IN-SITU STRESS EVALUATION IN CORE ANALYSIS

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ABSTRACT

Achieving the maximum economic benefit from core analysis requires a thorough understanding of reservoir in-situ stresses. The direct measurement of rock properties from oriented core is critical in the design of horizontal wellbores. An outline of the measures and testing necessary to effectively evaluate naturally fractured reservoirs using field and laboratory technologies is presented. The determination of rock mechanical properties, fracture strike and principal in-situ stress magnitudes-directions should be known prior to drilling a horizontal wellbore. These data can then be used to maximize the intersection of natural fractures and minimize the potential of borehole failure.

In exploration wells, it is necessary first to drill a vertical pilot-hole. The zone of interest is cored, field tests are performed, laboratory testing is completed and an evaluation of the reservoir is made. With this information available, decisions can be made to optimize the boreole azimuth and well placement. This approach to formation evaluation has been used widely by Oryx Energy Company in several reservoirs where rock characterization is an essential ingredient in the exploration and drilling program.

INTRODUCTION

In recent times, the oil and gas industry has experienced an enormous increase in horizontal drilling activity. In preparation for drilling a horizontal well, a number of existing technologies can be utilized to increase the chances of having a successful exploration program. Oryx Energy Company has effectively used vertical pilot-hole oriented-coring, rock characterization and openhole small-volume-hydraulic fracturing to evaluate formations targeted for horizontal completions. These methods are particularly useful in exploration wells where little or no data is available. This approach also allows for a timely evaluation of the reservoir prior to drilling the horizontal well section. First, the well is drilled vertically (Figure 1) to the zone(s) of interest and the microfracture tests are performed to determine the in-situ stress magnitude. Oriented cores are taken to measure the in-situ stress direction and mechanical testing is performed to determine the failure criterion of the rock. These data must be included in the design of the horizontal section of the wellbore *a priori* to achieve favorable results. The well can then be plugged-back and kicked-off horizontally in the optimum direction determined by the analytical program. For the pilot-hole coring and evaluation technique to be valid, the rock penetrated vertically must be representative of the rock that will also be drilled horizontally. Areas which are highly faulted may not be suited to this type of testing.

Most engineering and geological activities are dependent on a knowledge of the reservoir in-situ stresses, natural fracture characteristics and mechanical behavior. A melding of core analysis, rock mechanics, petrophysics, wellbore stability modeling and completion technologies is necessary to address all of the issues facing horizontal well design. Geologists and reservoir engineers are concerned with properties that affect the reservoir quality such as fracture intensity, fracture stress sensitivity, directional permeabilities and fluid saturations. Drilling engineers are interested in determining the minimum mud weight to drill the horizontal wellbore safely, while the completion engineer attempts to mitigate formation damage. Because most of the data collected for optimizing the well program are based on rock properties, the core analyst must be keenly aware of field and laboratory testing procedures.

A great deal of research, both theoretical and experimental, has been aimed toward a greater understanding of in-situ stresses.[1-9] Much of this work has been a result of horizontal drilling, hydraulic fracturing and the need to examine more closely the state of stresses at depth for wellbore stability prediction. Wellbores fail in a manner which is strongly controlled by the magnitude and orientation of the in-situ stress field.[10] Several papers have been published which review the measurement of in-situ stresses; however, none are directed towards the horizontal drilling of naturally fractured reservoirs. Only Soliman et al.[11] have applied the concept of utilizing comprehensive formation evaluation to the drilling and hydraulic fracturing of a horizontal well. Figure 2 illustrates the complete analytical scheme for the characterization of reservoir properties critical in horizontal drilling. The use of several techniques to determine a single reservoir parameter is encouraged to cross-check experimental results, e.g. static (core) vs. dynamic (log) elastic moduli, anelastic strain recovery vs. differential strain curve analysis for principal horizontal stress orientation, etc. Experience has shown that no single method will consistently yield reliable results in all formation types. Formation depth, lithology, rock fabric, paleo-stress and borehole conditions can adversely affect the assessment of the reservoir. The key

References and illustrations at end of paper.

to achieving success in horizontal drilling is integration of a wide variety of activities: core and log analyses, in-situ stress determinations, fracture diagnostics, well testing and various large-scale reservoir evaluation methods.

This paper reviews the methods by which field and laboratory techniques can be used to improve both the drilling and production phases of a horizontal drilling program.

ORIENTED CORING

The orientation of in-situ stresses, as well as fracture strike serves as the foundation for much of the horizontal wellbore evaluation. These data are most reliably obtained from vertical pilot-hole multishot or paleomagnetically oriented core.[12,13] Strict operating and handling procedures must be followed to obtain a *true* oriented core. The bottomhole coring assembly must be designed to withstand the rigors of the borehole environment and properly aligned to obtain accurate directional properties of the reservoir.

Once the core has been cut and brought to the surface, it must be handled in a manner which best preserves its in-situ saturation state.[14] Failure to do so will result in over/under-estimation of the mechanical strength and elastic moduli of the rock.

IN-SITU STRESSES

Many practices in the oil and gas industry benefit from an increased understanding of reservoir in-situ stresses. It has long been recognized that principal stress orientation controls the propagation direction of hydraulic fractures.[15] Present-day in-situ stresses can also be used to infer paleo-stress conditions when a time-geologic history model is used to interpret rock behavior.[16] More recently, the effects of variations in horizontal principal stress magnitude and direction have been shown to affect fracture containment[17] and borehole stability.[18] Therefore, to have a mechanical basis for anticipating the fracture behavior of the rocks in various localities, it is necessary that something be known concerning the expected stress states.

