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Predicting the Stability of Horizontal Wells and Multi-Laterals — The Role of In Situ Stress and Rock Properties

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Abstract

Drilling problems frequently result from severe mechanical failure of the wellbore wall and thus depend on the interplay between the magnitude and orientation of in situ stresses, rock strength, mud weight, and the orientation of the wellbore. Utilizing 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 from knowledge of the stress tensor. The analysis is a two step process - first, we determine stress from observations of failure in existing wells. We can then apply this knowledge to predict the stability of proposed wells both while drilling and later during production. We illustrate this type of approach using three case studies. First, we combine observations of failure in a vertical well with rock strength measurements to demonstrate the feasibility of horizontal drilling in poorly consolidated reservoir sands. Next, we analyze the stability during production of a series of multi-laterals drilled from a single inclined parent well. Finally, we show that wellbore stability can be controlled by the orientation of a well with respect to bedding, and illustrate a method to optimize the trajectory of wells to account for this effect.

Introduction

The process of drilling a well results in the development of a stress concentration at the borehole wall[1,2]. This is due to the fact that the rock surrounding the hole must support the stress previously supported by the material removed by drilling. Because the magnitudes of the principal stresses are generally different (that is, the vertical stress and the two horizontal stresses are 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 deviation and deviation azimuth and the magnitudes and orientations of the in situ stresses[8-10].

When the stress concentration exceeds the rock strength, the rock will fail. Failures can occur in compression, resulting in the development of wellbore breakouts[11,2] 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 of the principal stresses[16,15]. Thus, wellbore failures detected in image logs or multi-arm caliper logs can be utilized to determine the stress field[13,14,17-19]. Once stress magnitudes and orientations have been determined from observations of wellbore failure, this stress state can then be used to evaluate the stability of any well as a function of its trajectory.

The approach is illustrated in three case studies. In the first case study, observations in a vertical well combined with rock strength measurements were used to predict the stability of horizontal wells drilled in poorly consolidated sands. In the second example, we present an analysis of wellbore stability during drilling and production of multi-laterals drilled into rock with moderate strength. In the third example, we discuss the stability of wells drilled in steeply dipping strata, where the contribution to wellbore stability from strength anisotropy is important.

Depending on the stress state, deviated wells can be either more or less stable than vertical wells. In general, a well drilled in the direction of the greatest principal stress is more stable than one which is not. This in part explains why vertical wells are often found to be more stable than deviated wells in basins characterized by a normal faulting stress state. However, in areas in which the vertical stress is the least stress it is possible that deviated wells are more stable than vertical wells.

It is not necessary to entirely prevent wellbore failure to maintain wellbore stability. This is true for compressive failures (breakouts) because once formed, breakouts deepen but do not widen[2,20]. Thus it is necessary only to prevent breakouts from extending far enough around the well that the zone of intact rock is too small to maintain stability. As used below, this criterion can conveniently be quantified in terms of breakout width. Drilling-induced tensile wall cracks also do not necessarily affect stability, as no lost circulation occurs as long as the mud weight is below the fracture gradient.

Example 1: Horizontal drilling in a poorly consolidated sand

This study was performed to determine the feasibility of drilling inclined and horizontal wells in a poorly consolidated sand. Optimal exploitation of the field required a substantial program of horizontal drilling within a reservoir below 9000 ft. Two questions were addressed. The first was whether it would be possible to drill a horizontal well, and if so whether there were any constraints on its trajectory due to the mechanical effects of the stress field on wellbore stability. The second was whether the well would have to be cased to withstand the increased stresses associated with production-related drawdown.

Laboratory measurements revealed that the rock had extremely low compressive strength (3 kpsi). A standard logging suite including both electrical and acoustic image data was available from one vertical well. These data revealed compressive failures (breakouts) extending approximately 40° around the well within the reservoir.

In order to predict the stability of future wells it was necessary to utilize this information to constrain the in situ stress field. The vertical stress was determined from a density log by integration to be approximately 8.9 kpsi at the depth where breakouts were observed. Pore pressure at the same depth was determined by direct measurement to be slightly greater than hydrostatic, about 4.5 kpsi. The well was drilled with a 10.1 ppg mud, which resulted in an excess wellbore pressure of approximately 730 psi at the depth of interest. The magnitude of the least principal stress was determined from a leak-off test to be approximately 6.5 kpsi. The only remaining unknown was the magnitude of the greatest horizontal principal stress.

Simultaneous determination of the magnitude of S_{Hmax} and the stability of inclined wells

In this case we use a forward modeling approach to determine the magnitude of the greatest horizontal principal stress in which we vary this unknown stress magnitude until we match both the width of the breakouts in the vertical well and the known mud weight. We use the known values of the other stresses and of the pore pressure and rock strength. **Fig. 1** shows the result. In these and subsequent figures of the same type, wellbore trajectory is plotted using a lower hemisphere projection, such that a vertical well is in the center and increased deviations plot towards the figure edges. Horizontal wells plot along the outer edge. Blue colors indicate wellbore trajectories that are more stable relative to those with hotter colors.

In **Fig. 1a** we indicate the mud weight necessary to maintain a breakout width of 40°, for an assumed value of S_{Hmax} = 8 kpsi. As can be seen, the mud weight required in a vertical well corresponds to the actual value used during drilling of 10.1 ppg. This validates the prediction, which results in a magnitude of S_{Hmax} that is slightly less than the vertical stress, a pure normal faulting stress state. As a check on these results, we compared the measured width of a breakout at a slightly shallower depth in a formation with known strength to that predicted using the hypothesized stress state. The predicted width matched the observation, confirming the results of the analysis.

