# In-situ stress measurements can help define local variations in fracture hydraulic conductivity at shallow depth

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Fractures and faults provide permeable pathways for fluids throughout the crust, from aquifers in the shallow subsurface to crustal depths where they can control production in geothermal fields and hydrocarbon reservoirs. Fracture-enhanced permeability depends on fracture density, connectivity and, most importantly, the hydraulic conductivity of the different fracture and fault planes.

In several boreholes in the western United States, it has recently been demonstrated that the fractures controlling bulk permeability are optimally oriented shear faults. In these relatively deep crustal studies, relationships between in situ stress, fractures, and permeability were examined using borehole image data, knowledge of the orientation and magnitude of in situ stress, and independent indicators of fluid flow (precision temperature and spinner flowmeter logs) to determine if individual fracture or fault planes were relatively permeable.

In one study, temperature measurements detected thermal anomalies associated with fluid flow in and out of the borehole along relatively permeable fractures and faults. Although such measurements cannot be used to quantify permeability, they can indicate which fractures and faults are effective in conducting fluids. In another study, both temperature and spinner flowmeter logs, acquired with and without simultaneously injecting water into the well, were used to identify hydraulically conductive fractures and faults.

Figure 1 is an example of the data used in these studies. The data were acquired in a borehole which was crosscut by several natural fractures (the sinusoids in Figure 1a). A very large fracture at 2580 m clearly perturbs the temperature gradient at this depth (Figure 1b). Several smaller temperature gradient anomalies were also correlated with distinct fractures (e.g., 2545 m).

In these studies, fractures detected by BHTV within a meter of a temperature anomaly were assumed responsible for the inferred fluid flow. If more than one fracture was present, the dominant fracture orientation was selected. A control population of non-hydraulically conductive fractures was also extracted from the total population. For each 1-m interval with no indication of fluid flow (no temperature gradient anomaly above the designated cutoff value), a fracture was selected that represented the dominant fracture trend for that interval.

To determine if fractures are potentially active faults, the orientation and magnitudes of the in situ stresses must also be known. This is necessary because the shear and normal stresses acting on each fracture plane are a function of stress magnitudes and the orientation of the plane with respect to the orientation of the stress tensor.

In situ stress magnitudes were determined using a variety of methods including direct hydraulic fracturing tests and the analysis of compressional and tensile bore-

