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Earth stress, rock fracture and wellbore failure — Wellbore imaging technologies applied to reservoir geomechanics and environmental engineering

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ABSTRACT

Drilling-induced wellbore failures provide critical constraints on the in situ state of stress. Knowledge of the relationship between natural fracture systems and tectonic stresses has direct application to problems of reservoir performance, 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 to distinguish attributes of natural fractures and induced failures in borehole image data. We apply knowledge of natural fracture systems and the in situ state of stress to reservoir permeability and geotechnical site characterization studies.

KEY WORDS: Reservoir characterization, fractures, permeability, imaging

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 are used to constrain the orientation and magnitudes of in situ stresses. We then present brief overviews of two studies, which illustrate how the techniques have been applied to address specific issues of stress determination and 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

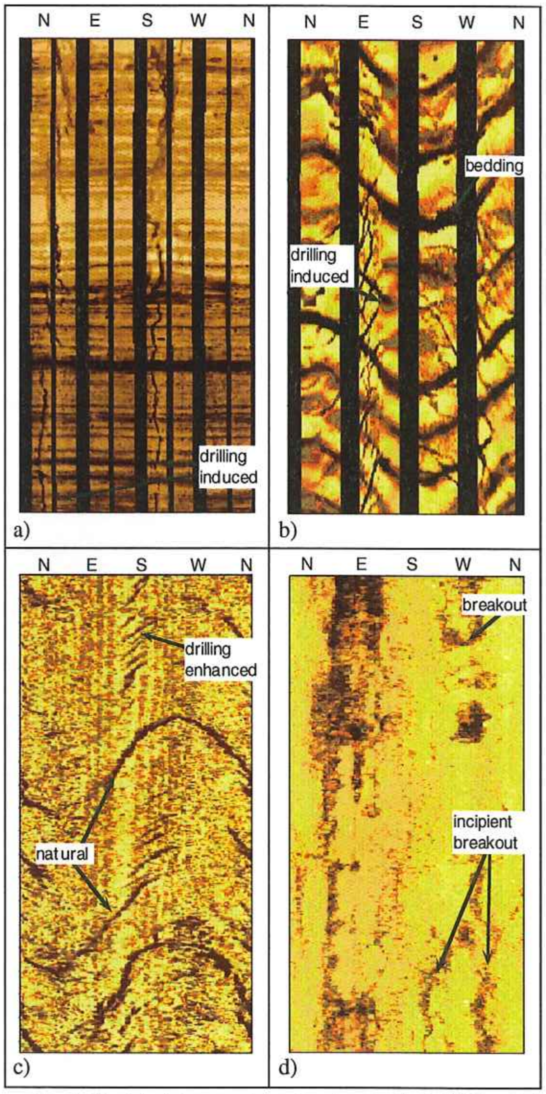

Figure 1. a) Electrical image data showing typical drilling induced tensile wall fractures in a vertical borehole and inclined tensile fractures in a deviated borehole (b); c) acoustic image data showing drilling enhanced fractures in a vertical borehole, and incipient wellbore breakouts in a vertical borehole (d).

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.

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 imaging devices (Zoback et al, 1985; Barton, Shamir) makes it possible to clearly identify such features and to utilize the for stress magnitude determination as well as stress orientation (Barton et al., 1988;)

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 are 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). As 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 mechanical 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 2D unwrapped view of wellbore image data.

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 1c). 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 1d). 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). 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 1d). The best way to analyze wellbore breakouts and incipient wellbore breakouts is through the use of polar cross sections or telescoping polar 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 workers 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. In environmental and geotechnical