Fig. 1a also provides predictions of the stability of non-vertical wells. From the figure it is clear that higher mud weights are needed in deviated wells than were used in the vertical well. However, breakouts can be constrained to less than 40° of the wellbore circumference in any well, regardless of its orientation, with a mud weight that is less than 11 ppg. As the fracture gradient from the leak-off test result (0.7 psi/ft) corresponds to a mud weight of 12.6 ppg, it is clear that wellbore stability during drilling does not pose an impediment to exploitation in this field. In fact, as shown in **Fig. 1b**, wells could probably be drilled with any orientation using the same mud weight as was used in the vertical well, and even in the worst case would be predicted to fail over less than 90°, a condition which is generally found to be stable, as mentioned above.

Stability during drawdown

The results for drawdown would be substantially different as revealed in **Fig. 1c**. This figure plots the widths of breakouts that would occur in wells of any orientation if the mud weight were 9 ppg, corresponding to a fluid pressure in the well just slightly above the pore pressure. Failure would occur completely around almost any well with the exception of a vertical well or one that is deviated in the direction of S_{Hmax} (N85°E). This problem would be exacerbated even further as the wellbore pressure is decreased to bring the well into production.

The results of wellbore stability analysis in this case clearly demonstrate that although it is possible to drill and complete wells drilled at almost any orientation, in spite of the extremely weak rock, it is not possible to produce safely from open holes regardless of orientation.

Example 2: Stability of multi-laterals

This case study presents an evaluation of plans to drill a series of laterals from inclined wells penetrating a mixture of sands, shales, and conglomerates with inter-bedded coal seams in a mature field. The study was undertaken primarily to assess the necessity to "tie back" liners to the parent well to isolate the ~15-foot open-hole section immediately below the kick-off point. We also considered whether it was possible to leave the reservoir section open during production. As this project was being conducted in an area of particularly high drilling costs, the estimated savings for each multi-lateral not tied back to the parent well was $500,000.

A summary of density log data vs depth in a number of wells was used to provide a field-wide density profile of the form $\rho_b = a + bz^c$. Vertical stress was then found by explicitly integrating this equation for density as a function of depth. Pore pressures were determined by direct measurement. Least principal stress data were provided in the form of leak-off test results and from analyses of fracture treatments including step-rate tests and fracture closure pressures. In general, the least principal stress is less than or equal to the vertical stress; the apparent fracture gradient varies between approximately 0.7 psi/ft to slightly more than 1.1 psi/ft. Within the data scatter there is no systematic evidence of differences between platforms or as a function of the date the test was acquired.

An electrical image log recorded in a deviated well over the interval from approximately 10,000 to 11,000 feet measured depth was analyzed to detect breakouts (compressive failures) and tensile fractures (tensile failures which indicate a high horizontal stress difference). No obvious tensile failures were detected in the interval analyzed. A number of intervals of breakouts were observed. However, although it is possible to detect breakouts in electrical image data, it is often difficult to quantify the precise width and length of breakout zones. In this case, however, clearly defined breakouts were identified 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 NW.

Simultaneous inversion for stress magnitude and orientation

Breakouts do not always occur at the azimuth of the least horizontal stress in a deviated well. Furthermore, at this point in the study we did not have rock strength data. 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 greatest horizontal stress is oriented in the plane of the well, and thus it 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 state of affairs differs from that described in 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

In order 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[21]. We also utilize the fact that no tensile failures were observed in this well. **Fig. 3** illustrates this approach. We require that the values for horizontal stresses at any depth not exceed the frictional strength of the earth's crust (polygon) corresponding to the particular depth and pore pressure of interest. The values of the two horizontal stresses are constrained by the range of measured frac gradients (S_{hmin}) and by the fact that breakouts with a width of 60° occur if rock strengths are between 10,000 and 20,000 psi (as shown by the gray box). As no drilling-induced tensile fractures were detected, this requires that values of S_{Hmax} not exceed those corresponding to the blue line. Thus, it appears that 18,000 psi is an upper bound for S_{Hmax} and 20,000 psi is an upper bound of the rock strength in this interval.

Rock strength measurements were obtained in a number of cores from selected clean intervals of the well. These were compared to a variety of log data, and the highest correlation was found between P-wave modulus (density times compressional-wave velocity squared) and the measured strength. Using this new calibrated rock strength log we find that the rock strength within the interval with 60° breakouts is 13.5 kpsi. Using this value in **Fig. 3**, we predict a magnitude of S_{Hmax} of 14 kpsi. The lack of tensile cracks then suggests that the magnitude of S_{hmin} is between 8 and 9.5 kpsi and thus lies within the upper range of the fracture gradients measured within the field. **Fig. 2** was prepared using S_{hmin}=9.5kpsi, and confirms that if the rock strength in this interval is 12.5 kpsi, the predicted magnitude of S_{Hmax} is 14 kpsi.

Wellbore stability predictions

Fig. 4a shows the expected breakout widths as a function of 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 prior to the initiation of drawdown. The image on the left corresponds to a moderate strength rock (13.5 kpsi). Note that in wells drilled at nearly all possible orientations, a high degree of wellbore failure is expected (i.e., there is really no chance of leaving sections of the wells uncased) as breakout widths exceed 100° for all orientations except horizontal holes at a very small range of azimuths. **Fig. 4b** shows a rock strength log obtained using the calibrated relationship between UCS and P-wave modulus discussed above. Although there are a small number of higher-strength sections, the interval is characterized by numerous intervals with strengths below 13.5 kpsi.

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 utilize well logs to quantify rock strengths. This in turn allowed drilling engineers to evaluate the effective strength of the rock at proposed kick-off points, and in addition indicated that horizontal wells drilled along the reservoir sands at any orientation except a NW or SE direction would require casing to ensure stability during production.

