Failures can occur in compression, resulting in the development of wellbore breakouts[2,11] or in tension, resulting in tensile wall fractures.[12–15] These failures occur at azimuths that are a function of the stress magnitudes and of the orientations of the well and the principal stresses.[15,16] Thus, wellbore failures detected in image logs or multiarm caliper logs can be used to determine the in-situ stress state.[13,14,17–19] Once stress magnitudes and orientations have been determined from observations of wellbore failure, the stress state can be used to evaluate the stability of any well as a function of its trajectory.

In evaluating wellbore stability, it is important to note that wellbore failures can occur (and are quite common) without leading to loss of the well. For example, drilling-induced tensile wall fractures occur at the wall of the hole, but they do not extend away from the near-wellbore region or lead to circulation losses unless the mud weight exceeds the fracture gradient. Similarly, wellbore breakouts, which form over a discrete range of azimuths depending on the interplay between effective rock strength and the magnitude of the wellbore stress concentration, only jeopardize wellbore stability if the well loses arch support. In practice, this is likely to occur only if breakout widths exceed 90°. In some cases, wells will remain stable even if larger breakouts form. Breakout formation does, however, increase cuttings volume and makes cleaning the hole more difficult owing to the increase in effective hole size.

Geologic Background of the McArthur River Field. The McArthur River field forms a north-northeast/south-southwest-trending anticline, typical of oil and gas reservoirs in the Cook Inlet, Alaska. The target-reservoir interval is the Oligocene-Age Hemlock formation, composed of interbedded, unconsolidated conglomerates, conglomeratic sandstones, and shales with a few minor coal seams. Within the McArthur River field, the Hemlock sands form a series of benches at depths of more than 8,000 ft.

The region of the Cook Inlet is cut by numerous northeast-trending faults. Some of these appear to have accommodated considerable reverse motion but have no evidence of recent activity. Others, such as the Castle Mountain fault that forms the northern boundary of the Cook Inlet basin, trend in more easterly directions and have been historically active as right-lateral strike-slip faults. This and other local faults accommodate residual relative motions associated with convergence of the Pacific plate beneath the overlying North American plate, which hosts the Cook Inlet fields.

Based on the recent tectonics summarized above, the region surrounding the Cook Inlet is clearly characterized by an active strike-slip/reverse faulting state. That is, the least principal stress $\sigma_{H\min}$ is likely to be less than the vertical stress, and the greatest principal stress σ_H is likely to be significantly greater than the vertical stress. Furthermore, the maximum horizontal stress is likely to be oriented in a northwest/southeast direction, based on recent strike-slip faulting activity on faults such as the Castle Mountain fault. By itself, this information allows a qualitative assessment of the stability of wells drilled in this field. The next section begins the process of quantifying the stress state based on actual measurements.

Stress Determination

Because the characteristics of wellbore failures depend on stress magnitudes, pore pressure, mud weight, and rock strength, it is possible to quantify the stress state with observations of wellbore breakouts and tensile wall fractures induced by drilling. This section presents the analysis methodologies used to define the stress state within the Cook Inlet McArthur River field.

Vertical Stress, Pore Pressure, and $\sigma_{H\min}$. A summary of density-log data vs. depth in a number of wells was used to provide a field-

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wide density profile of the form $\rho_b = a + bD^c$. The best-fitting relationship of this form has $a = 1$ g/cm^3; $b = 0.53235$ g/cm^3; and $c = 0.108$ g/cm^3. Vertical stress was then found by explicitly integrating this equation for density as a function of depth [that is, $\sigma(D_0) = \int G\rho_b(D)\partial D$]. Determined by direct measurement, pore pressures were approximately 0.4 psi/ft. Least-principal-stress data were provided from leakoff test results and analyses of fracture treatments, including step-rate tests and fracture closure pressures. The vertical and least-principal-stress data are presented as a function of depth in **Fig. 1.**

