Structural properties of the Southern San Andreas Fault system near Coachella Valley from magnetotelluric imaging

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1. Introduction

Structural properties of the Southern San Andreas Fault (SSAF) system at depth in Coachella Valley remain enigmatic despite several attempts at imaging fault structure in the area (e.g. Barak et al., 2015; Share & Ben-Zion 2016; Fuis et al. 2017; Ajala et al., 2019). One of several outstanding questions is whether the SSAF is vertical (SCEC-CFM5.2, Nicholson et al., 2018) or dipping to the northeast (Fialko 2006; Fuis et al. 2012), like the neighboring SAF section in San Gorgonio Pass (Fig. 1a). Much of our inability to adequately address this question stems from the lack of everyday seismicity along the SSAF (Ross et al. 2019a), which is usually used to capture fault geometry directly (e.g. Carena et al., 2004; Ross et al. 2019b), or as part of a tomographic inversion to image fault zone seismic velocities at high resolution (e.g. Allam & Ben-Zion; Share et al. 2019). The SSAF has not produced an M > 7.5 event over the past ~300 years and is estimated to pose the largest seismic risk in California (e.g. Weldon et al. 2005; Field et al. 2017). Properties such as fault geometry and damage play a major role in the expected seismic shaking from such a future large earthquake (Fialko 2006; Roten et al. 2015). Further work using newly applied geophysical tools is needed to help constrain SSAF properties and the associated seismic hazard, and, reveal the mechanisms behind its relative aseismic (Fig. 1a).

Here, we use an established electromagnetic imaging tool, namely magnetotellurics (MT, e.g., Cagnaird 1953), that does not depend on analyses of the irregular patterns (or lack) of seismicity, to image for the first time the electrical conductivity structure of the SSAF and complement earlier works. MT has been successfully used to infer fault zone properties such as amount of damage, fluid content, geometry and strain conditions in, for example, central California (e.g., Bedrosian et al. 2004; Becken et al. 2011), Japan (Ogawa & Honkura 2004; Yoshimura et al. 2009) and Turkey (Turkoglu et al. 2008). Despite these successes, MT is yet to be applied to fault zones in Southern California.

In this study, we apply MT imaging to a section of the SSAF in the northern Coachella Valley near the Thousand Palms Oasis Preserve (Fig. 1b, http://coachellavalleypreserve.org). The presence of several oases along the SSAF surface traces (e.g., Mission Creek and Banning strands, Fig. 1b) is indicative of a fault system acting as a conduit and/or barrier for aqueous fluids, making it an appropriate MT target. We employ data from a 2019 linear array transecting the SSAF near the Preserve supplemented by stations from a neighboring 2017-2018 array located in the Joshua Tree National Park (Fig. 1a) to constrain electric properties of the fault in the area. Local seismicity predominantly occurs at mid-crustal depths and ~10 km to the northeast of the SSAF surface trace (Fig. 1a). By analyzing array data that span the fault surface traces and a significant area to the northeast allows us to investigate the evolution of the electric fault zone and its connection to seismic activity at depth in the northeast.

2. Data and Methods

The MT imaging is based on ~1-day long recordings of natural variations in the Earth’s electromagnetic field at 27 sites crossing the SSAF in 2019 and 6 sites located in Joshua Tree in 2018 (Fig. 1a). These sites were acquired using the Zonge ZEN system. The ZEN system records continuously for ~8 hours at 256 sps with 10 minute burst sampling at 4096 sps separating consecutive 8 hour recording windows. Accompanying the 2019 survey was a magnetic remote reference (Clarke et al. 1983) installed in the Borrego Desert (33.271608° N 116.064469° W). This site consisted of two Scripps BF-4 coils recording the horizontal field continuously at 500
sps for the weeklong survey period. Given the depths of investigation in this study and that >500 sps data do not exist for the remote reference site, we exclude the 4096 sps ZEN data from further analysis. For uniformity, all ZEN data are up sampled to 500 sps and reformatted to conform to the remote reference data.

