RELATIVE IMPORTANCE OF PROCESSES LEADING TO STRESS CHANGES IN THE GEYSERS GEOTHERMAL AREA

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ABSTRACT
Quantification of the different processes that contribute to the spatio-temporal stress changes at geothermal sites is critical for the understanding of induced seismicity. Poroelastic coupling and thermal-mechanical processes during hot water extraction and cold water injection are probably the key processes that contribute to the stress changes in The Geysers geothermal field. In particular, with the onset of massive injection of wastewater into the reservoir the number of induced events with magnitudes M > 4 increased significantly. This raised the question which stress changing process is the key control of the induced seismicity rate. In addition to man-made stress changes the tectonic loading from the Pacific plate motion relative to the North America plate also alters the stress state as well as the co-seismic stress change of the induced events itself.

In order to assess the relative importance of the various stress changing processes, we built a 3D thermo-hydro-geomechanical numerical model of The Geysers geothermal field. The model accounts for the far-field tectonic loading as well as for the co-seismic stress changes of the M > 4 events. To solve the resulting fully coupled partial differential equations we use the commercial finite element code Abaqus. After the implementation of an initial stress state that is calibrated against data of the orientations of maximum horizontal stress and stress regime from earthquake focal mechanism solutions, we apply kinematic far-field boundary conditions derived from continuous GPS stations. First, preliminary results reveal that tectonic loading contributes within the reservoir little compared to the pore-pressure diffusion on time scales of several years. Furthermore, the relative importance of stress changes due to pore pressure diffusion strongly depends on the spatial and temporal scales that are analyzed as well as on the uncertainties of the rock properties in particular the permeability of the rock matrix.

INTRODUCTION
Fluid injection under high pressure to enhance permeability of geothermal reservoirs and massive injection of waste water to maintain reservoir is common practice (Tester et al., 2007). These processes are beside the hot water production, i.e. heat extraction from the underground the key man-made processes that alter the subsurface stress state. However, in the past decade the accompanying induced seismicity became an increasing problem not only at geothermal reservoirs (Evans et al., 2012; Majer et al., 2012, 2007) but also related to other types of underground mining activities such as hydrocarbon exploitation, as well as potash and coal mining (Suckale, 2009, 2010).

Whether injection-related seismicity or production-related seismicity is considered, both types of seismicity are induced by a stress change. These are caused by the injected or produced fluid. There are two components of the fluid, leading to stress changes. Fluid has a pore pressure component as well as a temperature component. Fluid injection increases the pore pressure increase and thus reduces the normal stress along nearby faults, and thus can cause seismicity (Byerlee, 1978). Fluid extraction and thus pore pressure decrease results in subsidence of the surface around the production well. The heat extraction and injection of cold water also changes the stress field by changing the thermal stresses.

Furthermore, depending on the predominant tectonic regime, in extensional regimes normal faults may be developed at the flanks of the reservoir, in compressional regimes thrust faults may be developed above and below the reservoir (Segall and Fitzgerald, 1998). Heating up the cold injected fluid cools down the hot rock and leads to volumetric contraction. This contraction reduces the friction on nearby faults (Eberhart-Philips and Oppenheimer, 1984) or even can create new cracks within the rock volume, both mechanisms resulting in potential seismicity.
Besides the man-made induced stress changes natural processes such as plate tectonics and co-seismic stress transfer due to major seismic events can alter the stress state substantially. In The Geysers geothermal field these processes can potentially contribute significantly to the overall stress state. To quantify the relative importance of these man-made and natural processes we built a 3D thermo-hydro-geomechanical numerical model of The Geysers geothermal field that describes the stress changes caused by fluid flow and by temperature changes as well as the ones from natural tectonic processes. Our model is a regional approach of the whole reservoir in contrast to other work that focus on single fluid injection experiment or 2D effects of poroelastic effects (Brue, 2007; Altmann et al., 2010; Kohl and Megel, 2007; Rutqvist et al., 2006; 2007; Ghassemi and Zhou, 2011; Fakcharoenphol, 2012;)

As we set-up a regional model of The Geysers area, we also consider fluid injection and production at different locations. This enables us to model injection and production scenarios within the entire geothermal field. As the seismic activity clearly increased with the start of SEGEP and SRGRP, our main interest of investigation is on the period starting on 1997 with SEGEP till now. We also implemented the major fault system of The Geysers as well as the reservoir bounding faults in order to assess at a later stage the reactivation potential of these long fault segments and the stress changes on these due to reservoir production and long-term waste water injection in comparison with tectonic loading.