In general, the least principal stress is less than or equal to the vertical stress. The apparent fracture gradient varies from approximately 0.7 psi/ft to slightly more than 1.1 psi/ft. There is no systematic evidence of differences in the data either between platforms or as a function of the date the test was carried out (different symbols identify wells from different drilling platforms). Because the least principal stress is only slightly less than the vertical stress, despite the fact that pore pressures are approximately hydrostatic, the maximum horizontal stress is likely to be significantly greater than the vertical stress. Because it is extremely difficult to quantify σ_H by direct measurement, we turn next to an evaluation of wellbore image data to identify breakouts and/or drilling-induced tensile fractures in existing wells. We then use the results to determine the magnitude orientation of σ_H.

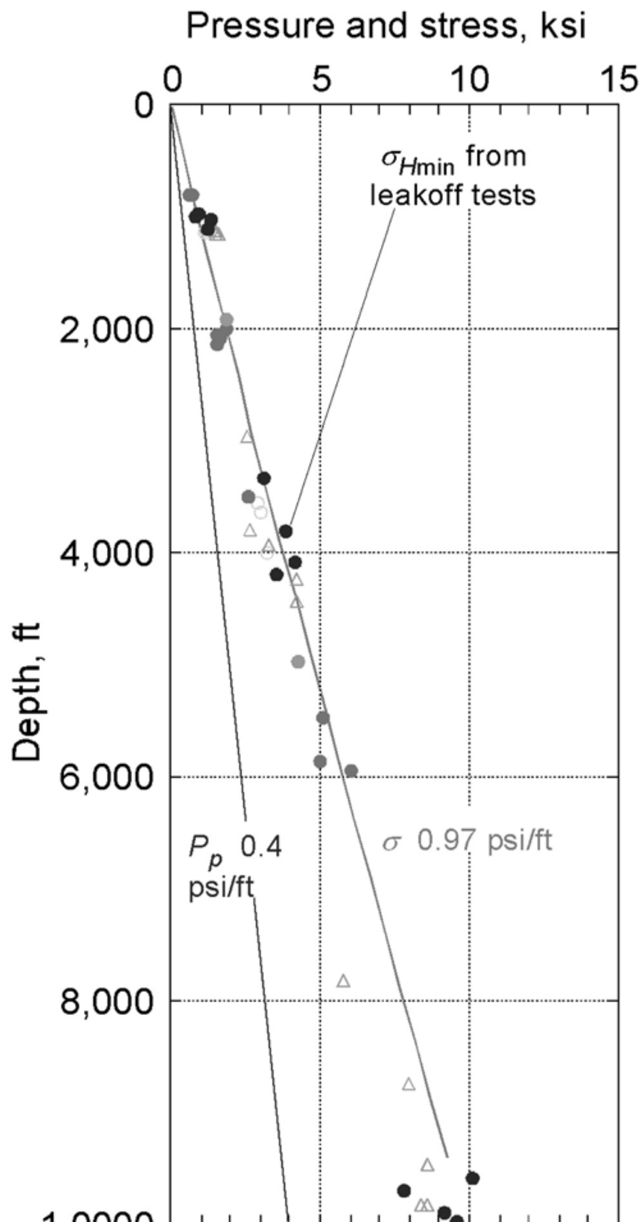

Fig. 1—Pore pressure obtained from direct measurements, vertical stress obtained from integrated density logs, and least principal stress derived from leakoff tests in the McArthur River field.

Observations of Wellbore Failure. An electrical-image log recorded in deviated Well K-26 over the internal from approximately 10,000 to 11,000 ft was analyzed to detect breakouts (compressive failures) and tensile fractures (tensile failures that indicate a high horizontal stress difference). No obvious tensile failures were detected in the analyzed interval, but a number of breakouts were observed. Although it is often difficult to quantify the precise width and length of breakout zones in electrical image data, it was possible in this case to measure these parameters in a number of intervals, including one in a clean sand in which the width of the failed zone was 60°. In this interval, the well was deviated 25° to the northwest.

