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Key Points:

- Local stress deviations from the regional stress field provide information on dominant local loadings
- Comparing stress field inversions using declustered seismicity and aftershocks help to identify the main source of stress for mainshocks
- Higher topography produces compressional stress components at the bottom of the seismogenic zone near Cajon Pass and San Gorgonio Pass

Supporting Information:

- Supporting Information S1
- Data Set S1

Correspondence to:

N. Abolfathian,
nabolfat@usc.edu

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Variations of Stress Parameters in the Southern California Plate Boundary Around the South Central Transverse Ranges

Niloufar Abolfathian¹ , Patricia Martínez-Garzón² , and Yehuda Ben-Zion^{1,3}

¹University of Southern California, Los Angeles, CA, USA, ²GFZ German Research Centre for Geosciences, Potsdam, Germany, ³Southern California Earthquake Center

Abstract We examine the stress field in Southern California with a focus on the region near the South Central Transverse Ranges (SCTR), using a refined stress inversion methodology. We independently invert declustered and aftershocks focal mechanisms from the years 1981 to 2017. Comparisons between the stress field orientations and the stress ratios from these inversions provide information on local sources of the stress field. Regionally, the S_{Hmax} tends to be toward NNE and the stress ratios vary from transtensional stress regime near the Eastern California Shear Zone (ECSZ), to strike-slip faulting near the SCTR, and toward transpression near the Western Transverse Ranges. Detailed analysis of stress parameters near the SCTR indicates deviations from the regional strike-slip faulting including the following: (1) The San Bernardino Mountain area shows S_{Hmax} direction toward NNW and transpressional stress components likely associated with the motions of the San Andreas Fault and ECSZ; (2) the Cajon Pass and San Gorgonio Pass show transpressional stress regime near the bottom of the seismogenic zone likely associated with the elevated topography; and (3) in Crafton Hills, rotation of the principal stress plunges and S_{Hmax} direction and transtensional stress regime below ~10 km, along with lower estimated apparent friction coefficient, suggest a weak fault possibly associated with deep creep. The performed multiscale analysis resolves effects of regional and local loadings. The average stress parameters in the analyzed 37 years do not show significant temporal variations of stress field near the SCTR region.

1. Introduction

The state of stress in the seismogenic crust and within fault zones is a fundamental component of tectonic interactions and earthquake fault mechanics (Scholz, 2002). Estimating detailed spatiotemporal variations of the stress field and improving the knowledge on the sources affecting the stress field can provide important information on earthquake physics and possibly help forecasting probabilities of large events. Recent enhancements in seismic data acquisition, improvements in the analysis methods, and computational capabilities make it possible to estimate the spatiotemporal variations of the crustal stress field in higher resolution (Abolfathian et al., 2019; Martínez-Garzón et al., 2016). In this study, we analyze the stress field orientations and stress ratios near the South Central Transverse Ranges (SCTR) in Southern California and investigate how the stress field parameters are affected by fault complexities and crustal features including topography.

The San Andreas Fault (SAF) and San Jacinto Fault Zone (SJFZ) accommodate the bulk of plate motion in Southern California (Fialko, 2006; Petersen & Wesnousky, 1994). These two major strike-slip faults link together near the SCTR in a highly complex faulting region that includes also multiple secondary faults and earthquake ruptures reflecting different faulting regimes (Figure 1). The SCTR consists of mountain ranges elevated up to ~3 km (e.g., the San Gabriel and San Bernardino Mountains (SBM)) near Cajon Pass (CP) and San Gorgonio Pass (SGP) and a set of reverse and strike-slip faulting (e.g., Fialko et al., 2005; Matti & Morton, 1993; Spotila et al., 2001; Yule & Sieh, 2003). The Crafton Hills (CH) area, located near SCTR between the SAF and SJFZ (Figure 1), includes a mixture of strike-slip and normal faulting with relatively deep and significantly high seismicity rate (Cooke & Beyer, 2018; Wdowinski, 2009).

Paleoseismic and historic records indicate that the area near SCTR has potential for large ($M_w > 6.0$) earthquakes (e.g., Petersen & Wesnousky, 1994; Rockwell et al., 2015). Although no significant recurrence interval is estimated for this region, five events with $M_w > 6.0$ occurred near SCTR (Figure 1) in past 40 years, with

Figure 1. Distribution of declustered seismicity with focal mechanisms in the selected region in Southern California, between 1981 and 2017, used for the stress inversion. Each event is color coded with its hypocentral depth. The brown rectangle denotes a selected region around the South Central Transverse Ranges (SCTR). The yellow squares show focused regions of study, Cajon Pass (CP), and San Geronio Pass (SGP). Faults are marked in black lines. Stars show events larger than Magnitude 6 in the region during the selected time period. SCTR and yellow fonts in the figure shows regions of study, while black fonts define geology of the area. (SGM: San Gabriel Mountains; SBM: San Bernardino Mountains; SJM: San Jacinto Mountains; CH: Crafton Hills; HS: Hot Springs).

