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Some Updates For Fracture, Lost Circulation, Leak-Off, And Pore Pressure Technology

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Abstract

This paper reviews the basic foundations for several commonly used approaches for quantifying operational limits associated with fracture, lost circulation, leak-off, and pore pressure gradients during drilling and related activities. Several rock mechanics tests are used to illustrate three-dimensional behavior of down hole formations, under three-dimensional subsurface pressures/stresses for formulating improved, more realistic models for fracture/failure/leak-off/pore pressure quantifications and associated technologies.

Several important and practical consequences result from assuming that subsurface formations are isotropic, homogeneous, and linearly elastic and that in-situ stresses are two-dimensional and independent of time. While a less assuming approach is certainly more complicated, such effort should lead to improved understanding of the directional, non-linear, and local, event-coupled processes and behavioral features that work collectively during rock/fluid/stress system interactions, even routine drilling and wellbore operations. Operating limits for fracture, lost circulation, leak-off, and pore pressure gradients are directly and inescapably related to depth and borehole trajectory. Costs for running too many or worse, too few, casing strings can be very high. Better quantification of these problems is urgent.

Introduction

In quantifying operational limits and preventive methods associated with fracture, lost circulation, leak-off, and pore pressure gradients during drilling, it is often assumed (implicitly or otherwise) that the rock is isotropic, homogeneous, and linearly elastic and that insitu stresses are two dimensional and independent of time. But frequently, operational problems are inadequately served thereby. A less assuming, but certainly a more complicated approach will lead to improved understanding of the directional, non-linear, and local, event-coupled processes and behavioral features that work collectively during rock/fluid/stress system interactions, even routine drilling and wellbore operations.

Casing Strings/Well Plan Graph

Casing strings as illustrated in Fig. 1 are designed for operationally limiting gradients, on the high side for overburden, fracture, borehole stability, etc. and on the low side for pore pressure control and/or wellbore integrity, for example. Fig. 2 shows a typical well plan graph for Deep Water, Gulf of Mexico (Eaton[1]). Overburden gradient is initially quite low and increases in a highly non-linear fashion with depth. Fracture gradient follows a similar trend, with separation from the overburden gradient diminishing with depth. Pore pressure increases with depth, details of which depend upon conditions in each formation penetrated. Separation of the upper limit (overburden or fracture) and lower limiting pore pressure is used to determine the number and depth of casing strings to be run. Closure between the two curves with depth emphasizes the need to quantify both curves as accurately as practical.

Fig. 2 may be viewed as a cross-section of the well as it is drilled, with the depth axis being taken as the vertical direction for the moment. Suppose the cross-section is rotated about the vertical axis. What happens to the upper and lower gradients and the separation between them? Would the casing string program be altered in any way?

Some Common Assumptions

Now consider some commonly used assumptions about the rocks being drilled and the insitu stresses operative during wellbore operations. For example, it is often assumed that the rock is isotropic, homogeneous, and linearly elastic and that in-situ stresses are two-dimensional (sometimes the stresses are assumed to be the same in all directions, i.e. hydrostatic).

Fig. 3 shows radial and tangential stresses around a vertical well for equal horizontal stresses and isotropic, linearly elastic rock. In the horizontal plane, all directions are principal directions; there are no shear stresses. Radial stresses are compressive, tangential stresses are tensile. Displacements are also symmetrical with respect to the well bore axis. Pore pressures are omitted here for simplicity but would be accounted for by using poroelasticity concepts and effective stresses.

Tensile or compressive failure criteria would be used here, but shear failure would not.

In Fig. 4 the material is still isotropic and linearly elastic, but the horizontal stresses (and displacements) are not equal. Now the radial and tangential stresses are principal stresses only at the wellbore and at the outer boundary. Everywhere internally there exists radial, tangential, and shear stresses. Principal directions are now oriented internally around the wellbore axis according to the horizontal stress ratio; likewise for shear stress distributions. Stability or failure criteria are now more complicated, with shearing stress and strains having non-zero values. Determining locations where stresses and associated strains (displacements) have their highest or lowest values for inputs into failure/stability criteria become significantly more involved than for the case shown in Fig. 3.

In Figs. 3 and 4, the rock is considered to be non-porous. Thus permeability is zero as well. If porosity and permeability parameters are added, then several directionalities are introduced. Effective stresses will have additional directional components, fluid leakoff into the rock will be related to directional permeabilities, for example, and the locations of maximum/minimum stress and displacement conditions will be altered. Even less symmetry with respect to the wellbore axis will occur. If the rock/fluid interaction is chemical as well as mechanical, a three-dimensional system becomes inevitable. In shale swelling, for example, surrounding rock limits the swelling displacements in all directions – but not equally in all directions. A 1-D stress causes 3-D displacements; for insitu displacement to be 1-D, 3-D stresses are required.

