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Article title: Subsurface Fault Geometries in Southern California Illuminated
Through Full-3D Seismic Waveform Tomography (F3DT)

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1. Introduction

Three-dimensional models of subsurface fault systems are playing an increasingly
important role in improving our understanding of regional tectonics. In Southern
California, the Community Fault Model (CFM) (Plesch et al., 2007), a three-
dimensional model of more than 140 major faults represented using triangulated
surfaces in a geologic computer-aided design (CAD) software, is being actively
developed and integrated into various applications including crustal deformation
modeling (e.g., Johnson, 2013), earthquake rupture dynamics (e.g., Oglesby, 2005),
earthquake rupture forecast (Field et al., 2014), probabilistic seismic hazard analysis
(Graves et al., 2010), and deterministic ground-motion simulations for different
earthquake scenarios (e.g., Day et al., 2012; Jones et al., 2008). At the current stage,
the geometries of the faults in the CFM are mainly determined based on maps of
surface fault traces (e.g., Jennings, 1994), earthquake hypocenters and focal
mechanisms (e.g., Hauksson, 2000; Richards-Dinger and Shearer, 2000), seismic
reflection profiles (e.g., Dolan and Pratt, 1997; Fuis et al., 2003), well penetrations,
trenches across faults and geologic cross sections.

Recent advances in seismic tomography techniques, in particular developments in full-3D seismic waveform tomography (F3DT) (e.g., Chen et al., 2007; Fichtner et al., 2009; Tape et al., 2010; Zhu et al., 2012; Lee et al., 2014a) have substantially improved the resolution and accuracy of regional 3D seismic velocity models obtained using seismograms from passive seismic sources (i.e., natural earthquakes and ambient noises). In this paper, we show that the recent regional 3D seismic velocity model for Southern California obtained through F3DT, CVM-S4.26, (Lee et al., 2014a), has reached a spatial resolution that allows us to systematically delineate subsurface 3D fault geometries based on seismic velocity contrasts across fault surfaces, thereby providing one additional technique for constructing and refining subsurface fault geometries in the CFM.

The velocity-model-based technique is highly complementary to existing techniques for delineating subsurface fault geometries. For instance, unlike techniques based on earthquake hypocenters or focal mechanisms, the velocity-model-based technique is applicable in regions and/or at depths with highly sparse and/or diffusive seismicity. Unlike conventional 2D seismic reflection profiles, which usually provide 2D images of the subsurface along a few seismic survey lines, CVM-S4.26 provides 3D images of the entire crust beneath Southern California and allows the construction of fault surfaces in any orientation at any location within our modeling volume. We expect our velocity-model-based technique, which is enabled by F3DT, to be a useful addition to the collection of techniques for constructing subsurface fault systems.

2. CVM-S4.26

The velocity-model-based fault construction technique requires a high-resolution seismic velocity model that can reveal the sharp contrasts in material properties across the fault surface. Unlike conventional ray-theoretic travel-time tomography

techniques (e.g., Iyer and Hirahara, 1993; Hauksson, 2000; Nolet, 2008), F3DT is based on purely numerical solutions of the 3D (visco)elastic wave equation and is capable of assimilating the rich information in the shapes of the seismic waveforms recorded by modern broadband seismometers to image the subsurface structure. Given sufficient seismic data coverage, the resolution and the accuracy of the seismic velocity models obtained through F3DT can be substantially better than those obtained through conventional ray-theoretic travel-time tomography (Chen et al., 2007; Fichtner et al., 2009; Tape et al., 2010; Zhu et al., 2012; Lee et al., 2014a). F3DT consists of iterated cycles of wave-propagation simulations, measuring discrepancies between model-predicted (i.e., synthetic) and observed seismograms, sensitivity kernel calculations, and inversions. Through these iterated cycles, the seismic velocity model is gradually modified and refined and the misfits between synthetic seismograms computed using the improved velocity model and the observed seismograms are reduced (Lee et al., 2014b). The differences between the starting seismic velocity model and the resulting velocity model after many F3DT iterations can be significant, depending upon the quality of the starting model. CVM-S4.26 is the latest 3D seismic velocity model for Southern California obtained after 26 F3DT iterations using the 3D model CVM-S4 as the starting model (Fig. 1).

