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## Key Point:

- Three-dimensional Vp and Vp/Vs models and earthquake relocations in the Coso geothermal field

Supporting Information:

- Readme
- catalog
- Figure S1
- velfile_fine_vp
- velfile_fine_vpvs

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# Three-dimensional Vp and Vp/Vs models in the Coso geothermal area, California: Seismic characterization of the magmatic system 

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#### Abstract

We combine classic and state-of-the-art techniques to characterize the seismic and volcanic features in the Coso area in southern California. Seismic tomography inversions are carried out to map the variations of $\mathrm{Vp}, \mathrm{V}$ s, and $\mathrm{Vp} / \mathrm{Vs}$ beneath Coso. The velocities in the top layers of our model are correlated with the surface geological features. The Indian Wells Valley, with high silica content sediment strata, shows low-velocity anomalies up to 3 km depth, whereas the major mountain ranges, such as the south Sierra Nevada and the Argus Range, show higher velocities. The resulting three-dimensional velocity model is used to improve absolute locations for all local events between January 1981 and August 2011 in our study area. We then apply similar-event cluster analysis, waveform cross correlation, and differential time relocation methods to improve relative event location accuracy. A dramatic sharpening of seismicity patterns is obtained after using these methods. We also estimate high-resolution near-source $\mathrm{Vp} / \mathrm{Vs}$ ratio within each event cluster using the differential times from waveform cross correlation. The in situ $\mathrm{Vp} / \mathrm{Vs}$ method confirms the trend of the velocity variations from the tomographic results. An anomalous low-velocity body with low $\mathrm{Vp}, \mathrm{Vs}$, and $\mathrm{Vp} / \mathrm{Vs}$ ratios, corresponding to the ductile behavior underlying the Coso geothermal field from 6 to 12 km depth, can be explained by the existence of frozen felsic magmatic materials with the inclusion of water. The material is not likely to include pervasive partial melt due to a lack of high $\mathrm{Vp} / \mathrm{Vs}$ ratios.


## 1. Introduction

The Coso geothermal field (CGF) is located between the Sierra Nevada batholith and the Basin and Range Province in southeastern California (Figure 1a). As one of the largest geothermal fields in the US, it has been exploited to generate power through over 100 production wells since 1987 [Adams et al., 2000]. The maximum heat flow of the geothermal field was estimated to be 10 times the value from the background Basin and Range [Combs, 1980] (Figure 1b). A crustal magma body has been assumed to provide the primary heat source for the present surface geothermal system [Combs, 1980; Bacon et al., 1980; Duffield et al., 1980].

Several lines of evidences favor the existence of a magma body beneath Coso. First, Coso is in a transtensional tectonic regime and the extension facilitates the ascent of magma. Coso sits in an extensional stepover between the dextral striking faults to the north and south. The geothermal field is surrounded by three main valleys with a series of strike-slip and normal faults [Reasenberg et al., 1980]. Lithospheric extension causes crustal thinning beneath the geothermal field, which favors the intrusion of basalt from the mantle into the crust, sustaining a long-lived magma reservoir in the crust [Duffield et al., 1980]. The crustal thinning at Coso is supported by the geochemical result of the isotopic composition of rocks, which are strongly influenced by the asthenosphere [Monastero et al., 2005].

The geothermal field is characterized by young volcanic rocks, mainly Pleistocene rhyolite dome, flanking basalt flows and cinder cones. The active volcanoes erupted around 4 Ma , and the Pleistocene bimodal eruptions continued from 1.04 to 0.03 Ma , while the latest active volcanism is estimated to be 0.03 Ma [Duffield et al., 1980; Manley and Bacon, 2000]. It is believed that the magmatic activity beneath the dome field triggered the Coso geothermal system around 0.2 Ma [Adams et al., 2000; Duffield et al., 1980]. Combs [1980] showed that the geothermal field is associated with 38 rhyolite domes, surface hydrothermal manifestations, and higher heat flows than the surrounding area. The highest heat values correspond to the geological features, such as the Sugarloaf Mountain (SM, the largest rhyolite dome in the area), the Devil's


Figure 1. Geologic map of the Coso area. Coso sits under the transition zone between the strike-slip San Andreas Fault and the extensional Basin and Range. It is bounded on the north by the northwest striking Owens Valley Fault while in the south is dominated by the dextral Little Lake fault zone (LLFZ) and Airport Lake fault zone (ALFZ). (a) Map showing tectonic features and our study areas I and II. Blue dots represent the earthquakes between 1981 and 2011 recorded by the Southern California Seismic Network (SCSN) stations shown by the red triangles. Black lines denote Quaternary faults. Our study area II for the fine-scale model marked by the red box encloses the geothermal field and the surrounding areas. In the inset map, the red star shows the location of the Coso area in California and the rectangle shows our study area I.
(b) A close-up of the study area II. Black dots denote the grid nodes for inversion. Blue dots are the master events for the tomographic inversions. Diamonds are colored by the heat values from Combs [1980] and Saltus and Lachenbruch [1991]. High heat flow values within the geothermal field are present in the Sugarloaf Mountain (SM), the Devil's Kitchen (DK), and the Coso Hot Springs (CHS). The geothermal field is surrounded by three main valleys, the Rose Valley (RV), the Coso Wash (CW), and the Indian Wells Valley (IWV). Other abbreviations are SSNFZ, Southern Sierra Nevada Frontal Fault Zone; WCF, Wilson Canyon Fault; and AHF, Ash Hill Fault.

