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Drilling in South America : A Wellbore Stability Approach for Complex Geologic Conditions

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Abstract

An analysis approach is described which includes the effects of rock fabric strength anisotropy on wellbore instability. When drilling in geologically complex conditions - shown to be commonplace in the Andean foothills of South America - bedding-plane slippage, resulting from an unfavourable interaction between in-situ stresses, the well trajectory and bedding, is shown to cause severe instability for certain well trajectories. Case-history examples from the Pedernales field (Venezuela) and Cusiana field (Colombia) are presented which confirm the analytical predictions.

Introduction

The foothills of the Andes mountains in South America continue to be an important area for hydrocarbon exploration and new field developments. However, with well costs as high as $40 million on occasion, and taking up to a year or more to drill, the drilling phase can represent a major component of the development cost. BP Exploration's experiences in South America in the 1990s have shown that tackling the problem of wellbore instability can save millions of dollars per well by reducing non-productive time associated with wellbore instability[1]. At the time of developing the Cusiana field in Colombia, the scale of the wellbore stability problem experienced was unprecedented. The unusual geological setting, characterised by high horizontal stresses, steeply dipping beds and alternating sand/shale sequences, posed additional instability problems not normally encountered in oil field drilling. As exploration proceeds in other areas of South America, it is evident that the drilling difficulties experienced are not solely confined to the Cusiana field. Wellbore instability problems have been encountered when drilling in similar complex geologic conditions; in Venezuela and Peru, for example.

This paper describes the way in which "complex geologic conditions" can result in severe wellbore instability problems, and presents analysis techniques which can incorporate their effects. Using these techniques, which correctly predict field drilling problems, it is expected that the impact of drilling difficulties can be greatly reduced, resulting in lower development costs.

Geologic Conditions and State of Stress in Northern South America

The physiography of northern South America is dominated by the Andes mountains in the west and the Amazon/Orinoco basin in the east. The Colombian Andes form three separate ranges - the Western, Central and Eastern Cordilleras (the last named known as the Merida Andes in Venezuela) - which merge southward into a single range (see Figure 1). East of the Eastern Cordillera are the Llanos and Barinas Basins, a savanna that is part of the catchment area for the Orinoco River.

The tectonic history of this region is dominated by the juxtaposition and relative movement between the Nazca, Caribbean and South American Plates. Inversion of shallow focal mechanisms shows that the tectonic thrust trends roughly northwest - southeast over the larger geographical area (Figure 2), though curvature in the Cordillera arc results in active thrusting to the southeast in the vicinity of BP Amoco's Cusiana field in Colombia[2].

The tectonic setting of the region has been studied extensively[3,4]. Simply put, six tectonic regions can be identified according to their stress regimes[5,6] : fore arc (in the west), western volcanic chain, altiplano, Cordillera, foothills and llanos (in the east). The fore arc is located along the Pacific Ocean between the off-shore subduction trench and the flanks of the volcanoes. It is characterised by a compressional stress drop and an extensional strain field. Like the fore arc, the altiplano located behind the volcanic chain also experiences extensional deformation. Unlike the fore arc and altiplano, the Cordillera and the foothills are characterised by a compressive stress regime. The shortening resulting from this compressional stress state is accommodated in the foothills by large thrust and strike-slip faults (e.g. the Guaicaramo fault system bounding the Eastern Cordillera, and the Yopal and Cusiana faults in the vicinity of the Cusiana field - see Figure 3). These major discontinuities release the stresses in the Llanos foreland basin, which is largely tectonically passive and undeformed.

Wellbore Instability Associated With Complex Geologic Conditions

In this paper the term "complex geologic conditions" is used principally to describe the state of sub-surface lithologies commonly encountered when drilling in the foothills of the Andes of South America. Here the stress regime may be associated with active thrust faulting or strike-slip fault motion. However, other authors have confirmed that similar stress conditions are prevalent in other hydrocarbon provinces - from the Tarim Basin (China), the Alberta Basin (Canada), to certain areas of the Norwegian Sea, and offshore Indonesia[7,8,9]. As a result, the methodologies described in the paper for wellbore stability analysis have far wider application than solely in South America.

Two field case-history examples are described in this paper. The first refers to drilling in the Cusiana and associated fields of Colombia. The second example relates to wellbore stability problems experienced when drilling on the flanks of a high-relief diapiric anticline structure in eastern Venezuela.

The wellbore instability problems in Colombia have been widely published[10,2,5]. The drilling challenges faced are best summarised in the simplified cross-section and stress vector plot shown in Figure 4. The overthrust formations in the hanging wall of the Yopal Fault dip at up to 50°; the foot-wall formations are more horizontal. The maximum horizontal stress has been determined to be larger than the vertical stress[2,5,7]. Numerical geomechanical analyses and DSCA tests on rock cores have also indicated that principal stresses may be rotated clockwise by as much as 45° in the hanging wall and by up to 10° anti-clockwise in the footwall[2,5]. Here the 'unusual' stress alignment and magnitude, and formation dip, interact to result in a preferential up-dip drilling direction[11]. Even so, extensive breakouts in overburden shales - of up to 44" in 12¼" hole - have occurred. The fissile and naturally fractured shales are also susceptible to spalling as a consequence of wellbore pressure penetration into microfractures. Where this occurs, the fractured blocks are no longer subject to the mud overbalance pressure, and the destabilised (or 'floating') blocks can cave into the wellbore as a result of swabbing the formation when tripping. Other authors have proposed a similar mechanism to explain instabilities in fractured shales[12].