As a well is inclined from vertical, as shown in Fig. 5, all manner of anisotropies and non-symmetries with respect to the wellbore become significant. The classic paper on failure of inclined boreholes by Bradley[2] illustrates ‘stress clouds’, the shape of which are not symmetric, owing largely to anisotropic stresses. The rock is assumed to be isotropic and linearly elastic, however. Thus, for inclined wells, symmetries with respect to the well bore disappear. Rarely will the vertical direction be a principal direction for any physical process or rock behavior in or near the well. Likewise, minimum and intermediate values for rock parameters and behaviors will not be in the horizontal directions, but at angles to them.

Some Rock Tests And Models

Several examples follow to illustrate the directional character of sedimentary rocks and results from a wellbore stability model which utilizes input parameters of this nature.

Fig. 6 shows bedding plane orientation with respect to applied confining pressure and incremental vertical stress required for sample failure. Fig. 7 illustrates the highly non-linear and non-symmetric failure strength with bedding plane orientation and net effective stress. Not shown here are stress-strain curves and failure conditions for triaxial stress states, from which 3-D behavior and failure surfaces are obtained.

Fig. 8 shows an axial stress-axial strain curve for a North Sea shale, the non-linear plot terminating at sample failure. Tests such as this, at various selected sample orientations and states of stress provide information to construct 3-D behavior and failure surfaces. Other data, such as P-wave and S-wave velocity measurements, are used to determine dynamic values for Young’s modulus and Poisson’s ratio and for correlation purposes.

Fig. 9, for several groups of shales, illustrates that tensile strengths are highly directional, as would be expected of such layered, grain-oriented rock. Tensile strength of rock is often assumed to be small enough to ignore. But more often than not, shale tensile strengths are significant, sometimes amounting to several hundred psi. And tensile strength is directional, reflecting the rock matrix and structures of very small scale.

Fig. 10 schematically shows fluid leakoff at a crack tip, when the wellbore fluid does or does not contain solid particles. Extensive tests were carried out to quantify some aspects of crack initiation and extension. Stress concentrations at the crack tip, filtrate leakoff into the rock, local and highly dynamic changes in effective stresses, are all important in what happens, when, and where. Fluid leakoff, for example, alters the dynamic effective stresses directionally, solids packing nearest the crack tip alters stress concentrations in the vicinity of the crack tip. Leakoff, fracture, and lost circulation behavior reflects these small-scale, dynamic, anisotropic processes.

It is emphasized again that while pore pressure changes are hydrostatic, equal in all directions, the resulting deformations are 3-D. Depending upon the stability or failure criterion being applied, dynamic effective stresses may be such that critical values are developed within the rock local to the wellbore, not at the wellbore wall itself. Strain-dependent rock moduli can contribute to the same result, i.e., failure beginning within the rock and propagating toward the wellbore and further outward into the rock formation at the same time.

Figs. 11-14 show some results from a wellbore stability model which can incorporate general anisotropy, three-dimensional stress states, 3-D orientation of weak planes, and other non-ideal behavior.

Fig. 12 shows upper and lower bounds for mud weight for a well drilled in transversely isotropic rock (five elastic constants rather than two for isotropic materials). The vertical stress is the largest and the two horizontal stresses are equal. A plane of weakness is suppressed in this example, but it could be significant depending upon its orientation relative to the insitu stresses. The mud weight window - fracture on the high side, bore hole collapse on the low side – narrows as the well orientation moves from vertical to horizontal.

Fig. 13 is for the same horizontal stresses, but the vertical stress has increased substantially. Now the mud weight window closes dramatically, and the well is unstable at inclinations from vertical greater than 60 degrees or so.

Fig. 14 is for a horizontal well, drilled in 3-D stresses. Here the mud weight window closes dramatically, depending upon the wellbore azimuth relative to the insitu horizontal stress directions. Such behavior is manifested in fracture pressures and orientations, parallel to the wellbore or perpendicular to it.

Fig. 15 relates to shale swelling by water uptake and anisotropic/time-dependent changes that occur. As the shale swells, in three dimensions, the surrounding rock limits the swelling by increased confining stresses and by alteration of the mechanical moduli of the shale.

Fig. 16 shows tangential stresses at the borehole wall for a well drilled in isotropic rock, relative to the angle from the maximum stress direction. The upper and lower solid lines bound various 3-D states of stress and various degrees of mechanical anisotropy. It is important to note the non-symmetric nature of tangential stress at the wellbore wall. Moreover, not shown in the bounding lines here are other locations and magnitudes for critical stress values resulting from fluid leak-off changes in effective stresses nearby to the well.

While evaluations for stresses, fracture, collapse, etc. are required, it is also necessary to be cognizant of the pore pressure or well control requirements reflected in lower bound mud weights that are required simultaneously with upper bound ones.