Kitchen (DK), and the Coso Hot Springs (CHS) with the presence of hot springs and fumaroles. The present geothermal production area lies in a $6 \times 10 \mathrm{~km}^{2}$ north-south trending zone between the SM and CHS [Bishop and Bird, 1987; Feng and Lees, 1998; Fialko and Simons, 2000]. The well log data up to 500 m show that the high-temperature system has been developed beneath the flank of the present production area, with temperatures up to $328^{\circ} \mathrm{C}$ [Adams et al., 2000]. The production wells are concentrated above 3 km depth. To 10 km south of the SM and CHS, the area has not been exploited widely, although the heat flow value is as high as $120 \mathrm{~mW} / \mathrm{m}^{2}$ (Figure 1b).

Exploring the existence of a residual magma chamber beneath the geothermal field has been the focus of numerous geophysical, geochemical, and geological studies [e.g., Duffield et al., 1980; Wu and Lees, 1996; Manley and Bacon, 2000; Lees, 2002; Wilson et al., 2003; Monastero et al., 2005]. The extensive studies reveal that a long-lived rhyolitic magma reservoir presumably emplaced around 0.03 Ma and provided the heat flux for the overlying hydrothermal system. However, the accurate location of the magma reservoir varies between different studies. Most previous geochemical and petrological studies suggest that the top of the magma begins below 6 km depth, based on analyses of mineralogy and ages of erupted volcanic rocks [e.g., Duffield et al., 1980; Bacon et al., 1981; Manley and Bacon, 2000]. The gravity data also suggest a low-resistivity and low-density zone 5 km beneath the CGF [Wamalwa et al., 2013]. With the advantage of mapping the subsurface structure, seismic studies have also pointed out that the anomalous body exists around 6 km depth from the teleseismic receiver function analysis [Wilson et al., 2003] and the ambient noise tomography [Yang lateral variation of the anomalies on a et al., 2011]. However, these large-scale studies failed to map the lateral variation of the anomalies on a fine scale comparable to the geothermal field. The local earthquake body wave tomography study by Hauksson and Unruh [2007] also detected a low $P$ wave velocity zone ranging from 5 to 10 km depth beneath Coso, but they argued that the slightly varied ratios of the $P$ and $S$ wave velocity ( $\mathrm{Vp} / \mathrm{Vs}$ ) cannot support the existence of a magma body shallower than 10 km .


Figure 2. Comparison of different 1-D velocity models. Blue line shows the model by Hauksson [2000] for southern California, which was used as the starting model to generate the 1-D Vp model for the Coso region by Hauksson and Unruh [2007] shown by the black line. Our minimum Vp model for the Coso region denoted by the red line is produced by using the model of Lin et al. [2007a] for southern California as the starting model (pink line).

In this study, we apply local earthquake body wave tomography to invert for three-dimensional (3-D) $P$ wave velocity (Vp) and Vp/Vs model in the Coso area. The objective is to image the high-resolution subsurface velocity structure underneath the Coso geothermal field and outline the location, geometry, and depth of the magma body. Combining these models with other geophysical studies, we try to understand how the geothermal and magmatic systems operate to generate the surface manifestations. By analyzing our tomography models and distribution of earthquake relocations, we aim to determine the accurate location of the magma body and answer the unsolved questions related to the magmatic system, such as the upper bound of the reservoir depth, the interface between silicic and mafic magma, and whether a large magma reservoir serves as the main heat source or several small heat sources exist.

## 2. Data and Methods

### 2.1. Data Set

We develop the regional and local velocity models for Coso (Figure 1) using data from the Southern California Earthquake Data Center (SCEDC). The regional study area I includes Coso and the adjacent areas, such as the Garlock Fault, the Sierra Nevada, and the Death Valley, and is referred to as the Coso region. Study area II focuses on the vicinity of the Coso geothermal field. We obtain $P$ and $S$ wave first arrival times and waveform data in our study area I from 159,295 events between January 1981 and August 2011 from the SCEDC. Seismic stations are more densely distributed in the vicinity of the geothermal area than other parts of study area I, which ensures the resolution and reliability of the tomographic models for our study area II (Figure 1a). The completeness magnitude for the entire study area II is estimated to be M1.3, and the maximum magnitude is $M_{w} 5.75$. The waveform data are resampled at 100 Hz sample rate and filtered by applying a bandpass $1-10 \mathrm{~Hz}$ for waveform cross correlation. These data-processing steps are similar to those in previous studies for southern California [e.g., Shearer et al., 2005; Lin et al., 2007a].

