



Structural properties of the Southern San Andreas fault zone in northern Coachella Valley from magnetotelluric imaging

Journal:	<i>Geophysical Journal International</i>
Manuscript ID	GJI-S-21-1108.R1
Manuscript Type:	Research Paper
Date Submitted by the Author:	n/a
Complete List of Authors:	Share, Pieter-Ewald; University of California San Diego Peacock, Jared; US Geological Survey Menlo Park Campus Constable, Steve; Scripps Institution of Oceanography, IGPP Vernon, Frank; IGPP/UCSD Wang, Shunguo; NTNU, ; Uppsala universitet
Keywords:	Electrical properties < GEOMAGNETISM and ELECTROMAGNETISM, Magnetotellurics < GEOMAGNETISM and ELECTROMAGNETISM, Fractures, faults, and high strain deformation zones < TECTONOPHYSICS, Continental tectonics: strike-slip and transform < TECTONOPHYSICS
Additional Keywords:	

1
2
3
4 1
5 2 **Structural properties of the Southern San Andreas fault zone in northern**
6 2
7 3 **Coachella Valley from magnetotelluric imaging**
8 3
9
10 4
11
12

13 5 Pieter-Ewald Share^{1*}, Jared R. Peacock², Steven Constable¹, Frank L. Vernon¹ and
14 5
15 6 Shunguo Wang³
16 6
17
18
19 7
20 7
21

22 8 ¹Institute of Geophysics and Planetary Physics, University of California San Diego, La
23 8
24 9 Jolla, CA
25 9
26

27 10 ²Geology, Minerals, Energy, and Geophysics Science Center, USGS, Moffett Field, CA
28 10
29

30 11 ³Department of Electronic Systems, Norwegian University of Science and Technology,
31 11
32 12 Trondheim, Norway
33 12
34

35 13 ^{*}Now at College of Earth, Ocean, and Atmospheric Sciences, Oregon State University,
36 13
37 14 Corvallis, OR
38 14
39

40 15
41 15
42
43 16 Corresponding author: Pieter-Ewald Share (pieter.share@oregonstate.edu)
44 16

45 17 *Geophysical Journal International 2022, in review*
46 17
47

48 18
49 18
50 19
51 19
52 20 **Key words:** Continental tectonics: strike-slip and transform; Fractures, faults and high
53 20
54 21 strain deformation zones; Electrical properties; Magnetotellurics
55 21
56
57
58
59
60

22 Summary

23 The Southern San Andreas fault (SSAF) poses one of the largest seismic risks in
24 California. Yet, there is much ambiguity regarding its deeper structural properties around
25 Coachella Valley, in large part due to the relative paucity of everyday seismicity. Here, we
26 image a multi-stranded section of the SSAF using a non-seismic method, namely
27 magnetotelluric soundings (MT), to help inform depth-dependent fault zone geometry,
28 fluid content, and porosity. The acquired MT data and resultant inversion models highlight
29 a conductive column encompassing the SSAF zone that includes a 2-3 km wide vertical to
30 steeply northeast dipping conductor down to ~ 4 km depth (maximum of $\sim 1 \Omega \cdot \text{m}$ at 2 km
31 depth) and another prominent conductor in the ductile crust ($\sim 1 \Omega \cdot \text{m}$ at 12 km depth and
32 slightly southwest of the surface SSAF). We estimate porosities of 18-44% for the
33 conductive uppermost 500 m, 10-15% porosity at 2 km depth and that small amounts (0.1-
34 3%) of highly interconnected saline fluids produce the deeper conductor. Located northeast
35 of this conductive region is mostly resistive crust indicating dry crystalline rock that
36 extends down to ~ 20 km in places. Most of the local seismicity is associated with this
37 resistive region. Located farther northeast still is a conductive region at >13 km depth and
38 separate from the one in the southwest. The imaged anomalies permit two interpretations.
39 The SSAF zone is vertical to steeply northeast dipping in the upper crust and (1) is near
40 vertical at greater depth creating mostly an impermeable barrier for northeast fluid
41 migration or (2) continues to dip northeast but is relatively dry and resistive up to ~ 13 km
42 depth where it manifests as a secondary deep ductile crustal conductor. We prefer
43 interpretation (1), but more MT investigations are required.

44

1. Introduction

The Southern San Andreas Fault (SSAF) has not produced a $M>7.5$ event for >300 years and is estimated to pose one of the largest seismic risks in California (Weldon et al. 2005; Sieh & Williams 1990). Several properties of the SSAF such as fault zone damage, geometry, and fluid content remain poorly understood despite several geoscientific studies (e.g., Catchings et al. 2009; Lindsey & Fialko 2013; Ajala et al. 2019). Informing these properties is essential as they may play key roles in the magnitude and subsequent shaking from future large events (e.g., Roten et al. 2015; Biasi & Wesnousky 2016).

One outstanding question is whether the SSAF at depth, if well localized as expected for a mature plate margin (Montési 2013), is near vertical or dipping to the northeast. In the Southern California Earthquake Center Community Fault Model (SCEC-CFM5.2, Nicholson et al. 2017) it is mapped as a vertical fault in the Coachella Valley (Fig. 1a). In contrast, analyses of interseismic strain fields (Fialko 2006; Tymofyeyeva et al. 2019) and potential field data (Fuis et al. 2012; 2017; Langenheim & Fuis 2021) point to a northeast dipping SSAF similar to its neighboring strand in San Geronio Pass (Fig. 1a), the latter being well constrained by small to moderate sized events (Jones et al. 1986; Nicholson 1996). A deep northeast dipping SSAF is supported by more abundant seismicity on that side of the surface SSAF, and a large structure with a prominent seismic velocity contrast (bimaterial interface) intersecting this seismicity (Fig. 1a, Share & Ben-Zion 2016). However, these features can also be attributed to secondary faults in the northeast (Fig. 1a, Nicholson et al. 2017). Much of our inability to resolve this fundamental question about deeper SSAF structure is owed to the general lack of seismicity in the region (Ross et al. 2019), which is essential to delineate fault geometry (e.g., Magistrale & Sanders 1996;

1
2
3 68 Carena et al. 2004) or in high-resolution seismic imaging studies (e.g., Share et al. 2019).
4
5 69 Thus, more studies using non-seismic geophysical tools are needed to help inform SSAF
6
7
8 70 properties and its associated seismic risk.
9

10
11 71 Here, we use an established electromagnetic imaging method, namely magnetotelluric
12
13 72 soundings (MT, Cagnaird 1953), that does not depend on seismicity (or paucity thereof as
14
15 73 in the study region) as a source, to image for the first time the electrical resistivity structure
16
17 74 of the SSAF throughout the crust. MT is a passive geophysical tool that measures
18
19 75 ubiquitous natural variations in the Earth's magnetic field and induced electric fields
20
21 76 generated in the subsurface. Resistivity within the Earth is then derived from frequency-
22
23 77 dependent transfer functions (MT tensor) between magnetic and electric fields.
24
25
26

27 78 MT data are preferentially sensitive to high conductivity (inverse of resistivity) regions
28
29 79 within the Earth (Chave & Jones (2012) and references therein). Relative to the deeper
30
31 80 mantle continental crust is electrically resistive (Schwarz 1990) except for anomalous
32
33 81 regions where conductive materials (e.g., aqueous fluids, graphite, melts) form
34
35 82 interconnected networks (e.g., Bahr 1997). Thus, active crustal fault zones are optimal
36
37 83 targets for MT imaging, where damaged and deformed rocks create pathways for
38
39 84 conductive fluids to percolate through the crust, and strain localization forms a mechanism
40
41 85 to connect fluids within these weakened zones (Becken & Ritter 2012). Structure, damage,
42
43 86 and deformation need not always be symmetric about a fault core and interconnected fluids
44
45 87 can be distributed asymmetrically with little fluid migration across an impermeable fault
46
47 88 (e.g., Caine et al. 1996; Bedrosian et al. 2004). MT has been successfully used to infer fault
48
49 89 zone properties such as amount of damage, fluid content, geometry, and strain conditions
50
51 90 in central California (e.g., Becken et al. 2011; Tietze & Ritter 2013), Japan (Ogawa &
52
53
54
55
56
57
58
59
60

1
2
3 91 Honkura 2004; Yoshimura et al. 2009) and Turkey (Turkoglu et al. 2008). Despite these
4
5 92 successes, MT has yet been broadly applied in Southern California.
6
7

8 93 In this study, we apply MT imaging to a section of the SSAF in northern Coachella
9
10 94 Valley near the Thousand Palms Oasis Preserve where the Mission Creek and Banning
11
12 95 fault strands merge (Fig. 1b). Despite ongoing debate over which strand is more active in
13
14 96 present day, both are well located at the study site using offsets in landforms and lithology
15
16 97 and trenching data (e.g., Fumal et al. 2002; Blisniuk et al. 2021). Near the surface, these
17
18 98 strands together with other minor faults comprise a ~3 km wide SSAF zone embedded in
19
20 99 Pliocene and Pleistocene stratified rock with Coachella Valley Quaternary sediments to the
21
22 100 southwest (up to ~2 km thick in central Valley, Ajala et al. 2019), thinner sediments
23
24 101 immediately northeast of the Mission Creek strand and the Little San Bernardino
25
26 102 Mountains (pre-Cenozoic metamorphic and crystalline rocks) outcropping ~10 km farther
27
28 103 northeast (Rymer 2000). The presence of several oases indicates a fault zone acting as a
29
30 104 conduit and/or barrier for aqueous fluid flow (Catchings et al. 2009), making it an attractive
31
32 105 MT target. We collected data in 2019 along a linear array transecting the SSAF around the
33
34 106 Preserve supplemented by stations from a neighboring 2017-2018 array located in the
35
36 107 Joshua Tree National Park (Fig. 1a) to image electric resistivities in the area. The abundant
37
38 108 seismicity to the northeast is ~10 km from the Preserve and locates at 4-11 km depth (Fig.
39
40 109 1a). Analyzing MT data that span the SSAF zone and a significant area to the northeast
41
42 110 allows us to investigate fault zone resistivities and its connection to local seismicity.
43
44
45
46
47
48
49
50

51

52 112 **2. Data and Methods**

53
54
55
56
57
58
59
60

1
2
3 113 The MT imaging was based on ~1-day long recordings of natural variations in Earth's
4
5 114 electromagnetic field at 27 sites crossing the SSAF in 2019 and 6 sites located in Joshua
6
7
8 115 Tree in 2018 (Fig. 1a). These sites were acquired using the Zonge International 32-bit ZEN
9
10 116 data logger with ANT-4 magnetic induction coils and Borin Ag-AgCl electrodes with 50
11
12 117 m dipoles. The ZEN was programmed to record in a sequence that started with 256 Hz
13
14 118 sampling for 8 hours followed by a burst of 4096 Hz sampling for 10 minutes. This
15
16 119 sequence repeated several times within the ~1-day recording window. Accompanying the
17
18 120 2019 survey was a magnetic remote reference installed at a low-noise site in the Borrego
19
20 121 Desert (33.271608° N 116.064469° W, ~66 km away). This site consisted of a Scripps
21
22 122 marine data logger (Constable 2013) to which a GPS clock had been added, collecting data
23
24 123 from two EMI-BF4 induction coils oriented north-south and east-west. Magnetic north was
25
26 124 used for orientation during all installations. These recorded continuously at 500 Hz for the
27
28 125 duration of the weeklong survey. Given the depths and scale of investigation in this study
29
30 126 and that >500 Hz data did not exist for the remote reference site, we excluded the 4096 Hz
31
32 127 ZEN data from further analysis. Without a remote reference and with coherent high-
33
34 128 frequency noise present across neighboring sites (spaced <500 m near the SSAF), the
35
36 129 single-station responses at these very high frequencies may have only yielded biased
37
38 130 estimates of near-surface resistivities. To better limit very near-surface properties, water
39
40 131 samples from the local oases were collected (Fig. 1b) and their resistivities were measured
41
42 132 using a laboratory 4-electrode setup. Both samples had similar measured resistivities of 6.2
43
44 133 $\Omega\cdot\text{m}$ (18.6°C) and 5.9 $\Omega\cdot\text{m}$ (18.5°C). Finally, for uniformity, all ZEN data were upsampled
45
46 134 to 500 Hz and reformatted to conform to the Scripps marine data format.
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 135 Next, recorded time series were inspected and trimmed where needed to remove times
4
5 136 with spurious noise. The time series were then transformed to the frequency domain and
6
7 137 the frequency coefficients of all stations overlapping in time (including the remote
8
9 138 reference) were processed with the code of Egbert (1997) to produce robust MT
10
11 139 impedances and induction vectors/tippers (Parkinson 1959). The 500 Hz sampling and the
12
13 140 recording period of ~ 1 day allowed reliable responses to be computed within the ~ 0.01 -
14
15 141 2000 s range. The use of the Borrego Desert remote reference significantly improved data
16
17 142 quality for some sites.

18
19
20
21 143 Following visual inspection of the calculated impedances and tippers, 20% of the
22
23 144 impedance data and 16% of the tipper were considered outliers and removed (Fig. 2a). The
24
25 145 outliers were generally associated with longest periods (fewer data points per frequency)
26
27 146 and southwestern most stations located near the central Coachella Valley where cultural
28
29 147 noise was most pronounced (Fig. 2a). This noise affected the electric field recordings more
30
31 148 than the magnetic field; thus, tipper data existed at several southwest stations/periods where
32
33 149 impedances were otherwise unreliable.

34
35
36
37 150 Given the linear nature of the MT array aligned in a southwest-northeast direction
38
39 151 where most fault zone structural changes are expected, and the large topographic gradient
40
41 152 in the area (22 m to 1495 m), we inverted the responses using the MARE2DEM 2D finite-
42
43 153 element algorithm with adaptive meshing that accommodates well irregular topography
44
45 154 (Key 2016). Prior to inversion an appropriate strike angle was determined through analyses
46
47 155 of the tipper azimuths and phase tensors (Caldwell et al. 2004).
48
49
50

51 156

52 53 54 157 **3. Data Analysis**

1
2
3 158 Frequency-dependent phase tensors and tippers provide indicators of the structural
4
5 159 characteristics in the area (Figs 2 & S1). Around the Mission Creek strand and shallow
6
7 160 depths (<1 s) structure is predominantly 1D, as evidenced by the near circular phase tensors
8
9 161 and relatively small tippers. This near surface region probably consists of a shallow layer(s)
10
11 162 of damage rock and unconsolidated sediments characteristic of an active fault zone
12
13 163 (Blisniuk et al. 2021; Share et al. 2022). After rotating the local coordinate system to the
14
15 164 average strike of the Banning and Mission Creek strands ($130^{\circ}/310^{\circ}$ E of N, Fig. 1b), the
16
17 165 properties of the phase tensor ellipses and tippers show that fault zone geoelectric structures
18
19 166 mostly align with fault orientation. At periods ~ 1 -50 s around the Mission Creek strand the
20
21 167 phase tensors become elliptical, have $<5^{\circ}$ beta angles and uniformly align with average
22
23 168 fault strike (median strike/ $\alpha=322^{\circ}$, Fig. 2b top). These properties highlight 2D
24
25 169 dimensionality at upper to mid crustal depths with geoelectric strike near parallel to average
26
27 170 fault strike. This is corroborated by a $\sim 90^{\circ}$ flip in beta $<5^{\circ}$ phase tensor orientations
28
29 171 (median strike/ $\alpha=25^{\circ}$, Fig. 2b top) northeast of stations m14-15 (arrow in Figs 1b and
30
31 172 2a), an indication that a prominent fault parallel electric interface has been crossed and the
32
33 173 mode with largest phase has flipped from transverse magnetic (TM, southwest conductive
34
35 174 side) to transverse electric (TE, northeast resistive side) (Fig. 3). Along the entire profile
36
37 175 and for periods up to 50 s, the largest tippers (real part) align with the fault normal (median
38
39 176 azimuth= $42^{\circ}/222^{\circ}$ E of N, Fig. 2b bottom), further evidence of geoelectric strike
40
41 177 approximating fault strike. Moreover, the tippers point (Parkinson convention) toward a
42
43 178 region of high conductivity within the SSAF zone (Fig. 2a), most likely related to a fluid-
44
45 179 rich region of deformation and damage with the sharp electric contrast around stations
46
47 180 m14-15 representing its northeastern edge. At periods >10 s, beta angles start to increase
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 181 for impedances recorded in the southwest, which may indicate 3D structure but also reflects
4
5 182 the noisy nature of these data. Across the array there is a progressive rotation of phase
6
7
8 183 tensor ellipses and tippers at long periods away from average fault strike (or the fault
9
10 184 normal), revealing a deep large-scale 3D plate boundary conductor to the northeast (Fig.
11
12 185 S1). This rotation starts at lower periods (~ 5 s) for northeast stations, highlighting again a
13
14 186 resistive region with larger skin depth compared to the conductive fault zone. It also causes
15
16
17 187 a median strike angle of 15° less than the fault normal for stations in the northeast (Fig. 2b
18
19 188 top). Taken together, the median of all phase tensor strike (α) and real tipper angles up
20
21 189 to a period of ~ 50 s (Fig. 2b) defines a coordinate system with $X=311.4^\circ$ (along fault) and
22
23 190 $Y=41.4^\circ$ (across fault). Consequently, the impedances and tippers were rotated and >50 s
24
25
26 191 data excluded from 2D modeling as these express 3D features.
27
28
29 192

30 31 193 **4. 2D Inversion**

32
33 194 In pseudosections of the rotated data (Fig. 3a), a broad region of high conductivity
34
35 195 encompasses the SSAF zone, with average resistivities to the southwest and highest
36
37 196 resistivities beneath stations in the northeast. To properly image the area and delineate
38
39 197 SSAF structures, we inverted these data using MARE2DEM. The inversion model space
40
41 198 consisted of a ~ 37 km long surface profile with the Mission Creek strand/Thousand Palms
42
43 199 Oasis at $Y=0$ km (Fig. 4) that included local topography (from Smith & Sandwell 1997)
44
45 200 and onto which the 33 station locations were projected. Beyond this 37 km profile,
46
47 201 topography was set to be flat and extended from $Y=-1,000$ km to $Y=1,000$ km. We fixed
48
49 202 the resistivity of the air above the surface to $100,000 \Omega.m$ and beneath the surface the initial
50
51
52 203 value was set to $100 \Omega.m$. The latter extended down to a depth of $1,000$ km. From the
53
54
55
56
57
58
59
60

1
2
3 204 surface to ~500 m depth beneath the stations the inversion mesh triangles had a target
4
5 205 length of 200 m (see Key (2016) for details). Given the dense station spacing (Fig. 1b) and
6
7
8 206 expected high conductivities of an active fault zone (Fig. 3a), we assigned a target length
9
10 207 of 500 m to the mesh from $Y=-5$ km to $+5$ km and down to 5 km depth. Outside that zone
11
12 208 and down to 10 km depth the target length was 1 km, which then gradually increased to 5
13
14 209 km at 50 km depth and 100 km on either side of the 37 km profile. Beyond that the mesh
15
16
17 210 triangles increased without a specified target length to the edges of the model space.

18
19 211 The impedances and tippers of all except the 5 southwestern most stations were
20
21 212 assigned error floors of 10% and 0.02, respectively. To the more 3D and/or noisy data in
22
23 213 the southwest (Fig. 2a), we assigned error floors of 15% and 0.03. To test the resolution
24
25 214 capabilities of these data plus errors, we constructed synthetic tests using hypothetical fault
26
27 215 models, data calculated at the same frequencies and locations as the recorded data, and the
28
29 216 same inversion mesh (Fig. S2). The test cases all included a $10 \Omega.m$ 2 km wide fault zone
30
31 217 but with attitudes varying from a vertical fault zone to one with a shallow dip of 30° to the
32
33 218 northeast (Fig. S2). By keeping the fault zone width and resistivity constant these tests
34
35 219 demonstrate the variable lateral and depth resolutions of the data and methodology. The
36
37 220 resultant inversions (Fig. S2) after adding Gaussian noise of 10% (impedances) and 0.02
38
39 221 (tippers) to the synthetic data suggest the recorded data are well suited to distinguish
40
41 222 between these different fault zone geometries.

42
43 223 Next, MARE2DEM was used to invert the recorded data. A target misfit of $rms=1$ was
44
45 224 set at the start of the inversion and a horizontal to vertical smoothing ratio of 0.5 was
46
47 225 selected to highlight expected vertical fault related features (Fig. S2). The MARE2DEM
48
49 226 algorithm attempts to reach the target misfit as fast as possible and then afterwards
50
51
52
53
54
55
56
57
58
59
60

1
2
3 227 determines the smoothest model at that misfit (see Key (2016)). The first inversion was run
4
5 228 without inverting for the static shifts produced by shallow small-scale features (e.g.,
6
7 229 structural heterogeneities, sedimentation/groundwater changes, etc.) and irregular
8
9 230 topography. After a few iterations (~5) the inversion was stopped to inspect which of the
10
11 231 sites may be affected by static shift. These were identified as sites that had low misfits for
12
13 232 TE and TM mode phases and TM mode apparent resistivity but had a parallel shift between
14
15 233 the TE mode apparent resistivity data and modeled responses. Of the 33 sites, 17 were
16
17 234 identified in this manner as having static shifts. Inversion for static shifts was activated for
18
19 235 the 17 sites and the inversion restarted with a homogenous 100 Ω .m subsurface. From a
20
21 236 starting rms=9.6, the inversion achieved an rms=1.65 after 13 iterations with only
22
23 237 incremental improvements after that. Because the initial target of rms=1 was not reached,
24
25 238 the model obtained at rms=1.65 was not necessarily the smoothest for that misfit. So, a new
26
27 239 target misfit of rms=1.65 was set and the model after 13 iterations was used as the new
28
29 240 starting model, and the inversion restarted. After a total of 18 iterations, the smoothest
30
31 241 model (Key 2016) with an rms=1.65 was obtained (Fig. 4). The difference between Figs
32
33 242 3a and 3b, and Fig. S3 illustrate how this misfit maps to the different sites and frequencies.
34
35
36
37
38
39

40 243 Three crustal resistivity regions characterize this model. First, a complex region of
41
42 244 average to high conductivity (minima of ~1 Ω .m at 2 km depth and 12 km depth, C1&C2)
43
44 245 exists in the southwest and terminates at a sharp change in resistivity extending from ~2
45
46 246 km northeast of the surface Mission Creek strand to beneath the Banning strand in the
47
48 247 ductile crust. The modeled values in this zone are comparable to those of the central San
49
50 248 Andreas fault (Bedrosian et al. 2004; Becken et al. 2011). Second, the crust is mostly
51
52 249 resistive northeast of this contrast reaching a maximum of ~10,000 Ω .m in places
53
54
55
56
57
58
59
60

1
2
3 250 (R1&R2). Finally, there exists a conductor, separate from C2, at >13 km depth beneath the
4
5 251 most elevated part of the Little San Bernardino Mountains in the Joshua Tree National Park
6
7 252 (C3). These features' general characteristics do not change with changes in model
8
9 253 smoothing or strike of the 2D profile and associated rotations of data responses (Fig. S4).
10
11

12 254 Given that some regions in the model space are more poorly resolved than others, such
13
14 255 as near surface areas with less station coverage, greater depths in general, and regions
15
16 256 beneath conductors (e.g., Chave & Jones 2012), we applied a few conductance-preserving
17
18 257 (conductivity-thickness product) alterations of particularly C1-C3 to test if small changes
19
20 258 in their properties are allowed without significantly affecting the misfit (i.e., changes within
21
22 259 the nullspace, Munoz & Rath 2006). MT data are most sensitive to changes in conductance
23
24 260 rather than conductivity, so by preserving conductance these tests highlight how changes
25
26 261 in the geometries and locations of C1-C3 affect data misfit. They also provide an indication
27
28 262 of their relative influence on misfit and, therefore, the relative data sensitivity to these
29
30 263 conductive parts of the model space. In general, the tests show that only small changes in
31
32 264 C1-C3 are allowed without significantly increasing the model misfit (Fig. 5). Specifically,
33
34 265 the steep northeast dipping geometry of anomaly C1 is well resolved as a more vertically
35
36 266 orientated structure in the inverted model increases the rms to ~1.8 (Fig. 5). And, the
37
38 267 resistive region separating C2 and C3 is similarly well resolved as extensions of either C2
39
40 268 or C3 towards the other lead to large increases in rms (Fig. 5). For example, extending C2
41
42 269 only 6 km to the northeast produces the same significant increase in rms as removing it
43
44 270 from the inverted model altogether (Fig. 5).
45
46
47
48
49
50

51 271 The model in Fig. 4 is our preferred result as it is equally well constrained by TE, TM
52
53 272 and tipper data (Fig. S3) and the majority of that data at periods <50 s is 2D in nature with
54
55
56
57
58
59
60

1
2
3 273 a consistent near fault-parallel strike (Fig. 2). However, as noted in Section 3, even at <50
4
5 274 s some stations and periods exhibit 3D characteristics, e.g., at the southwestern and
6
7
8 275 northeastern sites (Fig. 2). As a supplement and to test the effects of these minor 3D
9
10 276 features in a predominantly 2D upper to mid crustal region, we additionally applied a 2D
11
12 277 determinant inversion (Pedersen & Engels 2005; Wang et al. 2020; 2021). This type of
13
14 278 inversion has been shown to produce a less-distorted 2D model representations of a
15
16 279 predominantly 2D region that also includes 3D structures (Wang et al. 2020). However,
17
18 280 this lower distortion comes at the cost of larger model smoothness. The algorithm
19
20 281 employed is embedded in the MARE2DEM package, which facilitates comparison with
21
22 282 Fig. 4. During inversion, we used the same impedance tensor data (not tippers), matching
23
24 283 errors, and the model and inversion settings described above. Overall, all our resultant
25
26 284 determinant inversion models were consistent with Fig. 4. In fact, even when we included
27
28 285 data from all available periods, which constituted a significant increase in 3D data, the
29
30 286 determinant inversion result was still comparable to Fig. 4 (Fig. S5-S6). In Fig. S5,
31
32 287 anomalies C1-3 and R1-2 are all present, albeit the fact that C2 is more conductive and
33
34 288 extends to shallower depths, and the region containing R1, R2 and C3 is generally smoother
35
36 289 with R1-2 lower in resistivity and C3 smeared towards the northeast where there is less
37
38 290 station coverage and the data at longest periods reflect 3D structure (Figs 2 & S1).