The state of stress at a point within the earth can be completely described by three mutually perpendicular, principal stresses. In deep, normally pressured reservoirs, the compressive stress due to the weight of the overburden load is usually the primary principal stress, where $\sigma_1 = \sigma_v$. If the beds are relatively flat-lying, the intermediate and least principal stresses are oriented horizontally, where $\sigma_2 = \sigma_H$, $\sigma_3 = \sigma_h$, and therefore, $\sigma_v > \sigma_H > \sigma_h$ (Figure 3). Prior knowledge of the horizontal stress directions and magnitudes is particularly important in drilling horizontal wellbores. A significant difference between the horizontal stresses can cause complications during the drilling operation and may result in borehole failure. It is well accepted that the "effective" stresses acting on a reservoir and not the total stresses determine failure. Effective stresses are equivalent to the total stresses minus the pore pressure.[19]

VERTICAL (OVERBURDEN) STRESS, σ_v

The overburden stress, σ_v, can be evaluated through the integration of the bulk density wireline log from the surface to the depth of the reservoir. It is given by:

$$\sigma_v = \int_0^D P(z)gdz. \qquad (1)$$

The overburden gradient, P_o, can be calculated by:

$$P_o = \sigma_v / D. \qquad (2)$$

This stress is assumed to be due only to the weight of the overburden rocks in the absence of tectonic thrusting.[20] Overburden stress is generally assumed to be approximately 1.0 psi/ft and to increase uniformly with depth. This assumption is usually the exception rather than the rule for this nonconstant variable. One should realize that this assumption may be seriously in error in some areas, such as in shallow reservoirs where rocks are highly compressible or in deep drilling operations.

Borehole gravity meters can also be used to determine the density versus depth profile of a wellbore accurately. Velocity analysis of seismic sections may provide rough estimates of the formation bulk density prior to drilling a borehole.[21]

RESERVOIR (PORE) PRESSURE, P_i

The initial pore pressure, P_i, is the pressure acting upon the fluids in the pore space of the reservoir. Normal pore pressures in any geologic setting will equal the hydrostatic head (pressure) of water extending from the surface to the reservoir. Normal hydrostatic gradients which may be encountered during drilling for oil and gas range from 0.433 psi/ft in rocks containing fresh and brackish water to more than 0.465 psi/ft in highly saline water.

Abnormally high pore pressures are defined as being in excess of hydrostatic loading. In normal pressure environments the rock matrix stress supports the overburden load, σ_v, with grain-to-grain contacts. In unconsolidated sediments, any reduction in the grain-to-grain stress will cause the pore fluids to support an additional part of σ_v, the result being abnormally high pore pressure. In consolidated rocks, overpressuring is usually caused by gas generation. Subnormal pore pressures may also occur where reservoir fluids have been produced and an insufficient drive mechanism exists. The pore pressure gradient is given by:

$$P_p = P_i / D. \tag{3}$$

Considerable effort has been spent attempting to derive the initial pore pressure, P_i using: drilling and mud logging parameters,[22] wireline logging techniques involving the use of resistivity, sonic,[23] dielectric properties and more recently logging-while-drilling devices, pressure transient analysis methods utilizing drillstem tests (DST) or wireline formation testing techniques, and completion monitoring methods used during small-volume-hydraulic fracturing (microfracing).[24]

For the purpose of drilling and evaluating horizontal wellbores, pressure transient methods have proven to be most reliable and straightforward for estimating P_i.[25] If borehole conditions and reservoir properties permit, wireline formation testing techniques offer a means to obtain quick hydrostatic and formation pressures at a number of points within the zone of interest.[26]

FRACTURE PRESSURE, f

The fracture pressure, f, is the fluid pressure or stress magnitude necessary to overcome the earth's compressive stresses holding the rock material together. Other factors which affect this variable are the fracture toughness of the rock, fluid resistance factors and fracture tip effects. The rock will fracture along a plane perpendicular to the minimum compressive stress, σ_3, in the formation matrix. In deep, naturally fractured, tectonically relaxed reservoirs, the minimum compressive stress is oriented horizontally, σ_h, and can be measured by a number of methods. The fracture pressure gradient or frac gradient which is critical in borehole stability and hydraulic fracture operations is given by:

$$P_f = f/D. \tag{4}$$

Results of previous work suggests that the fracture pressure gradient is a function primarily of overburden stress, pore pressure and the ratio of horizontal to vertical stress. The horizontal stress in a non-porous, elastic, homogeneous, isotropic solid under vertical stress with no horizontal deformation is given by:

$$\sigma_h = \sigma_v \frac{\nu}{1-\nu}, \tag{5}$$

where ν is Poisson's ratio.

This relationship is impractical in reservoir applications because it ignores the effects of the porous nature of rocks and the reservoir pore pressure. Many empirical relationships have been developed to determine horizontal stresses which incorporate well log (dynamically) derived Poisson's ratio for Gulf Coast area rocks.[23,27] Anderson et al.,[20] derived an equation based on the work of Biot:[28]

$$\sigma_h = \sigma_v \frac{\nu}{1-\nu} + \alpha_B P_i \frac{1-2\nu}{1-\nu}$$

$$= \frac{\nu}{1-\nu} (\sigma_v - \alpha_B P_i) + \alpha_B P_i, \tag{6}$$

where;

$$\alpha_B = 1 - \frac{k_{dry\ rock}}{k_{matrix}} = \text{Biot poroelastic constant} \tag{7}$$

$k_{dry\ rock}$ = bulk modulus of dry rock frame
k_{matrix} = bulk modulus of constituent minerals.

The bulk modulus of the constituent minerals, k_{matrix}, is constant for a given lithology. However, the bulk modulus of the dry rock frame can vary substantially and is dependent on porosity, grain-to-grain contacts, cementation and the stress state of the rock. In a non-porous rock where $k_{dry\ rock} = k_{matrix}$, $\alpha_B = 0$. In unconsolidated and low porosity fractured rocks where the compressibility is much greater than that of the constituent minerals, $\alpha_B \approx 1$. The bulk modulus of the dry rock frame and constituent minerals can be determined experimentally. Warpinski and Teufel[29] have shown that the Biot poroelastic constant can vary substantially and is a function of stress distribution, pore pressure and rock type.

