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Proposal Category	Individual Proposal (Integration and Theory)
Proposal Title	Near real-time earthquake focal mechanism inversion in the Southern California region using the SCEC Community Velocity Models
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SCEC Priorities	P3.a., P1.d., P2.d.
SCEC Groups	Seismology
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Project Abstract

Focal mechanism and directivity of earthquakes put primary control on the distribution of ground motion, and also bear on the stress state of the crust. Focal mechanisms of small-to-medium-magnitude earthquakes in Southern California have been routinely processed by the Southern California Earthquake Center (SCEC) using a simple 1D Earth velocity model, yet recent tomographic studies demonstrate strong 3D velocity heterogeneities in the Southern California crust. Here, we adopt the 3D SCEC Community Velocity Models in near real-time focal mechanism inversion. Our study results in a new focal mechanism catalog for the Los Angeles basin region, and provide more accurate focal mechanism solutions. The catalog is made available for further seismological and geological investigations and will contribute to mitigating the seismic hazard and risk in the area.

Intellectual Merit

We have developed a highly automated and efficient algorithm to determine the moment tensor solutions for small-to-medium-sized earthquakes using 3D velocity models in the Los Angeles region. Our results show that incorporating the 3D velocity model can refine the existing moment tensor catalogs in the region, resulting in more accurate focal mechanism solutions, focal depth, and moment magnitude. In addition, our highly accurate, efficient, and automatic inversion approach can be expanded in other regions and can be easily implemented in near real-time system.

Broader Impacts

We have presented findings from this project at the 2019 SCEC Annual Meeting. In addition, a paper that detailed our findings has been published on the Geophysical Journal International.

Exemplary Figure

Figure 2. Comparison of moment tensor inversion results using 1D and 3D velocity models. The obtained focal mechanism solutions are shown as beachballs, where the black lines are optimal results, and the gray lines are uncertainties estimated by a bootstrapping method (95% confidence level). Histograms of the cross-correlation coefficients of waveform fits (including those discarded by our automatic data selection) are shown on the top. The comparison shows that the inversion using the 3D velocity model significantly reduces the moment tensor uncertainties, mainly owing to the accuracy of the 3D velocity model in predicting both the phases and the amplitudes of the observed seismograms.

Near real-time earthquake focal mechanism inversion in the Southern California region using 3D velocity models

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Reference: SCEC #19011

Motivation

A more accurate and comprehensive earthquake focal mechanism catalog is important to constraining the regional stress field, understanding tectonic processes, and potentially mitigating seismic hazard. Focal mechanisms of small-to-medium-size earthquakes in the Southern California region are routinely available through the Southern California Earthquake Center (SCEC) (Hutton et al., 2010; Yang et al., 2012). Usually, these focal mechanisms are determined by inverting either the P-wave first-motion polarities, S/P amplitude ratios, or seismic body and/or surface waveforms, and all of them assume simple 1D Earth velocity models (Zhu & Helmberger, 1996; Hardebeck & Shearer, 2002; Yang et al., 2012). However, recent tomographic studies demonstrate strong 3D velocity heterogeneities in the Southern California crust (Lee et al., 2014; Shaw et al., 2015), for example, the deep sedimentary basins and strong Moho lateral variations (Fig. 1). Thus, inversions based on simplified 1D velocity models may lead to biases and large uncertainties in focal mechanism solutions, as the complicated Earth 3D structure effects cannot be adequately quantified (Fig. 1).

To date, a series of 3D SCEC Community Velocity Models (CVMs) are available (Small et al., 2017), and these 3D velocity models have proved significantly more accurate in predicting the seismic waveforms compared to 1D velocity models (Lee et al., 2014). One of the main goals of these CVMs is to allow more accurate estimations of 3D Green's functions, which can be used to improve source inversions. Thus, it is natural to consider using realistic 3D velocity models in source inversion, which shall allow us to improve waveform fits and inversion accuracy.

