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Authors

Rutqvist, Jonny
Majer, Ernie
Oldenburg, Curt
et al.

Publication Date

2006-06-07

INTEGRATED MODELING AND FIELD STUDY OF POTENTIAL MECHANISMS FOR INDUCED SEISMICITY AT THE GEYSERS GEOTHERMAL FIELD, CALIFORNIA

Jonny Rutqvist, Ernie Majer, Curt Oldenburg, John Peterson, and Don Vasco
Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Key words - Induced seismicity, The Geysers, steam production, geomechanical modeling

ABSTRACT

In this paper, we present progress made in a study aimed at increasing the understanding of the relative contributions of different mechanisms that may be causing the seismicity occurring at The Geysers geothermal field, California. The approach we take is to integrate: (1) coupled reservoir geomechanical numerical modeling, (2) data from recently upgraded and expanded NCPA/Calpine/LBNL seismic arrays, and (3) tens of years of archival InSAR data from monthly satellite passes. We have conducted a coupled reservoir geomechanical analysis to study potential mechanisms induced by steam production. Our simulation results corroborate co-locations of hypocenter field observations of induced seismicity and their correlation with steam production as reported in the literature. Seismic and InSAR data are being collected and processed for use in constraining the coupled reservoir geomechanical model.

INTRODUCTION

This paper focuses on the progress of a project funded by the California Energy Commission (CEC), aimed at increasing the understanding of the relative contributions of different mechanisms that may be the cause of the seismicity occurring at The Geysers geothermal field. The approach was based on the integratation of: (1) coupled reservoir geomechanical numerical modeling, (2) data from recently upgraded and expanded NCPA/Calpine/LBNL seismic arrays, and (3) tens of years of archival InSAR data from monthly satellite passes.

The coupled reservoir geomechanical analysis is used to calculate the time evolution of the three-dimensional stress field during steam production and cold-water injection, and to evaluate the potential evolution and distribution of micro-earthquakes (MEQs) using various failure criteria. The results of the coupled reservoir geomechanical analysis will be corroborated with, and constrained by, data from the new NCPA/Calpine/LBNL seismic array, which began operating in October 2003, and by regional strain data derived from InSAR.

COUPLED RESERVOIR GEOMECHANICAL ANALYSIS

The coupled reservoir geomechanical analysis is conducted using TOUGH-FLAC (Rutqvist et al., 2002), a simulator based on linking the geothermal reservoir simulator TOUGH2 with the geomechanical code FLAC3D (ITASCA, 1997). In the case of The Geysers, TOUGH-FLAC is utilized to calculate the time evolution of the three-dimensional stress field during steam production and cold-water injection into the steam-dominated reservoir. This includes changes in thermal stress caused by temperature variations and changes in effective stress caused by pore pressure alterations. From the calculated evolution of the stress field (in time and space) various failure criteria can be applied to investigate the potential for induced seismicity at every point in the rock mass.

The first part of our study is a coupled thermal-hydrological-mechanical (THM) analysis of reservoir-wide steam production over three decades. As a first-order analysis we conduct a simulation on a cross-axis (NE-SW), two-dimensional model grid of The Geysers. Data from published papers on the geothermal system were used to establish the geometry of the computational grid. The conceptual model of the field, consisting of a low-permeability cap and a very low permeability lateral boundary defines a reservoir approximately 10 km wide by 3 km deep (Figure 1). The grid, taking advantage of symmetry, models a 5 km wide section in the northeastern part of The Geysers. The analysis was run to a steady, natural state followed by a 35-year steam-production simulation. Steam production was simulated by extracting steam at a constant rate at the left-hand boundary of the model (representing the center of the reservoir) between 1600 to 3000 m depth.