39
40 291 As a final reliability test on the inference of a mostly 2D subsurface, a 3D inversion
41
42 292 was also carried out using all available data and with the ModEM finite difference code
43
44 293 (Kelbert et al. 2014). The features of the 3D model were consistent with our 2D inversions,
45
46 294 but lacked the resolution of the MARE2DEM finite element code. These determinant and
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 295 3D inversions demonstrate that our 2D modeling approach applied to a limited dataset is
4
5 296 justified and features in the resultant 2D model (Fig. 4) can be reliably interpreted.
6
7

8 297

9 298 **5. Discussion**

10 299 Establishing properties related to structure and strain along the SSAF in Coachella
11
12 300 Valley is essential for quantifying the potential magnitude and hazard of future large
13
14 301 earthquakes. Fault geometrical irregularities play key roles in rupture propagation and
15
16 302 subsequently earthquake magnitudes (e.g., Biasi & Wesnousky 2016). Rupture along
17
18 303 dipping faults can produce 2-3 times larger ground shaking in the hanging wall compared
19
20 304 to the footwall (Fialko 2006). Strain distributed on several neighboring fault strands instead
21
22 305 of a primary fault, influences the likelihood of multi-fault rupture and the extent of the
23
24 306 resulting ground motion (Lozos 2016).
25
26
27
28
29

30 307 The results presented here provide insight into these topics as they relate to the SSAF
31
32 308 in the northern Coachella Valley (Fig. 4). Anomaly C1 represents the broad SSAF zone
33
34 309 (~3 km wide at the surface) in the upper crust. This near-surface width is corroborated by
35
36 310 the present of several anomalous fault damage-related structures within that same ~3 km-
37
38 311 wide zone as revealed by analysis of large-N seismic array data (Share et al. 2022). It
39
40 312 extends to ~4 km depth with largest amplitude at 2 km and locates northeast of the central
41
42 313 Coachella Valley, which implies its vertical to steep northeast dip is fault and not Valley
43
44 314 basin controlled (Fig 4). If the Banning and Mission Creek strands predominantly constrain
45
46 315 C1's geometry, then they likely have similar vertical to northeast dips at upper crustal
47
48 316 depths (Catchings et al. 2009; Chi et al. 2021; Langenheim & Fuis 2021). The emergence
49
50 317 of conductor C2 at depths >10 km is attributed to the transition from brittle to ductile
51
52
53
54
55
56
57
58
59
60

1
2
3 318 behavior in the area (Magistrale 2002; Smith-Konter et al. 2011) and a change in pore-
4
5 319 space geometry as deep creep causes minute amounts of migrating fluid to become trapped
6
7
8 320 and highly interconnected (Gough 1986; Park et al. 1992; Wannamaker et al. 2008). These
9
10 321 deep fluids are likely sourced from the dehydrating metasediments and/or Peninsular
11
12 322 Ranges batholith underlying the Coachella Valley sediments. The modelled location of C2
13
14 323 5-10 km southwest of the surface Mission Creek strand has some uncertainty, because of
15
16 324 limited station coverage on that side. In contrast, greater station coverage northeast of the
17
18 325 Mission Creek results in lower uncertainty and better model resolution and the data do not
19
20 326 require C2 to extend significantly in that direction (Fig. 5). Instead, resistor R1 fits the data
21
22 327 best and extends near vertically down to ~20 km depth. The high resistivities of R1 suggest
23
24 328 relatively dry hard rock, most likely crystalline basement (Catchings et al. 2009; Ajala et
25
26 329 al. 2019), and in case these rocks do contain minor conductive materials, then those
27
28 330 materials are not well interconnected and/or exist on such a small scale that they are poorly
29
30 331 resolved with the MT frequencies employed. Interestingly, most of the seismicity in this
31
32 332 area locates within the more resistive parts of the model (Figs 4 & S5) and is closer to
33
34 333 conductor C3 than C1 or C2. We propose C3 is a separate fluid or mineral rich creeping
35
36 334 zone in the ductile crust that helps drive local earthquake activity in the more resistive and
37
38 335 mechanically stronger crust above it. This correlation between smaller scale brittle failure
39
40 336 and high resistivity has been observed along minor faults in central California (Bedrosian
41
42 337 et al. 2004) and in Turkey (Gurer & Bayrak 2007).

43
44 338 The uppermost 500 m of C1 has an average resistivity of 35 Ω .m (Fig. 4). Assuming
45
46 339 the ~6 Ω .m oases samples are representative of the type of fluids reducing the observed
47
48 340 resistivities in the shallow fault zone (they interact and react with similar materials) and
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 341 using Archie's law (Archie 1942), gives porosity estimates of 18% (n=1, highly
4
5 342 interconnected crack network) to 44% (n=2, partially connected pores) for the near surface.
6
7
8 343 The further decrease in the resistivity of C1 with depth (minimum of $\sim 1 \Omega.m$ at 2 km depth)
9
10 344 can only be explained by decreased fluid resistivities as porosities are expected to decrease
11
12 345 with depth also. We suggest two mechanisms driving this. The first is a rapid decrease in
13
14 346 fluid resistivity expected in the upper crust due to temperature and pressure increases with
15
16
17 347 depth, which can lead to more than an order of magnitude reduction (Nesbitt 1993).
18
19 348 Second, because of the influx of fresh water from the surrounding creeks and mountains,
20
21 349 the oases fluids represent an adequate but diluted (more resistive) proxy for the fluids
22
23 350 present at 2 km depth in the fault zone. These two factors can result in a reduction of fluid
24
25
26 351 resistivities to $< 1 \Omega.m$ and produce the observed C1 minimum resistivity if well
27
28 352 interconnected cracks with porosities of 10-15% are assumed (e.g., Unsworth et al. 1997;
29
30 353 Bedrosian et al. 2004). In the mid-crust porosities decrease even further, the effects of
31
32 354 increasing temperature and pressure become negligible (Nesbitt 1993) and observed
33
34 355 resistivities are subsequently higher (bottom of C1, Fig. 4). We do not have direct bounds
35
36 356 on the conductive material properties producing deeper conductors C2 and C3. Others have
37
38 357 suggested that lower crustal conductors in active tectonic settings with resistivities of ~ 1
39
40 358 $\Omega.m$ only require porosities of 0.1-3% if the highly interconnected in situ fluids have
41
42
43 359 salinities close to that of seawater (e.g., Gough 1986; Hyndman et al. 1993; Becken &
44
45 360 Ritter 2012). C2 and C3 (at least in part) are likely caused by similar mechanisms.

46
47 361 Taken together, the imaged anomalies and other geophysical inputs permit two
48
49 362 interpretations for fault zone geometries and processes (Fig. 4). The major strands of the
50
51
52 363 SSAF zone in the upper crust are vertical to steeply northeast dipping and (1) evolve into
53
54
55
56
57
58
59
60

1
2
3 364 a near vertical fault zone at greater depth that acts mostly as a barrier to northeast migration
4
5 365 of fluids sourced in the southwest. A mature fault zone with a well-developed core but
6
7 366 diminished damage and deformation zones (i.e., SSAF at mid-crustal depths) is likely to
8
9
10 367 be impermeable (Caine et al. 1996). This type of impermeability and asymmetric
11
12 368 distribution of crustal fluids about a major transform fault at depth have been observed
13
14
15 369 along, for example, the central San Andreas and the Dead Sea Transform (Ritter et al. 2003;
16
17 370 Bedrosian et al. 2004). Consequently, the seismicity in the northeast is associated with
18
19 371 secondary or ancestral faults (Fig. 1a) with small (<5%) associated seismic velocity
20
21 372 contrasts (Barak et al. 2015; Share & Ben-Zion 2016; Share et al. 2019). This is in line
22
23
24 373 with the SCEC-CFM5.2 and high-resolution geophysical imaging of the same fault strands
25
26 374 but 25 km to the northwest (Catchings et al. 2009). Or (2) the SSAF zone continues to dip
27
28 375 northeast at greater depth, accommodates some of the local seismicity, manifests as C3 in
29
30 376 the ductile crust but is either dry or consists of disconnected small-scale fluid-rich cracks
31
32
33 377 from ~5 to 13 km depth. These characteristics (2) are not indicative of a mature and active
34
35 378 transform fault that has probably experienced many large earthquake ruptures (Weldon et
36
37 379 al. 2005). And, it requires an alternate explanation for the imaged near vertical crustal
38
39
40 380 resistivity contrast beneath the surface SSAF zone that is not the active plate boundary.
41
42 381 However, (2) is consistent with estimates from geodetic (Fialko 2006; Lindsey & Fialko
43
44 382 2013; Tymofyeyeva et al. 2019) and potential field (Fuis et al. 2012; 2017; Langenheim &
45
46 383 Fuis 2021) data, the latter being most sensitive to structures at <10 km depth though.

49 384 An argument can be made for a non-simple broad deep SSAF zone that is a mix of (1)
50
51 385 and (2), but that would require a lack of kilometer-scale localization of ductile fault roots
52
53
54 386 (e.g., Montési 2013) driven by high crustal temperatures and low viscosities (Takeuchi &

1
2
3 387 Fialko 2013). However, heat flow at the site is on par with well-localized fault systems to
4
5 388 the north and west (Lachenbruch et al. 1985; Magistrale 2002) and it only starts increasing
6
7 389 farther south, as does the observed shallow creep of the SSAF (Sieh & Williams 1990;
8
9 390 Tymofyeyeva et al. 2019). Moreover, the deep crustal conductors imaged in this study,
10
11 391 inferred to represent ductile fault roots, are not connected but separated by well-resolved
12
13 392 resistive crust (Figs 4, 5, S4 & S5).
14
15
16
17 393

18 19 394 **6. Conclusions**

20
21 395 Our results permit two interpretations of the electric SSAF zone. It is vertical to steeply
22
23 396 northeast dipping in the upper crust and (1) is near vertical at greater depth creating mostly
24
25 397 an impermeable barrier for northeast fluid migration or (2) continues to dip northeast but
26
27 398 is anomalously dry and relatively resistive up to 13 km depth where it manifests as a
28
29 399 secondary deep crustal conductor. We prefer the deeper near vertical fault interpretation
30
31 400 (1) as it is the simplest explanation for the active SSAF zone. It is also consistent with other
32
33 401 major transform fault systems both in terms of resistivity and its complex shallow to
34
35 402 simpler deeper fault zone nature. In any case, the general lack of seismicity and presence
36
37 403 of shallow aseismic creep along parts of the Coachella Valley SSAF remain enigmatic.
38
39 404 More insights from MT and other geophysical tools are required including joint inversions,
40
41 405 which is beyond the scope of this focused study. As a start, we suggest several new across-
42
43 406 fault MT arrays in the area. To the southeast these will help establish the along-strike
44
45 407 continuity of anomalies C1-C3 and R1, respectively, and delineate changing fault zone
46
47 408 widths, geometries, and their connection to seismicity, heat flow and creep. To the
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 409 northwest more MT data will illuminate the large-scale 3D conductor identified in Figs 2a
4
5 410 & S1 and its relation to regional tectonics.
6
7

8 411

9
10 412 **Acknowledgements**

11
12 413 We thank Deborah Rogers and Ginny Short (Center for Natural Lands Management
13
14 414 and Thousand Palms Oasis Preserve), Brian Ousley (Bureau of Land Management), Tom
15
16 415 Anderson, Chris Schoneman and Alicia Thomas (Sonny Bono Salton Sea National Wildlife
17
18 416 Refuge), and Martin Alvarez (City of Palm Desert) for help with permitting and access to
19
20 417 the field sites. We also acknowledge graduate students Hannah Peterson and Rosslyn King
21
22 418 for their assistance during field work. We thank Kerry Key and Gary Egbert for their
23
24 419 analysis codes, and Yuri Fialko, Rasheed Ajala and Victoria Langenheim for useful
25
26 420 discussions. This work was supported by the Southern California Earthquake Center
27
28 421 (SCEC) Award #19200. P.-E. Share was also supported by a Green Foundation
29
30 422 Postdoctoral Fellowship (Institute of Geophysics and Planetary Physics/Scripps Institution
31
32 423 of Oceanography). S.Wang was funded by the Norwegian Research Council (294404,
33
34 424 309960, and 324442) and the National Infrastructure for High-Performance Computing
35
36 425 and Data Storage in Norway (nn9872k).
37
38
39
40
41
42
43

42 426

44
45 427 **Data Availability**

46
47 428 All data are publicly available through ScienceBase (<https://doi.org/10.5066/P990U7GE>).
48

49 429

50
51 430 **References**
52
53
54
55
56
57
58
59
60

- 1
2
3 431 Ajala, R., Persaud, P., Stock, J. M., Fuis, G. S., Hole, J. A., Goldman, M. R., & Scheirer,
4
5 432 D. S. (2019). Three-dimensional basin and fault structure from a detailed seismic
6
7 433 velocity model of Coachella Valley, Southern California. *Journal of Geophysical*
8
9 434 *Research*, 124(5), 4728-4750.
- 10
11
12
13 435 Archie, G. E. (1942). The Electrical Resistivity Log as an Aid in Determining Some
14
15 436 Reservoir Characteristics. *Transactions of the AIME*, 146(01), 54–62.
16
17 437 <https://doi.org/10.2118/942054-G>
- 18
19
20 438 Bahr, K. (1997). Electrical anisotropy and conductivity distribution functions of fractal
21
22 439 random networks and of the crust: the scale effect of connectivity. *Geophysical Journal*
23
24 440 *International*, 130, 649-660.
- 25
26
27
28 441 Barak, S., Klemperer, S. L., & Lawrence, J. F. (2015). San Andreas Fault dip, Peninsular
29
30 442 Ranges mafic lower crust and partial melt in the Salton Trough, Southern California,
31
32 443 from ambient-noise tomography. *Geochemistry Geophysics Geosystems*, 16, 3946-
33
34 444 3972.
- 35
36
37 445 Becken, M., & Ritter, O. (2012). Magnetotelluric studies at the San Andreas Fault Zone:
38
39 446 Implications for the role of fluids. *Surveys in Geophysics*, 33(1), 65-105.
- 40
41
42 447 Becken, M., Ritter, O., Bedrosian, P. A., & Weckmann, U. (2011). Correlation between
43
44 448 deep fluids, tremor and creep along the central San Andreas Fault. *Nature*, 480(7375),
45
46 449 87-90.
- 47
48
49
50 450 Bedrosian, P. A., Unsworth, M. J., Egbert, G. D., & Thurber, C. H. (2004). Geophysical
51
52 451 images of the creeping segment of the San Andreas Fault: implications for the role of
53
54 452 crustal fluids in the earthquake process. *Tectonophysics*, 385, 137-156.

- 1
2
3 453 Biasi, G. P., & Wesnousky, S. G. (2016). Steps and Gaps in Ground Ruptures: Empirical
4
5 454 Bounds on Rupture Propagation. *Bulletin of the Seismological Society of America*,
6
7 455 *106*(3), 1110–1124. <https://doi.org/10.1785/0120150175>
9
10
11 456 Blisniuk, K., Scharer, K., Sharp, W. D., Burgmann, R., Amos, C., & Rymer, M. (2021). A
12
13 457 revised position for the primary strand of the Pleistocene-Holocene San Andreas fault
14
15 458 in southern California. *Science Advances*, *7*(13), eaaz5691.
16
17 459 <https://doi.org/10.1126/sciadv.aaz5691>
19
20
21 460 Cagniard, L. (1953). Basic theory of the magneto-telluric method of geophysical
22
23 461 prospecting. *Geophysics*, *18*, 605-635.
24
25
26 462 Caine, J.S., Evans, J.P., & Forster, C.B. (1996). Fault zone architecture and permeability
27
28 463 structure. *Geology* *24*, 1025–1028.
29
30
31 464 Caldwell, T. G., Bibby, H. M., & Brown, C. (2004). The magnetotelluric phase tensor.
32
33 465 *Geophysical Journal International*, *158*, 457-469.
34
35
36 466 Carena, S., Suppe, J., & Kao, H. (2004). Lack of continuity of the San Andreas Fault in
37
38 467 southern California: Three-dimensional fault models and earthquake scenarios.
39
40 468 *Journal of Geophysical Research: Solid Earth*, *109*(B4).
41
42 469 <https://doi.org/https://doi.org/10.1029/2003JB002643>
43
44
45
46 470 Catchings, R. D., Rymer, M. J., Goldman, M. R., & Gandhok, G. (2009). San Andreas
47
48 471 Fault Geometry at Desert Hot Springs, California, and Its Effects on Earthquake
49
50 472 Hazards and Groundwater. *Bulletin of the Seismological Society of America*, *99*(4),
51
52 473 2190–2207. <https://doi.org/10.1785/0120080117>
53
54
55
56
57
58
59
60

- 1
2
3 474 Chave, A. D., & Jones, A. G. (Eds.) (2012). *The Magnetotelluric Method: Theory and*
4
5 475 *Practice*. Cambridge University Press. 552 pp.
6
7
8 476 Chi, B., Qiu, H., Share, P.-E., Vernon, F. L., & Ben-Zion, Y. (2021). Reverse-time
9
10 477 migration of fault zone reflected waves: Methodology and application to the Southern
11
12 478 San Andreas fault. *Seismological Research Letters*, 92 (2B), 1422.
13
14 479 <https://doi.org/10.1785/0220210025>
15
16
17
18 480 Constable, S. (2013). Review paper: Instrumentation for marine magnetotelluric and
19
20 481 controlled source electromagnetic sounding. *Geophysical Prospecting*, 61(s1), 505–
21
22 482 532. <https://doi.org/https://doi.org/10.1111/j.1365-2478.2012.01117.x>
23
24
25 483 Egbert, G. D. (1997). Robust multiple-station magnetotelluric data processing.
26
27 484 *Geophysical Journal International*, 130, 475-496.
28
29
30 485 Fialko, Y. (2006). Interseismic strain accumulation and the earthquake potential on the
31
32 486 southern San Andreas fault system. *Nature*, 441(7096), 968–971.
33
34 487 <https://doi.org/10.1038/nature04797>
35
36
37
38 488 Fuis, G. S., Scheirer, D. S., Langenheim, V. E., & Kohler, M. D. (2012). A new perspective
39
40 489 on the geometry of the San Andreas fault in southern California and its relationship to
41
42 490 lithospheric structure. *Bulletin of the Seismological Society of America*, 102(1), 236-
43
44 491 251.
45
46
47
48 492 Fuis, G. S., Bauer, K., Goldman, M. R., Ryberg, T., Langenheim, V. E., Scheirer, D. S.,
49
50 493 Rymer, M. J., Stock, J. M., Hole, J. A., Catchings, R. D., Graves, R. W., & Aagaard,
51
52 494 B. (2017). Subsurface geometry of the San Andreas Fault in Southern California:
53
54
55
56
57
58
59
60

- 1
2
3 495 Results from the Salton Seismic Imaging Project (SSIP) and strong ground motion
4
5 496 expectations. *Bulletin of the Seismological Society of America*, 107(3), 1642-1662.
6
7
8 497 Fumal, T. E., Rymer, M. J., & Seitz, G. G. (2002). Timing of Large Earthquakes since A.D.
9
10 498 800 on the Mission Creek Strand of the San Andreas Fault Zone at Thousand Palms
11
12 499 Oasis, near Palm Springs, California. *Bulletin of the Seismological Society of America*,
13
14 500 92(7), 2841–2860. <https://doi.org/10.1785/0120000609>
15
16
17
18 501 Gough, D. I. (1986). Seismic reflectors, conductivity, water and stress in the continental
19
20 502 crust. *Nature*, 323, 143-144.
21
22
23 503 Gurer, A., & Bayrak, M (2007). Relation between electrical resistivity and earthquake
24
25 504 generation in the crust of West Anatolia, Turkey. *Tectonophysics*, 445, 49-65.
26
27
28 505 Hyndman, R. D., Vanyan, L. L., Marquis, G., & Law, L. K. (1993). The origin of
29
30 506 electrically conductive lower continental crust: saline water or graphite? *Physics of*
31
32 507 *the Earth and Planetary Interiors*, 81(1), 325–345.
33
34
35 508 Jones, L. M., Hutton, L. K., Given, D. D., & Allen, C. R. (1986). The North Palm Springs,
36
37 509 California, earthquake sequence of July 1986, *Bulletin of the Seismological Society of*
38
39 510 *America*, 76, 1830–1837.
40
41
42
43 511 Kelbert, A., Meqbel, N., Egbert, G. D., & Tandon, K. (2014). ModEM: A modular system
44
45 512 for inversion of electromagnetic geophysical data. *Computers & Geosciences*, 66, 40–
46
47 513 53. <https://doi.org/https://doi.org/10.1016/j.cageo.2014.01.010>
48
49
50 514 Key, K. (2016). MARE2DEM: a 2-D inversion code for controlled-source electromagnetic
51
52 515 and magnetotelluric data. *Geophysical Journal International*, 207(1), 571-588.
53
54
55
56
57
58
59
60

- 1
2
3 516 Lachenbruch, A. H., Sass, J. H., & Galanis Jr., S. P. (1985). Heat flow in southernmost
4
5 517 California and the origin of the Salton Trough. *Journal of Geophysical Research: Solid*
6
7 518 *Earth*, 90(B8), 6709–6736. <https://doi.org/10.1029/JB090iB08p06709>
9
10 519 Langenheim, V. E., & Fuis, G. S. (2022). Insights into the geometry and evolution of the
11
12 520 southern San Andreas fault from geophysical data, southern
13
14 521 California. *Geosphere*, 18(2), 458–475.
15
16
17 522 Lindsey, E. O., & Fialko, Y. (2013). Geodetic slip rates in the southern San Andreas Fault
18
19 523 system: Effects of elastic heterogeneity and fault geometry. *Journal of Geophysical*
20
21 524 *Research*, 118, 689-697.
22
23
24 525 Lozos, J. C. (2016). A case for historic joint rupture of the San Andreas and San Jacinto
25
26 526 faults. *Science Advances*, 2(3), e1500621.
27
28
29 527 Magistrale, H., & Sanders, C. (1996), Evidence from precise earthquake hypocenters for
30
31 528 segmentation of the San Andreas fault in San Gorgonio Pass, *Journal of Geophysical*
32
33 529 *Research*, 101, 3031-3044.
34
35
36 530 Magistrale, H. (2002). Relative contributions of crustal temperature and composition to
37
38 531 controlling the depth of earthquakes in Southern California. *Geophysical Research*
39
40 532 *Letters*, 29(10), 1447.
41
42
43 533 Montési, L. G. J. (2013). Fabric development as the key for forming ductile shear zones
44
45 534 and enabling plate tectonics. *Journal of Structural Geology*, 50, 254–266.
46
47
48 535 Muñoz, G., & Rath, V. (2006). Beyond smooth inversion: the use of nullspace projection
49
50 536 for the exploration of non-uniqueness in MT. *Geophysical Journal*
51
52 537 *International*, 164(2), 301–311.
53
54
55
56
57
58
59
60

