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SUMMARY

Previous magnetotelluric (MT) studies of the high-temperature Coso geothermal system in California identified a subvertical feature of low resistivity (2–5 Ohm m) and appreciable lateral extent (>1 km) in the producing zone of the East Flank field. However, these models could not reproduce gross 3-D effects in the recorded data. We perform 3-D full-tensor inversion and retrieve a resistivity model that out-performs previous 2-D and 3-D off-diagonal models in terms of its fit to the complete 3-D MT data set as well as the degree of modelling bias. Inclusion of secondary *Zxx* and *Zyy* data components leads to a robust east-dip (60†) to the previously identified conductive East Flank reservoir feature, which correlates strongly with recently mapped surface faults, downhole well temperatures, 3-D seismic reflection data, and local microseismicity. We perform synthetic forward modelling to test the best-fit dip of this conductor using the

response at a nearby MT station. We interpret the dipping conductor as a fractured and fluidized compartment, which is structurally controlled by an unmapped blind East Flank fault zone.
Inverse theory, Magnetotellurics, Hydrothermal systems
Issue Section:
Geomagnetism, rock magnetism and palaeomagnetism

1 INTRODUCTION

Our understanding of volcanic and hydrothermal processes on Earth is shaped by 3-D magnetotelluric (MT) surveys, and the way MT practitioners analyse their data (e.g. Hill *et al.* 2009; Bertrand *et al.* 2012; Kelbert *et al.* 2012; Key *et al.* 2013; Meqbel *et al.* 2014; Miensopust *et al.* 2014; Munoz 2014; Ogawa *et al.* 2014; Wannamaker *et al.* 2014; Comeau *et al.* 2015; Gasperikova *et al.* 2015; Peacock *et al.* 2016). Mapping electrical resistivity in regions with complex geology and geochemistry requires massive computing resources (Newman 2014); as a result, sometimes a choice is made to ignore part of the data—the on-diagonal components of the MT impedance tensor, Z_{xx} and Z_{yy}—in favour of a simpler and faster inversion that uses only the so-called primary, off-diagonal components, Z_{xy} and Z_{yx} (e.g. Tuncer *et al.* 2006; Newman *et al.* 2008; Patro & Egbert 2011; Zhdanov *et al.* 2011). We refer to this approach as ‘off-diagonal’ to distinguish it from full-tensor inversion. Meanwhile, Tietze & Ritter (2013) state that all impedance tensor components contain information about the subsurface, and recent modelling studies show how, in some particular cases, including the on-diagonal data change the recovered 3-D resistivity model in significant ways (Patro & Egbert 2011; Kiyan *et al.* 2014). Clearly, understanding when on-diagonal data are important to the interpretation is still open to debate.

One well-cited example of an off-diagonal approach is the study by Newman *et al.*(2008) of the East Flank of the Coso geothermal system in eastern California. Newman *et al.* (2008) imaged a subvertical low-resistivity (~5 Ohm m) feature in a zone of major geothermal energy production, and interpreted it as a zone of high temperature fluids residing in open fractures consistent with drilling mud losses at that depth. In this case, the on-diagonal data were not included because they significantly slowed the inversion. Other off-diagonal inversions of the Coso data, first by Maris *et al.* (2012) and then Wamalwa *et al.* (2013), arrived at similar conclusions regarding the necessary data components, and subvertical low-resistivity distributions in the area of the field identified in Newman *et al.* (2008). In this paper, we model the full-tensor Coso MT data set, and identify a robust and important difference from the off-diagonal models. Specifically, we find that the low-resistivity feature dips to the east, appearing to be controlled by normal faulting. Our main objective is to show how the retrieved resistivity distribution is modified by the inclusion of the on-diagonal data. To provide comparison with Newman *et al.* (2008), we utilize the same MT soundings and implement the same 3-D inversion code. The East Flank field of Coso has been the focus of cross-cutting geological, geochemical, geophysical, and reservoir engineering research, the product of which is an integrative conceptual model that we can use to judge the quality of our inversion results (Fournier *et al.* 1980; Sheridan *et al.* 2003; Unruh *et al.* 2006; Davatzes & Hickman 2010; Kaven *et al.* 2014). Therefore, Coso offers the MT community a unique opportunity to assess the benefit of 3-D full-tensor MT imaging.

