Critically-Stressed Faults in the Yucca Mountain Area and Observations of Complete Stress Drop

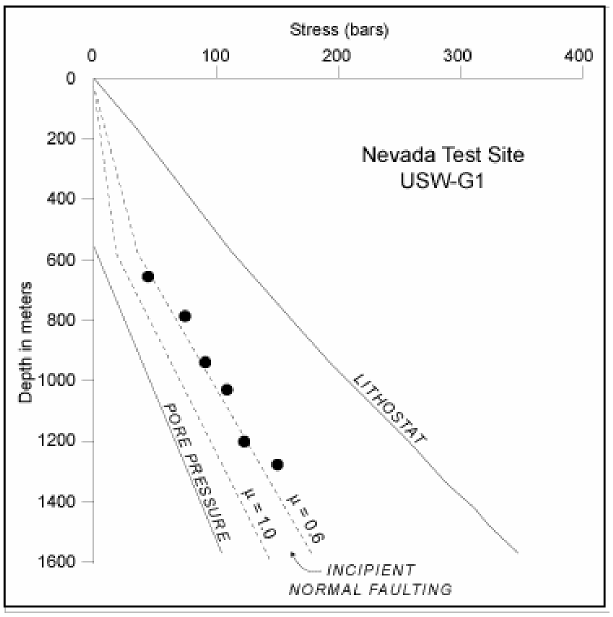
Mark Zoback
Department of Geophysics
Stanford University
Stanford, CA 94305

Abstract

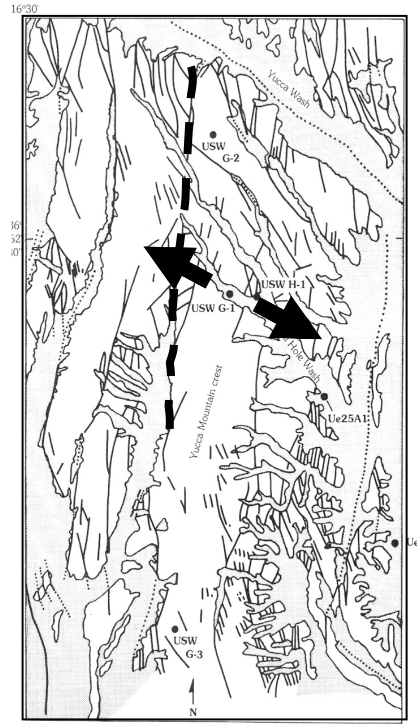
In situ stress data from the Yucca Mountain area indicate that the state of stress at depth is consistent with predictions of Coulomb faulting theory and laboratory-derived coefficients of friction. Similar data from other deep boreholes around the world that similarly imply that the state of stress in the earth's crust is generally in a state of frictional failure equilibrium. Anomalies of stress orientation observed in a number of these boreholes indicate that slip on critically-stressed faults cause stress variations of stress at a variety of scales. Dislocation modeling of these stress rotations (and observations of anomalous stress magnitudes in normal faulting areas) indicate that near-complete stress drop (on the order of 10-15 MPa) appears to have occurred on many faults.

Introduction

As illustrated in Fig. 1a, the magnitude of in situ stress near Yucca Mountain, as measured in relatively deep boreholes, is consistent with the values predicted from Coulomb faulting theory for critically-stressed normal faults [*Stock and Healy*, 1988; *Stock et al.*, 1985; *Zoback and Healy*, 1984]. This means that relatively small stress perturbations are required to activate movement on normal faults in the area that strike perpendicular to the least principal stress. The stress magnitudes shown in Fig. 1a are confirmed by the occurrence of drilling induced hydraulic fractures (and lost circulation) as the holes were being drilled. As shown in Fig. 1b, the direction of least principal stress in this area is approximately E-W, hence the N-S striking Solitario Canyon fault (dashed line in Fig. 1b) should be considered a well-oriented normal fault.



a)



b)