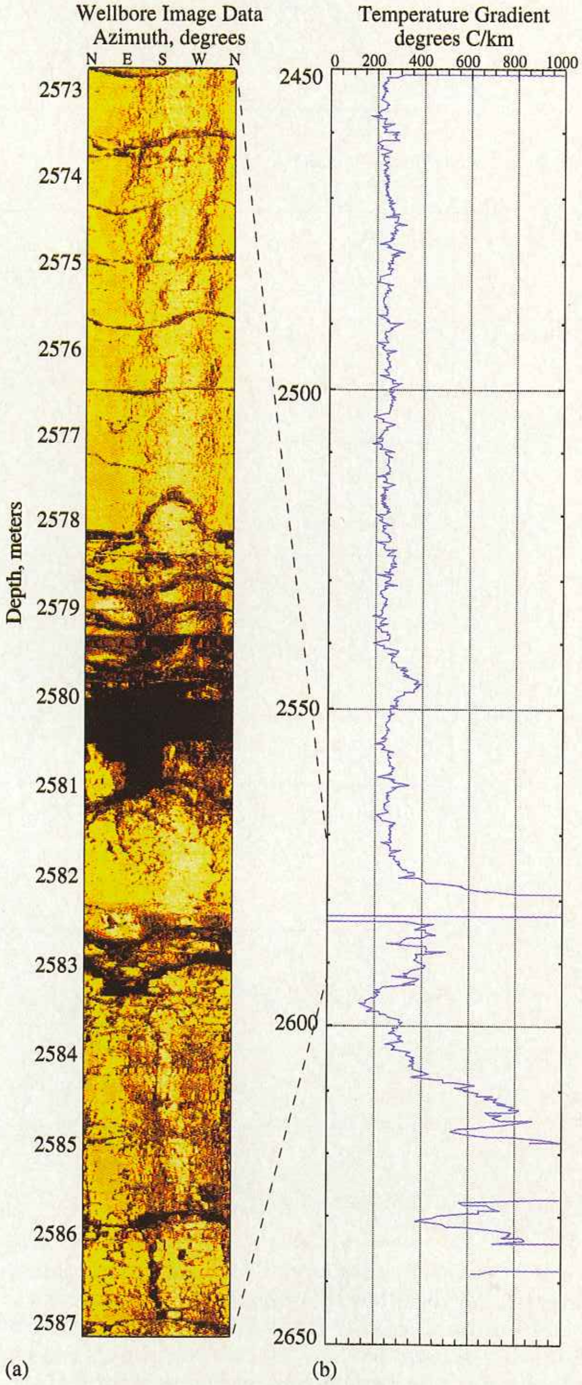

**Figure 1. (a) High temperature borehole televiewer (BHTV) data recorded in a producing well. (b) Precision temperature data recorded in the same well.**

hole failures. We used the Coloumb failure criterion to determine whether each plane is a potentially active fault. Planes with a ratio of shear to normal stress ≥0.6 are optimally oriented to the stress field for frictional failure. The shear and normal stresses on each of the hydraulically and nonhydraulically conductive fracture planes were computed using this criterion.

The results of these studies are summarized in Figure 2. As indicated by the Coloumb failure lines, a large percentage of hydraulically conductive fractures appear to be