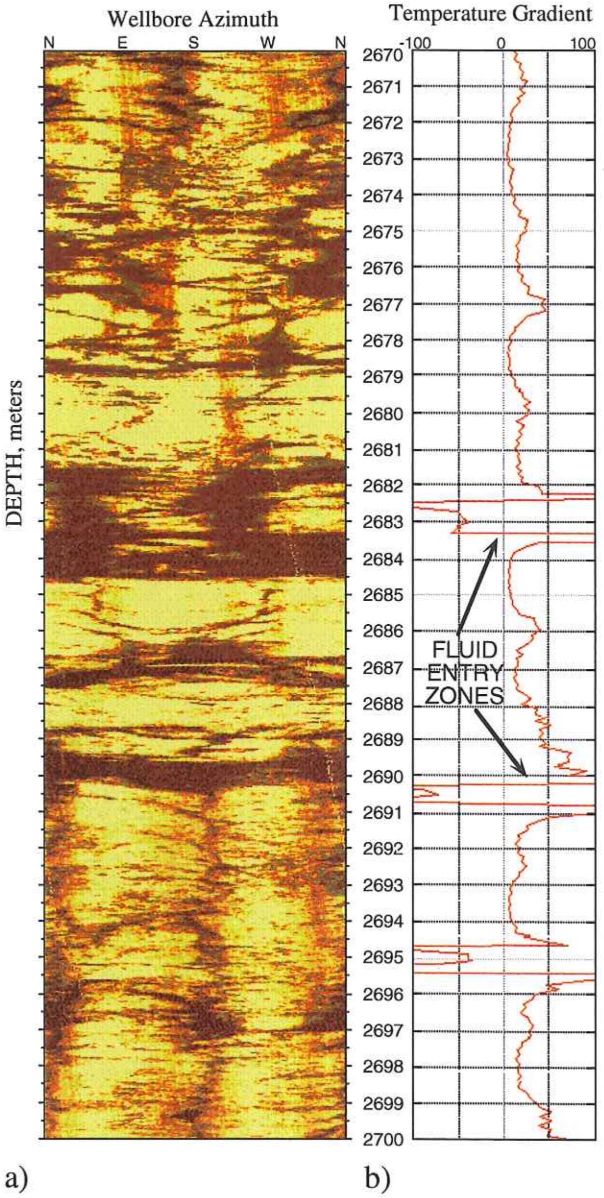

Figure 2. (a) High-temperature borehole televiewer data recorded over a 30 meter interval in a well located in the producing reservoir at Dixie Valley correlated with temperature gradient data recorded over the same interval (b).

applications, the identification (and prediction) of permeable fracture systems along which contaminants or groundwater can flow is a primary target in most site characterization studies. We demonstrate how the technologies we have developed to analyze and characterize fracture systems and determine the state of in situ stress can be directly applied to shallow fractured aquifers as well as reservoirs at depth.

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 2 shows an example of wellbore image data correlated with a temperature gradient log for a well in the producing reservoir at Dixie Valley, NV.

COULOMB FAILURE ANALYSIS

By utilizing results from in situ stress measurements and observations of wellbore failure in wellbore image data we can determined 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 Coloumb failure analysis are depicted as 3-D Mohr diagrams of shear versus effective normal stress (see Figure 5 below and refer to Jaeger and Cook, 1976 for an explanation of the construction of these diagrams). Fractures that lie between the Coloumb failure lines for $\mu = 0.6$ and $\mu = 1.0$ 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 ≥ 0.6 are optimally oriented to the stress field for frictional failure. Fractures that lie below the $\mu = 0.6$ Coloumb failure curve are not critically stressed shear fractures. There is an insufficient ratio of shear to normal stress on these fractures to promote slip.

DEEP RESERVOIR PERMEABILITY — THE DIXIE VALLEY CASE STUDY

The Dixie Valley Geothermal Field is a fault-controlled geothermal reservoir located in the Basin and Range Province of the western United States. 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 and 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 fracture 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.

Within the producing reservoir the dominant fracture strike is north to northeast (parallel to the local trend of the Stillwater fault) with shallow to moderate dips to the east or west (Figure 3, left column). Wells drilled into the relatively impermeable segments of the Stillwater fault located 8 and 20 km southwest of the main reservoir show well-developed sets of moderate to steeply dipping fractures (Figure 3, right column). In contrast to the fracture populations measured in wells drilled into the producing fault segments, however, the nonproductive wells have no significant population of low-angle fractures. The lack of low-angle fractures in these wells may impede fracture connectivity with the reservoir.