The Southern California Earthquake Center (SCEC) maintains and provides two major branches of seismic velocity models for Southern California, the Community Velocity Model—SCEC (CVM-S) and the Community Velocity Model—Harvard (CVM-H). The CVM-S was constructed by embedding rule-based velocity models of major basins within a background model determined from regional ray-theoretic travel-time tomography (Hauksson, 2000; Magistrale et al., 2000). It was later improved by adding geotechnical layers, a laterally varying Moho interface (Zhu and

Kanamori, 2000) and an upper-mantle velocity model (Kohler et al., 2003). The 4th version of this model is referred to as CVM-S4. In CVM-H, the basin models were mainly determined by applying geostatistical methods to direct velocity measurements derived from a large number of sonic logs and seismic reflection profiles (Shaw et al., 2015). The latest version of CVM-H, CVM-H15.1, includes the improvements made through 16 iterations of full-3D adjoint tomography (Tape et al., 2010). We have also included CVM-H15.1 in this paper for comparison (Fig. 1).

Using CVM-S4 as our 3D starting model, we have so far carried out 26 F3DT iterations by assimilating waveform data from more than 30,000 seismograms from about 300 regional small to medium-sized earthquakes and more than 20,000 ambient-noise Green's functions. The latest model, CVM-S4.26, reveals strong crustal heterogeneities throughout Southern California, some of which are completely missing in CVM-S4 and CVM-H15.1 but exist in models obtained from other independent crustal-scale 2D active-source seismic surveys (Lee et al., 2014a). Synthetic seismograms computed using CVM-S4.26 provide nearly perfect fits to observed seismograms from direct-arriving P-wave to 30 seconds after the surface-wave at frequencies up to 0.2 Hz for almost every seismogram used in our inversion and also a large number of independent seismograms not included in our inversion (Lee et al., 2014a). Validations and descriptions of CVM-S4.26, as well as our entire F3DT inversion process, including the inversions for earthquake source parameters using the gradually improved 3D velocity model, have been documented in our previous publications (Lee et al., 2011; Lee et al., 2014ab; Chen and Lee, 2015).

3. Fault Geometries in CVM-S4.26

An important feature of CVM-S4.26 is that there exists an excellent correlation between strong seismic velocity contrasts in CVM-S4.26 and known fault surfaces

both in CFM and in many other independent studies. From the shear-wave velocity map-view at 2-km depth shown in Fig. 1, we can easily observe the velocity contrasts associated with major strike-slip faults, such as the San Andreas Fault (SAF), Sierra Nevada Fault Zone (SNFZ), Northern Death Valley Fault Zone, Ozena Fault (OF), Garlock Fault (GF), Arroyo Parida Fault (APF), San Jacinto Fault (SJF) and the Elsinore Fault. For instance, the velocity contrast across SNFZ in CVM-S4.26 clearly separates the Sierra Nevada and the Walker Lane. The strong low-velocity anomalies in the Walker Lane imaged in CVM-S4.26 are correlated with the Owens Valley and the Indian Wells Valley (China Lake). Some of the faults are basin bounding. For instance, the APF forms the northern boundary of the Santa Barbara Channel.

In the following, we will focus on a few fault structures that are relatively more important for improving our understanding of regional tectonics and seismic hazard. We note that the strong velocity contrasts across fault surfaces that we have observed in CVM-S4.26 were not built into the parameterization of our starting model, neither were they enforced in any way during the F3DT iterations. These features were entirely constrained by the seismic waveform data used in our F3DT inversion and emerged gradually through our iterative inversion process.

