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STRESS IN GEOTHERMAL SYSTEMS

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ABSTRACT

This paper analyzes the components of stress in geothermal systems. Previous work has shown that geothermal systems often have a stress orientation different from the regional direction and that the orientation of the stress components may change within an individual well. Decoupling of the stress within a geothermal system from the regional stress appears to take place along faults that are inherently weak due to the presence of geothermal fluids. Variations in stress within a system could result from local stress due to fluid pressure, temperature or volcanic processes or to bend of stress lines around active faults. Analysis of data from the Baca geothermal system demonstrates that temperature variations are the principal cause of stress variations.

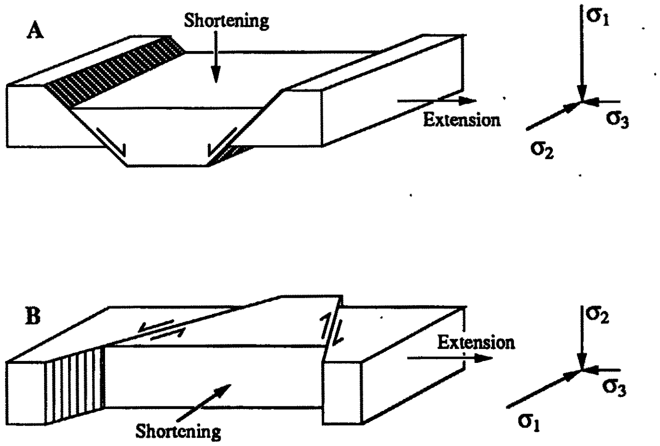
INTRODUCTION

The state of stress in geothermal fields directly relates to the formation and orientation of fractures and faults and the ability of those features to serve as hosts for geothermal fluids. The orientation of stress in active geothermal fields has been evaluated using data from the dipmeter log (Allison and Nielson, 1987, 1988 a, b). The purpose of this paper is to discuss general models for stress distribution in geothermal fields.

REGIONAL STRESS

Any applied stress may be resolved into three principal stress components. Generalized orientations of the stress components with respect to the faulting they produce are shown in Figure 1. In the Basin and Range and most volcanic environments, the stress orientation is similar to that shown in Figure 1a, where the greatest principal stress is vertical, and the strike of faulting and fracturing is perpendicular to the least horizontal principal stress. In this situation, the faulting is normal. The other environment in which geothermal systems are commonly found is that characterized by strike-slip faulting. The stress orientations responsible for this style of faulting are shown in Figure 1b. In this case, both the greatest and least principal stress directions are horizontal. Important geothermal districts such as the Imperial Valley and The Geysers are hosted by this type of regional environment.

Regional stress appears to fit a model where the applied stress is homogeneously distributed. However, a geothermal system, characterized by high heat flow, upwelling hot fluids, and perhaps an increase in fracturing, would theoretically represent an anomaly within the region. The following sections analyze the stress within geothermal systems and discuss the interface between the geothermal system and the regional stress.



A: Normal fault
B: Strike-slip fault

Figure 1 Diagram showing the typical stress orientations for an extensional environment characterized by normal faults (A) and a compressional environment characterized by strike-slip faulting (B).

STRESS IN GEOTHERMAL SYSTEMS

The investigations on in situ stress cited above and information from seismicity surveys indicates that the stress orientation in at least some geothermal fields is different from the regional stress. Walter and Weaver (1980) performed a detailed study of earthquakes from the Coso geothermal field in California. They noted a difference in the fault plane solutions of earthquakes in the geothermal system from those events located outside the system. They determined that strike slip movement on nearly vertical fault planes occurred everywhere except in the geothermal system. The regional motion is right lateral along NW striking planes and left lateral along the NE striking conjugate planes. This is consistent with the greatest principal stress oriented horizontally approximately NS and the least principal stress also oriented horizontally and in an EW direction. Within the geothermal system the fault plane solutions show predominantly normal movement with a small strike-slip component along NNE-trending planes.

This implies that the least principal stress is horizontal and oriented WNW and that the greatest principal stress is vertical.

A change in stress orientation can also be documented in the Roosevelt Hot Springs (RHS) geothermal system in Utah. This system is located within the transition zone between the Colorado Plateau and Basin & Range Provinces. In a nearby study of earthquakes, Arabasz and Julander (1986) have determined that the regional orientation of the least principal stress is 102 degrees, consistent with the EW extensional tectonics of the Basin & Range Province. Geologic mapping of the area around RHS (Fig. 2) shows that Recent normal faulting to the west of the geothermal system is north to NNE trending, consistent with the results of Arabasz and Julander.