Preliminary Results

In this study, we developed a highly automated and efficient algorithm to determine the moment tensor solutions for small-to-medium-sized earthquakes using 3D velocity models (Wang & Zhan, 2019). Our algorithm mainly includes two parts: the 3D Green's function calculation and the automated waveform inversion. The 3D Green's function calculation is conducted once before earthquakes, while the inversion part will run for the individual earthquake. We first established a 3D Green's function database using the SCEC 3D CVM-S4.26 (Lee et al., 2014) through a 3D Finite Difference method and source-receiver reciprocity approach (Graves, 1996; Zhao et al., 2006; Zhu & Zhou, 2016). With the pre-calculated 3D Green's function database, the synthetic seismograms for arbitrary locations/mechanisms of sources within the study area can be quickly simulated within seconds. We then invert the earthquake focal mechanism and other source parameters by minimizing the waveform misfits between observations and synthetics with automatic data quality control. More details about our algorithm are described in our recent publication (Wang & Zhan, 2019).

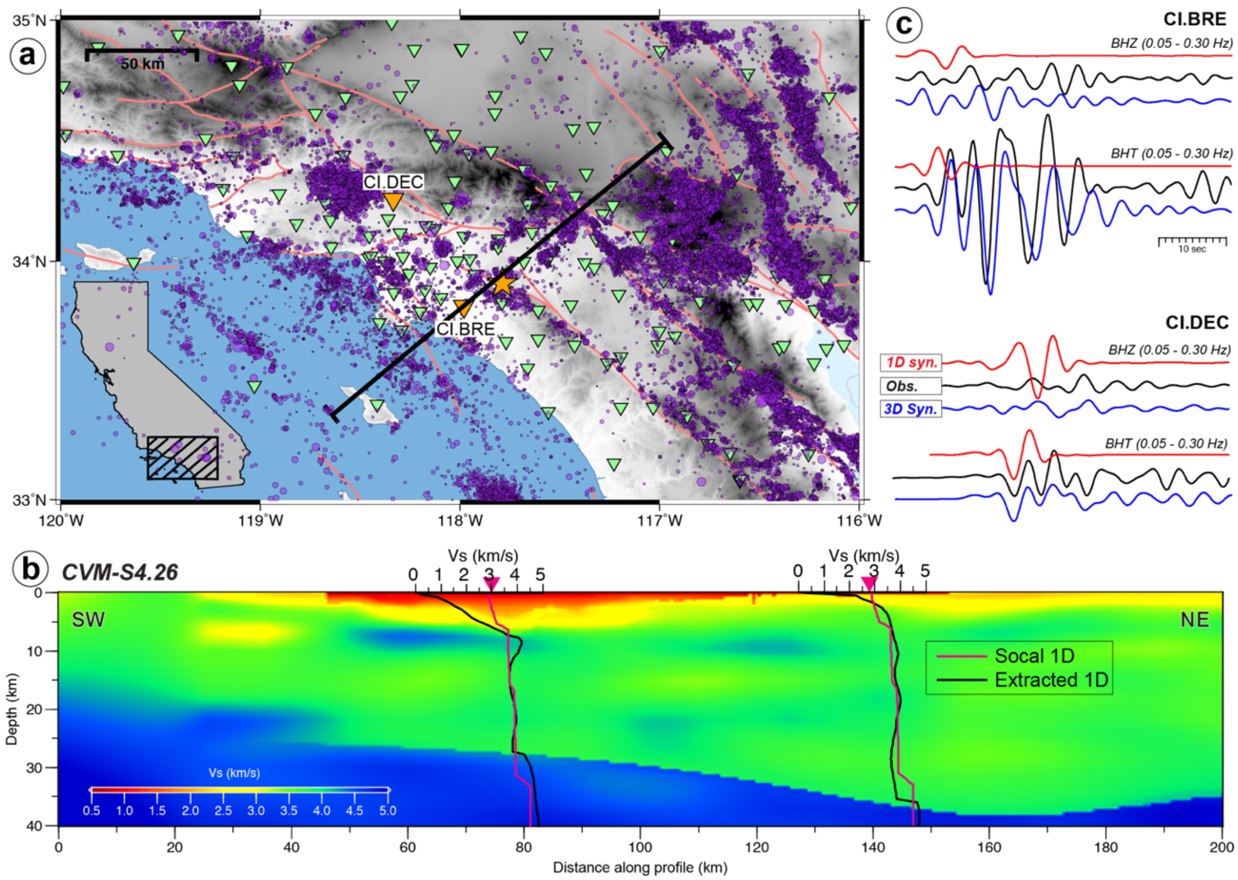

Figure 1. *Seismicity and velocity structure in the study region.* ***(a)*** *Purple dots are seismicity from 1981 to 2018 with magnitude above 2.0 from Hauksson et al. (2012). The triangles are the permanent broadband seismic stations in this area, a large portion of which are located within or near the Los Angeles basin.* ***(b)*** *The latest version of the Southern California Earthquake Center (SCEC) Community Velocity Model (CVM)–CVM-S4.26 (Lee et al., 2014)–along the profile in (a). The standard 1D Southern California velocity model (SoCal) (Hadley & Kanamori, 1977) (red) and the 1D velocity models (black) extracted from the 3D CVM-S4.26 model (Lee et al., 2014) are compared to demonstrate the strong lateral heterogeneities in this area.