Example 3: Wellbore stability in steeply dipping strata

The final case study investigates wellbore stability in a field containing highly deformed steeply dipping sands and shales. The region is active tectonically, and severe drilling problems have been encountered over a period of years. This study was undertaken both to evaluate a number of hypotheses to explain these problems and to propose solutions. We concentrate here on the evidence that demonstrated the importance of strength anisotropy in a several intervals encountered above the reservoir.

Angle of attack (that is, the orientation of a well with respect to bedding) can be defined schematically as shown in **Fig. 5a**. In evaluating stability using angle of attack it is generally found that there is a cone surrounding the bedding normal which defines "stable" trajectories. As the wellbore deviates from the bedding normal, stability generally decreases. Although this may be true as a first approximation, we have found that the radius of this "cone" varies with relative orientation, defined as the azimuth of the well w.r.t. the bedding dip direction. And, as shown below, there may be cases where wells drilled sub-parallel to bedding are more stable than those drilled at a more oblique angle. The effects on wellbore stability of the interaction between the well, the bedding planes, and the stress field can be predicted as discussed below.

Data from only one well is presented. Bedding orientations were determined using image data. The stress state was determined in intervals where strength anisotropy did not affect the results. Empirically calibrated relationships between rock strength and GR were used in the analysis.

Fig. 5b shows a scaled caliper log in this well. It is significantly enlarged throughout much of the depth interval shown. However, it is much less enlarged below approximately xx500, where the well crossed a fault and bedding orientations changed abruptly.

Fig. 6 contrasts the degree of failure expected at the depth indicated by "extreme enlargements" with and without incorporating the effects of weak bedding planes. **Fig. 6a** was prepared assuming that the rock is isotropic and its strength corresponds to that predicted from the laboratory-derived relationship between rock strength and the gamma ray log. Little wellbore failure is expected. When the effect of weak bedding planes is included in the analysis **(Fig. 6b)**, significant failure is predicted.

Between this interval and the interval indicated as having "slight enlargements" the bedding dip changes markedly. **Fig. 6c** shows a prediction of the region of failure in the well in the interval where little hole enlargement occurred. The only difference between this interval and the one at shallower depth is a change in bedding orientation. All other parameters (such as the stress and pore pressure gradients and rock strength) are exactly the same. Based on this analysis, the wellbore should be much more stable simply because of the change in bedding dip. These theoretical calculations match drilling experience and provide a physical model for the observation that both the orientation of the wellbore with respect to bedding and with respect to the maximum horizontal stress direction can be extremely important in controlling wellbore stability.

Fig. 7 and **Fig. 8** present plots of the stability of hypothetical wells drilled into anisotropic formations subject to the stress regime appropriate for this well. **Figs. 7a** and **8a** show the widths of breakouts expected to occur if the mud weight were 11.3 ppg, as used in drilling. **Figs. 7b** and **8 b** show the mud weight required to restrict the zone of failure to 60°. If the stability cone were independent of relative azimuth these plots would be symmetric about the bedding normal. They are not; the degree of asymmetry is a measure of the importance of incorporating stress into the analysis.

Fig. 7 was prepared using the bedding dip of strata encountered above the fault. **Fig. 8** was prepared using the average orientation of the bedding below the fault. In each case the uppermost figure shows the breakout width predicted for the anisotropic rock using a mud weight of 11.3 ppg used during drilling. The lowermost figure shows the required mud weight necessary to maintain wellbore stability using a stability criterion that the well is stable as long as less than half the circumference fails (that is, the width of a breakout is less than 90°).

In **Fig. 7** the actual wellbore trajectory is indicated by the white dot. It is clear that for the mud weight used breakouts would occur around more than half the circumference of the well. For a vertical well a modest increase in mud weight would be sufficient to confine failure to less than half the circumference; for the slightly inclined well it would require a somewhat greater increase. In either case it is clear that the original trajectory could have been drilled more safely with only a modest increase in mud weight.

However, a significant improvement in stability could have been achieved simply by changing the wellbore orientation. For example, breakouts would have been restricted to less than 30° with no increase in mud weight if the well had been deviated in a direction normal to bedding **(Fig. 7b)**. Similarly, a deviation of 30° to the SE would have restricted breakouts to less than 70°. Alternatively, breakouts of less than 90° would have resulted for a well drilled to the NW using a mud weight as low as 9.5 ppg, and a 30° deviation to the SE could have been drilled using a mud weight of less than 11 ppg.

The situation below xx500 is quite different, as illustrated in **Fig. 8**. Here the wellbore orientation indicated by the white dot is quite stable, as breakout widths of less than 70° are predicted. Also, it is apparent that inclined wells both normal to and subparallel to bedding are more stable than vertical wells.

Displays such as those shown in **Figs. 7** and **8** can provide valuable guidance for well design. For example, when designing the well to be stable above the fault, one option would be to choose to drill in a direction perpendicular to bedding. However, paradoxically, it would be almost equally beneficial to drill the well to the SE (parallel to bedding). Because the latter orientation is more appropriate to maintain stability deeper in the well **(Fig. 8)**, it would appear to be the more reasonable choice.

This type of display would also valuable in designing a build profile. For example, it may be advantageous to avoid building angle in one formation, if that formation is predicted to be particularly weak for a well drilled at the desired deviation. Alternatively, it may be safer to modify the azimuth of the well in the build section, to minimize the excess mud weight necessary to maintain stability.

Summary

The case studies described above illustrate a general approach to predicting wellbore stability that relies on data obtained in previously drilled wells to predict the stability of future wells. The specific examples chosen for this paper concentrate on issues related to stability of highly inclined wells. Similar analyses can be undertaken to determine the state of stress for other purposes. For example, identification of permeable fractures within a population, determination of the optimal angle for drilling to enhance efficiency of hydraulic fracturing operations, and planning patterns of wells to optimally drain a reservoir all require understanding of the in situ state of stress.