In the following sections we describe briefly the overall tectonic setting and the monitored induced seismicity. We then present the technical and geometrical setup of our model followed with a description how we introduce and calibrate the initial stress field and the loading from plate tectonics.

**TECTONIC SETTING AND GEOLOGY**

The Geysers geothermal field is located in northern California, in an active tectonic region. It is approximately 150 km north of San Francisco, about 60 km east of the San Andreas fault and 20 km south of the Clear Lake basin. The Geysers is located east of the Maacama fault and is bounded to the east by the Collayomi fault. Maacama as well as Collayomi faults are part of the broad right-lateral San Andreas transform fault system, where the Pacific plate adjoins the North American plate (McLaughlin, 1981; Allis, 1982; Donnelly et al., 1993; Boyle et al., 2011). Figure 1 shows a map of northern California, in which the location of The Geysers is marked as solid red line. The arrows show observed GPS velocity measurements with respect to a fixed North American plate. GPS-measurement were taken from the USGS SFBay area GSP network.

Numerous authors (Donnelly et al., 1993; Bufe et al., 1981; Oppenheimer 1986; Eberhart-Philips, 1988; Allis and Shook, 1999) point out that seismic measurements indicate that the Clear Lake area, where The Geysers geothermal field is located, is under extension. The Clear Lake basin is assumed to be a pull-apart basin (Crowell, 1974; Hearn et al., 1988; Donnelly et al., 1993) within the broad San Andreas fault system. The reason for the described complex tectonic and geological setting in the Clear Lake area is the subduction of the Farallon plate beneath the North American plate, which ended about 3 Ma ago at the latitude of the Clear Lake area (Donnelly et al., 1993; Boyle et al., 2011). After the Farallon plate was subducted beneath the North American plate 3 Ma ago, volcanism commenced in the Clear Lake area ca. 2.1 Ma ago (Donnelly et al., 1993). There is evidence that there is a large silicic magma body beneath the Clear Lake area, responsible for the heat anomaly of this area (Stimac et al., 1992; Donnelly et al., 1993; Boyle et al., 2011).

An intrusion of felsic rock into the Meta-Greywacke about 1.2 Ma ago led to the felsite layer, part of The Geysers geothermal reservoir (Brikowski 2001). The felsite layer varies in depth from 0.7 km depth in the southeast Geysers up to 2.5 km depth in the northwest Geysers (Brikowski 2001; Boyle et al., 2011).

The enormous heat in the underground leads to a natural geothermal activity in The Geysers area,
where hot spring and fumaroles appear at the surface. Due to this obvious thermal activity, already in the 1920’s The Geysers were discovered as potential energy source and eight wells were drilled during this time. Commercial energy production started in 1955 and was expanded since then to recently eighteen active power plants (Lipman et al., 1978; Sanyal and Enedy, 2011).

**OBSERVATION OF INDUCED SEISMICITY**

The massive development of the geothermal field as well as a lack of both natural and artificial recharge, the reservoir pressure began to decline in the late 1980’s. As a consequence, productivity began to decrease (Stark et al., 2005; Goyal and Conant, 2010; Sanyal and Enedy, 2011). In order to prevent the reservoir pressure to further decline, two injection projects were set up in order to pump secondary-treated and tertiary-treated wastewater from nearby communities into the underground (Goyal and Box, 2004; Stark et al., 2005; Goyal and Conant, 2010; Sanyal and Enedy, 2011). The Southeast Geysers Effluent Project (SEGP) started in 1997, the Santa Rosa – Geysers Recharge Project (SRGRP) started in 2003. Since then, the reservoir pressure was stabilized.