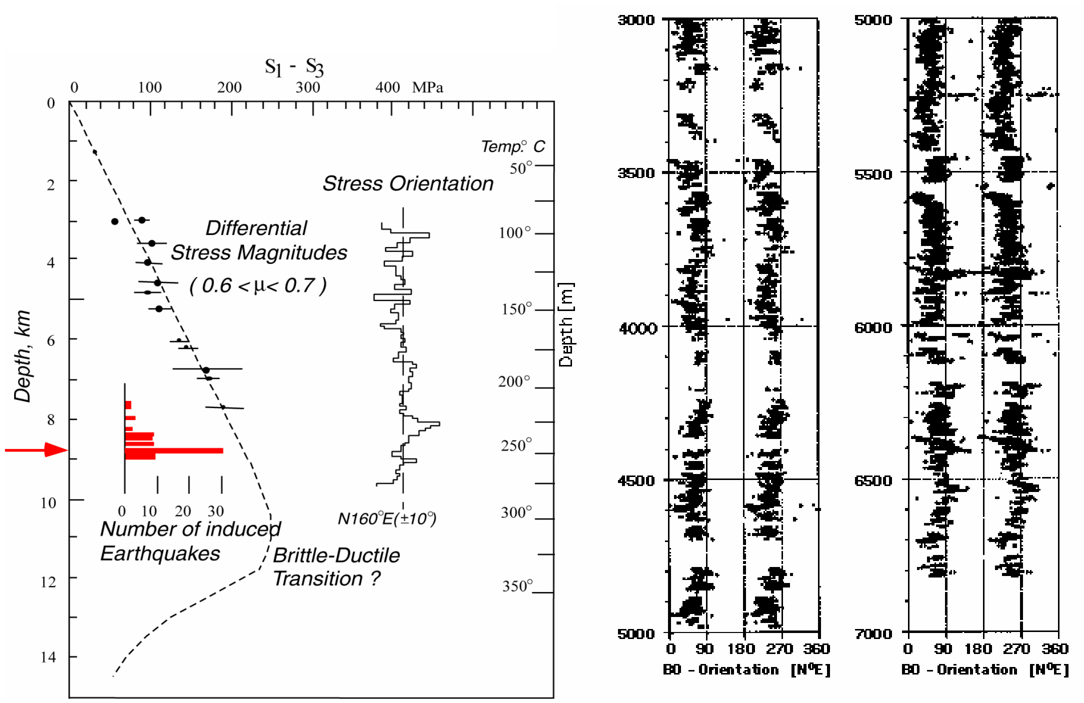
Figure 1 – a) Magnitude of the least principal stress in borehole USW G-1 (after [*Stock et al.*, 1985; *Zoback and Healy*, 1984]). b) The orientation of the minimum horizontal stress is hole USW G-1 is shown. It is approximately orthogonal to the strike of the Solitario Canyon fault (dashed line).

Stress measurements in deep boreholes around the world indicate stress magnitudes similar to those shown in Fig. 1a in that in the context of Coulomb faulting theory, the stress measurements indicate a crust in failure equilibrium [*Townend and Zoback*, 2000]. Fig. 2a shows a stress state in failure equilibrium to a depth of ~ 8km at the KTB site in southeastern Germany [*Zoback and Harjes*, 1997], in this case, it is a strike-slip faulting regime. Confirmation that the stress magnitudes indicate a stress state in frictional equilibrium is confirmed by the fact that small perturbations of pore pressure induced by fluid injection at ~9 km depth were sufficient to trigger microearthquakes.

Fig. 2b shows stress orientations in the pilot hole at depths between 3000 and 6800m as determined from wellbore breakouts [*Brudy et al.*, 1997]. In the figure, each point represents a breakout on one side of the well. In vertical boreholes, breakouts form in pairs, 180º apart, at the azimuth of the least principal stress. The KTB stress orientation profile indicates that on average, a constant stress orientation is seen with depth that corresponds with the NNE-SSW direction of maximum horizontal compression observed throughout this part of central Europe, but that many minor fluctuations of stress orientation are seen at a variety of wavelengths. Similar fluctuations in stress orientation have been seen in a number of boreholes including the Cajon Pass borehole, near the San Andreas fault. [*Shamir and Zoback*, 1989] showed that several detailed aspects of the breakout fluctuations could be explained by stress perturbations associated with slip on active faults penetrated by the borehole.