Nomenclature

S_{hmin} = minimum horizontal stress
S_{Hmax} = maximum horizontal stress
UCS = unconfined compressive strength

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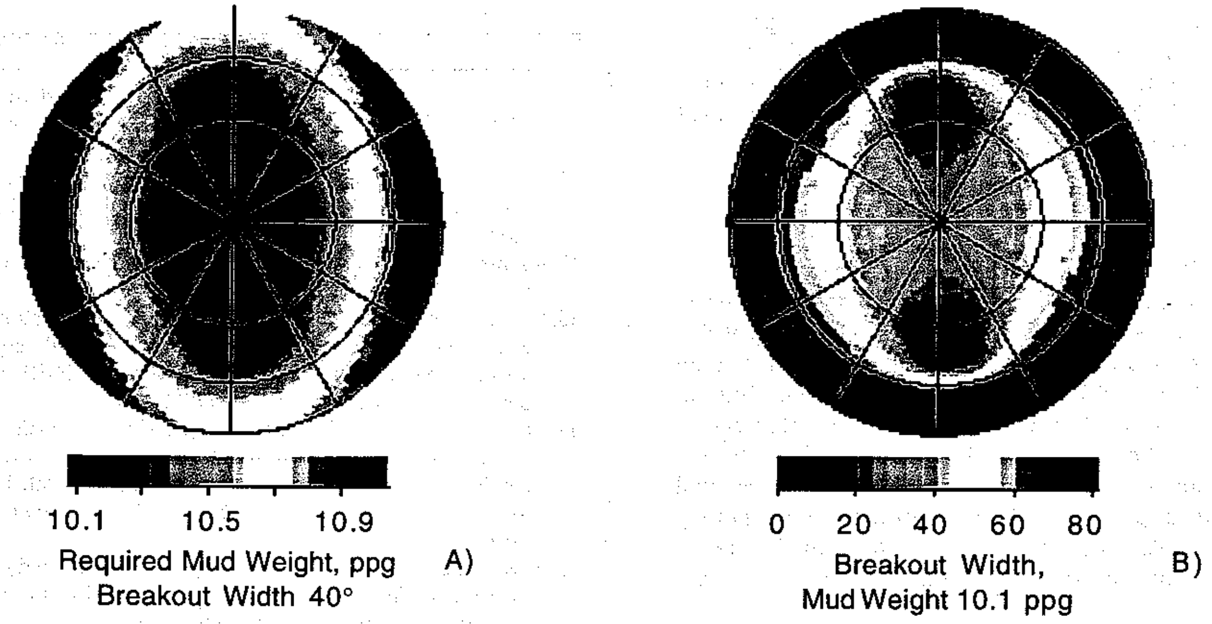
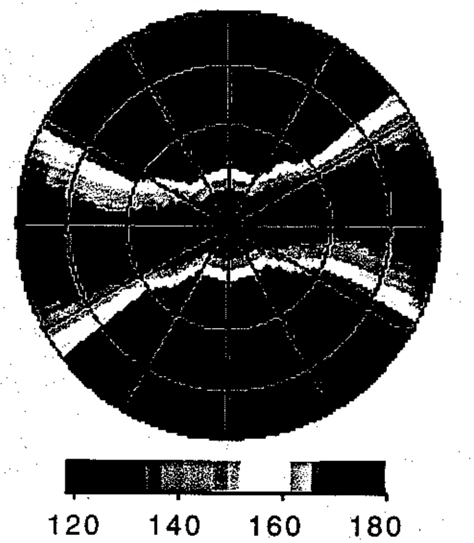


Required Mud Weight, ppg
Breakout Width 40°

A)

Breakout Width,
Mud Weight 10.1 ppg

B)



Breakout Width,
Mud Weight 9 ppg

C)

Figure 1. Tendency for breakouts as a function of wellbore trajectory (case study 1). (A) the mud weight which would allow the formation of a 40° wide breakout in rock with a strength of 3 kpsi, as observed in the vertical well. (B) breakout width predicted for a well of any orientation, using a 10.1 ppg mud. Inclined wells are generally predicted to experience more severe failure, although it is clear that not all deviated wells are less stable than a vertical well in this normal faulting environment. (C) the effect on wellbore stability of using a lower mud weight (close to but still greater than the pore fluid pressure).

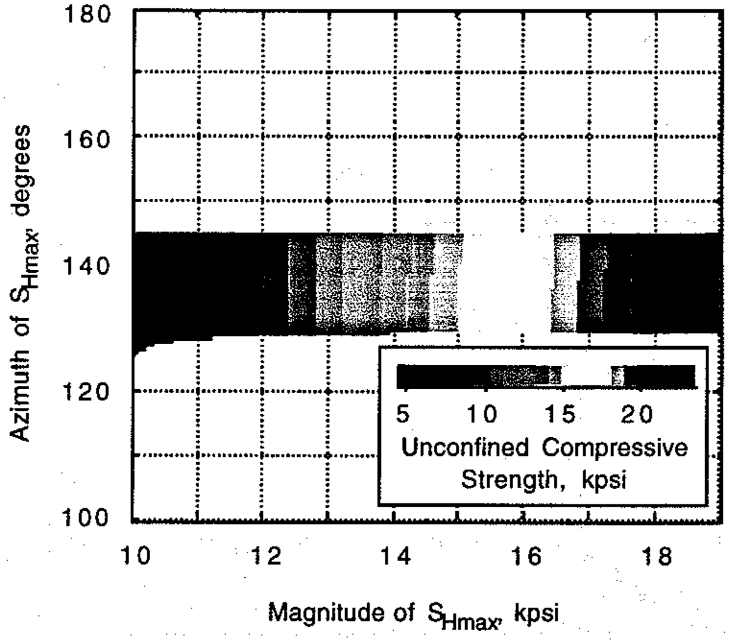


Figure 2. Orientation and magnitude of greatest horizontal principal stress, consistent with the observed azimuth and width of breakouts in an inclined well (case study 2).

