The Stress State of the Northwest Geysers, California Geothermal Field, and Implications for Fault-Controlled Fluid Flow

by Katie Boyle and Mark Zoback

Abstract A dataset comprised of well-constrained focal mechanisms for 6147 earthquakes recorded in the northwest Geysers geothermal field during the period of 2005–2012 was utilized to conduct a detailed stress study within and below the geothermal reservoir. The high-quality focal mechanisms were organized into grid blocks of varying size using a 3D octree gridding algorithm in which discretization was governed by data density. This method allows for separate inversions of contiguous blocks of seismicity at a relatively fine scale. We obtained the three principal stress orientations for every grid block containing at least 25 events by inverting for the best-fit stress tensor within each grid block. The principal stress orientations were used to determine which of the two nodal planes for each focal mechanism had the highest ratio of resolved shear-to-normal stresses and was thus more likely to be the fault plane. We found a normal/strike-slip faulting regime ($S_{H\text{max}} \approx S_v > S_{h\text{min}}$) both within and below the reservoir, consistent with the extensional and strike-slip tectonics in the region surrounding The Geysers. In addition, an average $S_{H\text{max}}$ orientation of N26°E was obtained for the studied crustal volume. These observations suggest that injection and production activities over the past 50+ years do not appear to have significantly affected the local stress field. The presumed fault planes are steeply dipping with northeast–southwest to east–west strike directions suggesting that these are the principal flow directions both within the low matrix permeability graywacke reservoir and in the wholly concealed granitic pluton (locally referred to as the felsite) basement below.

Introduction

The Geysers geothermal field (GGF) in northern California is a vapor-dominated steam field that provides the largest geothermal electricity generation in the world. Steam production in The Geysers began in 1960 with large-scale fluid injection starting about a decade later (Barker et al., 1992). The Geysers is located between several northwest-trending right-lateral strike-slip faults of the northern San Andreas fault (SAF) system, including the Bartlett springs and Maccama fault zones (Fig. 1). In addition to the right-lateral strike-slip faulting in the region surrounding The Geysers, there is evidence of shallow volcanism in the vicinity of the GGF. The high heat flow in The Geysers is thought to emanate from small scale, young intrusions within the northern portion of the Geysers steam field and extending to the northeast toward Clear Lake (Stanley et al., 1998). A high-temperature zone (HTZ) underlies the main graywacke reservoir. Temperature gradients in excess of 100°C/km have caused temperatures in at least one deep well to exceed 350°C at about 4 km depth. The HTZ is thought to reach greater depths in the northern Geysers than in the south (Stark, 2003). Although thermal stresses near injection wells can become very large (Segall and Fitzgerald, 1998), the degree to which the general stress state is altered by thermal stresses is a topic addressed in this article.

Outside the local region of the GGF, convergent tectonic behavior is seen throughout the coastal ranges. Focal mechanisms throughout the coast ranges are predominantly right-lateral strike-slip and reverse faulting (Castillo and Ellsworth, 1993; Provost and Houston, 2001). Inversion of focal plane mechanisms throughout the coast ranges by Provost and Houston (2001) using data from the Northern California Earthquake Data Center (NCEDC) consistently show northeast–southwest maximum compressive stress directions (dashed lines, Fig. 1). Previously, using less well-constrained focal plane mechanisms, Oppenheimer (1986) found a shallow orientation of $S_{H\text{max}}$ in the GGF (N26°E) similar to what Provost and Houston (2001) found in the surrounding region. The earthquakes within the GGF showed mostly a combination of strike-slip and normal faulting, with only a few reverse-faulting mechanisms.

Seismicity in the GGF is thought to arise from a variety of mechanisms. In addition to increased pore fluid pressure...
resulting from injection, seismicity could be induced by volumetric contraction during steam withdrawal and water injection (Eberhart-Phillips and Oppenheimer, 1984). Prior to the start of geothermal production activity in 1960, there was little historical seismicity in this region (Oppenheimer, 1986). Seismicity in the GGF increased over time as reservoir activity expanded to include both steam production and injection of ambient-temperature water. Seismicity is correlated spatially with regions of notable volume strain (Mossop and Segall, 1999), implying a relationship between the reduction of volume associated with steam withdrawal and the resultant increase in local shear stresses on faults optimally oriented for failure.