Newberry et al.,[30] modified the work of Anderson for low porosity microfractured rock. This model makes the additional assumption that microfractures align perpendicular to the minimum principal stress, σ_h, and their presence makes $\alpha_B = 1$ in the direction of least principal stress. The result is an approximation to a transversely anisotropic model where:

$$\sigma_h = \frac{\nu}{1-\nu} (\sigma_v - \alpha_B P_i) + P_i. \quad (8)$$

Unfortunately, the practice of using empirically derived values for the estimation of fracture pressures leads to many difficulties. Some of the major constraints are that the rock material is assumed to be a linear, elastic, homogeneous, isotropic solid which is only constrained laterally during compaction (plane strain). Further, the models assume no external or tectonic forces σ_T, horizontal stresses are equal and pore pressure must remain constant. Warpinski[16] recently concluded that a complete geologic stress-history analysis must be performed because of the variation in material properties over time.

The Warpinski model is the most rigorous in that it accounts for changes in pore pressure, temperature gradients, consolidation and diagenesis through time-varying material properties and varying tectonic episodes. Discrepancies between static and dynamic mechanical properties can also lead to the over/under estimation of the frac gradient. With few exceptions, dynamically determined elastic moduli values are higher than those measured statically. Differences between the static and dynamic elastic moduli/Poisson's ratio can be attributed to strain amplitude,[31] strain rate, time-effects (duration of stress), experimental conditions (laboratory and borehole), in-situ stresses, rock heterogeneity and saturation. Research suggests that the difference between static and dynamic measurements diminishes at high net effective stress for certain rock types.[32]

In-situ stress magnitudes can also be estimated using viscoelastic constitutive models and core-based strain data.[33-37] In general, these methods are controversial and have been used with limited success.

For these reasons, openhole small-volume-hydraulic fracturing techniques (microfracs) were used to determine σ_h for horizontal drilling targets. The microfrac is the only direct method of measuring the minimum principal horizontal in-situ stress in a reservoir. Openhole microfracturing is performed by isolating a zone with a packer, injecting a small volume of fluid through the drill pipe over a short period of time, shutting-in and measuring the fracture closure pressure. Figure 4 shows schematically the bottom of the wellbore, packer and drill pipe.[24] The induced fracture propagates vertically in a direction perpendicular to the minimum principal stress, σ_h, and its magnitude is determined from analysis of the pressure decline after shut-in. The minimum principal stress is equal to the fracture closure pressure and is approximated by the instantaneous shut-in pressure (ISIP) when fluid losses are high and the induced fractures close quickly.

The resultant induced vertical microfracture can be cored and retrieved to confirm the azimuth of σ_h and suggest the direction of the intermediate stress, σ_H. The orientation of the induced fracture is a direct means of interpreting the present-day in-situ stress field. This orientation can also be confirmed by well log imaging techniques, passive borehole seismic methods (acoustic emissions),[38] impression packers,[3] and in shallow reservoirs with surface tiltmeters or magnetometers.[39] The σ_h data may be valuable in the assessment of wellbore stability, for the determination of placement of perforations and in the design of hydraulic fracture treatments. The microfrac technique and associated methods are discussed in detail in a number of references.[7,24,40-44]

STRESS ORIENTATION

The orientation of present-day in-situ stresses in deep, naturally fractured formations must be known prior to drilling a horizontal well. The orientation of in-situ stresses affects the stability of the wellbore, the effectiveness of hydraulic fracture treatments and the potential for obtaining economic production rates. Present-day in-situ stresses can sometimes be infered from the paleo-stress regime and diagenesis of the formation. It is generally accepted that a horizontal well which intersects the natural fractures in a direction perpendicular to their surfaces will result in improved productivity.

The orientation of natural vertical fractures in areas of flat or gently dipping rocks may be ascertained using remote sensing techniques prior to drilling the well. Reconnaissance studies of surface joints and lineaments often gives clues to the orientation of the maximum horizontal stress in a reservoir.[45] Well logs can be used to make qualitative estimates of the orientation of in-situ stresses when stress-induced wellbore breakouts occur.[46,47] Calipers, dipmeters and more recently, oriented imaging logs are used to determine the azimuth of a borehole elongation. The long axis of a noncircular borehole cross-section is interpreted as the orientation of the minimum horizontal stress, σ_h.

Shear-wave splitting (bi-refringence) in synthetic three-component vertical seismic profiles (VSP) can also be used to interpret the orientation of in-situ stresses and fracture strike.[48] The evaluation of shear wave propagation in anisotropic media is an emerging technology which could have widespread applications in petroleum exploration.

Several core-based methods have the advantage of being more direct than field techniques and for the most part are reliable. Unfortunately, pre-existing rock fabric such as natural fractures or significant heterogeneities can adversely affect the results. The competency, cementation, lithology and saturation state of the rock also plays a major role in the viability of core-based in-situ stress analysis. Shales are particularly difficult to characterize because of their tendency to delaminate and lose appreciable water with time.

The primary core-based methods for the orientation of in-situ stresses in their order of importance in horizontal drilling are: anelastic strain recovery (ASR), differential strain curve analysis (DSA) and ultrasonic velocity analysis (UVA). Secondary core-based methods which have been found to be less desirable are: residual stress analysis (over-coring),[49] acoustic emission analysis[50,51] and thermal expansion methods.

ASR, DSA and UVA methods are all based on the theory that microcracks develop in rock during the coring and retrieval process. Microcrack theory has been discussed by Nur,[52] Simmons,et al.[53] Siegfried[54] Voight[55] and Teufel.[56] Strain recovery is considered to be a result of microcrack development for rocks which are isotropic and homogeneous at depth prior to coring and strain relief. The microcracks are aligned primarily by the directions of the principal stresses when the rock expands in response to the release of in-situ stresses (Figure 5).[56] The volume of the microcracks resulting from strain recovery is proportional volumetrically to the corresponding in-situ stress magnitudes. When a formation is cored and the rock is retrieved to the surface, the stress relief and microcrack development will maximize in the direction of maximum horizontal stress relief, σ_1. Expansion will be the least in the direction of minimum horizontal stress, σ_3. Natural macro-fractures generally align with the direction of the maximum (present-day) horizontal in-situ stress. Thus, confirmation of the intermediate stress, σ_2, can be made during the orientation of the natural fractures existing in the core.