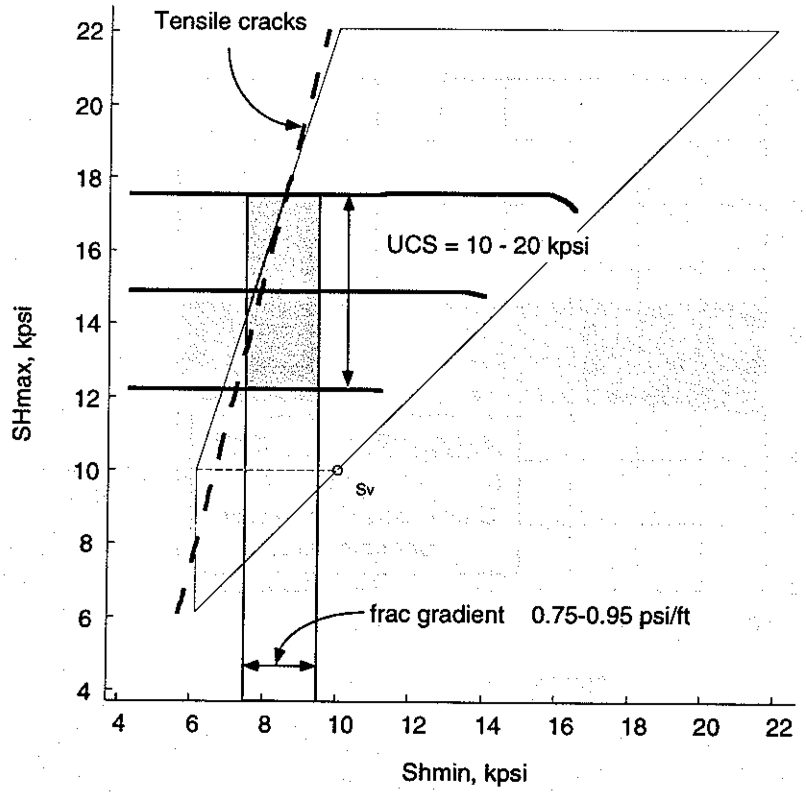


Figure 3. The magnitudes of the greatest and least horizontal principal stresses consistent with leakoff test results and observations of failure in the inclined well (case study 2) are indicated by the gray box. A rock strength of 13.5 kpsi predicted from a calibrated log strength indicator reduces the uncertainty in the magnitudes of both horizontal stresses.

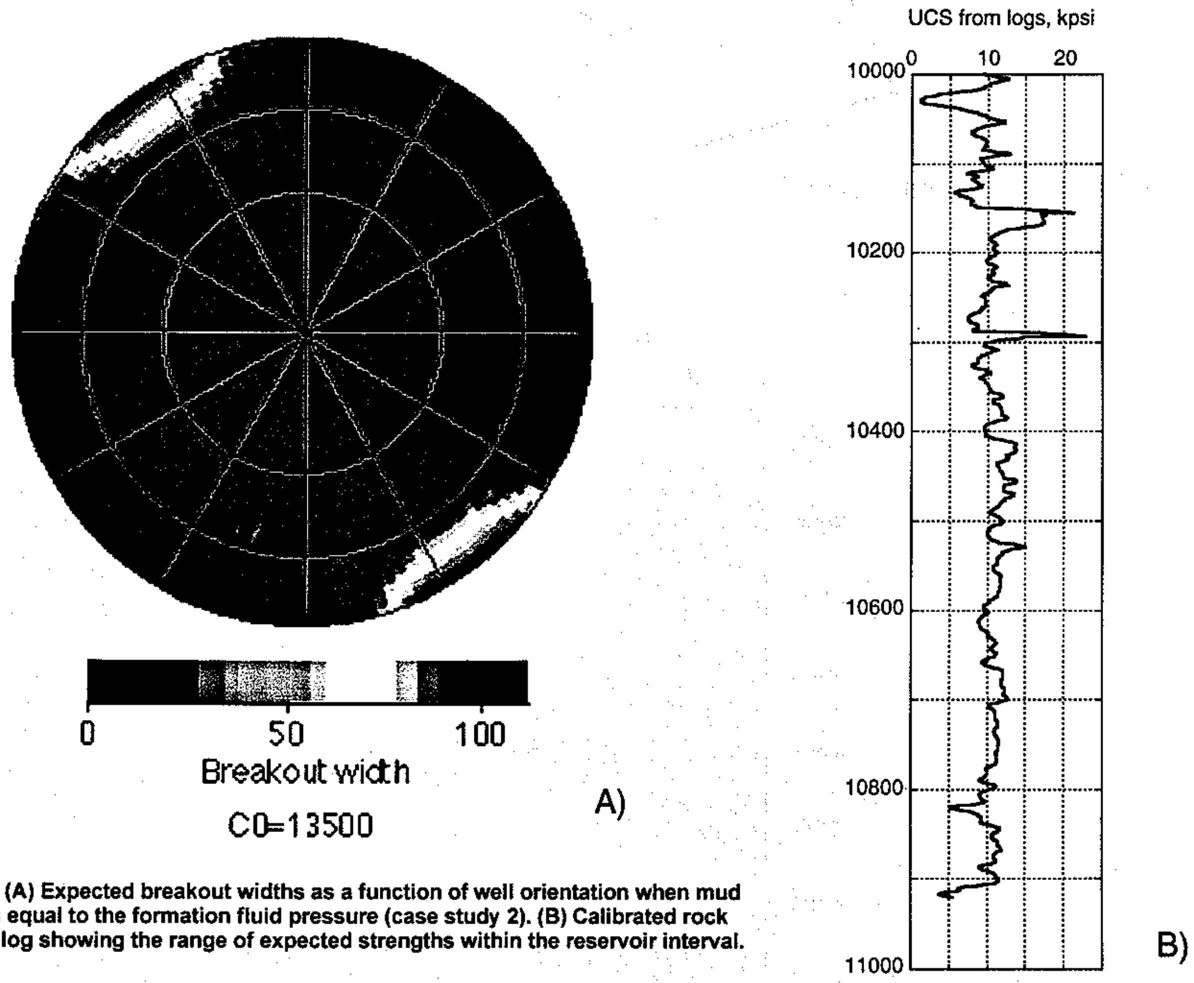
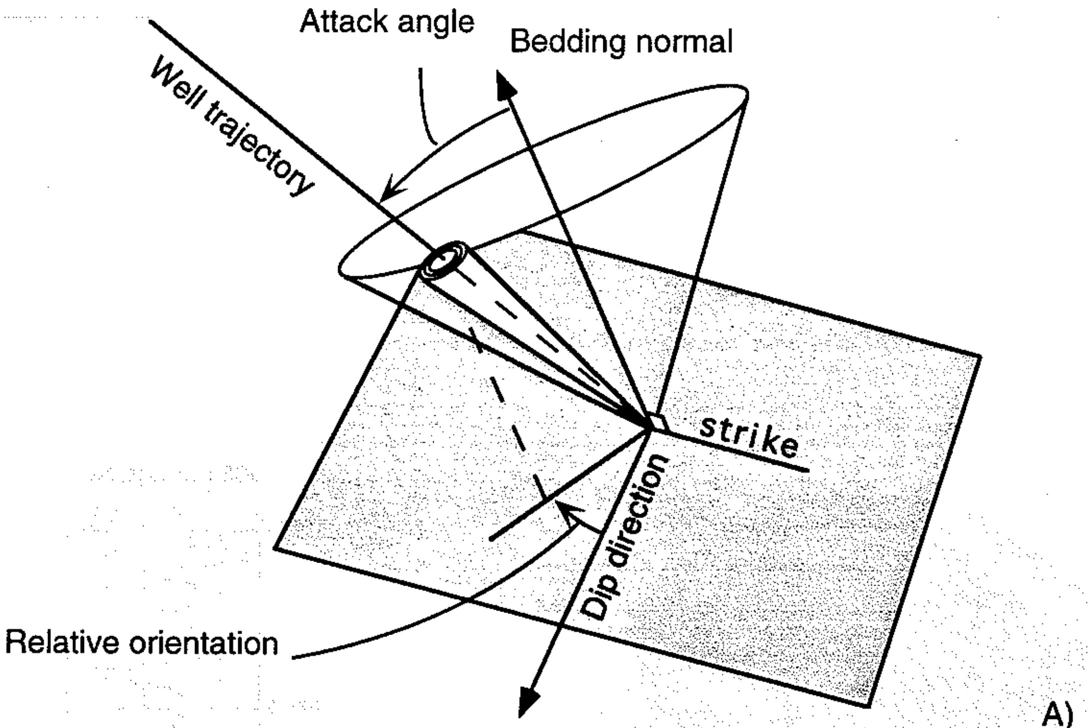