In the Pedernales Field of Eastern Venezuela instability is mostly associated with high-angle, cross-dip wells. Here "bedding-parallel shear" is the principal mechanism for instability - shown schematically in Figure 5 and by physical experiment in Figure 6[13]. Under these conditions the reduced strength properties (friction and cohesion) acting on the bedding planes can result in enhanced, and sometimes catastrophic, instability. The borehole failure patterns produced can be far more extensive than those that would be predicted assuming uniform rock properties. Here, the resultant instability can create "corners" to the breakout, forming a "square borehole", as seen in laboratory experiments[14]. (The analysis approach presented in this paper predicts similar borehole failure modes). It should also be emphasised that although the Pedernales Field experiences a strike-slip stress regime, the analytical approaches presented in this paper also have application to any high-angle well trajectory drilled close to the bedding-parallel direction. Here, bedding-parallel shear may occur in inverted well profiles (i.e. deviations in excess of 90°) or where a change in well azimuth is made. Additionally, when drilling uplifted formations around salt diapirs, where the salt stock has penetrated the overburden and reservoir formations, bedding-parallel shear can still occur, even at modest well deviations. Where this mechanism of instability occurs, the resulting "blocky" cavings usually possess two bedding-parallel surfaces, rather than the curved geometry normally associated with shear instability. Thus, many commonly drilled well trajectories may be considered as encountering "complex geologic conditions". It is the authors' contention that failure to recognise the additional mechanisms of instability which can arise in these situations is a major contributory factor to stuck-pipe and drilling problems often associated with these wells.

Analysis Approach

Case history experience and previous analysis work for the Cusiana field, Colombia, has shown that wells drilled up-dip are more stable than those drilled with a cross-dip or down-dip trajectory[10,11] (see Figure 7). Here, the "attack angle" is used to evaluate stability. This is defined as the orientation of the well with respect to the bedding. (In the nomenclature adopted in this paper, the attack angle is zero when the well is drilled perpendicular to bedding; if the attack angle is 90°, the well lies in the plane of the bedding. This definition is opposite to the convention adopted by Økland and Cook[13], where the bedding-parallel direction has a zero attack angle). As the wellbore deviates from the bedding normal, stability generally decreases.

Non-zero values of attack angle define a cone of possible well trajectories (see Figure 8). The field data, however, show that up-dip wells are more stable than down-dip wells drilled at a similar attack angle. Thus, defining an attack angle alone cannot describe the optimum well trajectory. To uniquely determine the optimum trajectory, additional information on bedding orientation is required - namely, the bedding dip and dip direction. This information defines the relative bearing of the well trajectory with respect to the bedding dip. This is defined as the difference in azimuth measured clockwise between the up-dip direction of bedding and the well azimuth (see Figure 8). This is equivalent to the difference between the orientation of the bottom of the hole and the bedding dip direction. The relative bearing is thus zero if the well is drilled in an up-dip direction, 90° or 270° if the well is drilled along strike, and 180° if the well is drilled in a down-dip direction. If the well is perpendicular to bedding the relative bearing is undefined.

Utilising these concepts, a wellbore stability prediction model was adapted to include slippage on bedding planes, as defined by a Mohr-Coulomb frictional surface[15]. Thus, by suitable transformations of the stress concentrations, it was possible to analyze both failure of the intact rock mass and allow for bedding-plane shear effects. For certain unfavourable well trajectories, this 'mixed mode' of instability permits far more severe breakouts than a simple analysis of intact rock failure would predict. To illustrate this effect, Figure 9 presents the computed breakouts evaluated with and without incorporating the effects of weak bedding planes. (The arrows indicate the direction of maximum compression). The necessary input data to the model are summarised in Table 1. Figure 9a assumes uniform rock strength; little wellbore failure is expected. However, when the effect of weak bedding planes is included in the analysis, significant borehole failure is predicted (Figure 9b). The enhanced breakout region depicted in Figure 9b is suggestive of the 'square borehole' seen in laboratory borehole failure experiments using laminated shale[14].

One of the features of drilling in geologically complex environments is that bedding dip can change markedly over relatively short sections of the wellbore. Figure 9c shows a prediction of the region of failure in the well, allowing only a small (30°) change in bedding dip azimuth. All other parameters - such as the state of stress, pore pressure and rock strength - are exactly the same. Based on this analysis, the wellbore is much more stable simply because of the change in bedding dip direction. These theoretical calculations are supported by field evidence. Figure 10 presents calliper hole size, attack angle and bedding/wellbore relative bearing for the depth interval 14,400 ft to 15,800 ft from a Colombian appraisal well. At the top of the section (at 14600 ft), the 20° attack angle and 210° relative bearing combine to produce a relatively in-gauge hole section (15" maximum calliper in a 12¼" hole section), even though the hole had been open for 30 days between drilling and logging. In contrast, the interval 14800 ft to 15400 ft is characterised by severe breakouts - in excess of 22" - due to unfavourable combinations of attack angle and relative bearing (30°-70° attack angle, 60°-90° relative bearing). In contrast again, the lowest section below 15500 ft shows improved hole quality because the combination of attack angle and relative bearing (30°-60° and ca. 240°, respectively) results in far less bedding-plane shear.

Thus, theoretical calculations and actual drilling experience are consistent. They confirm 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 are extremely important in controlling wellbore instability. The interaction between stress, bedding dip and wellbore instability is further illustrated in the two case-history examples following.

Case History Examples

Pedernales Field, Venezuela

The Pedernales Field is located in Eastern Venezuela at the mouth of the River Manamo, part of the Orinoco River, which flows into the Gulf of Paria. The field was originally discovered in 1933 by Creole Petroleum, part of the Exxon Company. Thirty-eight wells were drilled by Creole between 1938 and 1963. In 1970, Lagoven assumed Operatorship and reactivated the field. A further 17 wells were drilled. Production was limited and the project abandoned. In 1993, as part of the second International Licensing Round, the field was acquired by BP in association with Lagoven for further reactivation. BP Exploracion de Venezuela assumed Operatorship in August 1994 and continues to develop the field to date.