- 1
2
3 538 Nesbitt, B. E. (1993). Electrical resistivities of crustal fluids. *Journal of Geophysical*
4
5 539 *Research*, 98(B3), 4301-4310.
6
7
8 540 Nicholson, C. (1996). Seismic behavior of the southern San Andreas fault zone in the
9
10 541 northern Coachella Valley, California: Comparison of the 1948 and 1986 earthquake
11
12 542 sequences, *Bulletin of the Seismological Society of America*, 86, 1331–1349.
13
14
15 543 Nicholson, C., A. Plesch and J.H. Shaw (2017). Community Fault Model Version 5.2:
16
17 544 Updating & expanding the CFM 3D fault set and its associated fault database, 2017
18
19 545 *SCEC Annual Meeting Proceedings & Abstracts*, XXVII, poster 234, p.142-143.
20
21
22
23 546 Ogawa, Y., & Honkura, Y. (2004). Mid-crustal electrical conductors and their correlations
24
25 547 to seismicity and deformation at Itoigawa-Shizuoka tectonic line, Central Japan. *Earth*
26
27 548 *Planets Space*, 56, 1285-1291.
28
29
30 549 Park, S. K., Jiracek, G. R., & Johnson, K. M. (1992). Magnetotelluric evidence for a brittle-
31
32 550 ductile transition, peninsular ranges batholith, southern California? *Geophysical*
33
34 551 *Research Letters*, 19(21), 2143–2146. <https://doi.org/10.1029/92GL02439>
35
36
37
38 552 Parkinson, W. D. (1959). Directions of rapid geomagnetic fluctuations. *Geophysical*
39
40 553 *Journal of the Royal Astronomical Society*, 2(1), 1-14.
41
42
43 554 Pedersen, L. B., & Engels, M. (2005). Routine 2D inversion of magnetotelluric data using
44
45 555 the determinant of the impedance tensor. *GEOPHYSICS*, 70(2), G33–G41.
46
47
48 556 Ritter, O., Weckmann, U., Hoffmann-Rothe, A., Abueladas, A., Garfunkel, Z., & DESERT
49
50 557 Research Group (2003). Geophysical images of the Dead Sea Transform in Jordan
51
52 558 reveal an impermeable barrier for fluid flow. *Geophysical Research Letters*, 30.
53
54 559 <https://doi.org/10.1029/2003GL017541>
55
56
57
58
59
60

- 1
2
3 560 Roten, D., Olsen, K. B., Cui, Y. & Day, S. M., 2015. Quantification of fault zone plasticity
4
5 561 effects with spontaneous rupture simulations, in *Best Practices in Physics-based Fault*
6
7 562 *Rupture Models for Seismic Hazard Assessment of Nuclear Installations*, Vienna,
8
9 563 Austria.
- 10
11
12
13 564 Ross, Z. E., Trugman, D. T., Hauksson, E. & Shearer, P., (2019). Searching for hidden
14
15 565 earthquakes in Southern California, *Science*, 364(6442), 767-771.
- 16
17
18 566 Rymer, M. J. (2000). Triggered Surface Slips in the Coachella Valley Area Associated with
19
20 567 the 1992 Joshua Tree and Landers, California, Earthquakes. *Bulletin of the*
21
22 568 *Seismological Society of America*, 90(4), 832–848.
23
24 569 <https://doi.org/10.1785/0119980130>
- 25
26
27
28 570 Schwarz, G. (1990). Electrical conductivity of the earth's crust and upper mantle. *Surveys*
29
30 571 in *Geophysics*, 11, 133-161.
- 31
32
33 572 Share, P.-E., & Ben-Zion, Y. (2016). Bimaterial interfaces in the South San Andreas Fault
34
35 573 with opposite velocity contrasts NW and SE from San Gorgonio Pass. *Geophysical*
36
37 574 *Research Letters*, 43(20), 10680-10687.
- 38
39
40 575 Share, P.-E., Guo, H., Thurber, C. H., Zhang, H. & Ben-Zion, Y., 2019. Seismic imaging
41
42 576 of the Southern California plate-boundary around the South-Central Transverse
43
44 577 Ranges using double-difference tomography, *Pure and Applied Geophysics*, 176(3),
45
46 578 1117-1143.
- 47
48
49
50 579 Share, P., Qiu, H., Vernon, F. L., Allam, A. A., Fialko, Y., & Ben-Zion, Y. (2022). General
51
52 580 Seismic Architecture of the Southern San Andreas Fault Zone around the Thousand
53
54 581 Palms Oasis from a Large-N Nodal Array. *The Seismic Record*, 2(1), 50–58.

- 1
2
3 582 Sieh, K., & Williams, P. (1990). Behavior of the southernmost San Andreas fault during
4
5 583 the past 300 years. *Journal of Geophysical Research*, 95, 6629–6645.
6
7
8 584 Smith, W. H. F., & Sandwell, D. T. (1997). Global seafloor topography from satellite
9
10 585 altimetry and ship depth soundings. *Science*, 277, 1957–1962.
11
12
13 586 Smith-Konter, B. R., Sandwell, D. T., & Shearer, P. (2011). Locking depths estimated from
14
15 587 geodesy and seismology along the San Andreas Fault System: Implication for seismic
16
17 588 moment release. *Journal of Geophysical Research*, 116, B06401.
18
19
20
21 589 Takeuchi, C. S., & Fialko, Y. (2013). On the effects of thermally weakened ductile shear
22
23 590 zones on postseismic deformation. *Journal of Geophysical Research: Solid Earth*,
24
25 591 118(12), 6295–6310. [https://doi.org/https://doi.org/10.1002/2013JB010215](https://doi.org/10.1002/2013JB010215)
26
27
28 592 Tietze, K., & Ritter, O. (2013). Three-dimensional magnetotelluric inversion in practice—
29
30 593 the electrical conductivity structure of the San Andreas Fault in Central California.
31
32 594 *Geophysical Journal International*, 195(1), 130–147.
33
34 595 <https://doi.org/10.1093/gji/ggt234>
35
36
37
38 596 Turkoglu, E., Unsworth, M., Caglar, I., Tuncer, V., & Avsar, U. (2008). Lithospheric
39
40 597 structure of the Arabia-Eurasia collision zone in eastern Anatolia: magnetotelluric
41
42 598 evidence for widespread weakening by fluids? *Geology*, 36, 619–622.
43
44
45 599 Tymofyeyeva, E., Fialko, Y., Jiang, J., Xu, X., Sandwell, D., Bilham, R., Rockwell, T. K.,
46
47 600 Blanton, C., Burkett, F., Gontz, A., & Moafipoor, S. (2019). Slow slip event on the
48
49 601 southern San Andreas fault triggered by the 2017 M_w 8.2 Chiapas (Mexico)
50
51 602 earthquake. *Journal of Geophysical Research*, 124, B016765.
52
53
54
55
56
57
58
59
60

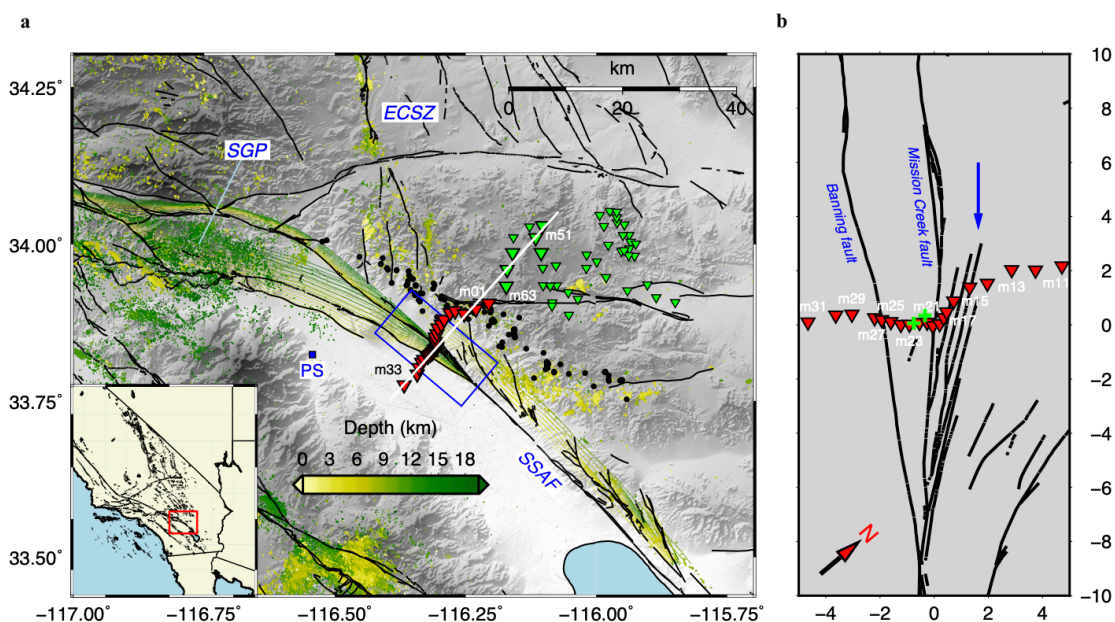
- 1
2
3 603 Unsworth, M. J., Malin, P. E., Egbert, G. D., & Booker, J. R. (1997). Internal structure of
4
5 604 the San Andreas fault at Parkfield, California. *Geology*, 25(4), 359–362.
6
7
8 605 Wang, S., Constable, S., Reyes-Ortega, V., Jahandari, H., Farquharson, C., & Avile-
9
10 606 Esquivel, T. (2020). Two-dimensional determinant inversion of marine
11
12 607 magnetotelluric data and a field example from the Gulf of California, Mexico.
13
14 608 *Geophysics*, 86, E37–E57.
15
16
17
18 609 Wang, S., Constable, S., Rychert, C. A., & Harmon, N. (2021). A lithosphere-
19
20 610 asthenosphere boundary and partial melt resolved using marine magnetotelluric data,
21
22 611 *Geochemistry Geophysics Geosystems*, 21, doi.org/10.1029/2020GC009177
23
24
25 612 Wannamaker, P. E., Hasterok, D. P., Johnston, J. M., Stodt, J. A., Hall, D. B., Sodergren,
26
27 613 T. L., Pellerin, L., Maris, V., Doerner, W. M., Groenewold, K. A., & Unsworth, M. J.
28
29 614 (2008). Lithospheric dismemberment and magmatic processes of the Great Basin-
30
31 615 Colorado Plateau transition, Utah, implied from magnetotellurics, *Geosystems*
32
33 616 *Geophysics Geochemistry*, 9, Q05019.
34
35
36
37
38 617 Weldon, R. J., Fumal, T. E., Biasi, G. P., Scharer, K. M. (2005). Past and future earthquakes
39
40 618 on the San Andreas fault, *Science*, 308, 966-967.
41
42
43 619 Yoshimura, R., Oshiman, N., Uyeshima, M., Toh, H., Uto, T., Kanezaki, H., Mochido, Y.,
44
45 620 Aizawa, K., Ogawa, Y., Nishitani, T., Sakanaka, S., Mishina, M., Satoh, H., Goto, T.,
46
47 621 Kasaya, T., Yamaguchi, S., Murakami, H., Mogi, T., Yamaya, Y., Harada, M.,
48
49 622 Shiozaki, I., Honkura, Y., Koyama, S., Nakao, S., Wada, Y., & Fujita, Y. (2009).
50
51 623 Magnetotelluric transect across the niigata-kobe tectonic zone, central Japan: a clear
52
53
54
55
56
57
58
59
60

624 correlation between strain accumulation and resistivity structure. Geophysical
 625 Research Letters, 36, L20311.

626

627

628



629

630 **Figure 1:** Study area in the context of the Southern San Andreas Fault (SSAF). (a) Fault traces at
 631 the surface (black lines) and contours along the SSAF planes from shallow (yellow) to 14 km depth
 632 (green) from the SCEC-CFM5.2 (see text). The SSAF strand accommodating most of the plate
 633 boundary strain to the south is estimated to be vertical and has no contours. Secondary or ancestral
 634 faults are associated with the dipping structures (contours) to the northeast. Magnetotelluric (MT)
 635 stations acquired in 2019 (red) and in the Joshua Tree National Park during 2017-2018 (green) are
 636 depicted by triangles. Larger triangles show stations used in the 2D inversion and the white line
 637 represents the inversion model transect in Fig. 4. Depth colored dots are local earthquakes from the
 638 Ross et al. (2019) catalog. Black dots are events illuminating a large bimaterial structure at depth.
 639 Note the relative lack of seismicity directly 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 zone, which consists of the Banning, Mission Creek, and other minor fault strands. The blue arrow shows the location of a large change in electric resistivity in the across-fault direction (same arrow appears in Figs 2-4). The Thousand Palms Oasis Preserve Visitor Center is located at the origin and the green crosses show the locations of two fluid samples taken from the oases.

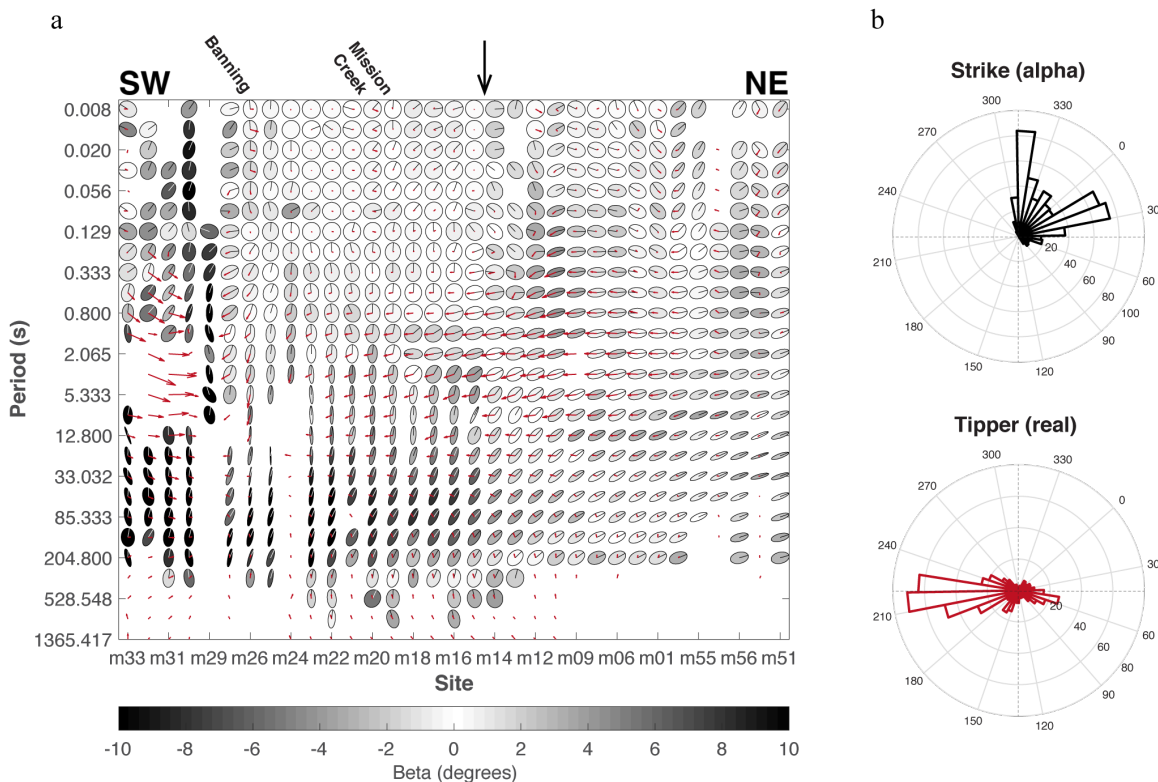
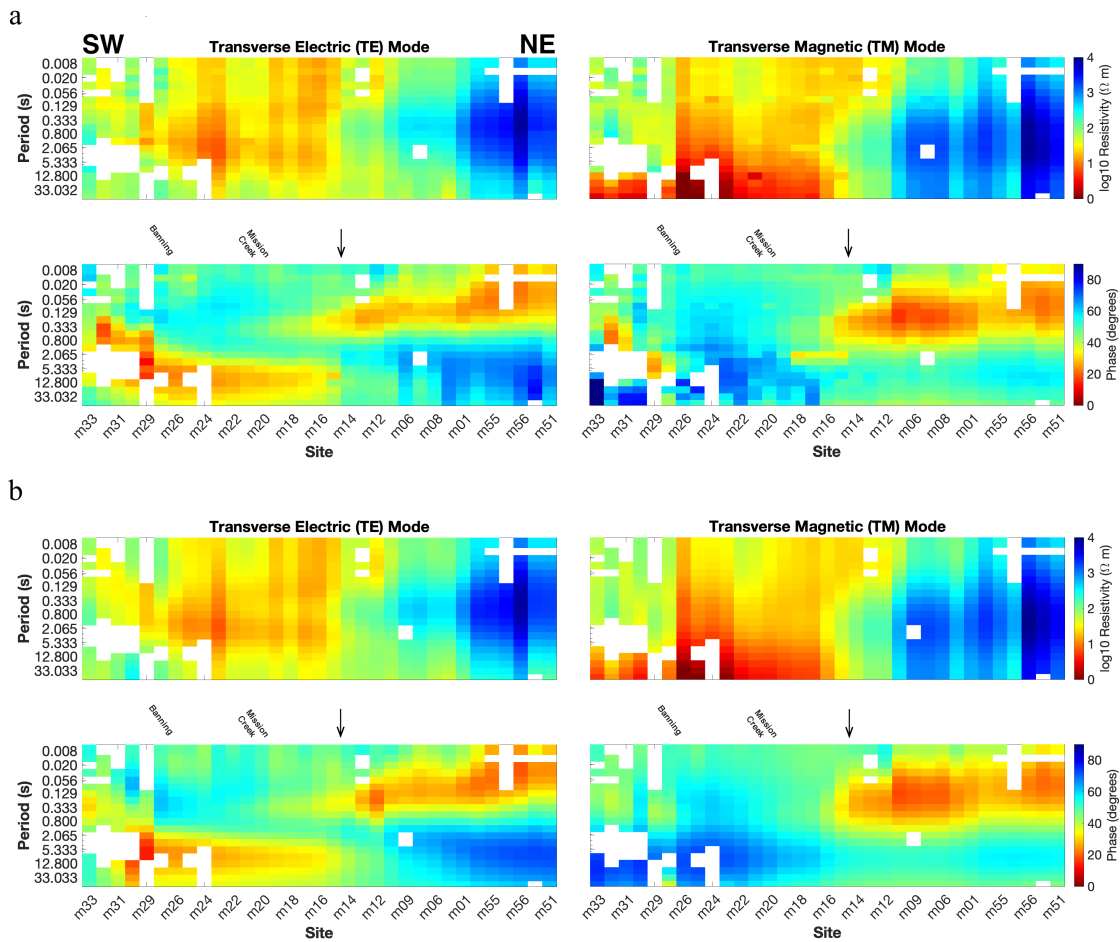


Figure 2: Phase tensor and tipper results. (a) Phase tensor ellipses and real tipper vectors (maroon arrows, Parkinson convention) of all data after outliers (gaps) were removed. The degree of ellipticity equals the difference between Φ -min and Φ -max, the black lines inside ellipses point to calculated strike (α) and the orientation of the major axes of ellipses relative to strike and the shading of the ellipses equals β . The coordinate frame is the same as in Fig. 1b. (b) Histograms of strike (top) and real tipper azimuths (bottom) for data up to 50 s. The dashed lines show the coordinate frame used (same as in (a)).

655

656



657

658 **Figure 3:** Pseudosections for the TE (left) and TM (right) modes up to 50 s period associated with

659 recorded (a) and modeled (b) data responses. The modeled data correspond to the inverted model

660 in Fig. 4. Differences between (a) and (b) are also illustrated in Fig. S3.

661

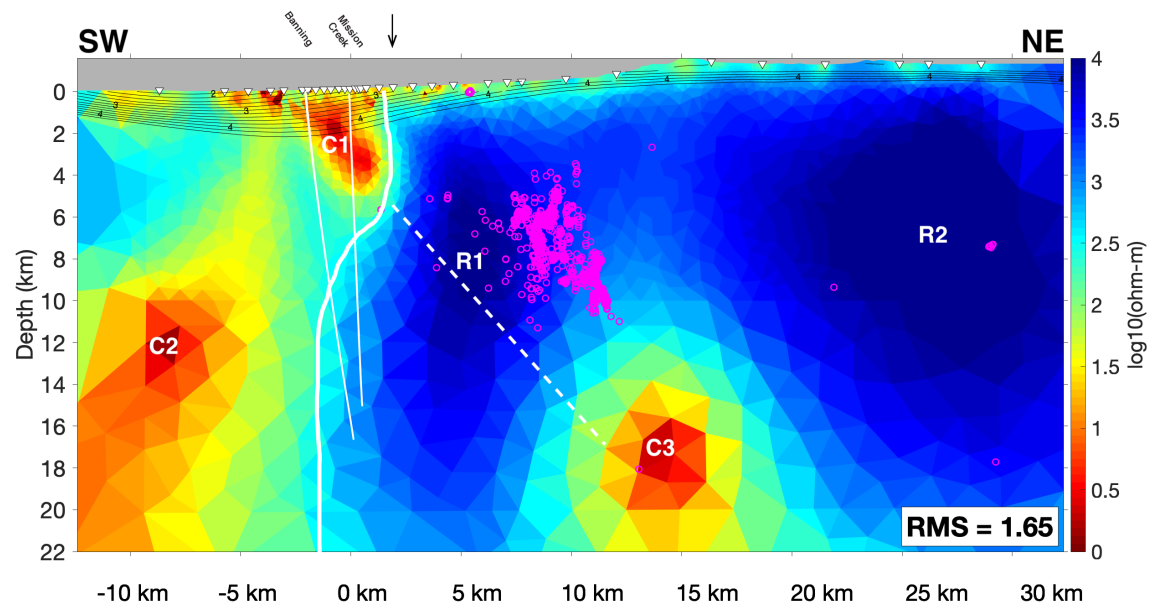
662

663

664

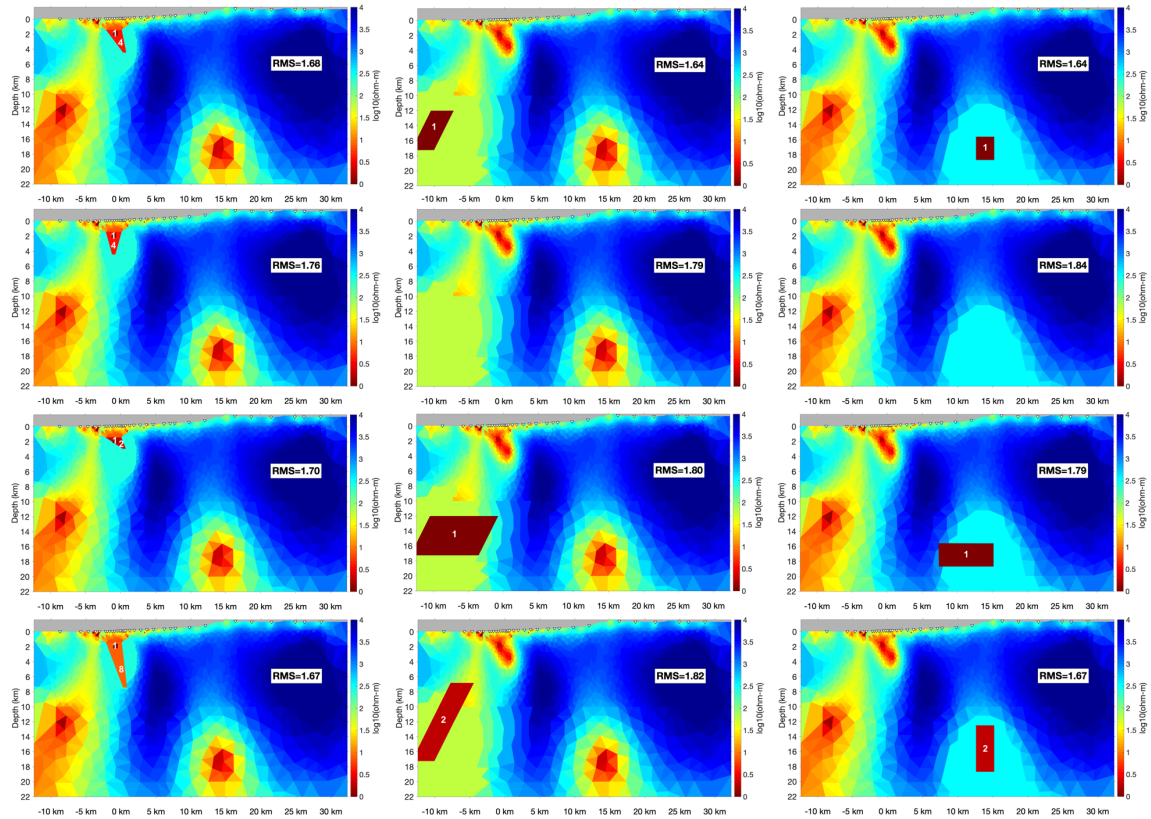
665

666



669

670 **Figure 4:** Final 2D inverted model with prominent conductors (C1-C3) and resistors (R1-R2)
 671 marked. Magenta circles are local earthquakes within 3 km of this 2D plane. The thick white line
 672 highlights a region of sharp resistivity change throughout the crust and represents one (and the
 673 preferred) interpretation for the location of the northeastern edge of the shallow SSAF zone and its
 674 near vertical geometry at greater depth. The nearby thinner white lines depict geometries of the
 675 Banning and Mission Creek strands from the SCEC-CFM5.2 (Fig. 1a). The dashed white line
 676 connecting C1 and C3 is an alternate interpretation of SSAF zone geometry at greater depth. Black
 677 contours are from the P-wave velocity model of Ajala et al. (2019) from 2 km/s to 4.4 km/s sampled
 678 at increments of 0.2 km/s and highlights mostly basin geometry in the central Coachella Valley.



