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Seismic velocity structure and characteristics of induced seismicity at the Geysers Geothermal Field, eastern California

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A R T I C L E I N F O

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A B S T R A C T

We present a newly developed three-dimensional seismic velocity model, high-precision earthquake relocations and focal mechanisms near the Geysers Geothermal Field in eastern California using seismic data recorded by the Northern California Earthquake Data Center from 1984 to 2015. The velocity model generally agrees with those in previous studies with the V_p model mainly corresponding to rock composition and the V_p/V_s model more correlated with fluid content. The dominating low V_p/V_s anomalies observed from 0 to 4 km depth below sea level is a reflection of the geothermal reservoir. The waveform cross-correlation relocated seismicity shows both spatial and temporal correlations with the geothermal operations in the study area, indicating that they are induced seismicity. Although the focal solutions are dominated by normal and strike-slip regimes throughout our entire study time period, there has been an increase in reverse faulting since 2008, which may be caused by the thermal contraction associated with the Northwest Geysers Enhanced Geothermal System project between 2008 and 2012. Our study provides a groundwork for future seismological studies in The Geysers.

1. Introduction

The Geysers Geothermal Field (GGF) in eastern California is situated approximately 110 km north of San Francisco and is the largest geothermal field in the world. Although intensively exploited, it still provides about 6% of California's electrical power. The Geysers is also one of the most seismically active regions in California and is dominated by shallow induced seismicity. It is located on the eastern side of the Maacama Fault Zone and the Healdsburg Fault, bounded by the right-lateral strike-slip Mercuryville Fault and Collayomi Fault, and surrounded by several Mountains, such as the Geyser Peak, the Cobb Mtn., the Boggs Mtn., the Seigler Mtn., and the Mt. Hannah (Fig. 1). Since the geothermal operations commenced in the 1960s, numerous studies have been conducted to investigate their effects on hydrologic and tectonic features in the area. The tectonic setting and structure in The Geysers have been reviewed by previous researchers (e.g., McLaughlin, 1981; Thompson, 1989, 1992). The spatial/temporal variations in seismic velocities have been intensively investigated (e.g., Majer and Mcevilly, 1979; O'Connell and Johnson, 1991; Zucca et al., 1994; Romero et al., 1995; Alwyn, 1996; Julian et al., 1996; Kirkpatrick et al., 1997; Boitnott and Kirkpatrick, 1997; Foulger et al., 1997; Gunasekera et al., 2003; Gritto et al., 2013; Gritto and Jarpe, 2014). The majority of these studies show that the shallow velocity structure correlates with the surface geology and the geologic and hydrologic features of the reservoir. Although some studies found no consistent correlation between injection and seismicity, it has been widely accepted that there is a correlation between the two parameters (Majer and Mcevilly, 1979; Denlinger and Bufe, 1980; Bufe and Shearer, 1981; Allis, 1982; Eberhart-Phillips and Oppenheimer, 1984; O'Connell and Johnson, 1991; Stark, 1992; Romero et al., 1995; Alwyn, 1996; Trugman et al., 2016). The stress state study by Boyle and Zoback (2014) revealed a normal/strike-slip faulting regime within and below the reservoir and also suggested that the geothermal operations have no significant effect on the local stress field.

In this paper, we aim to investigate the structural heterogeneities and examine the spatial and temporal variations and characteristics of induced seismicity in The Geysers Geothermal Field by using a newly developed high-resolution three-dimensional (3-D) V_p and V_p/V_s model, precise earthquake relocations, and focal mechanisms. This study is also motivated by a recent work on remotely triggered earthquakes by Zhang et al. (2017). They found that although the adjacent fault areas are responsive, the two hot water systems themselves, the Coso and the Salton Sea Geothermal Fields, are insusceptible to large distant earthquakes. The Geysers Geothermal Field is an under-pressurized, vapor-dominated field, which may have different response to remote earthquake triggering. Our results in this study will provide essential

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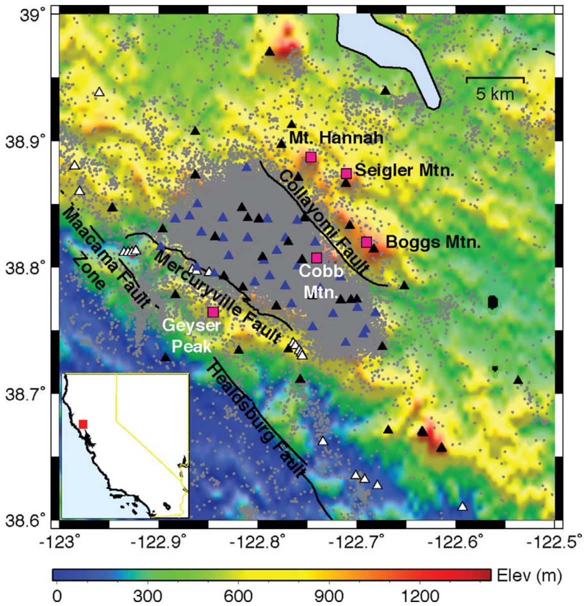

Fig. 1. Major geological structures in the study area, including the surface fault lines (black lines) and several mountain ranges (pink squares). Gray dots represent ~246,000 earthquakes between 1984 and 2015 recorded by the NCSN (black triangles). Blue and white triangles stand for the EGS and the temporary stations, respectively. The background is the topography base map from the U. S. Geological Survey. The red box in the inset map shows the location of our study area in California. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

