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# Discrimination of Natural Fractures from Drilling-Induced Wellbore Failures in Wellbore Image Data—Implications for Reservoir Permeability

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## Abstract

Natural fractures and drilling-induced wellbore failures provide critical constraints on the state of stress in situ and direct applicability to problems of reservoir production, hydrocarbon migration, and wellbore stability. Acoustic, electrical, and optical wellbore images provide the means to detect and characterize natural fracture systems and discriminate these from induced wellbore failures. We present new techniques and criteria to measure and characterize attributes of natural and induced fractures in borehole image data. These techniques are applied to the characterization of fracture permeability in two case studies.

## Introduction

Wellbore image logs are extremely useful for identification and study of a variety of modes of stress-induced wellbore failures. We present examples of how these wellbore failures appear in different types of image data and how they can be discriminated from natural fractures which intersect the wellbore. We then present brief overviews of two studies, which illustrate how the techniques have been applied to address specific issues of fracture permeability.

Drilling-induced failures are ubiquitous in oil and gas and geothermal wells because the process of drilling a well causes a concentration of the far-field tectonic stress close to the wellbore, which can often exceed rock strength. Through use of wellbore imaging and other logging techniques, stress-induced failures can be detected and categorized (compressive, tensile, or shear) and then utilized to estimate the unknown components of the stress field. We demonstrate how these modes of wellbore failures appear in different types of image data and the pitfalls in their interpretation.

The most valuable use of drilling-induced features is to constrain the orientations and magnitudes of the current stress field. The use of drilling-induced features as stress indicators has become routine in the oil and gas industry (Peska and Zoback, 1995; Zoback and Peska, 1995; Willson et al., 1999; Brudy and Kjorholt, 1999;. Stjern et al., 1999; Castillo and Moos, 2000; Wiprut and Zoback, 2000, Brudy and Zoback, 2000 and numerous other authors). The detection of these features at the wellbore wall has become a primary target for LWD/MWD (Logging While Drilling/Measurement While Drilling) real-time operations (Rezmer-Cooper et. al, 2000).

A strong correlation between critically stressed fractures (fractures optimally oriented to the stress field for frictional failure), and hydraulic conductivity has been documented in a variety of reservoirs worldwide (Barton, Zoback and Moos, 1995; Finkbeiner, et al., 1997, Barton et al., 1998). When faults are critically stressed, permeabilities are increased and the movement of fluid along faults is possible. We present examples of how knowledge of the stress state and natural fracture population may be used to access reservoir permeability.

## Drilling-Induced Tensile Wall Fractures

Compressive and tensile failure of a wellbore is a direct result of the stress concentration around the wellbore that results from drilling a well into an already-stressed rock mass (see Moos and Zoback, 1990). Compressive wellbore failures (wellbore breakouts), first identified using caliper data, are useful for determination of stress orientation in vertical wells (Gough and Bell, 1981; Zoback et al., 1985; Plumb and Hickman, 1985). Study of such features with acoustic and electrical imaging devices makes it possible to clearly identify such features and to utilize them for stress magnitude determination as well as stress orientation (Zoback et al., 1985; Barton and Zoback, 1988; Shamir, 1992; Barton et al., 1997).

It is well known that if a wellbore is pressurized a hydraulic fracture will form at the azimuth of the maximum horizontal stress (Hubbert and Willis, 1957). The formation of drilling-induced tensile wall fractures is the result of the natural stress state, perhaps aided by drilling-related perturbations, that causes the wellbore wall to fail in tension.

The general case of tensile and compressive failure of arbitrarily inclined wellbores in different stress fields is described by Peska and Zoback (1995). Peska and Zoback (1995) demonstrate that there is a wide range of stress conditions under which drilling-induced tensile fractures occur in wellbores even without a significant wellbore fluid overpressure. We term these fractures tensile wall fractures as they occur only in the wellbore wall due to the stress concentration. These failures form in an orientation of the maximum, principal horizontal stress in a vertical borehole (Figure 1a) and as en echelon features in deviated wells (Figure 1b). Because drilling-induced tensile wall fractures are very sensitive to the in situ stress they can be utilized for constraining the present state of stress (Hayashi and Abe, 1984; Aadnoy, 1990; Brudy and Zoback, 1993; Okabe et al., 1996; Peska and Zoback, 1995; Zoback and Peska, 1995).