679

680 **Figure 5:** Equivalent resistivity anomaly representations of conductors C1 (left column), C2
 681 (middle column) and C3 (right column) with similar misfits as in Fig. 4 (top row). Lower panels
 682 show removals, extensions and translations of these anomalies (all subsequent rows), and, the
 683 misfits associated with those alterations. Numbers inside anomalies represent resistivities in $\Omega.m$.

Supplemental Figures

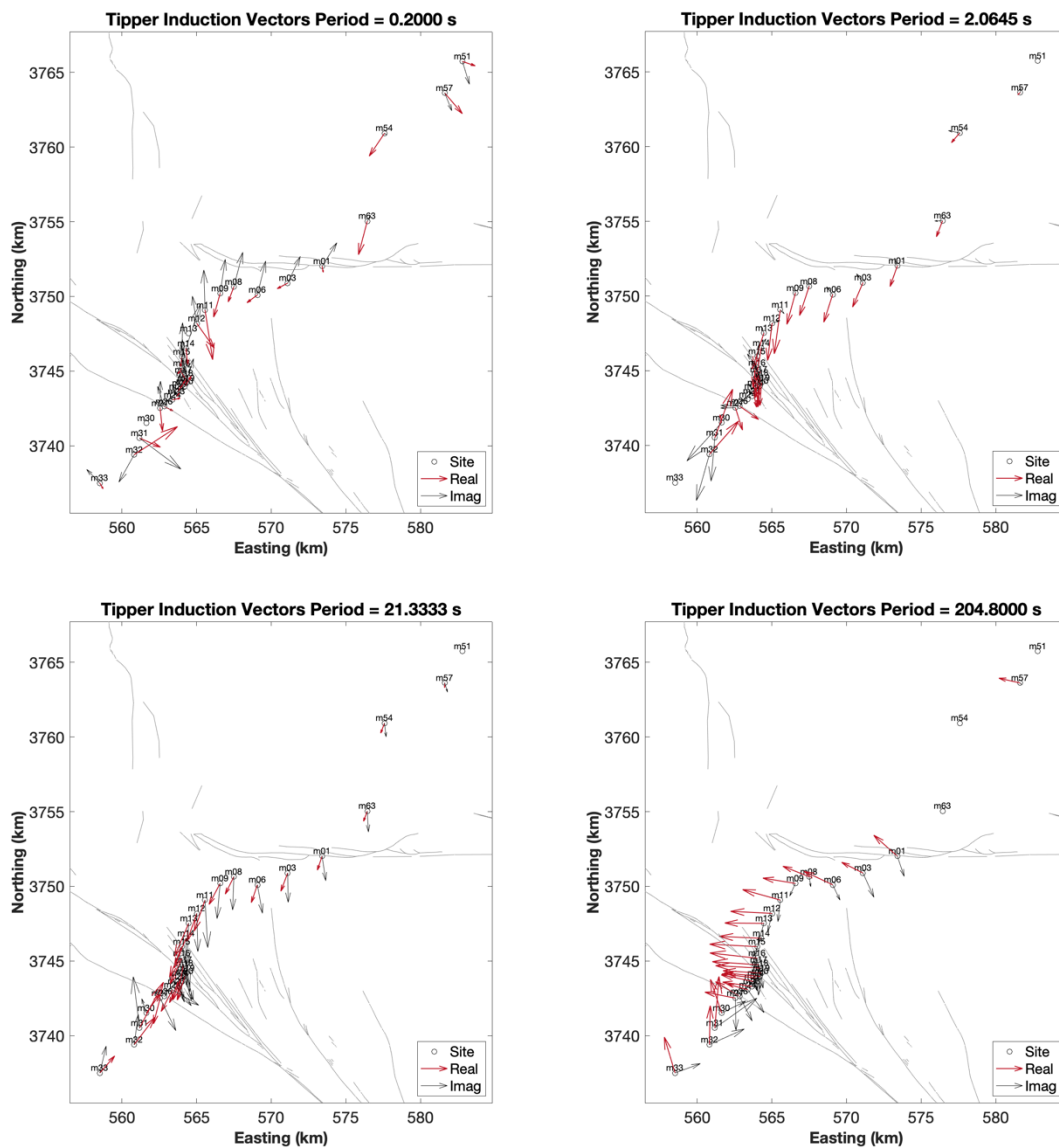


Figure S1: Tipper induction arrows (real-maroon, imaginary-black) from Fig. 2a at periods of approximately 0.2 s, 2 s, 20 s and 200 s plotted in map view. Note the rotation of real tippers away from the SSAF zone and towards a deep large-scale conductor in the northwest at longest periods.

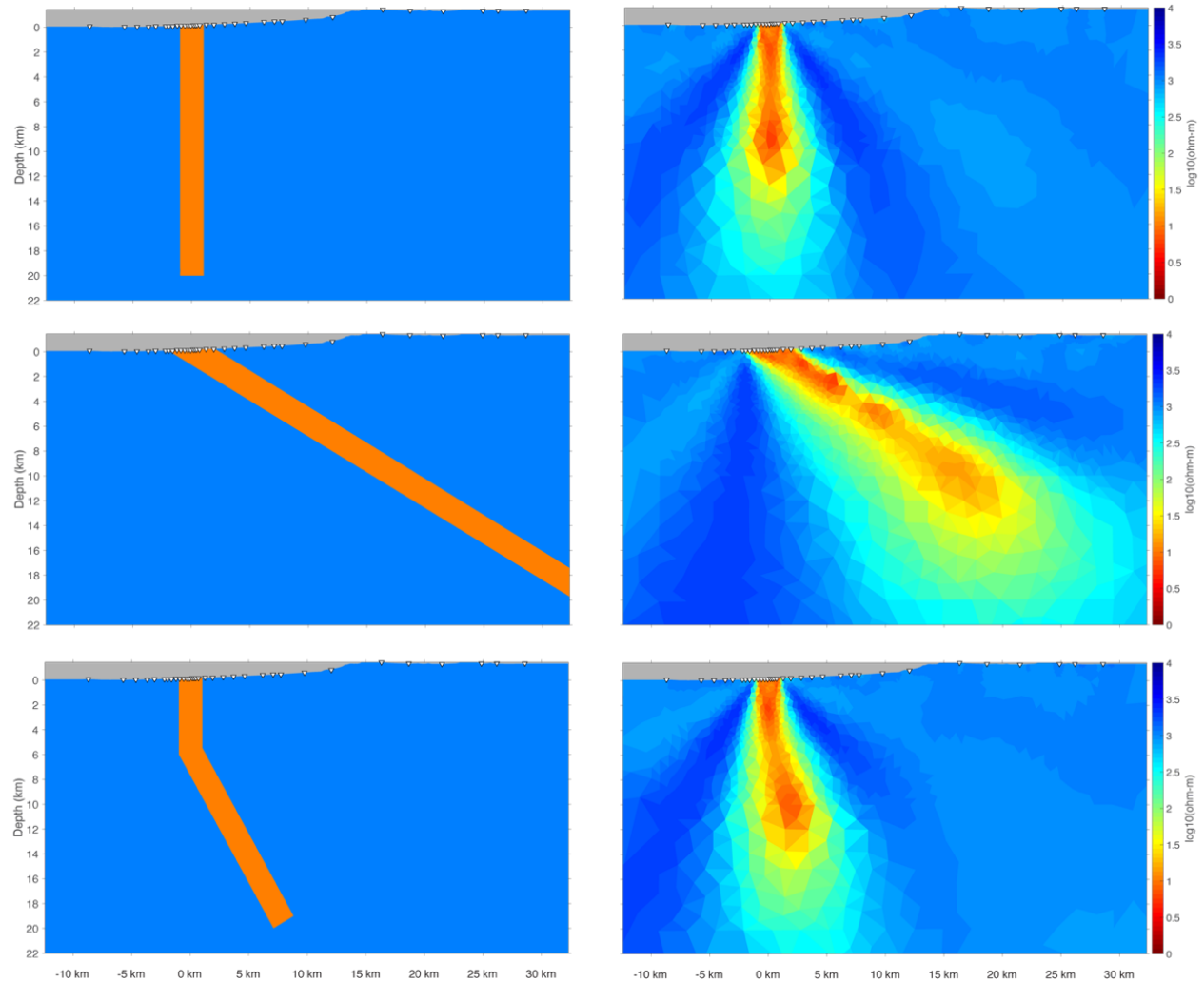


Figure S2: Synthetic forward models (left) and recovered inverse solutions (right) using different fault zone geometries. The geometries are (top) a vertical fault zone anomaly extending from the Mission Creek fault strand surface location to 20 km depth embedded in a surrounding host rock with resistivity of 1000 $\Omega\cdot\text{m}$, (middle) same as (top) but for a fault zone with a shallow dip of 30° to the northeast, and (bottom) similar resistivities again but a more geometrically complex fault zone that is vertical down to 6 km depth and starts to steeply dip to the northeast by 60° below that (see main text for details). The synthetic fault zone has a width of 2 km, a resistivity of 10 $\Omega\cdot\text{m}$ and is embedded in a 1000 $\Omega\cdot\text{m}$ host rock. The starting half-space for the inverse model has a resistivity of 100 $\Omega\cdot\text{m}$. The horizontal to vertical smoothing ratios used during inversion were 0.4 (top), 1.1 (middle) and 0.5 (bottom). All inverse models have a final rms of 1.

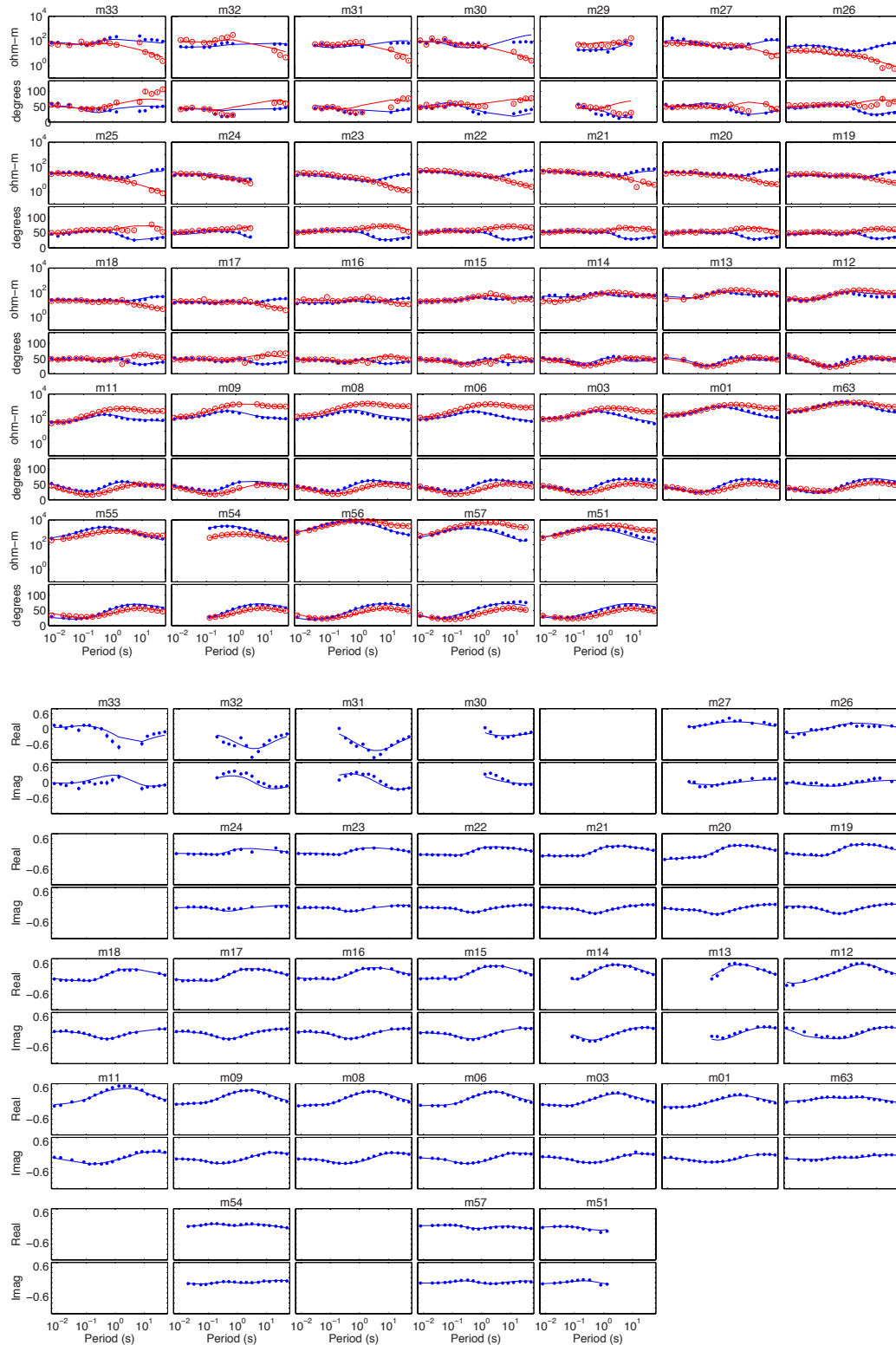


Figure S3: Data (dots and circles) and responses (lines) from our final 2D model (Fig. 4) for TE (top, blue), TM (top, red) and T_{ZY} (across-fault) tipplers (bottom, blue).

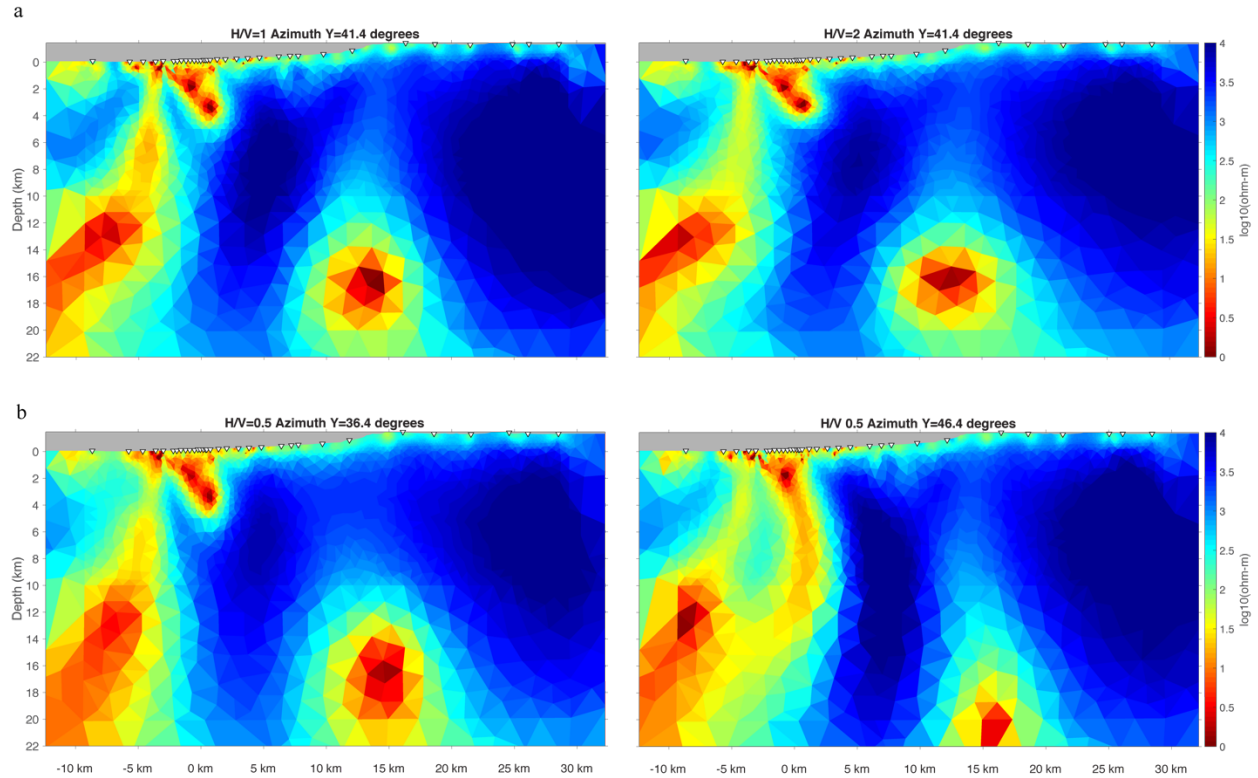


Figure S4: (a) Inversion results using the same data as in Fig. 4, but for a horizontal to vertical smoothing ratio of 1 (left) and 2 (right). (b) Inversion results using the data in Fig. 4 but rotated to $X=306.4^\circ$ and $Y=36.4^\circ$, and, $X=316.4^\circ$ and $Y=46.4^\circ$ (right), respectively. All other parameters are the same as in Fig. 4. All models have a final rms of 1.65.

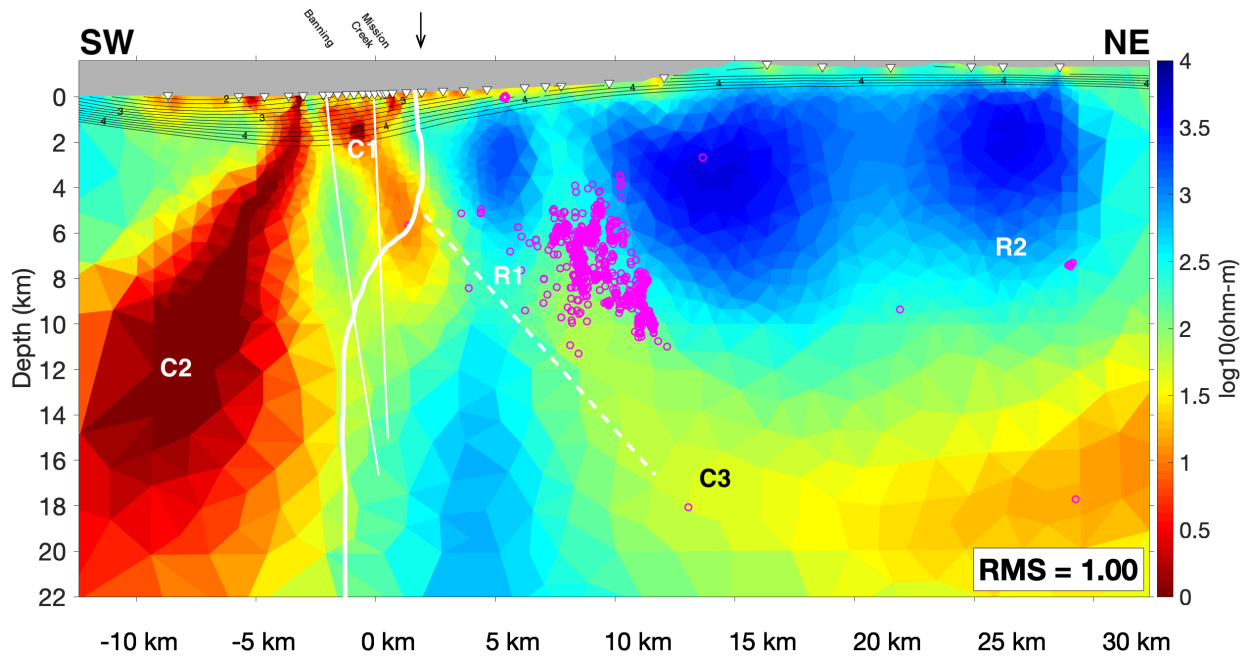


Figure S5: 2D determinant inversion result using all available data (>50 s also). The determinant data are obtained by multiplying the TE and TM mode data after rotation to strike (in-line direction). By definition, tipper data are not included in the determinant inversion. This image represents the smoothest model at a target misfit of rms=1. All references and symbols are in the same locations as in Fig. 4.

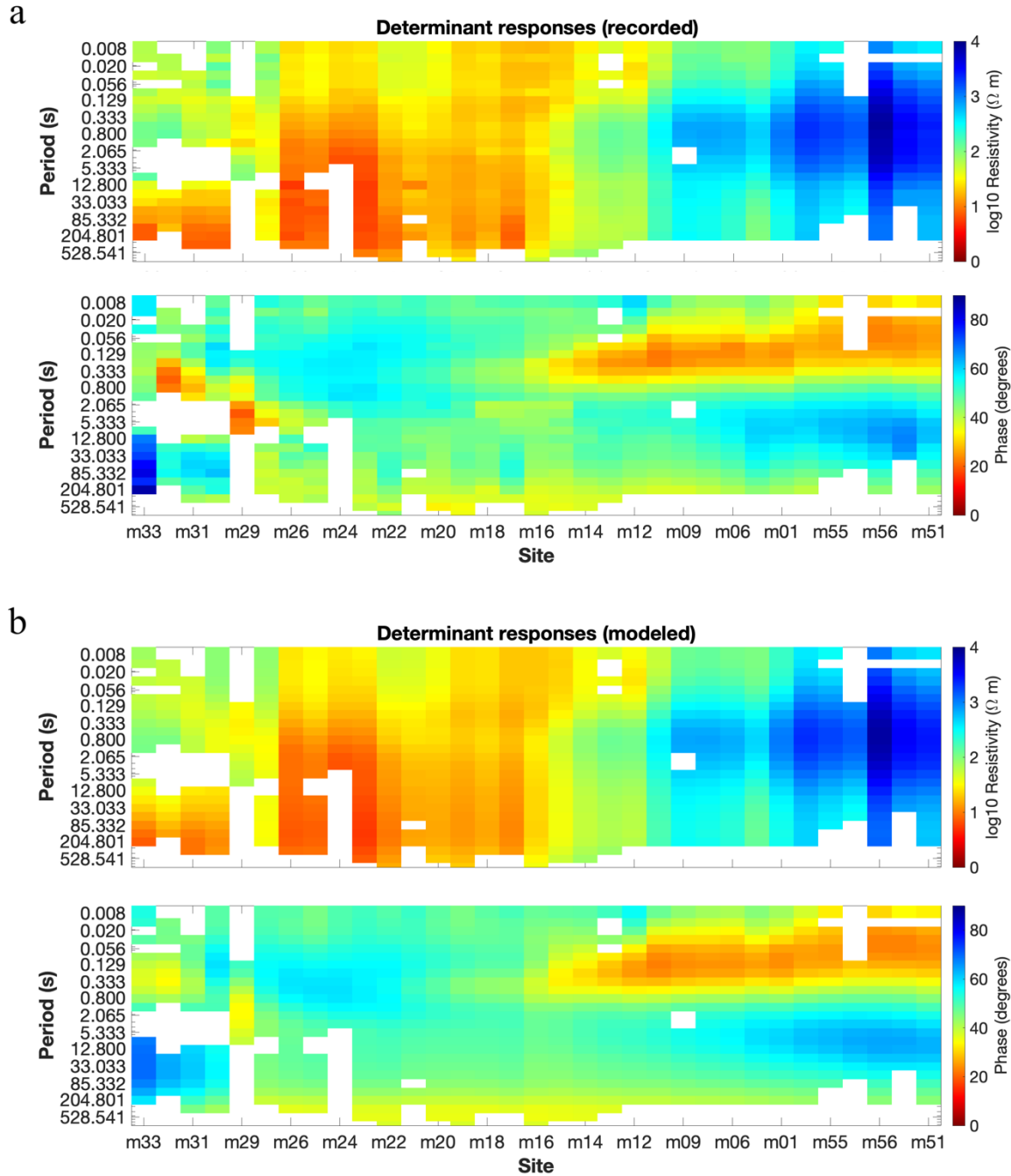


Figure S6: Pseudosections of the determinant data (all periods) associated with recorded (a) and modeled (b) responses. The modeled data correspond to the inverted model in Fig. S5.