Despite of a decreasing production rate since the end 1980’s, seismicity with events of magnitude M > 1.5 increased (Figure 2). A comparison of injection rate, production rate and observed seismicity (Figure 3) shows a clear correlation between injection rate and observed seismic events of M > 1.5. Especially after the start of the two wastewater injection projects in 1997 and 2003, seismicity increased.

After the start of SRGRP in 2003, also the occurrence of M > 4 earthquakes increased. But this increase could temporally not correlated to the wastewater injection (Majer and Peterson, 2007; Boyle et al., 2011). Rutqvist and Oldenburg (2008) suggest injection-related seismicity to occur due to cooling-induced shear slip along fractures, whereas Denlinger and Bufe (1982) suggest production-related seismicity to occur due to temperature and pore pressure decrease (Boyle et al., 2011).

**MODELS GEOMETRY AND DISCRETIZATION**

For our geomechanical-numerical model of The Geysers region we have chosen a rectangular area of approximately 60 km by 40 km that is oriented in the direction of the horizontal velocities derived from the continuous GPS station P195 (Figure 4).

The size for the geomechanical-numerical model is chosen at this regional scale in order to model the far field effect of tectonic loading on the state of stress within The Geysers and on the reservoir bounding faults, and that the distance between the model boundaries and the area of interest (reservoir) is large.
enough to avoid any boundary effects on the results. However, the model is small enough to have a high resolution in the center of the model to implement also injection and production points (Figure 5).

**Figure 5:** Finite element model of The Geysers area. The reservoir (blue layer) is located in the model center. Seven major faults included are: Maacama fault (MF), two branches of the Geyser Peak fault (GPF), two branches of the Wight Way fault (WWF), Cobb Mountain fault (CMF), Collayomi fault (CF).

The model geometry consists of three horizontal stratigraphic layers, representing the Greywacke layer from the surface to a depth of approximately 2.5 km, the Felsite layer down to a depth of 5 km and the upper crust from 5 km to a depth of 15 km (Figure 5 and 6).

**Figure 6:** Geothermal reservoir of The Geysers on top of the Felsite layer, realized in the geomechanical-numerical model.

The model geometry also contains seven major faults of this area, which are implemented as vertical contact surfaces, intersecting the entire model from the surface to the bottom in 15 km depth. The geothermal reservoir itself is located in the center of the geomechanical-numerical model on top of the Felsite layer.

In order to solve the fully coupled differential equations of poroelasticity and thermal diffusion we discretize the model geometry into 1.2 million tetrahedral poroelastic elements, to which pore pressure and temperature can be addressed to. The resolution increases from 25 m around the injection and production points to 200 m at the reservoir boundary up to 2.5 km at the model boundaries.

In order to simulate the effect of fluid injection and withdrawal on the pore pressure field and on the state of stress, we included 65 injection and production points in total. Injection points are located at SEGEP and SRGRP injection wells, production points around the power plants. Figure 7 shows a part of the injection and production points within the reservoir.

**Figure 7:** Injection and production sites are indicated as yellow dots, rupture planes of the induced events with magnitude four and larger are shown as inclined purple planes. Faults are represented as large vertical, colored planes.

Additionally, we included ten rupture planes of magnitude 4 earthquakes that occurred since the start of SEGEP in end of 1997 as planar contact surfaces. For the orientations of the rupture planes we used strike and dip from earthquake moment tensor solutions. This gives us the possibility to model the effect of co-seismic slips on the state of stress.

