

Two-Dimensional Magnetotelluric Resistivity Correlation For Estimating The Depth and Distribution of The Geothermal Top Reservoir In Babakan Bogor, Kepahiang

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Abstract.

Kepahiang Regency, Bengkulu Province, hosts an active hydrothermal system on the flank of the Mount Kaba volcanic complex, marked by hot springs and fumaroles around Babakan Bogor and Air Sempiang, yet subsurface information on the depth and lateral extent of its geothermal top reservoir remains limited. This study estimates the depth and spatial distribution of the top reservoir in Babakan Bogor by correlating three new magnetotelluric (MT) soundings (T1, T2, T3), spaced 0.8–1.3 km apart along a west–east line, into a two-dimensional resistivity cross-section. Data were acquired across low (128 Hz), medium (1024 Hz), and high (4096 Hz) frequency bands, processed using a robust, remote-reference-based approach, and interpreted following a three-layer conceptual model of cap rock, reservoir, and hot rock calibrated against previous Kepahiang and Bogor-segment MT studies. The resulting cross-section reveals two shallower reservoir compartments flanking a markedly thickened cap rock beneath the central station, with a resistive hot-rock body rising toward the surface beneath the western reservoir. The top reservoir shallows to about 0.5–2 km near the western station, closest to the surface manifestation, and deepens beyond 4 km toward the centre and east of the line. This geometry mirrors the neighbouring Bogor-segment section reported in earlier work and is independently supported by gravity modelling of the same area. These findings indicate that reservoir accessibility along the Bogor Fault segment is governed by structural position rather than by a uniform regional depth, and they provide a spatial framework to guide the siting of subsequent exploration lines and wells in the Kepahiang geothermal system.

Keywords: Geothermal Reservoir; Magnetotelluric; Resistivity Correlation; Bogor Fault and Kepahiang.

I. INTRODUCTION

A geothermal system develops where a deep magmatic or otherwise high-temperature heat source warms meteoric water that has infiltrated permeable rock, generating a convective reservoir of hot water and steam beneath a low-permeability, hydrothermally altered cap [1], [2]. Where faults and fracture zones provide high-permeability pathways, part of this heated fluid migrates upward and discharges at the surface as hot springs, fumaroles, or other thermal manifestations. Because the heat source, reservoir, and cap rock are all buried and cannot be observed directly, their depth, thickness, and lateral continuity must be inferred from subsurface geophysical data before a prospect can be considered for exploration drilling.

Indonesia's energy supply is still dominated by non-renewable fossil fuels whose reserves continue to decline, even though the country holds one of the largest geothermal resource bases in the world. Kepahiang Regency, Bengkulu Province, situated on the flank of the Mount Kaba volcanic complex within the Bukit Barisan mountain range, is one of the areas showing clear surface indications of an active hydrothermal system, expressed through hot springs and fumaroles around Babakan Bogor and Air Sempiang [3]. Realising this potential as a viable power-generation target, however, requires more than confirming that a system exists; it requires a reasonably detailed picture of where the top of the reservoir actually lies beneath the surface, since this depth directly governs drilling cost and exploration risk.

Earlier geophysical work in Kepahiang has approached this system from several directions. Sugianto & A.W [4] carried out one of the first regional magnetotelluric surveys of the area, later complemented by remote-sensing lineament mapping that linked northwest–southeast structural trends to the distribution of surface manifestations [5]. Simbolon et al. [6] mapped magnetic-anomaly intensity across the prospect, Sugianto et al. [7] delineated its three-dimensional geological structure using combined geophysical data, and Larasati et al. [8] integrated magnetotelluric, gravity, and remote-sensing data into a district-wide

structural model. Working with a denser, 17-station magnetotelluric network, Farid et al. [9] characterised the district-scale resistivity architecture of the Kepahiang system, while a more spatially focused survey by Hardiansa et al. [10] delineated resistivity values specifically along the Bogor Fault segment and estimated a potential capacity of up to 154 MW(e), consistent with the elevated tectonic activity documented for the regency [11]. A related one-dimensional lithological study near the Bogor Fault by Muammar et al. [12] and gravity modelling of the Babakan Bogor–Air Sempiang line by Telaumbanua et al. [13] further constrain the shallow subsurface in the same area.

