# On the Mechanical Stability of Inclined Wellbores

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## Summary

Consideration of the stress field around an arbitrarily oriented borehole shows that in an extensional stress regime ($\sigma_v > \sigma_H > \sigma_h$), wellbores parallel to the direction of minimum horizontal principal stress are the least prone to compressive shear failure (breakout). The most stable deviation angle (from the vertical) depends on the ratio of the horizontal principal stresses to the vertical stresses, and the higher the ratio $\sigma_H/\sigma_v$, the higher the deviation angle for minimizing breakout. In a strike-slip stress regime ($\sigma_H > \sigma_v > \sigma_h$), horizontal wells are the least prone to breakout, and the higher the ratio $\sigma_H/\sigma_v$, the closer the drilling direction should be to the azimuth of $\sigma_H$.

A new compressive shear failure criterion, which is a combination of the effective strength concept and the Drucker-Prager criterion, is proposed for quantifying the stresses at which borehole breakout occurs. The lowest mud weight, at and below which breakout will occur, can be predicted by combining this criterion with the stress field around an arbitrarily oriented borehole. The highest mud weight at and above which a tensional or hydraulic fracture is induced can be predicted by combining the tensile strength of the rocks of the wellbore wall with the stress field around an arbitrarily oriented borehole. For the in-situ stress environments considered, the optimally oriented inclined wellbore is less prone to breakout (i.e., allows a lower mud weight) and tensional or hydraulic fracture (i.e., supports a higher mud weight) than a vertical well.


## Introduction

It has been widely recognized that highly deviated, extended-reach and horizontal wells can offer economic benefits through lower field development costs, faster production rates, and higher recovery factors.[1,2] However, inclined and horizontal wells may be prone to mechanical instability problems associated with the in-situ stress field. Hence, an understanding and analytical design capability to manage wellbore stability in high in-situ stress fields should help realize the full benefits offered by current and emerging inclined well drilling technology.

Much progress has recently been made toward the determination of the magnitude and orientation of in-situ stress in the crust, in particular, by borehole breakout analyses and hydraulic fracturing techniques including modified leak-off tests.[3-8] With knowledge of the in-situ stress field, the most stable inclined well trajectory can be designed. In this paper, the concept of minimum stress anisotropy around the inclined wellbore wall is introduced. The condition of minimum stress anisotropy can be used to determine an optimum drilling direction and deviation angle. In this study, an elastic analytical approach is adopted for modeling the stress field of deviated wells in various stress regimes. By combining the effective strength concept[9] with the widely used Drucker-Prager failure criterion,[10] a new failure criterion for rocks is presented and tested with available rock strength data. Appropriate mud weights for mechanically stable wells can be determined based on this criterion.

### Stress Field Around an Arbitrarily Oriented Borehole

The three principal stresses are usually oriented vertically and horizontally because the Earth's surface is a free surface.[11] Although this may not be the case near the surface, particularly in areas of extreme topography, it has since been confirmed by numerous in-situ stress measurements,[12-14] and is further supported by the vast majority of intraplate crustal earthquake focal mechanisms.[15] In this paper, we assume that the principal stresses in the upper few kilometers of the Earth's crust generally act in the vertical and two orthogonal horizontal directions.

Based on this assumption, and the assumption that rock is isotropic and behaves like a linear elastic material up to the point of failure, an analytical solution of the stress field around an arbitrarily oriented borehole can be obtained.[16-20] The following summarizes the stress solution and coordinate system used in this paper.

For an arbitrarily oriented borehole, the rotation of the stress tensor from the global in-situ coordinate system to a local borehole coordinate system (**Fig. 1**) is given by[21]

$$\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{Bmatrix} = \begin{Bmatrix} \sin^2\beta & \cos^2\beta\cos^2\alpha & \cos^2\beta\sin^2\alpha \\ 0 & \sin^2\alpha & \cos^2\alpha \\ \cos^2\beta & \sin^2\beta\cos^2\alpha & \sin^2\beta\sin^2\alpha \\ 0 & -\sin\alpha\cos\alpha\sin\beta & \sin\alpha\cos\alpha\sin\beta \\ -\sin\beta\cos\beta & \sin\beta\cos\beta\cos^2\alpha & \sin\beta\cos\beta\sin^2\alpha \\ 0 & -\sin\alpha\cos\alpha\cos\beta & \sin\alpha\cos\alpha\cos\beta \end{Bmatrix}$$

$$\begin{Bmatrix}\sigma_v\\ \sigma_H\\ \sigma_h\end{Bmatrix}. \quad \text{(1)}$$

Following these equations, the stress field at the wall of the borehole is given by

$$\sigma_r = \Delta p, \quad \text{(2)}$$

$$\sigma_\theta = \sigma_x + \sigma_y - 2(\sigma_x - \sigma_y)\cos 2\theta - 4\tau_{xy}\sin 2\theta - \Delta p, \quad \text{(3)}$$