In local earthquake tomography, well-recorded and evenly distributed events are usually used in the inversion. We choose 1893 master events for study area I from the entire data set by applying the criteria of 5 km spacing in horizontal plane and 2 km in depth between master events and each event having more than $14 P$ and $9 S$ picks. As a result, a total number of $40,859 P$ and $20,321 S$ wave phase picks are selected for the inversion for the regional model. To invert for a finer model for study area II, we select 1263 master events with $25,248 P$ picks and $13,884 S$ picks with the criteria of 2 km spacing in horizontal and 1 km in depth between master events and each master event having more than $14 P$ picks and 9 S picks (Figure 1b).

### 2.2. One-Dimensional Starting Model

Three-dimensional velocity model inversions typically start with one-dimensional (1-D) models. We use the layer-average velocity model for southern California by Lin et al. [2007a] as the starting model and invert for the minimum 1-D model for Coso by using the program VELEST [Kissling et al., 1994, 1995]. The model damping parameters are chosen based on the trade-off tests of optimizing data misfit and model variance. We set the station corrections to be 0 during the inversion to avoid trade-off between the velocity structure and station corrections. The model variance from our minimum model is decreased by $35 \%$ from the starting model, and the data variance is reduced by $26 \%$. Hauksson and Unruh [2007] also inverted for a 3-D velocity model for Coso using with the average model of Hauksson [2000] for southern California as the 1-D starting model. Compared with the 1-D model by Hauksson and Unruh [2007], our minimum model is 3-14\%


Figure 3. Our regional-scale velocity model for study area I at 3 km depth. Vp perturbations are shown relative to the layer-average value. The thick black line encloses the area with the diagonal element of the resolution matrix greater than 0.1 , which is considered well resolved. Most of the observed velocity anomalies correlate well with the known geological features. For example, the Sierra Nevada, the Argus Range, the Granite Mountains, and the core of Mojave Desert are represented by high-velocity anomalies, whereas the Eastern California Shear Zone and the Indian Wells Valley show low-velocity anomalies. Coso is located at the north end of the Indian Wells Valley.
faster above 9 km depth, which mainly results from distinct starting models, data coverages, and different inversion parameters. These 1-D models are shown in Figure 2.

### 2.3. Three-Dimensional Tomographic Inversion

The goal of our study is to obtain an accurate velocity model for interpreting the crustal structure beneath the geothermal field. The inversion for $\mathrm{Vp} / \mathrm{Vs}$ ratios, which is indicative of both lithology and rheology of subsurface materials, depends on both $P$ and $S$ wave ray paths. Since there are fewer $S$ wave picks than $P$ wave picks and the quality of $S$ wave data is not as good as those of $P$ wave, Vs models are usually poorly resolved compared to Vp and the method of deriving $\mathrm{Vp} / \mathrm{Vs}$ ratio from Vp divided by Vs is not reliable [Thurber and Eberhart-Phillips, 1999]. In this study, we solve the $\mathrm{Vp} / \mathrm{Vs}$ model directly by using the $S$ - $P$ travel time differences. In the simul2000 algorithm [Thurber, 1983; Thurber and Eberhart-Phillips, 1999], ray paths are selected from the fastest travel time between the source and receiver and calculated by approximate ray tracing. These ray paths are curved nonplanar [EberhartPhillips and Michael, 1998], and the S ray paths are approximated by $P$ paths. The algorithm is a damped least squares inversion, and the optimal damping parameters are chosen based on the trade-off curve of data misfit and model variance [Eberhart-Phillips, 1986]. We run a series of inversions using different damping parameters and choose the damping values of 150 for Vp and 80 for $\mathrm{Vp} / \mathrm{Vs}$ in the inversion for the regional model.

We first solve the velocity model for study area I and then invert for the final 3-D velocity model for study area II, the vicinity of the CGF. The inversion follows two steps: (1) start with the minimum 1-D model of the Coso region and invert for the 3-D Vp and Vp/Vs models in study area I with a coarser uniform horizontal grid spacing of 6 km ; and (2) use the resulting 3-D model for the Coso region to invert for the final 3-D model of the CGF (study area II) with a finer horizontal spacing of 3 km . By doing this, the final model for the CGF shows more detailed velocity anomalies than the regional model. A constant $\mathrm{Vp} / \mathrm{Vs}$ ratio of 1.73 is used for the starting Vp/Vs model inversion for the region based on the Wadati diagram [Kisslinger and Engdahl, 1973]. The depth distribution of seismicity suggests that the seismicity is focused in the upper 15 km depth, and we set up the depth layers at $-5,0,3,6,9,12,15,20$, and 25 km . Note that in this study all depths are relative to mean sea level.

## 3. Results

### 3.1. Regional Coarse Model

The regional model is obtained after six iterations when the reduction of data variance becomes insignificant. Compared to the initial models, the data variance is reduced by $69 \%$ and $45 \%$ for final Vp and $\mathrm{Vp} / \mathrm{Vs}$ models, respectively. The root-mean-square (RMS) of the travel time residuals is reduced from 0.24 to 0.11 s . We show a representative velocity image at 3 km depth in Figure 3 with the Vp perturbations relative to the layer-average value of the inverted model. The inverted Vp anomalies reflect the near-surface geological


Figure 4. Map view of different catalogs in the Coso region. The red dots represent the common events that are relocated by different methods. (a) Southern California Seismic Network (SCSN) catalog, covering events in Coso from 1981 to 2011. Grey dots show the events that are not relocated but remain in the original SCSN catalog. (b) Three-dimensional relocations produced by the simul2000 algorithm [Thurber, 1983; Thurber and Eberhart-Phillips, 1999]. (c) HYS catalog, the relocation catalog for southern California between 1981 and 2011 by Hauksson et al. [2012]. (d) Highly correlated events in this study. See Figure 1 for the abbreviations.
features. The Indian Wells Valley and the Eastern California Shear Zone mainly exhibit low Vp. The mountain areas, such as the Sierra Nevada, the Argus Range, and the Granite Mountain with the Mesozoic granitic rocks, and the stable Mojave Desert show high Vp anomalies.

