THE CHARACTERISTICS OF BASE OF CONDUCTOR IN X GEOTHERMAL FIELD BASED ON THE MAGNETOTELLURIC AND WELL DATA

KARAKTERISTIK BASE OF CONDUCTOR DI LAPANGAN PANAS BUMI X PULAU FLORES BERDASARKAN DATA MAGNETOTELLURIK DAN SUMUR EKSPLORASI

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ABSTRACT

The X Geothermal Field in Flores, East Nusa Tenggara, has surface thermal manifestations such as hot springs, fumaroles, and alteration rocks, which indicate potential geothermal resources. This research aims to model and characterize the base of the conductor in X geothermal field as a supporting data for geothermal exploration studies. The modeling was performed using 3D magnetotelluric inversion analysis that was correlated with well data, i.e, drill cuttings, methylene blue, and Pressure and Temperature Test. According to the results, the subsurface condition of the study area consists of an argillic zone around 400-300 masl, a transition zone around 300 and 0 masl, and a propylitic zone below 0 masl. At an elevation of 400-300 masl, the base of conductor marks the boundary between the reservoir and the clay cap. The BOC distribution map reveals that the average BOC elevation is between 300 and 550 meters above sea level. The exploration potential is in the northern part with a prospect area of 3,4 km^2 in research.

Keywords: Base of conductor, Geothermal, Magnetotelluric, Well Data, Resistivity, 3D inversion

ABSTRAK

Lapangan Panas Bumi X di Pulau Flores, Nusa Tenggara Timur, memiliki manifestasi termal permukaan seperti mata air panas, fumarol, dan batuan alterasi, yang mengindikasikan potensi sumber daya panas bumi. Penelitian ini bertujuan untuk memodelkan dan mengkarakterisasi base of conductor di lapangan panas bumi X sebagai data pendukung eksplorasi panas bumi. Pemodelan dilakukan dengan menggunakan analisis inversi 3D magnetotellurik yang dikorelasikan dengan data sumur yaitu serbuk bor, metilen biru, dan Uji Tekanan dan Temperatur. Berdasarkan hasil penelitian, kondisi bawah permukaan daerah penelitian terdiri dari zona argilik sekitar 400-300 mdpl, zona transisi sekitar 300 dan 0 mdpl, dan zona propilitik di bawah 0 mdpl. Pada ketinggian 400-300 mdpl, base of conductor menandai batas antara reservoir dan claycap. Peta sebaran BOC menunjukkan bahwa rata-rata elevasi BOC adalah antara 300 dan 550 meter di atas permukaan laut. Potensi eksplorasi tertinggi terdapat di bagian utara daerah penelitian dengan luas prospek 3,4 km^2.

***Kata kunci**: Base of conductor, Panas Bumi, Magnetotellurik, Data Sumur, Resistivitas, Inversi 3D*

INTRODUCTION

Geothermal energy is thermal energy stored in the rock below earth surface as an alternative to renewable energy sources and as a source of electrical power. This energy is typically provided in hot fluids or steam with certain geological conditions under the earth's surface. The main components in the geothermal system include the reservoir zone, clay cap, and heat source (Yunus Daud et al., 2019). The reservoir zone is a permeable rock where hot fluids accumulate with a clay cap at the top. This clay cap zone can isolate hot fluid and steam in the system, preventing leakage (Syafitri and Putra, 2018). The hot fluid in the reservoir can be utilized to generate electricity. Therefore, an analysis of the conceptual model is required to describe the subsurface zone's condition for the guidance of well targeting.

One of the geophysical methods for describing the conceptual model of a geothermal system is the magnetotelluric (MT) method. This method is generally applied in geothermal exploration for mapping the subsurface resistivity structure associated with clay alteration cap, reservoir geometry and possible heat source. The MT method utilizes fluctuations in the perpendicular natural electric field and magnetic field at the earth's surface to determine the conductivity value of rocks under the surface (Simpson and Bahr, 2005). Zones in geothermal systems with high conductivity or low resistivity values of rock are clay cap zones due to hydrothermal alteration of the clay cap. Thus, the MT method can be used to map the clay cap zone, reservoir zone, and the boundary between the two zones (base of conductor) with 3D MT of inversion modelling. Correlating MT analysis with well data is necessary for supporting the geothermal system analysis, including Methylene Blue (MeB) analysis, drill cuttings, and pressure and temperature test (P&T Test).

The X geothermal field located on the island of Flores, East Nusa Tenggara (Figure 1) has great potential of geothermal energy. Because the field manifests hot springs and fumaroles, the X geothermal field indicates geothermal prospects (Harvey et al., 1998). The X geothermal field has hot springs with temperatures from 32-61^{o}C and fumaroles from 78-97^{o}C (Sarmiento et al., 2019). This nature indicates that the X geothermal field has the potential to be of geothermal energy. Unfortunately, there are no studies about the characteristic of the base of conductor as identification of geothermal energy potential based on MT analysis. Therefore, the objective of this research is to model and characterize the base of conductor zone of the X geothermal field.

