The Los Humeros and Acoculco Geothermal Resources in the Trans-Mexican Volcanic Belt: Magnetotelluric Phase Tensor Analysis and its Significance for Tectonic Interpretation

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ABSTRACT

The Acoculco and Los Humeros geothermal systems in the eastern sector of the Trans-Mexican Volcanic Belt are investigated for future exploitation and expansion, respectively. Electromagnetic methods are used to investigate the subsurface resistivity distribution in order to determine worthwhile future drilling targets. Magnetotelluric data are interpreted by using phase tensor analysis in order to derive the orientation of conductive features. For the Los Humeros geothermal system the caldera crossing NW-SE aligned Maxtayola fault can be identified by a clear change in phase tensor ellipses at high frequency ranges. At lower frequencies, the homogenous distribution of strongly elliptical phase tensors points at a strong conductivity contrast at greater depth. For the geothermal system at Acoculco the electromagnetic data indicate a partitioned subsurface resistivity distribution. Phase tensor ellipses on both sides of a NW-SE lineament, located east of the exploration wells, differ significantly.

1. INTRODUCTION

Fault zones, due to their enhanced permeability, control fluid flow. Volatiles, brines and magmas are ascending along fault zones. Often volcanic edifices are aligned along fault zones or occur at fault zone intersections (e.g. Cembrano and Lara, 2009). Also, the location of thermal hot springs or fumaroles match fault zone alignments (e.g. Giggenbach & Soto, 1992; Gudmundsson, 2000; Held et al., 2018). Thus, fault zones enable advective heat ascent generating heat anomalies that can be used efficiently for energy production.

Hydrothermal systems are characterized by a reservoir body overlie by a cap rock that seals the reservoir to the surface and prevents the fluid from escaping. The systems are driven by a heat source triggering fluid ascent. The cap rock, but also the reservoir body, in hydrothermal reservoirs contains hydrothermal alteration minerals. Thereby, the mineral assembly is governed by temperature and thus, a typical sequence is evident in several geothermal systems (Inoue et al., 1992; Spichak and Manzella, 2009). Smectites detectable by electromagnetic techniques due to their high conductivity, are formed at intermediate temperatures and thus, occur in upper layers of the cap rock (Vozoff, 1991). In the context of geothermal reservoirs fault zones are of utmost importance as 1) they connect the heat source to the reservoir and 2) by itself increase the reservoir permeability and enlarge the subsurface heat exchanger area (e.g. Held et al., 2014).

Besides geothermal exploration, the magnetotelluric (MT) method is used for investigations of the earth's mantle due to the ability to penetrate deep into the rock. These long frequency investigations target the roots of subduction processes (Bertrand et al., 2012; Wannamaker et al., 2014), melting processes (Brasse et al., 2015; Díaz et al., 2012) or deep rooting fault zones (Türkoğlu et al., 2015; Unsworth et al., 1997). Major scale crustal fault zones can be recorded by elevated conductivities (Bedrosian, 2002; Wannamaker et al., 2002), yet the conductivity mechanism is not fully investigated. Saline fluids, hydrothermal alteration products or a combination of both could cause the decrease in resistivity (Held, 2018).

The research presented here is conducted in the framework of the European-Mexican co-funded GEMex project, investigating the Los Humeros and Acoculco geothermal systems. Both systems are located inside a caldera collapse structure, but possess highly differing characteristics. The Los Humeros geothermal reservoir is a superhot geothermal resource that is operated successfully producing 70 MW$_e$ from 23 wells (Romo-Jones et al., 2017). The Acoculco system was investigated as an enhanced geothermal system (EGS). In order to explore the geothermal resource and guarantee a future sustainable exploitation, an extensive international research program was initiated, aimed at investigating the characteristics of both areas, superhot conditions for Los Humeros and the potential of EGS development at Acoculco.

Besides seismological and gravimetric techniques, at both research locations intensive 3D-MT campaigns were conducted, resulting in 122 measurements at Los Humeros and 68 measurements at Acoculco. The data acquisition, processing and inversion are presented in Hersir et al. (2020) and Benediktsdóttir et al. (2020), whereas sensitivity studies about 3D inversion of MT data from Los Humeros are presented by Ruiz-Aguilar et al. (2020). In this study, we use the phase tensor analysis to investigate the orientation of subsurface

resistivity structure. The phase tensor analysis was developed by (Caldwell et al., 2004) and enables a galvanic distortion independent visualization of the magnetotelluric data.