More Realistic Models And Data Interpretation

Much has already been made of the fact that sedimentary rocks are anisotropic in physical parameters and are generally under anisotropic stresses, some of which occur naturally and some of which are induced by drilling and related wellbore operations. Anisotropy includes complexities and difficulties in obtaining and interpreting realistic tests in the laboratory as well as acquiring and interpreting field data from various sources.

For example, while it is common to consider stress distributions for subsurface processes of interest, it is far less common to consider the strain or displacement distributions that are the consequences of these stresses. But displacements/strains are the measured physical parameters, not stresses. Stresses are obtained from the strains/displacements, using particular constitutive laws. For isotropic materials, axes for stress and strain coincide. For anisotropic rocks, that is not so. This means that the principal strains/displacements, for example, will not be in the same directions as the principal stresses. The location(s) then for failure, fracture, collapse, breakout, etc. at the wellbore wall will have directional relationships with the stresses that caused such behavior. This makes interpretation of measured data more involved and generally more difficult since principal directions for various anisotropies are not often known in advance.

In general, various data sets obtained in lab tests for a variety of rocks under a variety of stress states, indicate that principal axes for parameters used in interpreting subsurface rock behavior do not coincide. So while the maximum stress, for example, will be in some specific direction in three-space, maximum strain, maximum permeability, maximum wave velocities, maximum resist ivies, maximum effective stress changes due to leadoff, filtrate invasion, failures, and other wellbore region parameters will all have different directions. These directions are not independent of each other but, in fact, reflect details of sedimentary rock structures, on several scales.

For the above reasons and because of the large costs associated with wellbore stability problems, additional efforts are being undertaken to better quantify 3-D rock mechanical and 3-D acoustic model input parameters from laboratory tests and field, operational data[3].

With many, many redundancies in terms of three-dimensional subsurface realities, some comments are offered here with respect to important and useful model input parameters and/or elements therein. Many of them are related to a particular area, and compilations or case histories can be so useful. Moreover, data from actual subsurface rock/fluid/stress/displacement systems indicates subsurface realities, without assumptions. Assumptions come into play when such data are interpreted, using whatever rules, laws, equations, etc. are deemed acceptable or adequate to the task at hand.

Subsequent publications will address some of the enumerated items for which lab and/or field data are available for improved quantifications. (1) Overburden gradients depend upon location, geologic structures, sedimentary history, tectonics, and 3-D material behavior; (2) Fracture (Failure) gradients depend upon the elastic/plastic/viscoelastic model used, and criteria such as Mohr, Mohr-Coulomb, Griffith, von Mises, Drucker-Prager, parameters such as the J-envelope, tensile strength, compressive strength, shear strength, internal friction, 3-D stress/strain behavior, 3-D well orientation, and planes of weakness; (3) Fluid Leak Off details reflect stress distributions and anisotropy, particularly directional effective stress dynamics and time effects; (4) Lost Circulation involves fracture tip dynamics, dynamic filtration, stress reorientation near the wellbore, stress reorientation due to fracture development, 3-D well orientation and trajectory, 3-D rock behavior, and time effects; (5) Wellbore Stability in shales includes 3-D shale behavior, 3-D filtration, water uptake, and swelling, and time dependent rock behavior; (6) Formation Damage, or more specifically, porosity and permeability changes due to filtrate invasion, particle invasion, relative permeability and fluid saturation changes, fines movement, and 3-D stress alterations have bearing on MWD, LWD, PWD, and other types of subsurface signals or signatures: (7) Pore Pressures reflect sedimentary and geologic histories, filtrate invasion due to pressure overbalance, 3-D and time dependent effective stress changes around the well, 3-D rock behavior, and wellbore wall integrity.

No claim is made that the above listing is complete or exhaustive. Subsurface system signals come from Drilling, Logging, MWD, LWD, PWD, Seismic, Cores and a wealth of expertise based on experience.

The Well Plan or Graph Revisited

Consider again Fig. 2, as a cross section or horizontal view of the overburden/fracture/pore pressure limits with depth. Considering 3-D rock behavior under 3-D stress states, including whatever constitutive or failure laws are utilized, all three of the limiting curves can be moved in either direction. Closure between pore pressure on the one hand and failure/fracture on the other depends upon several interactions. If a plot such as Fig. 2 were rotated about the wellbore axis, then all of the lines would be moved – sometimes further apart, sometimes closer together.

Moreover, when the well is rotated from vertical, to inclined, to horizontal, all three of the lines will again be shifted, depending upon the depth and associated parameter changes.

What all of this means is that the cross section in Fig. 2 is, in reality, a cross sectional snap shot of a **three-dimensional surface** that itself is **time-dependent.** Construction of such a complex, 3-D surface for specific processes and interactions is difficult and time consuming. But it can reveal volumes about subsurface processes and interactions and more realistic modeling of them.

Conclusions

While the examples included herein are small in number in the interest of brevity, it is concluded that three-dimensional behavior of down hole formations, under three-dimensional subsurface pressures/stresses, has significant potential for improved, more realistic quantifying approaches to fracture, failure, leak-off, and pore pressure technologies.