## Pitfalls in Interpretation of Tensile Wall Fractures in Wellbore Image Data

In cases in which drilling-induced tensile fractures form at angle to the wellbore axis it can be difficult to distinguish them from natural fractures (especially in electrical image logs that do not sample the entire wellbore circumference). Because misinterpretation of such features could lead to serious errors in the characterization of a fractured (or possibly not fractured!) reservoir as well as the assessment of in situ stress orientation and magnitude, we present criteria that are useful for discriminating natural from induced tensile fractures when observed in wellbore image logs.

This is especially important because the wellbore stress concentration can have a significant effect on the appearance of natural fractures that intersect the wellbore. It is well known that fractures are mechanically weakened at their intersection with the borehole. This erosion causes the upper and lower “peak” and “trough” of the fracture sinusoid to be enlarged and subsequently enhanced in the standard 2-D unwrapped view of wellbore image data (Figure 2).

Where the borehole hoop stress is tensile, the intersection of a natural fracture or foliation plane with the tensile region of the borehole may be preferentially opened in tension (Figure 3a). These drilling-enhanced natural fractures can be easily mistaken for inclined tensile wellbore failures (Figure 1b) thus resulting in serious errors in geomechanical modeling.

Incipient wellbore breakouts are the early stages of wellbore breakout development where the borehole compressive stress concentration has exceeded the rock strength and initiated breakout development. The failed material within the breakout, however, has not yet spalled into the borehole (Figure 3b). In a vertical borehole these failures may appear as thin “fractures” that propagate vertically in the borehole and may be confused with drilling-induced tensile wall cracks.

Where image data are ambiguous and a possibility of misinterpretation exists, strict criteria need to be used for image interpretation. Both drilling-induced and drilling-enhanced fractures often form a systematic set with similar features over a depth range, for example, in en echelon fashion (Figure 1b, 3a). One of the best methods to discriminate inclined drilling-induced fractures from drilling-enhanced natural fractures is to attempt to fit a flexible sinusoid to the “pair” of features. Because drilling-induced tensile wall fractures are discontinuous around the wellbore circumference (they can only propagate in the tensile region of the borehole) it is not possible to fit them to a sinusoidal shape. In contrast, drilling-enhanced natural fractures can be fit by a flexible sinusoid.

To accurately measure the azimuth and inclination of true induced tensile wall fractures the most effective analysis tool is a specially designed interactive image analysis tool which can be used to fit the orientation and length of induced tensile wall fractures.

Understanding the wellbore stress state is also essential when interpreting possible incipient wellbore breakouts. Incipient breakouts should form in sets of four narrow vertical features unlike induced tensile wall fractures, which will form only two diametrically opposite fractures. If wellbore breakouts are present in the data under investigation the incipient breakouts should form at azimuths consistent with the outer edges of well-developed breakouts within the compressional region of the borehole (see Figure 2b). The best way to analyze wellbore breakouts and incipient wellbore breakouts is through the use of polar cross sections of acoustic wellbore image data.

## Implications for Fractured Reservoirs

In most fractured reservoirs the natural fractures and faults provide the primary pathways for fluid flow. We have used comprehensive in situ stress, fracture and flow information from a number of fractured reservoirs and found that critically stressed faults (the subset of pre-existing faults in a reservoir which are active in today’s stress field) systematically control formation permeability (Barton, Zoback, and Moos, 1995). Thus, while we agree with the many scientists who have suggested that the state of stress may influence fracture transmissivity, it is the critically stressed faults (not mode I tensile fractures, as is generally thought) that are the most permeable fracture planes in situ. We demonstrate how this new, predictable relationship between in situ stress and permeability can be used to optimize production from fractured and faulted hydrocarbon and geothermal reservoirs.

