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THOUGHTS ON STRESS AROUND THE GEYSERS GEOTHERMAL FIELD

Dennis L. Nielson(1) and Donald Brown(2)

(1) University of Utah Research Institute
(2) Los Alamos National Laboratory

ABSTRACT

This paper approaches the structural geology of The Geysers geothermal field from the perspective of stress relationships. The least principal stress is horizontal and oriented approximately N80W while $\sigma_1 \approx \sigma_2$. A number of published reports on production trends are reviewed and show that pressure sinks are developing along the conjugate shear directions while injected fluids preferentially utilize structures perpendicular to σ_3. Stress in the vicinity of the reservoir is approximated by a simple two-dimensional model for stress in the vicinity of a subsurface excavation. This model demonstrates areas of high and low stress surrounding the reservoir. It also demonstrates our concept that a structural arch has resulted in the decoupling of the reservoir from the vertical stress. These relationships may be important in planning and managing successful re-injection into the reservoir.

INTRODUCTION

The important papers of White et al. (1971) and Truesdell and White (1973) established a model for The Geysers geothermal field based on the boiling down of a hot water-dominated reservoir to form a vapor reservoir. The establishment and maintenance of vapor-dominated conditions require that the discharge from the system exceed the recharge. Recent pressure declines have dramatically confirmed the point that natural recharge to the system coupled with artificial recharge through injection have not been able to support the current level of production.

Actions to stop reservoir declines all involve the injection of fluid into the reservoir. Attempts at injection have met with variable degrees of success which are not understood. At times, injection accomplishes the required objectives; while, at other times it either reduces production or has no effect.

Our purpose in writing this paper is to present some thoughts on stress in The Geysers. The concepts discussed here will hopefully contribute to a broader structural model of the system which will be important in planning and implementing injection and additional production well drilling.

STRUCTURAL SETTING OF THE GEYSERS

The structural framework of The Geysers geothermal field is extremely complex. The reservoir is hosted by a Franciscan assemblage that contains graywacke, sandstone, shale, chert, and mafic igneous rocks. These rocks were initially metamorphosed and deformed in the Cretaceous and early Tertiary (McLaughlin, 1981). Thrusting took place along zones that presently dip to the northeast.

For the past several million years, the area has been under the influence of the dextral strike-slip faulting commonly associated with the San Andreas fault system. Strain measurements in the region (Prescott and Yu, 1986) demonstrate that relative motion between the North American and Pacific Plates is distributed over a wide belt to the northeast of the San Andreas fault, an area including The Geysers (Fig. 1).

The measurements of regional strain, which are consistent with the determinations of stress in The Geysers (Oppenheimer, 1986), show maximum extension oriented N79W and maximum compression oriented N11E. These orientations are shown on Figure 1 and are consistent with the orientations of stress that would be expected based on the orientation and sense of movement of the strike-slip fault zones associated with the San Andreas. These results are also consistent with those of Bufe et al. (1981) that are also shown in Figure 1.

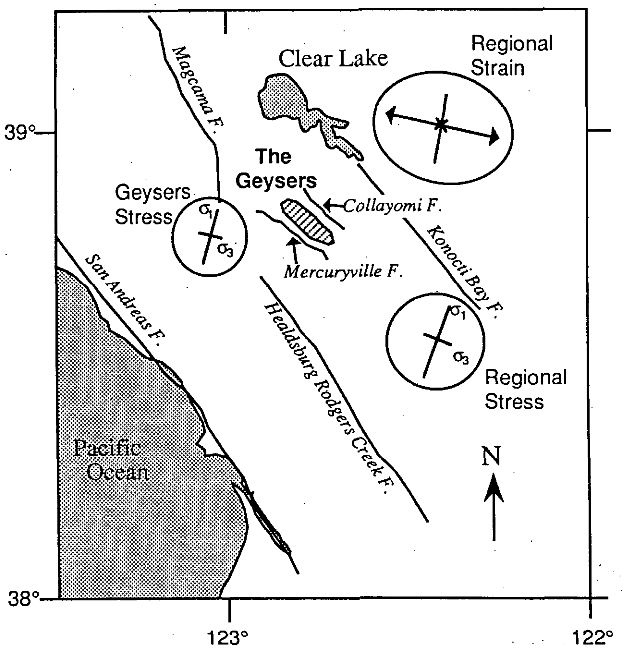

Figure 1 - Map of the vicinity of The Geysers geothermal field. Orientation of regional strain from Prescott and Yu (1986). Geysers stress orientation is from Oppenheimer (1986) and the regional stress orientation is from Bufe et al. (1981).