Because of the immediacy of the results, the anelastic (time-dependent) strain recovery (ASR) method is well suited to determine the orientation of principal stresses for horizontal drilling operations. ASR is performed at the wellsite immediately after the oriented core is surfaced. The vertical core is wrapped to prevent fluid loss and instrumented with a set of three horizontal displacement transducers offset at 45° (785 mrad) (Figure 6).[57] Data is then acquired under isothermal conditions by a microcomputer system. The recovered anelastic strains are assumed to be proportional to the recoverable strain. From this information the principal strain tensor can be determined. Presuming known relationships between strain and stress for a particular rock type, the principal stress tensor may be measured. Caution must be exercised when using ASR in heterogeneous rock samples. The ASR sample must be a homogeneous right cylinder which is competent enough to bond transducers to its surface. ASR cannot be utilized in rubbalized or unconsolidated sections and its use is restricted to deep reservoirs.

Fundamentally, DSA is very similar to ASR in that the microcracks created during coring are used to reflect the in-situ stress tensor.[52] The DSA method is more complex than ASR, laboratory intensive and can be time consuming. The DSA sample is first configured for attachment of strain gauges for the measurement of directional deformation (Figure 7). The sample is hydrostatically re-loaded above the effective in-situ reservoir stress magnitude. Conceptually, the deformation during re-loading is assumed to be proportional to the amount of deformation lost during the removal of the core from its in-situ environment. Maximum compressive strain will then be seen in the direction of maximum stress relief. As the sample is re-loaded in the laboratory, microcracks created by stress relief will close first, followed by deformation which is a function of the intrinsic mechanical properties of the rock. By differentiating intrinsic behavior at high pressures from deformation controlled by microcracks at low pressure, the directional contribution caused by microcracks can be measured.[54,58,59] Hence, the direction of the maximum principal strain, ε_H, will be orthogonal to the direction of maximum microcrack density (Figure 5).[56] DSA is used primarily to check ASR results which show significant statistical variation.

The UVA method is also a laboratory technique based on the microcrack theory.[52,60,61] Compressional wave, V_p, and shear wave, V_s, ultrasonic velocities are measured in three mutually perpendicular directions. The wave velocities are greatest in the direction of maximum strain recovery, ε_H, and stress release, σ_H, and lowest in the direction of minimum strain recovery, ε_h, and stress release, σ_h. Microcracks oriented parallel to the direction of ultrasonic transmission will not appreciably affect the wave velocities. Microcracks oriented perpendicular to the direction of ultrasonic transmission will disperse signals and wave attenuation will be at a maximum. Thus, ultrasonic wave velocities are at a minimum perpendicular to the microcracks, in the direction of the greatest principal in-situ stress, σ_H. Wave velocities can be strongly influenced by the rock fabric and pre-existing natural fractures and the use of this technique is sometimes limited. One clear benefit of the UVA method is the simultaneous acquisition of dynamic rock mechanical properties under triaxial conditions, i.e. elastic moduli, Poisson's ratio and compressive strength. Directional trends in these properties can be ascertained quickly and compared to dynamic values obtained with long-spaced sonic or dipole logging tools.

Whenever core is available, macro-features such as coring-induced fractures and bedding plane attitude should be used to gain insight to the in-situ stress distribution.[62-64] If oriented thin sections can be fabricated in a reasonable time-frame, the petrographic analysis of microstructural elements is useful in the evaluation of in-situ horizontal stresses. Microfracture azimuth, preferred micro-bedding patterns, and the alignment of crystals, grains and fluid inclusions are all indicators of the state of stresses at depth. Recent advances in nuclear magnetic resonance imaging (MRI) and CT X-Ray (CAT) scanning methods allow for non-destructive and timely means to investigate the structural elements of rock in three dimensions. Whenever possible, core-based, well log and geophysical techniques should be used collectively to assess the orientation of in-situ stresses.

ROCK MECHANICS

The basis for much of the horizontal wellbore evaluation lies in the discipline of rock mechanics. The acquisition of mechanical properties quantifies how rocks respond to stress. Strict wellsite preservation and laboratory handling procedures must be followed to obtain mechanical properties data representative of the reservoir.[14] Fresh core must be used in the laboratory evaluation to obtain field realistic results. Because the mechanical property data are used as critical input parameters in the wellbore stability analysis, this phase of the analytical program must be completed prior to kicking-off the horizontal wellbore. Operationally, this poses no problem because three to seven days are needed to run wireline logs, conduct pressure transient analysis, perform microfrac analysis, plug-back the vertical pilot-hole and prepare for the horizontal build section.

Static mechanical properties including: compressive strength uniaxial, C_o, and triaxial, C_T, Young's modulus, E, and, Poisson's ratio, ν, are obtained from cylindrical plug samples in a triaxial load frame. Dynamic mechanical properties can be acquired during the course of the static tests for correlation to wireline logs and geophysical data. A generalized static-to-dynamic baseline correction factor can be derived from the V_p and V_s data. This approach is useful when more than a single well is being drilled and not all of the wells will be cored (Figure 2).

The reloading of the samples in the laboratory must reflect the state of in-situ stresses in the reservoir. The total radial confining pressure, σ_c, for triaxial (biaxial) loading can be approximated by:

$$\sigma_c = \frac{\sigma_v + \sigma_H + \sigma_h}{3}, \qquad (9)$$

where σ_v is determined through integration of the bulk density wireline log (equation 1), σ_h is measured directly from the microfrac, and σ_H is estimated. Currently, no reliable means of measuring σ_H is available.

The reservoir (pore) pressure, P_i, and Biot's poroelastic constant, α_B, must be considered to determine the effective radial confining pressure, σ'_c, by:

$$\sigma'_c = \sigma_c - \alpha_B P_i, \qquad (10)$$

where, P_i, is measured using pressure transient methods and, α_B, is estimated by equation (7).