## Fracture and Fluid Flow Analysis

Precision temperature and/or spinner flowmeter logs provide information on the hydraulic conductivity of individual fractures and faults. Fluid flow into or out of individual fractures and faults can be determined through analyses of these temperature and spinner flowmeter logs (see Paillet, 1994). When a borehole is close to thermal equilibrium with the surrounding rock, heat transfer occurs primarily by thermal conduction and the temperature gradient in the borehole is a function of thermal conductivity and heat flux. Localized perturbations to wellbore temperature will result from localized fluid flow in the borehole and can be detected by precision temperature logging. Fractures or faults that correlate in depth with these localized temperature perturbations are therefore considered to be hydraulically conductive. Multi-pass temperature logs at various pumping rates allow the assessment of the persistence of these detected flow horizons. Figure 4 shows an example of wellbore image data correlated with a temperature gradient log for a well in the producing reservoir at Dixie Valley, Nevada.

## Coulomb Failure Analysis

By utilizing results from in situ stress measurements and observations of wellbore failure in wellbore image data we can determine the proximity of fractures and faults to Coulomb (i.e., frictional) failure. To apply the Coulomb criterion to a fracture population, the orientations and magnitudes of the three in situ principal stresses and the formation fluid pressure must be known.

The shear stress and effective normal stress (i.e., $S_n - P_p$) acting on each fracture plane are then functions of the principal stress magnitudes, the fluid pressure, and the orientation of the fracture plane with respect to the orientations of the principal stresses (see Jaeger and Cook, 1976).

The results of a Coulomb failure analysis are depicted as 3-D Mohr diagrams of shear versus effective normal stress. Poles to fracture planes are displayed on the Mohr diagram according to the magnitudes of the shear and effective normal stresses acting on the plane. The shear and effective normal stresses are calculated using the determined principal stress data from the vicinity of the well and the orientations of the fracture planes with respect to the principal stress axes. Poles to critically stressed fracture planes plot above the red Mohr-Coulomb failure line and are shown in red. The slope of the failure line is equal to the friction coefficient assuming zero cohesion. Fractures that lie above the Coulomb failure line for $\mu_f = 0.6$ are critically stressed, potentially active faults in frictional equilibrium with the current in situ stress field. Based upon laboratory measurement of the frictional strength of prefractured rock (Byerlee, 1978), we assume that fractures with a ratio of shear to normal stress $\approx 0.6$ are optimally oriented to the stress field for frictional failure. Fractures that lie below the $\mu_f = 0.6$ Coulomb failure curve are not critically stressed shear fractures. There is an insufficient ratio of shear to normal stress on these fractures to promote slip.

## Reservoir Permeability–Two Examples

The Dixie Valley Geothermal Field, a fault-controlled geothermal reservoir located in the Basin and Range Province of the western United States, has been the focus of a thorough study of the relationship between in situ stress and fracture permeability. The Stillwater fault, an active range bounding normal fault, is the producing reservoir for a geothermal plant operated by Oxbow Geothermal Corporation. However, there are well-documented lateral variations in productivity along the fault that are not fully understood. An ongoing integrated study of the fractured-rock hydrology within and outside the producing reservoir at Dixie Valley demonstrates the relationship between crustal fluid flow and the contemporary in situ stress field in this producing geothermal reservoir (Barton et al., 1998; Hickman and Zoback, 1998).

Sets of borehole televiewer (BHTV), precision temperature, and spinner flowmeter (TPS) logs were recorded from wells within the primary zone of geothermal production (transmissivities on the order of 1 $m^2$/min) and from wells within a few km of the producing zone that were relatively impermeable and, hence, not commercially viable (transmissivities of about $10^{-4}$ $m^2$/min). Using these logs, the natural fractures and faults were measured and their hydrologic properties studied through comparison with fracture-related thermal and flow anomalies. Observations of wellbore failure (breakouts and cooling cracks) together with hydraulic fracturing stress measurements made in these wells provide complete data for a systematic, comparative study of the effects of in situ stress on fracture permeability along producing and nonproducing segments of the fault. Fractures or faults that correlate in depth with localized temperature perturbations are considered to be hydraulically conductive.