Figure 4. (A) Expected breakout widths as a function of well orientation when mud weight is equal to the formation fluid pressure (case study 2). (B) Calibrated rock strength log showing the range of expected strengths within the reservoir interval.



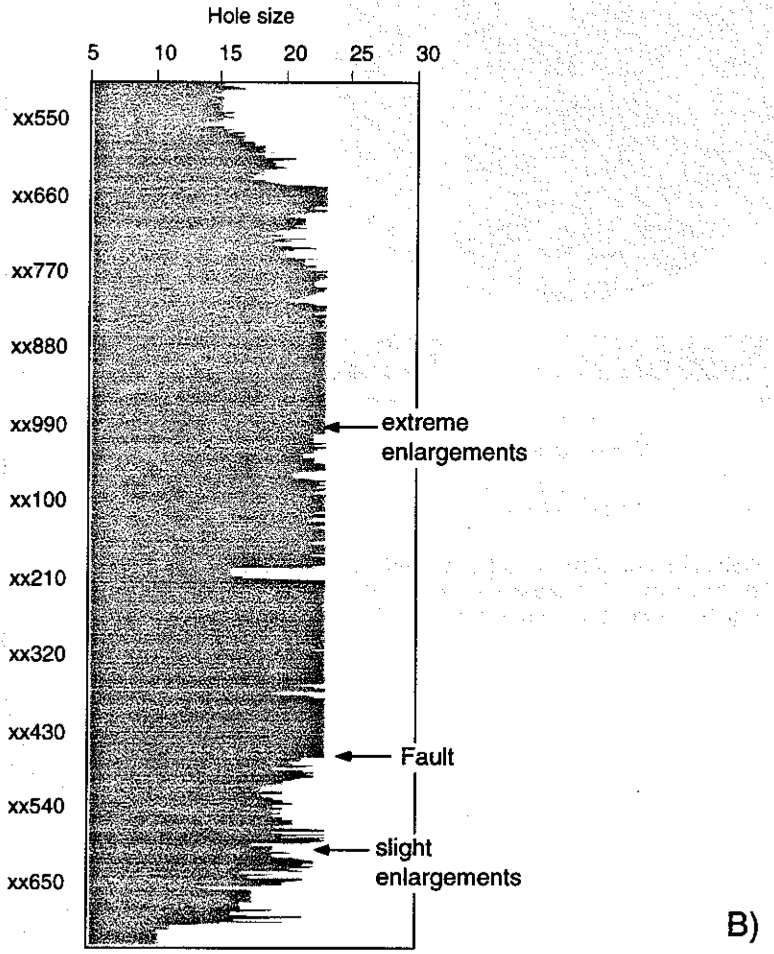


Figure 5. (A) Schematic illustrating the attack angle. The radius of the "cone" which defines the safe trajectory is likely to be a function of the relative orientation of the well with respect to bedding dip. (B) Equivalent hole size (from caliper data), case study 3 well. The hole size is greater than the maximum extension of the caliper arms in much of the interval above a fault at xx500. Below that interval the bedding orientation changes and the hole is closer to bit size.