METHODOLOGY

Identification of the base of conductor from X field is performed using MT analysis supported by well data MeB, drill cuttings, and P&T survey. A total of 65 MT stations are used for data collecting (Figure 2a). The data was then reprocessed using standard MT data processing, including static shift correction using StaticShifter-X software. This correction is supposed to eliminate the static effect of the data portrayed by a vertical shift of the apparent resistivity curve uniformly at all frequencies or periods intervals. The following stage 3D inversion using MT3DInv-X applications. The result of 3D inversion was visualized using GeoSlicer-X software. All the softwares are developed by NewQuest Geotechnology.
Supporting data for MT analysis is given in well data, MeB, drill cuttings, and P&T surveys. The results of MT data analysis are correlated with well data to construct a conceptual model supported by geological and geochemical data. The steps are illustrated in the flow chart as shown in Figure 2b.

GEOLOGICAL AND GEOCHEMICAL BACKGROUND

X geothermal field is located on Flores Island, Ende Regency, East Nusa Tenggara. Tectonically, this region is situated in the Banda Arc, where the Indo-Australian plate is subducting at a rate of about 6 cm per year (Hamilton, 1973). The geothermal volcanic complex in the study area covers about 400 km^2 and extends for 23 km in a southwest-southwest (SSW) - north-northeast (NNE) direction (Harvey et al., 2000).

The geothermal field X is controlled by a caldera, resulting from an active hydrothermal volcanic eruption (Harvey et al., 2000; Sarmiento et al., 2019). There is a fault extending from NNE-SSW, which triggers the structural collapse of the northern and southern areas. According to the geological map of Ende Regency (Suwarna et al., 1989), the study area is entirely covered by Young Volcanic rocks onsisting of lava, breccias, agglomerates, tuffs, and volcanic sand. Stratigraphy of young volcanic rocks in the area can be expressed from oldest to youngest formation consisting of Volcanic-M, Volcanic-K, and Young Volcanic SK (Sarmiento et al., 2019), as shown in Figure 3.

An analysis of the Cl, SO_4, and HCO_3 composition was performed by utilizing a Cl-SO_4-HCO_3 ternary diagram to determine the type of geothermal fluid (Figure 4a). Manifestations of WLBR1, WLBR2, DP, and LK hot springs tend to approach the Cl peak, confirming their classification as chloride springs. The SR, SK1, SK2, and SK3 manifestations are categorized as bicarbonate fluids, indicating that the water is a mixture of shallow groundwater and minor reservoir fluid. Gas analysis was carried out to determine the subsurface geothermometer from MTBU fumarole samples in X field. The results indicate that MTBU fumarole is an upflow from the SK geothermal system. HArCar plot for analysis gas geothermometer shows a subsurface reservoir temperature of about 230-250°C (Figure 4b).

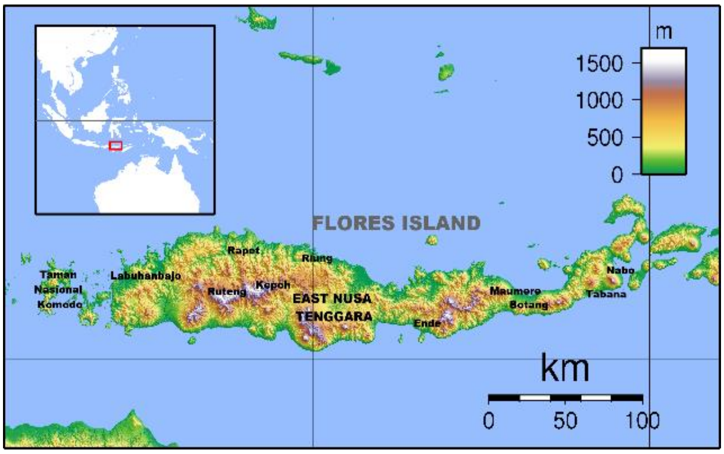

Figure 1. Map of Flores Island (Sadelmelik,2010)