Simultaneous Inversion for σ_H Magnitude and Orientation. Breakouts do not always occur at the azimuth of the least horizontal stress in a deviated well; furthermore, we did not have rock-strength data at this point in the study. Therefore, we investigated by forward modeling the relationships among rock strength, maximum horizontal stress, and stress orientation, as shown in **Fig. 2.** Again, the mud weight, least principal stress, pore pressure, and vertical stress were all constrained by direct measurement.

In this case, the analysis reveals that the orientation of the greatest horizontal stress is well constrained and does not depend on the stress magnitude. However, neither the magnitude of the greatest horizontal stress nor the rock strength can be quantified. This differs from the analysis presented by Zoback and Peska[19] in which breakouts encountered in a single deviated well allowed simultaneous inversion for stress magnitude and orientation.

Using Crustal Strength and Lack of Tensile Failure. To reduce the uncertainty in stress magnitudes, we rely on the observation that in many parts of the world, stress magnitudes are constrained by the strength of pre-existing faults.[20] We also use the fact that no tensile failures were observed in the K-26 well. **Fig. 3** illustrates this approach. We require that the magnitudes of the horizontal stresses at any depth not exceed the frictional strength of

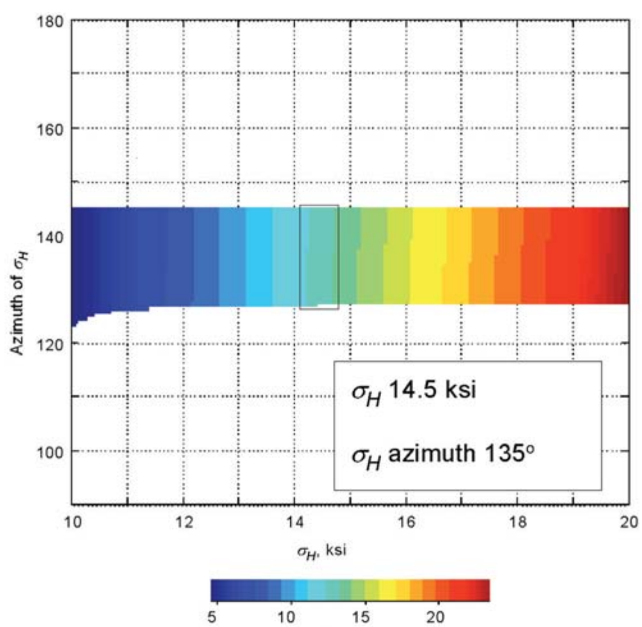

Fig. 2—Azimuth and magnitude of σ_H required to cause 60°-wide breakouts as observed in Fullbore Formation Microimager (FMI) log images from the K-26 well at a measured depth of 10,380 ft (TVD = 10,180 ft). Colors indicate the rock strength for which such breakouts would be expected to occur. The refined value of σ_H is also shown based on the calibrated strength log.