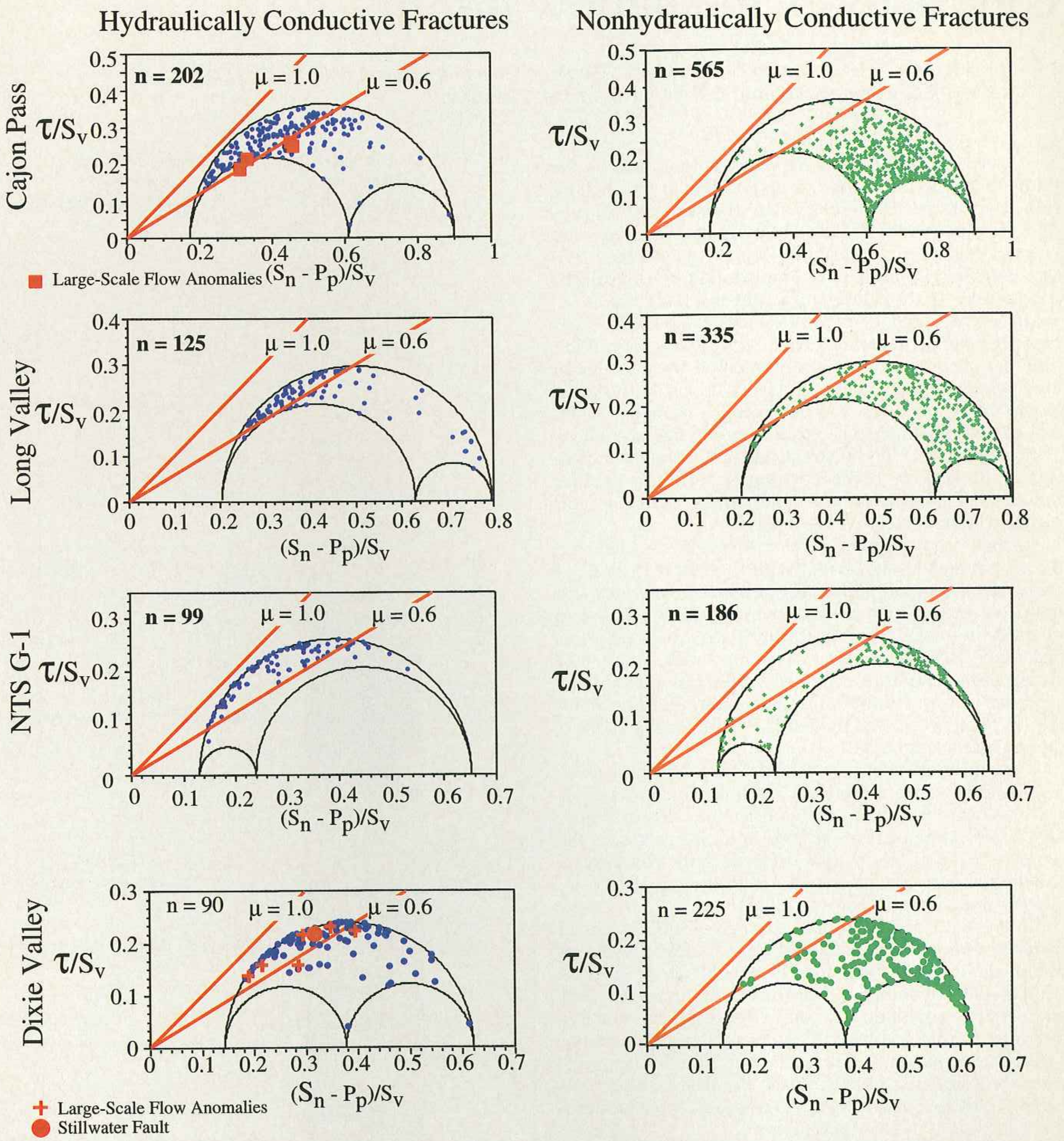

**Figure 2. 3-D Mohr diagrams illustrate the relationship between fracture orientation and the stress tensor. Fracture planes are represented by poles with coordinates τ (shear stress) and $S_n$ (normal stress). Fractures that plot above the red Coulomb failure lines for $\mu = 0.6$ are critically stressed, potentially active faults. Planes plotting below the failure line are stable. The left column shows the poles to the fractures identified using BHTV which were associated with thermal anomalies consistent with fluid exchange between the fractures and the well. The right column shows the poles to fractures not associated with a thermal anomaly. Also shown in the top row and the bottom row are poles to large-scale features known to be highly permeable. These data are consistent with the idea that critically stressed faults are permeable, and that fractures which are not critically stressed are not permeable.**