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, wells 73B-7 and 74-7, 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}. The populations of relatively permeable fractures in the two most southerly study wells (66-21 and 45-14, Figure 4) are somewhat different from the permeable fracture populations observed in the other wells. The more permeable fractures in well 66-21 generally strike in a more easterly direction than do the highly permeable fractures in the producing wells, but they remain approximately perpendicular to the local orientation of S_{hmin}. The orientations of relatively permeable fractures in well 45-14 are unusual in that they are not related in any simple way to the local direction of S_{hmin}.

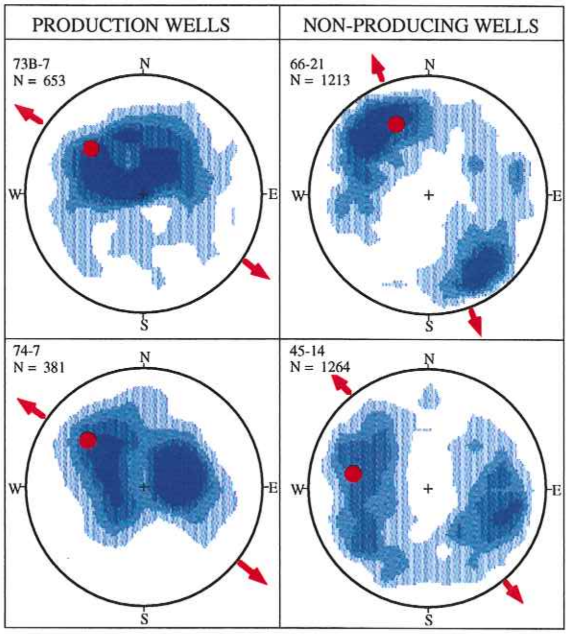

Figure 3. Kamb contours of poles to fracture planes for producing (left column) and nonproducing (right column) wells in Dixie Valley. The high permeability wells 73B-7 and 74-7 and the low permeability wells 66-21 and 45-14 penetrated the Stillwater fault zone at depths of 2-3 km. Hachured circles represent poles to the local trend of the Stillwater fault adjacent to each study well. Arrows indicate the orientation of S_{hmin} measured in each well by Hickman and Zoback (1998).

The absence of wellbore breakouts in the producing wells places an upper bound on S_{Hmax} magnitude. The presence of wellbore breakouts in wells 45-14 and 66-21 provides strong evidence that S_{Hmax} is higher outside the producing zone than it is within the production zone, with the magnitude of S_{Hmax} along the nonproducing segments of the fault being greater than or equal to S_V.

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 Coloumb failure criterion was used to determine whether or not each plane was a potentially active fault. This analysis was performed for all fractures and for the subsets of hydraulically conductive fractures both within and outside the producing segment of the fault.

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

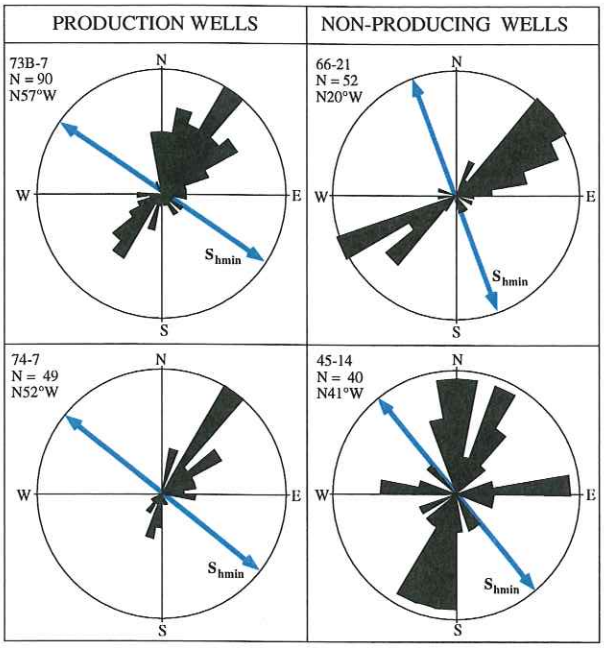

Figure 4. Histograms showing the subset of fractures from Figure 3 that are hydraulically conductive from the producing (left column) and non-commercial (right column) wells at Dixie Valley. The orientation of S_{hmin} is from Hickman and Zoback (1998).