Operational limits for fracture, lost circulation, leak-off, and pore pressure gradients are directly related to depth and borehole trajectory. Better understanding of the directional, non-linear, and local, event-coupled processes and behavioral features that work collectively during rock/fluid/stress system interactions will pay handsome return on resource investments required.

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References

1. Eaton, Ben: Personal Communication.
2. Bradley, W. B.: “Failure of Inclined Boreholes”, Trans. ASME, Dec. 1979, **Vol.** 101, 232-239.
3. Gray, K.E., Torres-Verdin, Carlos, and Daneshy, Ali: “3-D Fracture Gradient/Pore Pressure Operational Limits and Convergence With Formation Depth and Borehole Orientation”, The University of Texas at Austin, 2001.

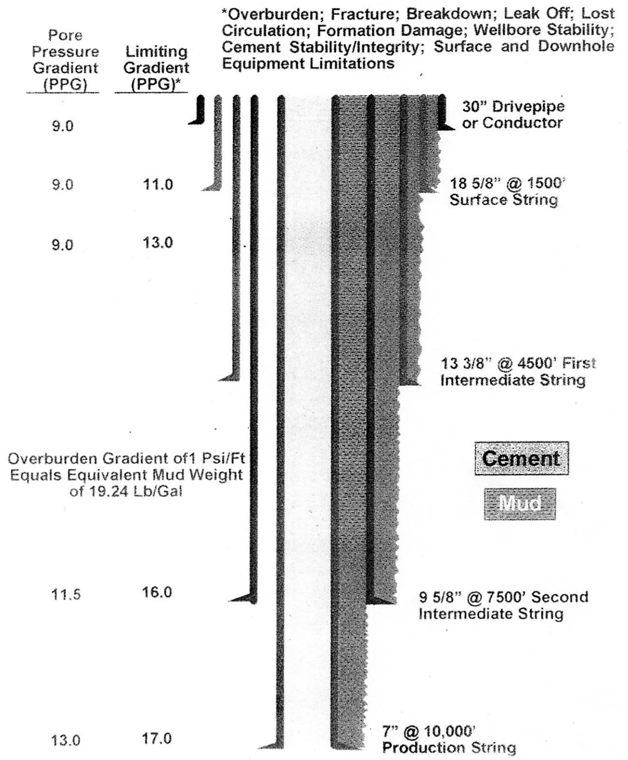


Figure 1. Example casing program.

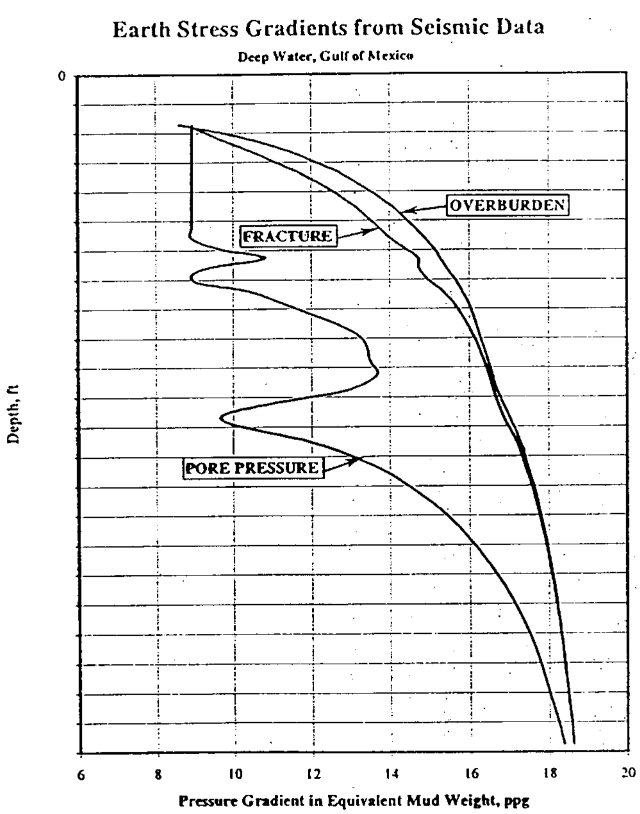


Figure 2. Basic well plan graph.

