



Evaluating phase-tensor-derived geoelectrical strike for two-dimensional magnetotelluric inversion in a geothermal field

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ABSTRACT

This study evaluates the effect of phase-tensor-derived geoelectrical strike on 2D MT inversion by comparing three processing scenarios: geoelectrical-strike-rotated data, geological-strike-rotated data, and unrotated statically corrected data. The analysis was based on secondary MT data in EDI format from the “ABL” geothermal field. Phase-tensor parameters, including (ϕ_{max}), (ϕ_{min}), and skew angle (β), were used to evaluate scale-dependent dimensionality and determine station-specific geoelectrical strike directions. The dominant geological strike derived from mapped structures is approximately N35°W, whereas geoelectrical strike varies markedly between stations, indicating significant lateral electrical complexity. Representative stations show transitions from predominantly 1D behavior at higher frequencies to 2D and locally 3D responses at lower frequencies. Two-dimensional inversions performed using the three datasets produce different resistivity distributions, particularly in the geometry and continuity of shallow conductive zones. The models rotated using phase-tensor-derived geoelectrical strike show the closest qualitative consistency with the available geological sections and with the shallow resistivity architecture inferred from 1D inversion. The resulting resistivity structure includes conductive zones consistent with hydrothermal alteration, moderately resistive domains that may represent permeable geothermal units, and deeper resistive bodies interpreted as basement-related structures. The results demonstrate that strike selection can materially influence 2D MT imaging and subsequent geothermal interpretation. Phase-tensor analysis therefore provides a useful framework for constraining dimensionality and selecting strike orientation prior to 2D inversion, although residual 3D effects and inversion non-uniqueness remain important limitations.

1. Introduction

Magnetotelluric (MT) methods are widely used to investigate subsurface electrical resistivity because their broad frequency range enables imaging from shallow geological structures to several kilometres depth. In geothermal exploration, MT is particularly useful for delineating electrically conductive alteration zones and contrasting resistivity domains associated with different geological and hydrothermal conditions. However, reliable interpretation of MT data depends not only on data quality and inversion strategy but also on whether the assumed dimensionality and coordinate orientation adequately represent the subsurface electrical structure. In structurally complex environments, inappropriate assumptions regarding dimensionality or electrical strike may substantially modify the

geometry and continuity of resistivity anomalies obtained from two-dimensional inversion [1, 2].

A major complication in MT interpretation is the presence of near-surface electrical heterogeneity and galvanic distortion. Such effects can modify the measured electric-field response and obscure the regional conductivity structure, potentially leading to erroneous interpretation if they are not recognized appropriately [3–5]. The original study notes that galvanic distortion commonly arises from charge accumulation along near-surface conductivity contrasts and may affect the measured MT response [6, 7]. This issue becomes particularly important for 2D inversion because the impedance tensor is generally rotated into a coordinate system aligned with the assumed electrical strike before inversion. Consequently, uncertainty in strike direction can propagate directly into the resulting resistivity model [8–10].

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The phase tensor provides a useful framework for evaluating this problem because it is constructed from the real and imaginary components of the MT impedance tensor and is theoretically independent of frequency-independent galvanic distortion [3, 11]. The original theoretical framework defines the phase tensor as $\phi = X^{-1}Y$, where X and Y are the real and imaginary components of the complex impedance tensor, respectively. Phase-tensor parameters such as the maximum and minimum principal phases ϕ_{max} and ϕ_{min} , orientation angle (α), and skew angle (β) provide information on the dimensionality and directional characteristics of the electrical structure. This makes phase-tensor analysis particularly attractive for identifying frequency-dependent transitions among approximately 1D, 2D, and more complex 3D responses before selecting an appropriate strike direction for 2D modelling.

An important issue, however, is that the geological strike inferred from mapped structures does not necessarily coincide with the geoelectrical strike derived from MT responses. Geological structures may contain several orientations, whereas electrical conductivity is influenced not only by faults and lithological boundaries but also by hydrothermal alteration, fluid distribution, and subsurface heterogeneity. In the ABL geothermal field investigated here, structural analysis of the geological map yields a dominant regional geological strike of approximately N35°W, which was originally applied as a uniform rotation of -35° to the MT dataset [12, 13]. In contrast, phase-tensor analysis indicates substantial station-to-station variation in geoelectrical strike, demonstrating that the electrical structure cannot necessarily be represented by a single regional strike direction. This discrepancy provides an opportunity to evaluate directly how strike selection affects the resulting 2D MT model.

The ABL geothermal field contains multiple geological structures (Fig. 1), hydrothermal alteration zones, and surface manifestations distributed across the MT survey area. The original regional geological map shows the locations of the MT stations and survey profiles together with mapped normal and strike-slip faults, alteration zones, fumaroles, hot springs, and other geothermal manifestations. It also provides geological sections approximately parallel to the two principal MT profiles used in the modelling [6, 14, 15]. These independent geological and geothermal constraints provide a useful basis for assessing whether differences among alternative MT processing strategies produce geologically plausible resistivity structures.