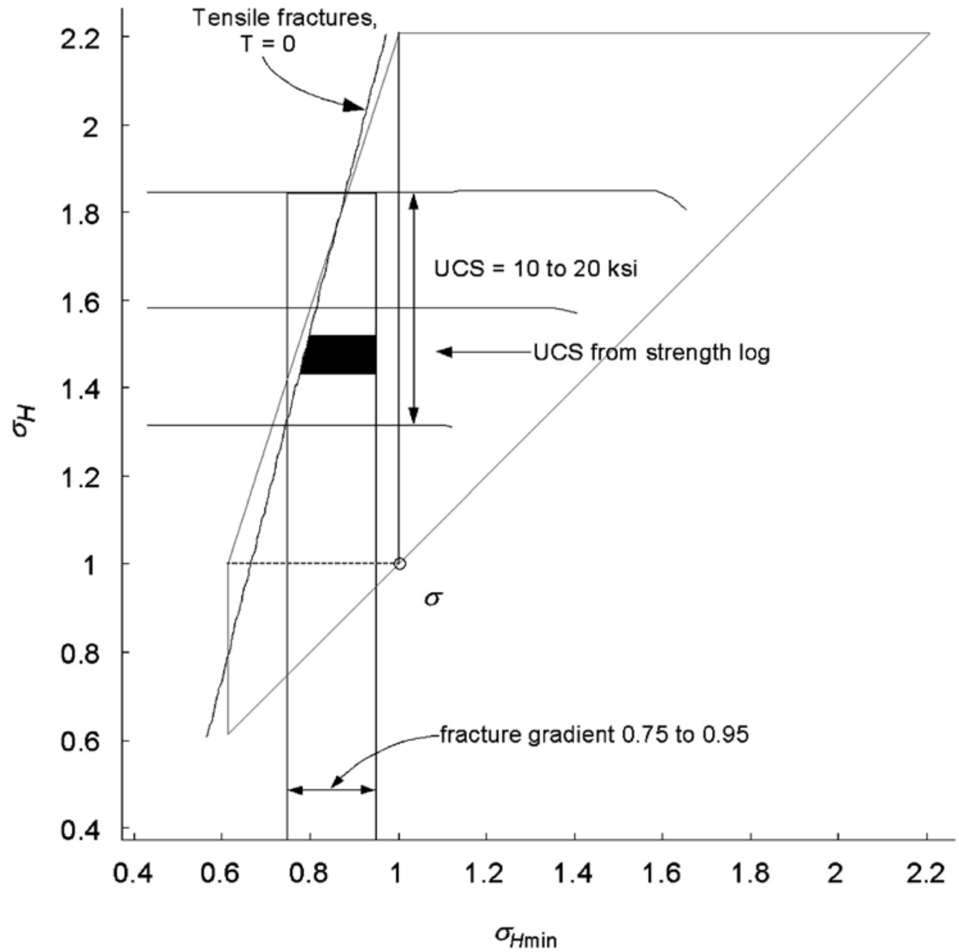

Fig. 3-Stress constraints imposed by the frictional equilibrium of the crust (polygon), by the occurrence of breakouts at 10,380 ft MD in Well K-26 (horizontal lines), and by the lack of tensile failure observed in FMI images (slanted line). The least horizontal stress range is defined by leakoff test results. Even without knowledge of rock strength, the stress state can be constrained to lie within the rectangle defined by the limits of the least principal stress and below the slanted line that defines the onset of drilling-induced tensile fracture development. Using the calibrated-strength log and knowledge of breakout width, the stress state is found to lie within the shaded box.

the Earth's crust (the stress state must lie inside the polygon) corresponding to the particular depth and pore pressure of interest. At this point, the horizontal stress magnitudes are constrained only by the range of measured $\sigma_{H\min}$ and the frictional strength of the crust.

The lack of drilling-induced tensile fractures requires that the values of σ_H not exceed those corresponding to the blue line for any given value of $\sigma_{H\min}$. This imposes a tighter constraint on σ_H than is imposed by the strength of the crust. Furthermore, it indicates that the unconfined compressive strength (UCS) must be less than 20,000 psi in the interval in which the breakouts occurred.

Calibrating a Rock-Strength Log. Rock-strength measurements were obtained in a number of minicores from selected clean intervals of two wells. Suites of cores from fine-, medium-, and coarse-grained intervals were tested under triaxial conditions to establish Mohr-Coulomb strength envelopes for each type of sand. The UCS and coefficient of internal friction (K_f) were determined from these envelopes.