3.1 San Andreas Fault (SAF)

The SAF is one of largest faults in Southern California and is potentially able to generate large earthquakes in the near future (e.g., Sieh and Williams, 1990). Imaging the detailed geometries of SAF not only improves our understanding of the tectonics in Southern California but also provides more reliable information for numerical simulations of potential large earthquakes (e.g., Day et al., 2008; Olsen et al., 2008). The SAF is usually treated as a vertical or steeply dipping strike-slip fault. Fuis et al. (2012) pointed out that the geometries of the SAF in Southern California could be

highly complex in certain segments. In general, the geometries of the SAF obtained from velocity contrasts in CVM-S4.26 are in good agreement with results obtained in Fuis et al.'s (2012). And CVM-S4.26 may also provide additional insights about the dip of the SAF near the McKittrick region, which has higher uncertainties in the model of Fuis et al.'s (2012).

Figure 2 shows 6 cross sections at different segments of the SAF in CVM-S4.26, CVM-S4, and CVM-H15.1. The 6 cross-sections A-A', B-B', F-F', G-G', I-I' and J-J' are near the McKittrick, the Big Bend, the northern and southern San Gabriel Mountain, the San Bernardino Mountain and the Salton Trough, respectively. In the cross sections near the McKittrick region (Fig. 2 A-A'), CVM-S4.26 shows a nearly vertical velocity contrast beneath the surface trace of the SAF. This nearly vertical velocity contrast separates the relatively shallow Cuyama Basin from the deeper Great Valley sediments. In Fuis et al.'s (2012), the SAF geometry in this region was extrapolated based on the geometries of other SAF segments. CVM-S4.26 thereby provides additional constraints for the detailed fault geometry in the McKittrick region.

In the Big Bend region (Fig. 2 B-B'), Fuis et al. (2012) suggest that the dip of the SAF is moderately southwest based on the model derived from gravity and magnetic field observations and dip estimates from trenches. The B-B' cross sections of both CVM-S4.26 and CVM-S4 show a west dipping low-velocity anomaly at 7~15 km, which is co-located with the west dipping low-density anomaly in the model derived from potential fields (e.g., Fuis et al., 2012 Appendix B). In addition, the high-velocity anomalies east of the SAF in CVM-S4.26 are well correlated with the high gravity and magnetic values east of the SAF (Fuis et al., 2012 Appendix B).

Results from the Los Angeles Region Seismic Experiment (LARSE) surveys suggest

that the SAF has a vertical or nearly vertical dip in the San Gabriel Mountain (SGM) region (Fuis et al., 2003; Fuis et al., 2012). The F-F' and G-G' cross sections in Fig. 2 are co-located with the LARSE II and LARSE I survey lines, respectively. In the northern SGM, CVM-S4.26 shows a nearly vertical velocity contrast across the SAF (Fig. 2 F-F'), which is also consistent with the SAF model in the CFM in this region. In the southern SGM (Fig. 2 G-G'), the velocity contrasts in all three CVMs are relatively weak, but the relatively thicker low-velocity anomaly in CVM-S4.26 seems to be associated with SAF.

In the San Bernardino Mountain (SBM) region (Fig. 2 I-I'), both CVM-S4.26 and CVM-S4 show a northeast-dipping velocity contrast, which is consistent with the projected SAF from the CFM in this region. The velocity contrast in CVM-S4.26 is sharper than that in CVM-S4, which is in better agreement with the findings in Fuis et al. (2012). The low-velocity anomaly underneath the SBM has been substantially enhanced in CVM-S4.26. And we also observe a low-velocity anomaly underneath the SGM in CVM-S4.26 at the G-G' cross section. These observations may suggest the close affinity of these mountains during their formation and their later separation through the translational motion across the SAF (Kerry Shieh, personal communication).