the largest being the 1992 M_w 7.3 Landers earthquake in the Eastern California Shear Zone (ECSZ), followed by M_w 6.4 Big Bear aftershock in SBM. Moreover, the possibility of earthquake rupture continuing from the SAF to the SJFZ and vice versa, together with its proximity to large urban areas, makes this region an important study area (e.g., Lozos, 2016; Onderdonk et al., 2013; Salisbury et al., 2012; Share & Ben-Zion, 2018).

Various previous studies inverted focal mechanisms to compute the stress tensor orientation and stress ratios in Southern California (e.g., Bokelmann & Beroza, 2000; Hardebeck & Hauksson, 2001; Jones, 1988; Yang & Hauksson, 2013). Hardebeck and Hauksson (2001) found that a homogeneous stress field is not able to explain the complex faulting system and stress variations near the SCTR. They also studied temporal changes of stress variations in 5-year time periods between 1980 and 1999 and found no significant changes detectable considering the noise level of the data. Yang and Hauksson (2013) analyzed multiscale stress field on regional (100- to 500-km resolution) and local scales (less than 100 km). They inferred that the local stress variations allow the possible occurrence of major earthquakes ($>7.0 M_w$). Investigation of the stress field orientation with depth through the seismogenic depth (e.g., Bokelmann & Beroza, 2000; Hardebeck & Hauksson, 2001) indicated that stress field orientation is generally consistent through the seismogenic depth in Southern California.

In the present study we use earthquake fault plane solutions from 1981 to 2017 (Yang et al., 2012; extended to later years) to examine the 3-D background stress field regionally (Figure 1) extending from the ECSZ to the Los Angeles basin (section 4.1), and detailed spatiotemporal variations of the stress field near the SCTR (section 4.2). We employ a refined stress inversion methodology developed by Martínez-Garzón, Ben-Zion, et al. (2016) over a large data set to obtain robust stress parameters (i.e., the principal stress orientations and the stress ratio) in finer resolution of an average ~ 5 km (actual resolution varies with the seismicity

distribution). All previous studies in this region have employed nondeclustered seismicity catalogs, and consequently, the recovered stress field combines the background stress field with local stress transfers from the aftershocks. With the new employed method, we separate the declustered seismicity from aftershocks to have better focus on the background tectonic loading. Compared to earlier studies on the stress field near the SCTR, this study provides also more detailed information on local stress field variations associated with mechanisms of aftershocks and crustal structures.

The background stress field consists of the regional far-field loading from the tectonic plates and the loading from local crustal structures. The total crustal stress field (τ_T) includes also stress transfer terms and can be written as the sum

$$\tau_T = \tau_R + \tau_L + \Delta\tau_{ST} \quad (1)$$

where τ_R is the regional far-field loading, τ_L represents additional loading due to local features such as topography, and $\Delta\tau_{ST}$ is stress transfer from earthquakes in the considered crustal volume. Various studies indicate that focal planes of aftershocks are generally consistent with the orientation of the major geological structures (Hardebeck, 2014; McCloskey et al., 2003). Inversions of focal mechanisms of declustered seismicity (mainshocks) provide information on the background stress field associated with $(\tau_R + \tau_L)$, while inversions of aftershock mechanisms reflect the background stress field together with the internal stress transfers of the mainshocks $(\tau_R + \tau_L + \Delta\tau_{ST})$. In other words, the stress inversions obtained from the aftershocks include an additional term dominated by the stress transfers from the mainshocks.

By comparing the background stress field with the stress field inverted from the aftershocks, and considering the expected two sources of background stress field (i.e., far-field tectonic loading and local crustal structures), we obtain information on the main stress source that may drive the aftershocks. In section 4.3 we compare the estimated stress fields from the mainshocks and the aftershocks in the focused study area around the SCTR.

2. Data and the Study Area

For the purpose of this study, the earthquake hypocenters are selected from the Southern California relocated catalog of Hauksson et al. (2012, extended to later years) (Figure 1) with horizontal and vertical location errors of 0.75 and 1.25 km, respectively. The fault plane solutions are selected from the Yang et al. (2012, extended to later years) focal mechanism catalog for the total time period of 1981–2017. The selected focal mechanisms have qualities from A to D, in accordance with 5° to 55° of uncertainty (Yang et al., 2012), where with the mentioned uncertainty range, inversions with ~40 events per grid cell resolves a stable stress field (Martínez-Garzón, Ben-Zion, et al., 2016).