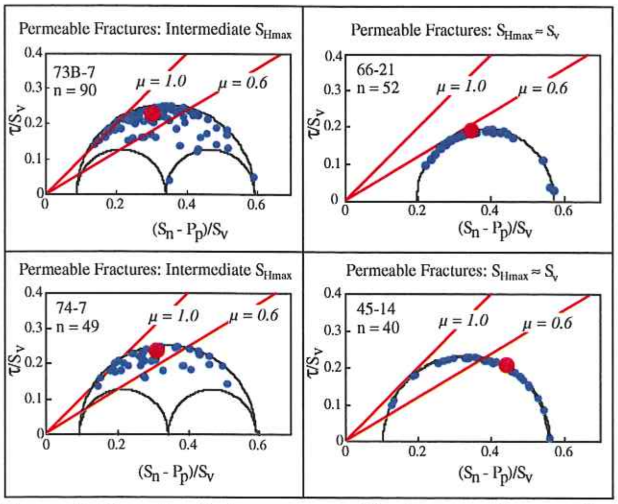

Figure 5. Normalized shear versus effective normal stress for hydraulically conductive fractures in the producing (left column) and non-commercial (right column) wells. Large hachured circles represent the shear and normal stresses for the Stillwater fault in proximity to each of the study wells.

stressed for frictional failure in the overall east-southeast extensional stress regime measured at the site (Figure 5, left column).

In contrast, in the nonproducing well 66-21 the higher ratio of S_{hmin} to S_V acts to decrease the shear stress available to drive fault slip. Thus, although many of the fractures at this site (like the Stillwater fault itself) are optimally oriented for normal faulting, they are not critically stressed for frictional failure (Figure 5).

Although some of the fractures observed in the nonproducing well 45-14 are critically stressed for frictional failure, the Stillwater fault zone itself is frictionally stable (Figure 5) The Stillwater fault zone in proximity to well 45-14 is severely missoriented for normal faulting in the current stress field.

A high horizontal differential stress together with the severe missorientation of the Stillwater fault zone for normal faulting at this location appear to dominate the overall potential for fluid flow.

SHALLOW RESERVOIR PERMEABILITY — THE ADCOH CASE STUDY

In regions where competent basement rock outcrops close to the surface in situ stress measurements can be made in a straightforward manner. It is precisely these cases, where shallow bedrock is the target lithology of a site investigation, where fluid flow is expected to be fracture controlled. The southeastern United States provides an excellent example of such a case. Wellbore image, hydraulic fracturing, and precision temperature log data were recorded in shallow (<300 m) wells near the border of North Carolina and Georgia as part the Appalachian Deep Corehole site investigation in 1985. Well ADCOH #2 was drilled into the gneissic and phyllitic rocks of the Brevard Fault Zone and ADCOH #4 into the schists and gneisses of the Blue Ridge.