A group of lithologically consistent and reservoir representative, preserved plug samples are screened for standard triaxial (biaxial) testing. Triaxial testing is preferred because of its near approximation to field conditions and simplicity of operation. Polyaxial or true triaxial tests are inappropriate in exploratory horizontal drilling applications. Polyaxial tests are experimentally complex, time consuming and not widely available. Hydrostatic loading is rarely applied when measuring mechanical properties and its use is restricted to DSA measurements. Figure 8 illustrates the various types of laboratory stress fields.

The Mohr-Coulomb failure equations are used to understand the stress conditions at which the rock sample fails. The equations describe a circular locus of paired values (σ_n, τ) of the normal and shear stresses that operate on any and all orientations within a given body that has been subjected to known values of σ_1 and σ_3. Using the Mohr-Coulomb failure diagram it is possible to identify a plane of any orientation relative to σ_1, and to read the values of normal stress, σ_n, and shear stress, τ, acting on the plane (Figure 9). The failure envelope is a collection of Mohr circles which is developed experimentally by subjecting a suite of samples to successively higher confining stresses, σ_3, and determining the resultant value for failure, σ_1. A minimum of four plug samples are used to construct the envelope. One sample is run under uniaxial (unconfined) compression and another is subjected to the in-situ effective confining stress, σ'_c. Two additional samples are run at conditions proportionally above and below, σ'_c, to complete the envelope.

Coulomb theorized that fracturing occurs when the shear stress on a plane exceeds both the cohesion of the material and the friction developed by stress normal to the plane. Thus, failure occurs outside of the envelope and the area within the envelope is referred to as the region of stability. The relationship between the magnitude of the shear stress, τ, and normal stress, σ_n, is:

$$\tau = \tau_0 + \sigma_n \tan \phi, \quad (11)$$

where, τ_0, is the cohesive or shear strength of the rock under zero normal stress and, ϕ, is defined as the angle of internal friction. Both of these variables are critical to the understanding of how rocks fail and the reader is referred to Jaeger and Cook[65] for a complete discussion on rock mechanics. The tensile strength of the rock, T_o, is measured indirectly by the Brazilian disk method and is used in the evaluation of rock failure mechanisms.

At this stage in the analytical scheme, it is convenient to quantify the percentage of mineral and organic constituents present in the rock. Standard X-Ray diffraction and geochemical (pyrolysis) analysis can be performed on the end-pieces of the samples designated for mechanical testing. These data are used to interpret the stress-strain relationship in terms of the rock's composition. Whether the formation will exhibit ductile or brittle behavior is closely tied to the physical make up of the rock, in-situ stress conditions, fluid saturation, cementation, temperature, etc.

The mechanical properties data are useful in ranking the natural fracture potential of the formation on a relative basis if more than one zone of interest is present. Drilling and completion fluid compatibility testing can also be performed on the vertical pilot-hole core to mitigate the potential of formation damage in the horizontal wellbore section.

WELLBORE STABILITY

The increase in horizontal drilling activity has intensified efforts within the petroleum industry to understand wellbore stability.[66,67] The removal of rock during the drilling operation disturbs the state of the compressive in-situ stresses in the reservoir. These stresses are redistributed and concentrated around the wellbore and the remaining rock must take on additional load. This is particularly critical in deep fractured reservoirs where the maximum in-situ stress, σ_1, is usually vertical and oriented perpendicular to the long axis of the wellbore (Figure 3).[68] In general, wellbores become less stable as a function of increasing well depth and inclination, thus, deep horizontal wells pose the greatest operational risk. Wellbore instability can occur during the drilling, completion or production phases of wellbore development. The consequences of wellbore instability can be higher drilling and completion costs, irreversible formation damage, and, in the most catastrophic case, wellbore collapse and abandonment.

Operationally, the stability of the wellbore is controllable by its orientation relative to the reservoir's in-situ stress field; the weight of the drilling fluid exerting a radial compressive stress on the surface of the wellbore counteracting the in-situ stresses and the pore pressure, P_i, and the drilling fluid chemistry.[69-71] The magnitude and direction of in-situ stresses, pore pressure and rock failure criterion must be considered when determining whether a reservoir targeted for horizontal drilling is a worthwhile objective. In many cases a compromise is necessary to meet the drilling, production and geological goals of the wellbore. The stability of the wellbore is maximized when it is drilled parallel to the direction of minimum horizontal stress, σ_h, and this orientation may not reflect the direction of maximum fracture intersection. In some cases, it may be necessary to decrease the well inclination allowing for lighter drilling fluid weights and consequently less damage to the formation. The in-situ reservoir conditions will also influence the placement of the horizontal wellbore with respect to zone and azimuth.

Wellbore instabilities can result in lost circulation where tensile failure occurs, when wellbore pressure is reduced such that the surface stress exceeds the compressive strength of the rock and crushing results, and when wellbore pressure is reduced below the reservoir pore pressure and spalling causes the borehole to breakout in the direction of minimum horizontal stress, σ_h.[19]

There are many analytical and numerical models available for the prediction of wellbore instability. McLean and Addis[68] recently compared linear-elastic and finite element methods using constitutive models. A major goal of the model should be to predict the minimum drilling fluid weight necessary to drill a horizontal wellbore safely while minimizing formation damage. Further, it should take into account the in-situ stress magnitude and orientation as well as the failure criterion of the rock.

CORE ANALYSIS

Standard core analysis methods are used to examine the distribution and orientation of fractures in the core. All structures that appear in the rock are oriented in three dimensions with a computerized digitizer. This phase of the laboratory program can be completed in two to three days and these data should be available prior to drilling the horizontal section of the wellbore. The fracture data are presented in rose diagrams or pole plots to illustrate the strike of the fracture planes. This information is compared to the ASR derived in-situ stress orientation to determine whether the natural fracture trend is in agreement with the present-day direction of maximum horizontal stress, σ_H. To confirm the azimuth of in-situ stresses, the microfrac induced fracture in the core is oriented and should be orthogonal to the present-day direction of minimum horizontal stress, σ_h.