1
2
3 Dear editors and reviewers,
4

5
6 We thank you for reviewing and considering the manuscript (GJI-S-21-1108) entitled “**Structural**
7 **properties of the Southern San Andreas fault zone in northern Coachella Valley from**
8 **magnetotelluric imaging**” for publication in GJI. The manuscript was recommended for
9 publication after *moderate* revision. The main concern for Reviewer #1 was the influence of 3D
10 structures and data (especially in the southwest) on our 2D modeling approach and interpretations.
11 Reviewer #2 was overall pleased with the state of the manuscript and recommended it for
12 publication as it is. In terms of the concerns about 3D effects, we emphasize that given the overall
13 2D nature of our selected data (and the mostly 2D shallow crustal transform plate boundary they
14 represent), the quasi-linear station layout and the local irregular topography, a 2D MARE2DEM
15 inversion approach is best (but not perfect) and the resultant 2D model accurately represents the
16 underlying structure at the depths presented. To corroborate this, we added determinant data
17 inversion results to the manuscript (Section 4 & Figs S5-S6). These type data were recently
18 embedded in the MARE2DEM inversion package, so have all the advantages stated above and in
19 addition are less susceptible to the distorting effects of 3D structures in cases where the region and
20 data are mostly 2D (i.e., our study region). The resultant determinant inversions were indeed
21 consistent and comparable to our original 2D inversion (Figs 4 & S5), emphasizing that the 3D
22 parts of the limited dataset employed and depths under investigation are minor and are not
23 significantly distorting our preferred 2D model (Fig. 4) and interpretations (Section 5). Finally,
24 and in response to the minor comments from both reviewers, we also modified several of the
25 figures and the text in order to improve accuracy, clarity and presentation.
26
27
28

29
30 Below we provide detailed replies to the comments of the editors and the two reviewers (noting
31 that line numbers have now changed in the revised version). We also upload an annotated version
32 of the revised manuscript (“Share_etal_2022_trackchanges.pdf”) showing all the changes made to
33 the original submission.
34

35 We thank you all again.
36

37 Yours sincerely,
38

39
40 Pieter-Ewald Share for all authors
41

42
43 Editor's Comments to the Author:
44

45
46 Dear authors,
47

48 Thank you for submitting your manuscript GJI-S-21-1108 to Geophysical Journal International
49 for which we have received two reviews.
50

51
52 Both experts come to a quite different assessment although both of them find the topic of your
53 manuscript interesting and publishable. Reviewer #2 has only some minor comments and in
54 summary finds your manuscript “publishable as it stands”. Reviewer #1 has some major issues
55 and asks for major modifications. He/She is not convinced that the data set is consistent with a
56
57
58
59
60

1
2
3 2D interpretation along the entire profile and for the entire frequency range. Looking at the phase
4 tensors together with the directions of the inducing vectors suggests that a 2D approach might
5 be too much of a simplification. He/She suggests two possible ways to solve this issue; either
6 with 2D modelling studies or by measures of synthetic 3D studies to evaluate possible artefacts.
7 As a comment from my side, it might be worthwhile to have a look at Cruces-Zabala, J., Ritter,
8 O., Weckmann, U., Tietze, K., & Schmitz, M. (2020). Magnetotelluric imaging of the Mérida
9 Andes and surrounding areas in Venezuela. *Geophysical Journal International*, 222(3), 1570-
10 1589 or Cruces-Zabala, J., Ritter, O., Weckmann, U., Tietze, K., Meqbel, N., Audemard, F., &
11 Schmitz, M. (2022). Three-dimensional magnetotelluric imaging of the Mérida Andes,
12 Venezuela. *Journal of South American Earth Sciences*, 103711.
13 Another issue concerns the resolution test presented in Figure 5. As indicated by reviewer #2, an
14 original model that apparently achieved the best fit to the data will in most cases have a higher
15 rms if additional features are included. Allowing the subsequent inversion to either keep or omit
16 features in the starting or prior model, will probably lead to a less biased result.
17 As additional modelling studies are necessary, I have classified the changes required as
18 "moderate revision". I expect to see the majority of the reviewers' comments implemented in
19 your revision. A point-by-point response will be needed to allow me to see how you have
20 implemented the requested changes. For easier recognition please mark changes in the revised
21 manuscript e.g. by using different colour.
22
23
24
25

26 Kind regards,
27 Ute
28

29
30 We thank you for all the substantial input and suggestions and for the literature to review. We
31 have taken all these on board while revising the paper. After weighing the options, we concluded
32 it was most appropriate to supplement the original manuscript with results from MT determinant
33 inversions. These are embedded in MARE2DEM, so have all the advantages of that package and
34 thus allows a more "apples-to-apples" comparison with our preferred model (Fig. 4). The
35 determinant inversion also provides a less distorted (but smoother) 2D slice through a region that
36 is predominantly 2D but contains some 3D features (e.g., our study region). In the end, all the
37 determinant inversions (Fig. S5-S6 shows one example) were highly consistent with our
38 preferred model, demonstrating that the Fig. 4 result is not significantly affected by the minor
39 amounts of 3D data present and that our model interpretations are reliable.
40
41

42 Please note, because of the additional work required for the determinant inversions, we have
43 added another co-author to the manuscript, i.e., Dr. S. Wang, who steered and performed these
44 inversions and helped with the interpretation of results.
45
46

47 Please see below for detailed responses to Reviewer #1 on the issue of the resolution tests in Fig.
48 5 as well as detailed responses to all the other comments from both reviewers.
49

50 We hope the resubmitted version is satisfactory for eventual publication in GJI. Thank you again.
51
52
53
54
55
56
57
58
59
60

Assistant Editor's Comments to the Authors:

As you are not paying for colour printing, you should ensure that all of your figures can be understood when printed in black & white, by e.g. changing line styles and plotting symbols, adding suitable labels etc., and avoid distinguishing features by colour alone in captions and legends.

Please ensure that all textual labels in figures are at least as large as the caption text; any smaller and they become too difficult to read.

We would like to change our selection, and request that the figures in print be in color also. We will pay the necessary additional fees. Please update the submission accordingly.

Reviewer: 1 - Anonymous

Comments to the Author(s)

The manuscript showcases a magnetotelluric study across the southern San Andreas Fault (SSAF) which is modelled and interpreted based on a 2-D modelling approach. The authors argue that for the relevant period range, the 2-D assumption is sufficiently fulfilled. Based on the resistivity model, they infer a near-vertical fault plane between 2 and 20 km depth, but cannot exclude a fault dipping to the NE. The two scenarios are discussed in view of existing additional information from geology and seismology.

MT is generally able to infer geometries and other properties of fault zones. The work is interesting and relevant since it studies a section of the SAF which is poorly understood so far, but poses a significant earthquake risk. Overall, the manuscript is well written and structured and the figures are usually illustrative. In principle, I consider the work suitable for publication in GJI, after revision.

Thank you for your thorough review. Please see below for detailed responses.

I have one major comment: I am not convinced that the 2D model and interpretation of the data set provides a reliable image for the first 15 km at the SW profile end. Yet, it is this section which is crucial for the delineation of the SAF.

The authors argue that 2D conditions are fulfilled for the data set for periods up to 50 s and, thus, 2D modelling and interpretation are sufficient. I agree that 2D properties are fulfilled up to 50 s for the NE half of the profile (NE of site m14) based on the phase tensor properties displayed in Fig. 2. But, for sites to the SW of site m14, 2D conditions are fulfilled for much shorter periods only. For sites m28- m16, the 2D assumption seems reasonable up to periods of 10 s, for periods of 12.8 s and above data are definitely 3D. For the three leftmost sites m33-m31, I would even interpret data > 1 s as 3D; m30 and m29 appear 3D throughout the available period range.

1
2
3 Also, real and imaginary parts of induction arrows at 20 s (Fig. S1) show significant deviations
4 from being (anti)parallel nearly everywhere, in particular for sites m33 to m11, and point at a 3D
5 subsurface.
6

7
8 Thanks for these key observations. Prior to describing our remedy for the 2D versus 3D issue
9 below, a few responses are warranted. First, we agree with the above points overall. It is clear
10 that some of the data have 3D characteristics. We note this in the text and re-emphasize it in the
11 revised version (L. 180-188 & 273-275). However, it is also clear from our analyses and your
12 description above that the vast majority of data up to 50 s are 1D to 2D in nature and thus lends
13 itself more to a 2D modeling approach. Second, the sites to the southwest are noisiest (L. 143-
14 149). Thus, the interpretation of 3D structure to the extent mentioned above for those sites hinges
15 on the fact that we know the contribution to those anomalous impedances (Fig. 2) from the noise
16 alone, which we do not. The rapid and non-smooth changes in phase tensor characteristics for
17 neighboring periods at sites m29-33 suggest that noise is indeed playing a significant role at
18 those sites. During inversion, increased error bars for these sites (L. 212-213) helps compensate
19 for this noise and any minor 3D structures that may be present.
20
21

22
23 I see two potential ways to approach this issue:
24

25 1) Performing a sincere and thorough analysis and discussion of the limitations of modelling,
26 resolution, and interpretation of the 2D-only approach. This would require more 2D modelling.
27 For example, what happens if all 3D data are omitted? How much structure can then be
28 revealed? Is there still enough resolution to discriminate between the various scenarios?
29

30
31 2) Performing additional 3D modelling of the data set. The current version of the manuscript
32 mentions that such tests were performed and “features of the 3D model were consistent with our
33 2D inversions, but lacked the resolution of the MARE2DEM finite element code”. Are they
34 consistent particularly in the 3D (SW) section of the survey? Do these 3D models even shed light
35 on the geometry of the SAF? Based on the comments to the initial version of the ms and related
36 answers of the authors I conclude that the 3D models appeared homogeneous at lower crustal
37 depths and did not allow to make inferences on the fault geometry.
38
39

40 Thank you for these suggested solutions. It has helped greatly improve the manuscript. After
41 weighing the options, we decided to go with option (1). A 3D approach has its own drawbacks
42 (e.g. can't constrain off-profile extent of anomalies, lacks the resolution of a finite-element code)
43 and we have concluded that the majority of data at <50 s is 1D/2D, the underlying transform
44 plate boundary structure is expected to be approximately 2D, and that the advantages of a finite-
45 element algorithm lend itself well to our specific high-relief setting and quasi-linear MT array.
46
47

48 As a supplementary to the existing results, we executed several MT determinant inversions.
49 These inversions provide a less distorted (but smoother) 2D slice through a region that is
50 predominantly 2D but contains some 3D features (e.g., our study site). Also, it is already
51 embedded in the MARE2DEM package so has the advantages of that finite-element algorithm
52 and allows a more “apples-to-apples” comparison to the results presented in this manuscript,
53 including our preferred model (Fig. 4). Results from all the determinant inversions we ran were
54 highly consistent with Fig. 4, especially in the conductive southwestern end of study region. This
55
56
57
58
59
60

1
2
3 demonstrates that the Fig. 4 result is not significantly distorted by the minor amounts of 3D data
4 and that our model interpretations are reliable. This holds true even in the case where we add all
5 available data (>50 s) representing a much more expanded 3D dataset. Example determinant
6 inversion results were added as new Figures S5 and S6. We added these in the Supplementary as
7 we want to focus the reader on our preferred model, Fig. 4, which is constrained by a larger and
8 more diverse dataset (TE, TM & tipper) and is less smooth and thus highlights better the rapid
9 changes in fault zone structures that are the key geologic targets in this study. The following
10 description of these results has been added as L. 271-290 in the main manuscript.
11
12

13
14 *“The model in Fig. 4 is our preferred result as it is equally well constrained by TE, TM and tipper*
15 *data (Fig. S3) and the majority of that data at periods <50 s is 2D in nature with a consistent near*
16 *fault-parallel strike (Fig. 2). However, as noted in Section 3, even at <50 s some stations and*
17 *periods exhibit 3D characteristics, e.g., at the southwestern and northeastern sites (Fig. 2). As a*
18 *supplement and to test the effects of these minor 3D features in a predominantly 2D upper to mid*
19 *crustal region, we additionally applied a 2D determinant inversion (Pedersen & Engels 2005;*
20 *Wang et al. 2020; 2021). This type of inversion has been shown to produce less-distorted 2D model*
21 *representations of a predominantly 2D region that also includes 3D structures (Wang et al. 2020).*
22 *However, this lower distortion comes at the cost of larger model smoothness. The algorithm*
23 *employed is embedded in the MARE2DEM package, which facilitates comparison with Fig. 4.*
24 *During inversion, we used the same impedance tensor data (not tippers), matching errors, and the*
25 *model and inversion settings described above. Overall, all our resultant determinant inversion*
26 *models were consistent with Fig. 4. In fact, even when we included data from all available periods,*
27 *which constituted a significant increase in 3D data, the determinant inversion result was still*
28 *comparable to Fig. 4 (Fig. S5-S6). In Fig. S5, anomalies C1-3 and R1-2 are all present, albeit the*
29 *fact that C2 is more conductive and extends to shallower depths, and the region containing R1, R2*
30 *and C3 is generally smoother with R1-2 lower in resistivity and C3 smeared towards the northeast*
31 *where there is less station coverage and the data at longest periods reflect 3D structure (Figs 2 &*
32 *S1).”*
33
34
35

36
37 I am agreeing with and supporting the first comment of Reviewer #1 to the initial version of the
38 manuscript and would like to cite this persons words here again, because it has already been said,
39 but I do not find this point addressed sincerely in the revised version:
40

41
42 *“Should we believe the 2D image or the 3D image? While 3D inversion has the benefit to*
43 *account for 3D effects in the data, it is known that regularization in ModEM often emphasizes*
44 *the shallow parts of the model. What is more, weakly constrained offprofile structures may*
45 *account for some aspects in the data as well. Therefore, 3D inversion of profile data is not*
46 *necessarily superior to 2D inversion, and both 2D inversion and 3D inversion of profile data*
47 *must be evaluated with equal care. The discussion of the 3D model must be broadened to make it*
48 *of value - or omitted completely, if arguments are presented to use a 2D interpretation only. In*
49 *any case, more work is required here.”*
50

51
52 We hope this issue has been adequately addressed above.
53

54 Besides, I am not really sure what I can learn from the resolution study in Fig. 5. I can only guess
55 from the very short description of this analysis in the main text (please expand!) that the test is
56
57
58
59
60

1
2
3 using pure forward simulations, where structures of the final inversion model are modified and
4 the response of this modified model is compared to the response of the original model and the
5 measured data. The significance of such comparisons, though, is limited. The inversion result
6 represents a (local) minimum in the misfit space. Any, even through “small”, modification of this
7 usually leads to an increase of the data misfit. For a more meaningful test, such alternative
8 subsurface structures would have to be included in the starting model and inversion has to be
9 rerun subsequently. Only such a test would enable the inversion scheme to (a) find a suitable
10 model around this assumption or to (b) fail to fit the data adequately, and would allow to accept
11 or reject the underlying hypothesis. What about other apparent hypotheses: A potential
12 connection between C1 and C2? Two conductive fault strands?
13
14
15

16 Thanks. It is true that once a minimum misfit is reached then small changes in conductive parts
17 of the model space can lead to large changes in misfit. However, this holds most true where your
18 data sensitivity to model parameters is relatively high, otherwise it does not. MT data are not as
19 sensitive to resistors and, also, to conductors located deeper than the skin depth of the employed
20 frequencies. The purpose of Figure 5 is to highlight to the reader critical parts of the Fig. 4 model
21 (C1-C3) that potentially lie in this type of nullspace. For example, near surface areas with less
22 station coverage and the bases of conductors are more poorly resolved. This is the reason a
23 connection between the base of C1 and the top of C2 was not more explored as that is
24 intrinsically a poorly resolved region (e.g., Fig. S4 shows a connection while other models do
25 not). Also, in general, changes at shallow depths have greater effects on misfit compared to
26 changes at depth. The former shows higher data sensitivity to model parameters compared to the
27 latter. These points are now more clearly stated in L. 254-270:
28
29
30

31 *“Given that some regions in the model space are more poorly resolved than others, such as near*
32 *surface areas with less station coverage, greater depths in general, and regions beneath*
33 *conductors (e.g., Chave & Jones 2012), we applied a few conductance-preserving (conductivity-*
34 *thickness product) alterations of particularly C1-C3 to test if small changes in their properties are*
35 *allowed without significantly affecting the misfit (i.e., changes within the nullspace, Munoz & Rath*
36 *2006). MT data are most sensitive to changes in conductance rather than conductivity, so by*
37 *preserving conductance these tests highlight how changes in the geometries and locations of C1-*
38 *C3 affect data misfit. They also provide an indication of their relative influence on misfit and,*
39 *therefore, the relative data sensitivity to these conductive parts of the model space. In general, the*
40 *tests show that only small changes in C1-C3 are allowed without significantly increasing the model*
41 *misfit (Fig. 5). Specifically, the steep northeast dipping geometry of anomaly C1 is well resolved*
42 *as a more vertically orientated structure in the inverted model increases the rms to ~1.8 (Fig. 5).*
43 *And, the resistive region separating C2 and C3 is similarly well resolved as extensions of either*
44 *C2 or C3 towards the other lead to large increases in rms (Fig. 5). For example, extending C2*
45 *only 6 km to the northeast produces the same significant increase in rms as removing it from the*
46 *inverted model altogether (Fig. 5).”*
47
48
49

50 Based on the above considerations I recommend publication of the manuscript after major
51 revision.
52
53

54 Thank you again. We hope the revised version is more suitable for publication in GJI.
55
56
57
58
59
60

1
2
3 Additional comments:

4 L 118-120: How long did the logger record? 8 hours + 10 minutes or 20 hours? L 121: Please
5 provide the distance to the remote site in km.
6

7
8 We have added “The ZEN was programmed to record in a sequence that started with 256 Hz
9 sampling for 8 hours followed by a burst of 4096 Hz sampling for 10 minutes. This sequence
10 repeated several times within the ~1-day recording window.” in L. 117-119 to clarify the
11 statement about recording. The distance (i.e., ~66 km) to remote reference has also been added to
12 L. 121.
13

14
15 L 128: While I agree, that frequencies > 500 Hz are probably not relevant to the study of the
16 SAF, I do not really understand why neighbouring sites should be too far away for remote
17 reference processing of frequencies > 500 Hz. Please explain.
18

19 Agreed, greater clarity is required here. We have modified the sentence L. 127-130 to read
20 “Without a remote reference and with coherent high-frequency noise present across neighboring
21 sites (spaced < 500 m near the SSAF), the single-station responses at these very high frequencies
22 may have only yielded biased estimates of near-surface resistivities.”
23
24

25 Fig. 1: Magenta circles and black dots are very hard to see both printed in original size but also
26 when zooming in into the pdf. Add north arrow to b) to make it easier to understand the
27 orientation of the coordinate system.
28

29
30 Thanks. We enlarged the size of the black circles to clarify and have removed the magenta
31 circles from Fig. 1. The latter omission reduces clutter and these events are already highlighted
32 in Fig. 4 and in the new Fig. S5. The north arrow has been added to (b).
33

34 Fig. 2: Consider adding labels SW and NE to the profile to facilitate grasping of the figure. Fig.

35 3: Labels are extremely small and hard to read, increase font size.

36 Fig. 4: As in Fig. 3, labels are extremely small. Thin white lines hard to see when printed.
37
38

39 Noted. We have made all these requested figure changes.
40
41

42
43
44 Reviewer: 2 - Anonymous

45
46 Comments to the Author(s)

47
48 Thanks for the revision! A very clear manuscript, well and concisely written, with all the
49 required information provided.
50

51
52 Thank you for reviewing and considering this suitable for publication after minor edits.
53

54 In the abstract, line 32, it is stated that ... (1 Ohm-m at 2 km and 12 km ...). It is unclear, to what
55
56
57
58
59
60

1
2
3 distance or depth the value of 2 km refers. It cannot be depth because the sentence refers to the
4 ductile crust, but it also does not seem to refer to distance. Just an error?
5

6
7 Thanks. The 1 Ohm-m at 2 km refers to the observed maximum within anomaly C1, the one at
8 12 km depth the maximum in C2. This has been clarified in the abstract by splitting up the two
9 descriptions into two different parentheses.
10

11 line 50: ..., damage zone, ... insert (zone)
12

13 The word “zone” is redundant here because we start that part of the sentence with a category,
14 i.e., fault *zone*, and then list the properties in that category that we are trying to inform. Though,
15 we did swap the words “zone” and “geometry” to improve readability.
16
17

18 line 78: inducing magnetic fields ... this is a bit oversimplified, because the magnetic field has
19 also secondary components, to be precise ...
20

21 Correct. The “inducing” reference has been removed.
22
23

24 line 202: 10^5 Ohms for the air maybe a bit too low
25

26 This is the representative value used in other successful MARE2DEM studies so we keep it as is.
27
28

29 line 328: ... evolves ... it should be plural here (evolve)
30

31 Corrected.
32

33 Figure 4: The thin white lines are difficult to discern. Perhaps use thicker (dashed) lines
34
35

36 We made the lines thicker.
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11 1
12 2 **Structural properties of the Southern San Andreas fault zone in northern**
13 3 **Coachella Valley from magnetotelluric imaging**
14 4
15
16
17

18 5 Pieter-Ewald Share^{1*}, Jared R. Peacock², Steven Constable¹, Frank L. Vernon¹ and
19
20 6 [Shunguo Wang³](#)
21
22
23 7

Deleted: and

24 8 ¹Institute of Geophysics and Planetary Physics, University of California San Diego, La
25
26 9 Jolla, CA

27
28 10 ²Geology, Minerals, Energy, and Geophysics Science Center, USGS, Moffett Field, CA

29
30 11 [Department of Electronic Systems, Norwegian University of Science and Technology,](#)
31
32 12 [Trondheim, Norway](#)
33

34 13 *Now at College of Earth, Ocean, and Atmospheric Sciences, Oregon State University,
35
36 14 Corvallis, OR

37
38 15
39
40 16 Corresponding author: Pieter-Ewald Share (pieter.share@oregonstate.edu)

41
42 17 *Geophysical Journal International 2022, in review*
43
44 18
45 19

Deleted: ¶

Deleted: ¶
¶

46
47 20 **Key words:** Continental tectonics; strike-slip and transform; Fractures, faults and high
48
49 21 strain deformation zones; Electrical properties; Magnetotellurics
50
51
52
53
54
55
56
57
58
59
60

27 Summary

28 The Southern San Andreas fault (SSAF) poses one of the largest seismic risks in
 29 California. Yet, there is much ambiguity regarding its deeper structural properties around
 30 Coachella Valley, in large part due to the relative paucity of everyday seismicity. Here, we
 31 image a multi-stranded section of the SSAF using a non-seismic method, namely
 32 magnetotelluric soundings (MT), to help inform depth-dependent fault zone geometry,
 33 fluid content, and porosity. The acquired MT data and resultant inversion models highlight
 34 a conductive column encompassing the SSAF zone that includes a 2-3 km wide vertical to
 35 steeply northeast dipping conductor down to ~4 km depth (maximum of ~1 Ω .m at 2 km
 36 depth) and another prominent conductor in the ductile crust (~1 Ω .m at 12 km depth and
 37 slightly southwest of the surface SSAF). We estimate porosities of 18-44% for the
 38 conductive uppermost 500 m, 10-15% porosity at 2 km depth and that small amounts (0.1-
 39 3%) of highly interconnected saline fluids produce the deeper conductor. Located northeast
 40 of this conductive region is mostly resistive crust indicating dry crystalline rock that
 41 extends down to ~20 km in places. Most of the local seismicity is associated with this
 42 resistive region. Located farther northeast still is a conductive region at >13 km depth and
 43 separate from the one in the southwest. The imaged anomalies permit two interpretations.
 44 The SSAF zone is vertical to steeply northeast dipping in the upper crust and (1) is near
 45 vertical at greater depth creating mostly an impermeable barrier for northeast fluid
 46 migration or (2) continues to dip northeast but is relatively dry and resistive up to ~13 km
 47 depth where it manifests as a secondary deep ductile crustal conductor. We prefer
 48 interpretation (1), but more MT investigations are required.

49 ▲

Deleted: 2 km and

Deleted: beneath

Deleted: a large resistor (maximum of ~10,000 Ω .m)

Deleted: vertically

Deleted: and hosts most

Deleted: .