The results of the simulation broadly show a pressure and temperature decline of a few MPa and a few degrees, respectively, as well as subsidence of about 1 meter that has been observed at The Geysers (Williams, 1992; Mossop and Segall, 1997, 1999a). A sensitivity study shows that most ground settlement is caused by poro-elastic contraction, with a small contribution from thermo-elastic contraction. In this simulation, a rock-mass bulk modulus of 3 GPa was adopted, which approximately corresponds to values back-calculated by Mossop and Segall (1997 and 1999a), based on strain analyses. The rock thermal expansion coefficient was set to 3×10^{-5} $°C^{-1}$, which corresponds to values determined on core samples of the reservoir rock at high (250°C) temperature (Mossop and Segall, 1997).

Rock mechanical experiments on Geysers samples performed by Lockner et al. (1982) indicate that the rock has undergone extensive hydrothermal alterations and re-crystallization, and that it is highly fractured. These authors suggested that fracturing has weakened the rock to such an extent that models of the geothermal field should assume that only a frictional sliding load can be supported by the rock. They maintained that shear stress in the region is probably near the rock-mass frictional strengths, and therefore very small perturbations of the stress field could trigger seismicity. This hypothesis is supported by recent Geysers studies of remotely triggered seismicity, which indicate that seismic events can be triggered by a stress change as low as 0.03 to 0.07 MPa (Prejean et al., 2004). Thus, one of the main mechanisms to investigate at The Geysers is shear slip caused by small stress-field perturbations.

Studies of fault plane analysis by Oppenheimer (1986) indicated seismic sources on almost randomly oriented faults. For such a case, and as a conservative assumption, we evaluated the potential for shear slip under the assumption that faults of any orientation could exist anywhere. Moreover, for a conservative choice of friction angle of 30° the onset of shear failure could occur if the maximum principal compressive effective stress exceeds three times the minimum principal effective stress (i.e., if $\sigma'_1 \geq 3\times\sigma'_3$, failure is likely). However, for The Geysers, it is quite possible that shear stress in the region is near the rock mass frictional strength. Therefore, we studied changes in the stress state (σ'_1, σ'_3) and investigated whether the stress state moves away or toward a condition of likely failure.

Figure 2 presents changes in fluid pressures and horizontal stresses after 35 years of production. The figure indicates that changes in the horizontal stress field are on the order of 1 MPa, with a reduction of total compressive stress in the reservoir and an increased compressive stress in the caprock near the ground surface. Because a stress change as low as 0.01 MPa might be sufficient to induce a seismic event, the 1 MPa stress change over 35 years might induce repeated events over the 35-year period. Moreover, the number of yearly events likely depends on the rate of stress change in a given year.

Figure 3 depicts the stress path for two points near the central part of the geothermal field. One is located in the caprock, 750 m below ground surface; the other in the reservoir near the center of the steam production. The stress path is compared to the failure envelope ($\Delta\sigma'_1 = 3\times\Delta\sigma'_3$) for the maximum compressible *in situ* stress being either vertical (Figure 3a) or horizontal (Figure 3b). Figure 3 shows that the potential for shear failure in the caprock would only occur if the maximum principal *in situ* stress is horizontal. Near the production zone, there is a high potential for failure in the first few years because of a reduction in both principal stresses. This reduction is a result of thermo-elastic contraction during evaporation cooling adjacent to the steam production zone. In the case of maximum *in situ* stress being vertical, the principal stress state moves out of the original failure zone after about 1 year (Figure 3b, green line). In the case of maximum principal stress being horizontal, the principal stress state moves out of the original failure zone after about 10 years (Figure 3a). However, the maximum potential for failure is reached after 1 year, whereupon the principal stresses return towards more stable conditions.