### 3.2. Earthquake Relocation

After obtaining the regional 3-D velocity model, we invert for the 3-D earthquake relocations in the simul 2000 by fixing the velocity model. The absolute earthquake relocations have been improved by taking into account the biasing effect of velocity structure. To improve the accuracy of relative earthquake locations, we implement the waveform cross correlation, similar-event cluster analysis, and differential time relocation methods by Lin et al. [2007b] to relocate all the events in the Coso region.

Both the absolute and relative locations are improved compared to the SCSN catalog locations. The improvement is demonstrated by the sharpening of the relocated seismicity in Figure 4. Our relocations are consistent with the previous relocation catalogs for southern California, such as the SHLK catalog [Shearer et al., 2005], the LSH catalog [Lin et al., 2007b], and the latest HYS location catalog by Hauksson et al. [2012] for events between 1981 and 2011. We use similar criteria for cross correlation to those for the LSH catalog such as the correlation coefficient cutoff, station-event distance range, and minimum average of the maximum correlation coefficient. The main difference between our catalog and previous ones stems from the different absolute locations, and we use the produced 3-D locations from simul2000 (Figure 4b). Our catalog chooses 0.65 as correlation coefficient cutoff and encompasses the highly correlated local events in Coso, whereas the HYS catalog uses the correlation coefficient cutoff of 0.6.

Quantitative estimates of location uncertainties indicate that both absolute and relative location accuracies are significantly improved. The absolute location error estimates are provided by the simul2000 algorithm [Thurber and Eberhart-Phillips, 1999]. The mean horizontal uncertainty is 120 m , and the vertical uncertainty is 300 m . The relative location uncertainties are estimated by a bootstrap method [Efron and Gong, 1983],


Figure 5. Distribution of the spread values for the final Vp model in study area II. Colored nodes denote spread values below 3 . Values greater than 3 are not shown. Black lines denote the diagonal elements of the resolution matrix greater than 0.1 , which are also shown in Figures 6-11.
similar to Lin et al. [2007b]. After resampling for 15 times, we obtain the median of the relative location uncertainties of 11 m in horizontal and 22 m in depth. In study area I , about $66 \%$ of events fall into 1225 clusters with at least five events. Three distinct clusters with more than 5000 events are observed from the distribution of the relocated hypocenters within the Rose Valley, to the east of the CGF, and around the Airport Lake Fault Zone, respectively.

### 3.3. Model Resolution Tests

Several parameters are used to examine the model quality, which mostly depends on the geometry and density of rays. Ray-dependent measurements and synthetic tests are conducted together to assess the resolution of the tomographic models. In this paper, we focus different resolution estimates on our study area II. We plot resolution estimates to assess the ray coverage including the derivative weighted sum (DWS) values, diagonal elements of resolution matrices (RDE) and spread function. The DWS values indicate the weighted ray density directly. The weight scheme is based on the distance of rays from each node. Based on the distribution of DWS values (supporting information Figure S1), high numbers of the DWS values ( $>2000$ ) with the maximums of 16,000 for $P$ rays and 10,000 for $S$ - $P$ rays are present in the vicinity of the Coso geothermal field and the adjacent areas, which make up of our study area II. The deficiency of the DWS measurement is that the ray directions are not taken into account; thus, smearing cannot be estimated.
The model resolution matrix gives the information for all the nodes, and each row represents the averaging vector of a model parameter. The RDE reflects the resolution for each node and provides relative measures of the ability of the data for detecting anomalies in different locations. Resolutions greater than 0.1 are considered to indicate good quality of the models in this study based on the synthetic data tests. However, the RDE values depend mainly on the grid spacing and damping parameters.


Figure 6. Distribution of the spread values for the final $\mathrm{Vp} / \mathrm{Vs}$ model in study area II. Colored nodes denote spread values below 3. Black lines denote the RDE values greater than 0.1.

The spread function investigates the dependence of a model parameter on the other grid nodes. Ideally, the velocity at each node is independent of other nodes, but common ray geometries can link neighboring model parameters and can lead to artificial smearing of anomalies across multiple nodes. Thus, the spread value will be zero in an ideal case. For the real data sets, we regard spread function values smaller than 3 as good values indicating that the peaked resolution is achieved at the grid and the distant nodes have no significant contribution. We choose the cutoff of 3 to represent low-spread values with good resolution because the distributions of the spread function values smaller than 3 for the $V p$ and $V p / V s$ models are consistent with the RDE contours with resolutions greater than 0.1 (Figures 5 and 6). The cutoff of 2.5 or 3 has been chosen by previous tomography studies [e.g., Sherburn et al., 2006; Reyners et al., 2006] to show the nodes without too much smearing.