**Figure 1:** Study area in the context of the Southern San Andreas Fault (SSAF). (a) Major fault traces at the surface (black lines) and contours along the SSAF planes from shallow (yellow) to 14 km depth (green) extracted from the SCEC-CFM5.2 (Nicholson et al. 2018). The SSAF to the southeast is estimated to be vertical and has no contours. Secondary faults are associated with the dipping structures northeast of this SSAF section. Magnetotelluric (MT) stations acquired in 2019 and in the Joshua Tree National Park during 2017-2018 are depicted by red and green triangles. Larger triangles show stations used in the 2D inversion. Colored dots are local earthquakes from the Ross et al. (2019a) catalog (yellow to green colors indicate depth). Magenta dots are events that highlight a major fault bimaterial interface at depth (Share & Ben-Zion, 2016). Note the relative lack of seismicity beneath the SSAF and especially near the study area. San Gorgonio Pass (SGP), the Eastern California Shear Zone (ECSZ) and the town of Palm Springs (PS) are shown for reference. (b) Zoom in of blue box in (a) showing the MT profile transecting the SSAF, which consists of the Banning, Mission Creek and other minor faults in the area. The blue arrow shows the location of a large across-fault change in electric conductivity (Figs 2&3). The Thousand Palms Oasis Preserve Visitor Center is located at the origin and the green crosses show water sample locations.

Next, time series are inspected and trimmed where needed to remove times containing spurious noise signals. The time series are then transformed to the frequency domain and for each day the frequency coefficients of all stations overlapping in time (including the remote reference for the 2019 data) are used with the robust multi-station processing code of Egbert (1997) to produce MT impedances and induction vectors/tippers (ratio of vertical to horizontal magnetic fields; Parkinson 1959). The sampling rate used and the recording period of ~1 day allows reliable responses to be computed within the 0.01-1000 s range.

Given the linear nature of the MT array, that most structural changes for the mature SSAF system is anticipated in the across-fault direction and the large topographic gradient in the study area (22 m to 1495 m), we invert the responses using the MARE2DEM 2D finite-element algorithm with adaptive meshing that can accommodate well the irregular topography (Key 2016). Prior to inversion an appropriate strike angle is determined through analyses of the tipper azimuths and phase tensors (Caldwell et al. 2004).

**3. Results**
Following visual inspection of the calculated impedances and tippers, 20% of the impedance data and 16% of the tipper data (not all stations had vertical magnetometers) are considered
outliers and removed (Fig. 2a). The outliers are generally associated with longest periods where the number of data points per frequency is at a minimum and with stations in the southwest located near the Coachella Valley center where cultural noise is most pronounced (Fig. 2a). The cultural noise affects the electric field recordings more than the magnetic field; thus, tipper data exists at several stations/periods in the southwest where impedances are unreliable.

**Figure 2**: Phase tipper and tensor results. (a) Phase tensor ellipses and real tipper vectors (maroon arrows, Parkinson convention) of all data after outliers (gaps) were removed. The degree of ellipticity equals the difference between Phimin and Phimax, the black lines inside ellipses point to calculated strike (alpha) and the orientation of the major axes of ellipses relative to strike and the shading of the ellipses equals beta (see Caldwell et al. 2004 for details). The coordinate frame is the same as in Fig. 1b. (b) Histograms of all strike (top) and real tipper azimuths (bottom) for all data up to 50 s. The dashed lines show the coordinate frame used (same as (a)).