The results obtained in our analysis are in agreement with the induced seismicity observed at The Geysers and reported in the literature since the late 1980s. This includes fault plane analyses by Oppenheimer (1986) and studies of MEQ mechanisms by Mossop and Segall (1999b). For example, Oppenheimer (1986) found from his fault plane analysis that in the upper 1 km, significant fraction of the earthquakes exhibit reverse focal mechanisms, indicating that σ_1 becomes horizontal as a result of steam production. Moreover, Mossop and Segall (1999b) found a significant correlation between steam production and shallow seismicity, with a >16 month-long time lag, as well as deep seismicity with a time lag < 2 months. They suggested that the shallow production-induced earthquakes are caused by poro-elastic stresses, whereas the deep production-induced seismicity could be explained by thermo-elastic stresses resulting from evaporative cooling. Our coupled reservoir geomechanical analysis also shows that shallow production-induced earthquakes are caused by poro-elastic stresses and can only occur if σ_1 is horizontal. At depth, our analysis indeed shows significant potential for seismicity induced by evaporative cooling.

The next step in the coupled reservoir geomechanical analysis will be to model cold-water injection. This injection is expected to induce significant cooling stresses near the injector, as well as contribute to the recovery of reservoir pressures, with an associated reduction in effective stresses. However, detailed analysis of potential MEQs near an injection well will probably also involve three-dimensional modeling at the scale of an individual injector.

NCPA/CALPINE/LBNL SEISMIC DATA ANALYSIS

By taking advantage of faster computing speed, of recent developments in elastic wave propagation theory, and of new ideas about seismic sources, it is now possible to make a number of significant improvements in the methods of automatic MEQ analysis. Given the number of stations now recording high-frequency digital seismic data at The Geysers and other areas, the first step was to develop a more detailed velocity model for the steamfield. This step consists of two parts, building a one-dimensional model describing the average depth-dependent material properties and constructing a three-dimensional model showing perturbations from this model. Developing the model in this manner has advantages in terms of the inversion methods used to estimate the characteristics of the model, such as the Born inversion methods of Keers et al. (2000) and the methods used for forward-wave propagation in source location and moment tensor estimation.

Another improvement over the last two years is the interpretation of source data in terms of an asperity model for earthquakes (Johnson and Nadeau, 2005). Recent analyses of small earthquakes along the San Andreas Fault have lead to the development of an asperity model that provides an alternative to the conventional model that has dominated the interpretation of seismic data for the past 40 years. Given the large number of small seismic events and the opportunity to estimate stress changes caused by the withdrawal and injection of fluids, The Geysers appears to be an ideal site for applying some of the techniques that were developed for the study of the small San Andreas events. Should the data indicate that the asperity model helps to explain the seismic events at The Geysers, our understanding of why these events occur could be significantly advanced.

Figure 4a shows the MEQ activity at The Geysers during November 2005, just at the beginning of increased injection in the Aidlin area. At that time the rate of water injection was quadrupled. Figure 4b shows the MEQ activity at Aidlin during March 2006. As can be seen by comparing these figures, the activity has become more focused and localized, but the magnitudes of the events have not shown any significant increase. It appears that the injection is indeed having an effect on the frequency and location of the seismic events.

INSAR DATA ANALYSIS

Synthetic Aperture Radar Interferometry (InSAR) has revolutionized our ability to measure crustal deformation, enabling great precision and spatial coverage (e.g., Bürgmann et al. 2000). A new approach, the permanent scatterer method (PS) introduced by Ferretti et al. (2000), has improved our ability to determine millimeter-scale displacements of individual features on the ground using all data collected over the target area by a SAR satellite (such as the European Space Agency's Earth Remote Sensing, ERS-1&2 spacecraft upon which we rely in this study).

The PS method uses individual radar-bright and phase-stable targets (i.e., monuments whose properties allow the reflection of a variety of incident radiation orientations) between many (> 15) SAR scenes to determine a high spatial- and temporal- resolution time-series of ground surface displacements. The method minimizes errors from atmospheric delays and orbital uncertainty, allowing for a theoretical precision of range-change rate determination at the 0.1-0.3 mm/yr level (Colesanti et al., 2003).