* ***(c)*** *Waveform comparison among real data, the synthetics generated using the 1D SoCal and the 3D velocity models, indicating the strong 3D structure effects. The location of earthquake and locations of stations are given in orange star and triangles in (a).*

We apply our automated inversion approach in the Los Angeles region. We focus on earthquakes with local magnitude larger than 3.5 in the SCSN catalog in this area from 2000 to 2018. For each earthquake, we use our proposed automated inversion approach to obtain the source parameters. To demonstrate the importance and feasibility of using 3D velocity models, we also invert for the focal mechanism solutions using either the 1D Southern California Model (1D-SoCal) (Hadley & Kanamori, 1977) or the 1D regional basin model extracted from the Crust 1.0 (1D-Basin) (Laske et al., 2013). Here, we keep the inversion parameters and automatic data selection criteria same in all three cases for fair comparisons. As shown in Fig. 2, the inversion using the 1D-SoCal model yields a strike-slip mechanism, with large uncertainties shown by the bootstrapping results. The inversion using the 1D-Basin model results a mixture of strike-slip and thrust mechanisms, with smaller scattering in the bootstrapping solutions. The inversion utilizing the 3D model suggests that this earthquake is almost a pure thrust event. The uncertainties in focal mechanism also decrease dramatically using the 3D velocity model, owing to the fact that we can better fit almost all the observations (Fig. 2). More quantitatively, the histogram of cross-correlation coefficients between observations and synthetics obtained by the 3D inversion are systematically concentrated at higher values than that from the 1D inversions (Fig. 2), indicating the importance of incorporating 3D velocity model in source inversion, especially in regions with complicated 3D structures.