The values of K_f and UCS were compared to a variety of log data. K_f did not depend on any of the logged parameters; in fact, it was similar for all the suites tested. The highest strength correlation was found between M, the P-wave modulus (density times compressional-wave velocity squared), and UCS. This sort of relationship is theoretically reasonable because modulus and strength both depend on grain contact properties, porosity, and lithology. The relationship for the fine-grained sands was indistinguishable from that for the medium- and coarse-grained sands, so a single relationship was used throughout.

$$\text{UCS (in psi)} = -3{,}043 + 253 \cdot \text{M (in GPa)}. \quad \text{(1)}$$

To illustrate the comparison between the rock-strength log determined from this relationship and the lab data, **Fig. 4** shows the calculated UCS from log data and the measured UCS from cores for the two wells from which the cores were taken. Note that because we did not have cores from lithologies other than the sands, the relationship cannot be relied upon outside these clean intervals. It is expected, however, that these intervals will be weaker than the sands, both because this is typical of most rocks[21] and because in this study, as in others, breakouts detected in shalier intervals are much wider than breakouts detected in sands.

Improved Stress Magnitudes Using Rock Strength. With this new calibrated-rock-strength log, we find that the rock strength in the interval with 60° breakouts is slightly less than or equal to 12.5 ksi. Using this value in Fig. 3, we predict the magnitude of σ_H to be 14.5 ksi. The lack of tensile fractures then suggests that the magnitude of $\sigma_{H\min}$ is between 8 and 9.5 ksi and thus lies within the upper range of the fracture gradients measured in the field. Fig. 2 was prepared with $\sigma_{H\min} = 9.5$ ksi and confirms that if the rock strength in this interval is 12.5 ksi, then the predicted magnitude of σ_H is 14.5 ksi. This result fully defines the in-situ stress state at the depth where the breakouts occurred.

Wellbore Stability Predictions

Wells are expected to remain stable as long as breakouts do not exceed approximately 90° in width. **Fig. 5a** shows the rock strength required to prevent breakouts larger than this value as a function of