Previous processing of the dataset involved three alternative approaches: phase-tensor-derived geoelectrical-strike rotation, geological-strike rotation, and an unrotated statically corrected dataset [4, 16]. Despite the clear methodological importance of this comparison, the original interpretation primarily focused on identifying geothermal components rather than systematically evaluating how strike selection alters the recovered resistivity architecture. Furthermore, dimensionality varies with frequency at individual stations, indicating that the validity of the 2D assumption itself is scale dependent. For example, representative stations exhibit transitions from approximately 1D responses at higher frequencies to predominantly 2D behavior at intermediate frequencies and increasingly 3D responses at lower frequencies. This raises a broader methodological question regarding how phase-tensor information should be incorporated when defining the frequency range and strike orientation for 2D MT inversion.

Accordingly, this study evaluates the influence of phase-tensor-derived geoelectrical strike and dimensionality constraints on two-dimensional MT inversion in a structurally complex geothermal field. Specifically, the study aims to (1) characterize the scale-dependent dimensionality and geoelectrical strike of the MT responses using phase-tensor parameters, (2) compare resistivity models obtained from geoelectrical-strike-rotated, geological-strike-rotated, and unrotated statically corrected datasets, and (3) assess how the

choice of strike direction influences the geological and geothermal interpretation of the resulting 2D resistivity structure. Rather than treating individual resistivity ranges as unique indicators of geothermal components, the resulting models are evaluated primarily in terms of their structural consistency, lateral continuity, and agreement with independent geological constraints.

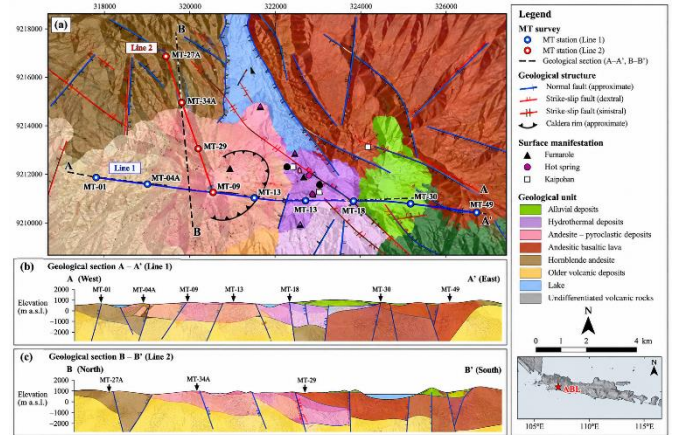


Fig. 1. Geological and geothermal setting of the ABL study area. **(a)** Regional geological map showing the distribution of MT stations, Line 1 and Line 2 survey profiles, major normal and strike-slip faults, alteration zones, and surface geothermal manifestations, including fumaroles, hot springs, and kaipohan. **(b)** Geological section A–A' approximately corresponding to Line 1, and **(c)** geological section B–B' approximately corresponding to Line 2. The geological sections provide independent structural and lithological constraints for evaluating the alternative 2D magnetotelluric inversion models.

2. Method

2.1. Magnetotelluric dataset and processing framework

This study used secondary magnetotelluric (MT) data provided in EDI format. Two principal datasets were available: MT data prior to static-shift correction and MT data that had previously been statically corrected using time-domain electromagnetic (TDEM) information. The original processing of the time-series data into EDI format and the TDEM-based static correction had been completed previously; the present study therefore focused on dimensionality analysis, strike determination, tensor rotation, one-dimensional inversion, two-dimensional inversion, and geological interpretation. Three processing scenarios were evaluated: 1). Phase-tensor-derived geoelectrical-strike rotation; 2). Regional geological-strike rotation; and 3). Unrotated statically corrected data.

The purpose of this comparison was to examine how strike selection and dimensionality constraints affect the resulting two-dimensional MT resistivity structure. The geological setting, MT stations, survey profiles, major structures, alteration zones, and geothermal manifestations used as independent interpretation constraints are shown in Fig. 1.

2.2. Geological strike determination

The regional geological strike was determined from mapped geological structures. Faults and structural lineaments were digitized from the geological map, and their orientations and lengths were calculated using a north-azimuth convention. The resulting directional data were summarized using a rose diagram. The structural analysis indicated a dominant orientation of approximately N35°W, equivalent to a rotation angle of approximately -35° . This orientation was subsequently applied

as the regional geological strike for the geological-strike-rotated MT dataset [17, 18]. The geological-strike approach therefore assumes that the dominant mapped structural orientation adequately represents the principal electrical strike throughout the study area.

2.3. Phase tensor analysis

Phase tensor analysis was applied to MT impedance data that had not undergone static correction. The phase tensor is defined as $\phi = X^{-1}Y$, where X and Y are the real and imaginary components of the complex impedance tensor, respectively (Fig. 2). The method was selected because the phase tensor is theoretically independent of frequency-independent galvanic distortion and therefore provides a useful framework for evaluating regional electrical dimensionality and orientation [1]. The analysis generated the principal phase values ϕ_{max} and ϕ_{min} , the orientation parameter (α), and skew angle (β). These parameters were used to evaluate the dimensionality and directional characteristics of the measured MT response.