1.1 Coso geothermal field

The Coso geothermal system at China Lake, CA operates over 100 geothermal wells, which supply three major power plants and inject spent brines underground. Production temperatures are in excess of 275 °C at depths of 3 km below sea level (kmbsl). The highest well temperatures (320–350 °C) are located in the East Flank field, which is the setting for the present study (Monastero *et al.* 2005).

Well logs and geological evidence at Coso suggest a characteristic metamorphic core complex (Monastero *et al.* 2005). Mesozoic plutons and minor metamorphic rocks form a fractured basement unit, which is believed to have been intruded by tens of rhyolite domes and fewer basalt dikes, and partially covered by Late Cenozoic volcanics. This period of activity began ~600 ka. Rhyolite eruptions are believed to emanate from below the brittle-ductile transition zone at ~4 kmbsl, the youngest of which are ~40 ka (Manley & Bacon 2000). Thin (~2 cm), interbedded illite and smectite clay, calcite veins and other fault gouge minerals proliferate damage zones as a result of progressive shearing accompanied by hydrothermal alteration (Davatzes & Hickman 2010). Observed downhole fluid temperatures and fluid inclusions from well cuttings suggest mineralogy is in disequilibrium with the occupying fluid, consistent with the timing of the most recent heating event.

The East Flank field lies within the Walker Lane Eastern California Shear Zone (Fig. 1), a region of transtensional stress and right-lateral, strike-slip motion (~11 mm yr^{-1} N–S; ~2 mm yr^{-1} E–W) between stable North America and Sierra Nevada (Roquemore 1980; Dixon *et al.* 2000; McClusky *et al.* 2001; Unruh *et al.* 2003). In the East Flank, faulting is an echelon and exhibits horse-tail fault termination (Unruh *et al.* 2002), structural characteristics associated with geothermal favourability (Curewitz & Karson 1997; Rowland & Simmons 2012; Faulds & Hinz 2015). A series of late Quaternary, NNE-striking, normal faults, encompassing the Coso Range, have been mapped at the surface (Duffield & Bacon 1981;

Unruh *et al.* 2006). Pre-existing faults and fractures are believed to provide and maintain permeability through continued deformation, however larger through-going faults also form boundaries to flow across which compartmentalizes the reservoir (Kaven *et al.* 2014). Partially as a result of tectonic stress, the Coso geothermal system experiences a high rate of seismicity, although most of the microearthquakes in the East Flank field are temporally and spatially correlated with injection and production activity (Kaven *et al.* 2014; Schoenball *et al.* 2015).

Figure 1.

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MT survey map of Coso East Flank geothermal field located in the Coso Range. MT sites are represented by phase tensors (period = 53 s) filled by skew value (Caldwell *et al.* 2004), indicating 3-D structure at depth. Green circles represent geothermal injection and production wellheads. Black fault traces are from Unruh & Streig (2004). Profile A–A´, shown in cross-section in Fig. 4, was selected from Unruh *et al.* (2006). Inset map at right shows transtensional tectonic environment in eastern California; red rectangle denotes survey location.

2 MT DATA

The MT method, summarized by Vozoff (1972) and Simpson & Bahr (2005), utilizes broadband electromagnetic (EM) time-series recorded on orthogonal electric (*E*) and magnetic (*H*) field sensors. Averaging in the Fourier domain results in a second rank (2 × 2) tensor, referred to as the MT impedance tensor ([*Z*]), that represents the subsurface impedance to vertically incident planar EM wave propagation:

$$E=[Z]H$$

$$[Z]=\begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}.$$

[Z] is related to electrical resistivity and can be predicted through numerical simulation of a resistivity model. Modelling effort is often dictated by the dimensionality of the data. Commonly, the off-diagonal impedance tensor components have larger amplitudes than on-diagonal components. In an ideal 1-D resistivity model, the on-diagonals are zero and the off-diagonals are equal in magnitude. For valid 2-D cases, rotating [Z] into a coordinate frame aligned with the regional geoelectric strike direction minimizes the on-diagonal elements. This enables inversion of the off-diagonal elements (now not necessarily equal in magnitude) for subsurface resistivity sampled by two dominant orientations of current flow (called the TE and TM modes). In 3-D, the on- and off-diagonal element amplitudes can be significant at all frequencies; however, on-diagonal amplitudes typically approach the off-diagonal element amplitudes at lower frequencies, and fall off at higher frequencies.

Between 2003 and 2005, a grid of 125 horizontal MT soundings was recorded across the East Flank field of the Coso geothermal system (Newman *et al.* 2008). A subset of 101 sites (Fig. 1) was used to model the geometry of a producing geothermal reservoir. The geothermal production facilities and the Bonneville Power Authority DC intertie transmission line were identified during the survey as sources of noise in the electric and magnetic fields. This led Wannamaker *et al.* (2004) to use two different long distance remote reference MT observatories at Parkfield, CA and Socorro, NM to retrieve the natural electromagnetic Earth response at Coso.

After data processing, ~90 per cent of the soundings exhibit a 3-D trend in Zyx phase, where the data wrap out of quadrant at frequencies below 0.1 Hz (Fig. 2). This is consistent with observations of phase tensor skew (Caldwell *et al.* 2004) in excess of 10° at low frequencies. For the 101 station array, phase tensor skew exceeds 5° at all stations, and 10° at 85 per cent of stations (Fig. 1).

Fig. 2 highlights this 3-D phase response and phase tensor skew feature as a function of frequency at a station (E28) located in the centre of profile A–A´. It is important to note that while the wrapping of an off-diagonal component is an obvious 3-D aspect of the MT impedance tensor data, the appreciable amplitudes of the on-diagonal data at low frequencies is equally suggestive of complex subsurface structure.

Figure 2.

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Example full-tensor data from MT site E28 with phase tensors plotted as a function of period and shaded by skew value. The anomalous long period out-of-quadrant *Zyx* phase trend, the relatively high amplitude *Zxx* and *Zyy* components, and the skew values all indicate full-tensor analysis may be important. Error bars represent the data weight assigned during inversion.

Figure 3.

View largeDownload slide

Cut-away perspective view through part of the 3-D full-tensor MT resistivity model (looking northwest) with microearthquake relocations (grey circles). Isosurfaces relating to C1 and R1 are selected for illustration: blue is 250 Ohm m; yellow is 10 Ohm m; red-orange is 4 Ohm m. Fig. 4 more accurately displays the complete electrical resistivity colour scale.

Despite this observation, Newman *et al.* (2008), Maris *et al.* (2012), and Wamalwa *et al.* (2013) each proceed with off-diagonal inversion. Newman *et al.* (2008) shows final 3-D inverse model datafits at sounding locations that do not reproduce the phase data in the *Zyx* component. This implies that the off-diagonal model misses important 3-D structure. In fact, in the case of Newman *et al.* (2008) the central sub-vertical low-resistivity vertical feature identified as a fractured production zone is actually visible in the original 2-D *Zyx* model which was used to create the starting model for 3-D inversion. Through additional off-diagonal inverse modelling, we find that preconditioning 3-D model space with results from 2-D TM-mode inversion is a necessary condition to retrieve this conductive structure, most likely because of non-uniqueness. In other words: we do not retrieve a low-resistivity feature when the off-diagonal data are inverted in a 3-D mesh initialized from an homogeneous 3-D starting model of 30 Ohm m (or 100 Ohm m).