At the national scale, geothermal characterisation studies employ a wide range of complementary approaches. Muhajir et al. [14] used ASTER TIR and Landsat 8 imagery to detect thermal anomalies at the Lahendong prospect, successfully delineating several surface thermal-anomaly zones, although this approach is inherently limited to surface temperature patterns and cannot resolve reservoir architecture at depth. Satrio et al. [15] integrated ground magnetic and satellite gravity data to identify the structures controlling a non-volcanic geothermal system in Karangrejo–Tinatar, Pacitan, successfully mapping the main fault acting as a fluid-migration pathway, but without characterising the resistivity signature of the reservoir itself. Abidin et al. [16] used isotope geochemistry to characterise the Kamojang reservoir and its long-term response to production, offering valuable insight into reservoir dynamics but from a production-well rather than a spatial-geophysical perspective, while Suranta et al. [17] focused on optimising drilling performance in Java and Sumatra without addressing the prospect-scale distribution of the reservoir itself. Collectively, these studies show that geothermal investigations elsewhere in Indonesia have tended to concentrate on surface manifestations, controlling structures, reservoir fluid chemistry, or drilling operations, rather than on a quantitative, spatially resolved estimate of top-reservoir depth derived from resistivity data.

Within this body of work, a resistivity-based estimate of the depth and lateral distribution of the top reservoir at Babakan Bogor – tied to new, closely spaced soundings and cross-checked directly against the existing regional and Bogor-segment models – has not been specifically reported. Resistivity-based geophysical surveys are well suited to closing this gap, since electrical resistivity is highly sensitive to hydrothermal alteration, porosity, and the presence of hot saline fluid [18], and magnetotellurics in particular can resolve resistivity structure to depths of several kilometres by exploiting naturally occurring electromagnetic field variations [19], well beyond the practical range of most galvanic resistivity methods. This study addresses that gap by acquiring three new magnetotelluric soundings (T1–T3) within the same spatial cluster used by Farid et al. [9] and Hardiansa et al. [10], correlating them into a two-dimensional resistivity cross-section, and interpreting the resulting reservoir geometry in light of the regional structural, gravity, and geomagnetic evidence available for the district. The aim is to produce a spatially explicit estimate of top-reservoir depth and distribution along the Babakan Bogor line that can directly support the siting of subsequent exploration lines and wells in the Kepahiang geothermal system.

II. RESEARCH METHOD

Study Area

The study area lies in Babakan Bogor village, Kabawetan Sub-district, Kepahiang Regency, on the flank of the Mount Kaba volcanic complex within the Bukit Barisan mountain belt, where hot springs and fumaroles are found around Babakan Bogor and Air Sempiang [3], [9]. Surface lithology is dominated by andesitic–basaltic lava, lava breccia, and pyroclastic deposits of Mount Kaba, part of which has undergone argillic to advanced-argillic hydrothermal alteration rich in kaolinite and montmorillonite, rendering it impermeable and electrically conductive; this altered unit forms the natural cap rock of the local system [9], [10], [5]. Regionally, the area is controlled by the Musi segment of the Sumatra Fault Zone, with the local Bogor Fault – part of the Sub-Musi Fault – and an inferred Kepahiang Fault acting as the main conduits for hydrothermal fluid migration from depth toward the surface [9], [10]. Hardiansa et al. [10] estimated the geothermal potential of this active fault zone at up to 154 MW(e), consistent with the high level of tectonic activity documented for Kepahiang Regency [11].

Three magnetotelluric sounding stations (T1, T2, T3), spaced approximately 0.8–1.3 km apart, were established along a west–east line crossing the manifestation zone (Figure 1). Their positions fall within the

same spatial cluster as stations T4, T6, T7, and A3 used by Hardiansa et al. [10] along the Bogor segment, and are consistent with the broader 17-station regional network of Farid et al. [9], allowing the results of this study to be directly compared with, and cross-checked against, the existing regional dataset.



Fig. 1. Location and distribution of the magnetotelluric measurement stations (T1, T2, T3) in Babakan Bogor Village, Kepahiang Regency, Bengkulu Province.

Data Acquisition

At each station, the natural electric field (E_x , E_y) and magnetic field (H_x , H_y , H_z) were recorded for approximately 16 hours across three frequency bands – low (128 Hz), medium (1024 Hz), and high (4096 Hz) – to obtain adequate signal penetration from shallow to deeper layers [10], [20]. This configuration follows the acquisition procedure used in earlier magnetotelluric surveys in Kepahiang, including the Bogor-segment study of Hardiansa et al. [10], allowing the acquisition methodology of both surveys to be compared on an equal footing. Field acquisition gave particular attention to environmental noise conditions, sensor stability, and GPS coordinate validation, since the survey line runs close to settlements and power lines. Surface geological observations – lithology, structural indicators, hydrothermal alteration, and thermal manifestations such as hot springs and fumaroles – were also recorded at each station to support the geophysical interpretation.