Figures 3 illustrate examples of larger scale stress rotations in the vicinity of active faults. Fig. 3a shows how the ENE-WES regional stress orientations is perturbed near an active fault in S. America. Fig. 3b shows perturbed stress orientations (based on observations of wellbore breakouts in oil wells) in the San Emidio, Los Lobos, Pleito Wheeler Ridge and North Tejon oil fields in the S. San Joaquin basin. [*Castillo and Zoback*, 1995] showed that the variation from the regional N-S stress orientation (seen in the oil fields immediately to the north), could be explained by the perturbation of the stress field caused by the occurrence of 1952, M~7+ Kern County earthquake.

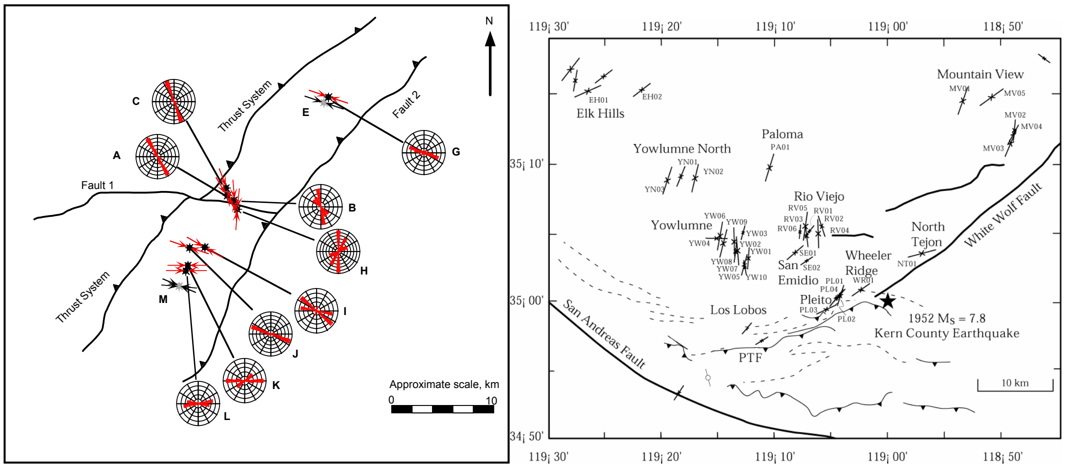
Following the generalized modeling of breakout rotations by [*Shamir and Zoback*, 1992], [*Barton and Zoback*, 1994] showed through dislocation modeling that specific rotations of breakouts observed in the KTB and other boreholes could only be explained if there was near-complete stress drop on the faults causing the breakout rotations. [*Castillo and Zoback*, 1995] found the same thing in modeling the stress anomaly in the Southern San Joaquin basin. Following the earthquake, principal stresses were oriented nearly parallel and perpendicular to the causative fault (as also seen in Fig. 3a). The same thing was found by [*Zoback and Beroza*, 1993] when analysing aftershock earthquake focal mechanisms following the 1989 Loma Prieta earthquake.



a) b)

Figure 2 – a) Magnitude of shear stress with depth in the KTB borehole south eastern Germany (modified after [*Zoback and Harjes*, 1997]). b) Breakout orientation with depth in the KTB borehole from 3000 to 6800m depth [*Brudy et al.*, 1997].