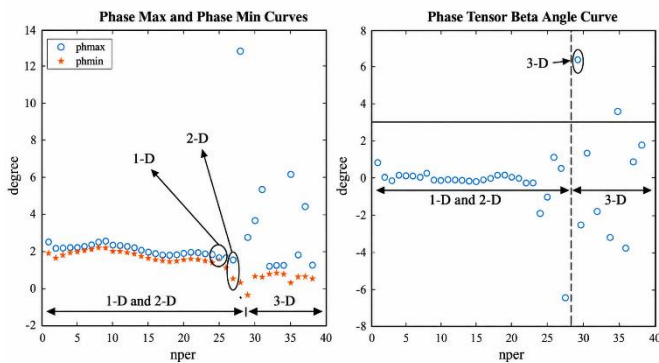


Fig. 2. Representative phase-tensor dimensionality analysis used to distinguish approximately 1D, 2D, and 3D magnetotelluric responses. **(a)** Variation of the maximum and minimum phase-tensor values (ϕ_{max} and ϕ_{min}) with data index (nper), showing intervals interpreted as predominantly 1D–2D and 3D responses. **(b)** Corresponding phase-tensor skew angle (β), where values close to (0°) characterize approximately 1D–2D behavior, whereas larger absolute (β) values indicate increasing three-dimensionality. The transition identified from these parameters was used to constrain the frequency range and geoelectrical strike considered for subsequent 2D MT inversion.

2.4. Dimensionality assessment

Electrical dimensionality was evaluated as a function of frequency using the phase-tensor parameters ϕ_{max} , ϕ_{min} , and (β). The original study used the following general criteria:

- an approximately 1D response where ϕ_{max} and ϕ_{min} are similar and β approaches zero;
- an approximately 2D response where $\phi_{max} \neq \phi_{min}$ but β remains close to zero;
- a more complex 3D response where the phase-tensor skew becomes appreciable, with the original analysis commonly using approximately $|\beta| > 3^\circ$ as an indicator of three-dimensional behavior.

Dimensionality was evaluated individually at each MT station because the transition between approximately 1D, 2D, and 3D behavior varied with frequency and location. Because dimensionality varies with scale, the resulting classifications were treated as frequency-dependent rather than as fixed properties of individual stations. Representative examples were examined in detail at stations MT-04A, MT-18, and MT-34A. The original analysis identified transitions from predominantly 1D behavior at higher frequencies to 2D behavior at intermediate frequencies

and more pronounced 3D responses at lower frequencies.

2.5. Geoelectrical strike estimation

The geoelectrical strike was derived from the phase-tensor orientation parameters. In the original processing framework, the strike direction was obtained from the relationship between the phase-tensor orientation angles and summarized using rose diagrams for selected frequency ranges. Unlike the geological-strike approach, which uses a single regional angle, geoelectrical strike was determined individually for each MT station. The original analysis shows substantial station-to-station variation in the preferred strike direction. For example, representative rotation angles include approximately -65° at MT-04A and -10° at both MT-18 and MT-34A.

The station-dependent strike values were then used to rotate both the impedance tensor and vertical magnetic-field component before inversion. Because geoelectrical strike may become poorly defined where the response is strongly three-dimensional, the resulting strike directions were interpreted together with the phase-tensor dimensionality analysis rather than treated as universally valid 2D orientations.

2.6. Data rotation and conditioning

Two rotated datasets were generated: 1). A geological-strike-rotated dataset, using the uniform regional rotation angle of approximately -35° ; and 2). A geoelectrical-strike-rotated dataset, using station-specific phase-tensor-derived rotation angles. Rotation was applied to the MT impedance tensor and the vertical magnetic-field component [19–21].

Following rotation, the data were subjected to quality-control procedures including masking of data with large error bars or poor cross-power quality and smoothing of the apparent-resistivity and phase responses. The original study reports that these processing steps were particularly important where the (ρ_{xy}) and (ρ_{yx}) responses showed strong separation at high frequency. Importantly, rotation, smoothing, masking, and static-shift correction represent different processing operations. Accordingly, differences among the three datasets were interpreted as reflecting the combined effects of their respective processing pathways rather than strike rotation alone [3, 6, 16].

2.7. One-dimensional inversion

One-dimensional inversion was performed on the geoelectrical-strike-rotated dataset using Occam inversion applied to invariant-mode sounding responses. The original processing used a five-layer parameterization and identical processing procedures for the selected MT stations. Before inversion, the apparent-resistivity and phase curves were edited and smoothed using the available D+ smoothing option, with the original procedure specifying approximately 5% error for apparent resistivity and phase [6, 14, 15].

The resulting 1D models were subsequently assembled into two-dimensional X-sections and used as an independent comparison for the shallow resistivity architecture obtained from the full 2D inversions. Because the source document does not report detailed model-sensitivity or depth-of-investigation calculations, deep interfaces derived from the 1D models were treated cautiously.