Deleted: separate

Formatted: Font: Not Italic

1. Introduction

The Southern San Andreas Fault (SSAF) has not produced a $M > 7.5$ event for >300 years and is estimated to pose one of the largest seismic risks in California (Weldon et al. 2005; Sieh & Williams 1990). Several properties of the SSAF such as fault zone damage, geometry, and fluid content remain poorly understood despite several geoscientific studies (e.g., Catchings et al. 2009; Lindsey & Fialko 2013; Ajala et al. 2019). Informing these properties is essential as they may play key roles in the magnitude and subsequent shaking from future large events (e.g., Roten et al. 2015; Biasi & Wesnousky 2016).

One outstanding question is whether the SSAF at depth, if well localized as expected for a mature plate margin (Montési 2013), is near vertical or dipping to the northeast. In the Southern California Earthquake Center Community Fault Model (SCEC-CFM5.2, Nicholson et al. 2017) it is mapped as a vertical fault in the Coachella Valley (Fig. 1a). In contrast, analyses of interseismic strain fields (Fialko 2006; Tymofyeyeva et al. 2019) and potential field data (Fuis et al. 2012; 2017; Langenheim & Fuis 2021) point to a northeast dipping SSAF similar to its neighboring strand in San Geronio Pass (Fig. 1a), the latter being well constrained by small to moderate sized events (Jones et al. 1986; Nicholson 1996). A deep northeast dipping SSAF is supported by more abundant seismicity on that side of the surface SSAF, and a large structure with a prominent seismic velocity contrast (bimaterial interface) intersecting this seismicity (Fig. 1a, Share & Ben-Zion 2016). However, these features can also be attributed to secondary faults in the northeast (Fig. 1a, Nicholson et al. 2017). Much of our inability to resolve this fundamental question about deeper SSAF structure is owed to the general lack of seismicity in the region (Ross et al. 2019), which is essential to delineate fault geometry (e.g., Magistrale & Sanders 1996;

Deleted: ¶

Deleted: , damage

Deleted: Montesi

1
2
3
4
5
6
7
8
9
10
11 83 Carena et al. 2004) or in high-resolution seismic imaging studies (e.g., Share et al. 2019).
12 84 Thus, more studies using non-seismic geophysical tools are needed to help inform SSAF
13
14 85 properties and its associated seismic risk.
15

16 86 Here, we use an established electromagnetic imaging method, namely magnetotelluric
17
18 87 soundings (MT, Cagnaird 1953), that does not depend on seismicity (or paucity thereof as
19
20 88 in the study region) as a source, to image for the first time the electrical resistivity structure
21
22 89 of the SSAF throughout the crust. MT is a passive geophysical tool that measures
23
24 90 ubiquitous natural variations in the Earth's magnetic field and induced electric fields
25
26 91 generated in the subsurface. Resistivity within the Earth is then derived from frequency-
27
28 92 dependent transfer functions (MT tensor) between magnetic and electric fields.

29 93 MT data are preferentially sensitive to high conductivity (inverse of resistivity) regions
30
31 94 within the Earth (Chave & Jones (2012) and references therein). Relative to the deeper
32
33 95 mantle continental crust is electrically resistive (Schwarz 1990) except for anomalous
34
35 96 regions where conductive materials (e.g., aqueous fluids, graphite, melts) form
36
37 97 interconnected networks (e.g., Bahr 1997). Thus, active crustal fault zones are optimal
38
39 98 targets for MT imaging, where damaged and deformed rocks create pathways for
40
41 99 conductive fluids to percolate through the crust, and strain localization forms a mechanism
42
43 100 to connect fluids within these weakened zones (Becken & Ritter 2012). Structure, damage,
44
45 101 and deformation need not always be symmetric about a fault core and interconnected fluids
46
47 102 can be distributed asymmetrically with little fluid migration across an impermeable fault
48
49 103 (e.g., Caine et al. 1996; Bedrosian et al. 2004). MT has been successfully used to infer fault
50
51 104 zone properties such as amount of damage, fluid content, geometry, and strain conditions
52
53 105 in central California (e.g., Becken et al. 2011; Tietze & Ritter 2013), Japan (Ogawa &

Deleted: inducing

Deleted: fields

Deleted: induced

Deleted:

1
2
3
4
5
6
7
8
9
10 110 Honkura 2004; Yoshimura et al. 2009) and Turkey (Turkoglu et al. 2008). Despite these
11 111 successes, MT has yet been broadly applied in Southern California.

12
13
14 112 In this study, we apply MT imaging to a section of the SSAF in northern Coachella
15 113 Valley near the Thousand Palms Oasis Preserve where the Mission Creek and Banning
16 114 fault strands merge (Fig. 1b). Despite ongoing debate over which strand is more active in
17 115 present day, both are well located at the study site using offsets in landforms and lithology
18 116 and trenching data (e.g., Fumal et al. 2002; Blisniuk et al. 2021). Near the surface, these
19 117 strands together with other minor faults comprise a ~3 km wide SSAF zone embedded in
20 118 Pliocene and Pleistocene stratified rock with Coachella Valley Quaternary sediments to the
21 119 southwest (up to ~2 km thick in central Valley, Ajala et al. 2019), thinner sediments
22 120 immediately northeast of the Mission Creek strand and the Little San Bernardino
23 121 Mountains (pre-Cenozoic metamorphic and crystalline rocks) outcropping ~10 km farther
24 122 northeast (Rymer 2000). The presence of several oases indicates a fault zone acting as a
25 123 conduit and/or barrier for aqueous fluid flow (Catchings et al. 2009), making it an attractive
26 124 MT target. We collected data in 2019 along a linear array transecting the SSAF around the
27 125 Preserve supplemented by stations from a neighboring 2017-2018 array located in the
28 126 Joshua Tree National Park (Fig. 1a) to image electric resistivities in the area. The abundant
29 127 seismicity to the northeast is ~10 km from the Preserve and locates at 4-11 km depth (Fig.
30 128 1a). Analyzing MT data that span the SSAF zone and a significant area to the northeast
31 129 allows us to investigate fault zone resistivities and its connection to local seismicity.

32
33
34
35
36
37
38
39
40
41
42
43
44 130

45 131 **2. Data and Methods**

46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11 132 The MT imaging was based on ~1-day long recordings of natural variations in Earth's
12 133 electromagnetic field at 27 sites crossing the SSAF in 2019 and 6 sites located in Joshua
13 134 Tree in 2018 (Fig. 1a). These sites were acquired using the Zonge International 32-bit ZEN
14 135 data logger with ANT-4 magnetic induction coils and Borin Ag-AgCl electrodes with 50
15 136 m dipoles. The ZEN was programmed to record in a sequence that started with 256 Hz
16 137 sampling for 8 hours followed by a burst of 4096 Hz sampling for 10 minutes. This
17 138 sequence repeated several times within the ~1-day recording window. Accompanying the
18 139 2019 survey was a magnetic remote reference installed at a low-noise site in the Borrego
19 140 Desert (33.271608° N 116.064469° W, ~66 km away). This site consisted of a Scripps
20 141 marine data logger (Constable 2013) to which a GPS clock had been added, collecting data
21 142 from two EMI-BF4 induction coils oriented north-south and east-west. Magnetic north was
22 143 used for orientation during all installations. These recorded continuously at 500 Hz for the
23 144 duration of the weeklong survey. Given the depths and scale of investigation in this study
24 145 and that >500 Hz data did not exist for the remote reference site, we excluded the 4096 Hz
25 146 ZEN data from further analysis. Without a remote reference and with coherent high-
26 147 frequency noise present across neighboring sites (spaced <500 m near the SSAF), the
27 148 single-station responses at these very high frequencies may have only yielded biased
28 149 estimates of near-surface resistivities. To better limit very near-surface properties, water
29 150 samples from the local oases were collected (Fig. 1b) and their resistivities were measured
30 151 using a laboratory 4-electrode setup. Both samples had similar measured resistivities of 6.2
31 152 Ω.m (18.6°C) and 5.9 Ω.m (18.5°C). Finally, for uniformity, all ZEN data were upsampled
32 153 to 500 Hz and reformatted to conform to the Scripps marine data format.

Deleted: continuously

Deleted: ~

Deleted: at 256 samples per second (sps) with 10-minute

Deleted: sampling at

Deleted: sps in between

Deleted: a total

Deleted: time of about 20 hours per site

Deleted: sps

Deleted: sps

Deleted: sps

Deleted: or the ability to use

Deleted: stations (too far away compared to wavelengths at 4 kHz) to help suppress local noise, the

Deleted:

Deleted: sps

1
2
3
4
5
6
7
8
9
10
11 169 Next, recorded time series were inspected and trimmed where needed to remove times
12 170 with spurious noise. The time series were then transformed to the frequency domain and
13 171 the frequency coefficients of all stations overlapping in time (including the remote
14 172 reference) were processed with the code of Egbert (1997) to produce robust MT
15 173 impedances and induction vectors/tippers (Parkinson 1959). The 500 Hz sampling and the
16 174 recording period of ~1 day allowed reliable responses to be computed within the ~0.01-
17 175 2000 s range. The use of the Borrego Desert remote reference significantly improved data
18 176 quality for some sites.

Deleted: sps rate

Deleted:

177 Following visual inspection of the calculated impedances and tippers, 20% of the
178 impedance data and 16% of the tipper were considered outliers and removed (Fig. 2a). The
179 outliers were generally associated with longest periods (fewer data points per frequency)
180 and southwestern most stations located near the central Coachella Valley where cultural
181 noise was most pronounced (Fig. 2a). This noise affected the electric field recordings more
182 than the magnetic field; thus, tipper data existed at several southwest stations/periods where
183 impedances were otherwise unreliable.

184 Given the linear nature of the MT array aligned in a southwest-northeast direction
185 where most fault zone structural changes are expected, and the large topographic gradient
186 in the area (22 m to 1495 m), we inverted the responses using the MARE2DEM 2D finite-
187 element algorithm with adaptive meshing that accommodates well irregular topography
188 (Key 2016). Prior to inversion an appropriate strike angle was determined through analyses
189 of the tipper azimuths and phase tensors (Caldwell et al. 2004).

Deleted: a

Deleted: exists

190

191 3. Data Analysis

1
2
3
4
5
6
7
8
9
10
11 196 Frequency-dependent phase tensors and tippers provide indicators of the structural
12 197 characteristics in the area (Figs 2 & S1). Around the Mission Creek strand and shallow
13 198 depths (<1 s) structure is predominantly 1D, as evidenced by the near circular phase tensors
14 199 and relatively small tippers. This near surface region probably consists of a shallow layer(s)
15 200 of damage rock and unconsolidated sediments characteristic of an active fault zone
16 201 (Blisniuk et al. 2021; Share et al. 2022). After rotating the local coordinate system to the
17 202 average strike of the Banning and Mission Creek strands (130°/310° E of N, Fig. 1b), the
18 203 properties of the phase tensor ellipses and tippers show that fault zone geoelectric structures
19 204 mostly align with fault orientation. At periods ~1-50 s around the Mission Creek strand the
20 205 phase tensors become elliptical, have <5° beta angles and uniformly align with average
21 206 fault strike (median strike/alpha=322°, Fig. 2b top). These properties highlight 2D
22 207 dimensionality at upper to mid crustal depths with geoelectric strike near parallel to average
23 208 fault strike. This is corroborated by a ~90° flip in beta <5° phase tensor orientations
24 209 (median strike/alpha=25°, Fig. 2b top) northeast of stations m14-15 (arrow in Figs 1b and
25 210 2a), an indication that a prominent fault parallel electric interface has been crossed and the
26 211 mode with largest phase has flipped from transverse magnetic (TM, southwest conductive
27 212 side) to transverse electric (TE, northeast resistive side) (Fig. 3). Along the entire profile
28 213 and for periods up to 50 s, the largest tippers (real part) align with the fault normal (median
29 214 azimuth=42°/222° E of N, Fig. 2b bottom), further evidence of geoelectric strike
30 215 approximating fault strike. Moreover, the tippers point (Parkinson convention) toward a
31 216 region of high conductivity within the SSAF zone (Fig. 2a), most likely related to a fluid-
32 217 rich region of deformation and damage with the sharp electric contrast around stations
33 218 m14-15 representing its northeastern edge. At periods >10 s, beta angles start to increase

Deleted: At

Deleted: 50

Deleted: >5° characterize

222 for impedances recorded in the southwest, which may indicate 3D structure but also reflects
 223 the noisy nature of these data. Across the array there is a progressive rotation of phase
 224 tensor ellipses and tippers at long periods away from average fault strike (or the fault
 225 normal), revealing a deep large-scale 3D plate boundary conductor to the northeast (Fig.
 226 S1). This rotation starts at lower periods (~5 s) for northeast stations, highlighting again a
 227 resistive region with larger skin depth compared to the conductive fault zone. It also causes
 228 a median strike angle of 15° less than the fault normal for stations in the northeast (Fig. 2b
 229 top). Taken together, the median of all phase tensor strike (alpha) and real tipper angles up
 230 to a period of ~50 s (Fig. 2b) defines a coordinate system with X=311.4° (along fault) and
 231 Y=41.4° (across fault). Consequently, the impedances and tippers were rotated and >50 s
 232 data excluded from 2D modeling as these express 3D features.

Deleted: .

Deleted: also

Deleted: large

Deleted: contain information about deeper larger-scale

234 4. 2D Inversion

235 In pseudosections of the rotated data (Fig. 3a), a broad region of high conductivity
 236 encompasses the SSAF zone, with average resistivities to the southwest and highest
 237 resistivities beneath stations in the northeast. To properly image the area and delineate
 238 SSAF structures, we inverted these data using MARE2DEM. The inversion model space
 239 consisted of a ~37 km long surface profile with the Mission Creek strand/Thousand Palms
 240 Oasis at Y=0 km (Fig. 4) that included local topography (from Smith & Sandwell 1997)
 241 and onto which the 33 station locations were projected. Beyond this 37 km profile,
 242 topography was set to be flat and extended from Y=-1,000 km to Y=1,000 km. We fixed
 243 the resistivity of the air above the surface to 100,000 Ω.m and beneath the surface the initial
 244 value was set to 100 Ω.m. The latter extended down to a depth of 1,000 km. From the

1
2
3
4
5
6
7
8
9
10
11 249 surface to ~500 m depth beneath the stations the inversion mesh triangles had a target
12 250 length of 200 m (see Key (2016) for details). Given the dense station spacing (Fig. 1b) and
13
14 251 expected high conductivities of an active fault zone (Fig. 3a), we assigned a target length
15 252 of 500 m to the mesh from Y=-5 km to +5 km and down to 5 km depth. Outside that zone
16
17 253 and down to 10 km depth the target length was 1 km, which then gradually increased to 5
18
19 254 km at 50 km depth and 100 km on either side of the 37 km profile. Beyond that the mesh
20
21 255 triangles increased without a specified target length to the edges of the model space.

22 256 The impedances and tippers of all except the 5 southwestern most stations were
23
24 257 assigned error floors of 10% and 0.02, respectively. To the more 3D and/or noisy data in
25
26 258 the southwest (Fig. 2a), we assigned error floors of 15% and 0.03. To test the resolution
27
28 259 capabilities of these data plus errors, we constructed synthetic tests using hypothetical fault
29
30 260 models, data calculated at the same frequencies and locations as the recorded data, and the
31
32 261 same inversion mesh (Fig. S2). The test cases all included a 10 Ω .m 2 km wide fault zone
33
34 262 but with attitudes varying from a vertical fault zone to one with a shallow dip of 30° to the
35
36 263 northeast (Fig. S2). By keeping the fault zone width and resistivity constant these tests
37
38 264 demonstrate the variable lateral and depth resolutions of the data and methodology. The
39
40 265 resultant inversions (Fig. S2) after adding Gaussian noise of 10% (impedances) and 0.02
41
42 266 (tippers) to the synthetic data suggest the recorded data are well suited to distinguish
43
44 267 between these different fault zone geometries.

45 268 Next, MARE2DEM was used to invert the recorded data. A target misfit of rms=1 was
46
47 269 set at the start of the inversion and a horizontal to vertical smoothing ratio of 0.5 was
48
49 270 selected to highlight expected vertical fault related features (Fig. S2). The MARE2DEM
50
51 271 algorithm attempts to reach the target misfit as fast as possible and then afterwards

Deleted: of

Deleted: stations

1
2
3
4
5
6
7
8
9
10
11 274 determines the smoothest model at that misfit (see Key (2016)). The first inversion was run
12 275 without inverting for the static shifts produced by shallow small-scale features (e.g.,
13 276 structural heterogeneities, sedimentation/groundwater changes, etc.) and irregular
14 277 topography. After a few iterations (~5) the inversion was stopped to inspect which of the
15 278 sites may be affected by static shift. These were identified as sites that had low misfits for
16 279 TE and TM mode phases and TM mode apparent resistivity but had a parallel shift between
17 280 the TE mode apparent resistivity data and modeled responses. Of the 33 sites, 17 were
18 281 identified in this manner as having static shifts. Inversion for static shifts was activated for
19 282 the 17 sites and the inversion restarted with a homogenous 100 Ω .m subsurface. From a
20 283 starting rms=9.6, the inversion achieved an rms=1.65 after 13 iterations with only
21 284 incremental improvements after that. Because the initial target of rms=1 was not reached,
22 285 the model obtained at rms=1.65 was not necessarily the smoothest for that misfit. So, a new
23 286 target misfit of rms=1.65 was set and the model after 13 iterations was used as the new
24 287 starting model, and the inversion restarted. After a total of 18 iterations, the smoothest
25 288 model (Key 2016) with an rms=1.65 was obtained (Fig. 4). The difference between Figs
26 289 3a and 3b, and Fig. S3 illustrate how this misfit maps to the different sites and frequencies.

27
28
29
30
31
32
33
34
35
36
37
38 290 Three crustal resistivity regions characterize this model. First, a complex region of
39 291 average to high conductivity (minima of ~1 Ω .m at 2 km depth and 12 km depth, C1&C2)
40 292 exists in the southwest and terminates at a sharp change in resistivity extending from ~2
41 293 km northeast of the surface Mission Creek strand to beneath the Banning strand in the
42 294 ductile crust. The modeled values in this zone are comparable to those of the central San
43 295 Andreas fault (Bedrosian et al. 2004; Becken et al. 2011). Second, the crust is mostly
44 296 resistive northeast of this contrast reaching a maximum of ~10,000 Ω .m in places

297 (R1&R2). Finally, there exists a conductor, separate from C2, at >13 km depth beneath the
 298 most elevated part of the Little San Bernardino Mountains in the Joshua Tree National Park
 299 (C3). These features' general characteristics do not change with changes in model
 300 smoothing or strike of the 2D profile and associated rotations of data responses (Fig. S4).
 301 Given that some regions in the model space are more poorly resolved than others, such
 302 as near surface areas with less station coverage, greater depths in general, and regions
 303 beneath conductors (e.g., Chave & Jones 2012), we applied a few conductance-preserving
 304 (conductivity-thickness product) alterations of particularly C1-C3 to test if small changes
 305 in their properties are allowed without significantly affecting the misfit (i.e., changes within
 306 the nullspace, Munoz & Rath 2006). MT data are most sensitive to changes in conductance
 307 rather than conductivity, so by preserving conductance these tests highlight how changes
 308 in the geometries and locations of C1-C3 affect data misfit. They also provide an indication
 309 of their relative influence on misfit and, therefore, the relative data sensitivity to these
 310 conductive parts of the model space. In general, the tests show that only small changes in
 311 C1-C3 are allowed without significantly increasing the model misfit (Fig. 5). Specifically,
 312 the steep northeast dipping geometry of anomaly C1 is well resolved as a more vertically
 313 orientated structure in the inverted model increases the rms to ~1.8 (Fig. 5). And, the
 314 resistive region separating C2 and C3 is similarly well resolved as extensions of either C2
 315 or C3 towards the other lead to large increases in rms (Fig. 5). For example, extending C2
 316 only 6 km to the northeast produces the same significant increase in rms as removing it
 317 from the inverted model altogether (Fig. 5).

318 The model in Fig. 4 is our preferred result as it is equally well constrained by TE, TM
 319 and tipper data (Fig. S3) and the majority of that data at periods <50 s is 2D in nature with

Deleted: smaller in scale than and

Deleted: All these features are robust, as their

Deleted: and

Deleted: inversion

Deleted: subsequent rotated

Deleted: Moreover,

Deleted: their locations and shapes

Moved (insertion) [1]

Deleted: Because of the 3D nature of the

Deleted: longer

Deleted: , 3D inversions were carried out

1
 2
 3
 4
 5
 6
 7
 8
 9
 10
 11 §30 a consistent near fault-parallel strike (Fig. 2). However, as noted in Section 3, even at <50
 12 §31 s some stations and periods exhibit 3D characteristics, e.g., at the southwestern and
 13 §32 northeastern sites (Fig. 2). As a supplement and to test the effects of these minor 3D
 14 §33 features in a predominantly 2D upper to mid crustal region, we additionally applied a 2D
 15 §34 determinant inversion (Pedersen & Engels 2005; Wang et al. 2020; 2021). This type of
 16 §35 inversion has been shown to produce a less-distorted 2D model representations of a
 17 §36 predominantly 2D region that also includes 3D structures (Wang et al. 2020). However,
 18 §37 this lower distortion comes at the cost of larger model smoothness. The algorithm
 19 §38 employed is embedded in the MARE2DEM package, which facilitates comparison with
 20 §39 Fig. 4. During inversion, we used the same impedance tensor data (not tippers), matching
 21 §40 errors, and the model and inversion settings described above. Overall, all our resultant
 22 §41 determinant inversion models were consistent with Fig. 4. In fact, even when we included
 23 §42 data from all available periods, which constituted a significant increase in 3D data, the
 24 §43 determinant inversion result was still comparable to Fig. 4 (Fig. S5-S6). In Fig. S5,
 25 §44 anomalies C1-3 and R1-2 are all present, albeit the fact that C2 is more conductive and
 26 §45 extends to shallower depths, and the region containing R1, R2 and C3 is generally smoother
 27 §46 with R1-2 lower in resistivity and C3 smeared towards the northeast where there is less
 28 §47 station coverage and the data at longest periods reflect 3D structure (Figs 2 & S1).

29
 30
 31
 32
 33
 34
 35
 36
 37
 38
 39
 40
 41 §48 As a final reliability test on the inference of a mostly 2D subsurface, a 3D inversion
 42 §49 was also carried out using all available data and with the ModEM finite difference code
 43 §50 (Kelbert et al. 2014). The features of the 3D model were consistent with our 2D inversions,
 44 §51 but lacked the resolution of the MARE2DEM finite element code. These determinant and

Deleted: 2014) to check the reliability of the 2D assumption at shorter periods.

Deleted:

355 3D inversions demonstrate that our 2D modeling approach applied to a limited dataset is
 356 justified and features in the resultant 2D model (Fig. 4) can be reliably interpreted.

357

358 5. Discussion

359 Establishing properties related to structure and strain along the SSAF in Coachella
 360 Valley is essential for quantifying the potential magnitude and hazard of future large
 361 earthquakes. Fault geometrical irregularities play key roles in rupture propagation and
 362 subsequently earthquake magnitudes (e.g., Biasi & Wesnousky 2016). Rupture along
 363 dipping faults can produce 2-3 times larger ground shaking in the hanging wall compared
 364 to the footwall (Fialko 2006). Strain distributed on several neighboring fault strands instead
 365 of a primary fault, influences the likelihood of multi-fault rupture and the extent of the
 366 resulting ground motion (Lozos 2016).

367 The results presented here provide insight into these topics as they relate to the SSAF
 368 in the northern Coachella Valley (Fig. 4). Anomaly C1 represents the broad SSAF zone
 369 (~3 km wide at the surface) in the upper crust. This near-surface width is corroborated by
 370 the present of several anomalous fault damage-related structures within that same ~3 km-
 371 wide zone as revealed by analysis of large-N seismic array data (Share et al. 2022). It
 372 extends to ~4 km depth with largest amplitude at 2 km and locates northeast of the central
 373 Coachella Valley, which implies its vertical to steep northeast dip is fault and not Valley
 374 basin controlled (Fig 4). ~~If the Banning and Mission Creek strands predominantly constrain~~
 375 C1's geometry, then they likely have similar vertical to northeast dips at upper crustal
 376 depths (Catchings et al. 2009; Chi et al. 2021; Langenheim & Fuis 2021). The emergence
 377 of conductor C2 at depths >10 km is attributed to the transition from brittle to ductile

Moved up [1]: 5).

Deleted: This shallow fault zone geometry is well resolved as a more vertically orientated C1 anomaly in the inverted model increases the RMS to ~1.8 (Fig.