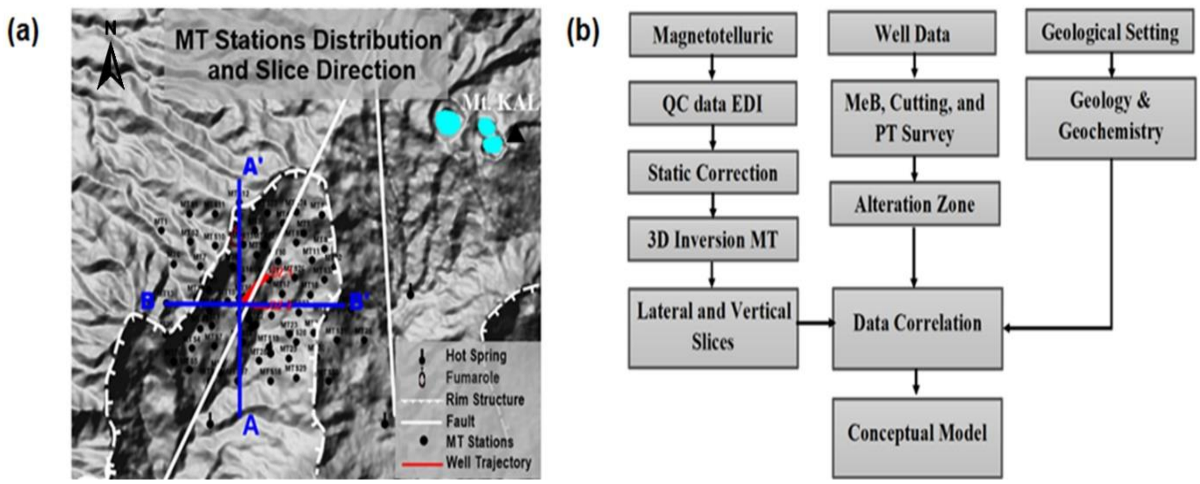

Figure 2. (a) MT stations in X geothermal field and (b) Flow chart of research

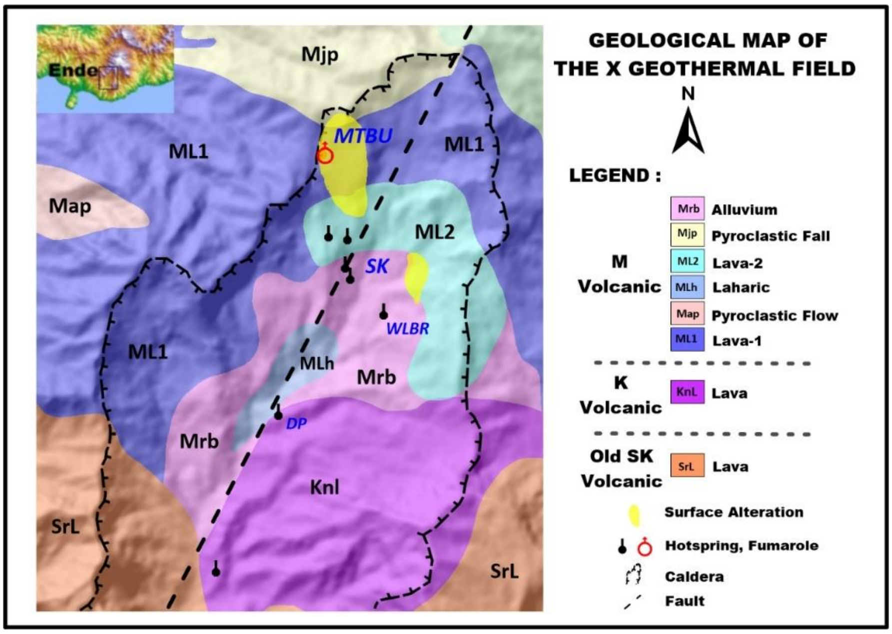

Figure 3. Geological map of X geothermal field (Modified Sarmiento et al., 2019)

Table 1. Molecular Content Values of Cl-SO_4-HCO_3

No	Sample Name	Temp °C	pH	Cl	SO_4	HCO_3
1	SR	46.8	7.63	2	120	214
2	SK1	34	7.6	11	12	134
3	SK2	34	7.44	4.9	12.8	214
4	SK3	34.8	7.99	4	9	159
5	LK	44.5	6.9	658	404	528
6	DP	47	6.9	1326	346	178
7	WLBR1	54	7.48	1423	440	259
8	WLBR 2	49.5	7.88	1194	92	175

Table 2. Geochmical data of gas field X

No	Sample Name	Weight Percent	CO_2	H_2O	NH_3	Ar	N_2	CH_2	H_2
1	$MTBU_1$	46.8	7.63	2	120	214	120	214	214
2	$MTBU_2$	34	7.6	11	12	134	12	134	134
3	MTLO	34	7.44	4.9	12.8	214	12.8	214	214

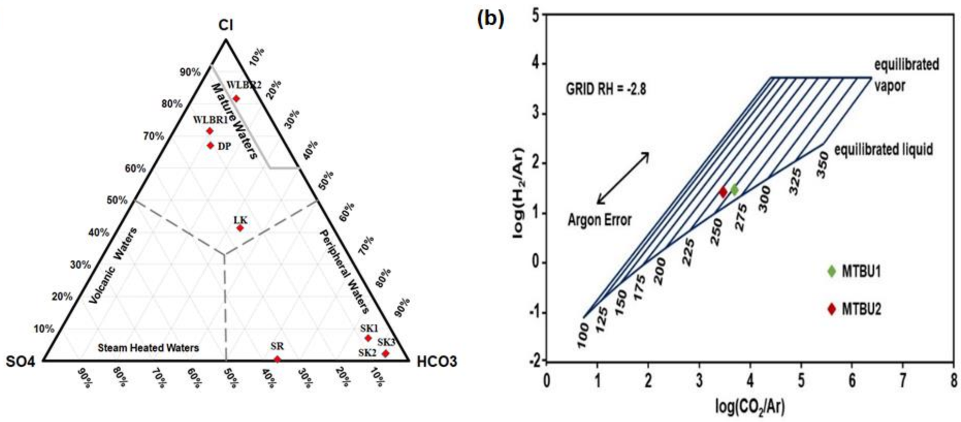

Figure 4. a) Cl-SO4-HCO3 ternary diagram and b) HArCar plot for analysis gas geothermometer

RESULTS AND DISCUSSIONS

RESULTS

MAGNETOTELLURIC DATA

The 3D inversion model from MT data indicates the conductive layer of the geothermal system through the distribution of subsurface resistivity values (Y. Daud et al., 2018). The conductive layer is a layer with a low resistivity value. The 3D inversion of MT data has been sliced laterally and vertically to describe the distribution of the conductor zones entirely in the study area. There are 60 measurement points using the Metronix measuring instrument where the measurement distance is 400 m.