3 3-D INVERSE MODELLING

To address this shortcoming, we applied 3-D inversion to the full-tensor data set. Aside from the added computational burden, a major challenge of full-tensor inversion relates to error weighting (Tietze & Ritter 2013). Data components are commonly weighted by a relative amplitude measure of 3–10 per cent (Heise *et al.* 2008; Hill *et al.* 2009; Xiao *et al.* 2010; Peacock *et al.* 2015). In the case of Coso, this approach failed to converge because the *Zxx* and *Zyy* amplitudes vary more dramatically than the *Zxy* and *Zyx* amplitudes, which results in the prioritization of noisy, low amplitude on-diagonal data in the inversion. To address this issue, we implemented an adaptive data-weighting scheme based on the standard deviation of the statistically determined error estimate (Patro & Egbert 2008), in addition to a relative amplitude error floor of 10 per cent. Thus, when the measurement was noisy, the data would be down-weighted. This style of composite data-weighting has been successful in previously 3-D full-tensor MT inversions (e.g. Meqbel 2009; Bertrand *et al.* 2012).

3.1 Numerical simulation

In order to provide an accurate comparison with the off-diagonal 3-D modelling of Newman *et al.* (2008), we inverted the same 101 post-processed transfer functions from the MT Coso survey, albeit with the off-diagonal data included, and executed the same 3-D finite difference algorithm, EMGeo (Newman & Alumbaugh 2000; Newman & Boggs 2004). We used a comparable data bandwidth (0.004–

120 Hz), interpolated to 4 periods per decade. Some authors argue that We initialized the imaging process from an homogeneous 3-D starting model of 30 Ohm-m, but when we used 100 Ohm-m the inversion retrieved similar features.

We followed the sequenced workflow described in Lindsey & Newman (2015). First, the low frequency data (0.004–1 Hz) were inverted using a coarse mesh. Then all of the data were inverted on a fine mesh that began from a reparametrized form of the final coarse-grid solution. Each mesh was carefully designed with uniformly spaced nodes across the core of the model domain, defined by the survey footprint, and slow growth of node spacing (10–15 per cent) from just outside the model core to a far boundary several low-frequency skin depths away. The coarse grid model core sampling was 500 m laterally and 250 m vertically, which was reparametrized to 250 m laterally and 100 m vertically in the fine grid. Topography was accurately represented in both meshes using very fine (50 m) vertical nodes ±1000 m around the land surface. In total, the coarse grid used 43 × 46 × 80 nodes and the fine grid used 86 × 92 × 145 nodes.

To stabilize the inversion, we included a smoothing criterion or Tikhonov regularization operator (λ) in the objective function (Tikhonov & Arsenin 1977; Newman & Alumbaugh 2000). For additional consistency with Newman *et al.* (2008), we applied the same regularization approach. Specifically, we initialized λ from 1.25, and made 50 per cent reductions in λ when the EMGeo algorithm stalled in its nonlinear-conjugate gradients line-search. λ was reset after model refinement (Lindsey & Newman 2015).

Full-tensor inversion was executed in parallel on ~4000 core processors of Hopper Cray XE6 (1280 × 1015 flops; 217 TB memory) located at Lawrence Berkeley National Laboratory's National Energy

Research Scientific Computing Center (NERSC). At this scale, the computational runtime was on the order of 30 hr.

The sequenced 3-D full-tensor inversion was truncated after 218 iterations with a final RMS of 3.5. The initial coarse inversion phase achieved an RMS of 2.7 after 93 iterations. 3-D full-tensor inversion required about an order of magnitude more resources than the off-diagonal 3-D inversion carried out by Newman *et al.* (2008), which achieved approximately the same RMS but only for the off-diagonal data. The cost of the full tensor inversion was significantly reduced by adoption of the sequenced workflow, which was not implemented in Newman *et al.* (2008).