Hydraulic fracturing stress measurements were made at multiple depths in these wells and indicate a reverse faulting state of stress consistent with the current regional Appalachian compressional tectonics. Values of the least horizontal principal stress, S_{hmin}, in Well ADCOH #2 lies close to the vertical stress indicating the stress state is more reverse/strike slip than well #4 drilled in the Blue Ridge which shows a pure reverse faulting state of stress (Figure 6). Pre and post hydrofrac borehole televiewer logging reveal the orientation of the induced hydraulic fractures to be northeast – southwest, an orientation consistent with other in situ stress measurements made in

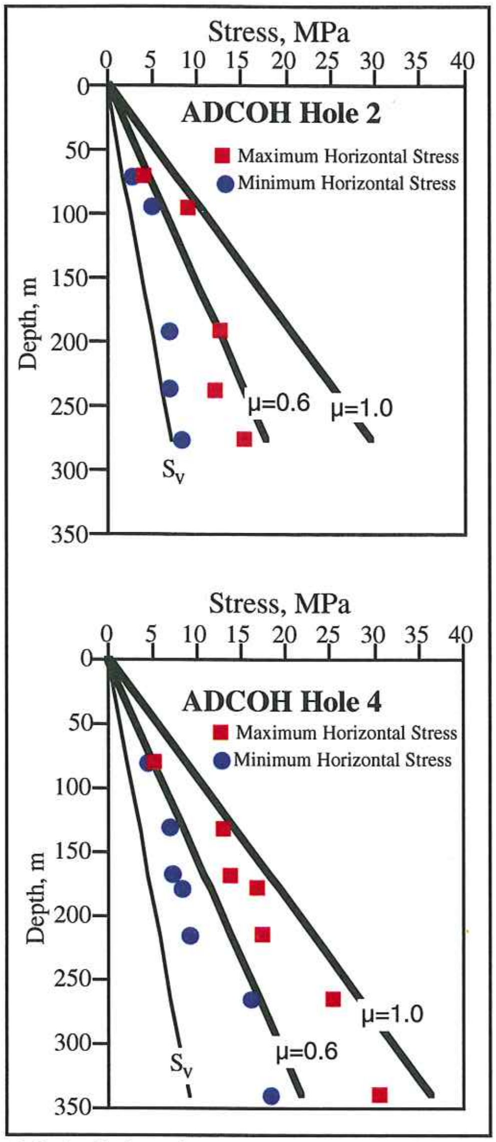

Figure 6. Hydraulic fracturing stress measurements made in wells #2 and #4 of the ADCOH study site indicating a reverse faulting state of stress in the shallow crust.

the shallow crust and at depth in the Southeast United States (Moos and Zoback, 1993).

The depth distribution and relative aperture of natural fractures were measured from borehole televiewer data recorded in the study wells. The measured fracture population for well ADCOH #2 is predominately high angle oriented in the direction of the maximum horizontal principal stress (Figure 7a). These fracture sets are likely related to the development of the extensional basins along the eastern margin of North America during the Triassic. Well ADCOH #4 also has a well developed high-angle fracture population in addition to a distinct population of more shallow east dipping fracture set (Figure 7b).

Precision temperature data were recorded in each of the site investigation wells (J. Costain personal communication). The temperature gradients computed from the temperature logs recorded in each well show significant variation with depth indicating fluid flow at the borehole wall along relatively permeable fractures and faults. The depth locations of significant temperature anomalies were used to determine the population of hydraulically conductive fractures in each fracture set (light gray symbols, Figure 7).

The hydraulically conductive fractures in well ADCOH #2 are high angle as is the predominant fracture population and cannot be readily distinguished from the overall fracture orientation. The hydraulically conductive fractures in well ADCOH #4, however, form a distinct subset in the overall fracture population correlating with the moderate to shallow east dipping fracture set (Figure 7b, black symbols).

Coulomb failure analysis of the fracture populations from these shallow wells clearly shows that hydraulically conductive fractures are critically stress and optimally oriented for frictional failure in the measured stress field in these wells (Figure 8).