**NUMERICAL MODELING OF STRESS AND STRESS CHANGES**

The model process consists of several consecutive steps with increasing model complexity. First we start with the definition of an appropriate initial stress state of the model area. Then we apply the lateral kinematic boundary conditions to simulate the stressing of past tectonic loading. These two initial phases will deliver the starting stress field before fluid injection and production are considered.
**Initial State Of Stress**

The k-ratio as the ratio of the mean horizontal stress to vertical stress can be used as parameter to describe the reference stress state of the Earth’s crust. The compilation of k-ratios presented in Figure 8 shows that it varies in the first two kilometers significantly. Measurements from the KTB site (Brudy et al., 1997) and the SAFOD pilot hole (Hickman and Zoback, 2004) show that the k-ratio is decreasing with depth and tends to converge to lithostatic (k=1) at greater depth. As SAFOD is in a tectonic very active region the k-ratio is much clearly higher due to higher horizontal stresses compared to the KTB site that is in central Europe in a tectonically inactive region.

The simplest way to define an initial state of stress is obtained by applying gravity to a geomechanical-numerical model with the model bottom and the model sides fixed in normal directions. However, this procedure results in a uniaxial stress state that is not justified by comparing the stress state with field data (Figure 8).

In order to define a reference stress state Sheorey (1994) presents a one-dimensional analytical elasto-static thermal earth model. He parameterizes the structure of his earth model in terms of thermal gradient, thermal expansion coefficient varying with depth and temperature, gravity and elastic constant varying with depth. He takes into account the effects of thermal expansion and gravitational compaction, and derives an expression for the k-ratio for the uppermost kilometers of the earth’s crust

\[
k = 0.25 + 7E \left( 0.001 + \frac{1}{H} \right)
\]  

(1)

where \(E\) is the Young’s modulus in GPa and \(H\) depth in m. This k-ratio is valid for areas with no lateral density changes and no active tectonics. For \(E=90\) GPa, the value for the KTB site (Brudy et al., 1997), this k-ratio fits very well the measured data from the KTB site (Figure 8). This implies that the simple uniaxial boundary conditions would not result in an appropriate initial stress state. Thus, in our model we thus use the k-ratios that result from the Sheorey model (1994) as it fits the observed data best.

In practical terms of modeling, we build a box around The Geysers geomechanical-numerical model with model boundaries inclined to the center of the earth. In the following, this box is called Sheorey-box. The inclined model boundaries increases the horizontal stresses compared to a model with vertical model boundaries, when the model compacts due to the applied gravity forces.

The Sheorey-box consists of two layers, an upper load frame with the same depth like The Geysers model and a lower layer called compaction layer. With Equation (1) Sheorey (1994) gives an estimate of the k-ratio in the upper crust. This formula is valid for an area without tectonic stresses and with no lateral density variations. Thus, Equation (1) is used to calculate an initial state of stress. \(E\) is known for the different layers of The Geysers model, so that we are able to calculate a k-ratio dependent on \(H\). This gives us theoretical curves of the k-ratio, one for each Young’s modulus of the model.

Now, gravity is applied, and from the resulting stress field k-ratios along vertical paths are calculated, which are in areas of no lateral density variations. We use the finite element solver ABAQUS to solve the resulting poroelastic partial differential equations in order to perform our modeling studies. We fit this modeling results to the theoretical curves calculated after Equation (1). The modeled k-ratios can be improved by variation of the Poisson’s ratios of The Geysers model and of the load frame, and by variation of the Young’s modulus of the compaction layer.

Figure 10 shows the best fit of modeled and theoretical k-ratios along two vertical profiles. There
are three different curves, because of three different layers in the model, which have different Young's moduli.

![Figure 10: Comparison of k-ratio curves after Sheorey (1994) (solid lines) with modeled k-ratios along two vertical paths (location 1, location 2). The difference between the modeled k-ratios in depths between 2 km and 3 km is due to different thicknesses of Greywacke and Felsite layers.](image)

This result is used as the initial stress state of the model area, the basis which in the following tectonic loading and fluid injection and production is applied on. The initial stress state does not consider any stress changes due to tectonics. As The Geysers is located in an active tectonic region, tectonic loading will change the initial stress state. In the following, we apply boundary conditions to the model, representing tectonic loading in this area.