The selected focal mechanism catalog is declustered using the nearest-neighbor proximity approach developed by Zaliapin and Ben-Zion (2013, 2020), separating the mainshock events from the aftershocks and the foreshocks. The declustered seismicity makes it possible to focus on the background stress field and separately on internal stress variations generated by stress transfers from the aftershocks (Martínez-Garzón, Ben-Zion, et al., 2016). The declustered events are also referred to as background seismicity.

The background hypocenters show notable variations in the selected focused area near the SCTR. The area between the main two faults of SAF and SJFZ includes 52% of all the selected background seismicity and has the deepest seismogenic thickness (defined as the depth above which 90% of the events are located) of 17.8 km (Figure 1). The background seismicity from east of the SAF comprises 34% of the selected events and displays a seismogenic thickness of 11.9 km, while the western section of the SJFZ includes 14% of the background seismicity and has a seismogenic thickness of 14.9 km.

We initially invert for the 3-D stress distribution in the study area. Then, based on the hypocentral variations of the background seismicity and geological structures such as mountain ranges and main faults, we divide the SCTR area into six smaller regions (Figure 2). The divided regions are as follows: (1) San Gabriel Mountains (SGM), (2) SBM, two areas in the (3) northern and (4) eastern sections of the SBMs including parts of the ECSZ and fault system near Landers, (5) between the two main fault strands of SAF and SJFZ, and (6) Western region of the SJFZ. We analyze the 2-D background stress field of the mentioned regions in their entire thickness.

Figure 2. Declustered seismicity divided in six geological domains in the study area around the South Central Transverse Ranges: (1) San Gabriel Mountains (SGM) in purple, (2) San Bernardino Mountains (SBM) in red, (3) northern part in yellow, (4) eastern section of the SBM in cyan, (5) between the San Andreas Fault (SAF) and San Jacinto Fault Zone (SJFZ) in green, and (6) western section of the SJFZ in blue.

The stress parameters are estimated independently for the mainshocks' and aftershocks' mechanisms. Aftershocks comprise the majority of events in the SCTR (~65%), while mainshocks (background events) are only ~21% of the earthquakes in the selected focused study area. Foreshocks comprise ~14% of the total seismicity in the study area and are not used in this study. It should be noted that the seismogenic thickness of the mainshocks is ~16.9 km, whereas the aftershocks show a shallower seismogenic thickness of ~13.5 km in the focused study area. The ~3.4-km average hypocentral difference of the mainshocks and aftershocks is correlated with the difference in their associated main loadings. Table 1 summarizes statistical information on the distribution of the mainshocks and the aftershocks.

3. Methodology

3.1. Stress Tensor Inversion of Focal Mechanisms

In this study, we apply the refined stress inversion method developed by Martínez-Garzón, Ben-Zion, et al. (2016) on double-couple earthquake focal mechanism catalog in Southern California. The inversion method employs the refined MSATSI software (Martínez-Garzón et al., 2014; Martínez-Garzón, Ben-Zion, et al., 2016), which is an updated version from SATSI algorithm (Hardebeck & Michael, 2006; Michael, 1984). The assumptions of the stress inversion include the following: (1) The stress field is homogeneous within a considered rock volume, (2) earthquakes occur on preexisting faults with varying orientations, and (3) slip on each fault occurs parallel to the direction of its tangential traction (Bott, 1959; Wallace, 1951).

Table 1
Seismic Statistics in SCTR, Comparing Foreshocks, Mainshocks, and Aftershocks

1981 to 2017 –1 to 30 km depth	No. of events	No. of events %	Seismogenic thickness (90%)	Maximum magnitude (90%)	Mean magnitude	Median magnitude
Foreshock	2,128	14.2	16.8	2.6	2.3	2.2
Mainshock	3,218	21.5	16.9	3.1	2.5	2.4
Aftershock	9,648	64.3	13.5	2.9	2.4	2.3

The employed method includes discretizing the events based on an optimum required number of focal mechanisms per grid cell to constrain a stable stress orientation of an area (McKenzie, 1969). In this study, the optimum number of events per grid cell is estimated to be ~40 (Martínez-Garzón, Ben-Zion, et al., 2016). The study volume is discretized using the *k*-means technique (Hartigan & Wong, 1979; Martínez-Garzón, Ben-Zion, et al., 2016) into Voronoi grid cells containing the mentioned number of events. The cell sizes vary in relation to seismicity density and provide estimates for the spatial resolution of the inversion (e.g., Figure 4).