2.8. Two-dimensional inversion

Two-dimensional inversion was conducted separately for the three datasets: 1). geoelectrical-strike rotated; 2). geological-strike rotated; 3). unrotated statically corrected. The same survey profiles and general inversion configuration were used to facilitate comparison among the resulting models. The original workflow reports that each 2D inversion used topography and a user-defined mesh and was run for approximately 30 iterations [3, 6, 16].

Initial density constraints were derived from regional geological information and published rock-density ranges. The resulting model was interpreted with reference to the principal geological units occurring in the Dendang area, including Alluvium, Tanjung Genting Formation, Klabat Granite, and basement-related rocks. Because gravity forward modelling is non-unique, the resulting geometry was treated as one geologically plausible density model rather than a unique reconstruction of subsurface lithology [19–21]. Two principal profiles were analysed:

- Line 1, containing MT-01, MT-04A, MT-09, MT-13, MT-18, MT-30, and MT-49;
- Line 2, containing MT-27A, MT-34A, MT-29, and MT-49.

The profiles were selected to approximately follow available geological sections and to cross the geothermal manifestations, allowing the inversion results to be compared with independent geological information. The original analysis restricted the minimum inversion frequency based on dimensionality assessment. The average transition between predominantly 2D and more complex 3D behavior was approximately 0.09 Hz, and frequencies below this value were excluded from the 2D inversion to reduce the influence of strongly three-dimensional responses. The source documents do not report several inversion parameters required for complete numerical reproducibility, including the exact regularization parameter, apparent-resistivity and phase error floors, initial half-space resistivity, and detailed mesh dimensions. These should be reported in the final article if they can be recovered from the original project files.

2.9. Comparison of alternative 2D models

The three inversion scenarios were compared in terms of the geometry, continuity, and geological consistency of the recovered resistivity structures. The comparison focused particularly on:

- Shallow conductive zones;
- Lateral continuity of low-resistivity bodies;
- Moderate-resistivity domains;
- Deep resistive structures;
- Agreement with mapped geological contacts and structural features.

Available geological cross-sections were used as independent constraints rather than as absolute ground truth. The geoelectrical-strike-rotated models were also compared with the 1D X-sections to assess whether both inversion approaches reproduced similar shallow resistivity patterns [19–21].

Following the methodological comparison, the preferred resistivity models were interpreted within the geological and geothermal framework. For descriptive purposes, the original study divided the models into approximate resistivity domains:

- $<10 \Omega\cdot\text{m}$: strongly conductive;
- $10\text{--}60 \Omega\cdot\text{m}$: moderately resistive;
- $60\text{--}100 \Omega\cdot\text{m}$: resistive;
- $>100 \Omega\cdot\text{m}$: strongly resistive.

The conductive domains were evaluated as possible clay-rich hydrothermal alteration zones, whereas moderate-resistivity domains were considered possible permeable geothermal units. Deeper highly resistive structures were interpreted more conservatively as probable basement or intrusive-related rocks rather than being identified directly as heat sources. Thus, resistivity ranges were used as geological constraints rather than unique indicators of caprock, reservoir, or heat source.

2.10. Geological interpretation

Interpretation of the gravity results was conducted at two levels. 1). Qualitative interpretation was based on the spatial distribution of Complete Bouguer, regional, and residual anomalies and their relationships with known geology and the Dendang hot-spring manifestation; and 2). Quantitative interpretation was based on the density geometries derived from the 2D forward model and 3D inversion. The original study describes this combined qualitative and quantitative interpretation framework explicitly. High-density domains were interpreted as being compatible with granitic and basement-

related rocks, whereas lower-density domains were associated with relatively lower-density sedimentary or altered materials. Lithological assignments were considered interpretations rather than unique identifications because different rock types can exhibit overlapping densities [14, 22, 23].

3. Results and discussion

3.1. Geological strike and structural framework

Structural analysis of the geological map indicates that the dominant mapped fault orientation in the ABL geothermal field is approximately N35°W, corresponding to an azimuthal rotation of about -35° . This direction was derived from the dominant orientation of digitized normal and strike-slip faults and was subsequently used as the uniform geological-strike rotation for the MT dataset. The resulting rose diagram should be presented as Figure 3a, together with the principal mapped structures and MT survey geometry in Figure 3b. The use of a single dominant structural strike provides a straightforward geological reference; however, it implicitly assumes that the subsurface electrical structure is regionally coherent and aligned with the mapped surface structures [24].

This assumption is only partly supported by the phase-tensor results. As discussed below, the geoelectrical strike varies substantially among stations, indicating that the electrical structure is more spatially heterogeneous than suggested by a single regional structural direction.