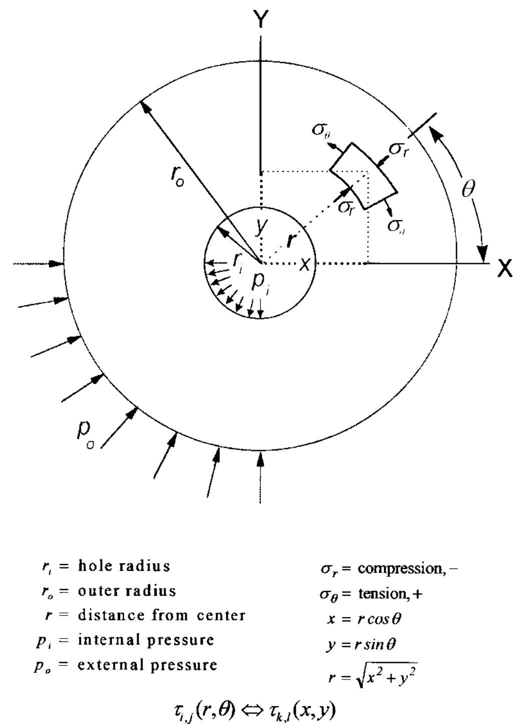


Figure 3. Stress distribution for equal horizontal far-field in-situ stress state - linearly elastic, non-porous, isotropic system.

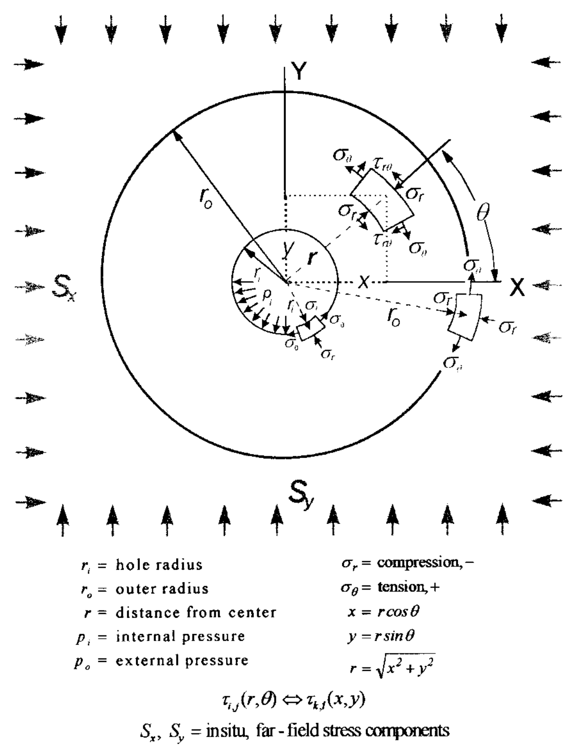


Figure 4. Stress distribution for unequal horizontal far-field in-situ stress state - linearly elastic, non-porous, isotropic system.

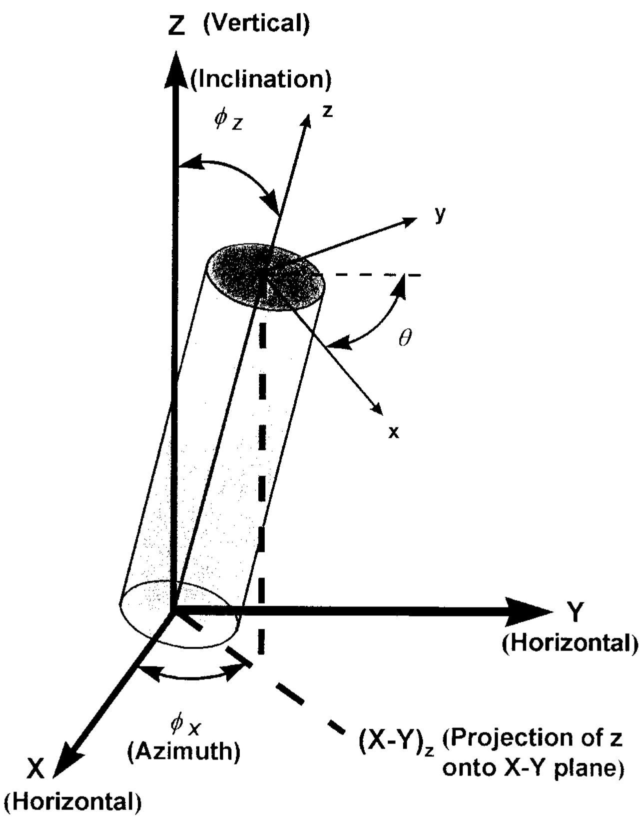


Figure 5. Far field and wellbore reference axes for inclined/horizontal wells.