The PS method has the potential to provide the necessary resolution to identify and characterize details of The Geysers surface displacement field, that cannot be obtained with the leveling and GPS measurements that have been previously used to study deformation at and around the steamfield (e.g., Mossop and Segall, 1997, 1999a). The PS method can detect surface strains on the order of 10^{-6} to 10^{-7} on a regional scale with a spatial resolution of 25 meters. It is well suited for long-term monitoring of regional and local strain fields. The technique uses the full archive of InSAR images, collected during a ten-year period of approximately monthly satellite passes over the region. As such, it is ideally suited for monitoring ground surface deformations.

Our collaborators, the Ferretti's group in Italy and the Burgmann's group at U.C. Berkeley, have examined the ERS and RadarSat archives for scenes that cover The Geysers region. They have determined that descending tracks 342 and 113 image that region. For track 342/frame 2835 and 2853, there are 25 double scenes. In total there are 28 full triple scenes in existence, from April 20, 1992 to July 11, 2002, plus six triple scenes where data are missing from the peninsular portion of frame 2853. For descending track 113 there are 52 double scenes spanning from May 9, 1992 to October 28, 2003. There is also an ascending track (478), which encompasses The Geysers; it contains 27 scenes, gathered from May 13, 1995 to May 16, 2004. Currently, we are processing observations from track 342, frame 2835, to determine the density of permanent scatters in the region from The Geysers to the south.

CONCLUDING REMARKS

We have conducted a coupled reservoir geomechanical analysis to study potential locations and mechanisms of seismicity at The Geysers associated with the exploitation of the geothermal steamfield. Our simulation results corroborate field observations of induced seismicity and its correlation with steam production, as reported in the literature. In addition, field data collected by the recently upgraded and expanded NCPA/Calpine/LBNL seismic array have provided improved seismic data collection during the recently begun injection at Aidlin (northwestern part of The Geysers). These data include information on the evolution and location of induced seismicity, as well as inferred mechanisms, in an area not previously subjected to water injection.

The next step in our investigations will be to use our reservoir geomechanical model ─ "validated" against observed patterns of production-induced seismicity ─ to investigate the potential mechanisms contributing to injection-induced seismicity. We will compare the results of our simulation against the new observations of induced seismicity at Aidlin, regarding location, distribution and mechanisms. Moreover, when strain data from the InSar become available they could be used to constrain mechanical boundary conditions for the coupled reservoir geomechanical model.