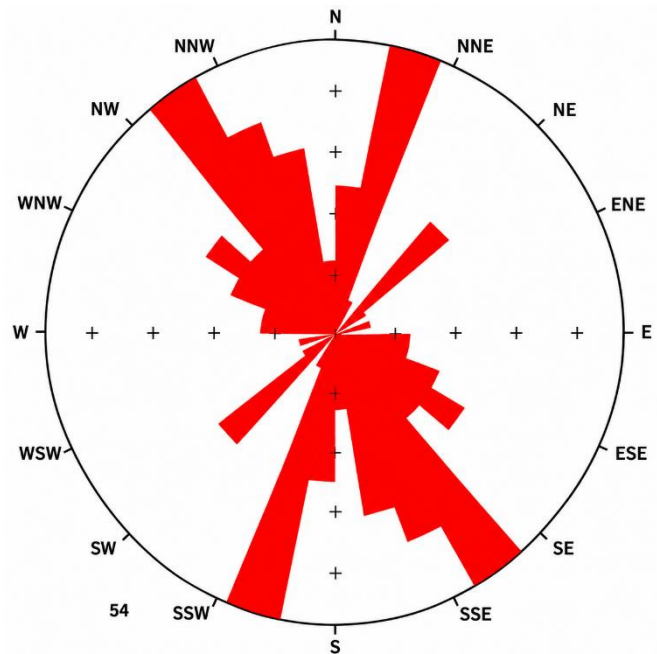


Fig 3. Rose diagram of mapped fault and structural orientations in the ABL geothermal field. The dominant structural trend is approximately N35°W, corresponding to a regional geological strike of about -35° , which was used as the rotation angle for the geological-strike MT dataset.

3.2. Scale-dependent dimensionality from phase tensor analysis

Phase-tensor analysis reveals clear frequency-dependent changes in electrical dimensionality. Representative stations MT-04A, MT-18, and MT-34A show a general transition from approximately 1D responses at higher frequencies to predominantly 2D behavior at intermediate frequencies, followed by increasingly 3D responses at lower frequencies [20, 21, 25].

At MT-04A, the original analysis identifies approximately 1D behavior from 320 Hz to 18.191 Hz, 2D behavior from 18.191 Hz to 0.078 Hz, and more complex 3D behavior below approximately

0.078 Hz. At MT-18, the corresponding transition occurs from approximately 320–180.505 Hz for the 1D regime, 180.505–0.03312 Hz for the 2D regime, and lower-frequency 3D behavior below about 0.03312 Hz. MT-34A similarly shows a 1D range from approximately 320 to 135.39 Hz, 2D behavior down to about 0.01052 Hz, and more pronounced 3D characteristics at still lower frequencies.

These results demonstrate that dimensionality in the ABL field is scale dependent rather than fixed. The shallow response is relatively simple, whereas deeper investigation increasingly encounters laterally complex conductivity structures. This behavior is important because a 2D inversion assumption becomes progressively less valid as 3D effects increase at lower frequencies. The phase-tensor results therefore provide a practical basis for restricting the frequency range used in 2D inversion. In the original workflow, an average lower-frequency boundary of approximately 0.09 Hz was adopted to reduce the contribution of strongly 3D responses.

3.3. Geoelectrical strike variability

The phase-tensor-derived geoelectrical strike is not uniform across the survey area. Representative rotation angles include approximately -65° at MT-04A, -10° at MT-18, and -10° at MT-34A, while other stations show values ranging from strongly negative to positive orientations. This spatial variation contrasts strongly with the single regional geological strike of -35° . The difference suggests that the electrical structure is influenced not only by regional fault orientation but also by local conductivity heterogeneity, alteration, lithological contacts, and possibly three-dimensional structure [16, 26, 27].

This result is scientifically important because it indicates that applying a single geological strike to all stations may oversimplify the electrical architecture. In contrast, station-specific phase-tensor-derived strike directions allow the MT tensor to be rotated according to the local electrical response (Table 1). However, where the response becomes strongly 3D, a unique 2D strike is not necessarily well defined. Therefore, the geoelectrical strike values should be interpreted as practical local orientation constraints rather than exact structural directions.

Table 1

Summary of phase-tensor-based dimensionality ranges and selected geoelectrical strike angles for representative magnetotelluric stations in the ABL geothermal field

Station	1D frequency range	2D frequency range	3D onset	Selected geoelectrical strike
MT-04A	320–18.191 Hz	18.191–0.078 Hz	<0.078 Hz	-65°
MT-18	320–180.505 Hz	180.505–0.03312 Hz	<0.03312 Hz	-10°
MT-34A	320–135.39 Hz	135.39–0.01052 Hz	<0.01052 Hz	-10°

3.4. Effect of strike rotation on mt sounding responses

Rotation affects the relative organization of the off-diagonal impedance responses and therefore influences how the data are represented before inversion. In the original processing, the geological-strike dataset was rotated uniformly by -35° , while the geoelectrical-strike dataset used station-specific phase-tensor-derived rotation angles [20, 21, 25]. At MT-04A, geological-strike rotation reduces the separation between the (ρ_{xy}) and (ρ_{yx}) responses but does not eliminate it completely. In contrast, rotation by the station-specific geoelectrical strike of approximately -65° produces a substantially closer correspondence between the two apparent-resistivity curves after additional editing and smoothing. Similar behavior is described for MT-18 and MT-34A, where rotation by approximately -10° improves the alignment of the principal MT responses (Fig. 4).

Nevertheless, this improvement should not be interpreted as evidence that rotation itself removes static shift. Rotation, masking, smoothing, and static correction are distinct processing steps. The observed changes therefore reflect the combined effect of coordinate rotation and subsequent data conditioning.