Resolution tests, i.e., checkerboard tests in this study, are also performed to compare with the ray-dependent measurements. Checkerboard models are constructed to assess the amount of image blurring. Five percent of synthetic velocity perturbations are assigned to blocks with dimensions of $6 \times 6 \mathrm{~km}$ at all layers. The synthetic travel times are then inverted to recover the velocity anomalies using the same parameterization method as in the real data set. The synthetic anomalies are reconstructed well underneath the geothermal field, especially at depths of 3 km and 6 km for both Vp and $\mathrm{Vp} / \mathrm{Vs}$ models (Figures 7 and 8). The RDE contour lines with resolutions greater than 0.1 are correlated with the well-resolved checkerboard patterns. For $\mathrm{Vp} / \mathrm{Vs}$, the ability of reconstructing checkerboard patterns is similar to that of Vp .
We assess the reliability of the velocity features by considering the RDE, spread values, and well-resolved checkerboard patterns. The area around the geothermal field shows reliable resolutions, especially at depths of 3 and 6 km . The RDE contour lines correlate mostly with the spread values and checkerboard test


## Velocity Models

3.4. Map Views of Final With the regional 3-D model as input, we invert for the velocity structure in study area II. Figures 9 and 10 show the velocity images above 9 km depth, below which the seismicity is sparse and rays are insufficient to resolve the velocity structure well. The lateral heterogeneities are large at near-surface depths of 0 and 3 km for both Vp and $\mathrm{Vp} / \mathrm{Vs}$. At the surface, a notable feature of low Vp (ranging between 3.6 and $4.6 \mathrm{~km} / \mathrm{s}$ ) is observed within and around the CGF. The nearby faults and valleys show low Vp, such as the Little Lake Fault Zone (LLFZ), the Airport Lake Fault Zone (ALFZ), and the Indian Wells Valley (IWV). The intensely high Vp anomalies lie along the Southern Sierra Nevada Frontal Fault (SSNFZ) and the Argus Range. At 3 km depth, the southeastern part of the CGF exhibits high Vp. Low Vp values are prominent in the upper 3 km near the IWV and the adjacent LLFZ and ALFZ. The ALFZ forms pull-apart basins and cuts the IWV [Monastero et al., 2005]. The low Vp anomaly is consistent with the geological study that the 3 km high silica-content sediment exists beneath the Valley [Monastero et al., 2002]. Below 6 km depth, the $V p$ lateral variations become small and a relatively low Vp is apparent at the CGF.

Spatial correlation between the Vp and $\mathrm{Vp} / \mathrm{Vs}$ anomalies is observed for most parts of our study area II. In the Argus range with strong high Vp , high $\mathrm{Vp} / \mathrm{Vs}$ anomaly is seen at the surface. However, we do not see high $V p / V s$ corresponding to the high $V p$ beneath the SSNFZ. There is a variation of $\mathrm{Vp} / \mathrm{Vs}$ anomalies across the CGF in the upper 3 km depth. The northern part of the geothermal field shows low $\mathrm{Vp} / \mathrm{Vs}$, whereas the other areas within and in proximity to the CGF show high $\mathrm{Vp} / \mathrm{Vs}$. The model in the vicinity of the CGF mainly shows low $\mathrm{Vp} / \mathrm{Vs}$ features below 6 km depth, but a notable high $\mathrm{Vp} / \mathrm{Vs}$ body (1.78-1.80) is observed around the ALFZ at 6 km depth.

### 3.5. Cross Sections of Final Velocity Models

The geometrical shapes of the velocity anomalies are easier to track in cross sections. Figure 11 shows the cross sections of the inverted velocity models beneath the CGF and surrounding geologic regions. The Vs model is obtained from Vp divided by $\mathrm{Vp} / \mathrm{Vs}$ model. We combine the $\mathrm{Vp}, \mathrm{Vp} / \mathrm{Vs}$, and V s models with the relocated seismicity to find out the prominent features around the geothermal field. Beneath profiles B, D, and E, which pass through the CGF, an extensive velocity anomaly of low Vp, low Vs, and low Vp/Vs from 6 to


Figure 8. Checkerboard test for the Vp/Vs model with blocks of $6 \times 6 \mathrm{~km}$. (a-d) The true velocity model. (e-h) The inverted velocity model. White lines denote the RDE values greater than 0.1.