The fracture and fluid flow analysis indicates that in both the producing and nonproducing wells there are relatively few fractures that dominate flow. The populations of highly permeable fractures from wells penetrating the producing segment of the Stillwater fault (for example, well 73B-7, Figure 4) clearly define a distinct subset of the total fracture population in each well that is normal to the local direction of the least horizontal principal stress, $S_{hmin}$.

Using the stress orientations and magnitudes measured in these wells together with fracture orientations obtained from BHTV logs, and measured formation fluid pressures, the shear and normal stress on each of the fracture planes was calculated and the Coulomb failure criterion was used to determine whether or not each plane was a potentially active fault. For the example well 73B-7 this analysis was performed for fractures characterized as hydraulically conductive based on spinner flowmeter and temperature gradient logs. For each 1 meter depth interval where no temperature or spinner anomaly was detected, the dominant fracture trend was selected as a control group of non-hydraulically conductive fractures.

Results of our analysis indicate that fracture zones with high measured permeabilities within the producing segment of the fault are parallel to the local trend of the Stillwater fault and are optimally oriented and critically stressed for frictional failure in the overall east-southeast extensional stress regime measured at the site. Figure 6 presents a typical example of the hydraulically conductive fractures identified from well 73B-7. The top part of Figure 6 is a stereographic projection of poles to the permeable fracture planes. The color scale in this plot represents the proximity of these planes to frictional failure. The white dots represent the planes which are critically stressed shear planes. The lower plot in this figure shows the same fracture distribution in 3-D Mohr representation. The red dots are the critically stressed fractures and the black dots are stable planes. Although there is some scatter in the data, most permeable fractures lie above or near the $\mu = 0.6$ Coulomb failure line. Similar results to these presented for well 73B-7 were obtained from our analysis of each commercially productive well of the Dixie Valley field.

In contrast, the majority of non-conductive fractures identified in well 73B-7 lie below the Coulomb failure curve and therefore do not appear to be critically stressed shear fractures (Figure 7). The nonproducing (i.e., relatively impermeable) wells to the south of the producing wells at Dixie Valley were found to have either 1) insufficient shear stress available to drive fault slip, or 2) fracture and fault populations misoriented for normal faulting in the current stress field. In Dixie Valley we found that fault zone permeability is high only when individual fractures as well as the overall Stillwater fault zone are both optimally oriented and critically stressed for frictional failure.

In a second example, stress-induced wellbore breakouts and tensile wall fractures were analyzed in wellbore image data recorded in wells drilled into a producing hydrocarbon reservoir located in the western United States. These wellbore failures were used to determine the full stress tensor throughout the field. The natural fracture population of this shale and sandstone reservoir was also characterized through wellbore image analysis. The primary purpose for the fracture and wellbore failure analysis was to determine the optimal drilling trajectories that serve to expose boreholes drilled in this field to the greatest population of oil-filled fractures.

With the stress orientations and magnitudes constrained it is straightforward to perform the Coulomb failure analysis to determine the set of critically stressed fractures in the reservoir. Figure 8 shows this technique applied to one of the wells of this field which demonstrates the importance of the relationship between the state of stress and fracture permeability. Although there are two significant clusters of natural fractures and bedding planes in this example, only one fracture set is optimally oriented to the stress field. These fractures act as strong hydraulic conductors because the crust is in frictional equilibrium and therefore conducive to repeated stress-induced slip.

To exploit the maximum number of critically stressed fractures in this portion of the field, the optimal borehole trajectory should be toward the southwest with inclinations of roughly 70°. This would correspond to a trajectory drilled in the direction of the cluster of white dots in the stereographic projection in Figure 8. In support of this analysis steeply inclined wells drilled to the southwest in this field do have relatively high hydrocarbon production. Production in wells drilled in other directions in this field is characterized as poor to nonexistent.