High precision earthquake epicenters in the GGF are shown in plan view in Figure 2a, with the study area indicated by the white box. The data used in this study were obtained during the period of 2005–2012 by a dense, high-resolution seismic network that was operated in the GGF by Lawrence Berkeley National Laboratory (LBNL). As seen in the cross section in Figure 2b, hypocenters are predominantly located below the reservoir. The horizontal dashed lines in Figure 2b indicate the approximate top and bottom of the fractured graywacke reservoir. Although the bottom of the reservoir is not known, it is shown here as the contact with the granitic basement, although the granitic basement may host and transmit reservoir fluids.

Recent seismicity in the northwest Geysers study area is shown in more detail in Figure 3. A region of diminished seismicity is seen near the center of the large swarm of earthquakes in Figure 3a and is also seen in the cross section (Fig. 3b,c). In the cross sections, both shallow and deep event clusters are seen although the majority of seismicity occurs below the reservoir. The shallow clusters tend to be smaller and occur close to local well termini within the presumed boundaries of the reservoir, whereas the deep clusters are larger and underlie groups of wells.

In the sections that follow, we first describe the development of a dataset of high-quality earthquake focal plane mechanisms. These focal plane mechanisms are then used to carry out a detailed study of the stress state within and below the geothermal reservoir in the northwest Geysers. We then combine knowledge of the stress state and focal plane orientations to infer the orientations of the faults associated with the earthquakes. As the matrix permeability of both the graywacke reservoir and granitic basement is quite low, it is likely that the earthquake fault planes provide flow paths for water and steam both within and below the reservoir.

**Methodology**

The events were located by the NCEDC using a local velocity model for the Geysers based on the joint hypocenter method combined with a high-quality regional velocity
model outside the Geysers. Both local and regional stations were used in the analysis. First-motion polarities were obtained for 6250 northwest Geysers events with moment magnitudes greater than 1.5 located using stations from both the LBNL and U.S. Geological Survey monitoring arrays (Fig. 4) via the NCEDC (see Data and Resources). These first-motion polarities were used to calculate the earthquake focal plane mechanisms. The majority of the high-quality earthquake hypocenters occur below the presumed steam reservoir, with a mean event depth of 2.7 km below sea level (Fig. 5). Seismicity drops off at around 4.5 km below sea level, presumably because of high temperatures at depth. This is approximately 2.5 km below the mean wellbore terminus of the nearly 120 injectors that blanket the area. The magnitudes of events ranged from $M_w$ 1.50 to 4.68, with a mean event magnitude of 1.9.

The first-motion data were input into FPFIT (Reasenberg and Oppenheimer, 1985) to obtain best-fit double-couple focal mechanisms. The events had a mean root mean square travel-time residual of 0.07 s, mean vertical and horizontal location errors of 0.34 and 0.18 km, respectively, and an average of 43 arrival-time picks, $P$ or $S$ phase, used during the location process. Of the 6250 input events, 6147 were found to have well-constrained mechanisms. The mean nodal plane uncertainty for a right-skewed distribution was 8.2°, and the arithmetic mean misfit was 13.0%. In the case of the misfit, right skewness indicates the prevalence of low misfit values, reflecting the high-quality nature of this set of focal mechanisms. Although there are reported non-double-couple components to focal mechanisms throughout the Geysers (Ross et al. 1996, 1999), the generally low misfit that we observed suggests that double-couple solutions provide useful constraint of the focal mechanism for earthquakes in the area studied.

The focal plane mechanisms were organized spatially using a recursive 3D grid following the methods of Townend and Zoback (2001). The grid design was driven by an octree algorithm that started with a single grid block encompassing all of the seismicity. This grid block was initially divided into eight equal-volume blocks, and those blocks that contained at least 25 events were subdivided again in the same way. This process continued until no grid block contained 25 events, and areas that contained greater data density were more finely gridded than regions that contained lower data density. This organization system allows each later stress inversion result to be considered valid and homogeneous for the body of seismicity from which it originated. Distinct clusters of seismicity can be used to compute independent values of the principal stress orientations and large clusters of seismicity can be broken into smaller clusters to investigate whether the stress field varies over smaller areas.