12 km depth is observed. The size of this anomaly is about 10 km in lateral and 6 km in depth. The distribution of the relocated seismicity underneath the CGF indicates that the brittle-ductile depth is around 5 km compared to 10 km in adjacent areas. This shallower brittle-ductile transition depth has also been mentioned by previous studies [e.g., Monastero et al., 2005; Hauksson and Unruh, 2007]. The anomalous zone of low-velocity anomalies between 6 and 12 km is aseismic. The combination of the ductile behavior and low-velocity features suggests that the circumstance in this depth range is different and we will discuss the possible conditions in the following section.
Comparing profiles $D$ and $E$, we can see that the $\mathrm{Vp} / \mathrm{Vs}$ ratio varies at the surface inside the CGF, while profile D passes through the geothermal exploitation area and E is roughly 7 km away. The $\mathrm{Vp} / \mathrm{Vs}$ ratio is lower in the northern part, the main exploitation areas with steam and hot water at the surface, than the southern part of the geothermal field. The other striking features include low Vp , low Vs , and low $\mathrm{Vp} / \mathrm{Vs}$ at the upper 3 km of the LLFZ, the IWV, and the ALFZ. The $\mathrm{Vp} / \mathrm{Vs}$ ratio changes to around 1.81 at depth of 6 km beneath the ALFZ and the adjacent eastern part. Some small velocity bodies of low $\mathrm{Vp} / \mathrm{Vs}$ are also visible in cross sections b and c (Figure 11), which may come from smearing of the low $\mathrm{Vp} / \mathrm{Vs}$ for the CGF.

### 3.6. In Situ Vp/Vs Ratios in Similar-Event Clusters

In order to complement our tomographic results, we estimate in situ Vp/Vs ratios within similar earthquake clusters using the demeaned $P$ and $S$ wave differential times from waveform cross correlation by applying the technique presented in Lin and Shearer [2007]. This technique assumes that the scale length of changes in $\mathrm{Vp} / \mathrm{Vs}$ ratios is greater than the size of the similar-event clusters and all the correlated events within each individual compact cluster have the same local $\mathrm{Vp} / \mathrm{Vs}$ ratio. It provides higher resolution for near-source Vp/Vs ratios than typical tomographic inversion methods by using high-precision differential times and a robust misfit function method, and it has been applied to study the near-source structure for the entire southern California [Lin and Shearer, 2009], the rupture zone of the 1989 Loma Prieta earthquake [Lin and Thurber, 2012], and Mammoth Mountain at the southwest rim of Long Valley caldera [Lin, 2013]. We applied this approach to all the 1225 similar-event clusters in study area I and estimated standard uncertainties in the in situ $\mathrm{Vp} / \mathrm{Vs}$ ratios. These uncertainties are computed using the bootstrap approach [e.g., Efron and Gong, 1983], in which the pairs of differential $P$ and $S$ times in the same cluster are randomly resampled 1000 times. In order to obtain the most robust results, we select 227 event clusters with uniformly distributed events and uncertainties of $\mathrm{Vp} / \mathrm{Vs}$ ratios less than 0.03 .


Figure 9. Map view of the final Vp model for study area II. Vp perturbations are shown relative to the layer-average values, which are also given for each slice. Dashed circle represents the location of the Coso geothermal field. Black dots show the grid nodes used in the tomographic inversions. Two red stars represent the geologic sites, SM and CHS. White lines denote the RDE values greater than 0.1. See Figure 1 for the abbreviations of the major geological faults and valleys around the geothermal field.


Figure 10. Map view of the final Vp/Vs model for study area II. The symbols are the same as in Figure 9.


Figure 11. Cross sections of the $V p, V p / V s$, and $V s$ structures across and in proximity to the CGF. The geothermal field is denoted by the dashed circle with the red stars marking the locations of the SM and CHS. The five profiles are shown by the black lines with profiles B, D, and E passing through the geothermal field and A and C off the CGF. Relocated earthquakes within 5 km of both sides of the profiles are projected to the Vs cross sections, denoted by grey dots. White contour lines represent the RDE values greater than 0.1. See Figure 1 for the abbreviations.

To compare with our tomographic results beneath the CGF, we project the in situ $\mathrm{Vp} / \mathrm{Vs}$ ratios along profile B in Figure 11. The in situ Vp/Vs ratios vary from 1.5 to 1.8 for the 36 clusters around the CGF (Figure 12). The mean value of six clusters with slightly higher $\mathrm{Vp} / \mathrm{Vs}(>1.7)$ is 1.786 , and these clusters mainly focus around the area with $V p / V s$ ratio of 1.77 inverted from the tomography. The other 30 clusters with low in situ $\mathrm{Vp} / \mathrm{Vs}$ ratios $(\leq 1.7)$ are mainly distributed along the low-velocity zone within 20 km away from the CGF resolved by the tomographic inversion. To further verify whether the observed low $\mathrm{Vp} / \mathrm{Vs}$ anomalies from 6 to 12 km from tomography is reliable, we plot the in situ $\mathrm{Vp} / \mathrm{Vs}$ ratios for each earthquake near the CGF within similar-event clusters within this depth range. The median value of the in situ $\mathrm{Vp} / \mathrm{Vs}$ ratios is 1.656 , consistent with the estimate of 1.667 from our tomography model. Therefore, the near-source in situ $\mathrm{Vp} / \mathrm{Vs}$ supports our tomographic results.


Figure 12. (a) In situ Vp/Vs ratios for the clusters around the CGF. Clusters are projected along profile B in Figure 11. The tomography results are the same as in Figure 11b2. Clusters with in situ Vp/Vs below 1.7 are shown by red dots, and clusters with higher Vp/Vs are shown by green dots. (b) Comparison of the in situ $\mathrm{Vp} / \mathrm{Vs}$ and tomography results for each event near the CGF between 6 and 12 km depth. Black dots show the in situ $\mathrm{Vp} / \mathrm{Vs}$ ratios, and red dots denote tomography results. The median values of the $\mathrm{Vp} / \mathrm{Vs}$ at 1 km depth intervals are given by the stars.