$$\sigma_{z'} = \sigma_z - 2\nu(\sigma_x - \sigma_y)\cos 2\theta - 4\tau_{xy}\sin 2\theta, \quad \text{(4)}$$

$$\tau_{\theta z'} = 2(-\tau_{xz}\sin\theta + \tau_{yz}\cos\theta), \quad \text{(5)}$$

$$\tau_{r\theta} = 0, \quad \text{(6)}$$

and $\tau_{rz'} = 0. \quad \text{(7)}$

Based on the above equations, the effective principal stresses on the borehole wall (which are orthogonal to each other) in the local borehole coordinate system can be expressed by

$$\sigma_1 = \frac{1}{2}(\sigma_\theta + \sigma_{z'}) + \frac{1}{2}\sqrt{(\sigma_\theta - \sigma_{z'})^2 + 4\tau_{\theta z'}^2}, \quad \text{(8)}$$

$$\sigma_2 = \frac{1}{2}(\sigma_\theta + \sigma_{z'}) - \frac{1}{2}\sqrt{(\sigma_\theta - \sigma_{z'})^2 + 4\tau_{\theta z'}^2}, \quad \text{(9)}$$

and $\sigma_3 = \sigma_r. \quad \text{(10)}$

The above solutions assume that the effective fluid pressure in the borehole is the effective minimum principal stress. However, if this pressure is sufficiently high (such as in the generation of hydraulic fractures), it may become the intermediate principal stress.

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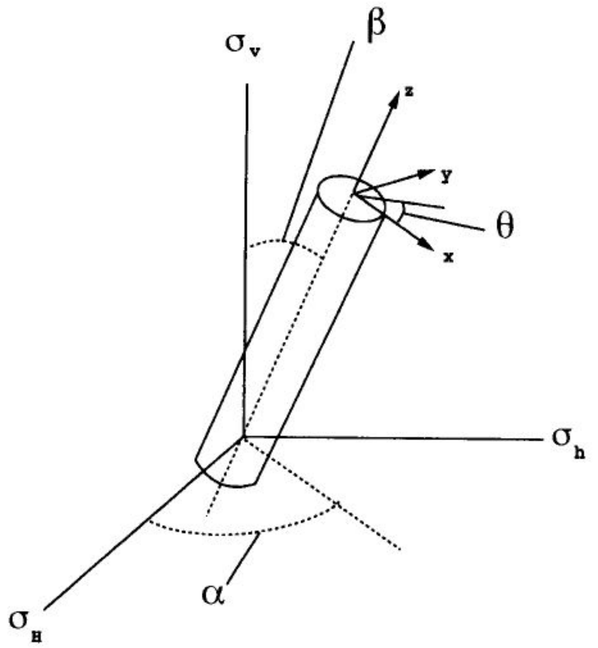


**Fig. 1—Borehole orientation and coordinate system used in this study.**

### Stable Drilling Direction and Deviation Angle

To define an optimum drilling direction and deviation angle, a useful parameter ($R_s$), called shear stress anisotropy around the wellbore wall, is defined by

$$R_s = \frac{\tau_{oct}(\max) - \tau_{oct}(\min)}{\tau_{oct}(\min)}, \quad \ldots\ldots (11)$$

where $\tau_{oct}$ is the octahedral shear stress,[21] and $\tau_{oct}(\max)$ and $\tau_{oct}(\min)$ are the maximum and minimum values of the octahedral shear stress around the wellbore wall, respectively. A number of measurements could be used to define the stress anisotropy around the wellbore, e.g., mean principal stress, maximum principal stress, or octahedral shear stress. Intuitively, a measurement of the stress anisotropy should incorporate all stress factors that control wellbore stability. The octachedral shear stress is used here because it is a critical controlling factor on the stress level at failure.[22-25]

The shear stress anisotropy, $R_s$ as defined in Eq. 11, is a function of the effective principal stress ratios $n_h(=\sigma_h/\sigma_v)$ and $n_H(=\sigma_H/\sigma_v)$, the Poisson's ratio, $\nu$, of the material, and effective well pressure, $\Delta p$. So for a given $\nu$ and $\Delta p$, $R_s$ can be uniquely determined by deviation angle from the vertical, $\beta$, and the drilling direction, $\alpha$, in a specified $n_h$ and $n_H$. The effective principal stress ratios, $n_h$ and $n_H$, uniquely define the tectonic stress regime, according to Anderson faulting mechanism.[11] For instance, $n_h < n_H < 1$ indicates extensional stress regime, while $n_h < 1 < n_H$ indicates strike-slip stress regime, and $1 < n_h < n_H$ indicates compressional stress regime. Therefore, a critical stable condition can be determined if the tectonic stress regime is known (i.e., the orientation and magnitudes of $\sigma_H$ and $\sigma_h$).