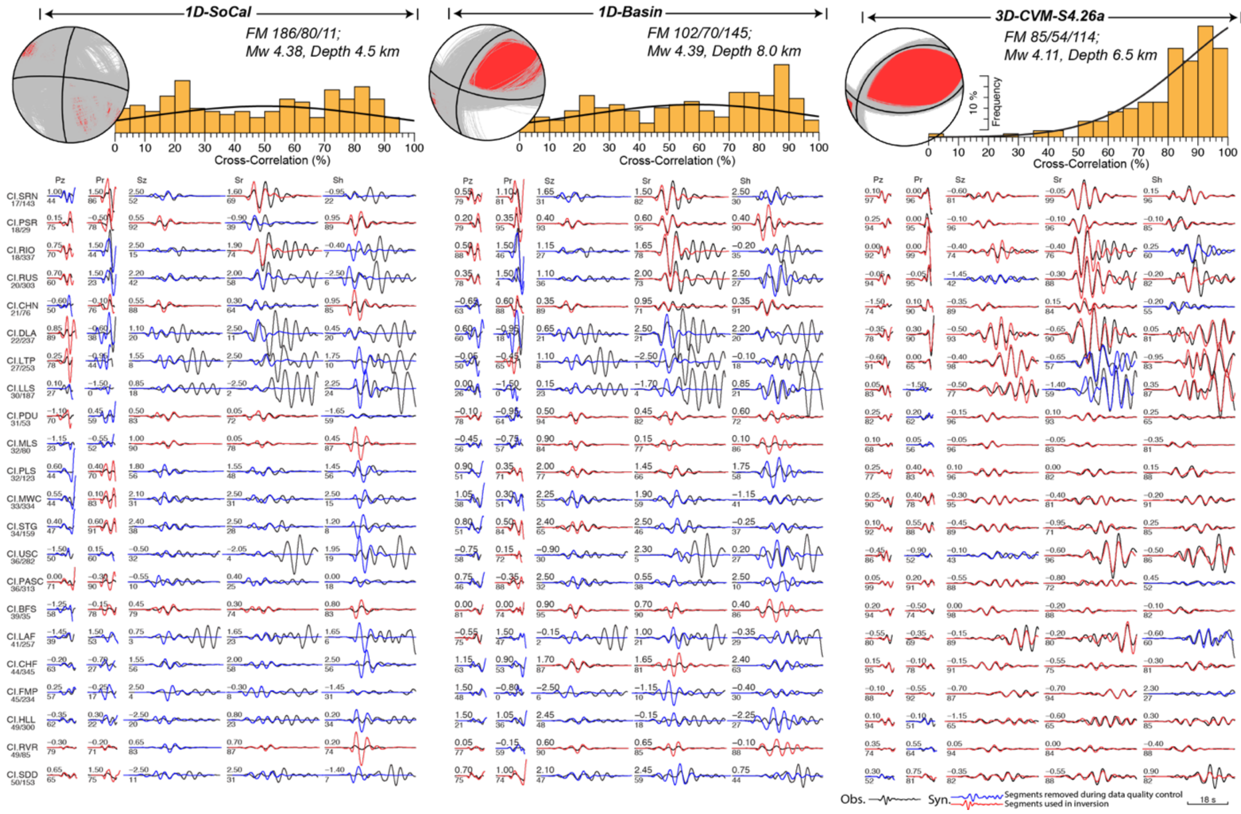

Figure 2. *Comparison of moment tensor inversion results using 1D and 3D velocity models. The obtained focal mechanism solutions are shown as beachballs, where the black lines are optimal results, and the gray lines are uncertainties estimated by a bootstrapping method (95% confidence level). Histograms of the cross-correlation coefficients of waveform fits (including those discarded by our automatic data selection) are shown on the top. The comparison shows that the inversion using the 3D velocity model significantly reduces the moment tensor uncertainties, mainly owing to the accuracy of the 3D velocity model in predicting both the phases and the amplitudes of the observed seismograms. The location of earthquake (2014/03/29 21:32 La Habra M4.1) and locations of stations are given in Fig. 1.*

In previous sections, we limited our moment tensor inversion for pure double-couple (DC) solutions, as expected for shear faulting in shallow tectonic earthquakes. However, a wide variety of processes (e.g., volumetric changes in source area, fault geometry complexity) can cause earthquake mechanisms to have significant non-Double-Couple components (non-DC) (Julian et al., 1998; Ben-Zion & Ampuero, 2009; Ross et al., 2015). On the other hand, the observed non-DC components in moment tensor solutions can be the artifacts in source inversion due to the unmodeled 3D or anisotropic velocity structure (Vavryčuk, 2004; Li et al., 2018). We invert for the pure deviatoric moment tensor solutions (DC + CLVD) (Fig. 3a) and full moment tensor solutions (DC + CLVD + ISO) (Fig. 3b) using either the 1D-SoCal (Hadley & Kanamori, 1977), or the 1D-Basin (Laske et al., 2013), or the 3D CVM-S4.26a model (Lee et al., 2014), by keeping the inversion parameters same in all cases for fair comparisons. Results show that a significant number of earthquakes have strong non-DC components in the inversions using 1D velocity models (Fig. 3), while the inversions using the 3D velocity model show that most events have nearly DC mechanisms with limited CLVD and ISO components (Fig. 3). The percentage of non-DC components decrease dramatically with the usage of the 3D velocity model, suggesting that the large percentage of non-DC components in the 1D inversions is a result of poorly constrained Earth structure. The comparison of the full moment tensor solutions derived using 1D and 3D velocity models reinforce the importance of incorporating 3D velocity model in inversion to understand the faulting behavior. We would expect a further decrease in the percentage of non-DC components in source inversion with improvements made to the 3D velocity model.