2. GEOLOGICAL SETTING

Los Humeros and Acoculco geothermal concessions are located in the eastern sector of the Trans-Mexican Volcanic Belt (TMVB), a 1200 km long active volcanic arc stretching from the Pacific to the Gulf of Mexico coast (Fig. 1a). The eastern sector of TMVB is characterized by the occurrence of several large scale caldera collapse craters (Ferrari et al., 2012). Both concession are located within major caldera collapse structures. Faulting in the TMVB decreases from west to east (Ferrari et al., 2012) but indications for preferential fault orientations of NW-SE, E-W and NE-SW are documented (Cadoux et al., 2011; Campos-Enriquez and Garduño-Monroy, 1987; García-Palomo et al., 2018; López-Hernández et al., 2009).

Los Humeros is the easternmost caldera of TMVB located in a 40 km-wide NNE–SSW aligned depression limited by volcanic chains to the east and west. The basement sequence comprise Late Paleozoic plutonic and metasedimentary rocks, Triassic-Cretaceous sedimentary rocks (e.g. thick limestone sequences) and Tertiary plutonic intrusions (e.g. Ferriz and Mahood, 1984). The caldera formation started at 500 ka (Carrasco-Núñez et al., 2017) and comprises two main collapse events (Los Humeros & Los Potreros calderas) (Campos-Enriquez and Arredondo-Fragoso, 1992). Caldera formation deposited two series of ignimbrites (Xaltipan, Zaragoza ignimbrites), accompanied by further volcanic manifestations e.g. monogenetic eruptive centers lava flows, pyroclastic deposits (Carrasco-Núñez et al., 2012; Norini et al., 2015). Following the collapsing phases, volcanic activity resumed after 50 ka, generating basaltic-andesitic lava flows and tephra deposits (Dávila-Harris and Carrasco-Núñez, 2014). Recently, magma temperatures are determined to 600°C – 650°C indicating solidified conditions in the magma chamber (Campos-Enriquez and Arredondo-Fragoso, 1992; Verma, 1983).