The Pedernales structure has been created by a diapiric mud anticline, where the strike of the anticline is approximately southwest-northeast (see Figure 11). Either side of the diapir, the Pliocene and Miocene sediments dip at up to 45°. Recent uplift on the flanks of the anticline - of up to 8500 feet - has resulted in a complex state of stress in the local area. The geologic column (shown in Figure 12) comprises interbedded unconsolidated deltaic to coastal sands and mudstones through the Paria, Las Piedras and La Pica formations. The principal oil reservoirs are located in the Pedernales Member - the Pedernales Member Shale (a high conductivity mudstone) and the Pedernales Member Sand. The sandstones are commonly very fine to fine grained, occasionally medium grained and commonly argillaceous. The sandstones are consolidated, but rarely cemented. The Paria and Las Piedras formations are normally pressured, whereas the La Pica formation is overpressured at ca. 12.25 ppg (1.47 SG). Within the Pedernales Member, intra-reservoir shales are thought to possess pore pressures close to these initial conditions, whereas the reservoir sandstone may be depleted to ca. 8 ppg, particularly in the southwestern area of the field.

BP's Phase 1 development strategy involved drilling twenty wells by the end of 1996 from two platform structures, 'B Platform' and 'F Platform', indicated on Figure 11. The majority of the wells were drilled cross-dip in a south-westerly direction at relatively high angle through the overburden (40° to 70° deviation). Well step-outs were up to 15,500 ft. These wells, drilled in the least stable directions, met with varied success. Problems were associated with bit balling, borehole instability, stuck-pipe, etc.

In light of this, a number of technical studies were commissioned during the Phase 1 drilling programme to optimize mud type, hole cleaning efficiency, wellbore stability and drilling practices. This work is summarized by Twynam et al[16].

The early stability work classified the Pedernales wells as falling into one of four categories - vertical, up-dip (~135° azimuth), down-dip (~315° azimuth) and cross-dip (~45° and

~225° azimuth). The mud weight data from drilling the reservoir section - where instability in the intra-reservoir shales was particularly troublesome - show a strong dependence on well deviation (Figure 13), but only minor correlation with well azimuth (from the historical data available at that time). The near vertical or up-dip Creole wells typically exhibited the highest mud weights of 11 ppg to 16 ppg (though this was largely due to operational limitations with mud cleaning equipment allowing a build-up of solids to increase mud weight). Lagoven wells, typically drilled at deviations of between 10° and 40° have the lowest mud weights (~11 ppg). Early BP wells, at deviations in excess of 40°, were found to require mud weights in excess of 12 ppg in order to combat instability. An empirical wellbore stability study undertaken at this time (in 1996) found a reproducible correlation between minimum mud weight required for stability and well deviation for the south-west area wells, of the form :

$$MW = 7 + 7e^{-0.79\alpha} + 0.114\alpha$$

In the above, mud weight (MW) is in ppg and deviation (α) is in degrees from the vertical. The exponential term has a rapidly diminishing value with increasing deviation. At deviations higher than 30° the term 0.114α dominates the change in mud weight, this being equivalent to 1.14 ppg per 10° deviation. This rate of mud weight increase is considerably higher than the 0.17 ppg per 10° deviation typically applicable to passive basin areas of the North Sea. However, the in-situ stress regime at Pedernales is far from being passive, and so correlations established in the North Sea (or elsewhere) could not be expected to apply equally to Pedernales.

Figure 13 shows that this empirical correlation fits the field data very well. However, it is completely divorced from the geomechanical processes controlling wellbore instability, and also requires several well failures to have occurred before the appropriate empirical relationship for the minimum safe mud weight can be established. This is not considered good operating practice and, wherever possible, credible wellbore stability predictions are required early-on in field planning and development, rather than incurring significant operational drilling problems to empirically define safe mud weights.

The analysis approach presented in this paper allows the proper analysis of cross-dip well trajectories, taking into consideration the multiple modes of failure which can occur as a result of bedding-plane shear. Figure 14 presents a polar plot of the required mud overbalance (in ppg) to successfully drill wells in Pedernales, calculated using the new anisotropic strength wellbore stability model. Figure 15 presents a comparable plot showing the extent of wellbore breakouts for possible well trajectories assuming a 12 ppg mud weight was used to drill the wells. (Table 2 summarises the common input data).

Figure 14 shows that up-dip wells (i.e. drilled to the south-east) are predicted to be stable with mud weights of around 11.5 ppg (2.5 ppg overbalance) - as borne out by the field evidence - but that a significant increase in mud weight is necessary to maintain stability in cross-dip north-easterly or south-westerly well trajectories. The predicted required mud weights in excess of 13 ppg for cross-dip well deviations of 60° and greater do agree with the empirical mud weight relationship established in Figure 13.

Figure 15 computes the extent of breakouts (in terms of total angular width around the circumference) which might be expected if wells were drilled with a 12 ppg mud weight. Wells drilled in a general up-dip direction are predicted to experience total breakout widths of up to 60° (i.e. up to one-sixth of the borehole circumference fails in shear). This is not excessive and wells can be successfully drilled under these conditions. High-angle cross-dip wellbores are predicted to suffer total breakout widths of about 220°, however; i.e. 60% of the borehole circumference fails. At high angles, such hole enlargements result in inadequate hole cleaning and subsequent stuck-pipe problems. (In deed, as were seen in the field).

Cusiana Field, Colombia

The drilling difficulties associated with developing the Cusiana field are well documented[10,2,5]. The petroleum geology of the region has also been described[4,17].

Figures 9 and 10 have shown that the bedding dip angle, and small changes in this dip angle, have a significant impact on wellbore stability. The influence of bedding plane effects will now be considered further to substantiate the observations of a preferential up-dip drilling direction shown by Figure 7.

The appropriate state of stress in Cusiana has been established previously[10,2,5], though the direct field evidence for the postulated rotations in principal stresses is limited. The in-situ stress data provided by Last and McLean[10] for conditions typical at 10,000 ft depth in Cusiana are used in the analyses. These are summarised in Table 3.

The previous work[10] correctly noted that conventional analyses assuming uniform rock properties cannot account for a preferential up-dip drilling direction. To invoke more stable conditions in the up-dip direction, a 30° rotation in the maximum horizontal stress was imposed to better correspond with the numerically computed stress vectors - see Figure 4. However, the computed 'drilling severity index' - reproduced as Figure 16 from Last and McLean[10] - is only a poor representation of the observed drilling response characterised in Figure 7. The acceptable stability seen in near vertical wells is not reproduced, for example.