Basic full-diameter core analysis procedures are used on fractured rock to measure the porosity, permeability and saturation state of the core. Open fractures enhance the permeability parallel to the fracture trend and this direction can be correlated to the known direction of fracture strike. Unfortunately, the time necessary to extract a core of its fluids and perform basic core analysis may preclude using these data in determination of optimum wellbore azimuth.

Because the majority of naturally occurring fractures will be oriented vertically with respect to the pilot-hole, some risk is involved with extrapolating this fracture analysis to the horizontal well section. For this reason, horizontal core is cut to examine directly the lateral evolution of rock facies, reservoir heterogeneity, vertical fracture spacing and fluid distribution. Fracture spacing is often predictable and periodic as demonstrated by Lorenz[72] in the Cozzette sandstone. Figure 10 shows the distribution of fractures, porosity and oil saturation for a continuous one-hundred foot horizontal core section in the Austin Chalk Formation of South Texas.

CONCLUSIONS

Vertical pilot-hole oriented coring, rock characterization and openhole small-volume-hydraulic fracturing can provide valuable insight to the design of a horizontal wellbore. These formation evaluation tools are used to reduce risk in the drilling of the horizontal wellbore and optimize its placement with respect to in-situ stresses and fracture orientation.

NOMENCLATURE

ϕ	=	*angle of internal friction, degrees [rad]*
α_B	=	*Biot poroelastic constant*
k	=	*bulk modulus of rock, psi [MPa]*
τ_0	=	*cohesive strength of material, psi [MPa]*
V_p	=	*compressional-wave velocity, ft/sec [m/sec]*
σ_c	=	*confining stress, psi [MPa]*
D	=	*depth, ft [m]*
σ'_c	=	*effective confining stress, psi [MPa]*
σ	=	*effective stress, psi [MPa]*
K	=	*formation permeability, md*
ρ	=	*formation bulk density, g/cm^3, as a function of depth, z, ft [m]*
P_f	=	*frac gradient, psi/ft [kPa/m]*
f	=	*fracture pressure, psi [MPa]*
g	=	*gravitational constant, ft/sec^2 [m/s^2]*
$ISIP$	=	*instantaneous shut-in pressure, psi [MPa]*
σ_H	=	*maximum horizontal in-situ stress, psi (MPa)*
σ_1, σ_2, σ_3	=	*maximum, intermediate and minimum in-situ principal stresses*
ε_H	=	*Maximum horizontal in-situ strain*
σ_h	=	*minimum horizontal in-situ stress, psi (MPa)*
ε_h	=	*Minimum horizontal in-situ strain*
σ_n	=	*normal stress, psi [MPa]*
P_o	=	*overburden gradient, psi/ft [kPa/m]*
ν	=	*Poisson's ratio*
p	=	*pore pressure (nonspecific), psi [MPa]*
P_i	=	*pore pressure initial, psi [MPa]*
P_p	=	*pore pressure gradient, psi/ft [kPa/m]*
$\emptyset$	=	*porosity*
τ	=	*shear stress, psi [MPa]*
V_s	=	*shear-wave velocity, ft/sec [m/sec]*
ε	=	*Strain (nonspecific)*
σ_t	=	*tectonic stress [general]*
T_o	=	*tensile strength, psi [MPa]*
C_T	=	*triaxial compressive strength, psi [MPa]*
C_o	=	*uniaxial compressive strength, psi [MPa]*
σ_v	=	*vertical (overburden) stress, psi [MPa]*
E	=	*Young's modulus, psi [MPa]*

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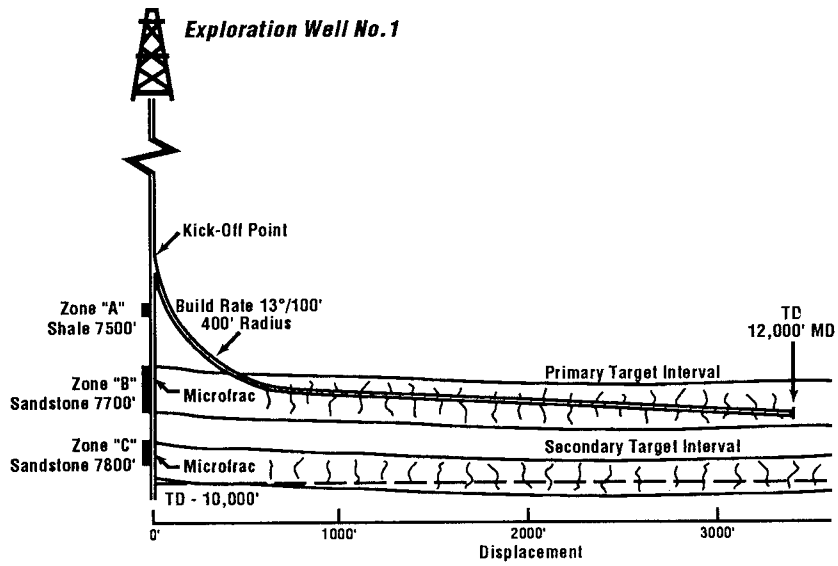