Lateral Distribution of MT Resistivity

The lateral MT resistivity distribution describes the resistivity value at each elevation to determine the conductor and reservoir zones. The resistivity value distribution laterally from X geothermal field is given at depths of 750 m, 0 m, -750 m, and 2000 masl as shown in Figure 5.

The map at an elevation of 750 masl shows a low resistivity value < 10 ohm-m in the middle and extends to the north of the area. This value indicates that this layer is dominated by the conductor layer, which is interpreted as a clay clap zone in geothermal system X. At an elevation of 0 m, the area that initially had a low resistivity (at an elevation of 750 masl) (i.e., the center area) increased its resistivity value. The significant difference in resistivity values suggests that the zone at 0 m could be the base of conductor (BOC) zone. Then, at an elevation of -750 masl, the resistivity value increases, indicating that the area includes less conductive materials. Furthermore, at an elevation of -2000 masl, the resistivity value increases, indicating that the area is not a reservoir but a basement. Based on lateral MT modeling in X geothermal field, it can be stated that as elevation decreases, resistivity increases.

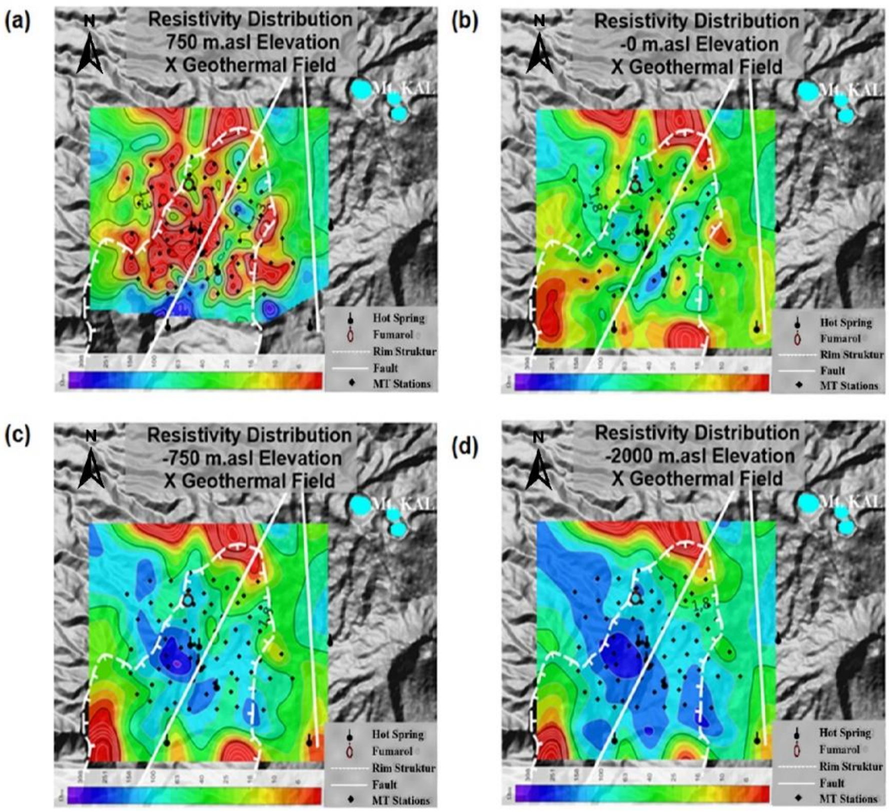

Figure 5. Mapping of the lateral distribution of MT resistivity in X geothermal field

Vertical Distribution of MT Resistivity

The vertical resistivity distribution of 3D MT inversion is determined by slicing 2 MT data at Lines A-A' (Figure 6) and B-B' (Figure 7). The direction of the lines can be seen in Figure 2. Vertical MT analysis is utilized to evaluate the thickness and presence of the structure of the clay cap and reservoir. Structure identification can be identified by analyzing the splitting of the TE (Transverse Electric) – TM (Transverse Magnetic) curve. The splitting frequency increases with the structure's closeness (Daud et al., 2015). The results of the 3D inversion on the A-A' lines going to S-N are shown in Figure 6. The results show that a yellowish-red color zone marks the clay cap layer due to this layer has a resistivity of <10 ohm-m (Y. Daud et al., 2018; Fauziyah and Daud, 2019). This layer's thickness varies depending on its area, ranging from about 800 masl in the updome to 300 masl on the south and north sides. The low-resistivity segment of the updome's upper part manifestations as an MTBU fumarole. This result shows that the upflow zone of geothermal system X is in this region. Moreover, there are intersections between the clay cap layers. This intersection may be due to fumaroles resulting in fractures, so there may be faults that have been unidentified geologically. This area needs to be analyzed further, for instance using gravity. At the MTS12 point, a splitting curve is also presented, which may confirm the presence of the caldera structure. While MTS 13, the occurrence of splitting in this curve identified a fracture near the fumarole manifestation.

Furthermore, the results of the 3D inversion on line B-B' leading to W-E are shown in Figure 7. The results indicate that the clay cap layer with a resistivity of <10 ohm-m is at an elevation of 400 masl in the west and 300 masl in the east. The deep clay cap thickness in the east indicates that the X field geothermal system is closing. In addition, the B-B' line also shows the presence of a separate clay cap. This may be due to a fault structure in geothermal field X as evidenced by the TE TM curve at the splitting points of MT17 and MTS27. The presence of splitting on MT14 and MTS32 indicates the structure of the caldera. On the lines A-A' and B-B', the area with a moderate resistivity of 16-100 ohm-m represents the reservoir zone (Arisbaya et al., 2018). At the same time, the high resistivity above 150 ohm-m on both lines indicates a basement.