Where there are two distinct fracture populations in well ADCOH #4 the subset of hydraulically conductive

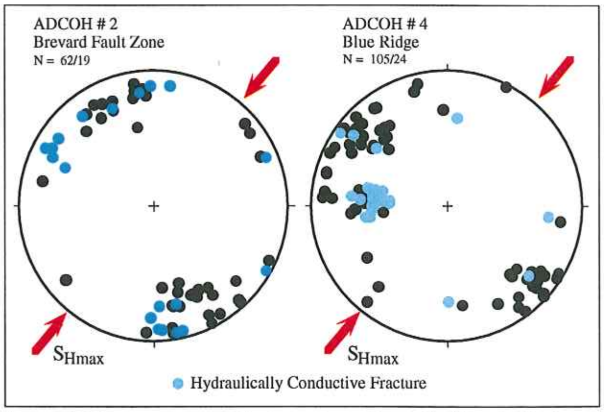

Figure 7. Poles to measured fracture planes for wells #2 and #4 of the ADCOH study site. Fractures that depth correlate with temperature gradient anomalies are shown in light gray.

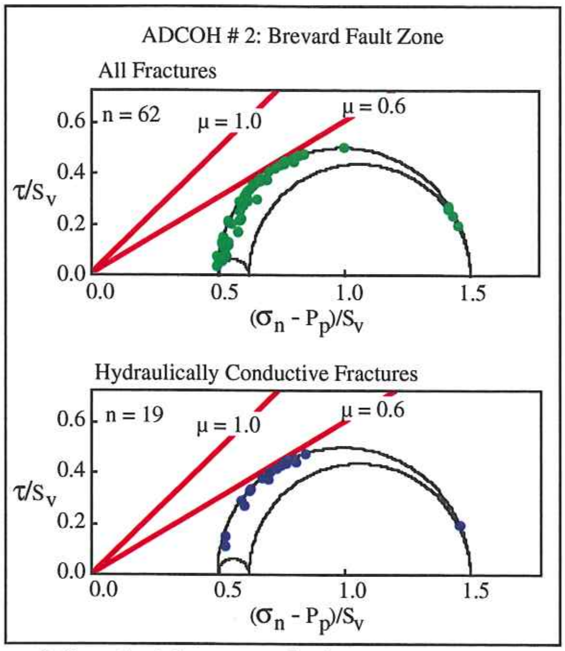

Figure 8. Normalized shear versus effective normal stress for all measured fractures in well ADCOH #2 (top) and for hydraulically conductive fractures (bottom) of the ADCOH study site.

fractures is optimally oriented for reverse faulting in the present day stress field (Figure 9). Higher angle fractures that correlate with fluid flow anomalies are likely ancient normal faults reactivated in a reverse sense of slip.

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.

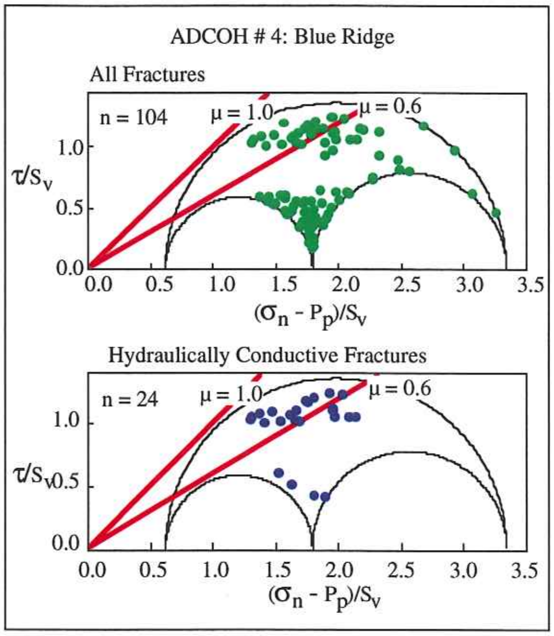

Figure 9. Normalized shear versus effective normal stress for all measured fractures in well ADCOH #4 (top) and for hydraulically conductive fractures (bottom) of the ADCOH study site.

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 in the near surface providing a new technique to characterize the hydrology of the shallow crust.

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REFERENCES

Aadnoy, B.S., 1990, In-situ stress direction from borehole fracture traces: J. Pet. Sci. Eng., **4**, 143-153.