3.2 3-D full-tensor inverse model

The final 3-D full-tensor model exhibits many of the same hydrothermal resistivity features that were revealed by earlier off-diagonal analysis, but we focus on the differences in the East Flank field (Figs 3 and 4). We find a conductive (2–5 Ohm m) feature dipping to the southeast at approximately 60°, referred to here as C1. C1 extends from 0.5 to 2 km below the surface (−0.7 to 3.2 kmbsl), and extends laterally approximately 1–1.5 km. In our model, the surrounding space in the East Flank field is characterized by sharp boundaries (~1 km wide) with higher resistivity volumes (200–500 Ohm m) to the northwest of C1 (i.e. R1) and also to the southeast, which dip at 60°. R1 extends to greater depth than C1. In the near surface there is a ~200 m conductive (2–5 Ohm m) veneer. Approximately 3 km southeast of the R1, there is additional conductive material from the surface to 300 mbsl (1.5 km depth).

The model achieves an acceptable-to-good level of fit at all stations, outside of the minimum signal dead band around 1 Hz. Figs A1–A3 show final model data plotted against the recorded data for the MT stations along profile A–A´ which traverses R1 and C1 (Fig. 4). At periods shorter than 10 s, off-diagonal data are fit as well with the full-tensor model as with the off-diagonal 3-D model of Newman *et al.* (2008). Perhaps most importantly, the full-tensor model does a much better job fitting the long-period out-of-quadrant *Zyx* phase trend, which was not fit by Newman *et al.* (2008). On-diagonal data are well fit at all periods, demonstrating the successful recovery of complex 3-D structure and the success of our adaptive data weighting scheme.

Figure 4.

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Cross-section through the 3-D full-tensor MT resistivity model along profile A–A´, shown in Figs 1 and 3. Proximate MT sites are shown above the model; Figs A1–A3 show MT site data and the model data fit. Solid black lines represent mapped faults projected to depth; the dotted line represents the location of the East Flank Fault (EFF; Unruh *et al.* 2006; Davatzes & Hickman 2010). Microearthquake relocations from ±1 km off-profile are shown as small black dots (*M* ≥ 1) and larger white circles (M ≥ 1). Hatched lines at bottom indicate where the surfaces representing 70 per cent and 80 per cent of maximum field temperature (T_{max}) intersect the cross-section (Navy Geothermal Program Office, 2015).

3.3 Model sensitivity

The dip of C1 was tested by forward modelling the response of simple 3-D test models at MT site E28, located above C1 (Fig. 5). The test models consisted of a 2 Ohm-m conductor of similar dimension, location, and geometry to C1, embedded in a 30 Ohm-m half-space. The dip of the conductor was varied between 40° and 90° degrees in increments of 10°. Fig. 5(a) portrays the difference between two of these models in cross-section, simulating the synthetic comparison of the final 3-D off-diagonal model (90° dip) from Newman *et al.* (2008) and the final 3-D full-tensor model (60°). Synthetic data from these two cases demonstrate that the dip of C1 strongly controls both the out-of-quadrant *Zyx* phase and the on-diagonal phase and amplitude (Fig. 5b). For example, the *Zxx* and *Zyy* amplitudes are off by 2–4 orders of magnitude in the 90° case, but are well fit in the 60° case; data fits degrade as the dip is increased or decreased from 60°. By isolating the forward response of a simplified C1 conductor with variable dip, we have discriminated between two hypotheses and shown how the out-of-quadrant phase data across the MT array at least partially support the interpretation of a normally-dipping C1.

Figure 5.

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(a) Cartoon showing the cross-section along 3-D synthetic models used to examine the sensitivity of the datafit to the dip of C1 (shown in Fig. 4). Dips of 90° and 60° are shown for their likeness to the off-diagonal model and the full-tensor model, respectively. (b) Predicted data fit (lines) from synthetic forward models in (a) to the recorded data (circles) at MT site E28 (shown in Fig. 2). Dotted lines represent the 60° case; solid lines represent the 90° case.

4 DISCUSSION

Geophysical models should always be judged by their congruency with outside information, in addition to the data fit. This is especially true of MT models, because of their high degree of non-uniqueness. Our ability to accurately characterize the complex electrical resistivity distribution at Coso using 3-D full-tensor MT inversion is demonstrated by how well the 3-D full-tensor resistivity model correlates with well temperatures, drilling evidence, mapped faults, seismic reflection data, and microseismic event locations.