The linear damped stress inversion is applied in order to reduce potential artifacts related to data discretization (Hardebeck & Michael, 2006). The performed inversion estimates the orientations of the three principal stresses σ_1 , σ_2 , and σ_3 (from most to least compressive) and the stress ratio parameter, *R*, defined as

$$R = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3} \quad (2)$$

The stress ratio (*R* value) ranges between 0 and 1, with smaller and larger stress ratios in a strike-slip environment corresponding to stress regimes closer to transtensional (i.e., mixed strike-slip and normal faulting) and transpressional (i.e., mixed strike-slip and reverse faulting) fields, respectively.

The orientation of maximum horizontal compressional stress, S_{Hmax} , is computed from the orientation of the principal stress axes following Lund and Townend (2007), and the estimated trends and plunges of the principal stresses are classified into Andersonian stress regimes: normal, strike-slip and reverse, and oblique faulting types (Zoback, 1992). Uncertainty estimations of the inversion outputs are obtained by bootstrap resampling of the original set of focal mechanisms (Michael, 1987) and provide 95% confidence intervals.

The method applies an iterative procedure to select the nodal plane that is optimally oriented for failure in the estimated stress field. During each iteration, the stress field orientation and the stress ratio are calculated, and the nodal plane with the largest instability coefficient *I* of each focal mechanism is selected for the next iteration (Martínez-Garzón et al., 2016; Vavryčuk, 2011, 2014). The parameter *I* is defined as

$$I = \frac{\tau - \mu(\sigma - 1)}{\mu + \sqrt{1 + \mu^2}}, \quad (3)$$

where μ is the apparent coefficient of friction. τ and σ are scaled shear and normal stresses, respectively. The parameter *I* takes values between 0 and 1, representing the least and most favorably oriented faults to failure within a given deviatoric stress field. When estimating the fault instability, a grid search is applied over values of coefficients of frictions, ranging between 0.2 and 0.8. For each grid cell, the estimated μ produces the highest overall instability coefficient (Vavryčuk, 2014). Since μ is selected based on iterative computations in the inversion procedure, we refer it as an apparent coefficient of friction.

4. Results

4.1. Regional Stress Variations in Southern California

Initially, we analyze the background stress field in a volume extending over the plate-boundary region in Southern California, extending from the ECSZ to the Los Angeles basin, using ~6,800 focal mechanisms from the declustered catalog between 1981 and 2017. To examine the 3-D spatial changes of stress parameters, the selected focal mechanisms in the study area are divided into 5-km-depth bins. The bin width is selected considering the overall depth uncertainty of ~1.25 km of the resolved hypocentral locations and the optimum number of seismicity, ~40 per grid cell, in a strike-slip regime to converge to a stable stress tensor (Martínez-Garzón, Ben-Zion, et al., 2016). Focal mechanisms in each grid cell are inverted, and the S_{Hmax} direction, the principal stress orientations, and the stress ratio *R* are estimated following the methodology discussed in section 3.

The S_{Hmax} orientation obtained from the selected declustered seismicity changes between the eastern and western sections of the study area (Figure 3). In the ECSZ, the S_{Hmax} is oriented NNE, with an average azimuth of ~12.5°. Near the SBM, the S_{Hmax} rotates counterclockwise to NNW, with an average trend of N7°W. Between the SAF and SJFZ, the S_{Hmax} is oriented north and NNE, while near CH the S_{Hmax} direction rotates

Figure 3. Regional distribution of the maximum horizontal compressional stress orientations (S_{Hmax}) at (a) 0- to 5-km, (b) 5- to 10-km, (c) 10- to 15-km, (d) 15- to 20-km-depth sections associated with declustered seismicity. The variations in S_{Hmax} orientations show the uncertainty of 95% confidence interval. The orientations are color coded in red, green, blue, and brown denoting reverse, strike-slip, normal, and oblique faulting, respectively. Purple dashed lines indicate the used Voronoi cells, and the two purple boxes indicate study areas near the Cajon Pass (CP) and San Gorgonio Pass (SGP). WTR: West Transverse Ranges; SGM: San Gabriel Mountains; CP: Cajon Pass; CH: Crafton Hills; SJM: San Jacinto Mountains; SGP: San Gorgonio Pass; SBM: San Bernardino Mountains; ECSZ: Eastern California Shear Zone.

significantly with depth. Near the West Transverse Ranges (WTR) and the Los Angeles basin, the spatial resolution is lower and the inferred S_{Hmax} direction includes higher uncertainty, but the S_{Hmax} is oriented NNE, similar to the ECSZ. The main S_{Hmax} variations are observed near CH.