Inside the caldera the major fault zones are documented by Campos-Enriquez and Arredondo-Fragoso (1992) and Carrasco-Núñez et al. (2017). The Maxtayola fault zone is oriented NW-SE, crossing Los Potreros scarp and running along the Xalapasco crater (Dávila-Harris and Carrasco-Núñez, 2014). Towards the north, the fault split into N-S oriented splay faults (Norini et al., 2015). In the eastern sector, E-W striking faults occur. The production (and also injection) wells are operated east of NW-SE Maxtayola fault and along the N-S aligned splay fault (Fig. 1b). Abandoned wells are located along E-W running faults or west of Maxtayola fault, besides individual wells located close to productive wells.
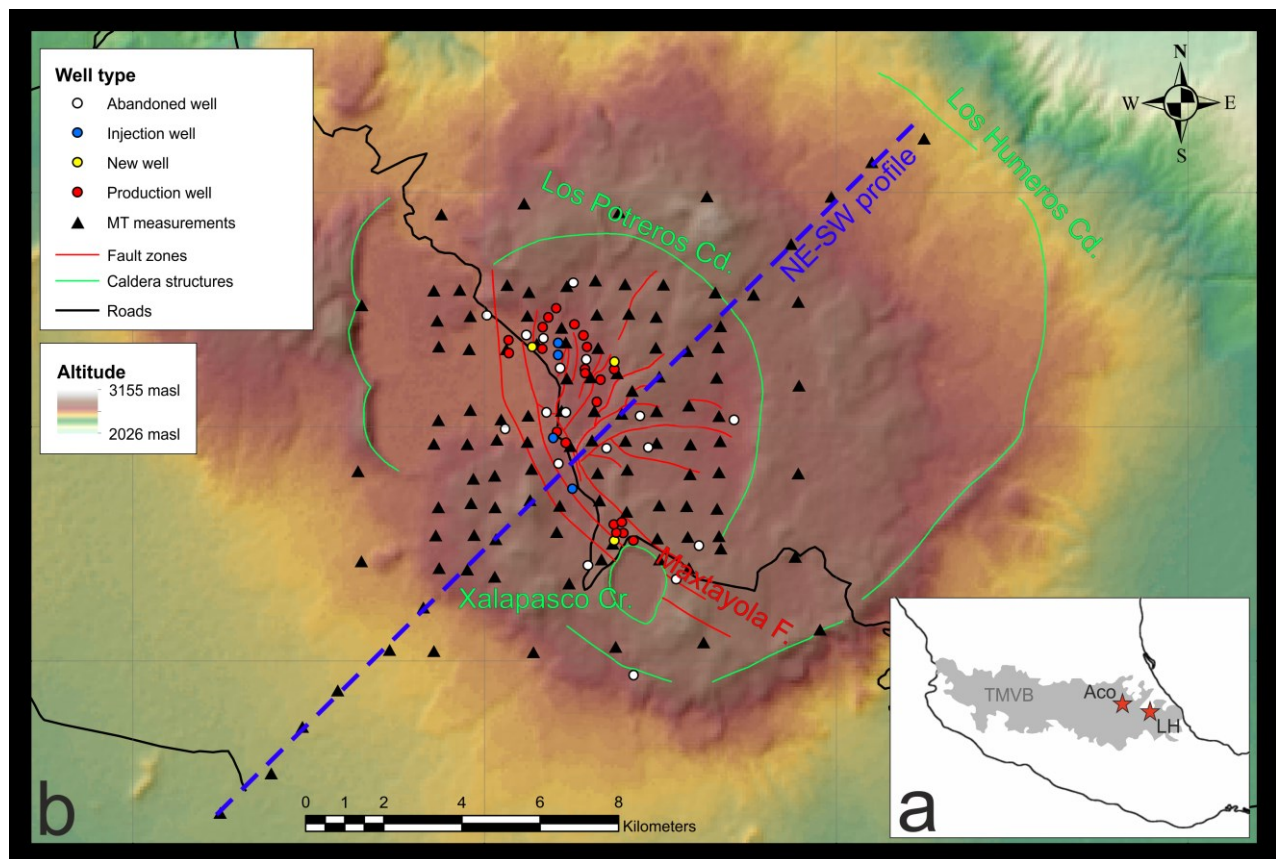
Figure 1: a) Location of Los Humeros (LH) and Acoculco (ACO) in the Trans-Mexican Volcanic Belt. B) the Los Humeros geothermal system including MT recording and well locations. Fault zone and caldera structure configuration after Calcagno et al. (2018). Digital elevation model from SRTM data with a resolution of 30 x 30 m. Blue dashed line = NE-SW MT profile displaying phase tensor ellipses vertically.

The Acoculco geothermal system lies 75 km northwest of the Los Humeros geothermal system and 120 km northeast of Mexico City. Exploration of Acoculco concession area was conducted by Comisión Federal de Electricidad resulting in the limited availability of freely accessible literature data. However, López-Hernández et al. (2009) combine not published data for internal reports to a comprehensive dataset. The consideration of Acoculco as being a geothermal prospective area occurred after a first exploration well was drilled in 1995 revealing a high geothermal gradient (Canet et al., 2015). The heat transport mechanism was characterized as

conductive resulting in an EGS development concept. The system is located in the Tulancingo–Acoculco caldera complex that is situated at the intersection of major NW-SE and NE-SW aligned fault zones (López-Hernández et al., 2009). The asymmetric caldera collapse structure has a diameter of 18 km and is filled with calcalkaline volcanic rocks overlying Mesozoic sedimentary rocks (Avellán et al., 2018; López-Hernández et al., 2009). Dating methods reveal a multi-stage evolution of the volcanic activity, with two documented caldera collapse events generating Tulancingo and Acoculco caldera (Avellán et al., 2018; Sosa-Ceballos et al., 2018). The caldera collapses generate ignimbrite series that are intercalated with lava flows, pyroclastic deposits (Canet et al., 2015; Sosa-Ceballos et al., 2018) and lacustrine sediments (Avellán et al., 2018). Volcanic rocks, ignimbrites, lava flow deposits and dome complexes range from (basaltic-) andesitic composition during Pliocene evolving to a rhyolitic composition in the Pleistocene (Sosa-Ceballos et al., 2018). Acoculco caldera is intersected by a complex fault pattern with NW-SE, ENE-WSE and NE-SW orientations prevailing (Avellán et al., 2018; Calcagno et al., 2018).