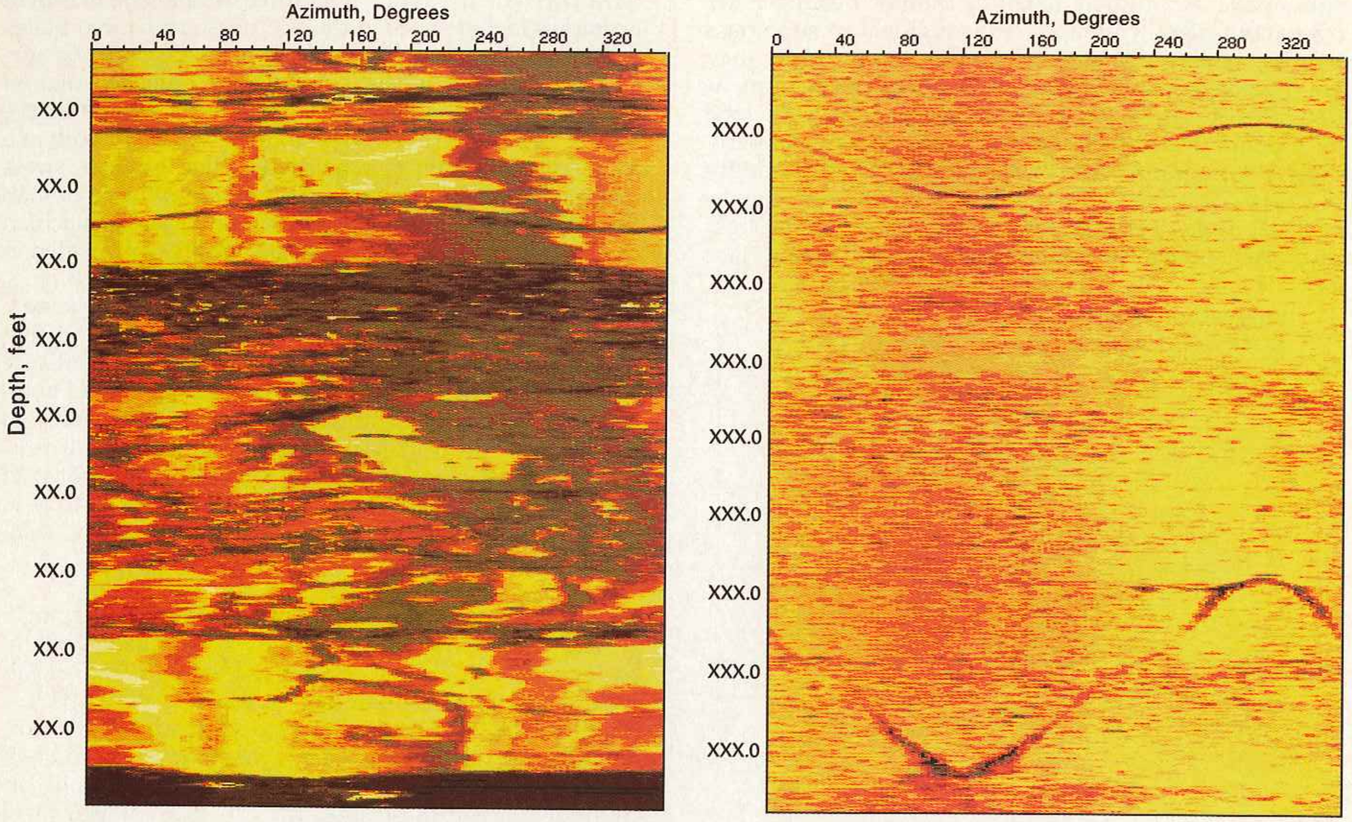

**Figure 3. Image data recorded over fractures with large measured permeabilities in borehole in the southeastern U.S. (Data courtesy of Harding-Lawson Associates.)**

critically stressed, potentially active faults in frictional equilibrium with the measured in situ stress field. The majority of fractures not associated with temperature anomalies clearly lie below the Coloumb failure line and therefore do not appear to be critically stressed shear fractures.

These data indicate that potentially active faults are the most important hydraulic conduits in situ and that the permeability of critically stressed faults is much higher than the permeability of faults which are not optimally oriented for failure in the current stress field. Although mechanical and geochemical processes may be acting to close fractures at these sites, it appears that slip along discrete fracture planes is maintaining permeability.

**Application to shallow depth studies.** Isolating which fractures are hydrologically important is fundamental to a conceptual model of a shallow geotechnical study site. Flow along discrete permeable pathways must be modeled and the subset of hydraulically conductive fractures must be known in order to constrain the model. The techniques described above to identify permeable fractures at depth can also be used in studies of the shallow crust.

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, where fluid flow is expected to be fracture controlled. Areas where shallow in situ stresses are difficult to measure correspond to areas where unconsolidated sediments lie within the zone of investigation. In these cases fractures are not as important to subsurface fluid flow.

The advent of slim-hole acoustic imaging, new optical-imaging technologies, and electrical image logging has increased the use of wellbore image data for engineering and environmental studies. These techniques provide accurate information on the distribution and orientation of individual fractures and the overall fracture statistics required to develop a model. The question remains, however, as to which fractures are permeable.

Standard methods to determine fracture hydraulic conductivity (such as packer testing and fluid replacement) have limitations. It is often not economically feasible to test all fractures using packer tests and, at some sites, geochemical constraints rule out the use of fluid replacement methods. Spinner flowmeter logs can provide information on fluid flow from fractures, but they are insensitive at low flow rates.

The approach we have used successfully at deeper crustal sites could provide an alternative and relatively noninvasive way to establish which fractures control subsurface fluid flow. Its use at shallow depths is limited only by the lack of high-quality, local stress measurements required to determine which fractures are critically stressed.

Measurements of the in situ stress field at shallow crustal depths can yield data that are difficult to interpret. Below 1 km, stress–orientation measurements generally have a consistent pattern and stress–magnitude measurements made at greater depths are often in accord with Andersonian faulting theory (i.e., one principal stress is vertical and equal to the weight of the overburden rock) and stresses are in equilibrium with the strength of preexisting faults. At shallow depths, however, stresses are affected by topography which can dominate regional stress patterns and may result in extreme heterogeneity over short lateral distances. Thus regional in situ stress trends or estimates based on data recorded nearby may not provide data relevant to the site. Accurate determination of in situ stress in the shallow crust can only be done by measuring it directly at the location using properly designed programs which can define the local variability of stress.

Fortunately, there are many regions where in situ stress measurements can be made at shallow depths using standard borehole hydraulic fracturing techniques. Excellent examples include sites in the southeastern United States where basement rocks extend to within 20 m of the surface. Studies within this region have established that, in the absence of topographic stress effects, where brittle rock is exhumed, stress orientation is consistent both at a local scale and with regional trends. For example, stress magnitudes measured at shallow depth at the Savannah River Site, the Monticello Reservoir and the Appalachian Deep Corehole Hole (ADCOH) survey area, all located in the Piedmont belt of South Carolina, reveal a high magnitude near–surface compressional stress field that is capable of causing reverse faulting on well-oriented preexisting planes of weakness. In these locations where relatively strong, elastic rock extends to the surface, the high, near-surface compressional stresses are likely the response of the lithosphere to plate-driving forces. In other words, compressional regional tectonic forces are distributed in such a way that there is an excess of horizontal stress at shallow depth resulting in what has been termed "thin-skin" reverse faulting.