The recursive grid defined by this seismicity contained 154 grid blocks of varying size. Each grid block contained at least 25 events, but some contained hundreds. The largest

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**Figure 3.** Seismicity (gray dots) and active injection and production well courses (black lines) in the northwest Geysers study area during the period of 2005–2012. Hypocenters and wells are shown in (a) plan view and (b, c) coplotted with terrain in the cross section. The dashed lines in plan view indicate the extents of the north–south and east–west cross sections shown in (b) and (c). The horizontal dashed lines in the cross sections (b and c) indicate the approximate top and bottom of the reservoir.
grid block (grid level 0) had dimensions 5.9 km \times 8.3 \text{ km} \times 6.1 \text{ km}, encompassing the entire study area, and the smallest grid block (grid level 4) had dimensions 0.4 km \times 0.5 \text{ km} \times 0.4 \text{ km}. The size of the very smallest grid blocks approaches the uncertainty in hypocenter locations, so the assumed homogeneous stress result for those grid blocks may be invalidated by the uncertainty in their hypocentral locations. Intermediate grid levels had blocks of dimensions 0.7 km \times 1.0 km \times 0.8 km (grid level 3), 1.5 km \times 2.1 \text{ km} \times 1.5 \text{ km} (grid level 2), and 2.9 km \times 4.2 \text{ km} \times 3.1 \text{ km} (grid level 1). Although grid level 1 covers 100\% of the spatial domain (that is, all 8 contiguous grid blocks contained at least 25 events), it groups together distinct clusters of seismicity separated by large distances. For grid level 2, 64 grid blocks are drawn, and 30 of them (47\%) contain enough seismicity to perform a stress inversion. Many level 2 grid blocks contain large areas without seismicity, with stress results being smeared across blank spaces from seismicity concentrated in one corner of a block. For grid level 3, 512 grid blocks are drawn, and only 67 of them (13\%) contain enough seismicity to perform a stress inversion. However, these 67 grid blocks very closely follow the spatial distribution of the seismicity, with very little blank space in the grid blocks and very little seismicity unrepresented by a grid block. For the reasons mentioned above and others discussed later, the results of this study are best expressed using blocks from grid levels 2 and 3.

The strike, dip, and rake of the two nodal planes for all events in each individual grid block were inverted to obtain stress information about that grid block. Inversion for orientations and relative magnitudes of the principal stresses was based on the methods of Michael (1984). The user specifies a value of the coefficient of friction; \( \mu = 0.8 \) was used in this study, the median of the standard range of measured values between 0.6 and 1.0 (Byerlee, 1978). By exploiting the fact that slip has occurred, one can conclude that the tangential components of traction on the fault plane obtained from the focal mechanism inversion must be significant (i.e., non-zero), such that the denominator of

\[
\hat{\tau} = \frac{\hat{\tau}(\hat{n}, \sigma)}{|\hat{\tau}(\hat{n}, \sigma)|}
\]

is not zero. In this expression, \( \hat{\tau} \) is a unit vector in the direction of the traction vector, \( \hat{\tau} \) is the normalized traction vector, \( \hat{n} \) is the unit normal to the fault plane, and \( \sigma \) is the normalized deviatoric stress tensor. The primary assumption in this method is that the tangential component of traction on a fault plane due to the surrounding stress field is parallel to the slip vector on that plane. This is known as the Wallace–Bott criterion and allows solution of the system of equations

\[
\hat{\tau} = \hat{s},
\]

in which

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

and \( \hat{s} \) is the slip vector. The eigenvalues and eigenvectors of the deviatoric stress tensor \( \sigma \) obtained from this inversion...
provide the relative stress magnitudes and absolute stress orientations, respectively. The best stress result will come from the solution of this system of equations for the possible fault planes within the applicable volume. We assume for the purposes of this study that fault planes are randomly distributed within each grid block. If, however, pre-existing faults with lengths larger than or equivalent to the grid block size exist, the stress result would be less reliable.

To determine which of the two focal plane mechanism nodal planes is most likely to slip in the stress field for each grid block, the ratio of resolved shear-to-normal stresses on each plane was computed, and the plane with the higher value of this ratio was taken as the fault plane. To compute the ratio of shear-to-normal stresses, we first calculated the normal to the nodal plane of interest. Then, we calculate the traction vector by multiplying the deviatoric stress tensor by the nodal plane normal vector. The normal component of traction \( t_n \) was determined by dotting the traction vector into the nodal plane normal vector, and the shear component was simply

\[
 tapered -\frac{1}{2} t_n^2.
\]

The nodal plane with the highest ratio of shear-to-normal stresses was retained and considered the preferred fault plane, the one most likely to slip in the stress field for its grid block.