STRUCTURE OF THE GEYSERS RESERVOIR

Discussions of the structure of The Geysers reservoir have been presented by a number of authors. McLaughlin (1981) pointed out that the geothermal field appears to be bounded on the southwest and northeast by the Mercuryville and Collayomi fault zones. He used surface mapping to define three structural units and produce a structural model of the system. Thomas (1981) redefined the structural stratigraphy on the basis of well data and concluded that the main reservoir unit included parts of all three of McLaughlin's units. Both of these authors explained the lack of lithologic continuity as resulting in part from steeply dipping thrust and strike slip faults. McNitt et al. (1989) simplified the interpretation to two units.

Another approach to structural interpretation has been taken by Thompson (1989) who defined stratigraphically continuous thrust packets that are composed of rocks of similar metamorphic grade bounded by thrust faults. These packets are reported to have stratigraphic continuity and can be identified in wells that are miles apart. Using this approach, Thompson reported that it was not possible to define significant displacement along high-angle faults within the field.

The above workers have reached somewhat different conclusions that can be attributed to the difficulty in working with both the surface and subsurface exposures in the area. Lithologies are heterogeneous and it is often difficult to correlate units between closely spaced drill holes. Contributing to this problem is the general fine-grained nature of cuttings from Geysers drill holes.

Recent work has also defined the location of a composite pluton that underlies most of the geothermal field (Thompson, 1989). Samples of this "felsite" have been dated as young as 0.9 Ma, and it is generally regarded as the source of heat for the geothermal system.

Beall and Box (1989), McNitt et al. (1989) and Thompson and Gunderson (1989) all concur that producing fractures in The Geysers are, in general, of random orientation when the entries are encountered in the graywacke. These fractures are often flat, leading Thompson and Gunderson to suggest that they were inherited from Franciscan thrusting. Oppenheimer (1986) similarly demonstrated on the basis of earthquake focal mechanisms that fractures within the reservoir had a random orientation. Thompson and Gunderson have shown that, in contrast with the graywacke, the entries encountered in the felsite are principally steeply dipping.

Sternfeld (1989) emphasized the importance of host rock lithology and igneous processes in the formation of producing fractures in the northwest Geysers. He defined three alteration zones: 1. A relatively unfractured and unproductive graywacke above the geothermal reservoir; 2. A hydrothermally altered steam zone with two generations of hydrothermal minerals (earlier hot-water mineralogy and the disappearance of Franciscan calcite that is superimposed by a prehnite + axinite assemblage that shows a good correlation with the presence of steam); and 3. hornfelsic graywacke characterized by the assemblage biotite + tourmaline + adularia + quartz + ilmenite. The hornfelsic graywacke is not a particularly good host for steam, a fact that Sternfeld attributes to its plastic nature during formation. He concludes that fractures were principally created by shearing and hydraulic fracturing caused by pluton emplacement.

In contrast to the above sited works, in this paper we will take a "macrogeologic" approach to the structural geology. In doing so, we will review information on stress and strain relationships in The Geysers and present some ideas concerning the importance of these factors in controlling the drainage of and injection into the reservoir.

STRESS IN THE GEYSERS

Oppenheimer (1986), in a study of induced earthquakes at The Geysers has shown that the greatest and intermediate principal stresses are nearly equal and that they are also approximated by the lithostatic pressure. Oppenheimer determined that the orientation of the least principal stress at depth is horizontal and N75W (Fig. 1). His analysis of earthquakes has shown that faulting in the reservoir is in response to the regional stress system and not in response to stresses induced by production.

Lockner et al. (1982) have performed laboratory measurements on surface and core samples from The Geysers. No samples were available from the reservoir, but most of the core samples were collected immediately above the reservoir zone. Their experiments have concluded that the reservoir rock is so weak that it can only support a frictional load. This weakness results from the highly fractured, and at times altered, nature of the rock.

Through a series of experiments, Lockner et al. (1982) determined that the coefficient of friction of the host rocks was 0.68. The fact that the region is tectonically active and generating earthquakes led these authors to conclude that the shear stresses in the region are very near those defined by the frictional of strength of this rock. This relationship has allowed the estimation of σ_3 using the Mohr circle. We have plotted total stress on Figure 2 that is equivalent to the effective stress plus the pore fluid pressure.

Figure 2 also shows reservoir pressures as a vaporstatic gradient in what is generally assumed to be the preproduction state. It is clear when this is compared with the hydrostatic gradient, that the reservoir is severely underpressured and should be recharging naturally. We will speculate on the reasons for this lack of recharge in a later portion of this paper.

A number of authors have explicitly or implicitly commented on the relationship of various observed phenomena at The Geysers to stress orientation. Both the steam reservoir and the underlying felsite body have an axial orientation of about N55W, coincident with the direction of regional strike-slip faulting. However, vents identified in the Clear Lake Volcanics, that are generally thought to be cogenetic with the felsite, show orientations of N to N10E, consistent with emplacement perpendicular σ_3 (Oppenheimer, 1986). The genetic relationship between the reservoir and the felsite has been identified by a number of authors (Sternfeld, 1989; Thompson, 1989; Thompson and Gunderson, 1989) and it is probable that the felsite was emplaced along strike-slip faults and was itself responsible for both the heat and fracturing required to form the steam reservoir.