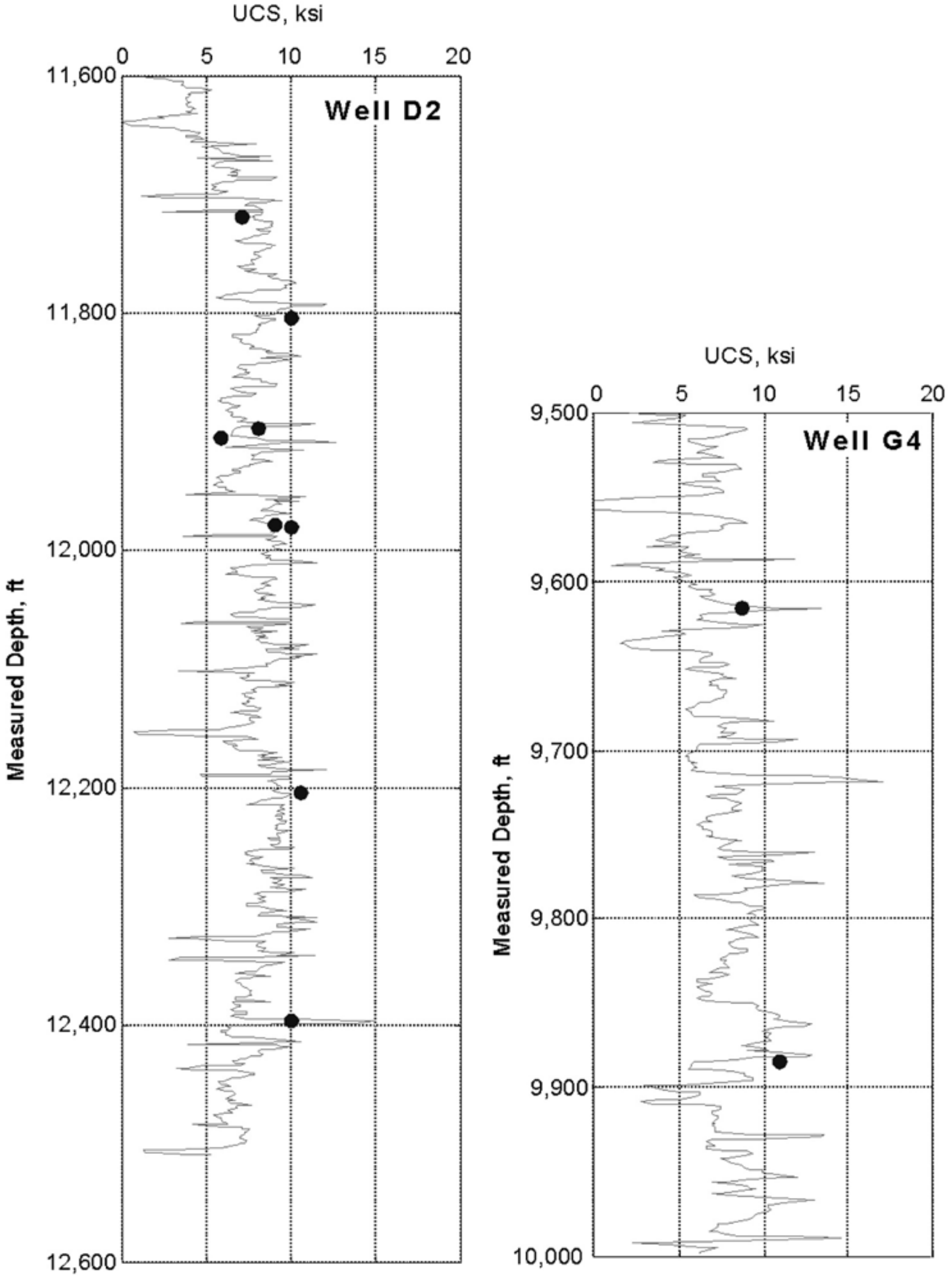

Fig. 4—Comparison of laboratory measurements of UCS to the predictions of the calibrated strength log in the two wells from which cores were obtained.

well orientation for a case in which the mud weight is equal to the formation-fluid pressure. This condition corresponds to the removal of support by the mud before the initiation of drawdown.

Fig. 5b shows a rock-strength log obtained in the K-26 well using the calibrated relationship between UCS and M discussed earlier. Although there are a few higher-strength sections, the interval is mostly characterized by rock in which UCS is less than 12 ksi. From the result shown in Fig. 5a, it is clear that for wells drilled at nearly all orientations possible, rock strength must be greater than 12 ksi. The only safe orientations are for near-horizontal wells drilled to the northwest or southeast (i.e., in the direction of σ_H). In fact, these wells will be more stable than vertical wells. This observation is typical of the stability pattern as a function of the orientation of wells drilled into reservoirs characterized by a strike-slip stress field.

Stability During Drawdown. During drawdown, fluid pressure in the wellbore is lower than that in the formation, and a pore-pressure gradient is established that results in fluid flow into the well. This gradient and the pressure drop at the well are time-dependent. Thus, static models for wellbore stability are not appropriate to evaluate failure during production.

A model for the poroelastic stress changes accompanying drawdown has been developed to provide predictions of time-dependent pore-fluid pressure changes. The model provides the capability to insert a near-wellbore "damage zone" for which permeability is lower than that of the virgin formation. This can be used to mimic the effect of mudcake development during drilling or to evaluate the importance of damage zones on fluid flow during production. Although not discussed here, other results indicate that these zones improve the stability of wells while they are drilled but promote failure when the well is brought on line.