It is now possible, using the analytical techniques described in this paper, to re-analyse the Cusiana example accounting for bedding-plane effects and rotated stress fields. Figure 17 presents a polar plot of the failed part of the circumference which is computed to arise from using a 12 ppg mud weight. This analysis considers only bedding-plane effects arising from bedding dipping at 30° to the northwest. No rotation in the principal stresses has been imposed. The computed breakout extent - which can be considered analogous to a drilling severity index - better reproduces the acceptable stability of near vertical wells, while still predicting improved stability in the up-dip direction. Thus, one can conclude that it is not a prerequisite that stresses be rotated for there to be a preferential up-dip drilling direction for wellbore stability. Directionality can result merely from bedding dip effects.

Figure 18 presents a comparable stability analysis, where both bedding effects and rotated stresses are included. (A 30° rotation is imposed). As expected, the stability of wells drilled in the up-dip direction is improved as a result of the more favourable interaction between bedding shear-planes and in-situ stresses. Here too, the computed extent of borehole failure provides a reasonable match with the observed drilling severity. The importance of this analysis is that it shows the predominant effect of considering bedding-dip effects - which are relatively easy to assess from dipmeter logs, etc. - compared to the requirement for determining the magnitude of a rotated stress field. This is not easy to do without recourse to complex numerical modelling[2,5].

Conclusions

The importance which the interaction between in-situ stresses, well trajectory and formation bedding has on wellbore stability is emphasised. Under certain conditions fissile shales, or formations with pronounced bedding, are shown to be extremely prone to catastrophic instability as a consequence of bedding-plane slippage. This additional mechanism for instability is one which is often overlooked, but it can be triggered by relatively small changes in bedding dip direction.

The often complex geology of the Andes foothills is considered to be particularly prone to this mechanism of wellbore instability - as evidenced at the Cusiana field, for example. However, not dissimilar geologic conditions are found in many hydrocarbon provinces around the world, and the concepts of bedding-plane slippage are expected to apply there also. The bedding need not be steeply dipping for this mode of instability to occur. Similar conditions for instability may also exist in conventional high-angle wells, especially if a change in azimuth is made to the well trajectory.

An analysis approach is described which can take into account the interaction between the well trajectory, in-situ stresses, and the relative strengths of the intact formation and bedding planes. Case-history examples have been presented which support the analytical results. One important observation is that bedding-plane slippage alone can impart a preferential drilling direction, without the need for significant in-situ stress rotation. Thus, bedding-plane slippage should be considered as a potential instability mechanism in any field with significant relief, or where complex deviated well profiles are planned.

Acknowledgment

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Parameter	
Depth	15,000 ft
Well deviation	12°
Well azimuth	260°
Pore pressure	6,300 psi
Overburden stress	16,200 psi
Maximum horizontal stress	20,400 psi
Maximum horizontal stress azimuth	150°
Minimum horizontal stress	11,250 psi
Mud weight	9,140 psi (11.7 ppg)
Unconfined compressive strength	10,150 psi
Angle of friction	31°
Bedding dip	60°
Bedding azimuth	135°
Bedding shear strength	300 psi
Bedding sliding friction	26.6 degrees

Table 1. Summary of Typical Input Parameters for Anisotropic Strength Wellbore Stability Model : Actual Data from Colombian Appraisal Well

Parameter	
Depth	5,500 ft
Pore pressure	2,570 psi (9 ppg)
Overburden stress	5,390 psi (18.9 ppg)
Maximum horizontal stress	6,600 psi (23.1 ppg)
Maximum horizontal stress azimuth	315°
Minimum horizontal stress	5060 psi (17.7 ppg)
Unconfined compressive strength	4,200 psi
Angle of friction	31°
Bedding dip	45°
Bedding azimuth	315°
Bedding shear strength	300 psi
Bedding sliding friction	26.6 degrees

Table 2. Summary of Input Parameters for Pedernales Wellbore Stability Analysis

Parameter	
Depth	10,000 ft
Pore pressure	4,415 psi (8.5 ppg)
Overburden stress	11,000 psi
Maximum horizontal stress	14,000 psi
Maximum horizontal stress azimuth	315°
Minimum horizontal stress	7,000 psi
Mud weight	6,230 psi (12.0 ppg)

Table 3. Summary of In-Situ Stress Data at 10,000 ft Depth, Cusiana Field (data from Last & McLean[10])

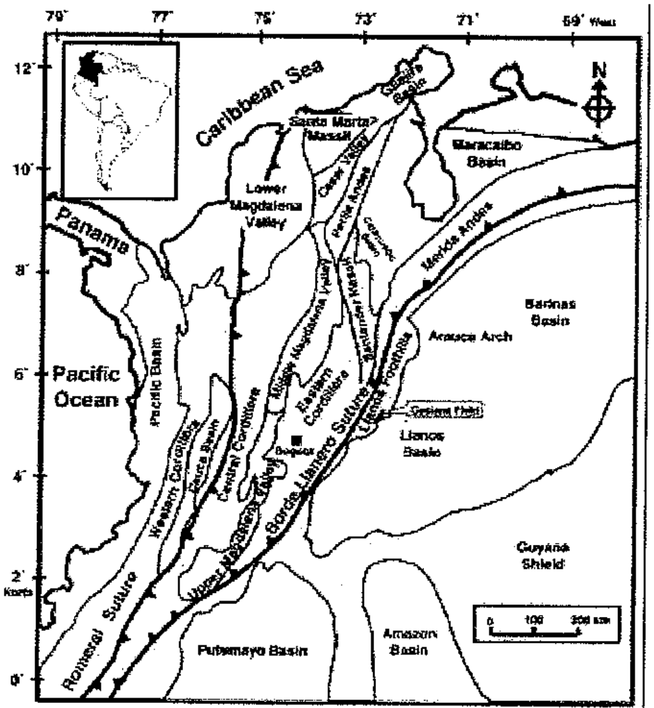

Figure 1. Main Structural Geologic Zones of Northern South America (from Cooper et al[4])