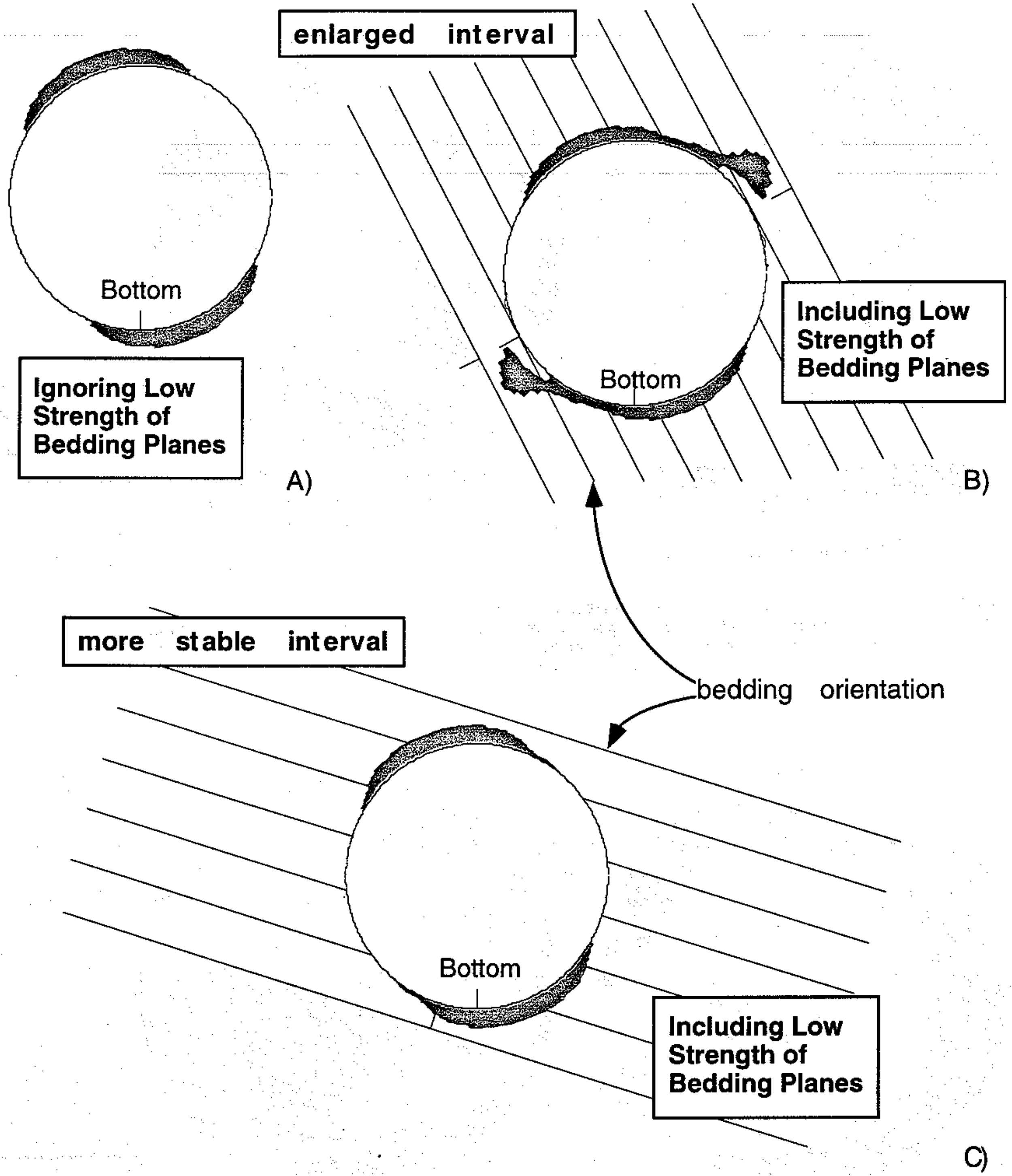


Figure 6. Shape of the zone of compressive failure around a deviated well drilled into a formation with anisotropic strength (case study 3). (A) If one ignores the presence of weak bedding-parallel planes, failure is confined to a relatively narrow zone around the deviated well. (B) If one includes the effects of weak bedding, failure extends more than 120° around the well, leading to severe instabilities. (C) In the deeper zone, a change in bedding orientation reduces the effect of weak bedding-parallel planes and the well is more stable.