1
2
3
4
5
6
7
8
9
10
11 382 behavior in the area (Magistrale 2002; Smith-Konter et al. 2011) and a change in pore-
12 383 space geometry as deep creep causes minute amounts of migrating fluid to become trapped
13
14 384 and highly interconnected (Gough 1986; Park et al. 1992; Wannamaker et al. 2008). These
15
16 385 deep fluids are likely sourced from the dehydrating metasediments and/or Peninsular
17
18 386 Ranges batholith underlying the Coachella Valley sediments. The modelled location of C2
19
20 387 5-10 km southwest of the surface Mission Creek strand has some uncertainty, because of
21
22 388 limited station coverage on that side. In contrast, greater station coverage northeast of the
23
24 389 Mission Creek results in lower uncertainty and better model resolution and the data do not
25
26 390 require C2 to extend significantly in that direction, (Fig. 5). Instead, resistor R1 fits the data
27
28 391 best and extends near vertically down to ~20 km depth. The high resistivities of R1 suggest
29
30 392 relatively dry hard rock, most likely crystalline basement (Catchings et al. 2009; Ajala et
31
32 393 al. 2019), and in case these rocks do contain minor conductive materials, then those
33
34 394 materials are not well interconnected and/or exist on such a small scale that they are poorly
35
36 395 resolved with the MT frequencies employed. Interestingly, most of the seismicity in this
37
38 396 area locates within the more resistive parts of the model (Figs 4 & S5) and is closer to
39
40 397 conductor C3 than C1 or C2. We propose C3 is a separate fluid or mineral rich creeping
41
42 398 zone in the ductile crust that helps drive local earthquake activity in the more resistive and
43
44 399 mechanically stronger crust above it. This correlation between smaller scale brittle failure
45
46 400 and high resistivity has been observed along minor faults in central California (Bedrosian
47
48 401 et al. 2004) and in Turkey (Gurer & Bayrak 2007).

49
50
51
52
53
54
55
56
57
58
59
60

402 The uppermost 500 m of C1 has an average resistivity of 35 Ω .m (Fig. 4). Assuming
403 the ~6 Ω .m oases samples are representative of the type of fluids reducing the observed
404 resistivities in the shallow fault zone (they interact and react with similar materials) and

Deleted: . Extending it only 6 km to the northeast produces the same significant increase in RMS as removing C2 from the inverted model altogether (Fig. 5).

Deleted: undetectable

Deleted: R1

Deleted: (R1&R2). The lateral extent of C3 is also well resolved and any attempt to connect it with C2 leads to significant increases in RMS (Fig. 5).

Deleted: also

1
2
3
4
5
6
7
8
9
10
11 414 using Archie's law (Archie 1942), gives porosity estimates of 18% (n=1, highly
12 415 interconnected crack network) to 44% (n=2, partially connected pores) for the near surface.
13
14 416 The further decrease in the resistivity of C1 with depth (minimum of ~1 Ω .m at 2 km depth)
15
16 417 can only be explained by decreased fluid resistivities as porosities are expected to decrease
17
18 418 with depth also. We suggest two mechanisms driving this. The first is a rapid decrease in
19
20 419 fluid resistivity expected in the upper crust due to temperature and pressure increases with
21
22 420 depth, which can lead to more than an order of magnitude reduction (Nesbitt 1993).
23
24 421 Second, because of the influx of fresh water from the surrounding creeks and mountains,
25
26 422 the oases fluids represent an adequate but diluted (more resistive) proxy for the fluids
27
28 423 present at 2 km depth in the fault zone. These two factors can result in a reduction of fluid
29
30 424 resistivities to <1 Ω .m and produce the observed C1 minimum resistivity if well
31
32 425 interconnected cracks with porosities of 10-15% are assumed (e.g., Unsworth et al. 1997;
33
34 426 Bedrosian et al. 2004). In the mid-crust porosities decrease even further, the effects of
35
36 427 increasing temperature and pressure become negligible (Nesbitt 1993) and observed
37
38 428 resistivities are subsequently higher (bottom of C1, Fig. 4). We do not have direct bounds
39
40 429 on the conductive material properties producing deeper conductors C2 and C3. Others have
41
42 430 suggested that lower crustal conductors in active tectonic settings with resistivities of ~1
43
44 431 Ω .m only require porosities of 0.1-3% if the highly interconnected in situ fluids have
45
46 432 salinities close to that of seawater (e.g., Gough 1986; Hyndman et al. 1993; Becken &
47
48 433 Ritter 2012). C2 and C3 (at least in part) are likely caused by similar mechanisms.

45 434 Taken together, the imaged anomalies and other geophysical inputs permit two
46
47 435 interpretations for fault zone geometries and processes (Fig. 4). The major strands of the
48
49 436 SSAF zone in the upper crust are vertical to steeply northeast dipping and (1) evolve into

Deleted: evolves

438 a near vertical fault zone at greater depth that acts mostly as a barrier to northeast migration
 439 of fluids sourced in the southwest. A mature fault zone with a well-developed core but
 440 diminished damage and deformation zones (i.e., SSAF at mid-crustal depths) is likely to
 441 be impermeable (Caine et al. 1996). This type of impermeability and asymmetric
 442 distribution of crustal fluids about a major transform fault at depth have been observed
 443 along, for example, the central San Andreas and the Dead Sea Transform (Ritter et al. 2003;
 444 Bedrosian et al. 2004). Consequently, the seismicity in the northeast is associated with
 445 secondary or ancestral faults (Fig. 1a) with small (<5%) associated seismic velocity
 446 contrasts (Barak et al. 2015; Share & Ben-Zion 2016; Share et al. 2019). This is in line
 447 with the SCEC-CFM5.2 and high-resolution geophysical imaging of the same fault strands
 448 but 25 km to the northwest (Catchings et al. 2009). Or (2) the SSAF zone continues to dip
 449 northeast at greater depth, accommodates some of the local seismicity, manifests as C3 in
 450 the ductile crust but is either dry or consists of disconnected small-scale fluid-rich cracks
 451 from ~5 to 13 km depth. These characteristics (2) are not indicative of a mature and active
 452 transform fault that has probably experienced many large earthquake ruptures (Weldon et
 453 al. 2005). And, it requires an alternate explanation for the imaged near vertical crustal
 454 resistivity contrast beneath the surface SSAF zone that is not the active plate boundary.
 455 However, (2) is consistent with estimates from geodetic (Fialko 2006; Lindsey & Fialko
 456 2013; Tymofyeyeva et al. 2019) and potential field (Fuis et al. 2012; 2017; Langenheim &
 457 Fuis 2021) data, the latter being most sensitive to structures at <10 km depth though.
 458 An argument can be made for a non-simple broad deep SSAF zone that is a mix of (1)
 459 and (2), but that would require a lack of kilometer-scale localization of ductile fault roots
 460 (e.g., Montési 2013) driven by high crustal temperatures and low viscosities (Takeuchi &

Deleted: around R1

Deleted: to the northeast

Deleted: exceptionally

Deleted: several

Deleted:), and

Deleted: but

Deleted: is

Deleted: within the uppermost 5-

Deleted: Montesi

1
2
3
4
5
6
7
8
9
10
11 470 Fialko 2013). ~~However~~, heat flow at the site is on par with well-localized fault systems to
12 471 the north and west (Lachenbruch et al. 1985; Magistrale 2002) and it only starts increasing
13
14 472 farther south, as does the observed shallow creep of the SSAF (Sieh & Williams 1990;
15
16 473 Tymofyeyeva et al. 2019). Moreover, the deep crustal conductors imaged in this study,
17
18 474 inferred to represent ductile fault roots, are ~~not connected but separated by well-resolved~~
19 475 ~~resistive crust (Figs 4, 5, S4 & S5).~~

Deleted: But

Deleted: indeed localized to a few kilometers (Fig. 5)

477 6. Conclusions

478 Our results permit two interpretations of the electric SSAF zone. It is vertical to steeply
479 northeast dipping in the upper crust and (1) is near vertical at greater depth creating mostly
480 an impermeable barrier for northeast fluid migration or (2) continues to dip northeast but
481 is anomalously dry and ~~relatively~~ resistive up to 13 km depth where it manifests as a
482 secondary deep crustal conductor. We prefer the deeper near vertical fault interpretation
483 (1) as it is the simplest explanation for the active SSAF zone. It is also consistent with other
484 major transform fault systems both in terms of resistivity and its complex shallow to
485 simpler deeper fault zone nature. In any case, the general lack of seismicity and presence
486 of shallow aseismic creep along parts of the Coachella Valley SSAF remain enigmatic.
487 More insights from MT and other geophysical tools are required including joint inversions,
488 which is beyond the scope of this focused study. As a start, we suggest several new across-
489 fault MT arrays in the area. To the southeast these will help establish the ~~along-strike~~
490 continuity of anomalies C1-C3 and R1, ~~respectively~~, and delineate changing fault zone
491 widths, geometries, and their connection to seismicity, heat flow and creep. To the

494 northwest more MT data will illuminate the large-scale 3D conductor identified in Figs 2a
 495 & S1 and its relation to regional tectonics.

496

497 **Acknowledgements**

498 We thank Deborah Rogers and Ginny Short (Center for Natural Lands Management
 499 and Thousand Palms Oasis Preserve), Brian Ousley (Bureau of Land Management), Tom

500 Anderson, Chris Schoneman and Alicia Thomas (Sonny Bono Salton Sea National Wildlife

501 Refuge), and Martin Alvarez (City of Palm Desert) for help with permitting and access to

502 the field sites. We also acknowledge graduate students Hannah Peterson and Rosslyn King

503 for their assistance during field work. We thank Kerry Key and Gary Egbert for their

504 analysis codes, and Yuri Fialko, Rasheed Ajala and Victoria Langenheim for useful

505 discussions. This work was supported by the Southern California Earthquake Center

506 (SCEC) Award #19200. P.-E. Share was also supported by a Green Foundation

507 Postdoctoral Fellowship (Institute of Geophysics and Planetary Physics/Scripps Institution

508 of Oceanography). S.Wang was funded by the Norwegian Research Council (294404,

509 309960, and 324442) and the National Infrastructure for High-Performance Computing

510 and Data Storage in Norway (nn9872k).

511

512 **Data Availability**

513 All data are publicly available through ScienceBase (<https://doi.org/10.5066/P990U7GE>).

514

515 **References**

Deleted: and

Deleted: site

Deleted: freely

Deleted: USGS

Formatted: Font: Cambria, Font color: Auto

Formatted: Left, Indent: First line: 0"

- 1
2
3
4
5
6
7
8
9
10 \$20 Ajala, R., Persaud, P., Stock, J. M., Fuis, G. S., Hole, J. A., Goldman, M. R., & Scheirer,
11 D. S. (2019). Three-dimensional basin and fault structure from a detailed seismic
12 521 velocity model of Coachella Valley, Southern California. *Journal of Geophysical*
13 522 *Research*, 124(5), 4728-4750.
14
15
16
17 \$24 Archie, G. E. (1942). The Electrical Resistivity Log as an Aid in Determining Some
18 525 Reservoir Characteristics. *Transactions of the AIME*, 146(01), 54-62.
19 526 <https://doi.org/10.2118/942054-G>
20
21
22
23 527 Bahr, K. (1997). Electrical anisotropy and conductivity distribution functions of fractal
24 528 random networks and of the crust: the scale effect of connectivity. *Geophysical Journal*
25 529 *International*, 130, 649-660.
26
27
28
29 530 Barak, S., Klemperer, S. L., & Lawrence, J. F. (2015). San Andreas Fault dip, Peninsular
30 531 Ranges mafic lower crust and partial melt in the Salton Trough, Southern California,
31 532 from ambient-noise tomography. *Geochemistry Geophysics Geosystems*, 16, 3946-
32 533 3972.
33
34
35
36 534 Becken, M., & Ritter, O. (2012). Magnetotelluric studies at the San Andreas Fault Zone:
37 535 Implications for the role of fluids. *Surveys in Geophysics*, 33(1), 65-105.
38
39
40 536 Becken, M., Ritter, O., Bedrosian, P. A., & Weckmann, U. (2011). Correlation between
41 537 deep fluids, tremor and creep along the central San Andreas Fault. *Nature*, 480(7375),
42 538 87-90.
43
44
45 539 Bedrosian, P. A., Unsworth, M. J., Egbert, G. D., & Thurber, C. H. (2004). Geophysical
46 540 images of the creeping segment of the San Andreas Fault: implications for the role of
47 541 crustal fluids in the earthquake process. *Tectonophysics*, 385, 137-156.
48
49
50
51
52
53
54
55
56
57
58
59
60

Deleted: ¶

Formatted: Justified

- 1
2
3
4
5
6
7
8
9
10 543 Biasi, G. P., & Wesnousky, S. G. (2016). Steps and Gaps in Ground Ruptures: Empirical
11 544 Bounds on Rupture Propagation. *Bulletin of the Seismological Society of America*,
12 545 *106*(3), 1110–1124. <https://doi.org/10.1785/0120150175>
13
14
15
16 546 Blisniuk, K., Scharer, K., Sharp, W. D., Burgmann, R., Amos, C., & Rymer, M. (2021). A
17 547 revised position for the primary strand of the Pleistocene-Holocene San Andreas fault
18 548 in southern California. *Science Advances*, *7*(13), eaaz5691.
19 549 <https://doi.org/10.1126/sciadv.aaz5691>
20
21
22
23 550 Cagniard, L. (1953). Basic theory of the magneto-telluric method of geophysical
24 551 prospecting. *Geophysics*, *18*, 605-635.
25
26
27 552 Caine, J.S., Evans, J.P., & Forster, C.B. (1996). Fault zone architecture and permeability
28 553 structure. *Geology* *24*, 1025–1028.
29
30
31 554 Caldwell, T. G., Bibby, H. M., & Brown, C. (2004). The magnetotelluric phase tensor.
32 555 *Geophysical Journal International*, *158*, 457-469.
33
34
35 556 Carena, S., Suppe, J., & Kao, H. (2004). Lack of continuity of the San Andreas Fault in
36 557 southern California: Three-dimensional fault models and earthquake scenarios.
37 558 *Journal of Geophysical Research: Solid Earth*, *109*(B4).
38 559 <https://doi.org/https://doi.org/10.1029/2003JB002643>
39
40
41
42 560 Catchings, R. D., Rymer, M. J., Goldman, M. R., & Gandhok, G. (2009). San Andreas
43 561 Fault Geometry at Desert Hot Springs, California, and Its Effects on Earthquake
44 562 Hazards and Groundwater. *Bulletin of the Seismological Society of America*, *99*(4),
45 563 2190–2207. <https://doi.org/10.1785/0120080117>
46
47
48
49
50
51

Formatted: Justified

- 1
2
3
4
5
6
7
8
9
10
11 564 Chave, A. D., & Jones, A. G. (Eds.) (2012). *The Magnetotelluric Method: Theory and*
12 565 *Practice*. Cambridge University Press. 552 pp.
- 13
14 566 Chi, B., Qiu, H., Share, P.-E., Vernon, F. L., & Ben-Zion, Y. (2021). Reverse-time
15 567 migration of fault zone reflected waves: Methodology and application to the Southern
16 568 San Andreas fault. *Seismological Research Letters*, 92 (2B), 1422.
17 569 <https://doi.org/10.1785/0220210025>
- 20
21 570 Constable, S. (2013). Review paper: Instrumentation for marine magnetotelluric and
22 571 controlled source electromagnetic sounding. *Geophysical Prospecting*, 61(s1), 505–
23 572 532. <https://doi.org/https://doi.org/10.1111/j.1365-2478.2012.01117.x>
- 25
26
27 573 Egbert, G. D. (1997). Robust multiple-station magnetotelluric data processing.
28 574 *Geophysical Journal International*, 130, 475-496.
- 29
30
31 575 Fialko, Y. (2006). Interseismic strain accumulation and the earthquake potential on the
32 576 southern San Andreas fault system. *Nature*, 441(7096), 968–971.
33 577 <https://doi.org/10.1038/nature04797>
- 34
35
36 578 Fuis, G. S., Scheirer, D. S., Langenheim, V. E., & Kohler, M. D. (2012). A new perspective
37 579 on the geometry of the San Andreas fault in southern California and its relationship to
38 580 lithospheric structure. *Bulletin of the Seismological Society of America*, 102(1), 236-
39 581 251.
- 40
41
42
43 582 Fuis, G. S., Bauer, K., Goldman, M. R., Ryberg, T., Langenheim, V. E., Scheirer, D. S.,
44 583 Rymer, M. J., Stock, J. M., Hole, J. A., Catchings, R. D., Graves, R. W., & Aagaard,
45 584 B. (2017). Subsurface geometry of the San Andreas Fault in Southern California:

- 1
2
3
4
5
6
7
8
9
10 585 Results from the Salton Seismic Imaging Project (SSIP) and strong ground motion
11 586 expectations. *Bulletin of the Seismological Society of America*, 107(3), 1642-1662.
12
13
14 587 Fumal, T. E., Rymer, M. J., & Seitz, G. G. (2002). Timing of Large Earthquakes since A.D.
15 588 800 on the Mission Creek Strand of the San Andreas Fault Zone at Thousand Palms
16 589 Oasis, near Palm Springs, California. *Bulletin of the Seismological Society of America*,
17 590 92(7), 2841–2860. <https://doi.org/10.1785/0120000609>
18
19
20
21 591 Gough, D. I. (1986). Seismic reflectors, conductivity, water and stress in the continental
22 592 crust. *Nature*, 323, 143-144.
23
24
25 593 Gurer, A., & Bayrak, M (2007). Relation between electrical resistivity and earthquake
26 594 generation in the crust of West Anatolia, Turkey. *Tectonophysics*, 445, 49-65.
27
28
29 595 Hyndman, R. D., Vanyan, L. L., Marquis, G., & Law, L. K. (1993). The origin of
30 596 electrically conductive lower continental crust: saline water or graphite? *Physics of*
31 597 *the Earth and Planetary Interiors*, 81(1), 325–345.
32
33
34 598 Jones, L. M., Hutton, L. K., Given, D. D., & Allen, C. R. (1986). The North Palm Springs,
35 599 California, earthquake sequence of July 1986, *Bulletin of the Seismological Society of*
36 600 *America*, 76, 1830–1837.
37
38
39
40 601 Kelbert, A., Meqbel, N., Egbert, G. D., & Tandon, K. (2014). ModEM: A modular system
41 602 for inversion of electromagnetic geophysical data. *Computers & Geosciences*, 66, 40–
42 603 53. <https://doi.org/https://doi.org/10.1016/j.cageo.2014.01.010>
43
44
45 604 Key, K. (2016). MARE2DEM: a 2-D inversion code for controlled-source electromagnetic
46 605 and magnetotelluric data. *Geophysical Journal International*, 207(1), 571-588.
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 606 Lachenbruch, A. H., Sass, J. H., & Galanis Jr., S. P. (1985). Heat flow in southernmost
 607 California and the origin of the Salton Trough. *Journal of Geophysical Research: Solid*
 608 *Earth*, 90(B8), 6709–6736. <https://doi.org/10.1029/JB090iB08p06709>.
- 609 Langenheim, V. E., & Fuis, G. S. (2022). Insights into the geometry and evolution of the
 610 southern San Andreas fault from geophysical data, [southern](https://doi.org/10.1029/2021GL094588)
 611 California. *Geosphere*, 18(2), 458–475.
- 612 Lindsey, E. O., & Fialko, Y. (2013). Geodetic slip rates in the southern San Andreas Fault
 613 system: Effects of elastic heterogeneity and fault geometry. *Journal of Geophysical*
 614 *Research*, 118, 689-697.
- 615 Lozos, J. C. (2016). A case for historic joint rupture of the San Andreas and San Jacinto
 616 faults. *Science Advances*, 2(3), e1500621.
- 617 Magistrale, H., & Sanders, C. (1996), Evidence from precise earthquake hypocenters for
 618 segmentation of the San Andreas fault in San Geronio Pass, *Journal of Geophysical*
 619 *Research*, 101, 3031-3044.
- 620 Magistrale, H. (2002). Relative contributions of crustal temperature and composition to
 621 controlling the depth of earthquakes in Southern California. *Geophysical Research*
 622 *Letters*, 29(10), 1447.
- 623 Montési, L. G. J. (2013). Fabric development as the key for forming ductile shear zones
 624 and enabling plate tectonics. *Journal of Structural Geology*, 50, 254–266.
- 625 Muñoz, G., & Rath, V. (2006). [Beyond smooth inversion: the use of nullspace projection](https://doi.org/10.1029/2005JB004111)
 626 [for the exploration of non-uniqueness in MT. *Geophysical Journal*](https://doi.org/10.1029/2005JB004111)
 627 [*International*, 164\(2\), 301–311.](https://doi.org/10.1029/2005JB004111)

Formatted: Font color: Text 1

Deleted: 2021

Formatted: Font color: Black

Formatted: Font color: Black

Deleted: Southern

Formatted: Font color: Black

Deleted:

Deleted: in press

Formatted: Font: Italic, Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Deleted:
[https://doi.org/https://doi.org/10.1016/j.jsg.2012.12.011 ...](https://doi.org/https://doi.org/10.1016/j.jsg.2012.12.011...)

Formatted: Not Highlight

- 1
2
3
4
5
6
7
8
9
10 634 Nesbitt, B. E. (1993). Electrical resistivities of crustal fluids. *Journal of Geophysical*
11 635 *Research*, 98(B3), 4301-4310.
- 12
13
14 636 Nicholson, C. (1996). Seismic behavior of the southern San Andreas fault zone in the
15 637 northern Coachella Valley, California: Comparison of the 1948 and 1986 earthquake
16 638 sequences, *Bulletin of the Seismological Society of America*, 86, 1331–1349.
- 17
18
19 639 Nicholson, C., A. Plesch and J.H. Shaw (2017). Community Fault Model Version 5.2:
20 640 Updating & expanding the CFM 3D fault set and its associated fault database, *2017*
21 641 *SCEC Annual Meeting Proceedings & Abstracts*, XXVII, poster 234, p.142-143.
- 22
23
24
25 642 Ogawa, Y., & Honkura, Y. (2004). Mid-crustal electrical conductors and their correlations
26 643 to seismicity and deformation at Itoigawa-Shizuoka tectonic line, Central Japan. *Earth*
27 644 *Planets Space*, 56, 1285-1291.
- 28
29
30 645 Park, S. K., Jiracek, G. R., & Johnson, K. M. (1992). Magnetotelluric evidence for a brittle-
31 646 ductile transition, peninsular ranges batholith, southern California? *Geophysical*
32 647 *Research Letters*, 19(21), 2143–2146. <https://doi.org/10.1029/92GL02439>
- 33
34
35
36 648 Parkinson, W. D. (1959). Directions of rapid geomagnetic fluctuations. *Geophysical*
37 649 *Journal of the Royal Astronomical Society*, 2(1), 1-14.
- 38
39
40 650 [Pedersen, L. B., & Engels, M. \(2005\). Routine 2D inversion of magnetotelluric data using](#)
41 651 [the determinant of the impedance tensor. *GEOPHYSICS*, 70\(2\), G33–G41.](#)
- 42
43
44 652 Ritter, O., Weckmann, U., Hoffmann-Rothe, A., Abueladas, A., Garfunkel, Z., & DESERT
45 653 Research Group (2003). Geophysical images of the Dead Sea Transform in Jordan
46 654 reveal an impermeable barrier for fluid flow. *Geophysical Research Letters*, 30.
47 655 <https://doi.org/10.1029/2003GL017541>
- 48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3
4
5
6
7
8
9
10
11 656 Roten, D., Olsen, K. B., Cui, Y. & Day, S. M., 2015. Quantification of fault zone plasticity
12 657 effects with spontaneous rupture simulations, in *Best Practices in Physics-based Fault*
13 658 *Rupture Models for Seismic Hazard Assessment of Nuclear Installations*, Vienna,
14 659 Austria.
- 17 660 Ross, Z. E., Trugman, D. T., Hauksson, E. & Shearer, P., (2019). Searching for hidden
18 661 earthquakes in Southern California, *Science*, 364(6442), 767-771.
- 21 662 Rymer, M. J. (2000). Triggered Surface Slips in the Coachella Valley Area Associated with
22 663 the 1992 Joshua Tree and Landers, California, Earthquakes. *Bulletin of the*
23 664 *Seismological Society of America*, 90(4), 832–848.
24 665 <https://doi.org/10.1785/0119980130>
- 28 666 Schwarz, G. (1990). Electrical conductivity of the earth's crust and upper mantle. Surveys
29 667 in Geophysics, 11, 133-161.
- 32 668 Share, P.-E., & Ben-Zion, Y. (2016). Bimaterial interfaces in the South San Andreas Fault
33 669 with opposite velocity contrasts NW and SE from San Geronio Pass. *Geophysical*
34 670 *Research Letters*, 43(20), 10680-10687.
- 37 671 Share, P.-E., Guo, H., Thurber, C. H., Zhang, H. & Ben-Zion, Y., 2019. Seismic imaging
38 672 of the Southern California plate-boundary around the South-Central Transverse
39 673 Ranges using double-difference tomography, *Pure and Applied Geophysics*, 176(3),
40 674 1117-1143.
- 45 675 [Share, P., Qiu, H., Vernon, F. L., Allam, A. A., Fialko, Y., & Ben-Zion, Y. \(2022\). General](#)
46 676 [Seismic Architecture of the Southern San Andreas Fault Zone around the Thousand](#)
47 677 [Palms Oasis from a Large-N Nodal Array. *The Seismic Record*, 2\(1\), 50–58.](#)