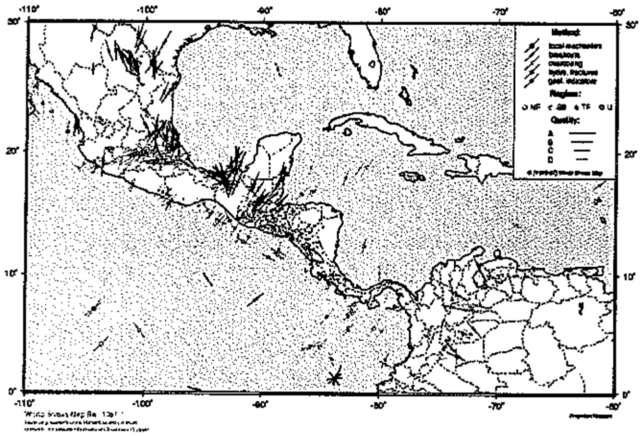

Figure 2. Regional Stresses in the Latin America / Caribbean Area

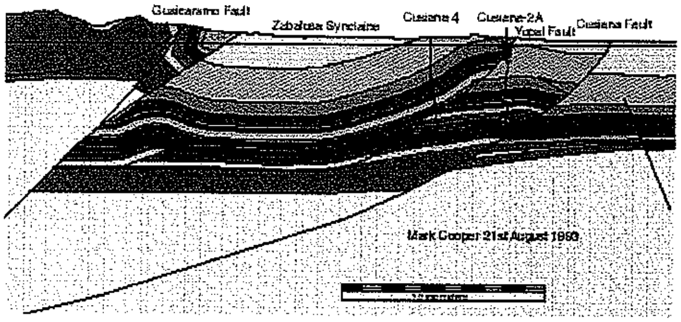

Figure 3. Cross-Section of Regional Geology in the Vicinity of the Cusiana Field, Colombia

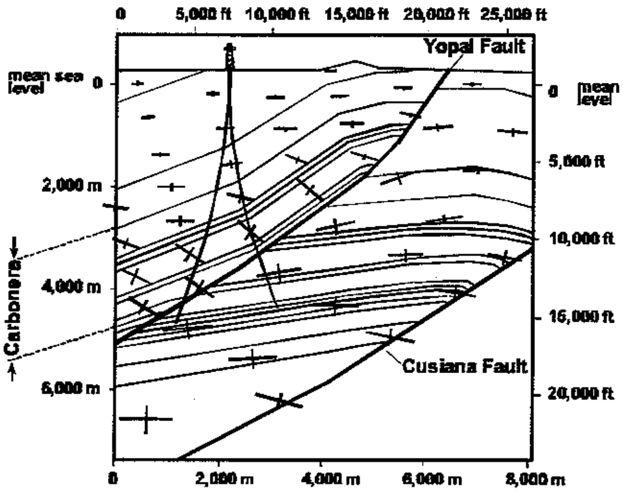

Figure 4. Simplified Cross-Section Through the Cusiana Field

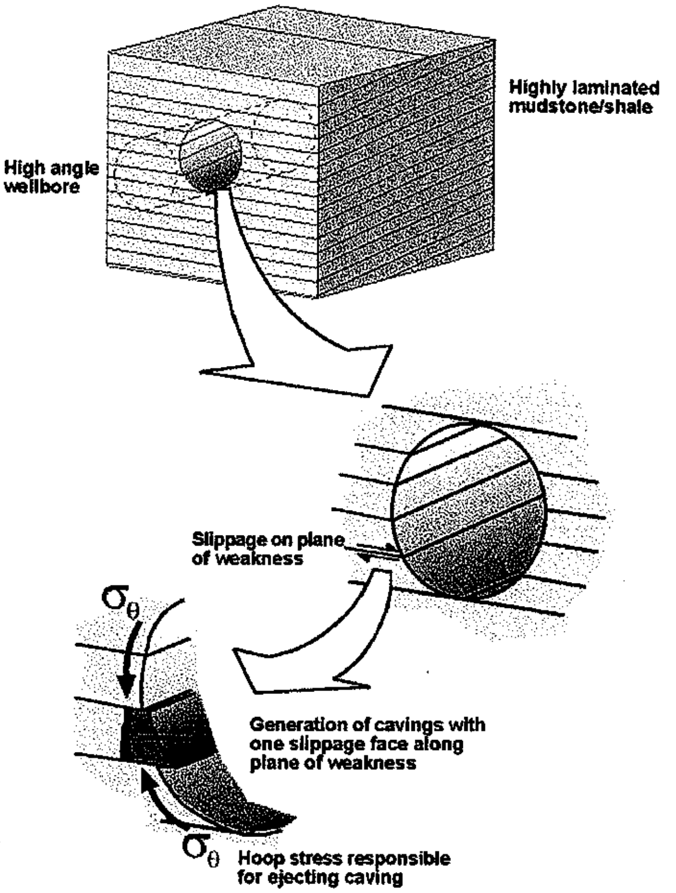

Figure 5. Schematic of Bedding-Plane Shear in High-Angle, Cross-Dip Wells

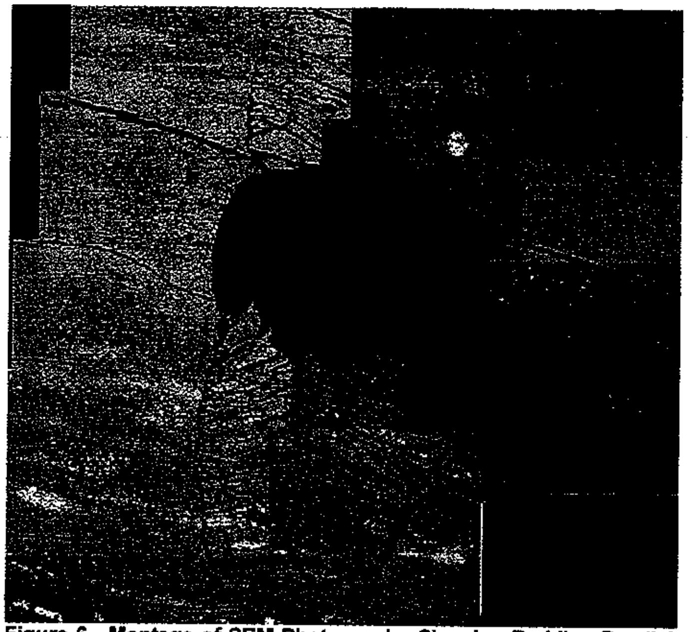

Figure 6. Montage of SEM Photographs Showing Bedding-Parallel Failure of a Wellbore Demonstrated in a Laboratory Experiment (data from Økland and Cook[13])