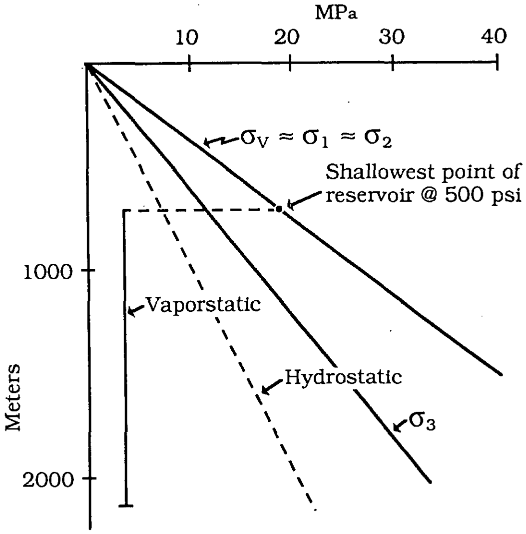

Figure 2 - Estimates of total stresses in the vicinity of The Geysers. Vertical stress (σ_v) is estimated on lithostatic stress resulting from rock density of 2.67 g cm^{-3}. Top of the steam reservoir is defined on the basis of 500 psi.

Although fractures that produce steam have a random orientation, both the injection and withdrawal of fluids appear to utilize structures preferentially that are either normal to the least principal stress or located along the conjugate shear directions. Bodvarsson et al. (1989) have documented the pressure decline with time in a portion of the field. A large diffuse area of pressure decline centered on the Big Geysers is elongated N25E to N50E, along a conjugate direction to the principal strike-slip faulting. A pressure sink in the area of the Little Geysers is developing about a N50W axis or parallel the strike-slip faulting in the area.

Beall et al. (1989) have documented the fluid-flow directions that result from injection of water into the reservoir. The injection of fluid into a fracture should tend to open fractures that are perpendicular to the least principal stress. The contours of isotopic values of injected fluid trend NS to N25E, which is, as the authors note, compatible with the orientation of σ_3 . This is a situation where hydrostatic pressure is being imposed on a portion of the underpressured reservoir. As a result, fractures perpendicular σ_3 are being utilized by the injected fluids.

Another interesting data set that has implications for the orientation of stress in the area is heat flow (Walters and Combs, 1989). The highest anomalies are associated with the producing field. However, a 4.0 HFU contour is elongate in a NNE direction; again, roughly perpendicular to the least principal stress and roughly parallel to the conjugate shear direction. One would normally look for zones of recharge, and resulting areas of depressed heat flow, associated with these directions. This data would suggest that the preferred direction for natural recharge is not being utilized.

STRAIN IN THE GEYSERS

Lofgren (1981) demonstrated subsidence over the producing system and correlated this subsidence with production from the reservoir. He has found that, between 1969 and 1973, there was 1 cm of surface subsidence for each 6.57 psia (.04 MPa) of pressure decline in the reservoir. During the time period of 1973 to 1977, there was an average subsidence of 3.4 cm/year. The analysis also showed that the pressure declines and resulting subsidence were greatest immediately after new plants were placed on line; both rates then decreased.

We have been struck by several seeming contradictions in reviewing the structure of The Geysers. First, although the reservoir is in a zone of active faulting, and is severely underpressured, it is not being recharged along the numerous faults that cut the area. Second, production of steam from the graywacke is from randomly oriented fractures, including fractures that have a flat orientation. Under calculated lithostatic pressure, open flat fractures should not be maintained even in the preproduction state (Fig. 2).We postulate that the reservoir is protected from the weight of the overlying rock by a structure that is analogous to an arch.

In order to test this model and give a first-order approximation of the stress distribution around The Geysers reservoir,we have applied a numerical model designed to determine stress orientation around an underground excavation (Hoek and Brown, 1980). The application of this model is warranted by the underpressured conditions of the reservoir. This is a two-dimensional model, and it does not consider thermal affects.

We have, as an initial approximation, applied calculated models from Hoek and Brown (1980) to determine the expected stress variation in the regions bounding the reservoir. The reservoir is approximated by an ellipse (Fig. 3) and the sections are parallel to the least principal stress (Fig. 3A) and perpendicular to the least principal stress (Fig. 3B) in the σ_1 - σ_2 plane. The lines (streamlines) plotted show stress trajectories or how the orientation of the stress changes due to the presence of the underpressured reservoir. In an elastic medium, the separation of streamlines demonstrates a low stress environment. In contrast, areas where the streamlines crowd together shows areas of high stress.