3.5. One-dimensional inversion characteristics

The geoelectrical-strike-rotated dataset was further evaluated using 1D Occam inversion. The original analysis used a five-layer parameterization and generated invariant-mode resistivity models for individual MT stations. The 1D models generally show three broad resistivity domains: a shallow moderate-resistivity interval, an intermediate conductive zone, and a deeper high-resistivity domain.

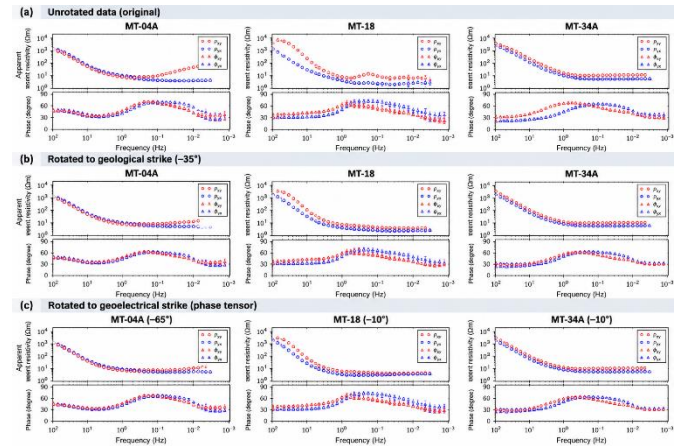


Fig 4. Representative magnetotelluric sounding responses at stations MT-04A, MT-18, and MT-34A under three processing conditions: **(a)** unrotated data, **(b)** data rotated to the regional geological strike of approximately -35° , and **(c)** data rotated to phase-tensor-derived geoelectrical strike directions. The apparent resistivity and phase responses illustrate how strike selection modifies the organization of the off-diagonal impedance components prior to 2D inversion. The selected geoelectrical-strike rotations are approximately -65° for MT-04A and -10° for both MT-18 and MT-34A.

At MT-04A, the conductive zone is interpreted between approximately 200 and 4000 m, with a deeper highly resistive response appearing at much greater depth. At MT-18, the conductive interval extends from approximately 115 to 2000 m, while the high-resistivity domain occurs at around 4.7 km. At MT-34A, the conductive zone is reported between approximately 1.0 and 3.4 km, followed by a deeper resistive response [16, 26, 27]. The large variation in the apparent depth of the deepest resistive layer, including values of several to more than 10 km in some models, indicates that these deep interfaces are not equally well constrained. They should therefore be regarded as broad depth tendencies rather than precise basement depths. The principal value of the 1D models in this study is not the exact depth of deep interfaces but their use as an independent comparison with the shallow-to-intermediate resistivity architecture obtained from 2D inversion.

3.6. Comparison of 2D inversion results: line 1

Line 1 includes MT-01, MT-04A, MT-09, MT-13, MT-18, MT-30, and MT-49 and approximately follows one of the available geological sections. Three inversion scenarios were compared: geoelectrical-strike rotation, geological-strike rotation, and unrotated statically corrected data. The geoelectrical-strike-rotated model shows a shallow conductive body of less than approximately 10 Ω -m beneath geological unit A and additional conductive zones locally associated with altered or structurally complex sectors. The geometry of these low-resistivity bodies shows relatively good spatial correspondence with the mapped shallow geology [16, 26, 27].

By comparison, the geological-strike-rotated model produces a more laterally extensive conductive anomaly that extends into geological units expected to be more resistive. The original interpretation considered this mismatch to indicate that the uniform regional strike does not fully represent the local electrical structure. The unrotated statically corrected model similarly shows low-resistivity bodies extending into areas associated with more resistive geological units. Taken together, these results indicate that the choice of strike orientation materially influences the geometry and continuity of conductive bodies in the recovered 2D model (Fig. 5).