However, much of the geothermal production at RHS is controlled by EW normal faults as exemplified by the Negro Mag fault (Fig. 2). Nielson et al. (1986) demonstrated that the Negro Mag is located along the axis of a complex graben structure. This structure would not form under the present regional stress orientation; it requires a least principal stress oriented approximately NS, at nearly a right angle to the regional orientation.

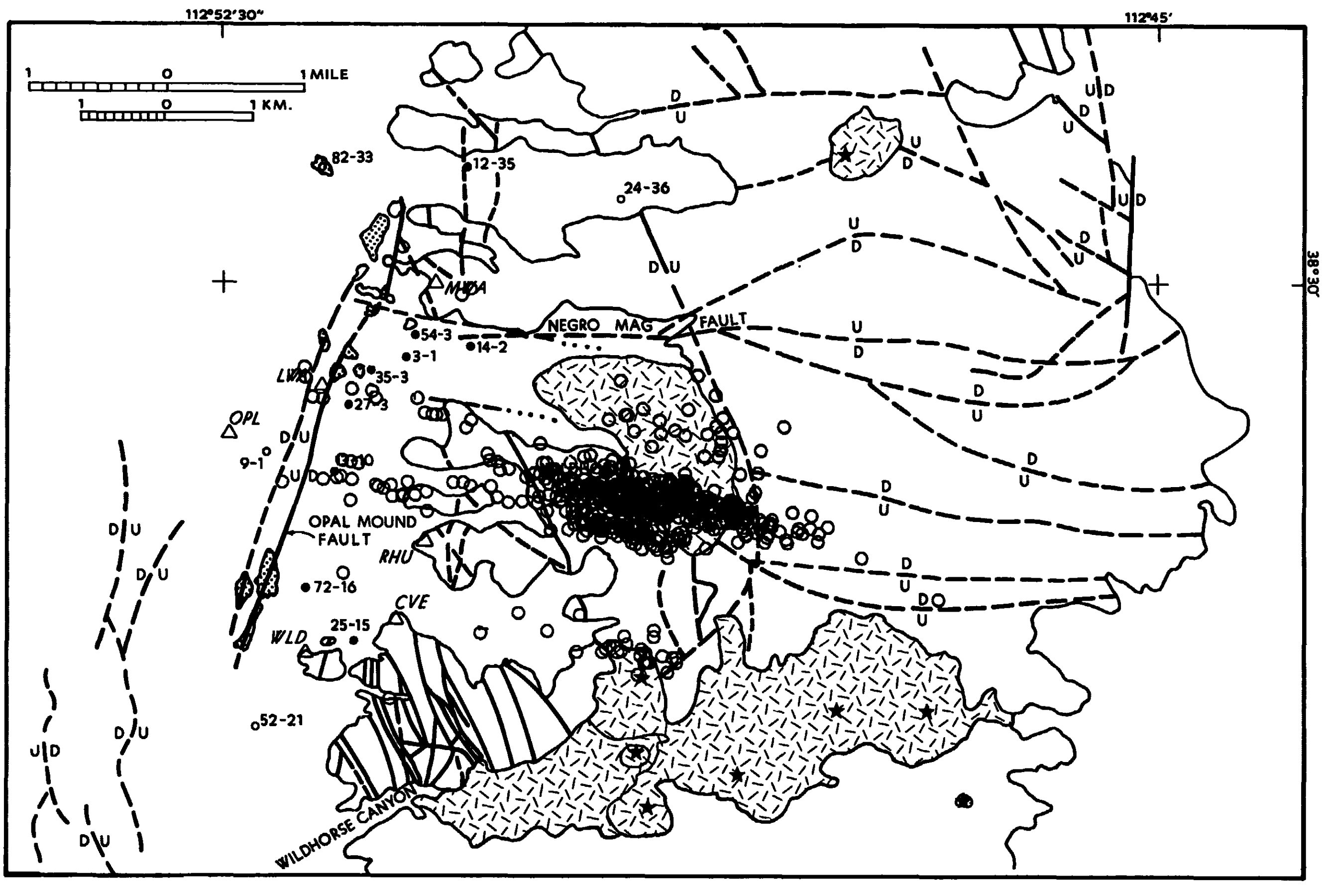


Figure 2-Map of Roosevelt Hot Springs geothermal field in Utah showing mapped faults from Nielson et al. (1986) and pre-production seismicity (G. Zandt, written communication).