Formatted: Font color: Custom Color(26,26,26)

- 1
2
3
4
5
6
7
8
9
10 678 Sieh, K., & Williams, P. (1990). Behavior of the southernmost San Andreas fault during
11 the past 300 years. *Journal of Geophysical Research*, 95, 6629–6645.
12
13
14 680 Smith, W. H. F., & Sandwell, D. T. (1997). Global seafloor topography from satellite
15 altimetry and ship depth soundings. *Science*, 277, 1957–1962.
16
17
18 682 Smith-Konter, B. R., Sandwell, D. T., & Shearer, P. (2011). Locking depths estimated from
19 geodesy and seismology along the San Andreas Fault System: Implication for seismic
20 683 moment release. *Journal of Geophysical Research*, 116, B06401.
21
22
23 685 Takeuchi, C. S., & Fialko, Y. (2013). On the effects of thermally weakened ductile shear
24 zones on postseismic deformation. *Journal of Geophysical Research: Solid Earth*,
25 686 118(12), 6295–6310. <https://doi.org/10.1002/2013JB010215>
26
27
28
29 688 Tietze, K., & Ritter, O. (2013). Three-dimensional magnetotelluric inversion in practice—
30 the electrical conductivity structure of the San Andreas Fault in Central California.
31 689 *Geophysical Journal International*, 195(1), 130–147.
32 690 <https://doi.org/10.1093/gji/ggt234>
33
34
35
36 692 Turkoglu, E., Unsworth, M., Caglar, I., Tuncer, V., & Avsar, U. (2008). Lithospheric
37 structure of the Arabia-Eurasia collision zone in eastern Anatolia: magnetotelluric
38 693 evidence for widespread weakening by fluids? *Geology*, 36, 619–622.
39
40
41
42 695 Tymofyeyeva, E., Fialko, Y., Jiang, J., Xu, X., Sandwell, D., Bilham, R., Rockwell, T. K.,
43 Blanton, C., Burkett, F., Gontz, A., & Moafipoor, S. (2019). Slow slip event on the
44 696 southern San Andreas fault triggered by the 2017 M_w 8.2 Chiapas (Mexico)
45 697 earthquake. *Journal of Geophysical Research*, 124, B016765.
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

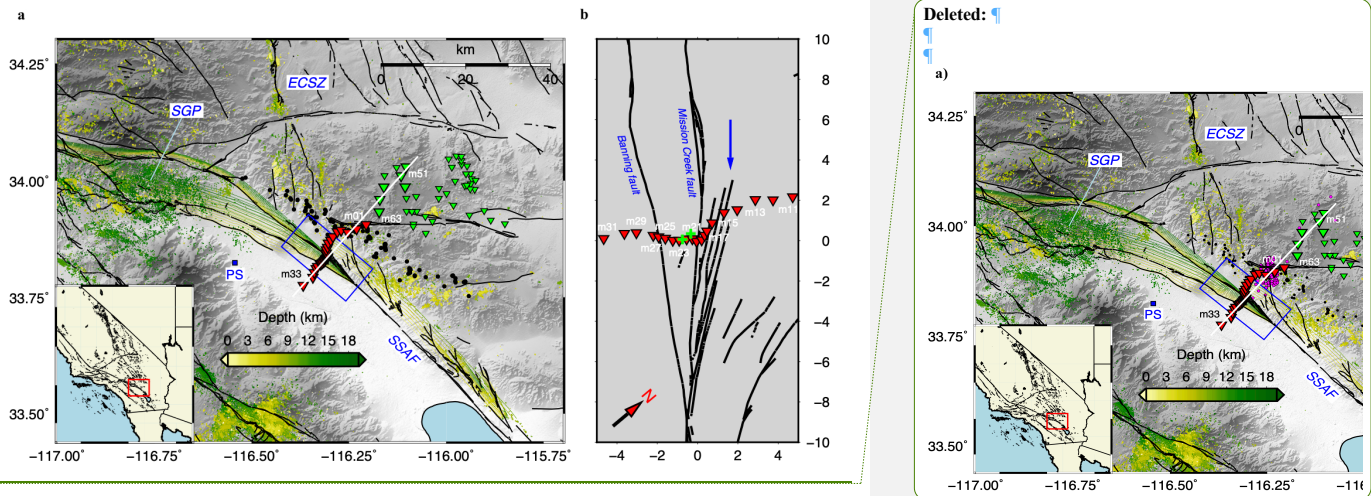
Formatted: Justified

- 1
2
3
4
5
6
7
8
9
10
11 699 Unsworth, M. J., Malin, P. E., Egbert, G. D., & Booker, J. R. (1997). Internal structure of
12 700 the San Andreas fault at Parkfield, California. *Geology*, 25(4), 359–362.
- 13
14 701 Wang, S., Constable, S., Reyes-Ortega, V., Jahandari, H., Farquharson, C., & Avile-
15 702 Esquivel, T. (2020). Two-dimensional determinant inversion of marine
16 703 magnetotelluric data and a field example from the Gulf of California, Mexico.
17 704 *Geophysics*, 86, E37–E57.
- 18
19 705 Wang, S., Constable, S., Rychert, C. A., & Harmon, N. (2021). A lithosphere-
20 706 asthenosphere boundary and partial melt resolved using marine magnetotelluric data,
21 707 *Geochemistry Geophysics Geosystems*, 21, doi.org/10.1029/2020GC009177
- 22
23 708 Wannamaker, P. E., Hasterok, D. P., Johnston, J. M., Stodt, J. A., Hall, D. B., Sodergren,
24 709 T. L., Pellerin, L., Maris, V., Doerner, W. M., Groenewold, K. A., & Unsworth, M. J.
25 710 (2008). Lithospheric dismemberment and magmatic processes of the Great Basin-
26 711 Colorado Plateau transition, Utah, implied from magnetotellurics, *Geosystems*
27 712 *Geophysics Geochemistry*, 9, Q05019.
- 28
29 713 Weldon, R. J., Fumal, T. E., Biasi, G. P., Scharer, K. M. (2005). Past and future earthquakes
30 714 on the San Andreas fault, *Science*, 308, 966-967.
- 31
32 715 Yoshimura, R., Oshiman, N., Uyeshima, M., Toh, H., Uto, T., Kanezaki, H., Mochido, Y.,
33 716 Aizawa, K., Ogawa, Y., Nishitani, T., Sakanaka, S., Mishina, M., Satoh, H., Goto, T.,
34 717 Kasaya, T., Yamaguchi, S., Murakami, H., Mogi, T., Yamaya, Y., Harada, M.,
35 718 Shiozaki, I., Honkura, Y., Koyama, S., Nakao, S., Wada, Y., & Fujita, Y. (2009).
36 719 Magnetotelluric transect across the niigata-kobe tectonic zone, central Japan: a clear

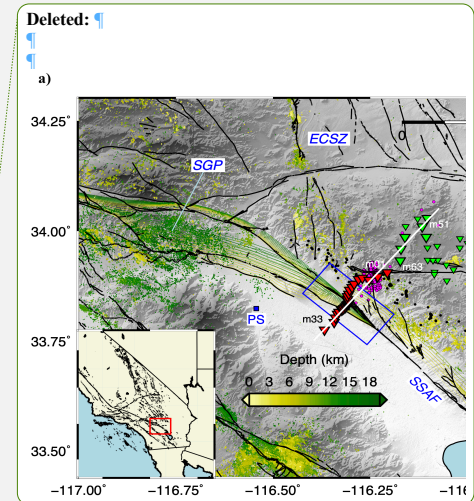
Formatted: Font: Times New Roman

720 correlation between strain accumulation and resistivity structure. Geophysical
 721 Research Letters, 36, L20311.

722
 723
 724



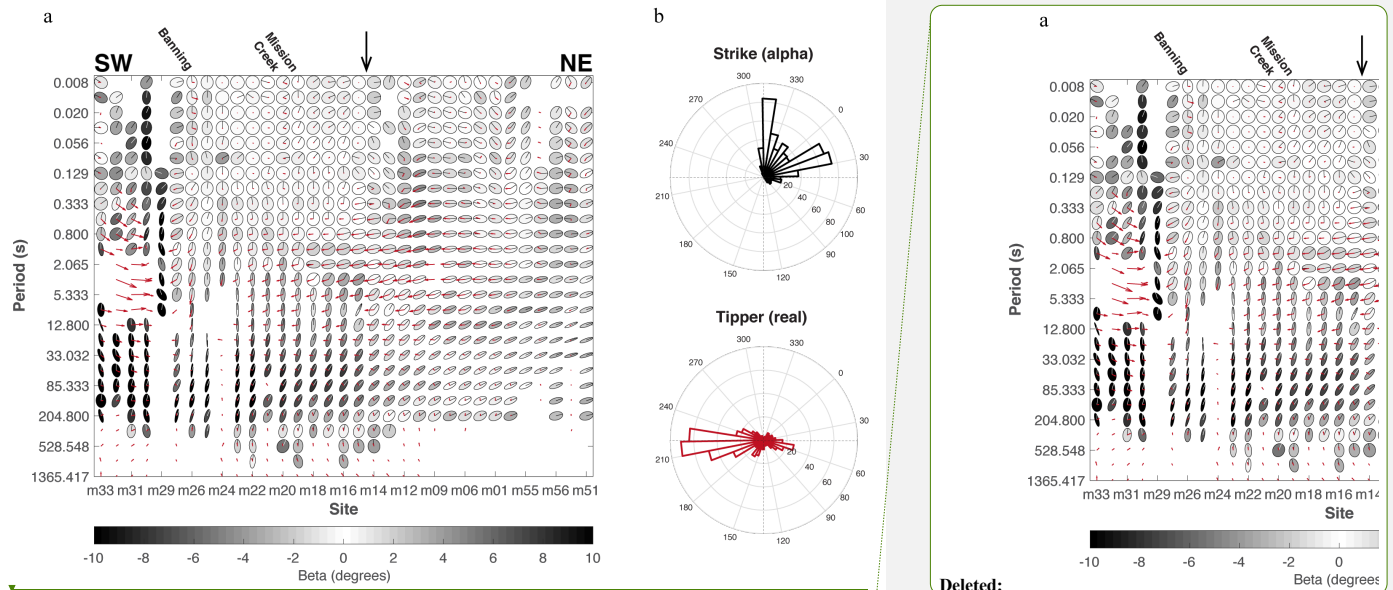
725
 726 **Figure 1:** Study area in the context of the Southern San Andreas Fault (SSAF). (a) Fault traces at
 727 the surface (black lines) and contours along the SSAF planes from shallow (yellow) to 14 km depth
 728 (green) from the SCEC-CFM5.2 (see text). The SSAF strand accommodating most of the plate
 729 boundary strain to the south is estimated to be vertical and has no contours. Secondary or ancestral
 730 faults are associated with the dipping structures (contours) to the northeast. Magnetotelluric (MT)
 731 stations acquired in 2019 (red) and in the Joshua Tree National Park during 2017-2018 (green) are
 732 depicted by triangles. Larger triangles show stations used in the 2D inversion and the white line
 733 represents the inversion model transect in Fig. 4. Depth colored dots are local earthquakes from the
 734 Ross et al. (2019) catalog. Black dots are events illuminating a large bimaterial structure at depth.
 735 Note the relative lack of seismicity directly beneath the SSAF and especially near the study area.



Deleted: and the magenta circles correspond to those plotted in Fig. 4

742 San Geronio Pass (SGP), the Eastern California Shear Zone (ECSZ) and the town of Palm Springs
 743 (PS) are shown for reference. (b) Zoom in of blue box in (a) showing the MT profile transecting
 744 the SSAF zone, which consists of the Banning, Mission Creek, and other minor fault strands. The
 745 blue arrow shows the location of a large change in electric resistivity in the across-fault direction
 746 (same arrow appears in Figs 2, 4). The Thousand Palms Oasis Preserve Visitor Center is located at
 747 the origin and the green crosses show the locations of two fluid samples taken from the oases.

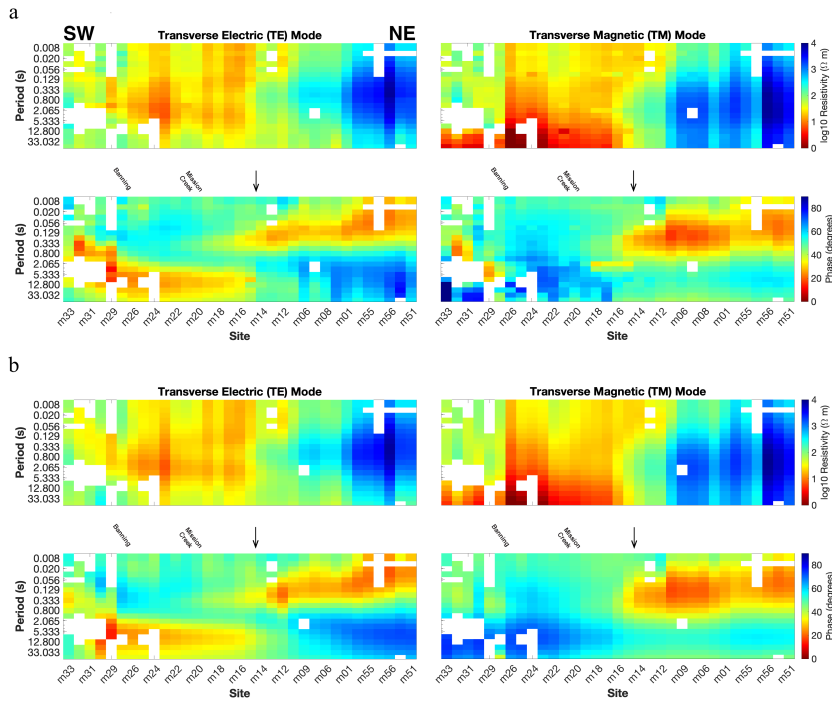
Deleted: , 3 &



Deleted:

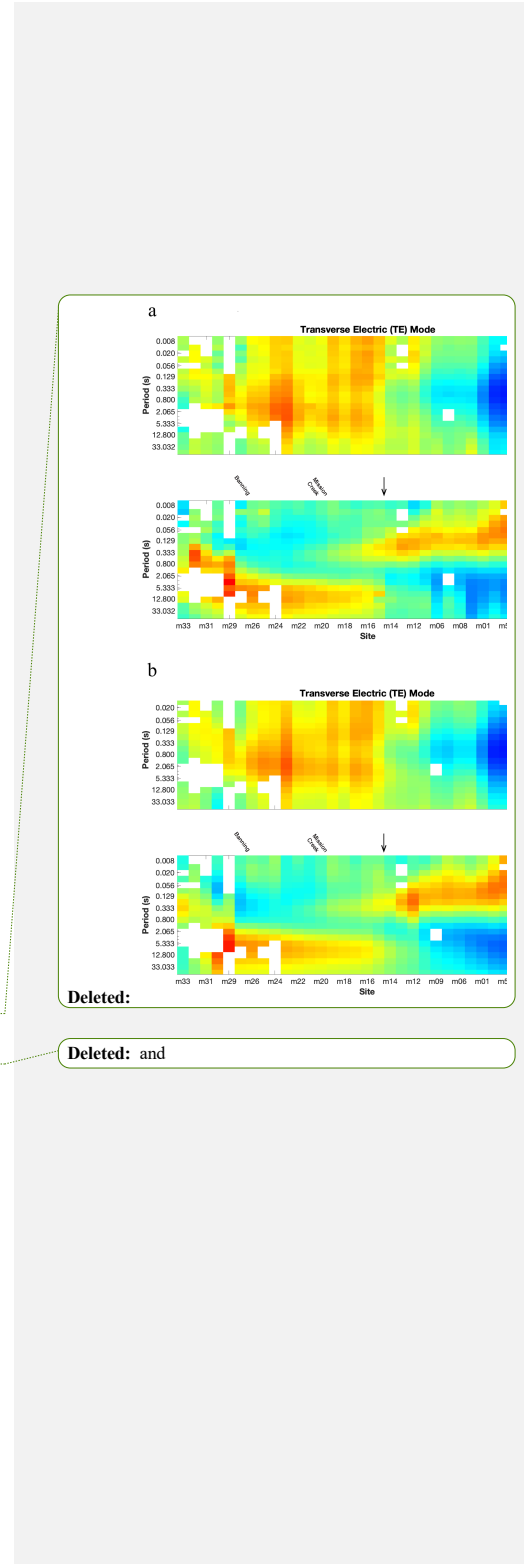
748
 749 **Figure 2:** Phase tensor and tipper results. (a) Phase tensor ellipses and real tipper vectors (maroon
 750 arrows, Parkinson convention) of all data after outliers (gaps) were removed. The degree of
 751 ellipticity equals the difference between Phi-min and Phi-max, the black lines inside ellipses point
 752 to calculated strike (alpha) and the orientation of the major axes of ellipses relative to strike and
 753 the shading of the ellipses equals beta. The coordinate frame is the same as in Fig. 1b. (b)
 754 Histograms of strike (top) and real tipper azimuths (bottom) for data up to 50 s. The dashed lines
 755 show the coordinate frame used (same as in (a)).

758
759
760



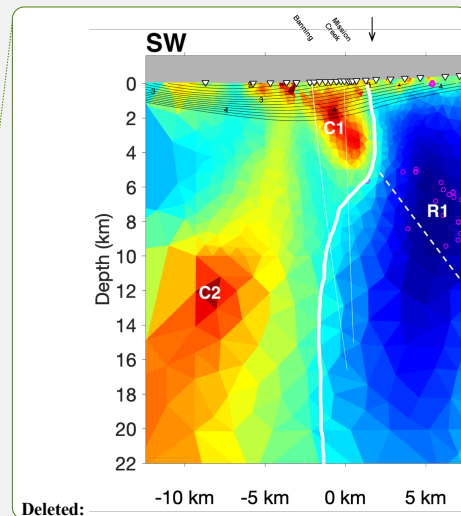
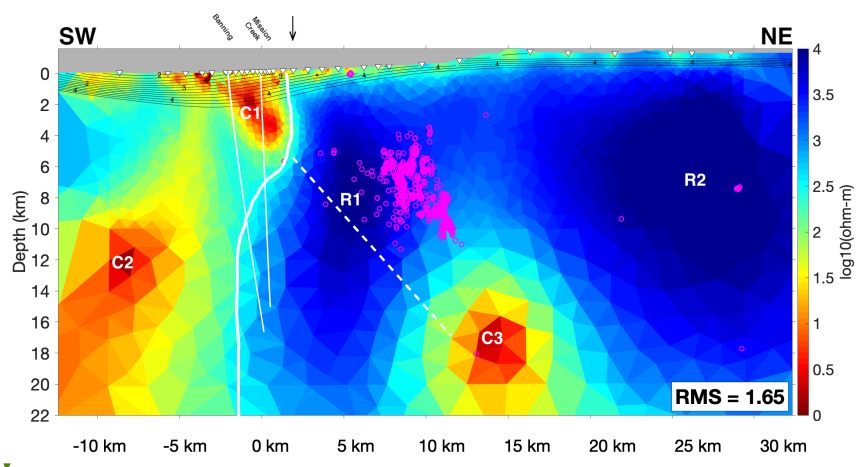
761
762
763
764
765
766
767
768
769

Figure 3: Pseudosections for the TE (left) and TM (right) modes up to 50 s period, associated with recorded (a) and modeled (b) data responses. The modeled data correspond to the inverted model in Fig. 4. Differences between (a) and (b) are also illustrated in Fig. S3.



Deleted:

Deleted: and



Deleted:

Deleted: (Fig. 1a).

Deleted: thin

772

773

774

775

776 **Figure 4:** Final 2D inverted model with prominent conductors (C1-C3) and resistors (R1-R2)

777 marked. Magenta circles are local earthquakes within 3 km of this 2D plane. The thick white line

778 highlights a region of sharp resistivity change throughout the crust and represents one (and the

779 preferred) interpretation for the location of the northeastern edge of the shallow SSAF zone and its

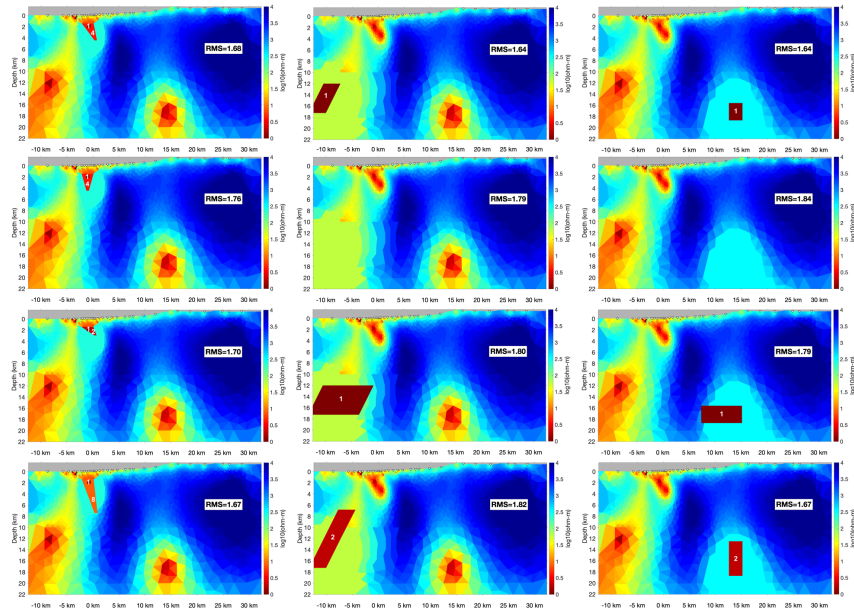
780 near vertical geometry at greater depth. The nearby thinner white lines depict geometries of the

781 Banning and Mission Creek strands from the SCEC-CFM5.2 (Fig. 1a). The dashed white line

782 connecting C1 and C3 is an alternate interpretation of SSAF zone geometry at greater depth. Black

783 contours are from the P-wave velocity model of Ajala et al. (2019) from 2 km/s to 4.4 km/s sampled

784 at increments of 0.2 km/s and highlights mostly basin geometry in the central Coachella Valley.



788

789 **Figure 5:** Equivalent resistivity anomaly representations of conductors C1 (left column), C2
 790 (middle column) and C3 (right column) with similar misfits as in Fig. 4 (top row). Lower panels
 791 show removals, extensions and translations of these anomalies (all subsequent rows), and the
 792 misfits associated with those alterations. Numbers inside anomalies represent resistivities in $\Omega.m$.

Deleted: the removals and conductance-preserving
 (conductance = electrical conductivity x thickness)

1
2
3
4 Dear Editor,
5

6
7 We would like to submit a revised version of the manuscript entitled “**Structural**
8 **properties of the Southern San Andreas fault zone in northern Coachella Valley from**
9 **magnetotelluric imaging**” for publication in *Geophysical Journal International*.
10

11 This concise paper provides, for the first time, relatively high-resolution electromagnetic
12 imaging results of the Southern San Andreas fault (SSAF) zone using a dense across-fault
13 magnetotelluric (MT) array. MT is a non-seismic tool here applied to an anomalously
14 aseismic and therefore poorly informed major fault system (i.e., SSAF) that is also one of
15 the largest seismic hazards and risks in Southern California. In general, MT is a largely
16 underutilized geophysical method in Southern California and this study therefore provides
17 a seed for many future works in the area using similar tools.
18
19

20 The imaged fault associated conductors and resistors reveal crustal fluids (or the lack
21 thereof) within shallow brittle damaged structures and highly interconnected minute
22 amounts of fluids in ductile fault roots beneath the SSAF. Taken together, these features
23 most likely suggest a near vertical San Andreas fault zone in the northern Coachella Valley
24 and more distributed deformation in the ductile crust than reported in previous studies.
25 These results help answer several outstanding questions about local fault structure and may
26 help consolidate some of the competing views between different geoscientific fields as it
27 relates to properties of the SSAF.
28
29

30
31 The paper has various figures that should be in color online and in print.
32

33 The first author of the paper was a postdoctoral researcher at the time of this project (now
34 an assistant professor). He took the lead on all the analyses performed in the study, as well
35 as on writing the results.
36

37
38 Yours sincerely,
39

40 Pieter-Ewald Share for all authors
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60