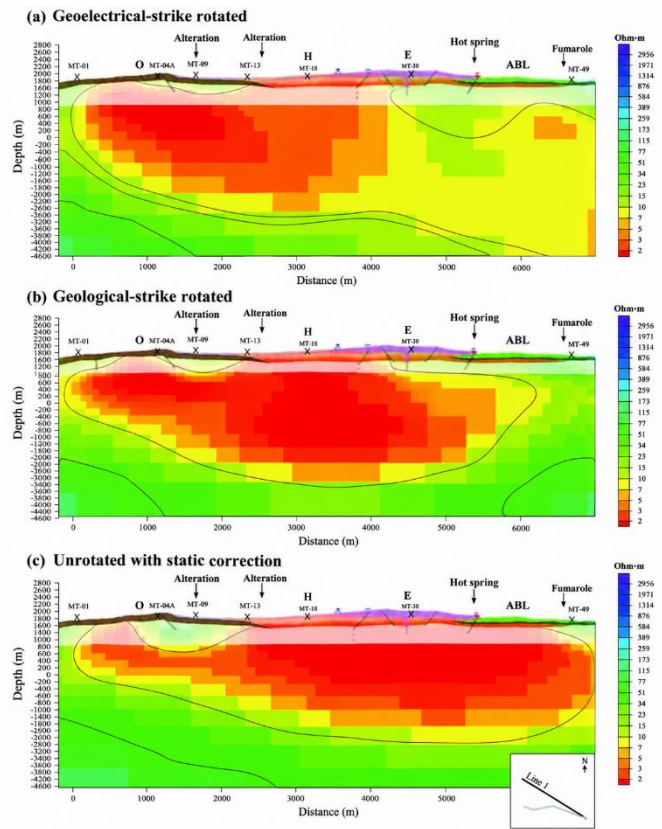


Fig 5. Comparative 2D resistivity inversion sections for Line 1 obtained from three processing approaches: **(a)** goelectrical-strike rotation, **(b)** geological-strike rotation, and **(c)** unrotated data with static correction. Each section illustrates the resistivity distribution beneath the Candradimuka geothermal prospect, integrated with the geological section and surface geothermal manifestations such as alteration zones, hot spring, and fumarole.

3.7. Comparison of 2D inversion results: line 2

Line 2 includes MT-27A, MT-34A, MT-29, and MT-49. The same three processing scenarios were applied. The goelectrical-strike-rotated model shows two prominent low-resistivity anomalies: one associated with geological unit A and another beneath or near the hot-spring manifestation. Moderate-to-high resistivity domains occur beneath units E and K, while a deeper resistive body is identified at approximately 2.4 km depth.

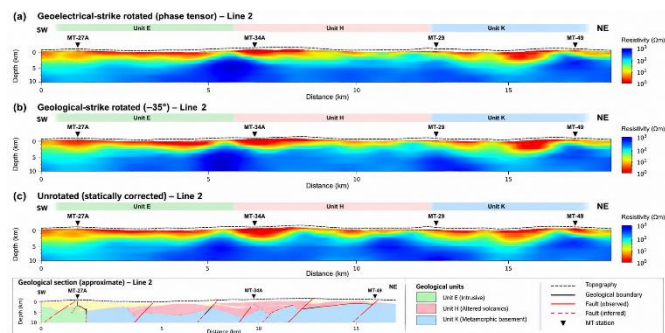


Fig 6. Comparison of two-dimensional magnetotelluric inversion models along Line 2 obtained using three processing scenarios: **(a)** phase-tensor-derived goelectrical-strike rotation, **(b)** regional geological-strike rotation, and **(c)** unrotated data with static correction. Line 2 comprises stations MT-27A, MT-34A, MT-29, and MT-49. The sections illustrate differences in the geometry, continuity, and depth extent of conductive and resistive zones produced by the alternative processing approaches and are evaluated against the corresponding geological section and surface geothermal manifestations.

The geological-strike-rotated model produces a broader low-resistivity zone extending across units A, H, and E. The original interpretation notes that this geometry is less consistent with the expected geological distribution, particularly where a conductive anomaly extends into unit E. The unrotated statically corrected model also produces a low-resistivity anomaly beneath units A and H but differs in the resistivity distribution around the hot-spring area (Fig. 6).

3.8. Consistency between 1D and 2D resistivity structure

The preferred goelectrical-strike 2D models were compared with X-sections constructed from the 1D inversion results. For Line 1, the original comparison shows broadly similar shallow resistivity patterns at MT-01, MT-04A, MT-09, MT-13, MT-18, and MT-49, particularly in the position of conductive and moderately resistive intervals.

A similar correspondence is reported for Line 2 at MT-27, MT-34, MT-29, and MT-49. Although the exact resistivity values and layer thicknesses differ, the overall vertical sequence of conductive and more resistive intervals is broadly comparable between the 1D X-sections and 2D inversion models. This agreement provides additional support for the internal consistency of the goelectrical-strike-based processing strategy, particularly in the shallow and intermediate depth range where both inversion approaches have greater sensitivity. The comparison should be condensed into Fig. 7, showing the 1D X-section above or beside the corresponding 2D inversion for both profiles.

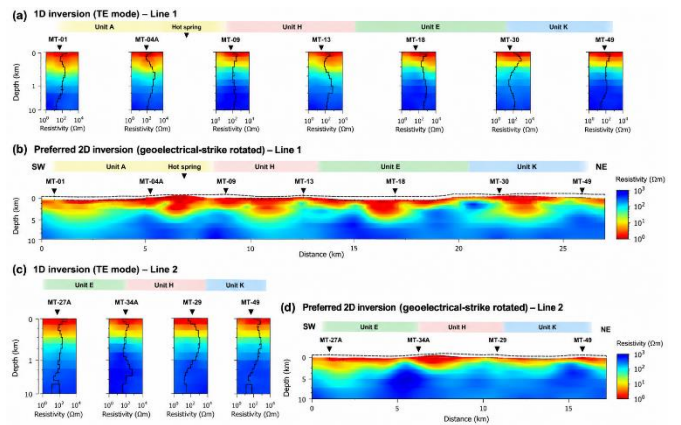


Fig. 7. Comparison between one-dimensional and preferred two-dimensional magnetotelluric resistivity models along the two principal survey profiles. **(a)** 1D inversion results along Line 1, **(b)** preferred 2D inversion model for Line 1 using phase-tensor-derived goelectrical-strike rotation, **(c)** 1D inversion results along Line 2, and **(d)** preferred 2D inversion model for Line 2 using the same goelectrical-strike approach. The comparison highlights the consistency of the shallow-to-intermediate resistivity architecture between the independent 1D and 2D inversion results and provides additional support for the preferred goelectrical-strike processing strategy.