Figure 1 – **Pilot Hole/Horizontal Well Plan.**

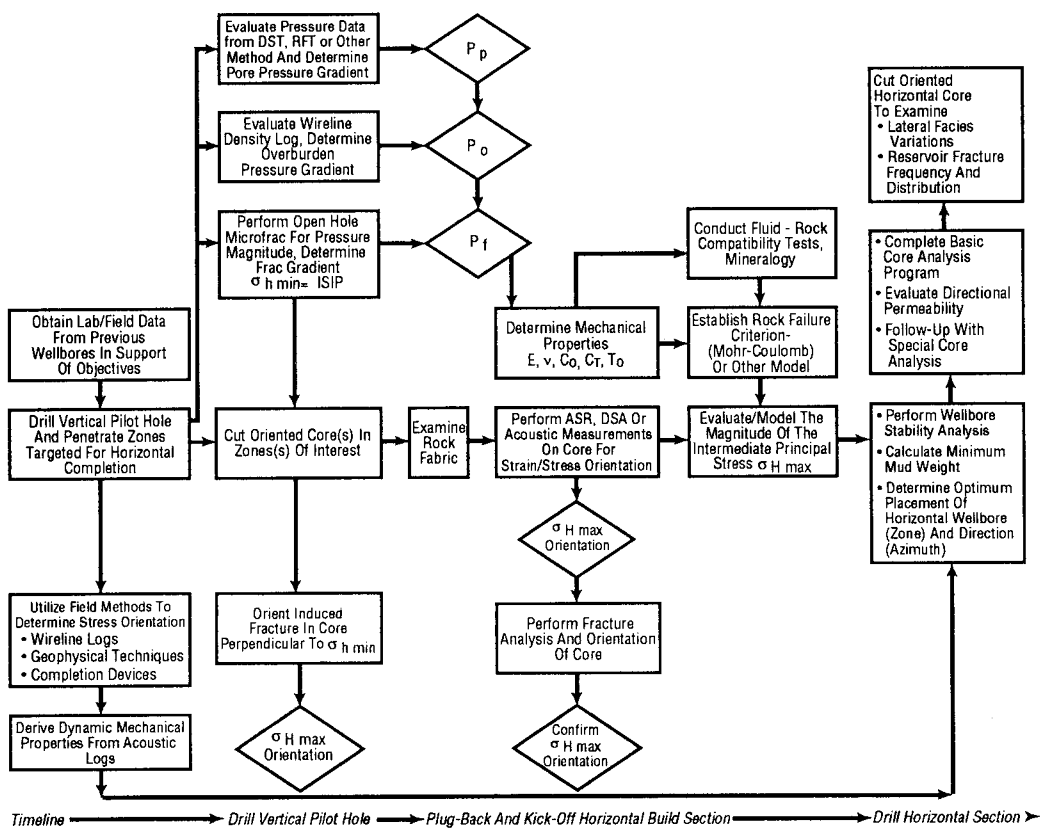

Figure 2 - **Reservoir Properties Critical In Horizontal Drilling.**

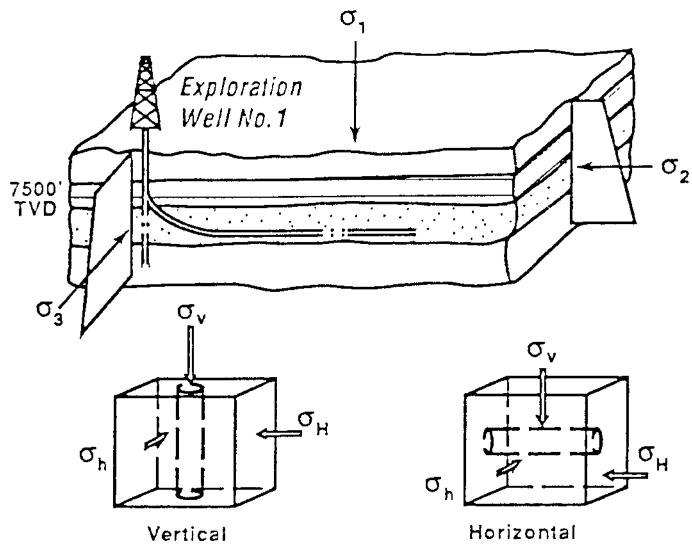

Figure 3 – In-Situ Stress Fields.

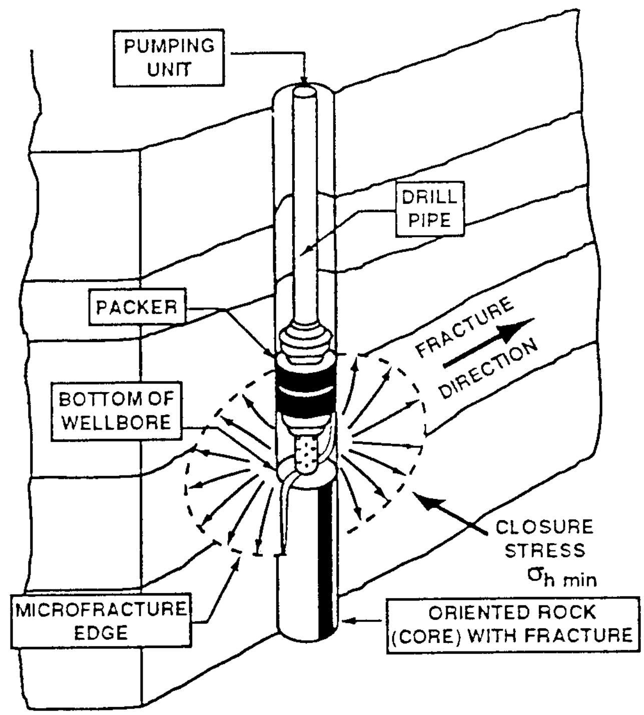

Figure 4 – Openhole Microfracturing.

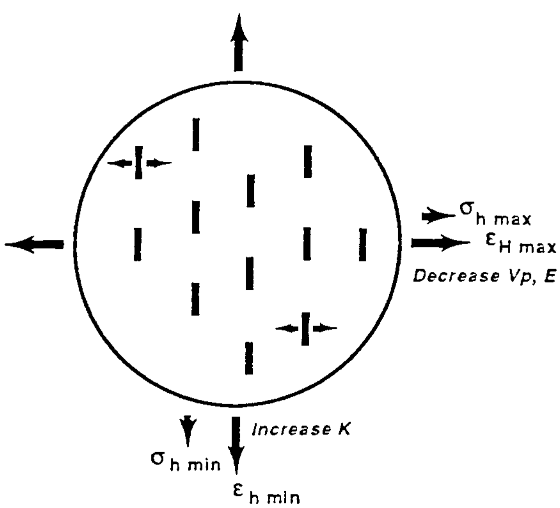

Figure 5 – Microcrack Development.