## Summary

Wellbore image interpretation is an important aspect of geomechanical modeling. The discrimination between drilling-induced and natural phenomena in borehole data is best guided by use of a set of specialized image analysis tools and an understanding of wellbore geomechanics. Misinterpretation of wellbore images can lead to significant error in geomechanical modeling and hence inappropriate analyses of reservoir permeability and wellbore stability.

The performance of low permeability, fractured, and often overpressured reservoirs is controlled by the in situ state of stress and by the distribution and orientation of natural fractures and faults. Only a subset of the total number of fractures is likely to be permeable, and the orientation of this subset is controlled by the state of stress. Maximizing productivity in fractured reservoirs requires intersecting the greatest number of permeable fractures.

The high degree of correlation found between critically stressed faults and hydraulic conductivity in a variety of wells drilled to mid-crustal depths appears to hold regardless of the type of reservoir fluid or the reservoir lithology.

## Acknowledgments

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## Nomenclature

$P_p$ = Pore fluid pressure, MPa

$S_{hmin}$ = Minimum horizontal principal stress, MPa

$S_n$ = Effective normal stress, MPa

$m_f$ = Sliding friction coefficient

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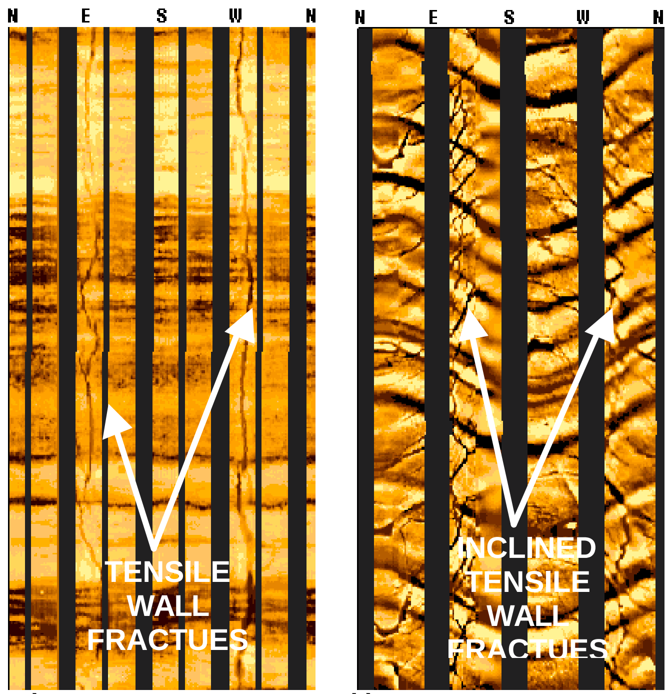



a) b)

**Fig. 1a Electrical image data showing typical drilling-induced tensile wall fractures in a vertical borehole and inclined tensile fractures in a deviated borehole (b). Note that electrical image data are acquitted using pad tools and as such the logs do not sample the complete wellbore circumference.**

