STRESS AND FRACTURE ORIENTATION IN THE NORTHWEST GEYSERS GEOTHERMAL FIELD

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ABSTRACT

A dataset comprised of 3946 well-located and well-constrained earthquake focal plane mechanisms recorded in the Northwest Geysers geothermal field during the period of Jan 2005 – May 2012 was used to determine stress orientations and relative magnitudes at fine scale. The stress inversions were organized into gridblocks of varying size using a three-dimensional oct-tree gridding algorithm in which scale of the gridblocks is governed by three-dimensional data density. This method retains the spatial distribution of hypocenters but allows separate inversions for contiguous blocks of seismicity at the finest scale warranted by the data. A minimum of 25 focal mechanisms were used to find the best-fitting orientation of the stress tensor in each gridblock. The stress orientations in each gridblock were then used to determine which of the two nodal planes of the focal mechanism had the highest ratio of resolved shear to normal stresses and was thus more likely to be the active fault plane. Not surprisingly, the faulting regime was found to be normal/strike-slip, as is known for the Geysers, and was nearly uniform, even at fine scale. The maximum horizontal principal stress orientation, S_{Hmax}, and the vertical principal stress, S_{v}, are approximately equal in value with an average S_{Hmax} of N23E. A very consistent stress field was found within the three-dimensional grid studied. The apparent fault planes (assumed to be the primary conduits for fluid flow) were found to be steeply dipping and include approximately north to east striking strike-slip faults and NE trending normal faults, all consistent with the regional SS/NS faulting regime. The greatly improved resolution of the earthquake data allows us to analyze the seismicity in great detail and to determine the orientations of faults providing pathways for fluid flow in the reservoir.

INTRODUCTION

The northern California coast ranges are characterized by right-lateral strike slip and reverse faulting (Castillo and Ellsworth, 1993; Provost and Houston, 2001). The Geysers Geothermal Field (GGF), which is nested between several northwest-trending right-lateral strike-slip faults that belong to the San Andreas Fault (SAF) system, is a tectonically unique region exhibiting normal and strike-slip faulting (Oppenheimer, 1986). A N/NE orientation of S_{Hmax} has been consistently observed throughout northern California (Provost and Houston, 2001) and in the Geysers Geothermal Field (Oppenheimer, 1986) based on inversion of groups of earthquake focal mechanisms to obtain the orientations of the principal stresses. Previous stress inversions were performed with few high-quality focal mechanisms (Oppenheimer, 1986) and had moderate angular misfit in nodal plane orientation (Provost and Houston, 2001) for Geysers events. Additionally, previous inversions of focal mechanisms for stress have assumed uniformity of stress orientation for large regions. Recent studies (Townend and Zoback, 2001) have revealed the benefit of recursive gridding of the study area when conducting the stress inversion. This method, which uses data density to determine gridblock size, leads to inversion for stress within spatially distinct but contiguous blocks of seismicity. This allows a stress result to be adopted with higher confidence for the local volume from which its focal mechanisms originated.

The GGF is a vapor-dominated steam field that is the largest-volume geothermal operation in the world. The reservoir consists of a fractured metagraywacke interval approximately 1 km thick overlaying felsite. A high-temperature reservoir, with temperatures exceeding 350°C, underlies the main reservoir, and is likely shallower in the northern section of the field than in the southern (Stark, 2003). Seismicity in the Geysers is ubiquitous, and is concentrated in regions
of high injection and production. The northwest section of the field alone contains more than 65% of the field’s seismicity, and its large, heterogeneously distributed seismic clusters make it perfect for implementation of the recursive gridding scheme in three dimensions. With some clusters so small that they may represent the stimulated volume for just a few wells, the results of a recursively-gridded inversion for stress may illuminate important details about stresses local to the wellbore in the context of a larger tectonic regime.

METHODOLOGY

Seismicity

The microearthquake catalog used in the inversion consists of \( M_w < 4.3 \) events located by the Lawrence Berkeley National Laboratory (LBNL) monitoring array between 2005 and 2012 in the northern section of the GGF. The events were located with SimulPS using a minimum of 22 picks, P or S. Events had a maximum RMS travel-time residual of 0.1s, and had horizontal and vertical location errors of 500 m or less. The majority of the seismicity occurs below the presumed reservoir interval (Figure 1, right), with a mean event depth of 3.08 km. The presumed upper and lower boundaries of the fractured metagraywacke reservoir, which likely coincide with the top of steam and top of felsite, respectively, are indicated with green dotted lines on the right side of Figure 1. The events highlighted in blue and green are shown in cross-section on the right side of the figure. Seismicity appears to coalesce at depth into larger clusters, and deep seismicity is difficult to associate with any one well as the density of well trajectories and overlapping injection and production schedules complicate temporal and spatial relationships with induced seismicity. Shallow seismicity, on the other hand, tends to occur close to wells and relates temporally to injection.