Pre-production seismicity from RHS is also shown in Figure 2. The earthquakes are clearly located along faults that are parallel to the Negro Mag fault. Analysis (G. Zandt, written communication) shows that the movement on the faults is predominantly normal with a strike-slip component. These data are consistent with the fault orientations discussed above and imply a roughly NS orientation of the least horizontal principal stress which is nearly perpendicular to the regional direction. It is also notable in Figure 2 that the earthquake swarms continue up to but do not cross the NNE-trending Opal Mound fault. The Opal Mound orientation is consistent with formation under the regional stress system. Sinter deposits and production wells along this fault also indicate that it contains geothermal fluids. Dry holes and a decrease in heat flow to the west suggest that the Opal Mound serves as the western boundary of the geothermal system.

Data from well bore breakouts at RHS (Allison and Nielson, 1988c) also demonstrate that the least horizontal principal stress within the geothermal system is oriented approximately NS and not in the regional direction.

In conclusion, the data from both RHS and Coso geothermal fields demonstrate that there is a difference in the orientation of the stress within these geothermal systems from the regional stress environment. These observations require 1. different forces within the geothermal system and 2. mechanisms of structural decoupling of the geothermal system from the regional stress. At RHS, this decoupling apparently takes place along the Opal Mound fault to the west. Extent of the local stresses in the other directions is not known.

FAULT AND FRACTURE STRENGTH

Faults and fractures are mechanical heterogeneities. Their strength is a function of the character of brecciation during fault movement and of mineral deposition along the features. It is not uncommon to find fractures that have been totally sealed by silica and are tougher than the host rock. However, fractures that exhibit high fluid to rock ratios are zones of weakness relative to the surrounding rock. As such, they serve as zones of stress release through faulting, and, by this mechanism, permeability is maintained rather than lost through the process of hydrothermal mineral deposition.

Pollard and Segall (1987) have demonstrated through numerical simulation that a crack will distort remotely applied stress trajectories. Similarly, in a paper on stress along the San Andreas fault, Zoback et al. (1987) determined that although theory would predict a stress orientation similar to that shown in Figure 1b, measurements and geologic relationships showed that the greatest principal stress is oriented perpendicular the fault. Remote from the fault, the stress orientation conforms with that predicted by theory. They attributed this reorientation of stress to the inherent weakness of the San Andreas fault.

Allison and Nielson (1988a, b) have discovered that in many geothermal wells there is a dramatic change in stress orientation with depth. They have documented that, in some instances, this change takes place across faults. This, in addition to the data from RHS cited above, makes it clear that geothermal faults, due to their inherently weak nature, serve as zones of decoupling between different stress systems. In addition, Allison and Nielson found that there were often variations in stress orientation between wells within systems. The problem remaining is to explain the reason that stress may change orientation at the boundary of a geothermal system or within the system.

GEOTHERMAL FAULT MODEL

Following Engelder (1987) a distinction will be made between the pore pressure and fluid pressure. Pore pressure results from fluid in closed pores that acts against applied tectonic stress and results in an effective stress. In contrast, the fluid pressure is produced by fluid filling a fracture and acting against the walls of that fracture. In a system open to the atmosphere, the fluid pressure is the hydrostatic pressure. Sealing can allow pressures to increase to a level defined by the applied stress plus the pressure required to either fracture or open pre-existing fractures in the rock. If this level of fluid pressure is reached, hydraulic fracturing will result (Hulen and Nielson, 1988).

In order to evaluate some of the variables effecting stress, data from the Baca geothermal system in New Mexico are utilized. Figure 3 shows estimates of the average state of stress in the geothermal reservoir. The vertical stress is estimated using measured densities of rock from the system. The least principal stress is estimated from several experiments that are cited in the figure. The average least principal stress gradient was established on the basis of the Baca-20 hydrofracture experiment and assumes that the fractures opened were pre-existing and had no strength. The average hydrostatic gradient is also shown and is based on an average depth to water of 365 meters.

Analysis of pressure data from individual wells demonstrates that pressure differences exist throughout the field. Figure 4 shows the hydrostatic head differences measured through the Baca reservoir. From Figure 4, the highest pressure difference between two wells is apparently between Baca-9 and Baca-10. with an elevation difference of 152 meters. A hot water column density of 0.79 g/cc was calculated from well pressure data. Using this density a stress gradient of 0.003 MPa/m was calculated to exist between Bacas 9 and 10.

Temperature variation across the geothermal system could also contribute to variations in the stress. Figure 5 is a temperature contour map at an elevation of 1700 meters above sea level covering the same area as Figure 4. This figure is taken from Nielson and Hulen (1985) who demonstrated that at 2200 m and 1200 m above sea level, the temperature distribution was apparently controlled by flow along EW faults while at the 1700 m elevation, the isotherms were parallel the NE-trending faults of the Redondo Creek graben.