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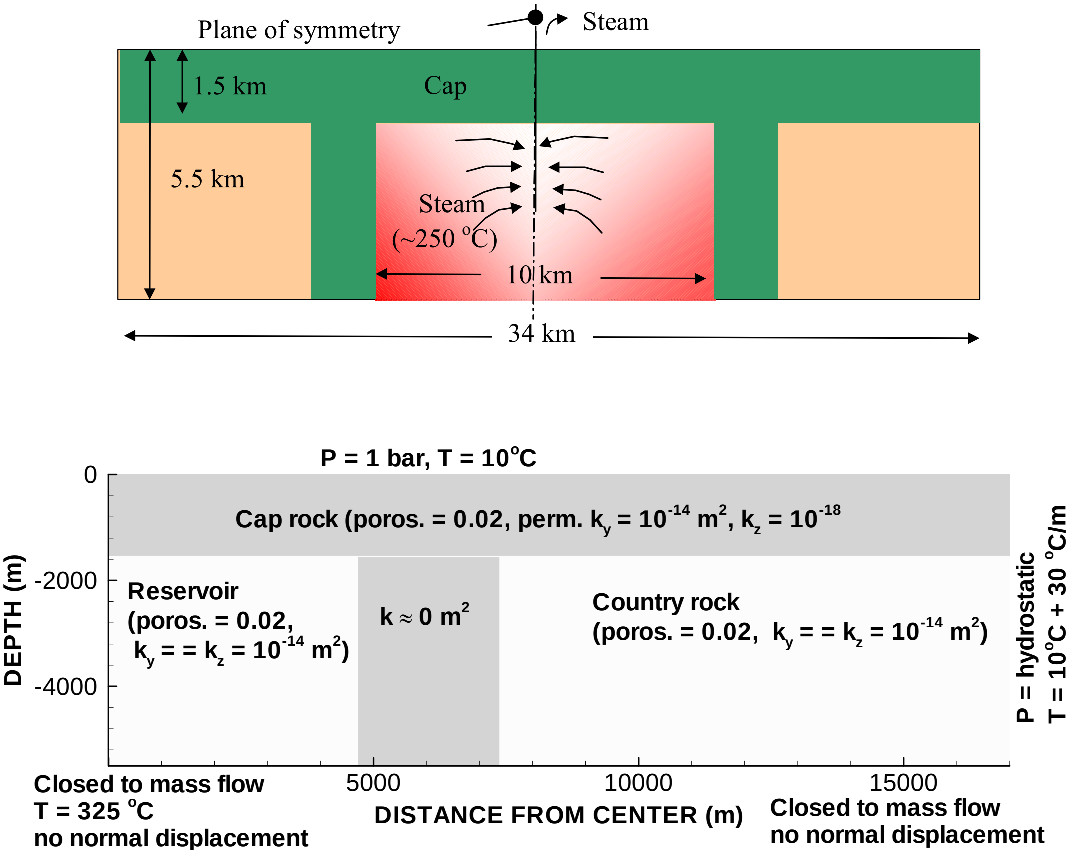
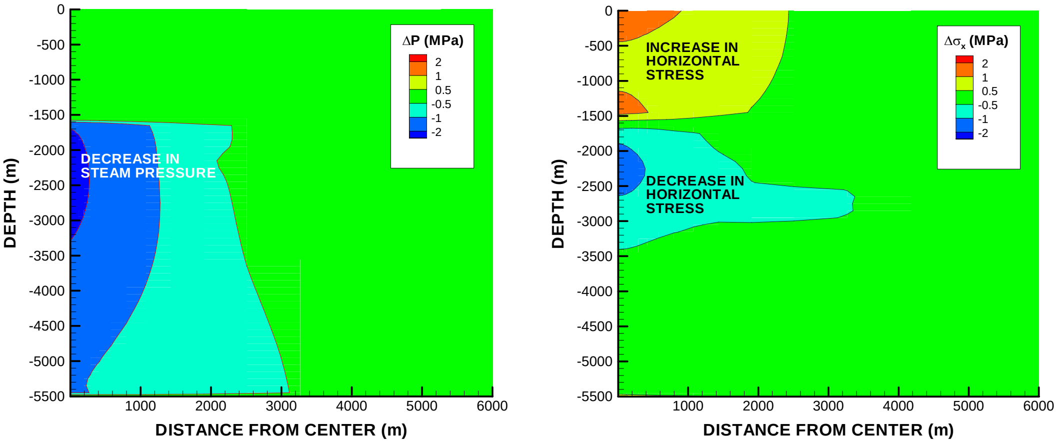


(A)