The stable configurations, as given by an optimum set of the deviation angle, $\beta$, from the vertical and the drilling direction, $\alpha$, with respect to the azimuth of the maximum horizontal principal stress, of deviated wells in various tectonic stress environments are defined to be those in which the stress anisotropy as defined in Eq. 11 is minimized. In what follows, only extensional and strike-slip stress regimes are considered because compressive stress regimes exist in very few sedimentary basins.[4-8]

The calculated stable conditions for an extensional stress regime show that the stable drilling direction is always parallel to the azimuth of the minimum horizontal principal stress $\sigma_h$, and that the optimum deviation angles (**Fig. 2**) depend on the ratio of the horizontal principal stresses to the vertical stresses. In general, the deviation angle is controlled by both $n_H$ and $n_h$. The higher the stress ratio $n_H$, the higher the deviation angle required for maximizing stability. At a given $n_h$, the deviation angle increases with $n_H$. In addition, for some cases where both horizontal principal stresses are equal in magnitude, vertical wells ($\beta = 0°$) would be most stable in terms of stress anisotropy around the borehole. When $n_H = 1$, the well should be drilled horizontally (i.e., $\beta = 90°$) for maximizing stability. The stress anisotropy, associated with the most stable condition, is generally less than 15% (without excess fluid pressure in the wellbore), and for $n_h > 0.2$, the stress anisotropy is always less than 5%.

The calculated stable conditions for a strike-slip stress regime suggest that the deviation angles should always be 90° (horizontal wells), and that the drilling directions (**Fig. 3**) with respect to the azimuth of $\sigma_H$ are controlled by the stress ratios ($n_h$ and $n_H$). The higher the ratio $n_H$, the closer the drilling direction should be to the $\sigma_H$ azimuth. When $n_h = 1$, the well should be drilled along the azimuth of

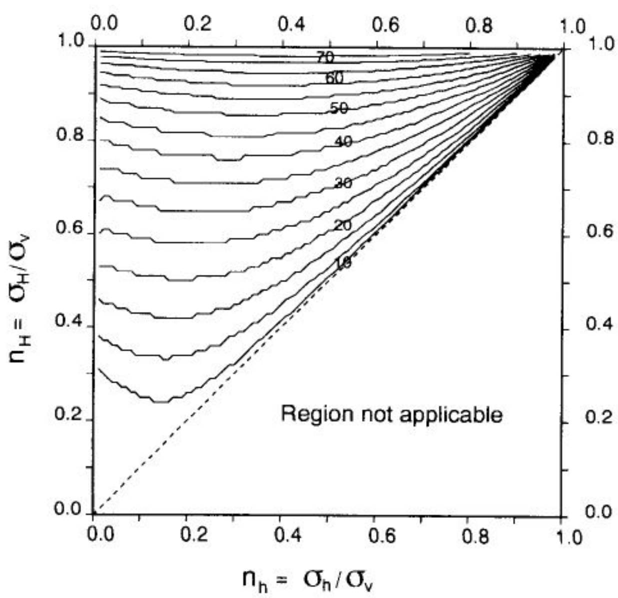


**Fig. 2—Deviation angle from the vertical at which the stress anisotropy around the well wall is minimized in extensional stress regimes with $\Delta p=0$ and $\nu=0.25$. The drilling direction ($\alpha$) is equal to 90° in all cases.**

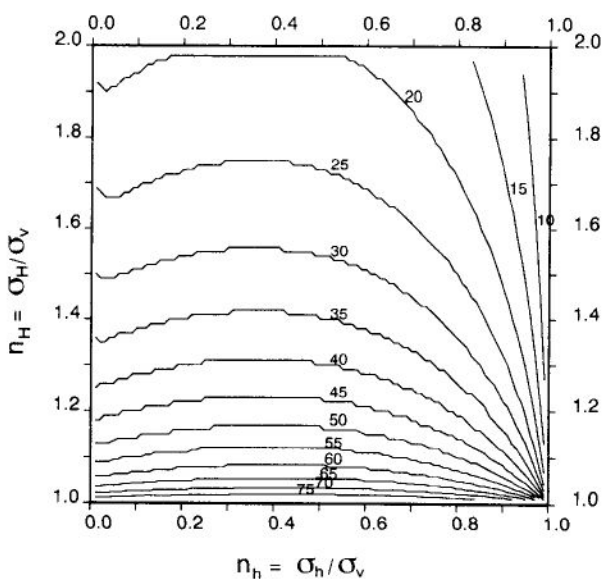


**Fig. 3—Drilling direction with respect to $\sigma_H$ at which the stress anisotropy around the well wall is minimized in strike-slip stress regimes with $\Delta p=0$ and $\nu=0.25$. The deviation angle ($\beta$) is equal to 90° in all cases.**