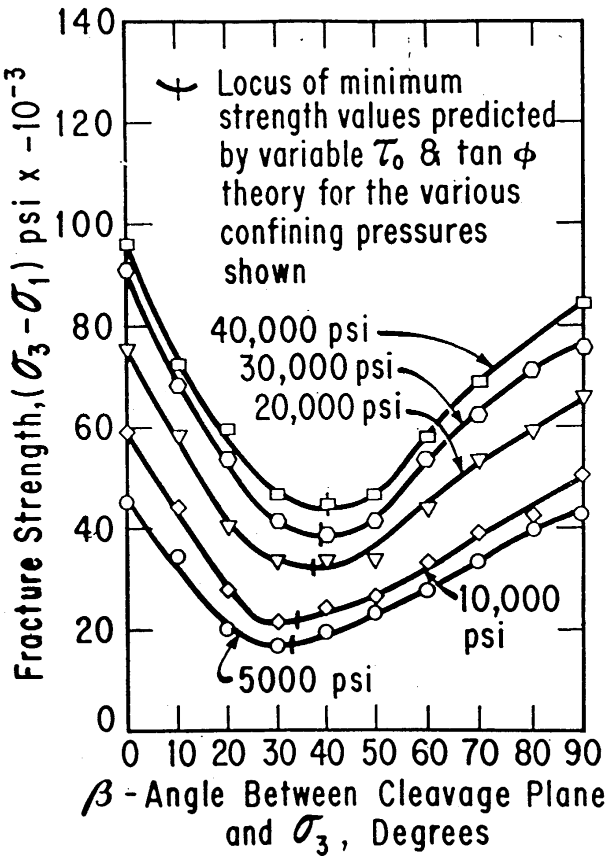


Figure 7. Fracture strength anisotropy due to bedding planes.

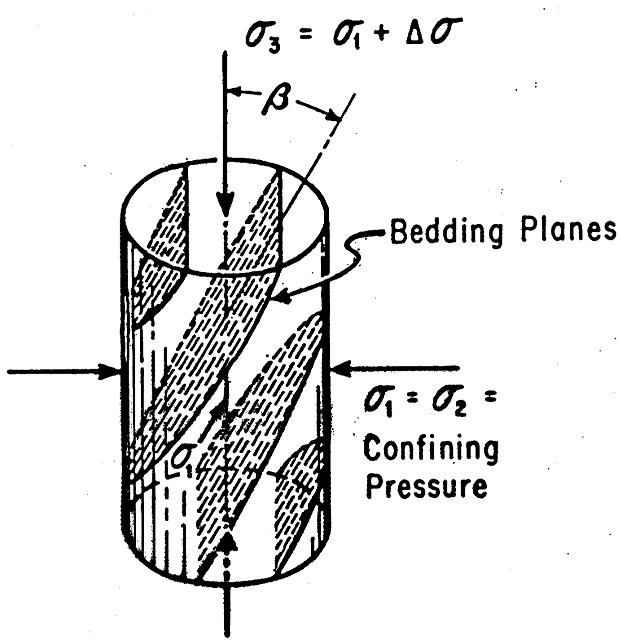


Figure 6. Bedding plane orientations for strength tests.

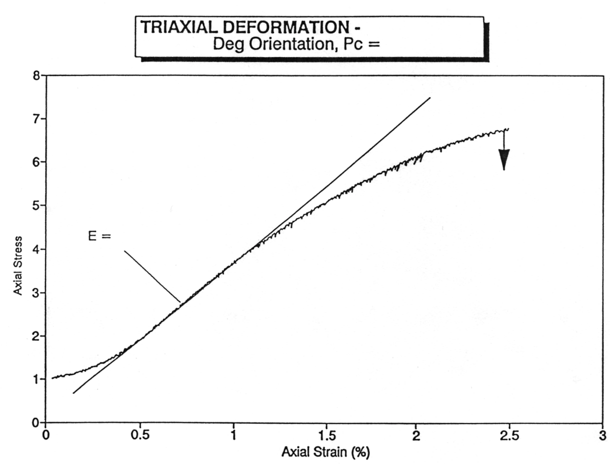


Figure 8. Stress, strain, and failure test on North Sea shale.

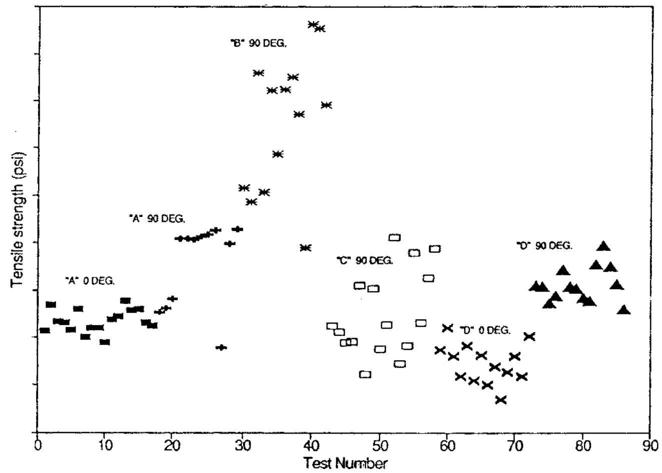
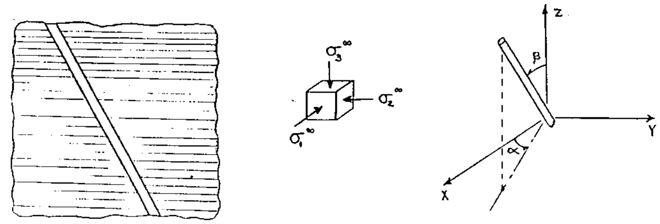


Figure 9. Anisotropic tensile strength of shales.