![Figure 1](image.png)

**Figure 1.** Seismicity used in inversion (dots) shown in plan view (left), latitude vs. elevation cross-section (upper right) and longitude vs. elevation cross-section (lower right). Wells are co-plotted with seismicity, with injectors as blue lines, producers as red lines, and high-volume injectors plotted as yellow lines. Approximate reservoir boundaries shown as green dotted lines in cross-section.
Earthquake Focal Mechanisms

Focal mechanisms were obtained with the program HASH (Hardebeck and Shearer, 2002) using a combination of takeoff angles, azimuths, and first motions from LBNL and Northern California Earthquake Data Center (NCEDC) datasets. The datasets were comprised of locations, takeoff angles, azimuths, and first motions that were obtained in different velocity models using different location algorithms. Since the LBNL recording stations reside within the boundaries of the field, and since its locations are performed in a local three-dimensional velocity model, the LBNL location was chosen over the NCEDC location even though takeoff angles and azimuths based on the NCEDC location were retained. The resulting dataset consisted of 1684 high quality ‘A’ mechanisms, 1533 ‘B’ mechanisms, and 729 ‘C’ mechanisms. There was high angular uncertainty in nodal plane orientation, with an aggregate plane uncertainty of 26.7 degrees, and uncertainties of 20.0, 29.4, and 36.7 degrees for A, B, and C mechanisms respectively.

The average first motion misfit was 22.7 degrees for all mechanisms, and 20.9, 24.3, and 23.3 degrees for A, B, and C mechanisms, respectively. The mean station distribution ratio (STDR), an indicator of spatial coverage of the focal sphere relative to theoretical radiation patterns, was 0.536 for all mechanisms, and was highest in the ‘C’ mechanism group. The FPFIT user manual, upon which the definition of this parameter is based, recommends retaining only data for which STDR is greater than 0.5 (Reasenberg and Oppenheimer, 1985).

Recursive Gridding

Stress inversions were carried out in each gridblock of a complex three-dimensional recursive grid that encompassed the data. The grid was formed using an oct-tree gridding algorithm that began by surrounding the entire dataset with a single three-dimensional gridblock and allowing this gridblock to be subdivided into eight equi-volume gridblocks, each of which was subdivided further if it contained at least 25 events. For each successively smaller gridblock that contained at least 25 events, the subdivision occurred again. The subdivision stopped when the number of events in a gridblock fell below the 25-event threshold. The result was a heterogeneous gridding of regions where grid discretization was based on the local quantity of data (Figure 2).

Figure 2. Three edge-on views of the recursive grid co-plotted with seismicity (blue circles).

The largest gridblock had dimensions 5.8 km x 8.3 km x 5.6 km while the smallest gridblock had dimensions of 0.3 km x 0.5 km x 0.4 km. The greatest balance of spatial continuity, number of included hypocenters, and block fineness came in the third level of gridding with blocks of dimensions 1.45 km x 2.06 km x 1.40 km. These gridblocks had the most comprehensive spatial coverage with the fewest gaps in data. Additionally, the fact that a greater number of focal mechanisms were used for the stress inversion performed in these blocks makes the results more stable, but also means that stress results are smeared over large volumes when only a small portion of the gridblock may be occupied by seismicity. There are benefits and drawbacks to choosing this gridding level, but the desire for data stability overrode the desire for fine discretization.

Inversion for Stress and Choice of Nodal Plane

We inverted gridded groups of focal mechanisms to obtain the deviatoric stress tensor in each gridblock following the method of Michael (1984). This method operates on the assumption that the tangential component of traction is parallel to the slip vector on the fault plane for a given event. This principle, called the Wallace-Bott criterion, allows one to obtain the eigenvalues and eigenvectors of the deviatoric stress tensor for the system of equations
\[ \bar{\tau} = \hat{s}, \]  

(1)

where

\[ \hat{\tau} \sim \bar{\tau} = \sigma \hat{n} - \left[ (\sigma \hat{n}) \cdot \hat{n} \right] \hat{n} \]  

(2)

In (1), \( \bar{\tau} \) is the traction vector and \( \hat{s} \) is the threecomponent slip vector. In (2), \( \hat{\tau} \) is a unit vector in the direction of the traction vector, \( \bar{\tau} \) is the traction vector, \( \hat{n} \) is the unit normal to the fault plane, and \( \sigma \) is the deviatoric stress tensor. Solution of these systems of equations for multiple events within the relevant volume leads to a stable stress result for that volume. Once a stress result has been obtained for a given gridblock, the ratio of resolved shear to normal stresses is computed for both nodal planes of every focal mechanism within that block. The nodal plane that has the largest ratio of resolved shear to normal stresses is the most likely plane to slip in the stress field, and is chosen as the likely fault plane orientation for that mechanism. The plane most likely to slip in the stress field is also the most likely to be hydraulically conductive, according to the critically stressed fault theory (Barton et al. 1995; Zoback, 2007), so these results have important implications for fluid flow.