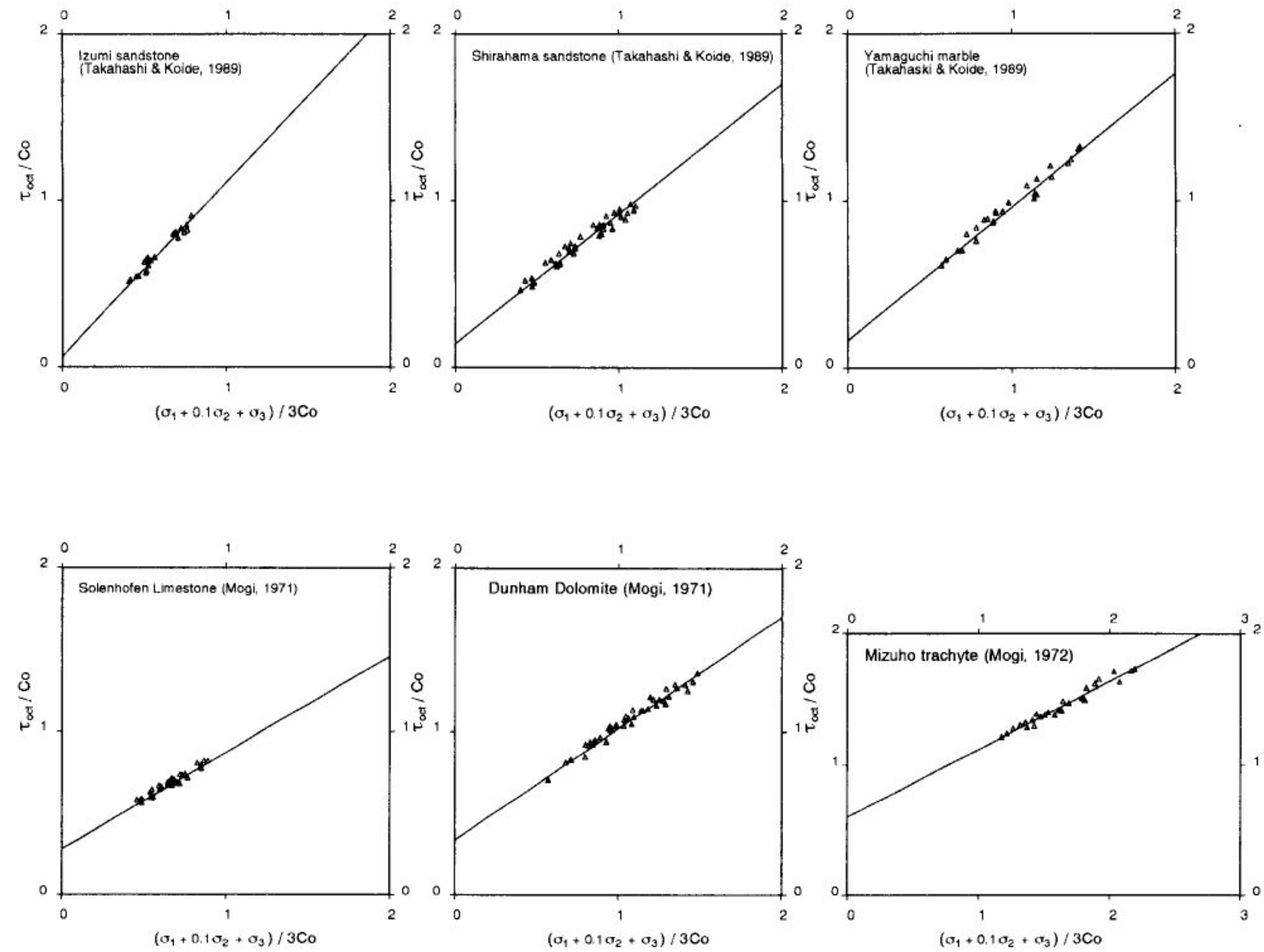


**Fig. 4—Rock strength data, derived from the published experimental results under the polyaxial states of compression.[25,35,37]**

$\sigma_H$ (i.e., $\alpha = 0°$). In general, the calculated minimum stress anisotropy is less than 20% (without excess fluid pressure in the wellbore), and for $n_h > 0.4$, the stress anisotropy is always less than 5%.

Poisson's ratio $\upsilon$ has been taken to be 0.25 in the above calculations; a change of the Poisson's ratio by $\pm 0.1$ has a minimal effect on the stress field of deviated wells. Hence, the value of Poisson's ratio selected is not critical for this study.