Data Processing and Two-Dimensional Correlation

Recorded time-series data were transformed into the frequency domain using the Fast Fourier Transform and processed with a robust-processing approach following the remote-reference principle introduced by Gamble et al. [19], which is specifically designed to suppress coherency bias from cultural noise – a relevant consideration given the proximity of the survey line to inhabited areas and power infrastructure. Data processing was carried out using MAPROS software to obtain apparent-resistivity and impedance-phase curves at each station. A resistivity-versus-depth model was then derived independently at each station using the ZondMT2D inversion package, and the three station models were subsequently correlated along the survey line to construct a two-dimensional resistivity cross-section. Because this cross-section is built from the lateral correlation of three separate station models rather than from a continuous, pixel-by-pixel two-dimensional inversion, the lateral continuity of each resistivity zone between stations is interpretive and will be verified further through a full two-dimensional inversion and dimensionality analysis – for example using skew or phase-tensor parameters – once additional stations along the line become available.

Resistivity Classification Framework

Interpretation of the resulting cross-section follows the conceptual model in which resistivity structure within a high-temperature geothermal system is controlled primarily by the mineralogy of hydrothermal alteration rather than by rock type alone [1], [2]: a very-low-resistivity clay cap is associated with low-temperature smectite alteration and forms the cap rock; an overlying moderate-to-high resistivity zone reflects propylitic alteration and hosts the active reservoir; and a high-resistivity zone at greater depth represents fresh or weakly altered rock associated with the heat source. Because resistivity in volcanic-hydrothermal terrain is inherently overlapping between lithologies – governed jointly by mineral assemblage, porosity, fluid saturation, pore-fluid salinity, and temperature [21] – a single resistivity value cannot be

assigned to a specific lithology or system component without considering its depth, its position relative to adjacent layers, and the surrounding geological and structural context. This three-layer framework has previously been applied consistently to Kepahiang, both through magnetotellurics [9], [10], [3] and through comparative methods such as gravity [13] and geomagnetics [6]. Table 1 compares the specific resistivity ranges reported for this scheme by the studies most directly comparable to the present survey, which are adopted here as the primary reference for interpretation.

Table 1. Resistivity classification schemes for the cap rock–reservoir–hot rock system reported by previous magnetotelluric studies in Kepahiang and the Bogor Fault segment.

Source	Cap rock (Ωm)	Reservoir (Ωm)	Hot rock (Ωm)
Farid et al. [9] – regional, 17 stations	2.7–45	0.13–2.9	120–800
Hardiansa et al. [10] – Bogor segment	2.5–45	0.14–1	120–800
Muammar et al. [12] – near Bogor Fault	31–80	0.21–4.0	≥ 200

III. RESULTS AND DISCUSSION

Results

The correlation of the three magnetotelluric stations along the west–east Babakan Bogor line produces the two-dimensional resistivity cross-section shown in Figure 2. The section resolves the three-layer architecture anticipated from the regional and Bogor-segment models [9], [10]: a conductive reservoir zone (about 2–17 Ωm), an overlying cap rock of variable thickness (about 20–111 Ωm), and a resistive hot-rock body (about 330–790 Ωm) that rises close to the surface beneath the westernmost station. Rather than lying as flat, laterally continuous sheets, however, the three zones form a stepped geometry that tracks the underlying structure.

Beneath the western station (T1), the reservoir zone is shallow, extending from near the surface to about 4 km depth, and is separated from the underlying hot-rock body by only a thin transitional layer, placing this position close to, or within, the upflow zone of the system. Toward the centre of the line (T2), the cap rock thickens markedly and forms a prominent resistive ridge that separates the western reservoir from a second, reservoir-like conductive zone that reappears beneath the eastern station (T3) at a considerably greater depth, on the order of 3.5–8.5 km. The hot-rock signature identified beneath T1 is not yet resolved beneath T2 within the depth range covered by the survey, implying that the top of the heat source beneath the central and eastern parts of the line lies deeper than beneath T1.