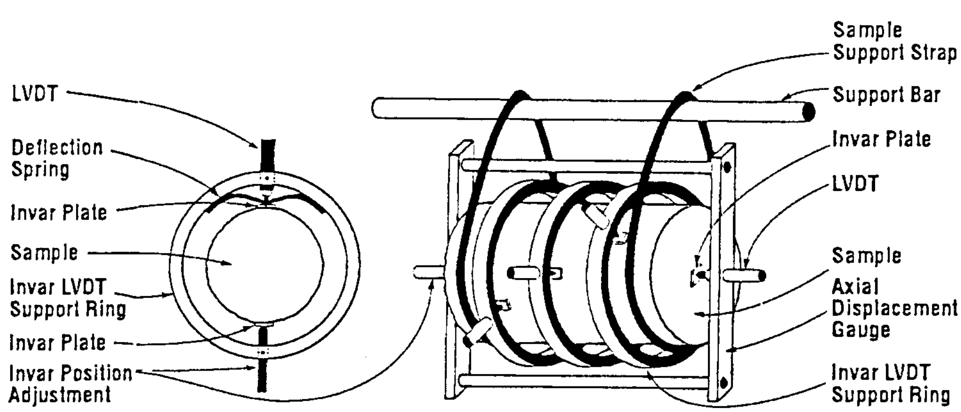

Figure 6 – Anelastic Strain Recovery Assembly.

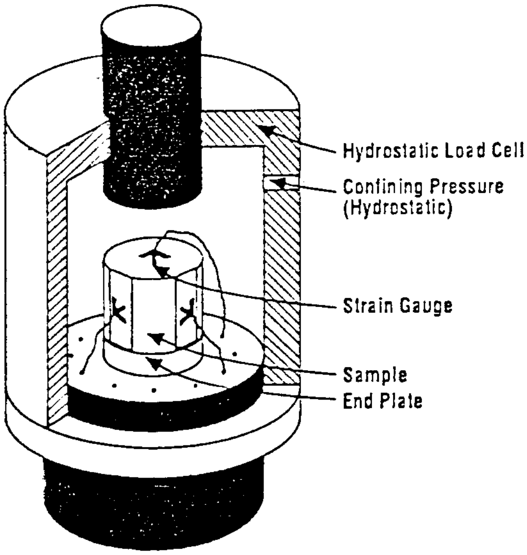

Figure 7 – Apparatus for Differential Strain Curve Analysis.

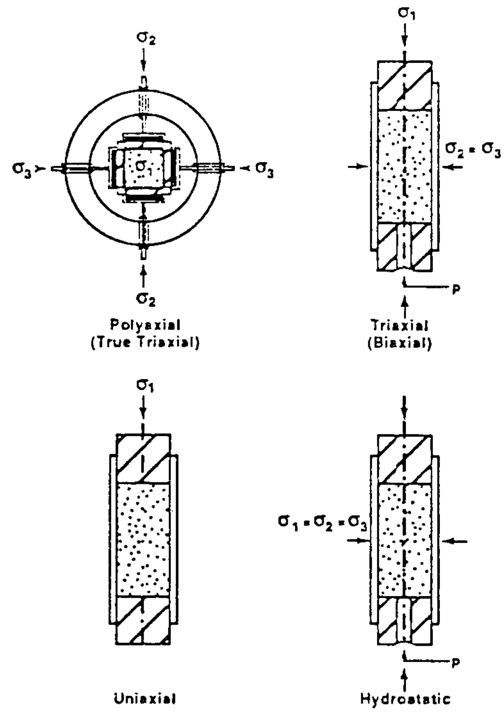

Figure 8 – Laboratory Stress Fields.

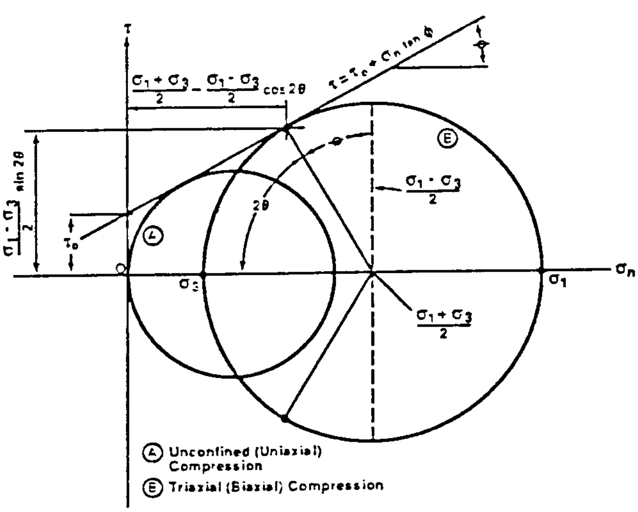

Figure 9 – Mohr-Coulomb Failure Criterion.

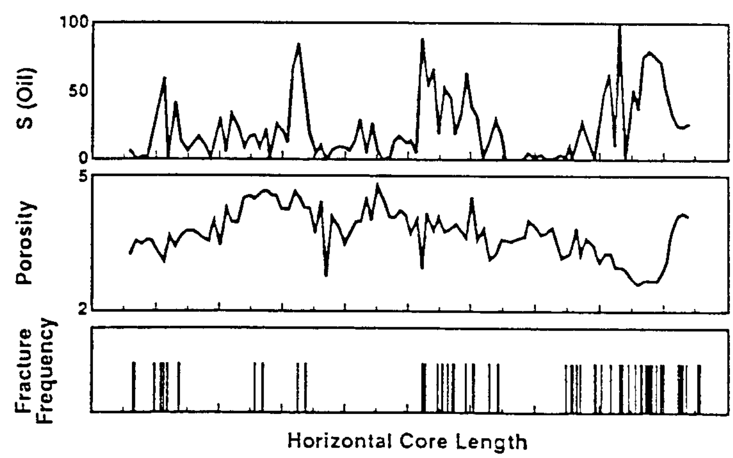

Figure 10 – Horizontal Rock Properties.