3. PHASE TENSOR ANALYSIS

The phase tensor concept was introduced by Caldwell et al. (2004). The galvanic distortion independent phase tensor Φ can be calculated from the impedance tensor by

$$\begin{bmatrix} \Phi_{11} & \Phi_{12} \\ \Phi_{21} & \Phi_{22} \end{bmatrix} = \frac{1}{det(X)} \begin{bmatrix} X_{22}Y_{11} - X_{12}Y_{21} & X_{22}Y_{12} - X_{12}Y_{22} \\ X_{11}Y_{21} - X_{21}Y_{11} & X_{11}Y_{22} - X_{21}Y_{12} \end{bmatrix}$$

with *X* and *Y* being real and imaginary part of the impedance tensor. The phase tensor can be visualized as an ellipse with its main axes Φ_{max} and Φ_{min}, maximum and minimum value of the ellipse, respectively, representing the principal axes of the tensor. Phase tensors analysis has been proven as a valuable tool for the investigation of geoelectric strike direction (Ichihara et al., 2011; Schäfer et al., 2011; Stagpoole and Nicol, 2008), partial melting and magma chambers identification (Díaz et al., 2015; Heise et al., 2007; Hill et al., 2009; Ingham et al., 2009) and is used for geothermal reservoirs exploration (Heise et al., 2008) and even geothermal monitoring (Peacock et al., 2013). With the phase tensor, analysis orientations of current channeling can be visualized indicating possible pathways for fluids, gases or magmas.

Homogenous and thus, circle shaped ellipses indicate no preferential geoelectric strike direction. The size and color code of the ellipses, displayed as $\sqrt{\Phi max * \Phi min}$, exhibit the vertical conductivity change. In Los Humeros at high frequency (71.1 Hz) large phase tensor ellipses are displayed west of the NW-SE Maxtayola fault pointing at increasing conductivity in shallow depth (Fig. 2). The vertical NE-SW profile (Fig. 3) confirms the occurrence of enlarged phase values at high frequencies at stations SW of Maxtayola fault. East of the Maxtayola fault the enlarge phase values occur at intermediate frequencies (10 Hz – 1 Hz). This conductive layer is described as the cap rock of Los Humeros geothermal system by Benediktsdóttir et al. (2020). The lateral extension of the cap rock is significantly affected by the fault zone. Towards the SE sector the E-W aligned fault zones seems to constrain high phase tensors to the north.