Figure 3A shows the stresses that would develop along a NW-SE section parallel to the least principal stress. Note that the approximation assigns volumes of $\sigma_1 = 1.0$ and $\sigma_3 = 0$. Here the streamlines are affected considerably above the reservoir, and low-stress zones are developed at the top of the reservoir.

An implication of the stress distribution on Figure 3A is that the approach to the reservoir boundary may be predictable using measurements of borehole elongation or breakouts (Allison and Nielson, 1988). Since stress orientation is changing because of the presence of the reservoir, this change should be measurable and detectable using either Dipmeter or Televiewer tools.

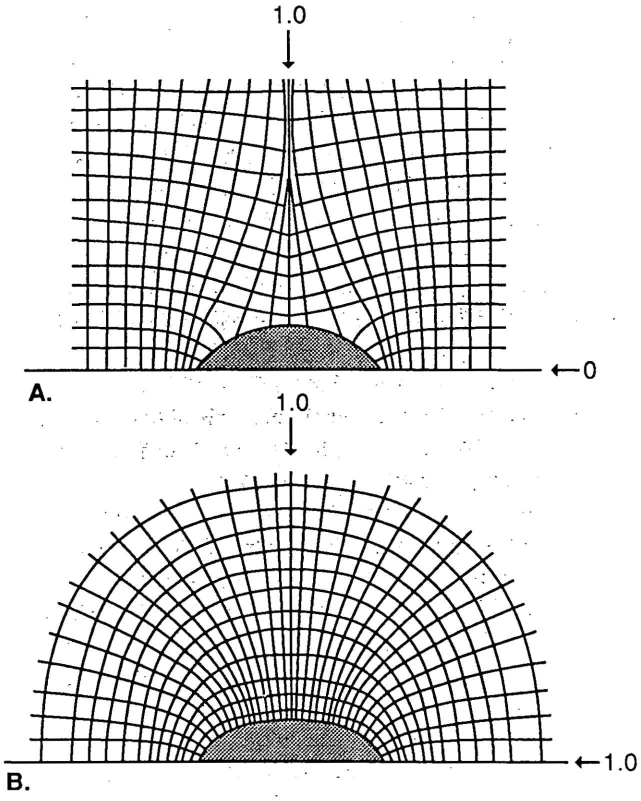

Figure 3 - Two-dimensional models of stress trajectories around a cavity. A. Greatest principle stress is vertical with least principal stress horizontal. B. Representation of stress trajectories in the $\sigma_1 = \sigma_2$ plane.

Figure 3A also suggests that steep structures should be open above the reservoir while flat structures should be closed. This would imply that steep structures should be capable of recharging the reservoir, but this is apparently not taking place. It is suggested that the fractures may have been closed by partial collapse of the arch.

The situation changes considerably at right angles to this section (Fig. 3B). In this section that represents the $\sigma_1 = \sigma_2$ plane, compressional stresses are concentrated along the top and sides of the reservoir. In addition, there is a concentric or hoop stress surrounding the reservoir. Another way of looking at this situation is that the overburden pressure must be distributed through the reservoir "cap" in order for the underpressured conditions, and reservoir permeability, to be sustained. In this section, the distributed loads will tend to close permeable channels oriented parallel to the long axis of the reservoir, thus limiting recharge along strike-slip faults.

It is clear from this simple representation that three-dimensional modeling of the stress environment is required to depict accurately the conditions in the vicinity of the reservoir.

DISCUSSION

In this paper we have discussed the structural geology and reservoir controls of The Geysers reservoir in the context of the tectonic stresses that are acting upon the area. The lack of natural recharge to the system can be attributed to the relative impermeability of the rocks surrounding the reservoir and to the stress closure of joints and fractures.

Application of a simple stress model helps explain one of the enigmas of the system; the existence of flat, steam-producing fractures in an underpressured reservoir. As the model suggests, the reservoir is apparently protected from the lithostatic stresses in much the same manner that a tunnel is; the stresses are distributed along the reservoir margins. However, it is also clear that this structural seal is not perfect since surface subsidence is measurable and earthquakes in the reservoir are responding to regional tectonic stresses (Oppenheimer, 1986).

We postulate that the reservoir developed by contraction of the felsite pluton following emplacement and initial contact metamorphism of the country rock. Pluton contraction could have resulted from processes of cooling or tectonically induced magma withdrawal. Country rock collapsed into the space created by the withdrawal up to the point that the overburden was supported by an arch. Note that this process of roof collapse may have been responsible for the transition from the liquid the vapor dominated state.

The models also demonstrate areas about the reservoir that may be appropriate candidates for injection. We recommend injection from the ends of the reservoir into fractures that are orthogonal to σ_3.

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