In the Salton Trough region (Fig. 2 J-J'), the SAF has a nearly vertical dip in the CFM but a moderately northeast dip in the model of Fuis et al.'s (2012). The J-J' cross section in CVM-S4.26 shows a high-velocity anomaly beneath the Salton Trough, which is consistent with the tomography model of (Lin, 2013), and also a low-velocity anomaly to the east of the surface trace of the SAF. The velocity contrast in CVM-S4.26 in this region may suggest a moderate northeast dip of the SAF.

3.2 Dip-Slip Faults and Decollements

In addition to major strike-slip faults, several velocity contrasts with oblique angles in CVM-S4.26 show excellent agreement with major dip-slip faults in Southern California. In Fig. 2 we observe the Sierra Nevada Fault Zone (SNFZ) on C-C'; the White Wolf fault (WWF) and Garlock Fault (GF) on D-D'; the Gravel Hill-Harper Fault (GH-HF) on E-E'; the Northridge and San Fernando thrusts (Carena and Suppe, 2002) on F-F'; the Whittier Fault (WF) and Sierra Madre Fault Zone (SMFZ) on G-G'; the SAF and Frontal Fault (FF) on I-I'. Even in the offshore region (Fig. 2 H-H'), where the seismic waveform data coverage is relatively poor in our F3DT inversion, the velocity contours in CVM-S4.26 show better agreement with the faults in the CFM. We note that the basins in CVM-H15.1 on Fig. 2 H-H' were constructed using techniques other than tomography (Shaw et al., 2015).

In Fig. 2, the F-F' and G-G' cross sections are co-located with the LARSE II & I profiles, respectively. On the F-F' cross section, the velocity contrasts in CVM-S4.26 are perfectly aligned with the fault surfaces in the Northridge and the San Fernando regions derived from aftershock hypocenters and geologic data (Carena and Suppe, 2002). Velocity contrasts on this cross section indicate that the low-angle north-dipping fault extends to about 20-km depth beneath the San Gabriel Mountain, which is consistent with the postulated San Fernando decollement derived from reflection data of LARSE II and other observations (Fuis et al., 2003). On the same cross section, the south-dipping velocity contrast extending from about 6-km depth to about 20-km depth is co-located with the Northridge blind thrust fault (Carena and Suppe, 2002; Fuis et al., 2003), on which the 1994 M_w 6.7 Northridge earthquake occurred. On the cross section G-G' (Fig. 2), CVM-S4.26 shows high similarities with interpretations based on the LARSE-I reflection data (Fuis et al., 2003, 2001; Ryberg and Fuis, 1998). The LARSE-I reflection data show a strong negative-polarity seismic

phase reflected at mid-crustal depths, which was interpreted as a mid-crustal low-angle, east-dipping low-velocity layer associated with a detachment structure filled with fluids (Fuis et al., 2003, 2001; Ryberg and Fuis, 1998). On cross section G-G', CVM-S4.26 shows a northeast-dipping low-velocity layer extending from about 13-km depth to about 20-km depth beneath the SGM, which is consistent with the fluid-filled detachment structure. This cross section also shows that the WF is likely to be truncated by the detachment at about 10-km depth, as suggested in the LARSE-I study (Fuis et al., 2003), rather than extends to about 15-km depth, as in the current version of the CFM. Between the WF on the west and the SMFZ on the east, the high-velocity anomaly right above the mid-crustal low-velocity layer in CVM-S4.26 is also consistent with results from the LARSE-I study (Fuis et al., 2003, 2001; Lutter et al., 1999).