Phase tensors and tippers provide indicators of the structural characteristics of the SSAF (Fig. 2). Around the Mission Creek fault strand and shallow depths (<1 s) structure is predominantly 1D, as evidenced by the near circular phase tensors. This area probably consists of a shallow layer(s) of damage rock and unconsolidated sediments, a characteristic of the internal structure of a mature fault zone. After rotating the local coordinate system to the average strike of the SSAF (130°/310° E of N, Fig. 1b), the properties of the phase tensor ellipses and tippers show the fault conductivity structures mostly align with fault coordinates. At periods ~1-50 s around the Mission Creek fault the phase tensors become more elliptical, have <5° beta angles and uniformly align with the fault strike direction (median strike/alpha = 322°, Fig. 2b top). These properties highlight 2D dimensionality at upper to mid crustal depths with geoelectric strike near parallel to the SSAF surface trace. This is corroborated by a ~90° flip in beta <5° phase tensor orientations (median strike/alpha = 25°, Fig. 2b top) for stations northeast of m14-15 (arrow in Figs 1b and 2a), an indication that a prominent fault parallel electric interface has been crossed and the largest phase has changed from transverse electric (TE, largest on resistive side) to transverse magnetic (TM, largest on conductive side) modes. At periods up to 50 s, the largest tippers (real part) point in the fault normal direction (median azimuth = 42°/222° E of N, Fig. 2b bottom), further evidence of geoelectric strike being approximately equal to fault strike. Moreover, the tippers point (Parkinson convention) toward a region of high conductivity beneath the Banning and Mission Creek faults (Fig. 2a), most likely related to a fluid-filled zone of deformation and damage with the sharp electric contrast around m14-15 representing the northeastern edge of this damage zone. At periods >50 s, beta angles >5° characterize impedances.
recorded in the southwest. Furthermore, moving from southwest to northeast, there is a progressive rotation of phase tensor ellipses and tippers to angles that are oblique to SSAF strike, revealing a large-scale 3D conductor at greater depth. This rotation starts at lower periods (~5 s) for stations in the northeast, highlighting again a resistive region with larger skin depth compared to stations atop the SSAF. It also explains why the median phase tensor strike angle for northeast stations is 15° less than the fault normal direction (Fig. 2b top).

Taking together, the median of all phase tensor strike (alpha) and real tipper angles up to a period of ~50 s (Fig. 2b) define a coordinate system where X=311.4° (along fault) and Y=41.4° (across fault). The impedances and tippers are rotated accordingly and >50 s data are excluded from 2D modeling as these contain information about 3D features deeper than the seismogenic crust. To constrain better these conductivities and the geometry of the SSAF system, we next invert these data using MARE2DEM. The impedances and tippers of all except the 5 southwestern most stations are assigned error floors of 10% and 0.02. Given the greater noise and 3D nature of the southwest stations (Fig. 2a), we assign error floors of 15% and 0.03 to their impedances and tippers. A target misfit of rms=1 is set at the start of the inversion and a horizontal to vertical smoothing ratio of 0.5 is selected to highlight expected vertical fault related features. Of the 33 sites, 17 were identified as having static shifts (Jiracek 1990). Inversion for static shifts is activated for the 17 sites and the inversion is started with a homogenous 100 Ω.m subsurface model. From a starting rms=9.6, the inversion converges to an rms~1.65 after 13 iterations with only incremental decreases in rms after that. So, a new target misfit of rms=1.65 is set and the model after 13 iterations is used as the new starting model, and the inversion is restarted. After a total of 18 iterations the smoothest model with an rms=1.65 is achieved (Fig. 3).

Three crustal electrical conductivity regions characterize the obtained model. First, a complex region of average to high conductivity (minimum~1 Ω.m, C1&C2) exists in the southwest and terminates at a sharp change in conductivity extending from ~2 km northeast of the Mission Creek fault near the surface to beneath the Banning fault in the lower crust. The high conductivities in this zone are comparable to those in the central SAF (Bedrosian et al. 2004; Becken et al. 2011). Second, northeast of this contact the crust is mostly resistive (maximum~10,000 Ω.m, R1&R2). Finally, there exists a conductor, smaller in scale than the first, located at >10 km depth beneath the most elevated part of the Little San Bernardino Mountains in Joshua National Park (C3).

4. Interpretations and discussion

Establishing properties related to structure and strain along the SSAF is essential for quantifying the potential and likely magnitude of a future large earthquake in the area. Fault geometrical irregularities such as discontinuities, bends and shallow dips generally hinder (but may also facilitate) rupture propagation and subsequently influence earthquake magnitudes (King & Nabelek 1985; Wesnousky 2006; 2008). Rupture along dipping fault segments can produce 2-3 times larger ground shaking in the hanging wall compared to the footwall (e.g., Fialko 2006). Strain distributed on several neighboring faults instead of a primary fault, influences the likelihood of multi-fault rupture and the extent of the resulting ground motion (e.g., Lozos 2016).