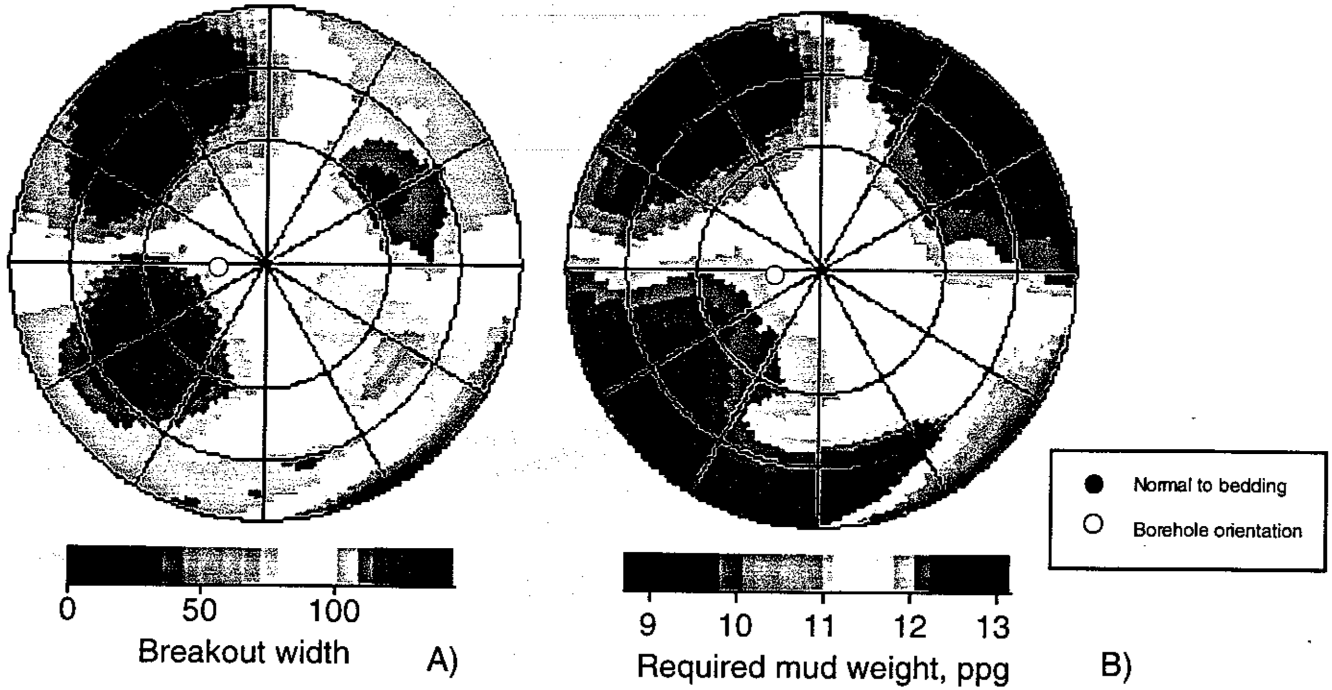


Figure 7. Stability of wells drilled within a formation with anisotropic strength. On the left is shown the width of breakouts which would be expected to occur using a mud weight of 11.3 ppg. On the right is shown the mud weight required to prevent breakouts from extending more than 60° around the wellbore. The bedding orientation is taken from measurements of bedding above the fault in case study 3.

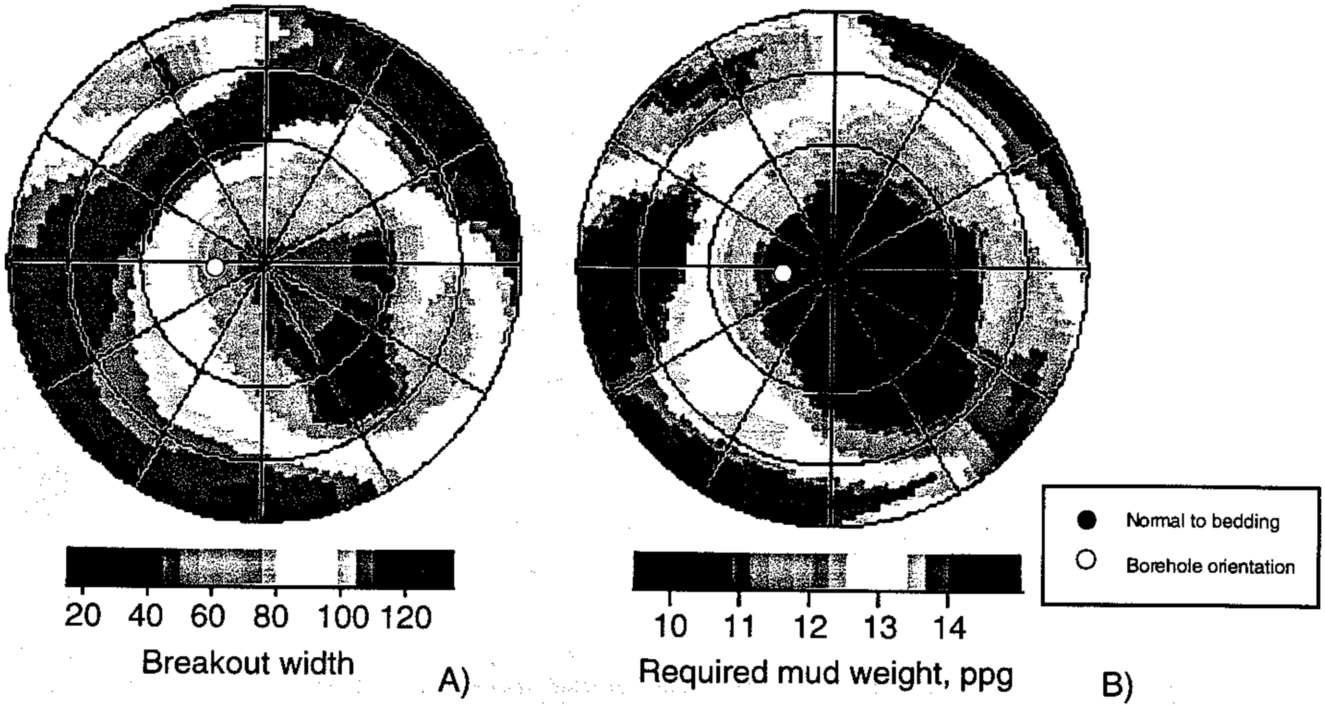


Figure 8. Stability of wells drilled within a formation with anisotropic strength. On the left is shown the width of breakouts which would be expected to occur using a mud weight of 11.3 ppg. On the right is shown the mud weight required to prevent breakouts from extending more than 60° around the wellbore. The bedding orientation is taken from measurements of bedding below the fault in case study 3.