Brudy, M. and M.D. Zoback, 1993, Compressive and tensile failure of boreholes arbitrarily-inclined to principal stress axis: Application to the KTB boreholes, Germany, 34th U.S. Rock Mech. Symposium, Int'l. Jour. Rock Mech. Min. Sci. and Geomech. Abstr. **30** (7), 1035-1038.

Barton, C. A., S. Hickman, R. Morin, M. D. Zoback, and D. Benoit, 1998, Reservoir-scale fracture permeability In the Dixie Valley, Nevada, geothermal field, SPE/ISRM: 47371, in Proceedings of Eurock '98, Rock Mechanics in Petroleum Engineering, July, Trondheim, Norway.

Barton, C. A., M. D. Zoback, and D. Moos. Fluid flow along potentially active faults in crystalline rock, *Geology*, **23,** 8, 683–686 (1995).

Barton, C.A., Zoback, M.D., and Burns, K.L. 1988, In-situ stress orientation and magnitude at the Fenton geothermal site, New Mexico determined from wellbore breakouts. Geophys. Res. Let., **15**, 467-470.

Hayashi, K and H. Abe, 1984, A new method for the measurement of in situ stress in geothermal fields, J. Geothermal Res. Soc. Japan, **6**, 203-212.

Hickman, S., and M. D. Zoback,. 1998, Tectonic controls on fracture permeability in a geothermal reservoir at Dixie Valley, Nevada, SPE/ISRM: 47213, in Proceedings of Eurock '98, Rock Mechanics in Petroleum Engineering, July, Trondheim, Norway.

Hubbert, M.K. and D.G. Willis, 1957, Mechanics of hydraulic fracturing, AIME Trans., 210, 153-168.

Jaeger, J. C. and Cook, N. G. W., 1979, *Fundamentals of Rock Mechanics* (Third Edition): New York: Chapman and Hall, pp. 28–30.

Moos, D., and M.D. Zoback, 1993, Near-surface, "thin skin" reverse-faulting stresses in the southeastern United States, 34th US Symposium on Rock Mechanics; Int. J. Rock. Mech. Min. Sci. & Geomech. Abstr. **30** (7), 965-971.

Moos, D. and M.D. Zoback, 1990, Utilization of observations related to wellbore failure to constrain the orientation and magnitude of crustal stresses: Application to continental, DSDP and ODP boreholes, J. Geophys. Res., 95, 9305-9325.

Okabe, T. N. Shinohara and S. Takasugi, 1996, Earth's crust stress field estimation by using vertical fractures caused by borehole drilling, in Proceedings of the 8th Int. Symp. on the Observation of the Continental Crust Through Drilling, Tsukuba, Japan, Feb 26-28.

Paillet, F.L. and Ollila, P.:, 1994, "Identification, Characterization, and Analysis of Hydraulically Conductive Fractures in Granitic Basement Rocks, Millville, Massachusetts", *Water Resources Investigations, U.S.G.S.*, WRI, 94-4185.

Peska, P., and Zoback, M.D., 1995, Compressive and tensile failure of inclined wellbores and determination of in situ stress and rock strength, J. Geophys. Res. **100**, B7, 12,791- 12,811.

Plumb, R.A., and Hickman, S.H., 1985, Stress-induced borehole elongation – a comparison between the four-arm dipmeter and the borehole televiewer in the Auburn geothermal well: Journal of Geophysical Research, **90**, no. B7, 5513-5521.

Shamir, G. and M. D. Zoback, 1992, Stress orientation profile to 3.5 km depth near the San Andreas fault at Cajon Pass, California, Journal of Geophysical Research, **97**, 5059-5080.

Zoback, M.D. and P. Peska, 1995, In-situ stress and rock strength in the GBRN/DOE Pathfinder Well, South Eugene Island, Gulf of Mexico, Journal of Petroleum Technology, July, 582-585.

Zoback, M.D., D. Moos, L. Mastin, and R.N. Anderson. 1985, Wellbore breakouts and in-situ stress. J. Geophys. Res., **90**, 5523-5530.