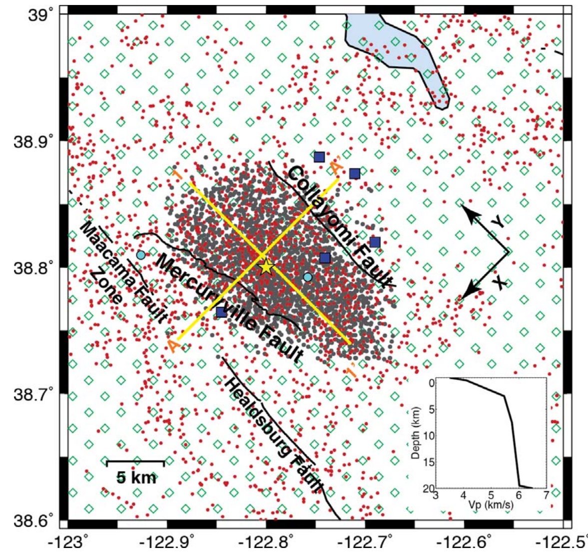

Fig. 2. Events (dots) and inversion grid nodes (green squares) used in the tomographic inversion. Gray dots stand for earthquakes that are only recorded by the EGS stations, red ones for those recorded by the NCSN stations, and two big blue ones for the three explosion events (with two at the same location). The Cartesian coordinate is rotated 45° counterclockwise with respect to latitude and longitude, with the X axis pointing to the southwest and Y axis to the northwest direction. The origin is located at (38.8°, −122.8°) (shown by the yellow star). Dark blue squares denote the same mountains in Fig. 1. The two yellow straight lines are the profiles for the cross-sectional views in the following figures. The inset figure shows the 1-D initial V_p model for the tomographic inversion, which is used for the NCSN daily operation in the Geysers area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

groundwork for the future fine-scale remote triggering analyses and other seismological studies in The Geysers.

2. Data

We obtained all the seismic data used in this study from the Northern California Earthquake Data Center (NCEDC, 2014). These data are mainly recorded by the Northern California Seismic Network (NCSN) stations (black triangles in Fig. 1), consisting of ~246,000 local earthquakes (gray dots in Fig. 1) from 1984 to 2015 with 3.7 million compressional (P) and 0.18 million shear (S) wave first-arrivals and all their waveform data. The majority of these events are confined within the steam-production zone of the Geysers Geothermal Field, bounded by the Mercuryville Fault to the southwestern side and the Collayomi Fault to the northeastern side.

For the tomographic inversion, due to the small number of S-picks available in the NCSN catalog, we also take advantage of the seismic record from the Enhanced Geothermal Systems (EGS) stations (blue triangles in Fig. 1), operated by the US Department of Energy Geothermal Technologies Program. The EGS data include ~444,000 earthquakes since April 2003 with over 5 million P- and 2 million S-picks. Note that the EGS catalog events are only used in the velocity tomography, not in the relocation or focal mechanism inversions.

For the selection of the master events used in the tomographic inversion, we apply different requirements for the NCSN and EGS network catalogs. For the EGS catalog events, we require more than 8 P picks and 4 S-P times per event. The resulting 1937 events (gray dots in Fig. 2) consist of 26,975 P and 12,243 S picks. Due to the very few number of S-picks in the NCSN catalog, we require at least 8 P picks and no constraints on the number of S picks for each event. The 2038 events (red dots in Fig. 2) comprise 34,617 P and 333 S picks. The inclusion of the events outside of the GGF are helpful to improve deep velocity structure resolution. These total 3975 events and their corresponding picks are used in our final velocity model inversion. P-wave arrival times for 3 active-source data (big blue dots in Fig. 2), recorded by temporary seismic stations (white triangles in Fig. 1) and collected by previous investigators (Meador et al., 1985), were also included in the tomographic inversion to constrain the shallow crustal structure and absolute hypocenter locations.

3. Results

3.1. 3-D seismic velocity model

The simul2000 algorithm is one of the most widely applied tomographic programs, which solves for 3-D V_p, V_p/V_s models and earthquake locations simultaneously (Thurber, 1983, 1993; Eberhart-Phillips, 1990; Thurber and Eberhart-Phillips, 1999). It combines parameter separation and damped least squares for model perturbations. The original simul2000 algorithm allows a constant minimum earthquake depth, i.e., none of the earthquake locations can be shallower than the given minimum depth. In this study, we apply a modified version of the simul2000 that replaces the constant minimum depth with the specific topographic information to avoid artificial effects (Lin, 2015).

The horizontal grid spacing in our 3-D velocity model is 2 km (rotated squares in Fig. 2). The vertical node intervals range between 1 and 4 km from −1 to 20 km depth. Zero depth corresponds to mean sea level. Note that in this paper all depths are relative to mean sea level, unless otherwise stated. A one-dimensional (1-D) V_p model (inset in Fig. 2), which is used for the NCSN daily operation in the Geysers area, is applied as the initial model for the 3-D tomographic inversion. The starting value for the V_p/V_s inversion is a constant ratio of 1.732.

In order to investigate the model recovery, we performed a checkerboard resolution test similar to previous studies (e.g., Thurber et al., 2009; Lin et al., 2010, 2014; Lin, 2013, 2015). We created a synthetic velocity model based on the 1-D starting model with ± 5% V_p and ∓5% V_p/V_s perturbations (i.e., opposite signs) that alternate at different depths and across two grid nodes. Synthetic times were computed