The calculation of a thermal stress between two points is discussed by Turcotte and Schubert (1982). They present the following equation for the maximum thermal stress: $\sigma_{max} = \frac{E\alpha\Delta T}{1-\nu}$ where E is Young's Modulus estimated at 60 GPa, ν is Poisson's ratio estimated at .25, α is the coefficient of thermal expansion equal to $10^{-5}\ K^{-1}$. The

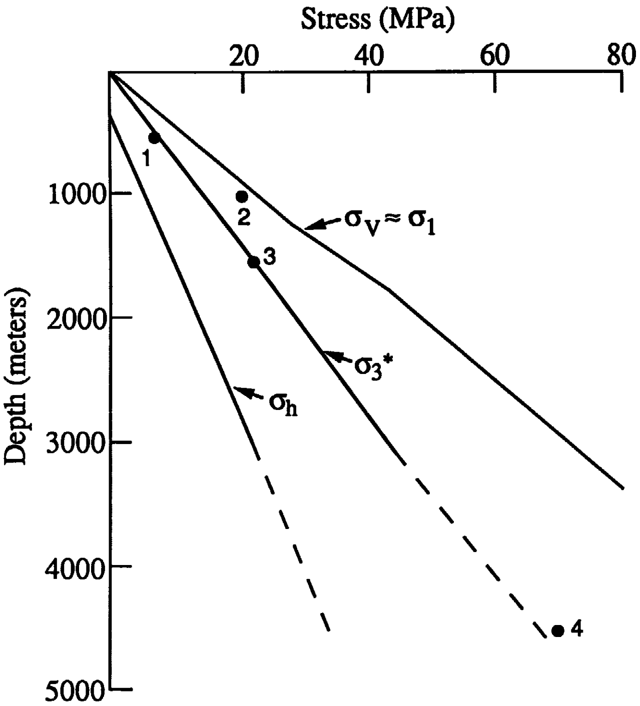
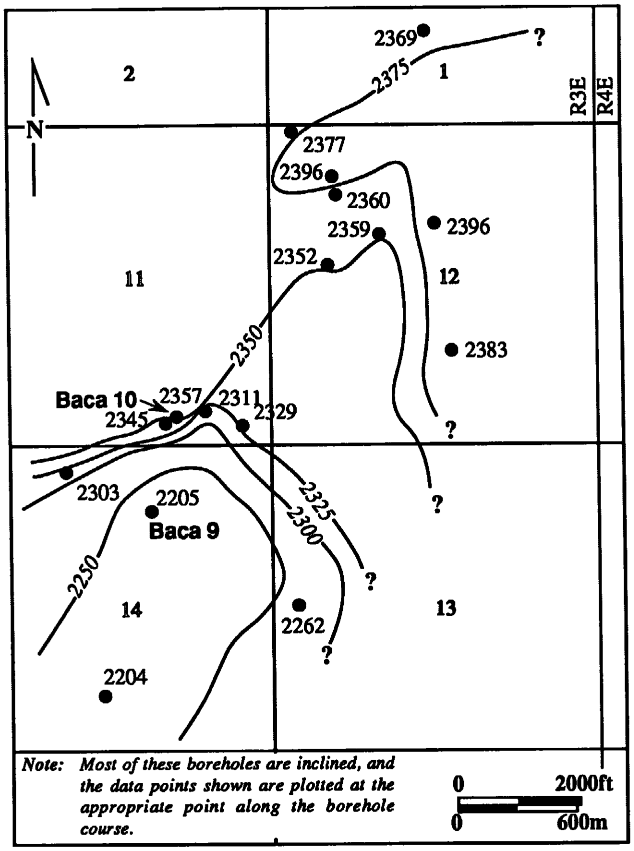


Figure 3 Estimated stress gradients in the Baca geothermal system, New Mexico. Hydrostatic gradient (σ_h) calculated from data presented in Nielson and Hulen (1985) based on an average water level of 365 meters. Vertical stress (σ_v) is lithostatic and calculated from measured rock densities. The estimated least horizontal principal stress (σ_3^*) is based on hydrofracture experiments in Baca-20. Applicable data points are as follows.