The stress regimes are estimated based on the relative position of the σ_1 , σ_2 , and σ_3 axes. The regional background stress regime is in general strike-slip with deviations near the WTR deeper than 10 km showing reverse faulting and in the ECSZ, at the 5- to 10-km-depth section, showing oblique faulting with a mixture of strike-slip and normal faulting (Figure 3).

The variations of the estimated stress ratio R represent the deviation from the regional strike-slip faulting toward transtensional and transpressional stress regimes. In general, clear variations from transtension near the ECSZ to transpression near the WTR are observed at all depth ranges (Figure 4). Deviations from the regional strike-slip stress field near the SCTR include areas of higher transpressional components near CP and SGP (Figure 4c) and higher transtensional stress regimes observed near the CH (Figures 4b-d). The CP, SGP, and CH areas are considered to display local stress components related to the local geological structures, which are discussed in more detail in the following section 4.2.

4.2. Stress Variations Near the SCTR

In this section, we focus on the area near the SCTR using ~3,300 focal mechanisms from the declustered catalog in the selected time period (brown box in Figure 1). We first examined the 3-D variations of the stress

Figure 4. Regional seismicity distribution color coded with values of the stress ratio R at (a) 0- to 5-km, (b) 5- to 10-km, (c) 10- to 15-km, (d) 15- to 20-km-depth sections associated with declustered seismicity. In a strike-slip faulting environment, R values around 0.5, 0, and 1 indicate pure strike-slip, transtensional, and transpressional stress regimes, respectively. Purple dashed lines indicate the used Voronoi cells, and the two purple boxes indicate study areas near the Cajon Pass (CP) and San Geronio Pass (SGP).

parameters by dividing the selected focal mechanisms into 5-km-depth bins. This section follows with the 2-D spatial variation of the stress parameters dividing the background focal mechanisms based on geological features near the SCTR with no depth division.

The S_{Hmax} orientations near the SCTR are generally toward the north and NNE direction (Figure 5), with significant variations in the CH area from 15- to 20-km depth, where the S_{Hmax} direction rotates $\sim 23^\circ$ clockwise from the surface to ~ 20 -km depth (Abolfathian et al., 2019).

Based on the Andersonian theory of faulting, in a strike-slip regime, the intermediate principal stress is vertical, and the least and most compressional principal stress orientations are parallel to the Earth surface. The orientations of the estimated principal stresses (shown as stereonet in Figure 5) indicate strike-slip faulting

Figure 5. Distribution of the maximum horizontal compressional stress orientations (S_{Hmax}) in fan symbols and the principal stress orientations (Stereonets) in the selected region around SCTR at (a) 0- to 5-km, (b) 5- to 10-km, (c) 10- to 15-km, (d) 15- to 20-km-depth sections associated with declustered seismicity. The variations in S_{Hmax} orientations show the uncertainty of 95% confidence interval. The maximum, intermediate and minimum principal stresses in the stereonets are indicated with red, green, and blue, respectively. Purple dashed lines indicate the used Voronoi cells and the two purple boxes indicate study areas near the Cajon Pass (CP) and San Geronio Pass (SGP).

to be the main background stress regime. The Andersonian theory for strike-slip faulting holds overall from the surface to 15-km depth in the focused study area. However, below 15-km depth, the most compressive and intermediate principal stresses' plunge angles rotate about $\sim 30^\circ$ in the CH area, and all principal stresses' plunge angles in the southern part of SGP area and close to the Hot Springs (HS) area rotate about $\sim 15^\circ$ to $\sim 30^\circ$ (Figure 5). In addition, in this depth section, the hypocenters of the selected focal mechanisms are mainly located between the two main faults of SAF and SJFZ.

Significant variations in the stress ratios are observed in the area near the SCTR. In the shallowest depth bin, 0-5 km, the stress ratios follow the regional overall strike-slip faulting, varying from slightly transtensional in the most eastern section toward transpression in the most western section of the selected study area (Figure 4a). The same variations are observed in 5- to 10-km depth with amplified transtension in the eastern section and transpression in the western section (Figure 4b). At 10- to 15-km depth, higher transtensional stress regime appears near the highest peaks of the SBM near SGP and San Gabriel Mountains close to CP (Figure 4c). At the same depth range, transtensional stress regime emerges in the CH area. In this analysis, a damped linear inversion is applied and the inversion results from neighboring domains are smoothed (Hardebeck & Michael, 2006; Martínez-Garzón et al., 2014). Below ~ 5 km, the stress ratio near the CP area changes sharply from transpression in the northwest to transtension in the southeast. In the CP area, where the SJFZ branches from the SAF, there is a strong change in topography at the edge of the San Gabriel Mountains.