## 4. Discussion

With the finer 3-D seismic velocity model, we resolve the subsurface structure beneath the geothermal field. The velocity of seismic waves can be affected when they propagate through different materials due to changes in lithology, mineral composition, presence of fracture, temperature, pore pressure, and fluid saturation. Here we combine the velocity structure, the seismicity distribution, and the geological and geochemical knowledge to infer the dominating factors for the observed anomalies.

### 4.1. Geothermal Reservoir

Our tomographic results map the feature of the geothermal reservoir in the shallow depth. In map views shown by Figures 9a and 10a, low Vp and low $\mathrm{Vp} / \mathrm{Vs}$ anomalies dominate the geothermal production area at the surface. Our velocity structure reflects the vapor-dominated geothermal field in high-temperature system. Because seismic velocities reduce with increased temperatures [e.g., Mueller and Raab, 1997; Fielitz, 1976; Sato et al., 1989; Ito et al., 1979], we observe low Vp at the surface. Similar low $\mathrm{Vp} / \mathrm{Vs}$ features within the production area were observed by previous studies [Walck, 1988; Lees and $W u, 2000]$ and were interpreted to be affected by vapor.

### 4.2. Magmatic System

Although upwelling magma beneath the geothermal field has been proposed in previous studies [e.g., Wu and Lees, 1996, 1999; Lees and Wu, 2000; Lees, 2002], the velocity anomalies we observe beneath the CGF are low Vp , low Vs , and low $\mathrm{Vp} / \mathrm{Vs}$ between 6 and 12 km depth, which may be a candidate for magmatic materials but refute the possibility of a magma chamber with a large amount of partial melt. The low-velocity zone with ductile behavior is the typical feature associated with magma, but the low $\mathrm{Vp} / \mathrm{Vs}$ ratios suggest a lack of pervasive partial melt. To validate the low Vp/Vs structure, we conduct the recovery test for the observed low $\mathrm{Vp} / \mathrm{Vs}$ anomaly from the real data inversion underneath the CGF shown in Figure 11b2. A cross section of the true and recovered $V p / V s$ structure is shown in Figure 13. The anomalous body between 6 and 12 km depth is recovered well, although slight horizontal smearing is observed.

We take into account the chemical composition of magma from other studies in Coso to further detect if the anomalous velocity zone can refer to magmatic material. It has been argued that different silica contents of magma, crack aspect ratios, and volume percentage of magma can make magmatic system behave with both low or high Vp/Vs ratios [Nakajima et al., 2001; Hauksson and Unruh, 2007; Patane et al., 2006]. In our tomographic results, the Vp and Vs anomalies show similar lateral and vertical geometry. This means that the lithology influences both Vp and Vs but affects Vp more to result in low Vp/Vs. The anomalies do not vary with depth, and we may assume a conductive temperature gradient and hydrostatic pore pressure


Figure 13. Recovery test for the $V p / V s$ anomaly in the CGF. (top) The true model and (bottom) the recovered model. The zero distance refers to the location of the CGF. The Vp/Vs anomaly beneath the CGF corresponds to the anomaly at depths between 6 and 12 km shown in Figure 11b2. The anomaly is recovered well in depth with some horizontal smearing.


Figure 14. Conceptual model of the subsurface structure for the Coso geothermal field. The schematic diagram shows the main features derived from our results: (1) low-velocity zone beneath the geothermal field shown by Vp cross section; (2) shallow brittle-ductile depth (around 5 km depth) beneath the geothermal field; (3) crystallizing magma body with the inclusion of water between 6 and 12 km depth; and (4) water that may result from the underlying crystallizing basaltic magma. Lateral scale is approximate.
in this anomalous zone. The mineral composition and fluid content may play an important role in affecting the seismic velocity ratio among all the other factors. The study by Christensen [1996] suggests that the ratio is decreased with increased silica contents for the rocks with 55-75\% of silica contents. Previous studies [e.g., Sanders et al., 1995; Nakajima et al., 2001; Lin and Shearer, 2009] reported that cracks with a small volume percent of $\mathrm{H}_{2} \mathrm{O}$ could decrease Vp, Vs, and Vp/Vs. From the estimate of Nakajima et al. [2001], 2\% of water with aspect ratio of 0.1 can reduce Vp from the original $6.31 \mathrm{~km} / \mathrm{s}$ to $6.1 \mathrm{~km} / \mathrm{s}$ and $\mathrm{Vp} / \mathrm{Vs}$ as low as 1.67 compared to the reference value of 1.71 , which is consistent with our observations in the upper and middle crust. The presence of gas can also decrease Vp and $\mathrm{Vp} / \mathrm{Vs}$ ratios because of the very low bulk modulus [Husen et al., 2004; Lin, 2013]. The geochemical study by Manley and Bacon [2000] pointed out that the erupted magma in Coso was felsic with 66.5 wt \% of silica contents and saturated with an $\mathrm{H}_{2} \mathrm{O}$-rich fluid, with the presence of the vapor phase in melt inclusions. The percentage of $\mathrm{H}_{2} \mathrm{O}$ in the melt inclusion can be around 4.5-6.2 wt \% in different dome groups [Manley and Bacon, 2000], which is larger than the typical percentage of gas dissolved in magma, 0.2-3 wt \%. Thus, we suggest that the low Vp , low Vs , and low Vp/Vs body lacking of seismicity may indicate that the molten material is felsic, rich in gas, or with the inclusion of water. Although we cannot link the large quantities of hot water near the surface to the presence of water at 6 km depth, it is possible that water is rich in the anomalous velocity zone and high content of water can facilitate magma crystallization [Ritchey, 1980], which will further lower Vp/Vs ratios.