In CVM-S4.26, there exists a mid-crustal velocity reversal mainly beneath the Western Mojave, the San Gabriel Mountain, and the southern tip of the Sierra Nevada (Fig. 3). Previous seismic reflection and receiver-function studies have revealed major mid-crustal interfaces underneath the Western Mojave (Cheadle et al., 1986; Porter et al., 2011). In Cheadle et al. (1986), reflection profiles along the COCORP seismic survey lines show low-angle, southwest-dipping horizons at mid-crustal depth beneath the Western Mojave region. The A-A' cross section (Fig. 3) is roughly co-located with the COCORP Mojave survey line (Cheadle et al., 1986) and CVM-S4.26 also shows a southwest-dipping interface at about mid-crustal depth. Another noticeable feature is that the “ramp and flat” geometry of the velocity contrast in CVM-S4.26 is consistent with the structure imaged in Cheadle et al.’s (1986).

The receiver function study in Porter et al. (2011) revealed a mid-crustal low-velocity layer beneath the San Gabriel Mountain and the Western Mojave. The B-B' cross

section (Fig. 3) is roughly co-located with the profile in Porter et al. (2011). CVM-S4.26 also shows a clear low-velocity layer at mid-crustal depth. The existence of a velocity reversal underneath the Western Mojave region was also confirmed in other independent studies such as the unpublished 1D velocity model of G. Fuis (1991), which was cited in Li et al. (1992). A southward-dipping layer with high reflectivity between depths of 10 km and 15 km in the mid-crust beneath Mojave Desert (Fig. 3 C-C' cross section) was also imaged by Li et al. (1992). They interpreted this high-reflectivity zone (with P-velocity of 6.3 km/s instead of 6.8 km/s) imaged in the CDP depth/time sections to be a transition zone between the brittle and ductal lower crust, based on the rheology, composition and extent of the ductile lower crust.

3.3 Possible Fault Structures in High Heat Flow Areas (Coso geothermal field and Salton Trough)

In Southern California, the majority of the natural earthquakes are located in the proximity of faults (Hauksson et al., 2012) and earthquake hypocenters have been used to delineate faults in CFM (Plesch et al., 2007). However, in areas with high heat flow, such as the Coso geothermal field and the Salton Trough region, seismicity is high, but without coherent surface tracks for the seismogenic structures. Sometimes the diffusive seismicity in the region is difficult to delineate faults based solely on earthquake hypocenters. Under such circumstances, the spatial gradients in high-resolution velocity models may provide an alternative or additional constraints for fault detection.

To investigate the relationship between seismicity and spatial gradients in the velocity models, especially in areas with high heat flow, we have relocated a large collection

of earthquakes from 1981 through June 2016 using cross-correlation differential arrival times (Hauksson et al., 2012). Fig. 4 shows the hypocenters of the relocated earthquakes for the entire Southern California and within ± 2 km along the two cross sections through the Coso and Salton Trough area. In Fig. 4, we only plotted earthquake hypocenters with location errors less than 1 km in both horizontal and vertical directions.

The Coso geothermal field is one of the most seismically active areas in Southern California and the geothermal resource has been utilized for the generation of electricity. It has been suggested that the heat comes from the magmatic system in the region (Yang et al., 2011). It is, therefore, critical to be able to image magma chamber(s) and to investigate the interaction between the magmatic system and the fault system for geothermal energy exploration through enhanced geothermal systems (EGS). By using travel-time data from local earthquakes, Hauksson and Unruh (2007) carried out 3D ray-theoretic travel-time tomography for the Coso region and obtained both P- and S-velocity models. Using local ambient-noise Green's functions, Yang et al. (2011) obtained a 3D shear velocity model. It was found in both studies that a low-velocity body lies beneath the Coso geothermal field within the depth range from about 4 to 14 km. This low-velocity body is also imaged in CVM-S4.26 and CVM-H15.1, but it does not exist in our initial model, CVM-S4 (Fig. 4).

In general, the seismicity in the Coso area is diffusive. However, along with the cross-section A-A', we can still observe some spatial trends in the relocated hypocenters. For example, the cluster of earthquakes in the eastern Coso region extends vertically from about 4-km depth to about 8-km depth. The lateral position of this

approximately vertical seismicity trend is well aligned with the eastern boundary of the low-velocity body in CVM-S4.26. But there is no clear spatial correlation between this seismicity trend and velocity gradients in the other two CVMs (Fig. 4). The current version of CFM does not contain any fault surfaces interpolating this seismicity trend.