Figure 6. Seismicity color coded with values of the stress ratio R in the selected region around SCTR associated with declustered seismicity. The background seismicity division in six geological regions are selected based on the distribution indicated in Figure 2. The two purple boxes indicate study areas near the Cajon pass (CP) and San Geronimo Pass (SGP). Symbols are as in Figures 4.

The region between the SJFZ and SAF near the SCTR is highly seismically active (more than 50% of the background events in the SCTR region are between the two fault strands), and the hypocenters of the declustered seismicity are on average ~ 5 km deeper than the ones located outside of this region. In an effort to clarify stress variations related to fault-system interactions and topographic variations, we divide selected declustered mechanisms into six separate geological regions (see section 2) and invert independently for 2-D stress parameters in each region. The divided areas are shown in Figure 2 with color-coded seismicity distribution. The results from the independent inversions of the six geological regions indicate the overall strike-slip faulting near the SCTR, with deviations including amplified reverse faulting close to CP and oblique/normal faulting in the ECSZ (Figure S1 in the supporting information). The estimated stress ratios are indicated together in Figure 6. The stress ratio variations show compressional stress regime near CP. The stress ratio changes strongly between the NW and SE of the SAF and SJFZ junction (Figure 6), where the compressional regime in the NW is likely associated with the higher topography. The transtensional stress components close to the junction could be explained in terms of the extension associated with the right-lateral strike-slip motion on the SJFZ and the nearby SAF. This region also includes areas dominated by transtensional stress field near CH. The areas near SGP and SBM show clear transpression.

The spatiotemporal variations of background stress field are also examined and found to be in general in agreement with the discussed spatial background stress field variations (Figure S2). For this purpose, we divide the entire selected declustered focal mechanisms into five time periods of ~ 8 years, namely, 1981–1985, 1986–1993, 1994–2001, 2002–2009, and 2010–2017 and estimate the stress parameters independently. The estimated stress parameters do not show any significant changes within these time periods.

4.3. Stress Variations in the SCTR—Aftershocks and Depth Dependency

In the last part, we compare the background stress variations with results obtained from the inversion of aftershock mechanisms. The focused study area near the SCTR has $\sim 3,300$ focal mechanisms from the declustered catalog, while $\sim 9,600$ aftershock mechanisms are available in the selected area within the same time period. We divide the aftershock mechanisms in 5-km-depth bins as applied on the background seismicity and invert for their stress parameters (Figure 7).

Figure 7. Seismicity color coded with values of the stress ratio R , at (a, b) 0- to 5-km, (c, d) 5- to 10-km, (e, f) 10- to 15-km, and (g, h) 15- to 20-km-depth sections. Subplots (a), (c), (e), and (g) show the variation of the stress ratio R , utilizing the background events, while (b), (d), (f), and (h) are estimated inverting the aftershock events. Symbols are as in Figures 4.

The transtensional background stress near the CH area is amplified between ~5- and 15-km depths in the stress field inverted from the aftershocks. The transpressional stress regime near the SGP are also amplified in the results obtained from the aftershock mechanisms, with the difference that the areas with transpressional stress fields are located shallower compared with the ones obtained from the mainshocks. The aftershocks show the overall thinner seismogenic thickness and amplified shallower transtensional and transpressional stress components in the CH and SGP areas, respectively. In contrast, no evidence of transpression near the CP area is observed in the aftershock results. Considering that in the CP area comprises sparse aftershock distribution, we might not have enough resolution to resolve properly the stress field from the aftershocks. The comparison of the estimated stress field from the background declustered seismicity and aftershocks help to infer on the dominant local loadings as discussed in the following section.

To test the robustness of the obtained background stress field with respect to the focal mechanism uncertainty, we repeated the depth dependent background stress inversions using only declustered focal mechanisms with Qualities A and B ($<35^\circ$ nodal plane uncertainty). The corresponding results (Figure S3) confirm the reported stress field variations indicating that the fault plane uncertainties do not strongly affect the results. However, to maximize the resolution, we utilize the inversions obtained from Qualities A–D for the purpose of this study. Moreover, the average misfit angle of the inverted declustered mechanisms with Qualities A to D, for all the depth sections is $\sim 18.2^\circ$, with a standard deviation of 7.1° . When only using Qualities A and B, the average misfit angle is $\sim 14.6^\circ$ with a standard deviation of 5.4° . The similarity between the misfit angles supports using Qualities A to D mechanisms in the study.

5. Discussion

We examine spatiotemporal variations of the stress field in the plate-boundary region around the SCTR based on inversions of earthquake focal mechanisms, and attempt to interpret the results in relation to different loadings, fault properties, topography, and crustal depth. The primary analyzed data set is a declustered catalog of earthquake focal mechanisms in Southern California from 1981 to 2017 and is used to derive the background stress fields in different scales of space and time. We also invert separately focal mechanisms of aftershocks that are generally triggered by stress transfers from the mainshocks. Comparisons between inversion results based on the declustered seismicity and aftershocks allow us to infer dominant local loading mechanisms that exist in different crustal volumes in addition to the large-scale tectonic loading.