**Stress Change Due To Tectonic loading**

The Pacific plate moves north-northwest with 51.5 mm/a with respect to a fixed North American plate. In The Geysers area, this movement decreases from 31 mm/a at the Maacama fault to 21 mm/a east of the Collayomi fault. This means a difference of 10 mm/a within our modeling area (Figure 4). Therefore, to model this effect, the southwestern model boundary is aligned along the measured GPS-vector, so that we can apply a shear boundary condition of 10 mm/a to this model boundary. The northeastern model boundary is fixed, and along the other model boundaries we apply a linearly decreasing velocity from 10 mm/a in the west to zero in the east. These boundary conditions are marked as red arrows and triangles in Figure 4.

For our modeling approach, we use poroelastic material properties, given in Table 1.

**Table 1: Poroelastic material properties with void ratio n, hydraulic conductivity k, Poisson’s ratio, bulk modulus of the solid grains K_s, bulk modulus of the wetting liquid K_l and drained bulk modulus K_d.**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Greywacke</th>
<th>Reservoir</th>
<th>Felsite</th>
<th>Upper Crust</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (%)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>k_l(m/s)</td>
<td>1.0E-10</td>
<td>5.0E-8</td>
<td>5.0E-10</td>
<td>1.0E-10</td>
</tr>
<tr>
<td>v</td>
<td>0.32</td>
<td>0.35</td>
<td>0.32</td>
<td>0.30</td>
</tr>
<tr>
<td>K_s(GPa)</td>
<td>40</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>K_l(GPa)</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>K_d(GPa)</td>
<td>18</td>
<td>26</td>
<td>37</td>
<td>50</td>
</tr>
</tbody>
</table>

After applying these boundary conditions to the model, the initial state of stress has changed. We use the regime stress ratio (RSR) after Simpson (1997) and the orientation of the maximum horizontal stress to compare the modeling results with observed data. The RSR has values between 0 and 3 and is a continuous scale for the stress regime, covering radial extension (RSR=0), extension or normal faulting (RSR=0.5), transtension (RSR=1.0), strike slip (RSR=1.5), transpression (RSR=2.0), compression or thrust faulting (RSR=2.5) and constriction (RSR=3.0).

Figure 11 show a RSR contour plot in a depth of 2 km. Values range from 0.65 to 1.3 within The Geysers. These means, that there is a transtensional regime with some normal faulting and strike slip components. This result, we compare to focal mechanism solutions of earthquakes occurred in The Geysers (Figure 12). These data show normal faulting and strike slip regimes. The modeling results, which also show regime between normal faulting and strike slip, fit to these observations.

Figure 13 shows a contour plot of the orientation of the maximum horizontal stress S_H in 2 km depth. The S_H orientation varies in the model results between 8 and 18 degrees within The Geysers. These values are in average about 10 degrees smaller than the observations (Figure 12), but are within the standard deviation of mean S_H orientation with 27° ± 20°.

To summarize, after applying tectonic boundary conditions to the geomechanical-numerical model, the results can explain observed data of tectonic regimes and S_H orientations. In the next step, fluid
injection and production is applied to the model and stress changes due to these processes are modeled.

Figure 11: RSR (Regime stress ratio) contour plot in 2 km depth. Values within The Geysers range between 0.65 and 1.3 indicating transtension to strike slip regime. Note that The Geysers is in the center of the model (see Figure 4).

Figure 12: Stress map of The Geysers area. Lines show the orientation of the maximum horizontal stress $S_h$ derived from earthquake focal mechanisms solutions following the World Stress Map quality ranking scheme (Heidbach et al., 2010); color indicate the tectonic regime with NF=normal faulting (red), green strike-slip (green) and TF=Thrust Faulting (blue). Rose diagram shows the mean $S_h$ orientation with 27° ± 20°.