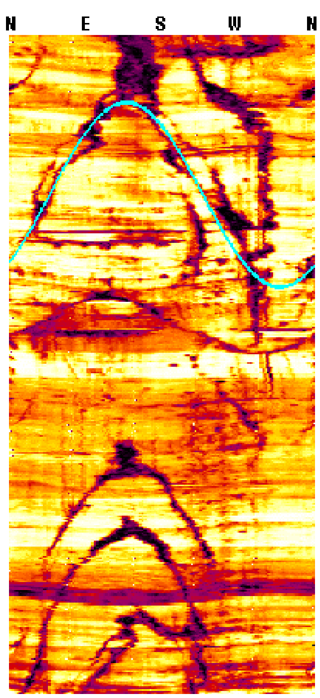
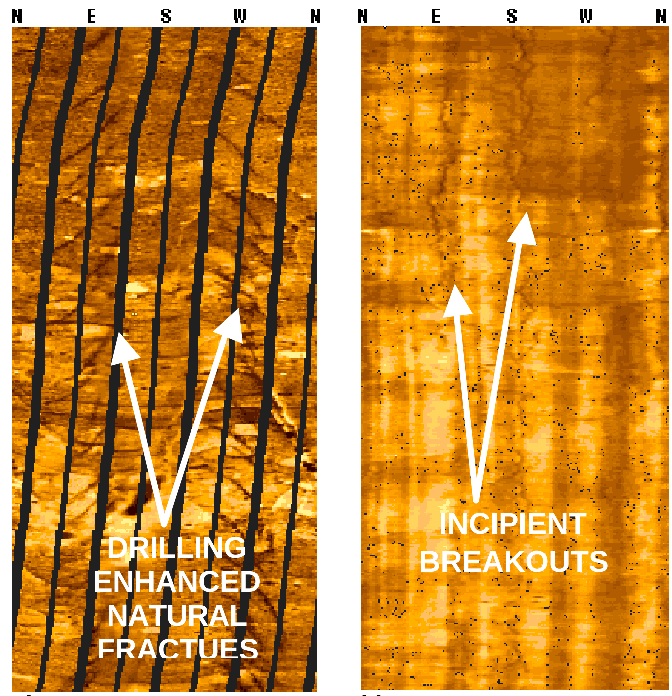
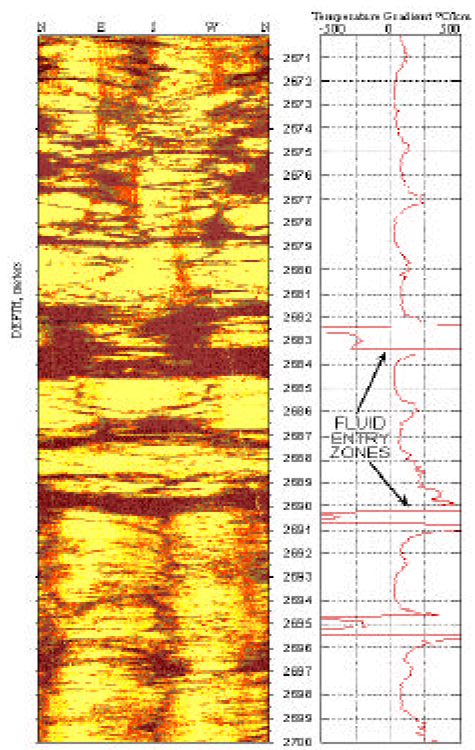



**Fig 2. Standard 2-D "unwrapped" view of acoustic image data showing the preferential erosion of the peak and trough of fractures intersecting a wellbore. The vertical axis is depth and the horizontal axis is azimuth around the wellbore. Color represents the amplitude of the reflected acoustic signal.**




a) b)

**Fig. 3a Electrical image data showing drilling-enhanced fractures in a vertical borehole and incipient wellbore breakouts detected in acoustic image data (b).**




a) b)

**Fig. 4a High-temperature borehole televiewer data recorded over the interval 2670–2700 m in well 37-33 located in the producing reservoir at Dixie Valley correlated with temperature gradient data recorded over the same interval (b).**