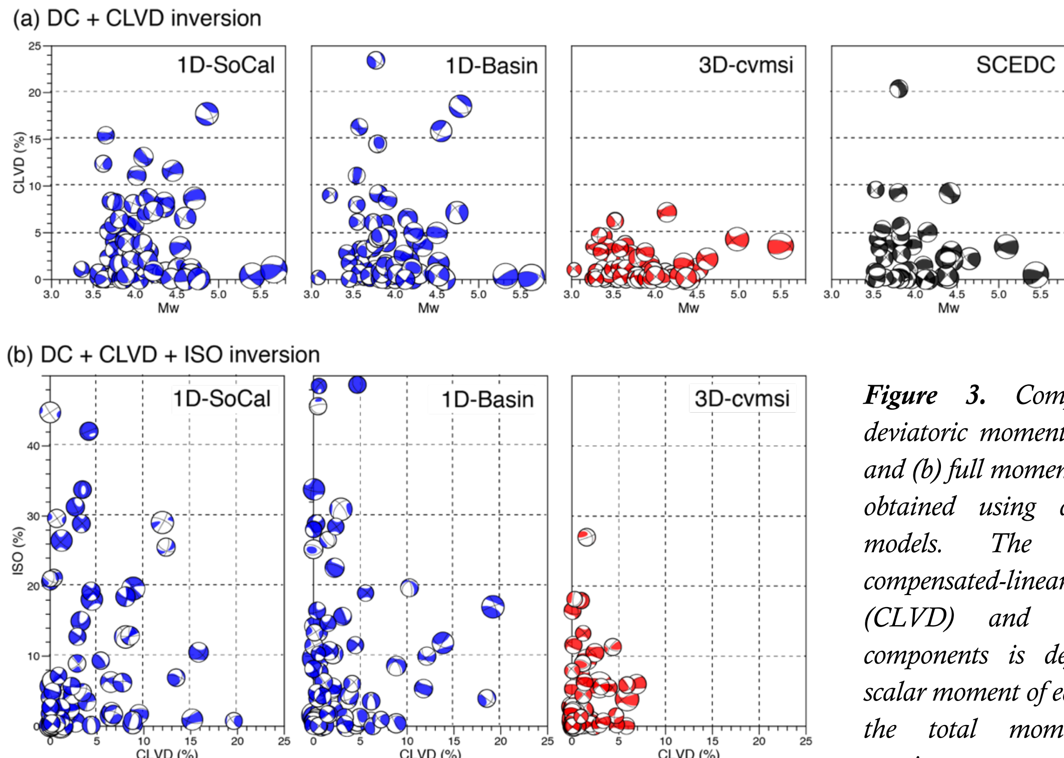

Figure 3. *Comparison of (a) deviatoric moment tensor solutions and (b) full moment tensor solutions obtained using different velocity models. The percentage of compensated-linear-vector-dipoles (CLVD) and isotropic (ISO) components is defined using the scalar moment of each component to the total moment, with the maximum percentage of CLVD and ISO being 25% and 100%, respectively (Zhu & Ben-Zion, 2013). The percentage of non-double-couple components (CLVD and/or ISO) decrease dramatically with the usage of the 3D velocity model, suggesting that the large percentage of non-double-couple components in the 1D inversions mainly comes from the unmodeled 3D velocity structure.*

In this study, we developed a highly automated and efficient procedure to determine the moment tensor solutions for small-to-medium-sized earthquakes using 3D velocity models. We applied our approach in the Los Angeles region to demonstrate the importance and feasibility of using 3D velocity models in automated moment tensor inversion. We generated a new moment tensor catalog in the Los Angeles region with the completeness of ML≥3.5. By comparing our catalog with the current catalogs, our results show that incorporating 3D velocity models can refine the existing moment tensor catalogs in the region, resulting in more accurate focal mechanisms, non-double-couple components, focal depths, and moment magnitudes.

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