Determination of Base of Conductor (BOC)

As BOC is the lowest part of the clay cap zone, it can be used to denote the boundary between the clay cap and the reservoir. The BOC elevation map (Figure 8) is based on the boundary between a conductive layer with a < 10 ohm-m resistivity and a layer with a higher resistivity. Generally, BOC elevation map can also identify upflow and outflow zones. The upflow zone is characterized by a shallower BOC elevation. A deeper BOC elevation, on the other hand, is typical of the outflow region. The upflow zone in geothermal field X is below the MTBU fumarole area. The south area is an outflow zone, which manifests as chloride spring. The distribution of BOC at elevation reveals that the depth of BOC is shallower in the north-west than in the south. In addition, it is observed that the BOC depth at geothermal location X has an average elevation of 300 – 550 masl. Compared to the southern area, which has a deeper BOC depth, the field prospect area in the average elevation area has more significant potential.

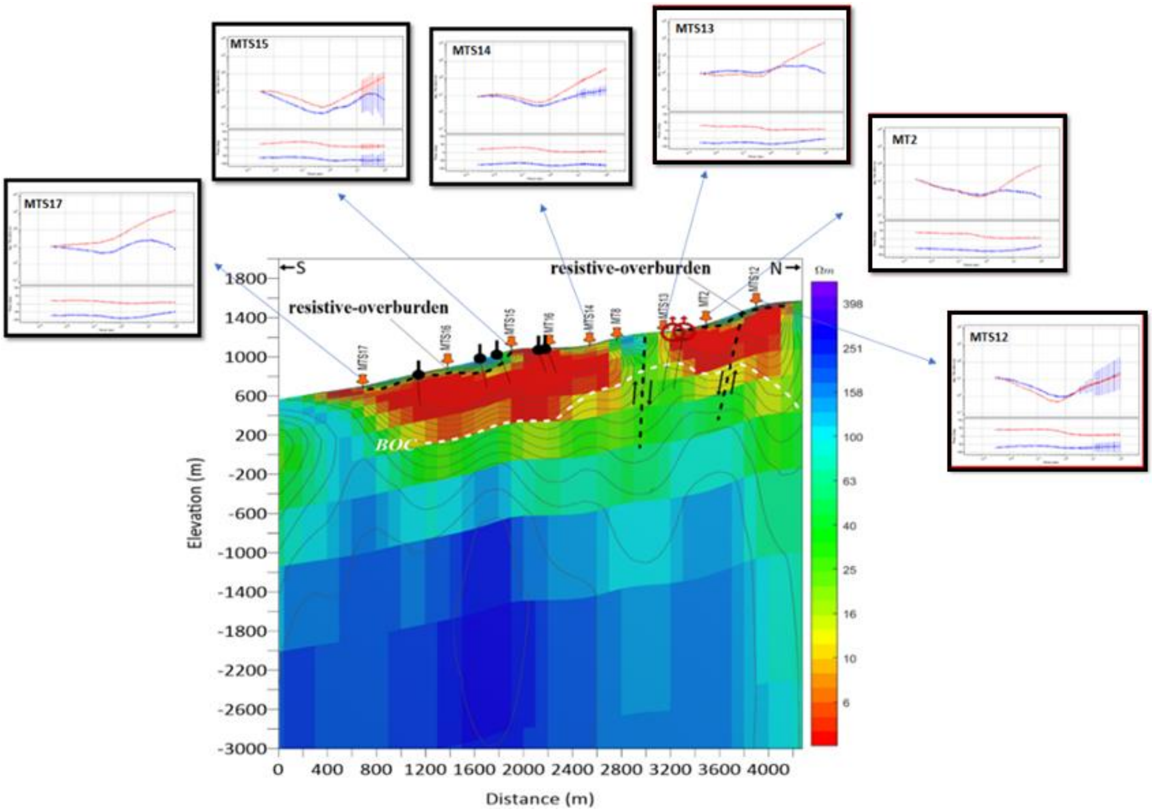

Figure 6. 3D inversion on line A-A' and TE-TM curve

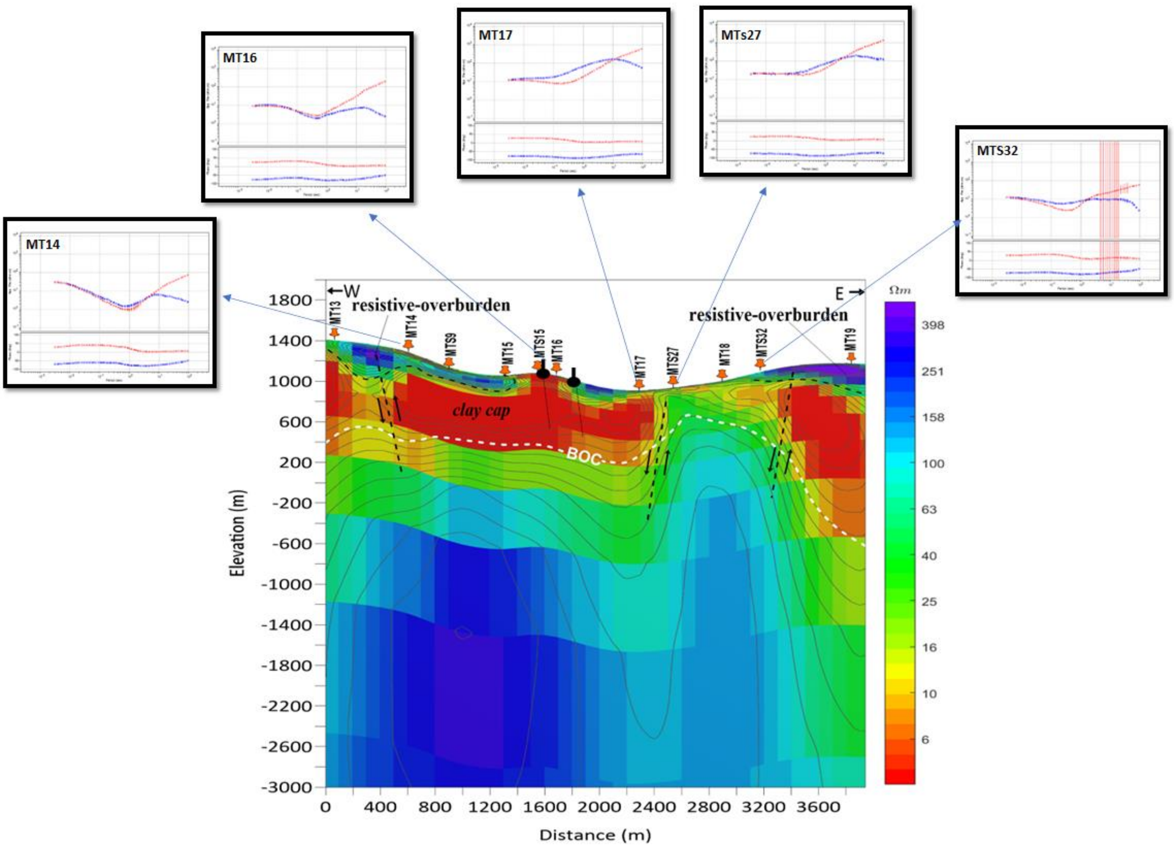