On a regional scale, the background stress field inverted from the declustered catalog (Figures 3 and 4) are generally consistent with previous studies, showing transtensional stress regime in the ECSZ moving toward strike-slip regime near the SCTR and further transpressional stress regime in the WTR and Los Angeles basin (Hardebeck & Hauksson, 2001; Yang & Hauksson, 2013). The S_{Hmax} trends show NNE direction near the ECSZ and the WTR (Figure 3) in agreement with the regional S_{Hmax} directions in Southern California (Yang & Hauksson, 2013). Although the main expected regional stress field is strike-slip faulting, detailed analysis including inversions over distinct geological regions show clear transpressional and transtensional stress regimes near the SBM, CH, SGP, and CP in the SCTR, which suggest additional stress component associated with local structures.

The stress inversion results based on the declustered catalog in the SBM show an average S_{Hmax} trend of $N7^\circ W$ (Figure S1). Yang and Hauksson (2013) estimated S_{Hmax} variations toward the NNW in this area and presented a schematic model of the ECSZ and SAF movements near CP, with a wedge-shaped area of SBM having counter clockwise loading. This scenario can induce compressional stress components near SBM that are observed ($R \sim 0.6$) in the inversion results of this study (Figure 6). However, the stress field estimated from the aftershocks does not show the NNW rotation of the S_{Hmax} direction and the transpressional stress components, indicating that the proposed loading in the SBM accounts only for a small fraction of the total background loading in this area.

Previous observations found normal stress near the CH area (Abolfathian et al., 2019; Hardebeck & Hauksson, 2001; Yang & Hauksson, 2013). Several studies connected the deeper seismicity and increase of normal faulting in the northern SJFZ with deep creeping below the seismogenic fault (Cooke & Beyer, 2018; Wdowinski, 2009). Our inversion results based on the declustered mechanisms are consistent

Figure 8. Variations of the stress ratio results versus elevation. The displayed elevations are the maximum associated value in each grid cell. The colors indicate derived stress ratios for different depth sections. The two dashed lines highlight the two end ranges of elevations. Indicated Depth Ranges are in 'km'.

with these inferences. The results of the background stress field provide the following lines of evidence that the SJFZ is weak near the bottom of the seismogenic zone in the CH area: (1) The inversion results indicate that the S_{Hmax} of the background stress field rotates clockwise below 10-km depth, with maximum rotation at 15 km where the S_{Hmax} trend is almost perpendicular to the main surface fault trace. (2) The estimated apparent coefficient of friction indicates a weak zone with an average μ of ~ 0.4 below 10-km depth compared to an average value of ~ 0.55 in the focused study area (brown box in Figure 1) (Abolfathian et al., 2019). (3) The maximum and intermediate principal stress plunges rotate more than 45° below ~ 12 -km depth (Abolfathian et al., 2019).

The stress inversions of aftershocks' mechanisms indicate transtensional $0 < R < 0.2$ stress components in the CH area (Figure 7). The aftershock results are consistent with the local background stress field estimated for the CH area rather than the regional strike-slip stress field. This suggests that the dominant loading in the CH area is associated with a local structure that may be associated, as suggested in previous studies, with creep below the seismogenic fault. Evidence for a wide damage zone below 10 km in this area (Ben-Zion & Zaliapin, 2019) suggests that the deep creep may be associated with a wide shear zone rather than aseismic slip on a fault interface.

In the SCTR region, the SAF is associated with significant bending of the main fault (~ 20 – 30°) and elevated terrain. The fault bending and topography produce perturbations of the intermediate (vertical) stress on a nonoptimally oriented fault (dipping fault) at seismogenic depth (Fialko et al., 2005). In the strike-slip regime, excess vertical stress will lead to normal faulting. To maintain balance with the regional strike-slip faulting, the fault will rotate to introduce compressional stress. The CP and SGP areas, located near elevated topography in the SCTR, are associated with transpressional stress fields. In the SGP area, the strike-slip faulting regime is dominant from the surface to 10-km depth, while transpressional stress components are significant below 10 km. The same stress pattern exists in the CP area, with significant transpressional stress components below ~ 5 km (Figure 4). Figure 8 displays the variations of the stress ratio and maximum surface elevation in each inverted grid cell. To better illustrate the relation between stress ratios and elevation, we focus on the longitude range -117.6° to -116.5° . A linear regression of the results has a

p -value of <0.0001 and R -squared value of 25%. The obtained p -value and R -squared values indicate that there is a significant relationship between the two variables and that 25% of the stress ratio variability may be explained by the topography. The stress ratios at the two ends of the elevation range are especially notable. Locations with elevations <500 m have stress ratios of 3.5 or lower indicating transtension; in contrast, the stress ratios for elevation $>2,500$ m is 80% larger than 6.5 indicating transpression. The analysis shows that topography is one of the main sources of stress loading in this region.