The results obtained here provide insight into these topics as they relate to this section of the SSAF (Fig. 3). Anomaly C1 is complicated in shape and amplitude given that it corresponds to aqueous fluid interactions along and between the Banning, Mission Creek and other minor faults, each striking differently near the surface (Fig. 1b). It is largest in amplitude within the top 3 km and decreases below 5 km depth. We interpret the latter decrease to be caused by a decrease in the number and size of fluid-filled pores within a fractured fault zone undergoing increasing normal stress with increasing depth. A potential steep northeast dip of C1 is consistent with the dip of the shallow SSAF south of the study area estimated from episodic creep events (Tymofyeyeva et al. 2019). The emergence of conductor C2 at depths >10 km is attributed to the transition from brittle to ductile behavior in the Coachella Valley (Magistrale 2002; Smith-Kanter
et al. 2011) and a change in pore-space geometry as deep creep causes fluids to become highly interconnected (Gough 1986; Wannamaker et al. 2008). The data also constrain a vertical resistor R1 that extends into the lower crust. The high resistivities of R1 reveal rocks that are relatively dry and contain only minor amounts of interconnected conductive minerals. Interestingly, the majority of seismicity in this area locates within R1 and is closer to conductor C3 than C1 or C2. We suggest C3 is a secondary fluid rich creeping zone in the ductile crust that, together with deformation along the SSAF, drives brittle failure (earthquakes) in the resistive and mechanically stronger crust above it (R1&R2). This correlation between brittle failure and high resistivity has been observed along other major faults (Bedrosian et al. 2004; Gurer & Bayrak 2007).

![Figure 3: Electrical resistivity (conductivity) along the acquired MT profile. Final 2D inverted model with prominent conductors (C1-C3) and resistors (R1-R2) marked. Magenta circles are events from the Ross et al. (2019a) catalog within 3 km of the 2D plane.](image)

Taken together, the imaged anomalies and seismicity distribution support fault geometry as documented in the SCEC-CFM5.2 (Nicholson et al. 2018). The simplest interpretation of Fig. 3 is that the SSAF system at depth acts either as a barrier to fluid flow (e.g., Bedrosian et al. 2004) and locates along the contact between conductors C1/C2 and resistor R1, or, as a conduit (e.g., Becken et al. 2011) and lies somewhere within the core of the conductive zone containing C1 and C2. Irrespectively, both of these scenarios suggest a vertical or steeply dipping SSAF system in the northern Coachella Valley. Therefore, the seismicity in R1 is associated with secondary or ancestral faults to the northeast (Fig. 1a), which do not act as major conduits for aqueous fluids. Finally, we hypothesize that observed interseismic strain accumulation (Fialko 2006; Lindsey & Fialko 2013) will be more consistent with a near vertical SSAF, if these secondary faults and conductor C3 are explicitly accounted for in geodetic data modeling. A vertical SSAF plus a second dislocation point located at the contact between the base of seismicity in R1 and C3 will probably (1) better fit the observed asymmetric long-term deformation profiles across the SSAF and (2) reduce the required slip rate along a vertical SSAF from >20 mm/yr (Lindsey & Fialko 2013) to <20 mm/yr, which coincides better with paleoseismic estimates (e.g., Behr et al. 2010). The mechanisms responsible for the minimal microseismicity along the SSAF proper, especially around this study area with complex faulting, remain unclear. It is well documented that the shallow SSAF has been creeping consistently since the last major earthquake ~300 ago (Sieh & Williams 1990) and episodically in response to remote large earthquakes (e.g., Lindsey et al. 2014; Tymofyeyeva et al. 2019). The imaged SSAF is also more consistent with the creeping section of the Parkfield SAF (than the nearby locked section), where a conductive fluid source in the ductile crust connects with a fault zone conductor in the brittle crust (Becken et al. 2011). Therefore, accumulated elastic strain is being released by aseismic processes throughout the crust and helps explain the lack of strain released by brittle failure along the SSAF proper.
References


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