At lower frequencies (0.0142 Hz) and thus higher depth, all phase tensors show an almost uniform ellipticity and orientation in NE-SW direction. The phase tensor appearance take an elliptic shape, when huge conductivity contrasts exist (Bertrand et al., 2013; Caldwell et al., 2004), with Φ_{max} pointing in the direction of conductivity enhancement. Thus, it is assumed that in greater depth a conductivity change is occurring located NE or SW of the Los Humeros caldera. A closer inspection reveals a trend of increasing ellipticity from SW to NE. In figure 3, the measurements in the SW possess an elliptic shape at higher frequencies (1 Hz – 0.1 Hz). Considering the radial propagation of electromagnetic waves the measurements in the SW are located closer to the expected conductor and thus record the signal "earlier" meaning at shallower depth. These findings are consistent with the induction arrow (not shown here) that point also towards a conductive body to the SW. As a conclusion, a conductivity enhancement is expected in SW direction. Considering the parallel orientation of the phase tensor ellipses a linear feature is assumed.
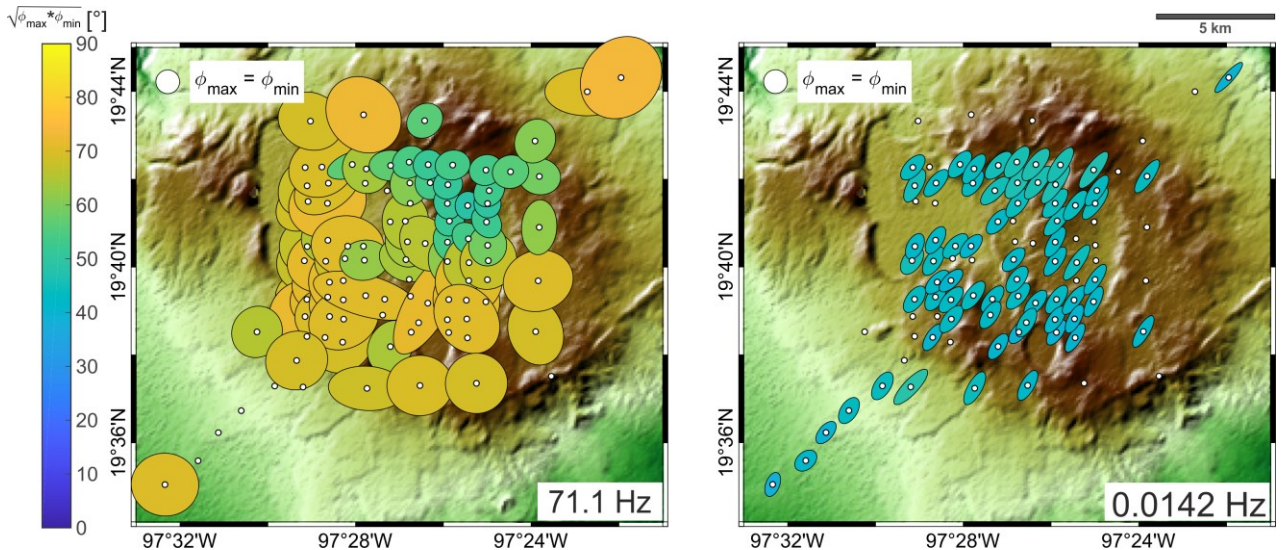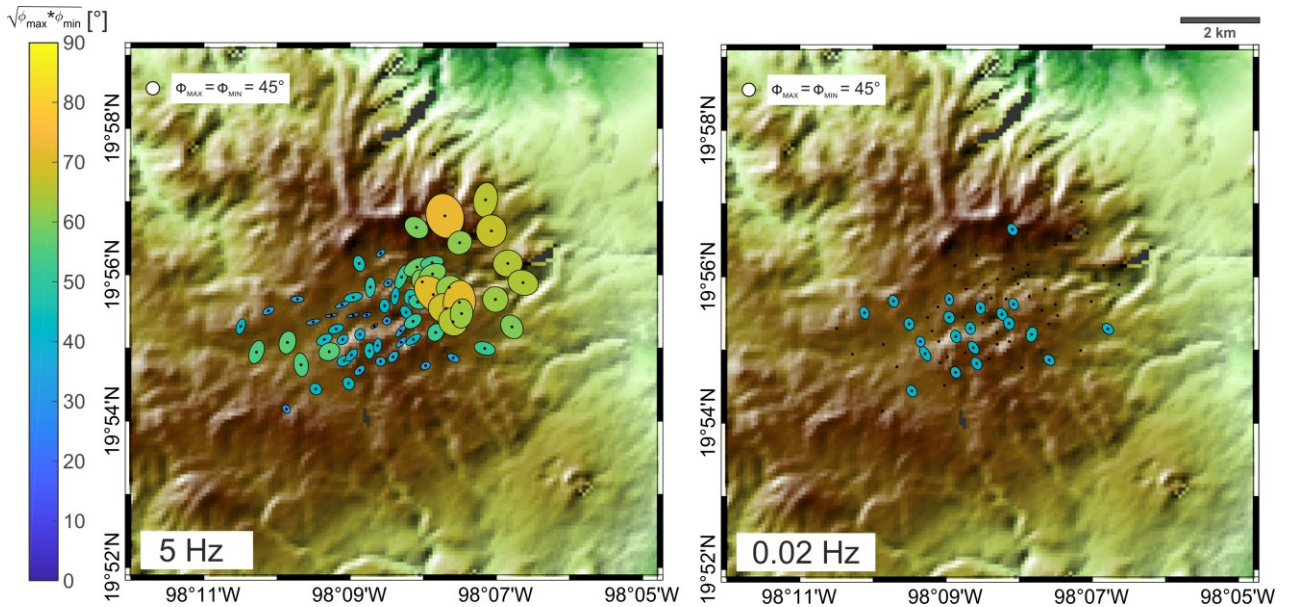