4.1 3-D full-tensor MT modelling

Inverting the full MT impedance tensor retrieves a better fit to the off-diagonal data when compared with Newman *et al.* (2008). In particular, the out-of-quadrant Zyxphase data are fit at most stations, while they were not fit in the off-diagonal approach. The most reasonable explanation for the lack of fit by an off-diagonal modelling approach is that a significant part of the 3-D Earth response is buried in the on-diagonal components. Inversion settings are another important feature in the MT modelling process (Miensopust *et al.* 2013; Tietze & Ritter 2013). Our FD algorithm, data-weighting scheme, parametrization, regularization approach, and segmented inversion workflow appear to reproduce the available geophysical and geological information, although this does not imply that other inversion settings would be less effective. The lack of any structure in the 3-D starting model is an advantage in understanding which resistivity structures are demanded by the MT data. Hypothesis testing with simple forward models reveals how the MT data are strongly sensitive to the dip of C1, which was only introduced when the on-diagonal data were added to the inversion. The link between 3-D data characteristics and 3-D model structure is often limited by non-uniqueness; however, if a robust link can be identified it promotes confidence in the related model structure.

4.2 Interpretation

Unlike previous inversions of the Coso MT data, we find that C1 is separated from more resistive zones (~200 Ohm m) to the east and west by sharp east-dipping boundaries, which we interpret as major compartmentalizing fault zones. The most productive wells in the Coso geothermal system exploit these NNE-striking normal faults (Sheridan *et al.* 2003; Davatzes & Hickman 2010). A good example is the Coso Wash fault, whose surface trace coincides with the location of one such dipping resistivity boundary in the full-tensor model. Similarly, we interpret the west boundary of C1 as a blind normal fault, which we call the EFF. Although there is no evidence of a fault trace at the surface, the EFF was identified in seismic reflection surveys by Unruh *et al.* (2006) as a detachment fault with more listric character than is observed here. The EFF is visible in the full-tensor resistivity model from 500 m depth (−1 kmbsl) near MT station E19 down to 3.7 km depth (2.5 kmbsl). The EFF has a roughly constant dip of 60° over its full extent. We find no evidence for west-dipping faults, hypothesized to terminate into the EFF at depth, perhaps because they are permeable.

The EFF zone correlates with a dense locus of microseismic events in the East Flank field, which form an east-dipping lineament in cross-section from 1 to 2.8 kmbsl. Kaven *et al.* (2014) studied single-event (absolute) relocations for approximately ~70 000 natural and induced microearthquake recordings using the local seismic network of the Navy Geothermal Program Office. Approximately 7600 events with magnitudes $ML \geq 2.9$ occurred in the area of the East Flank around the timing of the MT survey (2004–2006). By using a 3-D velocity model Kaven *et al.* (2014) found the largest seismic events ($M > 1.5$) in the area occur along the EFF lineament that extends into R1 in our model. Higher resistivity in R1 could result from lower permeability and a more conductive (as opposed to advective) temperature profile, which might explain the potential for higher stress concentrations. Throughout C1, Kaven *et al.* (2014) finds diffuse, relatively lower magnitude brittle deformation, potentially accommodated along intra-compartment structures. The highest temperature fluids in the field have been recovered from below 2–3 kmbsl, down-dip of C1, where no microseismic events are found (Fig. 4). These findings are consistent with the location of brittle-ductile transition based on seismic reflection, and the expected onset of plasticity for quartz, plagioclase and feldspar based on well-field temperature records (300–450 °C).

The general location of C1 is consistent with previous 2-D and off-diagonal 3-D inversion (Newman *et al.* 2008; Maris *et al.* 2012; Wamalwa *et al.* 2013), but the new model has a different dipping geometry. Typical geothermal reservoirs are commonly found to be more resistive (Pellerin *et al.* 1996), although low-resistivity anomalies in geothermal systems have been identified and explained with a small amount of partial melt (e.g.