Figure 7. 3D inversion on line B-B' and TE-TM curve

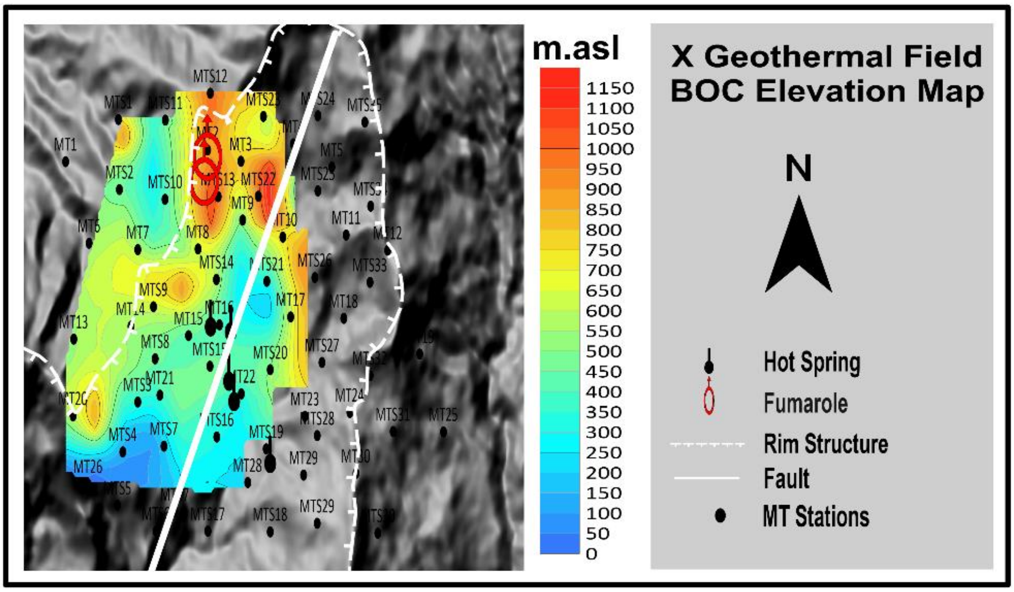

Figure 8. Elevation map of base of conductor from X geothermal field

WELL DATA

The well data samples used were collected from the core cuttings of the exploration wells DZ-1 and DZ-2, as shown in Figure 9. Both the DZ-1 and DZ-2 wells were drilled to a depth of 1925 mMD and 2000 mMD, respectively. MeB measurements and P&T tests were used in this analysis to identify the characteristics and subsurface alteration zones in the two exploration wells. MeB measurement utilizes the organic dye methylene blue due to its high selectivity for smectite clay adsorption in a rock layer (Gunderson et al., 2000).The measurement results indicate that the MeB analysis of the DZ-1 well starts detecting smectite at an elevation of 1060 masl. The smectite concentration is highest at an elevation of 694 masl and then decreases to 314 masl. Meanwhile, in the DZ-2 well, smectite content was detected at a depth of 1050 masl. The high smectite content at an elevation of 792 masl then decreased to 404 masl. This trend indicates that the depth is identified as a clay cap zone .