### Results

The stress regime in the northwest GGF is one of the combined normal and strike-slip faulting (Fig. 6), with an average azimuth of \( S_{H\text{max}} \) in the range of N26°E, varying slightly depending on the grid level for which it is calculated. This result is similar to the previous estimates of \( S_{H\text{max}} \) in the region. The values of \( S_{H\text{max}} \) for grid levels 0, 1, and 2 are very consistent (20.82, 21.07, 21.10, respectively) as are those for grid levels 3 and 4 (27.69, 26.64, respectively). The change in \( S_{H\text{max}} \) at the transition from grid level 2 to grid level 3 may indicate that grid blocks at level 3 are imaging features (perhaps faults) oriented at \( \sim N26^\circ E \) that are smaller than or equivalent in size to the level 3 grid blocks. However, it may also simply represent the change from grid blocks containing large blank areas (level 2) to grid blocks that are more uniformly populated by seismicity (level 3). We also note that the \( 5^\circ-6^\circ \) rotation falls within the nodal plane uncertainty of the focal mechanisms, and so this rotation may not be significant. In addition, reported variance of misfit for the stress inversion decreases by nearly 10% from grid level 0 to grid level 4, indicative of a better stress inversion at smaller gridding levels. As mentioned previously, a better stress inversion relies heavily on the presence of randomly oriented fractures, so the decreased misfit variance may indicate a better inversion for smaller grid block sizes. The decreased misfit variance may also, however, reflect the decreased amount of data that needs to be fit into the smaller grid blocks. For the reasons mentioned above, both gridding levels are valuable, and both are used to represent the results of this study.

In each grid block shown in Figure 6, the earthquakes used in the inversion are seen as light gray dots. The stress directions are indicated in the lower hemisphere stereonets by the red \((S_1)\), yellow \((S_2)\), and purple \((S_3)\) dots. The observed strike-slip/normal stress regime \((S_{H\text{max}} \sim S_v > S_{h\text{min}})\) requires that sometimes \( S_1 \) is the maximum horizontal stress \((S_{H\text{max}})\) and sometimes it is the vertical principal stress \((S_v)\) as they are approximately equal in magnitude in such a regime. This stress field persists with depth both within the reservoir interval and below it. In the approximate reservoir interval, for grid level 2, there is slightly more normal faulting (NF) and combined NF/strike-slip faulting in the north than in the south, where there is more strike-slip (SS)
faulting. Using grid level 3, which separates the reservoir level from the basement more clearly, the north–south dependence is weaker and does not persist with depth. In deeper layers, most grid blocks at level 2 exhibit a normal-faulting regime. Using grid level 3, deeper layers are also shown to exhibit more normal faulting than strike-slip faulting or combined NF/SS. The orientation of $S_{\text{H max}}$ persists with depth at all grid levels but as noted previously rotates clockwise as grid blocks become smaller.

The nonuniform distribution of seismicity within level 2 grid blocks means that stress results from distinct clusters of seismicity are being combined and that stress results are implied for the areas within a given grid block with little or no seismicity. However, the consistency between the stress fields determined in adjacent grid blocks means that this is not a significant issue.

For the NF/SS regime observed in this area, the stress results imply that two sets of conjugate faults are likely to be active: one set being near vertical and trending $\pm 30^\circ$ to the northeast–southwest direction of $S_{\text{H max}}$, corresponding to the strike-slip faults, and another set less steeply dipping and trending northeast–southwest, corresponding to the normal faults. The apparent fault-plane orientations associated with the earthquakes in each grid block are shown in the stereonets in Figure 7 for the reservoir interval and as rose diagrams of the fault strikes in Figure 8. At the depth interval corresponding to the reservoir (Fig. 7 and upper panels of Fig. 8a,b) the fault plane strikes appear to be bimodal at grid level 2, with large numbers of fault planes striking at N45°E and $\sim$N70°E. For grid level 3, there is a prominent set of fault planes striking at around N70°E and another less prominent set striking at N125°E. This smaller set of northwest/southeast-striking fractures more closely aligns with the faults of the surrounding SAF system, but the majority of the faults, which strike N45°E–N70°E, do not. Linear features striking near northeast–southwest are visible in a high-quality double-difference catalog (see Data and Resources) providing support for the northeast-striking fault set. Additional support comes from shear-wave splitting studies. These are mentioned in more detail in the Discussion section.