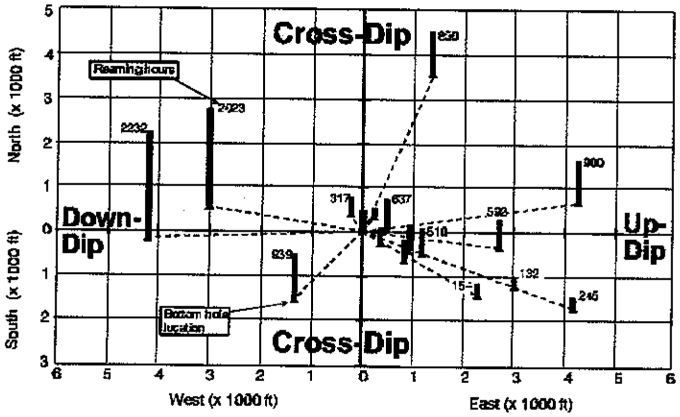

Figure 7. Field Well Reaming Hours Summary Indicating Preferential Up-Dip Drilling Direction (from Last and McLean[10])

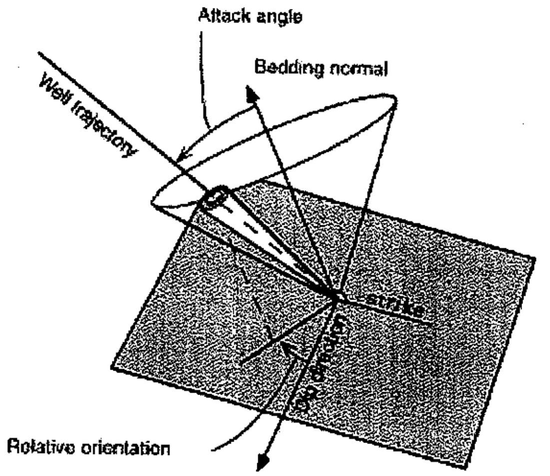

Figure 8. Schematic Illustrating Definition of Attack Angle and Relative Bearing

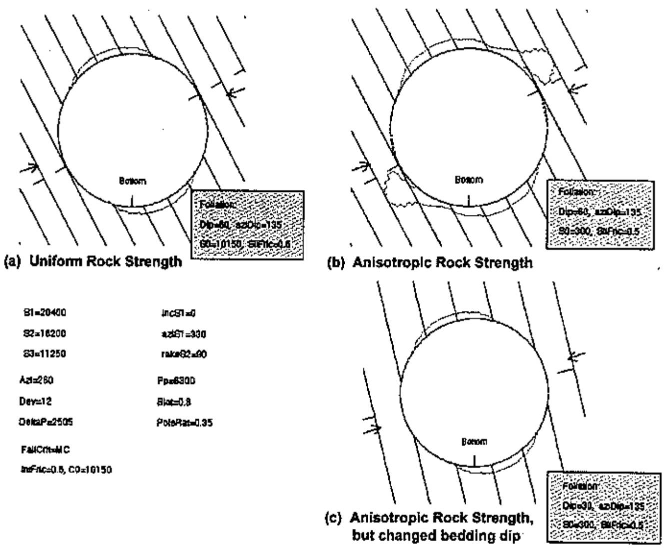

Figure 9. Computed Breakout Geometries Illustrating Influence of Bedding Plane Slippage and Relative Bearing on Stability

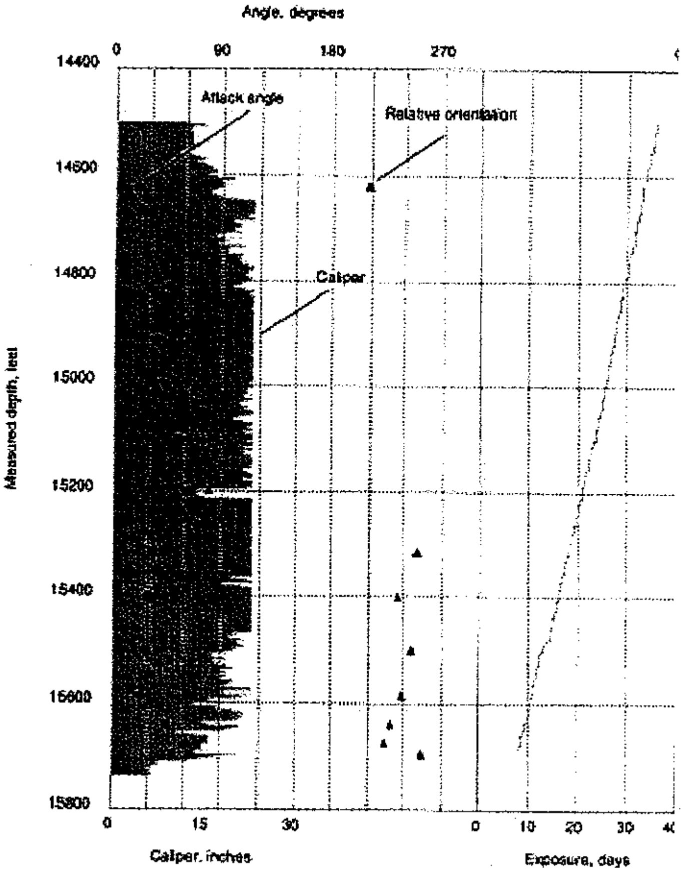

Figure 10. Calliper Hole Size, Attack Angles and Relative Bearings in Interval 14,400 ft to 15,800 ft in Colombian Appraisal Well