We show a conceptual model for subsurface structure in Figure 14. The content of the erupted magma suggests that the material is felsic, which is much more viscous than mafic magma. The felsic magma originates from the basaltic magma in deeper depth, which ascended to crystallize and expelled gas to induce fluid accumulation. Between 6 and 12 km depth beneath the CGF, the magmatic material is likely to exist in the form of magma mush, with a small percent of melt trapped among small crystals. The
silica-rich magma mush might also contain a high portion of water. Our model shows the velocity anomaly up to 12 km depth, and it could be the interface of the silicic magma and mafic magma or the mafic magma could be deeper. However, the ray coverage is insufficient to resolve the structure well at those depths.

### 4.2.1. Comparison With Previous Seismic Studies

The low-velocity body in the middle crust below the geothermal field has been observed in previous tomography studies [e.g., Reasenberg et al., 1980; Walck and Clayton, 1987]. In the study by Hauksson and Unruh [2007], variation in Vp/Vs model is too small to confirm the existence of the magma body and they interpret the low Vp and normal $\mathrm{Vp} / \mathrm{Vs}$ features to be the possibility of brine. We include more $S$ wave arrival times for the inversions and our Vp/Vs model shows low value of 1.667 beneath the geothermal field, which may be associated with the magmatic system. Other factors causing differences between these two models are the two-step inversion scheme and grid spacing of 3 km in this study. The 10 km grid used in Hauksson and Unruh [2007] may hide some local anomalies with short wavelengths. Our Vp model is generally consistent with their model but shows more variations in the vicinity of the geothermal field. Some features are revealed by both models, such as the low Vp and low $\mathrm{Vp} / \mathrm{Vs}$ anomalies beneath the IWV.

A low Vp anomaly beneath the CHS with the top at 5 km depth was detected by calculating teleseismic receiver functions [Wilson et al., 2003]. They interpreted this as the top of the magma chamber and estimated the amount of melts to be $1.5-5 \%$ by assuming a $V p / V s$ ratio of 2.5 . Their $\mathrm{Vp} / \mathrm{Vs}$ model was obtained by dividing the preferred 1-D $P$ and $S$ velocity models, which were used for the receiver function analysis. Our high-resolution $\mathrm{Vp} / \mathrm{Vs}$ model shows that the ratio is estimated to be around 1.667 and does not agree with such an amount of melt.
The 3-D shear wave velocity model resolved by ambient noise tomography revealed a low shear velocity zone between 6 and 12 km depth beneath the Coso geothermal field [Yang et al., 2011]. Their tomographic results showed Vs structures at grid spacing of $0.25^{\circ} \times 0.25^{\circ}$. The low Vs body was estimated to be at the size of $0.5^{\circ} \times 0.5^{\circ}$, which covers an area larger than the entire geothermal field. Our Vp and $\mathrm{Vp} / \mathrm{Vs}$ models show that the velocity varies inside the geothermal field and the prominent low Vp , low Vs , and low $\mathrm{Vp} / \mathrm{Vs}$ anomalies exist in the similar depth range as they indicated.

## 5. Conclusion

We developed 3-D high-resolution Vp and $\mathrm{Vp} / \mathrm{Vs}$ models for the Coso region in southern California. A by-product of this study is a high-precision earthquake relocation catalog. We focus our interest on exploring the 3-D velocity structure in the vicinity of the Coso geothermal field. The tomographic results reveal the features of the geothermal reservoir and the magmatic materials. Our observations suggest a lack of a large amount of remnant melt from the Pleistocene volcanic activity underneath the geothermal field, but the detected low-velocity anomalies could be associated with the magmatic system. The tomography results reveal a low-velocity body of 10 km diameter in the depths between 6 and 12 km . Another technique of estimating near-source in situ $\mathrm{Vp} / \mathrm{Vs}$ was used to compare with our tomography models. The low in situ $\mathrm{Vp} / \mathrm{Vs}$ around the geothermal field is consistent with the low-velocity anomalies derived from the tomography models. We interpret the $6 \times 10 \mathrm{~km}^{2}$ low-velocity anomaly to be a region of hot and weak felsic rocks, trapped with a series of small silicic magma chambers, sills, or dikes under the cooling phase with inclusion of water. The data cannot show good resolutions below 15 km depth, and whether the low-velocity anomalies extend to the deeper depth needs further investigation with more seismic data.

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