The Analytical Solution Allows For:

- **General Anisotropy**
- **3-D Stress States**
- **3-D Wellbore Trajectory**
- **Elliptic Wellbore**
- **Inelastic Rock Behavior**
- **User-Defined Failure Criteria**
- **3-D Orientation of 'Weak Plane'**
- **User-Defined Rock Parameters**
- **Rock/Wellbore Fluid Interaction**

Figure 11. Wellbore stability in anisotropic rocks.

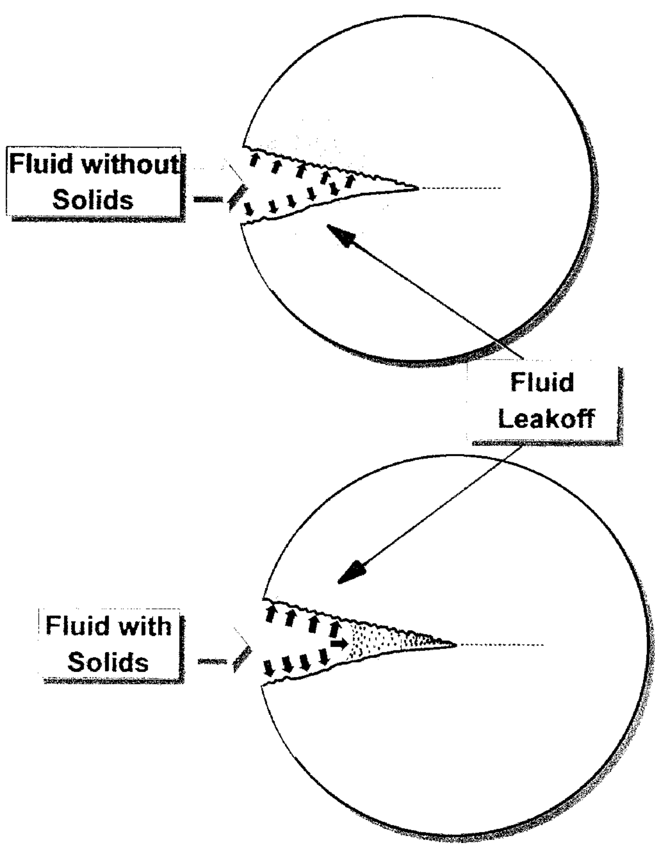


Figure 10. Hydrofracture tip dynamics.

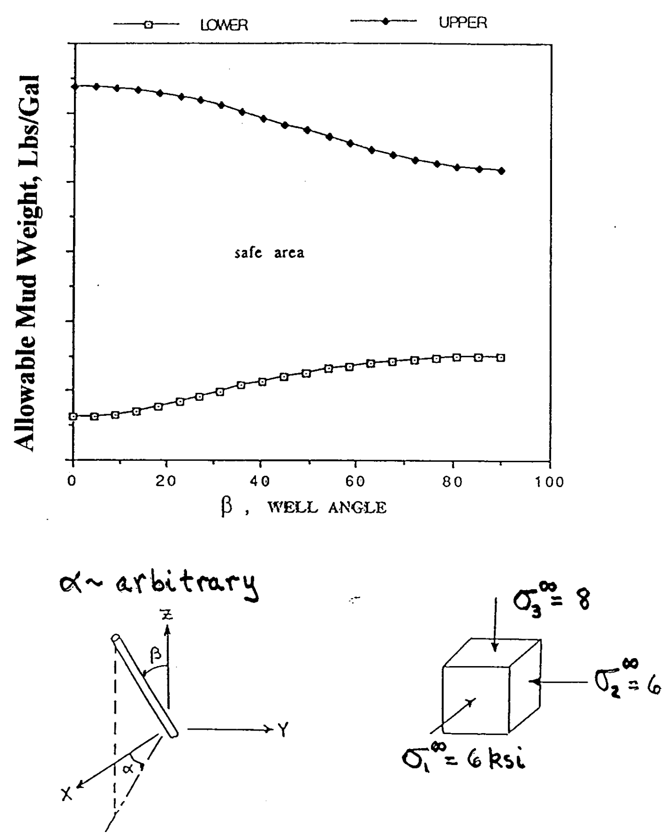


Figure 12. Allowable mud weights, transversely isotropic rock in biaxial stress state.