Figure 2: Horizontal view of the phase tensor ellipses at Los Humeros at different frequencies and hence depth. Lengths of the axes are proportional to principle values (Φ_{max}, Φ_{min}) of the phase tensor. Color code of ellipses display the geometric mean.
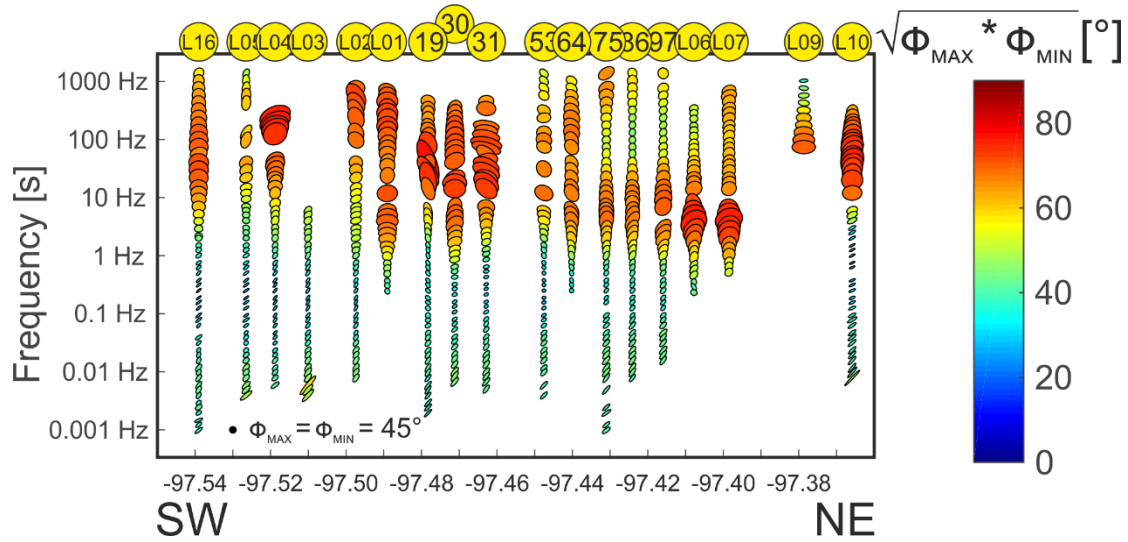
Figure 3: Phase tensors at high frequencies along the NE-SW profile, crossing the Los Humeros geothermal system and the Los Humeros caldera. Lengths of the axes are proportional to principle values (Φ_{max}, Φ_{min}) of the phase tensor. Color code of ellipses display the geometric mean. Station numbers named in yellow circles.

At Acoculco widespread elevated phase values are not documented as observed for Los Humeros neither at highest nor intermediate frequencies (Fig. 4). At intermediate frequencies (5 Hz) a partition of the geothermal system is recorded. The eastern sector possess an increased geometric mean of the phase tensor values and circle-shaped ellipses. The sector is divided to the west by a NW-SE striking lineament that is located in the eastern sector of the survey area. Coincidence can be noticed in the results of the magnetotelluric inversion (Hersir et al., 2020). Further investigations and interpretations have to fathom the origin of this geologic feature. The sharp NW-SE aligned boundary and the coincidence with observed strike directions (Avellán et al., 2018; Calcagno et al., 2018) is remarkable. Differing from Los Humeros, at greater depth no prevailing strike direction is recorded.

Figure 4: Horizontal view of the phase tensor ellipses at Acoculco at different frequencies and hence depth. Lengths of the axes are proportional to principle values (Φ_{max}, Φ_{min}) of the phase tensor. Color code of ellipses display the geometric mean.

4. CONCLUSION

The magnetotelluric method reveals the subsurface resistivity structure of the Los Humeros and Acoculco geothermal systems in the eastern sector of the Trans-Mexican Volcanic Belt. The distortion independent phase tensor analysis investigates the orientation of current channeling structure and thus, in a geothermal context allows the identification of fluid pathways. For the Los Humeros geothermal system the Maxtayola fault, crossing the entire caldera, can be identified in shallow-intermediate depth by the occurrence of circle- shaped phase tensors of enhanced geometric mean values west of the fault zone. At greater depth the phase tensor show a homogenous orientation in NE-SW direction indicating a strong conductivity contrast. For the Acoculco EGS a partition of the geothermal reservoir can be observed. At intermediate depth a NW-SE oriented feature divides the system. The phase tensor analysis could reveal fault zones with impact on the resistivity structure and their effects to the geothermal reservoir structure.

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