## Failure Criteria of Rocks

The drilling direction, $\alpha$, and deviation angle, $\beta$, that minimize the shear stress anisotropy of inclined wellbore in the extensional and strike-slip stress regimes were discussed in the previous section. However, to make quantitative predictions of the borehole fluid pressure (mud weight) required to prevent compressive shear failure of the wellbore wall (breakout) and tensional or hydraulic fracture in the optimum (or any other) drilling trajectory, one needs to further consider the mechanisms of breakout and hydraulic fracture and develop an appropriate failure criteria. Borehole breakouts are spalled regions centered on the azimuth of the least horizontal principal stress for vertical wells and are generally formed by compressive shear failure.[26-29] Comparison between field observations from borehole breakouts and theoretical predictions has shown that the Mohr-Coulumb criterion tends to underestimate the stability (i.e., the rock strength),[30] while recent laboratory tests on hollow cylinders have demonstrated that the circumscribed Drucker-Prager criterion (another version of the extended von Mises criterion) tends to underestimate the rock strength at small stresses and overestimate the rock strength at large stresses.[31] Wiebols and Cook[9] proposed an effective strain energy criterion for rock failure. They assumed that a rock contained a large number of randomly distributed pre-existing cracks, and rock failure under any system of compressive stresses occurred at a critical value of the effective shear strain energy. The adoption of their criterion has led to much more successful predictions of rock strength.[22-24] Use of Wiebols and Cook's criterion in the study of borehole breakouts has recently been successfully made.[6] However, the mathematical formula used to calculate failure stresses in a polyaxial state of compression in the effective strain energy criterion are complex. Given the fact that there is no universal law governing the level of stress at rock failure, it is often desirable to develop simple and workable models, based on both empirical studies and theoretical analyses of the physical mechanisms of fracture initiation and propagation, to predict rock strength. We propose a new criterion for compressive rock failure, which is a combination of the effective strength concept[9] with the widely used Drucker-Prager failure criterion.[10] This criterion can be also regarded as a simplified form of a general yield function proposed by Desai,[32] who postulated that rock failure could be governed by a yield function expressed as a polynomial of the three stress invariants, $J_1$, $J_2$, and $J_3$. A truncated form of Desai's yield function is adopted here, that is, the yield function is simply given by $f(J_1, J_2) = 0$, on the basis that only $J_1$ and $J_2$, have obvious physical significance, being directly related to the dilatational and distortional elastic strain energy, respectively.[21] Our new yield function is expressed by

$$J_2^{1/2} = A + BJ_1 + CJ_1^2, \quad \ldots\ldots\ldots\ldots \quad (12)$$

where $J_2^{1/2}(=\tau_{oct}) = \frac{1}{3}\sqrt{(\sigma_1-\sigma_3)^2 + (\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2}$

and $J_1 = (\sigma_1 + \sigma_2 + \sigma_3)/3$. Here the constants A, B, and C are determined such that Eq. 12 is constrained by rock strengths under both triaxial and biaxial compression. In the triaxial state of stress (i.e., $\sigma_2 = \sigma_3$ ), the rock strength is given by $\sigma_1 = C_0 + q\,\sigma_3$, where $C_0$ is

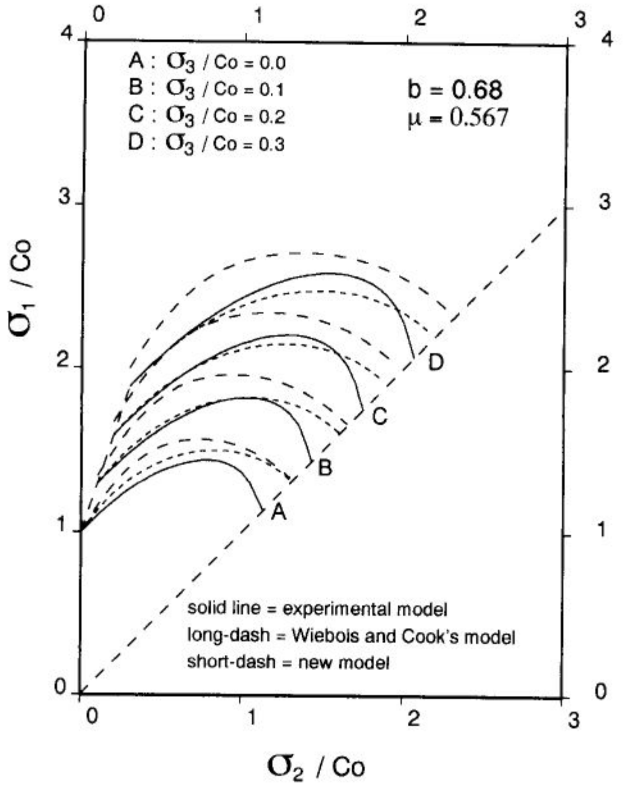


**Fig. 5—Comparison of failure models with coefficient of internal friction $\mu = 0.567$ and stress slope $b = 0.68$: the experimental derived criterion,[35] the effective strain energy criterion,[9] and the criterion proposed in this paper.**