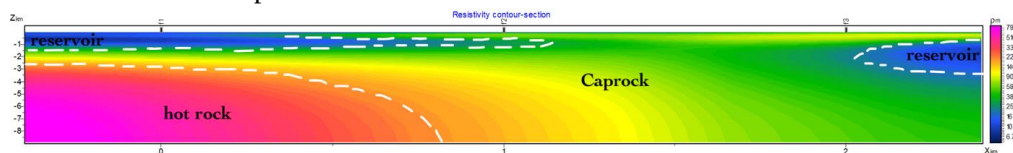


Fig. 2. Two-dimensional resistivity cross-section along line T1–T2–T3, showing the geometry of the reservoir (blue), cap rock (green–yellow), and hot rock (orange–red) zones obtained from lateral correlation of the station models.

This “reservoir–thick cap rock–reservoir” geometry closely resembles the two-dimensional section reported by Hardiansa et al. [10] for the neighbouring T4–T6–T7–A3 line on the Bogor segment, where a comparable cap-rock ridge separates reservoir compartments at both ends of the line. The recurrence of this pattern on two adjacent, structurally related lines suggests that it reflects a genuine structural feature – an uplifted, cap-rock-thickened block flanked by fault-bounded reservoir compartments – rather than an artefact specific to a single survey, consistent with the fault-controlled outflow–upflow behaviour reported for the wider Kepahiang system [8], [7].

Table 2. Comparison of resistivity ranges and estimated top-reservoir depth between this study and previous magnetotelluric studies in Kepahiang.

Parameter	Farid et al. [9]	Hardiansa et al. [10]	This study (T1–T2–T3)
Cap rock (Ωm)	2.7–45	2.5–45	20.5–111.0
Reservoir (Ωm)	0.13–2.9	0.14–1	2.0–16.5 (west); 13.7 (east)
Hot rock (Ωm)	120–800	120–800	330.5–790.5 (beneath west)
Top reservoir depth	variable, generally >2 km	$\approx$ 2–3 km	$\approx$ 0.5–2 km (west); >4 km (centre); $\approx$ 3.5–4 km (east)

As an independent check on the shallow-reservoir interpretation at T1, the estimated top-reservoir depth in the western part of the line (about 0.5–2 km) is consistent, in order of magnitude, with the reservoir depth of about 1.2 km inferred from gravity modelling of the Babakan Bogor–Air Sempiang line by Telaumbanua et al. [13], while the roughly 500 m cap-rock depth obtained from that gravity model coincides with the transitional resistivity layer identified above the reservoir at both the western and eastern ends of the line. Because gravity and magnetotellurics respond to different physical properties – rock density and electrical resistivity, respectively – this agreement provides independent support for the presence of a genuine shallow reservoir near the western station, rather than an artefact of the resistivity model alone.

Discussion

Taken together, the correlated cross-section reproduces the same reservoir–cap rock–hot rock architecture reported for the Kepahiang system at both the district scale [9] and the Bogor-segment scale [10], which is a meaningful outcome in itself: the three-layer conceptual model, originally built from a much denser regional network, remains valid when tested against an independent, more closely spaced set of stations within a single manifestation zone. The clearest point of agreement lies at the most resistive part of the section, where the hot-rock signature beneath T1 (about 330–790 Ωm) falls squarely within the 120–800 Ωm range reported by both comparison studies [9], [10], suggesting that the broad thermal architecture of the Babakan Bogor prospect – a hot, resistive body underlying a conductive hydrothermal system – is a robust regional feature rather than an artefact of a single survey.

At the same time, the cap-rock and reservoir resistivity values obtained along this line are noticeably higher than those reported regionally: the upper cap-rock bound identified beneath the central station exceeds the 45 Ωm ceiling reported by both comparison studies by a wide margin, while the lower reservoir bound is roughly an order of magnitude higher than the 0.13–0.14 Ωm reported for the district and the Bogor segment [9], [10]. Rather than treating this gap as a simple inconsistency, it is more informative to read it against the well-established principle that resistivity in volcanic-hydrothermal terrain is inherently overlapping and site-specific, jointly governed by mineral assemblage, porosity, fluid saturation, pore-fluid salinity, and temperature [21]. A cap rock dominated by mature smectite clay, for example, can be an order of magnitude more conductive than one where argillic alteration is only partially developed or intermixed with less-altered volcanic breccia, and a reservoir carrying more dilute fluid will likewise register as less conductive than one saturated with concentrated brine. Because the central and eastern stations sit progressively farther from the main surface manifestation than the western station, a plausible explanation is that alteration intensity and fluid saturation genuinely decrease away from the immediate upflow zone, producing authentically higher resistivity values at those positions rather than merely reflecting model uncertainty.