There are 3-types of hydrothermal alteration identified from the drill cuttings: (a) argillic - low temperature hydrothermal clay alteration, (b) transition between the argillic and the high-temperature hydrothermal alteration, typically containing chlorite and mixed-layer clays, and (c) propylitic – alteration common in the high-temperature section of geothermal reservoirs (Sarmiento et al., 2019). Based on the cutting data, epidote mineral was found at an elevation of -81 masl in the DZ-1 well, while the DZ-2 well did not find any cutting data. Epidote mineral is a characteristic of the propylitic zone which is formed at a temperature of 230-340°C.

The P&T survey on the DZ-1 and DZ-2 wells was conducted during shut-in, i.e. when the well was being closed after drilling the geothermal well. This condition is performed to recover the well's temperature after it has been cooled by the drilling fluid (Axelsson et al., 2001). The P&T survey measurements depicted in Figure 9c indicate that the highest temperature of the DZ-1 well is about 231°C, and the DZ-2 well is about 211°C. Drilling reports show total circulation loss (TLC) at depths of -189 masl (well DZ-1) and 16 masl (well DZ-2). TLC refers to the loss of all or a portion of the drilling mud that enters the formation. TLC occurs when the hydrostatic pressure 144.07 masl in well DZ-2.

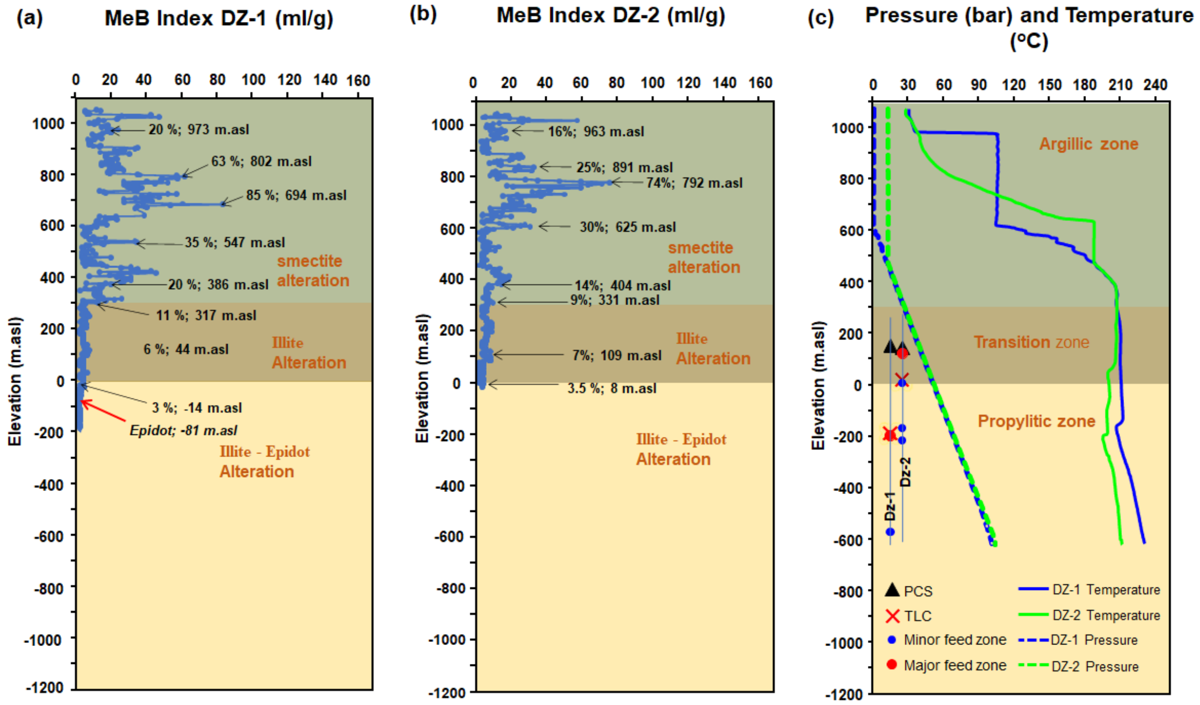

Figure 9. Well data of X geothermal field with MeB index of: (a) DZ-1 well and (b) DZ-2 well; (c) Pressure and temperature test (P&T)

CONCEPTUAL MODEL

The Conceptual Model is a correlation of geoscientific parameters of a geothermal system, including geological, geochemical, geophysical, and well data. The conceptual model of X geothermal field is shown in Figure 10. The BOC in geothermal field X is located between 300 and 400 msal above sea level. The area above the BOC is usually an argillic zone, which has high conductivity (<10 ohm-m) and a high amount of smectite and chlorite (Cumming, 2016). The presence of argillic zones, as indicated by clay cap, correlates relatively with the resistivity values 10 ohm-m (Cumming, 2016; Iskandar and Daud, 2022). This mineral is provided by a MeB index of medium-high results. According to the P&T analysis results, this zone has a temperature <200°C (Binsar et al., 2017). The increasing temperature of the fluid indicates a significant thinning of the clay cap zone (argillic zone) toward the fumarole. The transition zone is between smectite-rich rocks and smectite-poor rocks, or indirectly, rocks containing illite alteration. The resistivity of the transition zone ranges between 10-20 ohm-m. This transition zone is illite-rich with a lower MeB index and a temperature range of 200-210°C. This zone contains a mixture of illite-smectite with pyrite, quartz, depth illite, and the presence of the mineral hydride, which is the main distinguishing factor from argillic minerals.
While the propylitic zone is part of the main reservoir, its temperature is higher than in the other zones. This zone is located below 0 masl and is distinguished by the presence of abundant illite and epidote. In addition, the predominant chlorite mineral is coincident with the principal clay minerals quartz, calcite, pyrite, and illite. The resistivity of this zone is between 20-100 ohm-m (Arisbaya et al., 2018), with MeB content below 4% and temperature >210°C, according to the MT data. Epidote minerals are found in the -81 msal elevation depth zone in the DZ-1 well but not in the DZ-2 well due to shallow TCL.