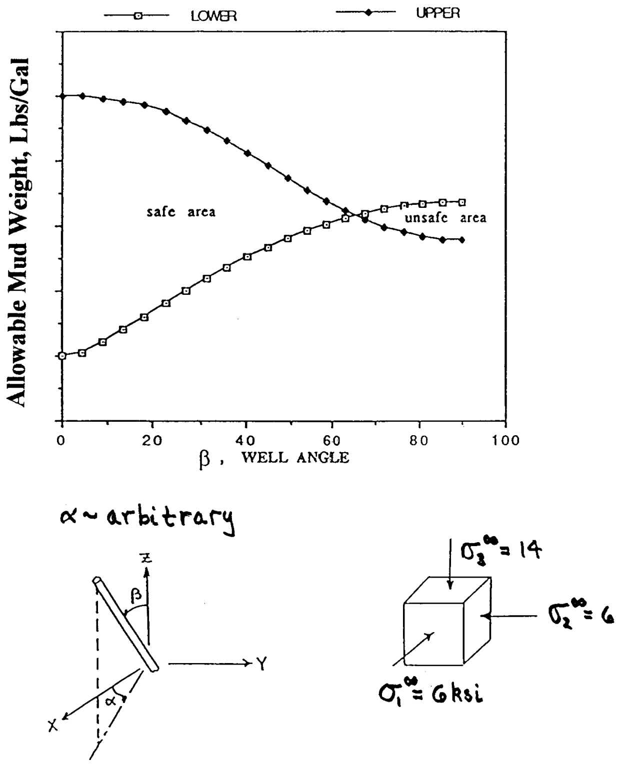


Figure 13. Allowable mud weights, transversely isotropic rock, elevated vertical stress.

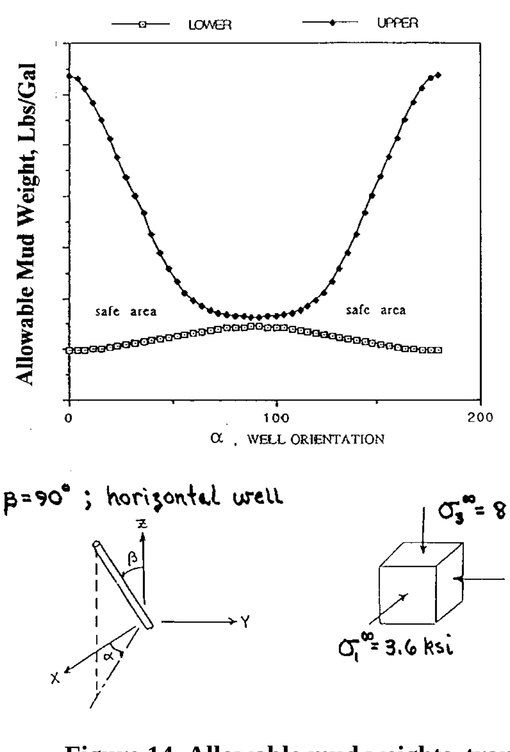


Figure 14. Allowable mud weights, transversely isotropic rock, triaxial stress state for horizontal well.

The distribution of adsorbed water in a region bounded internally by a circular cylinder can be written as an analog to the temperature distribution in radial heat flow shown by Carslaw and Jaeger[1].

$$W_D = \frac{W(R,t)}{W_s} = 1 - \frac{2}{\pi}\int_0^\infty e^{-\tau\eta^2}\,\frac{J_o(\eta)Y_o(R\eta) - Y_o(\eta)J_o(R\eta)}{\eta\left[J_o^2(\eta) + Y_o^2(\eta)\right]}\,d\eta \qquad (1)$$

where:

$$R = \frac{r}{a} \qquad (2)$$

$$\tau = \frac{ct}{a^2} \qquad (3)$$

r	=	radial distance
a	=	radius of cylinder
t	=	time, hours
c	=	adsorption constant
W_D	=	dimensionless water content
W_s	=	water content on wellbore well, weight %
$W(R,t)$	=	water content at dimensionless radius at time t, weight %
J_o and Y_o	=	Bessel functions of first order and first and second kind, respectively

When shale adsorbs water, it swells. As swelling continues the resulting increase in confining pressure regulates the swelling, limiting the amount of water uptake and altering the mechanical moduli of the shale.

Figure 15. Borehole instability: shale swelling models.

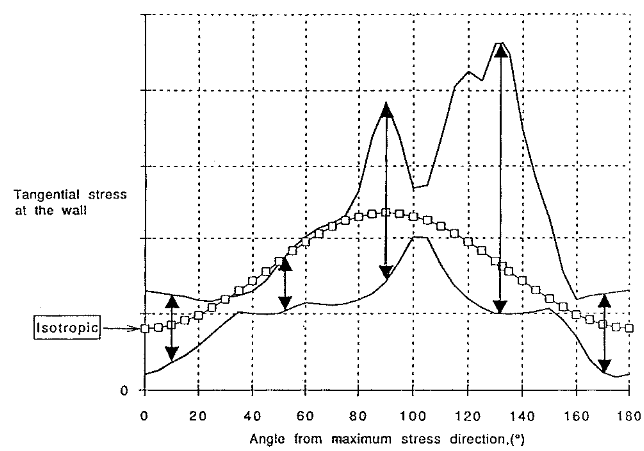


Figure 16. Tangential stresses on wellbore for isotropic and anisotropic rock, 3-D stress states.