Fluid Injection And Production Induced Stress Changes

Here, we show first results of modeling the pore pressure and stress change due to fluid injection and production at The Geysers. For this purpose, we modeled a scenario of fluid injection and production starting in end of 1997 with the start of SEGEP, added in 2003 the injection due to SRGRP and ended in 2013 with our modeling. Fluid injection due to SEGEP is represented by fluid injection at 10 injection points, due to SRGRP at further 13 injection points and due to production at 42 production points. Injected and produced fluid amounts correspond to real injected and produced amounts. We have averaged the injected and produced amounts over the entire model run time and over all injection and production points. This means, 28 l/s at each SEGEP injection point, 30 l/s at each SRGRP injection point and 48 l/s at each production point.

Figure 14 shows the pore pressure change within The Geysers. The reservoir pressure is lowered by approximately 20 to 30 MPa, with higher values in the vicinity of the production points and with lower values towards the reservoir boundary. There are local increases of pore pressure in the vicinity of the injection points. The overall picture is a decrease of pore pressure in the reservoir. A decrease in pore pressure increases the stress components. Figure 15 shows the change in maximum principal stress in the reservoir. Fluid production and pore pressure decrease increases the maximum principal stress by 10 to 30 MPa with higher values in the vicinity of the production points.
DISCUSSION

As no stress magnitude data are available from The Geysers, we used the reference state of Sheorey (1994) that provides k-ratios as well as information on the $S_H$ orientation and the tectonic regime to calibrate the initial stress state of the model.

The data from the KTB-site can be well explained by the Sheorey-concept (Figure 8), but not the data from the SAFOD pilot hole. In principle the Sheorey reference stress state is only valid for regions with no active tectonics and no large lateral density variations. This holds on for the KTB-site, but not for the SAFOD pilot hole.

Also The Geysers is in an active tectonic region. Calculating the k-ratio without applying tectonic boundary conditions, k-ratios and thus RSR values are too low compared to measured data. Figure 16 shows the RSR in a depth of 2 km before applying tectonic boundary conditions. The values within The Geysers range between 0 and 0.3; thus the regime is highly extensional, and the measured tectonic regimes could not explained by these results. The tectonic loading increases the horizontal stresses and thus the k-ratio and the RSR. Compare the results of Figure 16 to those of Figure 11, where RSR is plotted after tectonic loading is applied.

Not only RSR values change by adding tectonic loading to the modeling process. There is also a change in the $S_H$ orientation. Before applying tectonic loading to the model, the $S_H$ orientation covers the entire range from 0 to 180 degrees (Figure 17).

The more or less stable measured orientation (Figure 12) cannot be explained by these results. Therefore, it is essential to add tectonic loading to the modeling process.

Injection and production of fluid have a clear impact on the pore pressure field and on the state of stress. However, the results showing changes in the order of a few tens of MPa are overestimated; these are preliminary results that depend significantly on the assumed permeability of the rock. There are
estimates that the reservoir pressure dropped by a few MPa (Mossop and Segall, 1997).

Figure 17: Orientations of the maximum horizontal stress in 2 km depth, only due to gravity field (no tectonic loading).

CONCLUSION

In order to quantify the relative importance of the man-made and natural processes that change the stress state in The Geysers geothermal field a regional model is needed. Furthermore, we showed that the implementation of an appropriate initial stress field of The Geysers is of key importance. Tectonic regimes and orientations of the maximum horizontal stress, both derived from focal mechanism solutions, can be explained by the model results with the initial stress field and tectonic loading due to the locked San Andreas fault system.

First results, preliminary results, of long-term injection and long-term production of fluid show a decreasing pore pressure and increasing effective stresses. However, the absolute values seem to be overestimated given the pore pressure observations that indicate a smaller stress drop.

For the future, we have developed a tool to make the permeability of the reservoir dependent on the pore pressure. When pore pressure exceeds a certain pore pressure value, permeability increases. This will increase the fluid flow and lower the pore pressure changes. Additionally, we intend to investigate stress changes due to co-seismic slip and in particular the stress loading history at the reservoir bounding faults.

ACKNOWLEDGEMENT

The work presented was mainly funded by the Department of Energy Geothermal Technologies Program under Award Number DE-EE0002756-002 and co-funded by the European Commission within the FP7 project GEISER, grant agreement no. 24132.

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