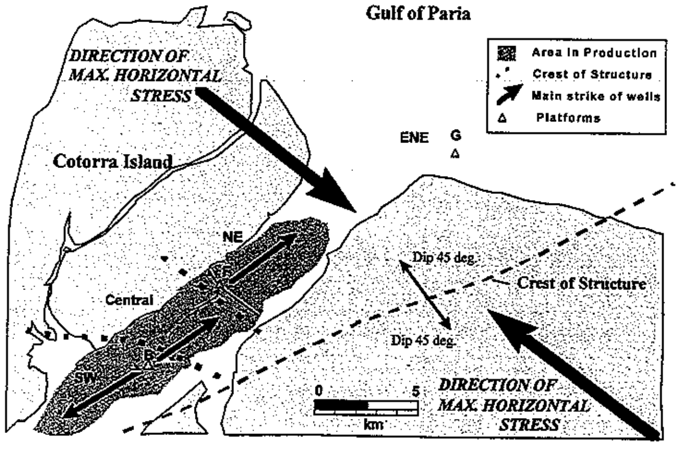

Figure 11. Pedernales Field Showing Main Strike of Wells

Pedernales
Prognosis Geologica
Columna Estratigrafica

<table>
<tr><th>Unidad Cronologica</th><th colspan="4">Litoestratigrafia</th></tr>
<tr><td>Pleistoceno Reciente</td><td>Paria</td><td colspan="3">Arenas y Lutitas no Consolidadas</td></tr>
<tr><td>Plioceno</td><td>Las Piedras</td><td colspan="3">Arenas con Lutitas</td></tr>
<tr><td rowspan="3">Superior</td><td rowspan="7">La Pica</td><td rowspan="3">Cotorra</td><td colspan="2">Lutitas con Arenas</td></tr>
<tr><td colspan="2">Arenas de La Cotorra</td></tr>
<tr><td colspan="2">Lutitas</td></tr>
<tr><td rowspan="2">Plioceno</td><td rowspan="4">Pedernales</td><td rowspan="2">P-2</td><td>Lutitas con Arenas</td></tr>
<tr><td>Arenas de Pedernales</td></tr>
<tr><td rowspan="2">Inferior</td><td rowspan="2">P-5</td><td>Lutitas</td></tr>
<tr><td></td></tr>
</table>

Nivel Del Mar

Figure 12. Geological Column of the Pedernales Field

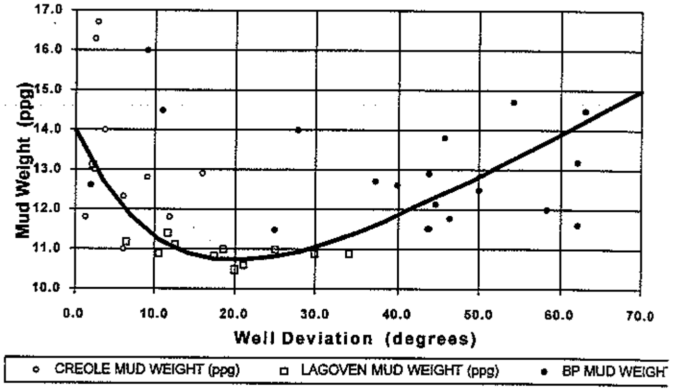

Figure 13. Empirically Derived Minimum Safe Mud Weight For South West Area Pedernales Wells

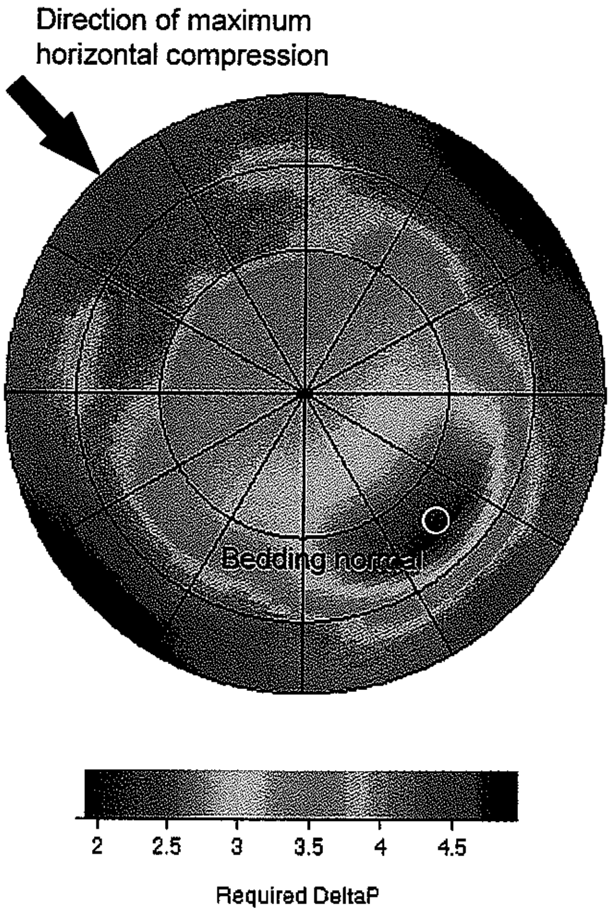

Figure 14. Required Mud Overbalance (in excess of a 9 ppg pore pressure) For Stable Well Trajectories at Pedernales