To evaluate stability during drawdown, we present two results of poroelastic modeling in **Fig. 6.** The first result (Fig. 6a) shows the effect of rapidly establishing a 1,000-psi drawdown. Two images are presented; at the top is the pore pressure after establishing drawdown over a 10-minute period (a very steep cone can be seen clearly), and below is the effect on wellbore stability for a well drilled in the optimal direction (horizontal and deviated to the northwest or southeast). For a rock strength of 10 ksi, failure is

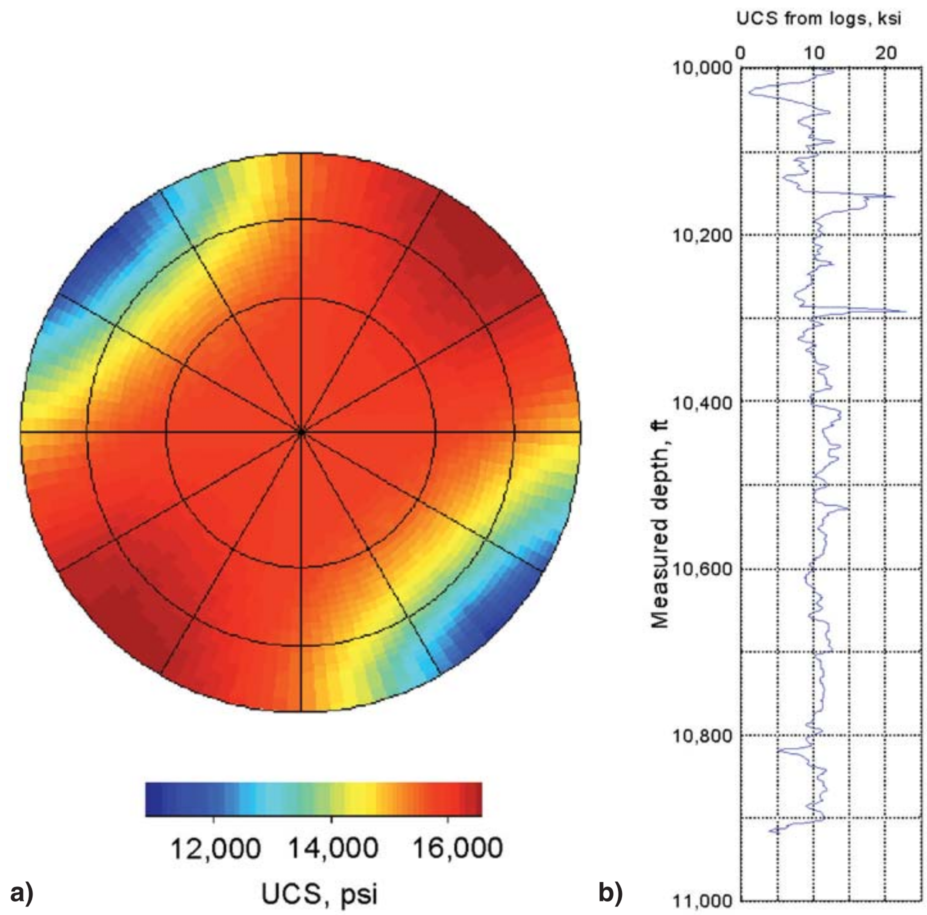

Fig. 5—(a) Rock strength required to maintain wellbore stability as a function of well orientation when the mud weight is equal to the fluid pressure. (b) Calibrated rock-strength log showing the distribution of expected strengths in the reservoir.

predicted to occur around more than 90° of the well, probably leading to wellbore collapse.

In contrast, Fig. 6b illustrates the effect of bringing the well online more slowly. In this case, the 1,000-psi drawdown was established over 100 minutes. The fluid-pressure gradient is clearly much shallower. As a result, the zone of failure for a 10-ksi rock is more modest and extends over approximately 60° of the well.

Drilling and completion experiences in two wells provided further confirmation of the study results. In one lateral well, previously drilled at an azimuth of 31° to the northeast, wellbore collapse occurred within the openhole section. However, horizontal laterals subsequently drilled to the northwest were successfully completed. Given the results of this study, these wells were cased back during completion to reduce the risk of production-related failures.