If the fluid flows primarily in the reservoir interval, then much of the lateral flow will occur in a northeast–southwest direction or nearly east direction, but some would also occur to the northwest/southeast based on results obtained using grid level 3. For grid level 2, the flow would be split between N45°E and N80°E. Below the reservoir, most of the flow is also expected to occur to the northeast and southwest based on grid level 2 results, with most faults trending around
Figure 7. Gridded stress inversion results (colored dots: S$_1$, red; S$_2$, yellow; and S$_3$, purple), hypocenters (gray dots), and preferred fault planes (gray lines) plotted on stereonets for the depth layer corresponding to the reservoir interval. Results are shown for (a) grid level 2 and (b) grid level 3. The grid level depicted in (a) has blocks 1.5 km × 2.1 km × 1.5 km, and the level depicted in (b) has blocks 0.7 km × 1.0 km × 0.8 km.

Figure 8. Rose diagrams showing azimuth of preferred fault plane strike by depth layer. (a) Preferred fault-plane orientation at grid level 2, (b) preferred fault plane orientation at grid level 3. In both (a) and (b), the topmost panel corresponds to the approximate reservoir interval, whereas the panels below correspond to the basement.
N40°E and a second set of faults trending closer to N80°E. For grid level 3, most of deep fault planes strike N30°E and N70°E–N80°E, with the deepest basement layer shown in Figure 8 containing fault planes that strike predominantly N30°E. This constitutes a shift from the predominant N80°E flow direction observed in grid level 2, and especially grid level 3, at the reservoir interval.

Discussion

Inversion of focal mechanisms in the northwest GGF revealed a consistent normal/strike-slip faulting regime with similar stress orientations within and below the reservoir at all gridding levels. However, some rotation of the stress field was observed between gridding levels, with smaller grid blocks showing an average N26°E–N27°E direction of $S_{H\text{max}}$ and larger grid blocks showing an average N20°E–N21°E direction of $S_{H\text{max}}$. Although this result may represent structural differences that appear at different observation scales, it falls within the uncertainty of nodal plane orientations and may not be significant. Overall, the orientation of $S_{H\text{max}}$ within and below the reservoir is highly consistent across all grid levels, depths, and lateral distances. That the results of this inversion are very similar to the regional orientation of $S_{H\text{max}}$ suggests that neither thermal stresses nor the pressure front associated with movement of fluids and steam in The Geysers seems to perturb the orientation of $S_{H\text{max}}$ at the scale considered. This also means that tectonic stresses are implicated in the creation of faults and fractures in The Geysers and accommodation of slip along those fractures, with the transit of liquid water and steam providing only a temporary perturbation to the stress state. Despite the consistency of the $S_{H\text{max}}$ orientation with that of the regional stresses, The Geysers is tectonically unique in its NF/SS faulting regime, nested within a region characterized by reverse and strike-slip faulting associated with the SAF system.

The reservoir rock, a metagraywacke, has low matrix permeability, but the orientation of likely fault planes suggests permeability anisotropy mainly in the northeast–southwest directions and east–west directions, with a small portion of fault planes striking parallel to the SAF fabric in a northwest/southeast direction. The permeability anisotropy is most likely associated with brecciation and damage zones from slip along small faults and fractures. The dominant hydraulically conductive fault orientations in the field are expected to be directly related to the orientation of the principal stresses, because, according to the critically stressed fault theory (Barton et al., 1995; Zoback, 2007), those fractures that are critically stressed in the current stress field will experience slip and contribute to hydraulic conductivity. This theory has been applied to explain massive gas flow in faulted basement rocks in Indonesia (Hennings et al., 2012) and applied to flow in the Coso (Sheridan and Hickman, 2004) and Dixie valley (Hickman et al., 1998) geothermal fields.

With a mean moment magnitude of 1.9, most of these faults are about 100 m in size and slip a few millimeters based on a stress drop of several MPa. It would take communication between multiple faults of this size to provide fluid flow conduits between wells in The Geysers. We observe no correlation between event magnitude and preferred fault-plane orientation, suggesting that even the smallest grid blocks in our grid are likely not dominated by large through-going faults.

Lipman et al. (1978) notes that fractures observed in Geysers core samples are typically near vertical, but the strike direction could not be determined. Exposed reservoir rocks contain randomly oriented fractures that have long been sealed through diagenesis (Sammis et al., 1992), but these sealed fractures reflect prior tectonic states and do not relate to the current state of stress in the region. Shear-wave splitting studies also indicated a near-vertical fracture orientation (Elkibbi and Rial, 2005). In the upper 1.5 km of the field, fast polarization directions are observed both parallel to northwest-trending strike-slip faults that bound the field on either side and striking in a north–northeast direction (Evans et al., 1995). Deeper shear-wave splitting results showed a more heterogenous distribution of fast-polarization direction (Evans et al., 1995) to depths of 5 km. Other studies confirmed a dominant fast polarization direction trending between N10°E and N40°E (Lou et al., 1997).