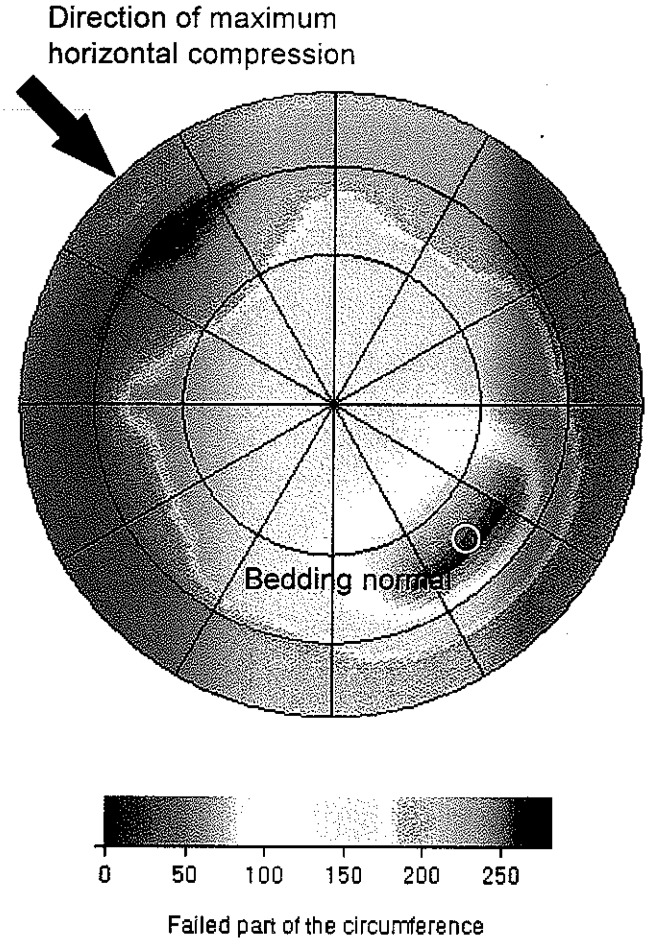

Figure 15. Computed Breakout Extent For Pedernales Well Trajectories Drilled With a 12 ppg Mud Weight

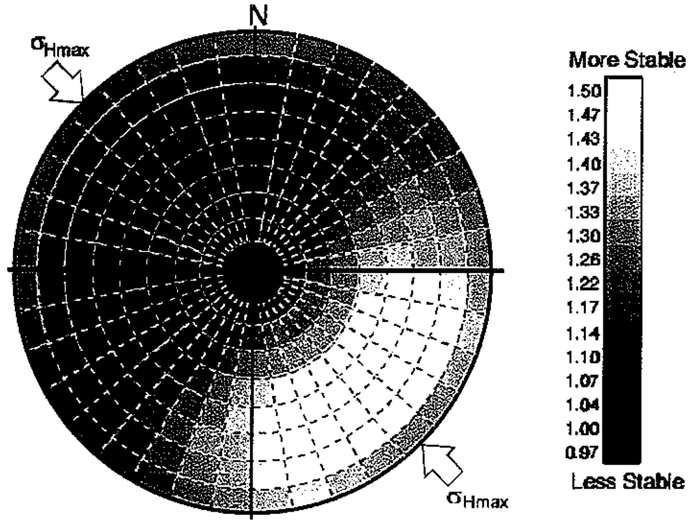

Figure 16. Dependence of Hole Stability on Well Trajectory - Cusiana Field - Principal In-Situ Stress Rotated 30° From Vertical and Horizontal Axes (reproduced from Last & McLean[10])

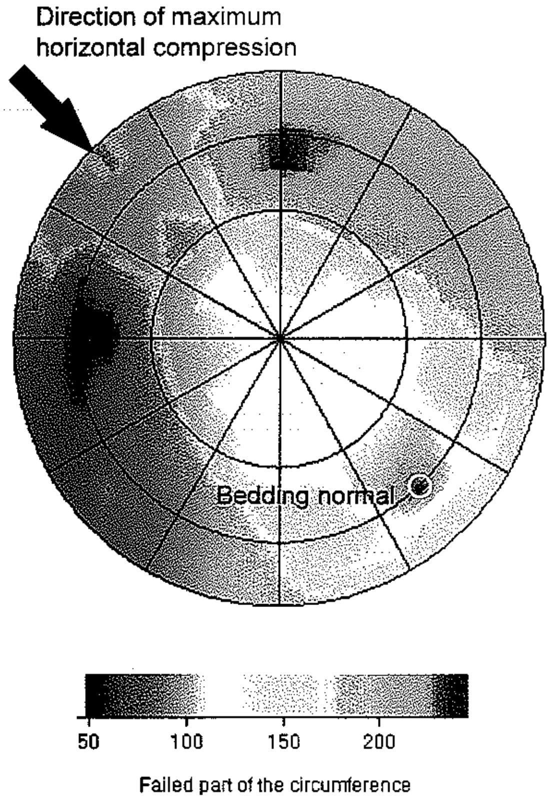

Figure 17. Borehole Failure for 10,000 ft Cusiana Example, Accounting For Bedding Plane Effects Only (No Stress Rotations)

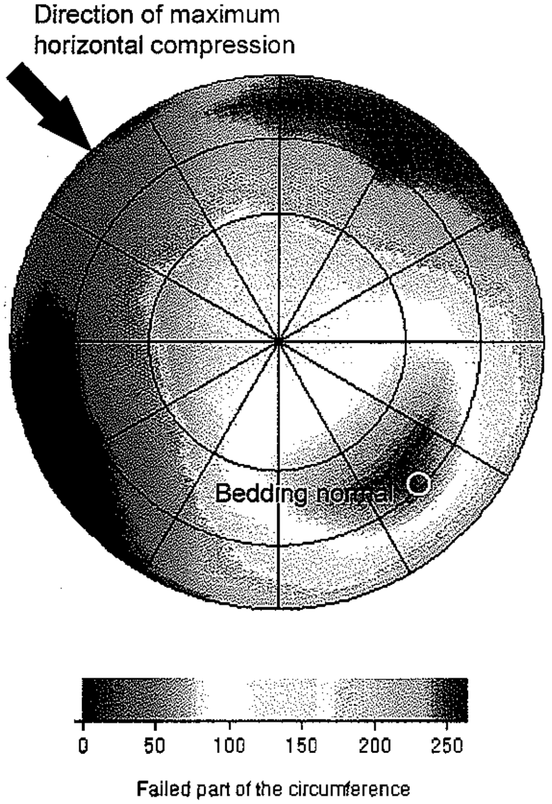

Figure 18. Borehole Failure for 10,000 ft Cusiana Example, Accounting For Bedding Plane Effects *and* Stress Rotations