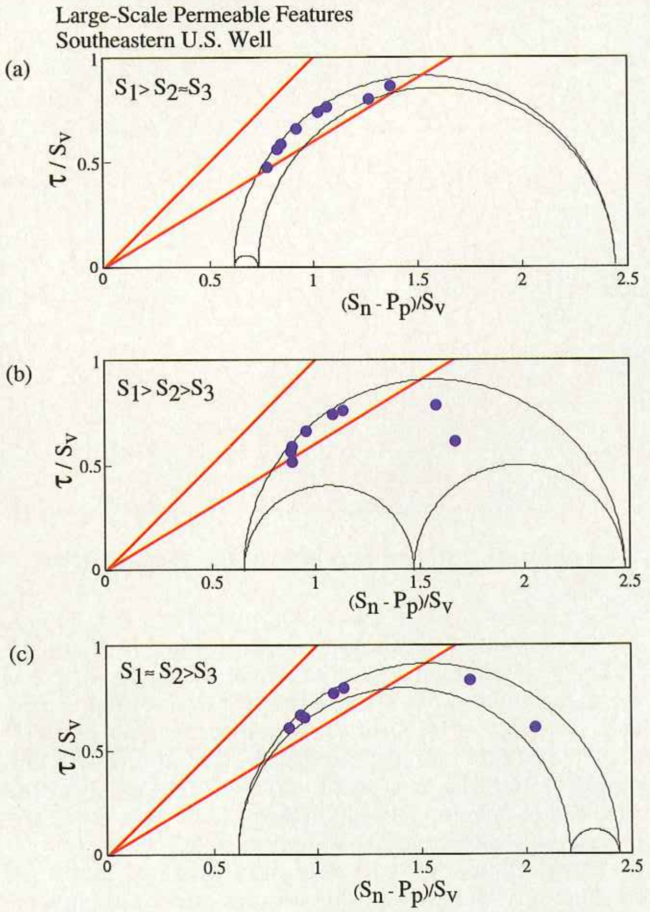

**Figure 4. Shear versus effective normal stress computed for fractures dominating fluid flow in a shallow well using three possible stress states.**

**A case in point.** Figure 3 shows image data recorded over producing fractures intersected by a well in the southeastern U.S. Fluid flow appears to be dominated at this location by bedding-parallel fractures at very shallow depth and by higher angle fractures at greater depth, possibly as a result of increasing lithostatic load. To completely determine the role in situ stress plays in the hydrogeology at these sites, the full stress tensor must be known.

There is evidence from core failure from wells at the site that the stress state is compressional. Based on this, Figure 4 shows a series of 3-D Mohr diagrams of shear versus effective normal stress for the fractures in this well that are known to be producing large-scale flow. In this compressional stress regime, the least principal stress is vertical (and equal to the lithostatic load) and rough bounds on the magnitude of the maximum principal stress can be obtained from core failure analysis. The magnitude of the intermediate stress is not yet known at this site because direct in situ stress measurements have not been made.

The Mohr diagrams in Figure 4 indicate which of these fractures would be critically stressed for values of the intermediate principal stress (a) close to the least principal stress; (b) intermediate between the least and maximum principal stress; and (c) close to the maximum principal stress. If the intermediate stress is close to the least principal stress, then all producing fractures are critically stressed planes which can undergo discrete slip events to remain open in the current stress field. If, however, the intermediate principal stress is close to the maximum principal stress, high angle fractures at this site are not critically stressed.

**Conclusion.** A high degree of correlation has been found between critically stressed faults and hydraulic conductivity in a variety of wells drilled to mid–crustal depths. If this relationship also holds in the near surface, it can provide a new technique to characterize the hydrology of the shallow crust. Application of this technique requires the acquisition of borehole image data in conjunction with in situ stress measurements, and high precision flow data as part of site characterization activities. LE

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