The structural setting offers further support for this reading. The recurring reservoir–thick cap rock–reservoir geometry observed both in this study and along the neighbouring Hardiansa et al. [10] line indicates that the Bogor Fault segment is organised into discrete, fault-bounded blocks, with an uplifted, cap-rock-thickened block separating shallower reservoir compartments on either side – a pattern broadly consistent with the fault-controlled structural framework established through three-dimensional geophysical delineation [7], airborne geomagnetic mapping [6], structural-lineament analysis from remote sensing [5], and the

integrated magnetotelluric–gravity–remote sensing analysis of the wider district [8]. In such a setting, the central station most plausibly sits over, or close to, the crest of an uplifted, relatively less-fractured block, where hydrothermal fluid circulation and associated clay alteration are naturally more limited than along the bounding faults that channel fluid toward the stations on either side. This structural control carries a direct practical implication for exploration: targets positioned close to fault-bounded margins, as at the western station, appear more favourable for shallow reservoir access than positions over the central, uplifted block.

The vertical position of the reservoir-like zone beneath the eastern station adds a further layer of structural interpretation. Rather than a simple lateral continuation of the shallow reservoir identified in the west, its reappearance at considerably greater depth, beneath an overlying interval of comparatively resistive, weakly altered volcanic rock, is more consistent with a separate, deeper fluid-conduction pathway associated with the Bogor or Kepahiang faults than with a single, laterally continuous reservoir sheet. This distinction is practically relevant, since it suggests that the eastern part of the survey line may require deeper exploration targets than the west, and that any future well design in this sector should be guided by structural mapping of the fault trace rather than by a simple depth projection from the western station.

More broadly, these results reinforce the view that the Kepahiang geothermal system, and the Bogor Fault segment in particular, behaves as a fault-segmented outflow–upflow system in which reservoir accessibility is tied to structural position rather than to a uniform regional depth. For future exploration, this points to two priorities: first, extending the present three-station line into a denser two-dimensional, or where feasible three-dimensional, survey grid that can resolve the lateral boundaries of the reservoir compartments bracketing the central resistive high more precisely; and second, integrating the resistivity model developed here with the existing gravity [13], geomagnetic [6], and structural [7], [8] datasets available for the wider district, so that future well siting can draw on a single, internally consistent conceptual model rather than on any one geophysical method in isolation. Achieving this integration would move the present interpretation from a single correlated line toward a spatially continuous model of top-reservoir depth across the Babakan Bogor prospect, directly supporting the broader goal of sustainable geothermal development in Kepahiang Regency.

IV. CONCLUSION

Correlating three magnetotelluric soundings (T1, T2, T3) along a west–east line in Babakan Bogor, Kepahiang Regency, into a two-dimensional resistivity cross-section reveals a three-layer geothermal architecture comprising a conductive reservoir zone (about 2–17 Ωm), a cap rock of markedly variable thickness (about 20–111 Ωm), and a resistive hot-rock body (about 330–790 Ωm) that rises close to the surface beneath the western station. The top reservoir is estimated to lie at a shallow depth of about 0.5–2 km near the western station, closest to the surface thermal manifestation, and to deepen beyond 4 km toward the centre of the line, before a second, deeper reservoir-like compartment reappears beneath the eastern station at roughly 3.5–8.5 km. This reservoir–thick cap rock–reservoir geometry mirrors that reported for the neighbouring Bogor-segment line by Hardiansa et al. [10] and is consistent with a fault-controlled outflow–upflow system in which reservoir depth and resistivity character vary systematically with structural position rather than remaining uniform along strike. The resulting resistivity ranges are qualitatively consistent with previous regional and Bogor-segment magnetotelluric studies, particularly at the hot-rock level, while the comparatively higher cap-rock and reservoir values obtained here are plausibly explained by genuine local variation in alteration intensity and fluid saturation away from the main upflow zone, a reading further supported by an independent gravity cross-check [13]. As an initial three-station framework, the model developed here would benefit from denser spatial coverage and a full two- or three-dimensional inversion integrated with existing regional geological, gravity, and geomagnetic data, in order to refine the lateral boundaries of the reservoir compartments and to support more targeted geothermal exploration and sustainable energy development in Kepahiang Regency.

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