In addition to the low-velocity body beneath the Coso region, CVM-S4.26 reveals another low-velocity volume extending from about 9-km depth to about 16-km depth beneath the Death Valley, which is correlated with the Panamint Valley Fault Zone (PVFZ). A similar feature was also imaged in Yang et al.'s (2011).

The Salton Trough is located between the transpressional stress regime to the north and the divergent stress regime to the south and an accurate velocity model can be very helpful to improving our understanding of the tectonic processes between the Pacific and the North American Plates. The Brawley Seismic Zone (SBZ) in the Salton Trough is a region with high seismicity. Figure 4 shows the shear wave velocity along B-B' profile in the three CVMs. In CVM-S4.26, a relatively high-velocity body is truncated by the relocated seismicity in the BSZ and the San Jacinto Fault (SJF), but this feature is not obvious in CVM-S4 and is absent in CVM-H15.1 (Fig. 4). A similar feature has also been imaged in the Barak et al.'s (2015) ambient-noise tomography (the STa-STa' and STb-STb' profiles in their Figure 11), which is an improved version of CVM-H by using ambient noise Green's functions.

4. Summary and Discussion

Many strong velocity contrasts in CVM-S4.26 are well correlated with major fault systems both in the CFM and in other independent studies. This high-resolution 3D

309 seismic velocity model obtained through iterative F3DT inversion provides a more
310 comprehensive image of subsurface fault systems. The velocity-model based fault
311 construction technique not only allows us to delineate fault geometries but also
312 reveals differences in the material properties across the fault, which is not available in
313 some other types of fault construction techniques.

314 At the current stage, seismic waveforms with frequencies up to 0.2 Hz have been
315 assimilated to generate CVM-S4.26. Waveforms with frequencies above 0.2 Hz can
316 potentially improve the spatial resolution of our seismic velocity model even further,
317 thereby revealing velocity contrasts associated with even smaller faults. CVM-S4.26
318 can serve as the starting model for future inversions that will assimilate seismic
319 waveforms at higher frequencies.

320 CVM-S4.26 has opened up the possibility for the systematic construction of 3D blind
321 thrust faults and decollement surfaces at shallow to mid-crustal depths. A reliable 3D
322 decollement model can have important implications for understanding regional
323 tectonics and also deformation modeling in Southern California. Johnson et al. (2007)
324 introduced a multi-layered model consisting of an elastic upper crust and viscoelastic
325 mid- and lower-crust for the Mojave region to explain the significant discrepancies
326 between the SAF slip rates estimated based on elastic models and those obtained
327 based on geologic observations. The slip rate estimates are nonunique and various
328 factors, such as the design of the model and material assumptions, could affect
329 simulation results. The detachment structure imaged in CVM-S4.26 underneath the
330 Mojave region may provide additional constraints for slip rate estimates.

331 The seismic risk in Southern California is high and a more realistic fault model can
332 benefit seismic hazard analysis. The newly imaged velocity contrasts across the faults
333 could have significant impacts on the propagations of seismic energy and therefore

affect the ground-motion simulations. For example, the large sedimentary basin, the Great Valley, is mostly absent in the CVM-S4 and CVM-H15.1. In the CVM-S4.26, the improved structures of Great Valley agree well with surface geology and its western and southern boundaries are consistent with the SAF and WWF (Fig. 1 & 2). Based on the catalog of historical earthquakes in California, the region has potential to generate large earthquakes such as the 1952 Ms 7.8 Kern County earthquake on WWF (Castillo and Zoback, 1995) and the 1857 M 7.9 Fort Tejon earthquake, which mainly ruptured from the Parkfield to 300 km south of the Parkfield along the SAF (Stover and Coffman, 1993). The synthetic seismograms computed using CVM-S4.26 show substantially better fit to observed waveforms than those computed using other 3D models with lower resolution (Lee et al., 2014ab) and therefore could potentially improve the accuracy of the simulations of large earthquakes in Southern California for various purposes such as emergency responses and educations (Jones et al., 2008). Also, an accurate velocity model could reduce the structure errors during the earthquake rupture inversions and could improve the reliabilities of source inversion results and understanding mechanisms of earthquake ruptures. We anticipate the CVM-S4.26 will be useful for a broad range of other communities in earth sciences.