3.9. Implications for geothermal resistivity structure

The preferred goelectrical-strike models contain three broad resistivity domains. A strongly conductive zone, generally below approximately 10 Ω -m, occurs in the shallow-to-intermediate subsurface. In the original interpretation, this zone is associated with hydrothermally altered volcanic and pyroclastic materials containing secondary clay minerals. Such an interpretation is consistent with a possible clay-rich alteration zone, although resistivity alone cannot uniquely establish mineralogy or permeability.

A moderately resistive domain, approximately 10–60 Ω -m, occurs below or adjacent to the conductive zone and is associated in the original geological interpretation with andesitic to basaltic volcanic rocks. This domain may represent a more resistive and potentially permeable geothermal host, but it should not automatically be identified as a reservoir without independent hydrological or drilling evidence. At greater depth, resistivities exceeding approximately 100 Ω -m define a

deep resistive body. The original manuscript interprets this zone as “basement/heat source”. A more conservative interpretation is that it represents competent resistive basement or intrusive-related rock. Its thermal role cannot be established from MT resistivity alone. Accordingly, the geothermal interpretation should be expressed as:

- Conductive zone → consistent with clay-rich hydrothermal alteration;
- Moderate-resistivity zone → possible geothermal host/reservoir-related domain;
- Deep resistive zone → probable basement or intrusive-related structure.

The main methodological result of this study is that strike selection has a measurable influence on the recovered 2D resistivity architecture. Using a single regional geological strike of -35° produces models that are broadly similar to the phase-tensor-derived models but differ significantly in the geometry and lateral extent of conductive anomalies. The station-dependent geoelectrical-strike models exhibit closer qualitative agreement with the available geological sections and with the shallow resistivity pattern derived independently from 1D inversion [28, 29].

These results suggest that phase-tensor-derived strike information can provide a useful constraint where local electrical structure deviates from the dominant regional geological orientation. However, this conclusion should not be interpreted as evidence that station-by-station geoelectrical rotation universally solves 3D effects. The phase-tensor analysis itself shows increasing three-dimensionality at lower frequencies. Therefore, the geoelectrical-strike approach is best viewed as a practical method for improving 2D approximation over the frequency range where the response remains sufficiently close to two-dimensional [16].

4. Conclusion

This study demonstrates that the choice of strike orientation and dimensionality constraint has a substantial influence on two-dimensional magnetotelluric inversion in the ABL geothermal field. Phase-tensor analysis reveals that the electrical response is scale dependent, with representative stations showing predominantly 1D behavior at higher frequencies, 2D behavior at intermediate frequencies, and increasingly 3D characteristics toward lower frequencies. The dominant geological strike derived from mapped structures is approximately $N35^\circ W$ (-35°), whereas the phase-tensor-derived geoelectrical strike varies significantly among stations, indicating that the subsurface electrical structure cannot be adequately represented by a single regional strike direction. Comparison of the three processing scenarios shows that the geoelectrical-strike-rotated models provide the closest qualitative agreement with the available geological sections and with the shallow-to-intermediate resistivity architecture obtained independently from 1D inversion. In contrast, the geological-strike-rotated and unrotated statically corrected models produce broader conductive anomalies that are less consistent with the mapped geological framework. The comparison between 1D and preferred 2D models further indicates broadly similar vertical and lateral resistivity patterns along both Line 1 and Line 2, supporting the internal consistency of the phase-tensor-constrained processing approach. The preferred resistivity models identify three principal electrical domains: a shallow-to-intermediate conductive zone generally below approximately $10 \Omega\cdot m$, a moderately resistive domain of approximately $10\text{--}60 \Omega\cdot m$, and deeper resistive material exceeding approximately $100 \Omega\cdot m$. These features are respectively consistent with clay-rich hydrothermal alteration, possible geothermal host or reservoir-related rocks, and deeper competent basement or intrusive-related structures. However, these interpretations remain non-unique and should not be regarded as direct proof of caprock, reservoir, or heat-source conditions from resistivity alone. Overall, the results indicate that phase-tensor-derived geoelectrical strike provides a more appropriate basis for 2D MT interpretation than applying a uniform geological strike across a structurally complex geothermal system. Nevertheless, the

increasing three-dimensionality at lower frequencies and the different preprocessing histories of the compared datasets remain important limitations. Future work should therefore include full 3D MT inversion and additional geological, geochemical, and subsurface constraints to test the robustness of the interpreted conductivity structures and their geothermal significance.

CRedit authorship contribution statement

Suharno: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **I Gede Boy Darmawan:** Writing – review & editing. **Medi Kurnia Putri:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Data curation. **Akroma Hidayatika:** Writing – review & editing. **Vishal Panse:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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