Conceptual model construction are summarized as: The upflow zone in X geothermal system leads to manifestation In MTBU. This is evidenced by the presence of surface manifestations in the form of fumaroles and surface alteration zone. From manifestation and alteration zone analysis, heat source is located vertically beneath the surface manifestation fumaroles MTBU. The hypothesis is supported by geophysical MT measurement where the clay cap is thinning in that area. The region is considered to be a potential location for the X geothermal field. Moreover, the X geothermal field has outflow towards the south. This outflow interpret as hot spring manifestation from WLBR, DP and LK which is containing Chloride fluids.

CONCLUSIONS

The base of conductor (BOC) in geothermal field X, which serves as a framework for exploration studies, has been successfully modeled using 3D MT inversion analysis and well data. Vertical MT modeling indicates that the elevation BOC is 300 - 400 masl underneath the clay cap layer, with a resistivity of <10 ohm-m and a temperature of <200ºC. The layer above the BOC is a clay cap layer in the argillic zone and has high smectite and chlorite quantity. This layer is thinned to the southeast at the formation of MTBU fumaroles. A transition zone has been identified at 300 - 0 masl as a layer with 10 – 20 ohm-m resistivity and 200 - 210ºC temperature. This zone is a layer between the conductive zone (clay cap) and the non conductive zone (reservoir). This zone's composition consists of a mixture of illite-smectite with pyrite, quartz, illite, and hydride. Illite and epidote minerals were discovered in the propylitic zone at elevations below 0 masl and temperatures >210ºC. The modeling of subsurface zones and the determination of BOC boundaries in geothermal field X facilitates exploration of the area and proves that geothermal field X has the potential for further development and wide the prospect area research is 3.4 km^2.

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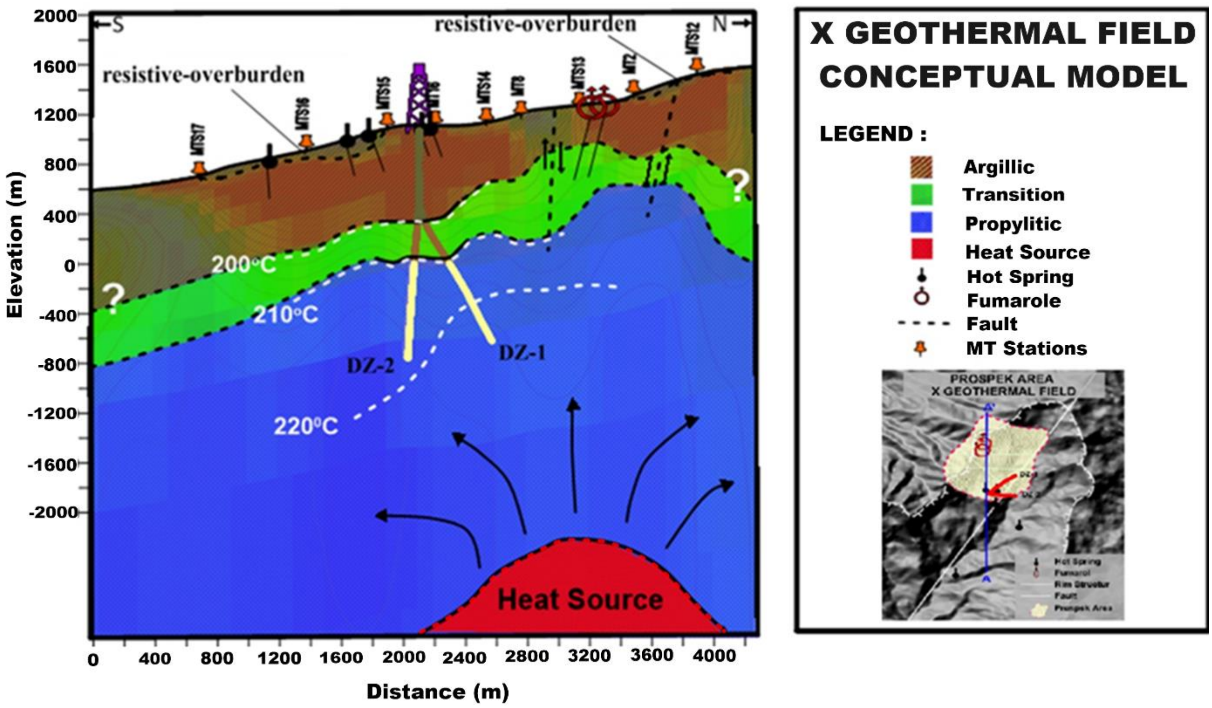

Figure 10. Conceptual model X geothermal field

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