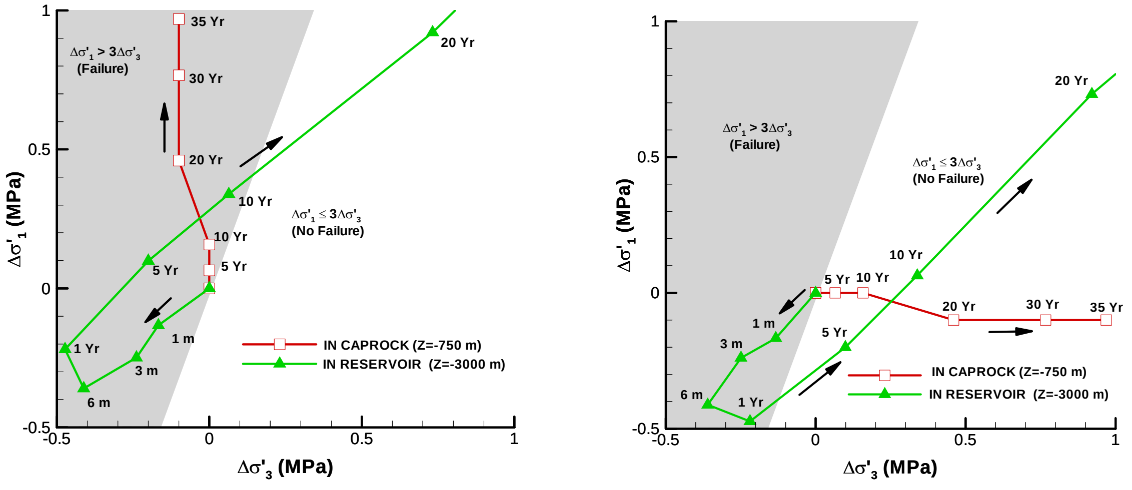
(B)

Figure 1. Domain and boundary conditions for the first-order coupled geomechanical reservoir Geysers model aligned NE-SW across The Geysers geothermal field. (A) Schematic model of the field, and (B) half-symmetric model with hydraulic properties and boundary conditions.



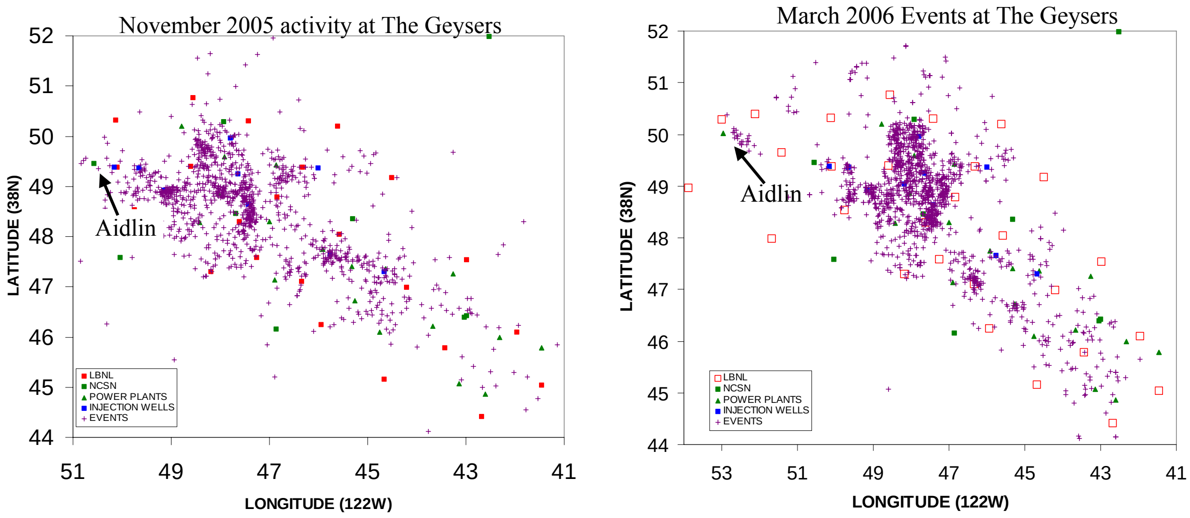
(A) (B)

Figure 2. Calculated changes in (A) steam pressure and (B) horizontal stress.



(A) (B)

Figure 3. Calculated path of changes in the stress state (σ'_1, σ'_3) for (A) a compressional stress regime ($\sigma_h > \sigma_v$) and (B) an extensional stress regime ($\sigma_h < \sigma_v$).



(A) (B)

Figure 4. MEQ activity at recorded at The Geysers during: (A) Geysers MEQ activity–November 2005 and (B) Geysers MEQ activity – March 2006.