RESULTS

We observed a remarkably consistent N/NE \( S_{\text{hmax}} \) orientation and a regime characterized by normal and strike-slip faulting (\( S_{\text{hmax}} \approx S_0 > S_{\text{hmin}} \)) for the northwest GGF. There was strong consistency between stress inversion results obtained in the smallest gridblocks and the larger gridblocks within which they were nested, inferring that the scale of any potential stress variations was much larger than the gridblocks used for this dataset. The most finely gridded blocks show consistency in \( S_{\text{hmax}} \) even though there is variation in the faulting regime (normal vs. strike-slip) from gridblock to gridblock. The larger gridblocks show minute variations in \( S_{\text{hmax}} \) orientation, but these variations appear random and no systematic or significant trends exist.

At the optimal level of gridding (Figure 3), no systematic rotation of \( S_{\text{hmax}} \) was observed with depth and there was no consistent lateral division of the study area into faulting types. However, in the reservoir interval and in the basement just below it (Figure 3 top and middle), slightly more normal faulting regimes were observed in the north and slightly more strike-slip faulting regimes were observed in the south. The deepest layer in this grid exhibited a slightly higher percentage of strike-slip faulting regimes than did the shallower layers, and the middle layer of the grid exhibited a greater tendency toward normal faulting. The shallowest grid layer, which corresponds roughly to the reservoir interval, seemed to have an equal mix of normal and strike-slip faulting regimes. Since the \( S_{\text{hmax}} \) orientation is consistent with that of the surrounding region, it appears that the ambient stress state is unperturbed by reservoir activity on the spatial and temporal scales considered. This is an important result for a region characterized by high thermoelastic stresses near wells (Segall and Fitzgerald, 1998) and pore pressure perturbations associated with the movement of subsurface fluids. Since these stress results cover a 7-year time period, any transient stress perturbations related to reservoir activity seem to have little effect on the aggregate stress state over time. To investigate temporary perturbations to the stress state associated with injection and production activity, a detailed stress inversion would need to be performed on an isolated injection with clear ‘before’ and ‘after’ inversions (Martinez-Garzon et al., 2013).

Choosing the focal mechanism nodal plane with the largest ratio of resolved shear to normal stresses as the fault plane for each event, we found fault planes to be steeply dipping (45-90 degrees), and we observed a change in fault plane strike with depth (Figure 4). The presumed boundaries of the fractured metagraywacke interval are associated with a predominantly \( \sim N60E \) fault plane (fracture) orientation while the basement just below appears to contain a wider range of fracture orientations, from roughly N40E to N80E. The deepest basement layer has a bimodal fracture distribution, with predominant fracture sets at approximately N30E and N85E/due east. With a mean SHmax orientation of N23E, the fracture set at \( \sim N30E \) likely corresponds to normal faults while the set striking roughly N85E/due east corresponds to strike-slip faults. With a mean moment magnitude of 2.02, most of these faults are a slab of rock approximately 100 m long that slips a few millimeters. Since all fractures were steeply dipping, differential flow patterns are more related to the spread of fault plane strikes, with the majority of reservoir-level fluid flow occurring along N60E-directed fractures and any deeper fluid flow moving in the direction specified by the bimodal fracture orientation observed in the basement. Shear-wave splitting studies support the finding of a near-vertical fracture orientation (Elkibbi & Rial, 2005). Additionally, fast polarization directions have been found to strike nearly northwest for stations near the regional faults that bound the field, and north/northeast for interior stations (Evans et al., 1995). Lou et al. (1997) found fast polarization directions trending between N10E and N40E.
Figure 3. Hypocenters (black circles) and stresses plotted on stereonets for the reservoir (top) and basement (middle, bottom).

Figure 4. Distribution of preferred fault plane strike for the reservoir (top) and basement (middle, bottom).
CONCLUSIONS

A consistent N/NE $S_{\text{Hmax}}$ orientation was observed for the northwest Geysers Geothermal Field for the period of 2005-2012. The faulting regime is one of normal and strike-slip faulting, where $S_{\text{Hmax}}=S_{V}$. There appears to be equal mixing of faulting types in the fractured metagraywacke interval, slightly more normal faulting observed in the basement just below the reservoir (depths of 2.5km – 3.9km, b.s.l.), and slightly more strike-slip faulting observed in the deepest basement layer studied. In the reservoir interval and the basement layer immediately below, there is slightly more strike-slip faulting in the south than in the north. The highly consistent orientation of $S_{\text{Hmax}}$ obtained for a dataset that spans 7 years suggests that stress perturbations associated with reservoir activity are transient on these spatial and temporal scales. While temporary perturbations to the stress state might exist, they may be smoothed out by the inclusion of events from a wide range of dates. Future work would include similar studies at smaller time intervals, and confined to regions immediately surrounding spatially isolated injection and production wells.

Fractures appear to exhibit a N60E direction of strike in the fractured metagraywacke interval comprising the main reservoir, and predominant fracture orientation changes with depth, culminating in a bimodal distribution of fractures in the deepest basement layer beneath the reservoir. The two predominant fracture sets for the deep basement layer are approximately N30E and N85E. The majority of the induced seismicity occurs below the reservoir interval. If seismicity is a proxy for the presence of reservoir fluids, then the majority of fluid flow in the northwest GGF may be governed by the bimodal permeability anisotropy inferred for the two layers beneath the reservoir.

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REFERENCES