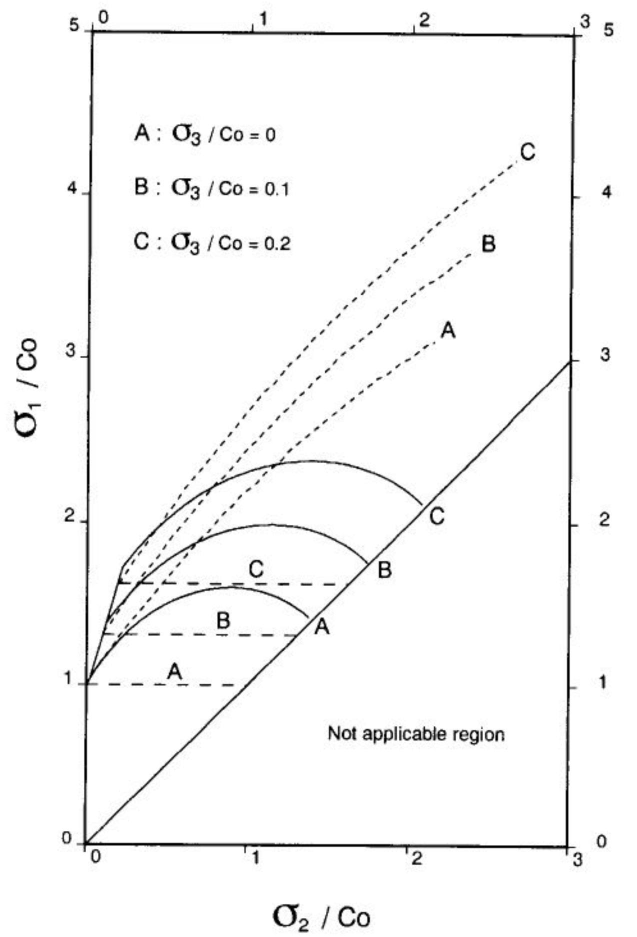


**Fig. 6—Comparison of failure models with coefficient of internal friction $\mu = 0.6$: Mohr-Coulomb criterion (long dash line), the extended von Mises criterion (short dash line), and the criterion proposed in this paper (solid line).**

the uniaxial compressive strength, and $q = \left(\sqrt{1 + \mu^2} + \mu\right)^2$. In the biaxial state of stress (i.e., $\sigma_1 = \sigma_2$), the rock strength is given by $\sigma_1 = C_1 + q\sigma_3$, where $C_1$ is the biaxial plane strength.[9] By substituting the above conditions plus the uniaxial rock strength ($\sigma_1 = C_0$, $\sigma_2 = \sigma_3 = 0$) into Eq. 12, it can be found that

$$C = \frac{\sqrt{18}}{2c_1 - c_0 + (q-1)\sigma_3}\left[\frac{c_1 - c_0 + (q-1)\sigma_3}{2c_1 - c_0 + (2q+1)\sigma_3} - \frac{q-1}{2+q}\right]$$

$$B = \frac{\sqrt{2}(q-1)}{2+q} - \frac{1}{3}[2c_0 + (2+q)\sigma_3]C$$

$$A = \frac{\sqrt{2}}{3}c_0 - \frac{c_0}{3}B - \frac{c_0^2}{9}C.$$

Currently available rock strength data are gathered and replotted in terms of octahedral stress and a modified mean confining stress to test the proposed failure criterion. The results shown in **Fig. 4** clearly indicate that octahedral stress at failure is a linear function of the modified mean confining stress.[33-37] **Fig. 5** shows the new model prediction, in comparison with the experimentally based model (Mogi empirical criterion) and Wiebols and Cook's criterion. It can be seen that the new criterion provides a better prediction than that of Wiebols and Cook's criterion. The new model result deviates very little from the experimental result except at near biaxial state of compression.

**Fig. 6** shows a comparison of the Mohr-Coulomb criterion, the extended von Mises criterion, and the proposed criterion. In a polyaxial state of stress, the prediction made by the new criterion is greater than that given by the Mohr-Coulomb criterion and generally less than that given by the extended von Mises criterion. Our proposed failure criterion has a number of advantages: (1) it takes into account most stress loading conditions associated with various breakout types,[38-40] (2) it is a much simpler analytical expression than the original equations of Wiebols and Cook[9] for predicting rock strength in the polyaxial state of stress $\sigma_1 > \sigma_2 > \sigma_3$, and (3) available laboratory rock strength tests are more consistent with the new model predictions (Fig. 5). Therefore, for the quantitative forward modeling of borehole mechanical stability in the following section we use the criterion given by Eq. 12 to predict compressive rock failure and breakout generation around wellbores.

## Mud Weights for Mechanically Stable Deviated Wells

A measure of the borehole stability can be made by defining an effective failure stress[10] as

$$J_{2eff}^{1/2} = J_{2\text{rockfailure}}^{1/2} - J_{2\text{borehole}}^{1/2}, \qquad (13)$$

where $J_{2\text{rockfailure}}^{1/2}$ is the rock shear strength evaluated using Eq. 12, and $J_{2\text{borehole}}^{1/2}$ is the octahedral shear stress at the point on the borehole wall under consideration, calculated by using Eqs. 1 through 10. A positive value of the effective failure stress indicates a stable condition, and a negative value indicates an unstable or failed condition. Based on the concept of the effective failure stress as defined in Eq. 13, the lower limit for borehole fluid pressure (mud weight), i.e., the minimum borehole fluid pressure required to avoid compressive shear failure, can be calculated for a given well trajectory.