The stress field estimated from the aftershock mechanisms in the SGP indicates higher compressional, $0.8 < R < 1$, stress components (Figure 7) and is in agreement with the loading from the topography rather than the regional strike-slip stress field, suggesting that the dominant stress field near SGP is associated with the topography (e.g., Fialko et al., 2005). In contrast, no evidence of compressional stress components is observed in the stress field inverted from the aftershock mechanisms near CP; this may be due to the fewer available aftershock mechanisms in this area.

Large contrasts in the stress field and seismicity depth are observed across the junction between the SAF and SJFZ near CP. To the northwest of the junction in the San Gabriel Mountains, the dominant stress field is transpressional ($R \sim 0.9$), while to the southeast, the dominant stress field is transtensional ($R \sim 0.2$) and the average S_{Hmax} direction rotates more than 15° . The seismogenic depth varies by ~ 7 km from northwest to southeast of the SAF and SJFZ junction. These variations occur over a distance less than 20 km, implying strong effects of fault properties on the stress field and the importance of high-resolution analysis of the stress field of the type done in this study.

Results of stress ratios inverted from the background seismicity in five separate time intervals of ~ 8 years between 1981 and 2017 are overall consistent with the discussed stress ratio variations for the combined 1981 and 2017 data, showing compressional stress components near high topography and tensional stress components near CH. The time interval 1986–1993 produces the largest transpressional stress components near the SGP area, where two transpressional events with magnitudes M_w 5.6 and 5.0 occurred in 1986 and 1988 (Figure S2).

Earthquake ruptures produce rock damage in their source volume (e.g., Aben et al., 2019; Lockner et al., 1992; Lyakhovsky et al., 1997). The evolution of rock damage can modify the properties and dynamics of fault zones on a geological time scale (e.g., Ben-Zion & Sammis, 2003). Estimated rock damage production by ongoing background seismicity in Southern California shows several prominent damage zones (Ben-Zion & Zaliapin, 2019). The SJFZ and the SCTR, especially near major fault junctions (CP and SGP), are among the regions with the highest relative damage production, and the seismicity and rock damage become more pronounced and continuous with depth. The depth ranges with high concentration of seismicity and rock damage near CH, SGP, and CP areas are consistent with the depth range of the highest transpressional and transtensional stress components.

The Moho has significant depth variations below the SCTR (Ozakin & Ben-Zion, 2015; Zhu & Kanamori, 2000), and several studies discussed the association of Moho depth changes with enhanced generation of rock damage and reduced ability of faults to localize in the upper brittle crust (Lyakhovsky & Ben-Zion, 2009; Ben-Zion & Zaliapin, 2019). Earthquakes in such areas are expected to be distributed in space and exhibit a high diversity of mechanisms as observed near the SCTR. All three faulting types (strike-slip, reverse, and normal) estimated from focal mechanisms of the declustered events exist in the entire SCTR, with increased number of normal and reverse faulting around CH and CP areas, respectively (Figure S4). The dip-slip events near the SCTR comprise a smaller fraction of the background seismicity than the strike-slip events and have mostly $M_w < 3.5$. The relatively small magnitudes of the dip-slip events suggest that they are mainly associated with off-fault damage zones rather than the main strike-slip plate-boundary faults. Another manifestation of complexity in the SCTR is that strike angles of the declustered focal mechanisms are distributed in a range of directions (Figure S4) with no clear relationship between the strike angles and faulting types.

Additional insights on dominant loading mechanisms and crustal stress parameters in different areas can be obtained by comparing the stress inversion results with surface strain rate from geodetic data in regions with/without topography and with/without inferred deep creep (e.g., Townend & Zoback, 2006). Deriving focal mechanisms for smaller events will allow stress inversions to be done using smaller areas

and time intervals, leading to better resolution of stress variations in space and time. Numerical simulations of stress/strain evolution in crustal models with different loadings, different fault geometries, and different in viscoelastic structures can aid the interpretation of results. These studies will be attempted in future work.

Data Availability Statement

The earthquake and focal mechanism catalogs used in the paper are available in the open source repository at Southern California Earthquake Data Center (<https://scedc.caltech.edu/research-tools/alt-2011-yang-hauksson-shearer.html>). The employed data set is provided in the supporting information.

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