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524 Figure 1. (a) Map shows topography, bathymetry, major geological provinces and
 525 active faults in Southern California. The San Gabriel Mountain (SGM) and San
 526 Bernardino Mountain (SBM) are the major mountains in the Traverse Ranges. Major
 527 faults are drawn in bold black: SAF-San Andreas Fault, SNFZ-Sierra Nevada Fault
 528 Zone, WWT-White Wolf Fault, GF-Garlock Fault, SYF-Santa Ynez Fault, SGF-San
 529 Gabriel Fault, EF-Elsinore Fault, SJF-San Jacinto Fault, and ECSZ-Eastern California
 530 Shear Zone. Major basins are labeled 1~12: (1) Santa Maria Basin, (2) Cuyama Basin,

531 (3) Southern San Joaquin Basin, (4) Owens Valley, (5) Indian Wells Valley (China
532 Lake), (6) Santa Barbara Channel, (7) Santa Monica Basin, (8) Antelope Valley, (9)
533 San Bernardino Valley, (10) Venture basin, (11) Los Angeles Basin, and (12) Salton
534 Trough. The red dash line outlines the region of our tomography study and yellow
535 dash line outlines the simulation region of Tape et al.'s (2010) study. (b~d) S wave
536 velocities at 2 km in the CVM-S4, CVM-S4.26, and CVM-H15.1.

538 Figure 2. Map of cross sections of the shear velocities in the 3 CVMs. On the cross-
539 sections, black solid lines are projections of fault surfaces in the CFM; the purple
540 lines on cross-section F-F' are projections of the fault surfaces from the Carena &
541 Suppe's (2002) fault model; brown lines on cross-section F-F' and G-G' are
542 postulated decollement from LARSE surveys (Fuis et al., 2003; Ryberg and Fuis,
543 1998). Faults on cross sections are: San Juan Fault Zone (SJFZ), San Andreas Fault
544 (SAF), Big Pine Fault (BPF), Pleito Fault (PF), Sierra-Nevada Front Fault Zone
545 (SNFZ), White Wolf Fault (WWF), Garlock Fault (GF), Lenwood Fault (LF), Gravel
546 Hills-Haper Fault (GH-HF), Santa Susana Fault (SSF), San Gabriel Fault (SGF),
547 Whittier Fault (WF), Sierra Madre Fault Zone (SMFZ), Banning Fault (BF), and
548 Frontal Fault (FF).

549

550 Figure 3. Map shows the cross-sections in West Mojave region. The A-A' is roughly
 551 along the COCORP Mojave survey line (Cheadle et al., 1986) and the dash line
 552 indicates the “ramp and flat” geometry imaged in CVM-S4.26. The B-B' is along the
 553 profile in Porter et al.'s (2011) study and black lines indicate the interfaces in Porter
 554 et al.'s (2011) result.

Figure 4. Map shows the distribution of relocated earthquake epicenters (color dots) in Southern California from 1981 through June 2016 and the cross-sections show S-velocities in the three CVMs along the profile in the Coso geothermal field (A-A') and the profile in the Salton Trough (B-B'). The blue star in the map view indicates the location of the Coso geothermal field. Black dots on the cross-section views show hypocenters of relocated earthquakes within ± 2 km of the profiles. Black solid lines on cross sections are projected faults in the CFM. PVFZ: Panamint Valley Fault Zone.