Borehole fluid pressure must not be so high as to cause hydraulic fracturing and associated fluid loss caused by high mud weight. The upper limit for borehole fluid pressure can be calculated based on the assumption that hydraulic fracturing occurs when the minimum effective principal stress becomes tensile and equal to rock tensile

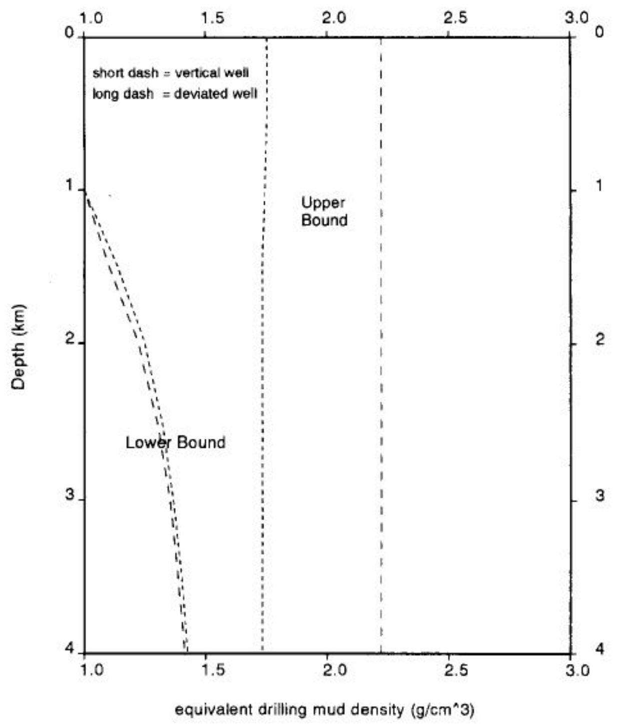


**Fig. 7—Mud weight stability profile for vertical and optimally deviated wells for stress ratios $n_H = 0.9$ and $n_h = 0.5$ and effective vertical stress gradient = 12 MPa/km. The rock strength parameters are $C_0 = 20$ MPa (uniaxial compressive rock strength), $\mu = 0.6$ (coefficient of internal friction), and $T = 0$ (tensile strength). The deviated well trajectory ($\alpha = 90°$ and $\beta = 55°$) is that given by the optimum set of drilling direction and deviation angle as shown in Fig. 2 for the given stress ratios $n_H$ and $n_h$. Pore pressure is assumed to be hydrostatic. It should be mentioned that there is no compressive shear failure at shallow depth less than 1 km for the given stress field and rock strength parameters. The recommended upper mud weight for the deviated well is given by the overburden pressure (i.e., bulk rock density of 2.22 g/cm$^3$ derived from the given effective vertical stress and pore pressure), hence, in this case horizontal fracture would be readily induced by excessive mud weight (see text for further discussion).**

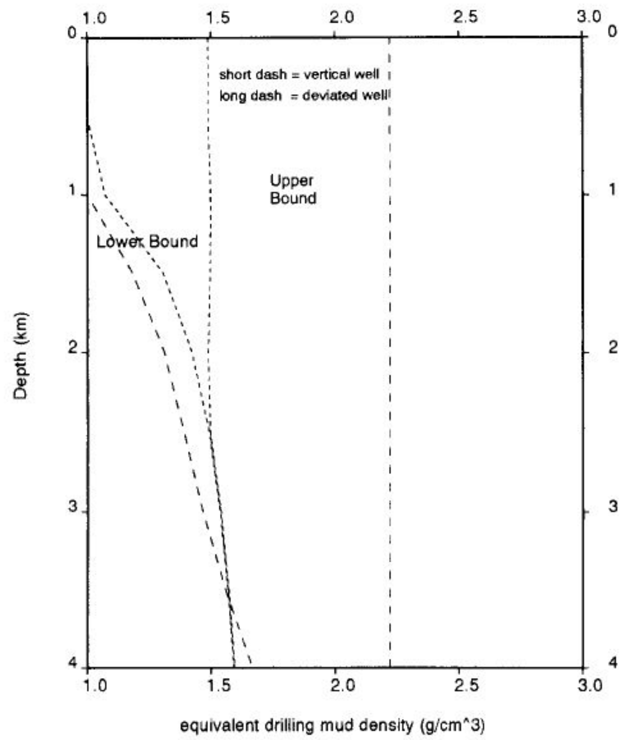


**Fig. 8—Mud weight stability profile for vertical and optimally deviated wells for stress ratios $n_H = 1.1$ and $n_h = 0.5$. The deviated well trajectory ($\alpha = 55°$ and $\beta = 90°$) is that given by the optimum drilling direction and deviation angle as shown in Fig. 3 for the given stress ratios $n_H$ and $n_h$. The diagram is otherwise the same as in Fig. 7.**

strength.[11] Such rock tensile strength can be derived from the unconfined compressive strength (i.e., $T = C_0/12$, based on the extended Griffith criterion) or directly measured by extended leakoff test. However, for previously fractured rocks, $T = 0$, and this value is used in our calculations to provide an upper limit for mud weight. In addition, to avoid horizontal hydraulically induced fractures, the mud weight should not be higher than the overburden pressure.[21,41] Hence, the upper mud weight limit is taken as the lower of the values of bulk rock density or that calculated from the tangential stress described above.