Didana *et al.* 2014; Gasperikova *et al.* 2015), clay (e.g. Heise *et al.* 2008; Cumming & Mackie 2010), or upwelling, hot, saline brine (Heise *et al.* 2008; Bertrand *et al.* 2012), all of which depress electrical resistivity. We consider each of these hypotheses in relation to C1. First, the recent volcanic history and seismic reflection data support a shallow (3–4 kmbsl) brittle-ductile transition, and it is at least possible that some percent partial melt could exist there (Unruh *et al.* 2006). However, drilling records, well temperatures, and microseismic relocations all reject the hypothesis that partial melt extends to 1–2 kmbsl. The second hypothesis suggests that intra-compartment deformation and subsequent fault healing promotes secondary mineralization of calcite, illite and smectite clays across the East Flank field, depressing electrical resistivity. Indeed, Davatzes & Hickman (2010) showed how lost circulation within the East Flank field (down to 3 km depth in one well) was caused by intersection of the wellbore with a remarkably high density of fractures related to broad and intense transtensional shearing. However, well temperatures have been directly observed in the range 200–220 °C, outside of the stable thermodynamic regime for these minerals. We hypothesize that C1 is, in fact, a dense fracture network that is saturated or partially-saturated with hot, saline fluids. Intra-compartment deformation along mineralized shear surfaces would only further enhance electrical conductivity, which is plausible if field temperatures are not accurately or completely represented by well records. Based on the agreement between surface faulting, seismic reflection data, microseismic analysis, available wellfield temperatures, and the full-tensor resistivity model, fluids pathways related to the east-dipping C1 may be structurally-controlled by the EFF. Structural-control of fluid pathways has been observed elsewhere in the Basin and Range (e.g. Faulds *et al.* 2010). Advective heat transport through this dense fracture network may characterize a significant piece of the heat extraction process. Within the Coso system, compartmentalization is known to limit reservoir fluid recharge, in which neighbouring high and low permeability zones are separated by a fault boundary. For example, drawn-down accompanying geothermal production is highly localized as evidenced by InSAR measurements of surface deformation (Fialko & Simons 2000; Wicks *et al.* 2001). Compartmentalization creates field-wide well management issues and poses a significant geophysical imaging challenge to guide citing new injection and production wells.

5 CONCLUSIONS

We presented the results of 3-D full-tensor inversion of 101 MT soundings, including a new 3-D resistivity model of the producing East Flank field at Coso. No assumptions about dimensionality, geoelectric strike, or geological structure were made. Improving upon earlier models that relied on these biasing assumptions and only considered the off-diagonal components of the data, the full-tensor 3-D model achieves better data fit and better agreement with well temperature data, seismic reflection data, mapped surface faults, and microseismic event relocations. In particular, it captures a 3-D *Zyx* phase response, which could not be retrieved by off-diagonal inversion. A critical feature in the new model is an east-dipping resistivity boundary, interpreted as the EFF, which we believe serves to compartmentalize a broad, high temperature, fluid-filled fracture reservoir zone within the East Flank field.

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APPENDIX A: FINAL 3-D FULL-TENSOR MODEL DATA FITS

Figure A1.

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Data fit from final 3-D full-tensor model (lines) to the recorded data (circles) from MT sites E18, E19, E20 located along profile A–A´. Colour indicates tensor component: *Zxy* = red; *Zyx* = blue; *Zxx* = green; *Zyy* = cyan.

Figure A2.

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Data fit from final 3-D full-tensor model (lines) to the recorded data (circles) from MT sites E28, E29, E39 located along profile A-–A´. Colour indicates tensor component: *Zxy* = red; *Zyx* = blue; *Zxx* = green; *Zyy* = cyan.

Figure A3.

View largeDownload slide

Data fit from final 3-D full-tensor model (lines) to the recorded data (circles) from MT sites E41, E50 located along profile A–A´. Colour indicates tensor component: *Zxy* = red; *Zyx* = blue; *Zxx* = green; *Zyy*= cyan.