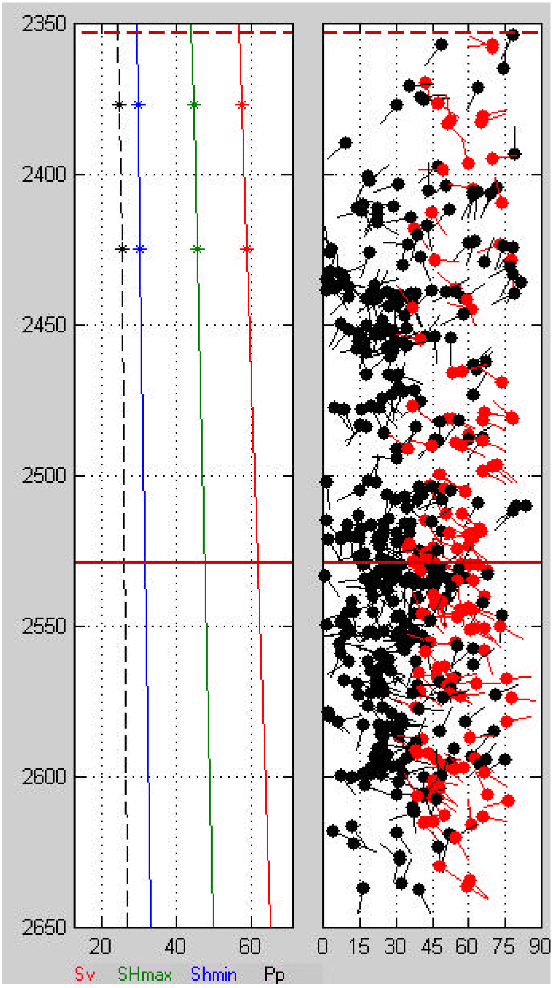



**Fig. 5 Principal stress magnitudes after Hickman and Zoback, 1998, (left plot) and natural fracture population (right plot) measured in well 73B-7 at the Dixie Valley Geothermal Field in Nevada. The fracture tadpoles shown in red define the subset of optimally oriented and critically stressed fractures in this well.**

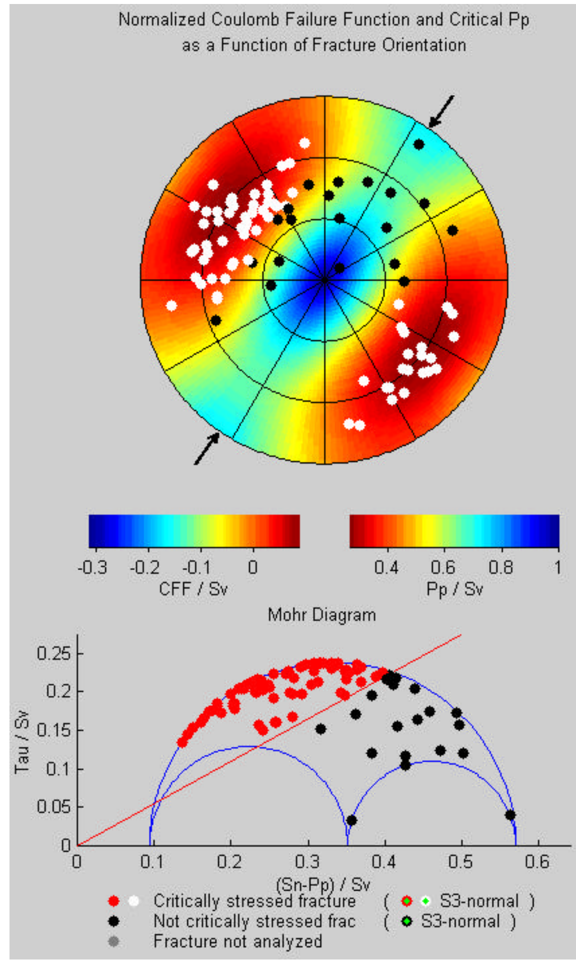



**Fig. 6 Upper plot shows lower hemisphere stereographic projection of poles to hydraulically conductive fracture planes in Dixie Valley well 73B-7. White dots represent the poles of fractures that are both optimally oriented and critically stressed for frictional failure. Lower plot is a 3-D Mohr diagram including the Coulomb frictional failure line. Red color represents critically stressed fracture planes. Note that the majority of hydraulically conductive fractures lie above the Coulomb failure line and can maintain permeability through repeated stress-induced slip.**