In general, flow paths in the reservoir are poorly understood. Tracer tests in the northwest Geysers reveal the complexity of the major flow conduits. Tests in wells HJ12, Curry8513, OS-11, and GDC53A13 (Enedy, 1985b; Beall, 2002, 2010; Wright, 2010) show primary flow consistent with a north–northeast-directed permeability anisotropy, whereas a test in well SB-1 (Enedy, 1985a), located in the southwest region of the study area, shows southeast and eastern movement of tracer, which does not agree with the majority of fault orientations obtained from our study. In addition, the OS-11 tracer study supports a slower southeast flow direction, with tracer arriving southeast of the injection point at lower concentrations and later times than it arrives northeast–southwest of the injection point. Although the subhydrostatic reservoir pressures cause the injected fluid to flow downward, facilitated by steeply dipping fault planes, fracture strike controls lateral flow directions. The fault orientations (Fig. 8) show a bimodal distribution with a prominent set of fractures nearly east–west and another set northeast–southwest. We suggest that these should correspond to the lateral flow directions within and below the reservoir. In this case, shallow fluids will tend to move in a northeast–southwest direction, while there is also a tendency for a more east–west direction of flow in the basement. Circumstantial evidence (J. Beall, personal comm., 2011) supports the idea of flow along a northeast–southwest-directed normal fault in the southwest study area. This proposed structure is consistent with the preferred fault-plane orientations observed for the northwest Geysers seismicity.
Conclusions

Use of high-quality earthquake focal mechanisms to understand stresses and fracture orientations in the northwest Geysers has helped to provide a physical interpretation of reservoir architecture that governs fluid flow. The orientations of $S_{\text{H max}}$, obtained in the study area are remarkably consistent with independent estimates of $S_{\text{H max}}$ in this region associated with the SAF system. In contrast to the typical reverse and strike-slip faulting types observed in the coast ranges and the SAF system in northern California, The Geysers appears to be characterized by strike-slip faulting, normal faulting, and combinations thereof. In the northwest Geysers, the inversion of focal mechanisms within closely spaced grid blocks reveals a consistent NF/SS faulting regime with similar stress orientations—both within and below the reservoir. This suggests that even after decades of operation, neither the production of steam nor injection of relatively cool, ambient temperature water has significantly perturbed the stress state.

Two dominant fault sets emerge from this study: one oriented northeast–southwest and another oriented east–west. The presence of earthquakes beneath the injector wellbores is consistent with a subhydrostatic reservoir that results in fluid penetration to greater depths because of the growing disparity between the hydrostatic water column and subhydrostatic reservoir pressures that increases with depth. In the reservoir interval, the predominant fracture orientation is N70°E–N80°E for grid level 3 and is bimodally divided between N40°E and N80°E for grid level 2. Below the reservoir, the fracture orientation is predominantly N30°E–N40°E at both gridding levels. As reservoir flow in these very low permeability layers is influenced by faults and fractures that are actively slipping in the current stress field, the results obtained have important implications for fluid flow in The Geysers. Namely, shallow fluids will tend to move in a northeast–southwest direction, whereas fluids are anticipated to flow in northeast–southwest and east–west directions at depth. Tracer tests generally support the idea of north–northeast flow, although other flow directions are also observed.

Data and Resources

Lawrence Berkeley National Laboratory (LBNL) hypocenter locations and phase data for The Geysers can be obtained by e-mailing Stephen Jarpe (SPjarpe@lbl.gov) or Katie Boyle (Kboyle@lbl.gov), Northern California Earthquake Data Center (NCEDC) hypocenter locations and phase data for The Geysers can be obtained at http://www.ncedc.org/ncedc/catalog-search.html (last accessed 22 April 2013). Directional surveys for the Geysers wells were obtained from The California Department of Conservation Division of Oil, Gas, and Geothermal (DOGGR) website at geosteam.conservation.ca.gov/WellSearch/GeoWellSearch.aspx (last accessed November 2012). The double-difference hypocenter catalog for The Geysers (Schaaf and Waldhauser, 2005; Waldhauser and Schaff, 2008) can be obtained at http://www.ideo.columbia.edu/~felixw/NCAeqDD/NCAeqDD.GGF.upd.jpg (last accessed 23 March 2014).

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