Conclusions

The results of this study provided quantitative input into drilling decisions for this field. They provided both a determination of the stress field and a method to use well logs to quantify rock strengths. This allowed drilling engineers to evaluate the effective strength of the rock at proposed kickoff points and indicated that horizontal wells drilled along the reservoir sands at any orientation except a northwest or southeast direction would require casing to ensure stability during production. Given these results, the requirement that some laterals be drilled to the northeast and southwest, and the relatively small thickness of the highest-strength target sands, the decision was made to case all the laterals back to the parent well.

Nomenclature

a, b, c = empirical coefficients of the density-depth relationship
D = depth, ft
G = gravitational constant
K_f = coefficient of internal friction, dimensionless
M = P-wave modulus, GPa
p_p = pore pressure, psi, ksi
ρ_b = bulk density, g/cm^3
T = tensile strength, psi, ksi
σ = vertical stress, psi, ksi
σ_H = maximum horizontal stress, psi, ksi
$\sigma_{H\min}$ = minimum horizontal stress, psi, ksi

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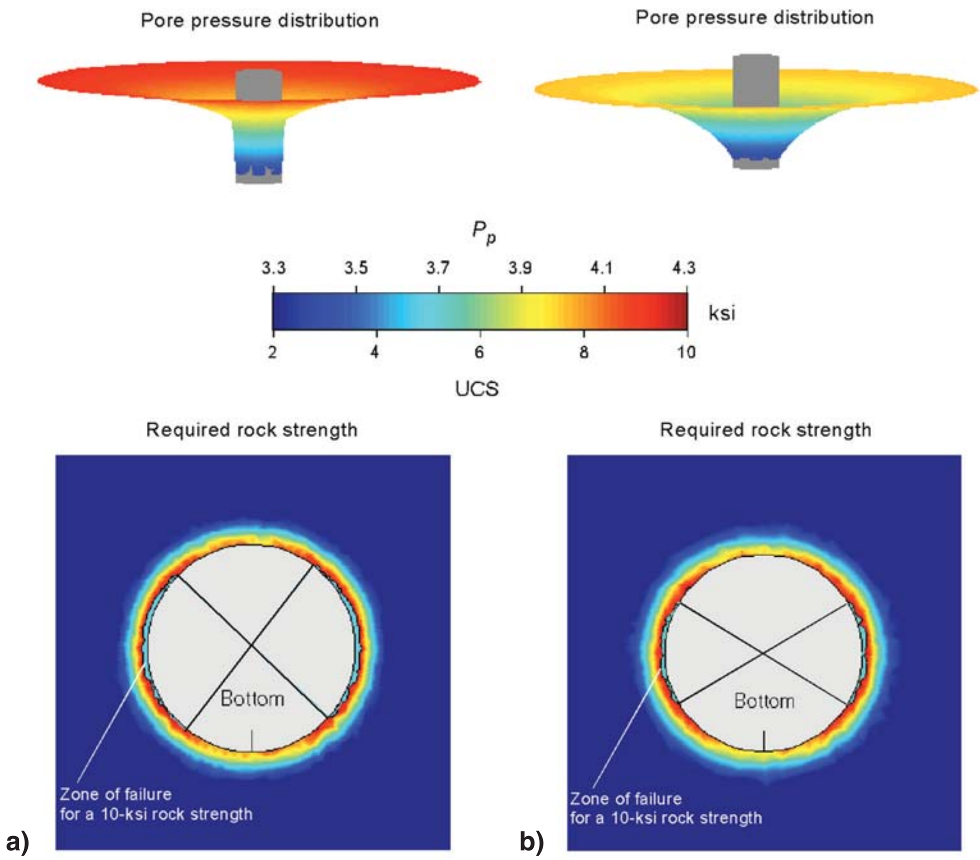

Fig. 6—(a) The pore-pressure profile and the rock strength required to prevent failure surrounding a horizontal well drilled to the northwest or southeast, where a 1,000-psi drawdown is achieved rapidly. (b) The pore-pressure profile and the rock strength required to prevent failure surrounding a horizontal well drilled to the northwest or southeast, where a 1,000-psi drawdown is achieved slowly.

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