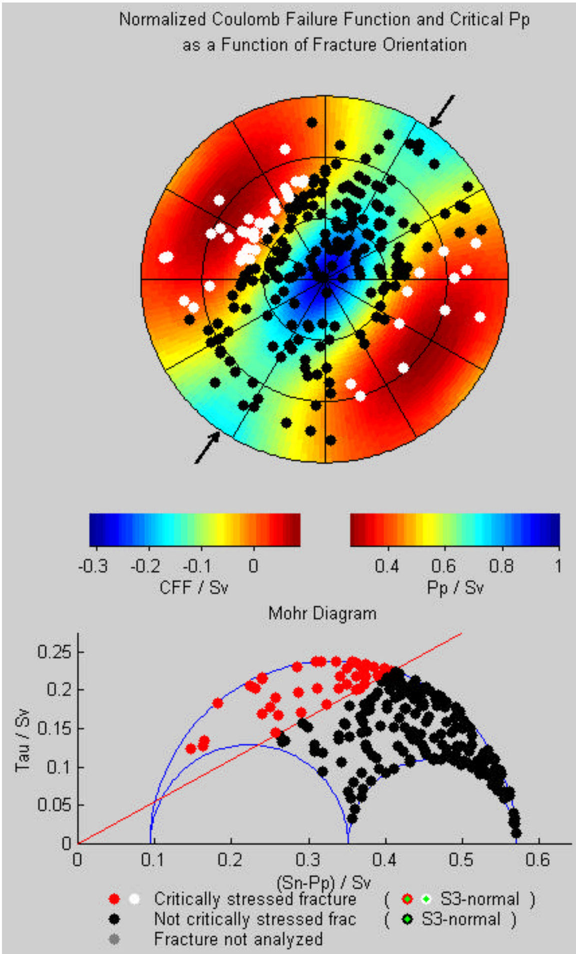



**Fig. 7 Upper plot shows lower hemisphere stereographic projection of poles to non-hydraulically conductive fracture planes in Dixie Valley well 73B-7. White dots represent the poles of fractures that are both optimally oriented and critically stressed for frictional failure. Lower plot is a 3D Mohr diagram including the Coulomb frictional failure line. Red color represents critically stressed fracture planes. Note that the majority of non-hydraulically conductive fractures lie near or below the Coulomb failure line and are therefore stable planes.**

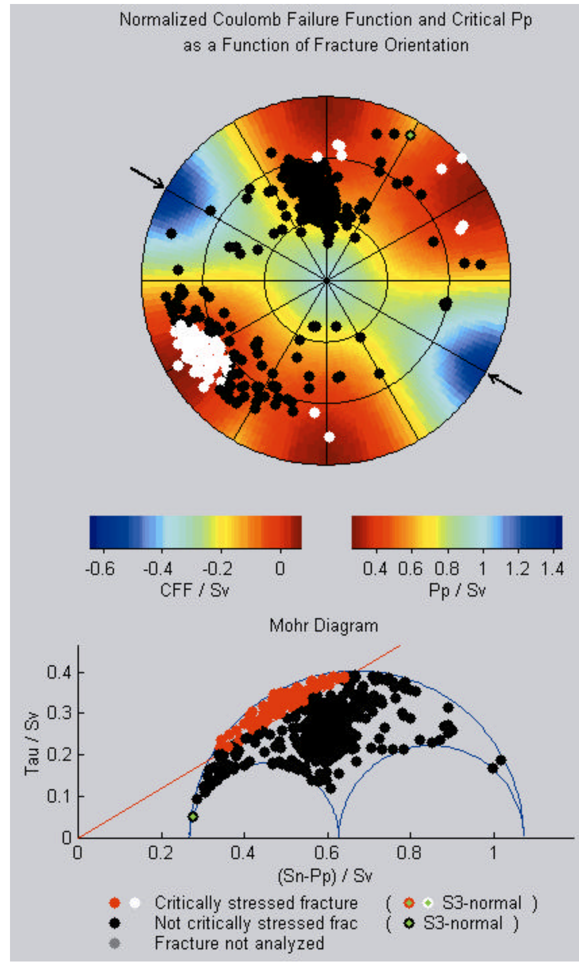



**Fig. 8 Upper plot shows lower hemisphere stereographic projection of poles to all fracture planes in a well located in a producing hydrocarbon field in the western United States. The white dots represent the poles of fractures that are both optimally oriented and critically stressed for frictional failure. The lower plot is a 3-D Mohr diagram including the Coulomb frictional failure line. Red color represents critically stressed fracture planes. Note that the optimal trajectory for drilling a well perpendicular to the greatest population of critically stressed fractures is to the southwest.**