1. Estimate from natural hydrothermal brecciation in VC-1 from Hulen and Nielson (1988).
2. Hydrofracture of Baca-23 from Verity and Morris (1981).
3. Hydrofracture of Baca-20 from Republic Geothermal (1983).
4. Hydrofracture at Fenton Hill from Murphy et al. (1983).

temperature difference between wells 14 and 10 is 43 degrees C at 1700 m elevation. The maximum thermal stress calculated between these two wells is 34.4 MPa. This yields a horizontal stress gradient between the two wells of 0.075 MPa/m or 25 times the stress gradient generated by the hydraulic head difference between the same two wells. It should be noted that the gradients due to pressure and temperature variation are additive. Comparison of the magnitude of the thermal stress with the estimate for the state of stress (Fig. 3) demonstrates that thermal stress could easily become the dominant stress-controlling process, particularly in the upper parts or the margins of hydrothermal systems where temperature gradients are the most extreme. Thermal stresses can also be an order of magnitude greater than regional tectonic stresses (Allison, 1988).

DISCUSSION AND CONCLUSIONS



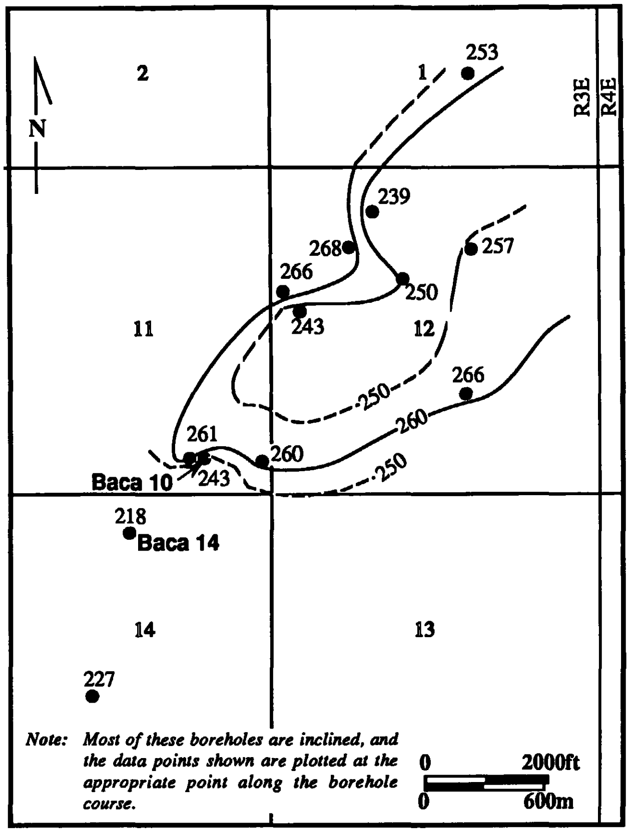
Note: Most of these boreholes are inclined, and the data points shown are plotted at the appropriate point along the borehole course.

Figure 4 Contoured hydraulic head data for the Baca geothermal reservoir. Data is elevation of water level in meters above sea level. The contour interval is 50 meters.

The evaluation of data from the Baca system shows that the stress due to temperature gradients is significant and in many cases may be the principal cause of stress variation within a geothermal system. In some instances, differences in fluid may also be important, but they were much less so in the example analyzed. Stress due to upper level volcanic processes may be important in some fields and promote a difference in orientation from the regional environment.

It has been shown that faults within a geothermal system have low strength due to the presence of hot fluids. Theoretically the regional stress is distorted by the presence of a geothermal system. This could be used as an exploration tool; however, there is not at present any evidence that this distortion process is measureable. The evidence from RHS does demonstrate, however, that the geothermal system is effectively decoupled from the regional stress along a single fault zone on one side of the field. This change in orientation should be considered in an effective exploration and development strategy.

One of the principal problems in exploration concerns the location and orientation of fractures that could provide geothermal production. Although determination of stress orientation will not locate fractures, it makes it possible to predict the orientation of fractures that are forming under the present-day stress system, or that will be kept open by the in-situ stresses. This allows directional drilling programs to be designed such that wells cut across the fracture trend resulting in the maximum opportunity to intersect an open fracture.



Note: Most of these boreholes are inclined, and the data points shown are plotted at the appropriate point along the borehole course.

Figure 5 Temperatures at 1700 m elevation for the Baca geothermal system from Nielson and Hulen (1985). Map covers the same area as shown on Fig. 4.

It can be visualized that the geothermal fluid in a fracture exerts pressure against the fracture walls, helping to keep the fracture open. Removal of fluid from the fracture could result in the decrease in permeability. The solution to this problem would be injection along the structure to maintain fluid pressures, but care must be taken to avoid significant enthalpy decrease.

It is also evident from this analysis that the processes of production and injection will change the stress orientation in a reservoir as the temperatures are modified. This could have the effect of generating new permeability depending on the positions of the production and injection wells with respect to the stress system.

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