As examples, the lower and upper mud weight limits for wells drilled in the optimum trajectories with respect to mechanical stability in two tectonic stress regimes have been calculated (**Figs. 7 and 8**). In a tectonic stress regime of relatively large anisotropy, wellbore mechanical stability can be improved by inclined wells drilled with optimum drilling direction and deviation angle. High in-situ stresses may create a less stable environment for vertical wells. The mud weight stability field associated with the optimum drilling direction and deviation angle, much wider than that for vertical wells, shows the importance of drilling trajectory to the mechanical stability of the wellbore.

## Conclusions

In this paper, we have presented a straightforward methodology to deal with the mechanical stability of inclined wells. It has been shown that mechanical stability can be improved by adopting optimum deviation angle and drilling direction. Based on a new compressive rock failure criterion presented here, our predictions on mud weight stability profiles show that, contrary to intuitive expectation, regions of high tectonic stress anisotropy may produce a more stable environment for inclined wells than vertical wells. Obviously, mechanical stability will not generally be the primary factor in selecting well trajectory. For example, deviated wells may be targeted to access reservoirs remote from surface facilities or oriented such as to maximize intersection with open natural fractures. The methodology presented here allows mechanically safe mud weight limits to be determined for a well in any trajectory. It should be noted that it has been shown elsewhere[42] that the well trajectory that maximizes intersection with open, natural, or hydraulically induced fracture is consistent with the optimum drilling direction and deviation angle in both the extensional and the strike-slip stress regimes where $0.9 < n_H < 1.1$.

The conclusion herein applies only to isotropic rocks with linear elasticity up to the point of failure. In the real earth, the rock properties are often complex because of various geological processes.[43] For material with a Young's modulus depending on the effective mean stress, the stress field around a well has been shown to be lower than the prediction based on linear elasticity.[44-45] From the stability point of view, this would tend to increase the stability of the deviated wells because of the reduction of stress concentration around a wellbore. Temperature fluctuations associated with mud circulation during drilling will not influence the stress anisotropy around the wellbore because the temperature effect should alter the tangential and vertical stresses by an equal amount. However, rock properties may be altered as a result of temperature changes, which may increase or reduce the possibility of mechanical failure, depending on the actual effect on the rock properties.[43]

## Nomenclature

$C_0$ = uniaxial rock compressive strength, m/Lt$^2$, MPa

$C_1 =$ biaxial plane strength, m/Lt$^2$, MPa
$J_1 =$ mean effective confining stress, m/Lt$^2$, MPa
$n_h =$ ratio of the effective minor horizontal principal stress to the effective vertical stress
$n_H =$ ratio of the effective major horizontal principal stress to the effective vertical stress
$\Delta p =$ excess fluid pressure in the borehole (i.e., mud pressure less pore pressure in the formation), m/Lt$^2$, MPa
$R_s =$ shear stress anisotropy around the wellbore wall
$T =$ rock tensile strength, m/Lt$^2$, MPa
$\alpha =$ the angle between $\sigma_H$ and the projection of the borehole axis onto the horizontal plane
$\beta =$ the angle between the borehole axis and the vertical direction
$\theta =$ polar angle in the borehole cylindrical coordinate system
$\mu =$ coefficient of internal friction
$\nu =$ Poisson's ratio
$\sigma_H =$ effective major horizontal principal stress, m/Lt$^2$, MPa
$\sigma_h =$ effective minor horizontal principal stress, m/Lt$^2$, MPa
$\sigma_r, \sigma_\theta, \sigma_{z'}, \sigma_{\theta z'}, \sigma_{r\theta}, \sigma_{rz'} =$ stress tensor in the borehole cylindrical coordinate system, m/Lt$^2$, MPa
$\sigma_v =$ effective vertical stress, m/Lt$^2$, MPa
$\sigma_x, \sigma_y, \sigma_z, \sigma_{xy}, \sigma_{xz}, \sigma_{yz} =$ stress tensor in the borehole Cartesian coordinate system, m/Lt$^2$, MPa
$\sigma_1 =$ effective maximum principal stress in the borehole cylindrical coordinate system, m/Lt$^2$, MPa
$\sigma_2 =$ effective intermediate principal stress in the borehole cylindrical coordinate system, m/Lt$^2$, MPa
$\sigma_3 =$ effective minimum principal stress in the borehole cylindrical coordinate system, m/Lt$^2$, MPa
$\tau_{oct} (= J_2^{1/2}) =$ octahedral shear stress, m/Lt$^2$, MPa

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## SI Metric Conversion Factors

| | | |
|---|---|---|
| in. | $\times$ 2.54* | E+00 = cm |
| in.$^3$ | $\times$ 1.638 706 | E+01 = cm$^3$ |
| mile | $\times$ 1.609 344* | E+00 = km |
| psi | $\times$ 6.894 757 | E+00 = kPa |

*Conversion factor is exact.

**SPEDC**

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