Stress magnitude observations in a number of wellbores provide additional evidence of complete (or near complete) stress drop. Fig. 4 shows least principal stress magnitudes from three wells in normal faulting environments (after [*Barton and Zoback*, 1994]). The normal/strike slip setting of the Cajon Pass borehole in S. California, near the San Andreas fault, the 6th Water Canyon on the Wasatch front in Utah and compilation of hydraulic fracturing stress measurements in several wells near Yucca Mountain. In normal faulting environments, complete stress drop would be associated with a marked increase in the magnitude of the least principal stress (to values approaching the vertical.stress). As the magnitude of the least principal stress can usually be measured with accuracy by hydraulic fracturing, it is noteworthy that while the majority of



a) b)

Figure 3 – a) Marked stress anomaly near an active fault in South America. Wellbore breakout data from four wells near the fault show a markedly different stress orientation than the NNE-SSE orientation of regional stresses observed in surrounding wells. B) Unusual stress orientations in oil fields in the southernmost San Joaquin basin are explainable in terms of the perturbation of the regional stress field caused by the 1952 Kern county earthquake.

measurements of the least principal stress are consistent with Coulomb faulting theory for frictional faulting equilibrium (as illustrated in Figs. 1 and 2), localized increases in the least principal stress are observed in the vicinity of shear zones in each case. These localized increases of the least principal stress indicate changes in shear stress on the faults in question of 10-15 MPa.

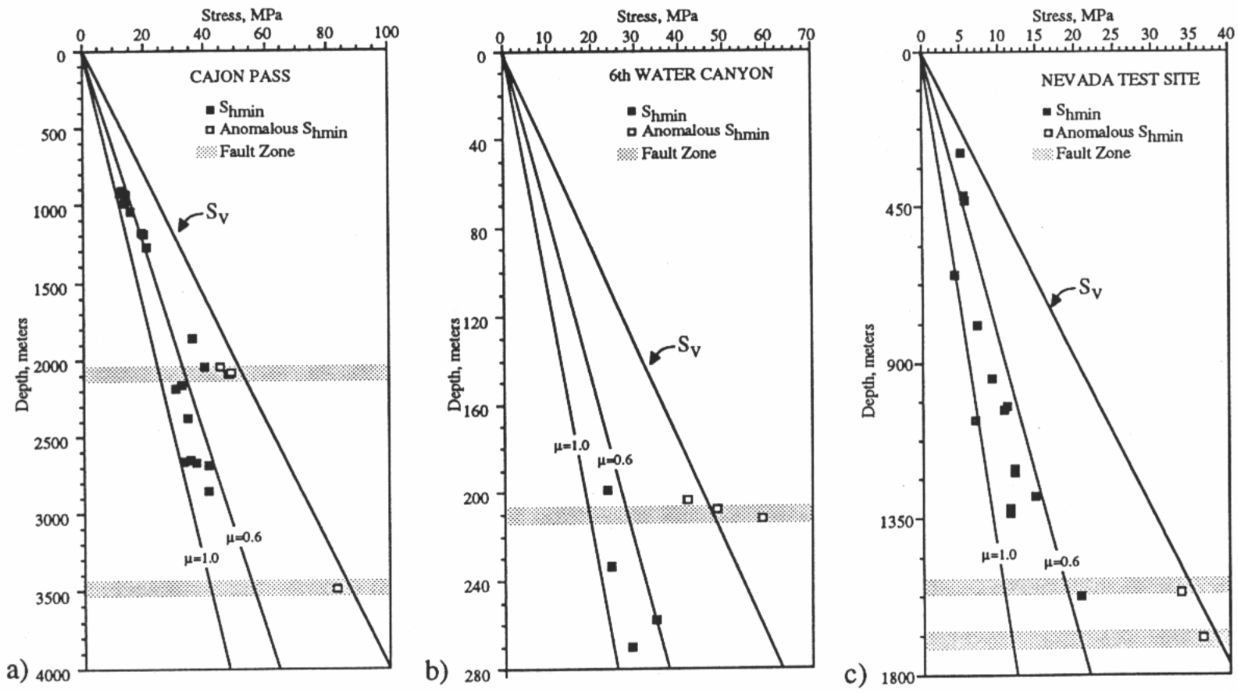


Figure 4 – Measurements of the least principal stress in wellbores in normal (or normal/strike-slip) faulting stress states show *i*) overall magnitudes consistent with Coulomb faulting theory and *ii*) localized increases in stress magnitude in the vicinity of shear zones showing near complete stress drop (after [*Barton and Zoback*, 1994]).

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