Bonjol Geothermal Structure Based on 2D Inversion of Magnetotelluric Data

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Abstract. Bonjol geothermal area is located in Pasaman Regency, Province of West Sumatera. The existence of geothermal system is characterized by hot springs, and rock alterations by temperature 50 - 88°C. Magnetotelluric (MT) survey had been conducted by Geological Agency in 2009 and 2018 to identify the geothermal promising zones. Utilizing 2D inversion model of MT data can delineate the conductivity structure to identify where geothermal system is located. MT data result showed that low resistivity in the northern part is around Takis, Sungai Limau, and Kambahan hot springs, and in the southern part is around Padang Baru hot spring interpreted as cap rock of Bonjol geothermal system. The existence of top reservoir of Bonjol geothermal system is about 800 until 1000 meters depth. The promising area are located in the northern part area around Takis, Sungai Limau, and Kambahan hot springs, and in the southern part area around Padang Baru hot spring.

1. Introduction
Indonesia archipelago has more than 200 volcanoes located along Sumatera, Java, Bali, and the islands of eastern Indonesia, and it is known as part of Pacific Ring of Fire. It makes Indonesia abundant of geothermal resources. Bonjol area is one of prospect geothermal resources located in West Sumatera Province and situated in a segment of Sumatera fault zone (Figure 1). Indication of geothermal area by evidence of hot spring and altered rocks.

Geological Agency had conducted 3G survey (Geology, Geochemistry, and Gravity, Magnetic, and DC Resistivity) in 2007, and Magnetotelluric survey in 2009. Based on 3G survey shows that the Bonjol geothermal prospect area is associated with young volcanic in Bukit Binuang and Sumatera fault activities which had published [1] [2] [3] [4]. Meanwhile, based on MT survey which had published [5] show that the conductive layer around Padang Baru, Sungai Limau, and Takis hot springs assumed as hydrothermal alteration zone, where the top reservoir of geothermal system is 800 meters depth. This alteration zone spread to the northern of Takis and Sungai Limau hot springs, and also spread to the southern of Padang baru hot spring. The conductive layer beneath Padang Baru, Sungai Limau, and Takis hot spring corresponds to promising zone correlated with a potential geothermal reservoir [5].

The distribution of conductive layer which is assumed as alteration zone and promising area has not been clearly delineated because of the limited coverage of MT stations. To confirm that, Geological Agency in 2018 had continued conducted MT survey in this area. This paper is made by combining MT data survey in 2009 and 2018, to get more clearly promising area deliniation of Bonjol geothermal system.
2. Basic of Theory

The Magnetotelluric (MT) technique is a passive Electromagnetic (EM) technique that involves measuring fluctuations in the natural electric (E), and Magnetic (B) fields in orthogonal directions at the surface of the Earth as a means of determining the conductivity structure of the Earth at depths ranging from a few tens of meters to several hundreds of kilometers. The penetration depths of electromagnetic fields within the Earth depend on the electromagnetic sounding period, and on the Earth's conductivity structure [6].

The generic Magnetotelluric inverse problem can now be posed as a sequence of Magnetotelluric data, $d_i, i = 1, ..., N$, have been acquired in a field experiment whose objective is to determine the Earth resistivity structure of a sequence of real-valued model parameter, $m_j, j = 1, ..., M$. A best-fitting model is most commonly defined as one minimizing an objective, or penalty, function that measures the discrepancy between $d$ and $F(m)$. In geophysics, this function is often referred to as the data misfit, or just misfit. In application to geophysical inverse problems, the stabilizing functional is typically chosen to be a measure of the spatial roughness of the unknown model. A damped least-squares estimate of $m$ can be defined as constrained least-squares estimate $\Omega(m) \leq \mu$, where $\mu > 0$ dan $\Omega$ is positive-valued function known as a stabilizing functional, in the terminology of Tikhonov regularization. By combining (undamped) least-squares to damped least-squares with some modification to account for the additional term in the objective function, the damped least-squares objective functional becomes [7],

$$\psi(m) = (d - F(m))^T W (d - F(m)) + \lambda m^T L^T L m$$  \hspace{1cm} (1)
for given $\lambda$, $W$, and $K$. The regularization parameter, $\lambda$, is positive number. The positive-definite matrix $W$ plays the role of the variance of the error vector, and $L$ as a second-difference operator of matrix, $Lm$ approximates the Laplacian of $log\rho$ [8].

3. Geoscience Review
Bonjol geothermal area is formed in volcanic area where is mainly covered by Tertiary and Quaternary lava, and sedimentary rock (Figure 2). The Tertiary rock are old andesite lava and Malintang dacitic located in relatively in the northern and eastern part of area. The Quaternary rock mostly in andesite lava where Bukit Binuang as the youngest lava (Pleistocene). Geological structure is mainly trending to northwest – southeast correlated to Sumatera Fault Zone. This normal fault made graben in the central of area and filled by sediment and pyroclastic flow. Another normal fault is trending to southwest – northeast [1].

![Geological map of Bonjol geothermal area](image)

**Figure 2.** Geological map of Bonjol geothermal area

The geothermal surface manifestations appear in Takis, Sungai Limau, and Kambahan hot springs in the northern part of area which has temperature vary 73.4 - 87.9°C (normal pH), and Padang Baru hot spring in the southern which has lowest temperature 49.7°C (normal pH) in the Figure 3.

4. MT Survey
MT measurement had conducted in 2008 totally 25 station along 4 lines trending to SW - NE. In 2018, Geological Agency had continued MT measurement which has 50 stations, therefore totally 75 MT stations along 10 lines trending to SW - NE (Figure 4). The additional MT station in order to confirm the distribution of alteration zone of Bonjol geothermal area. The modelling of MT data use 2D Inversion apply Non-Linear Conjugate Gradients (NLCG) algorithm as described by [8]. This 2D inversion method utilize WinGLink software.
5. MT Result
In Figures 5 and 6 show model section of line 2, 3, 5, 7, and 8 is derived by 2D model inversion, and the position of each line in Figure 4. The upper boundary of low resistivity layer generally are similar trend for each line, where this low resistivity in the southwestern part is thicker rather than in north eastern part. This low resistivity layer on the north eastern part is assumed as altered rock that proved by the appearance of hot springs and mineralization rocks.

Figure 8 shows six sections at depths of 500 m, 700 m, 800 m, 900 m, 1000 m, and 1100 m. The resistivity distribution in the shallow layer in 500 m depth show that low resistivity mostly dominate area which relatively northwest - southeast direction. In 700 m depth, low resistivity in the vicinity of
hot springs relatively become higher. The relative low resistivity around Padang Baru hot spring become medium resistivity and it is assumed as top reservoir of Bonjol geothermal system at 800 m depth. In the northern part around Takis, Sungai Limau, and Kambahan hot springs also become medium resistivity at 1000 m depth and it is assumed as top reservoir of Bonjol geothermal system.

6. Discussion

Figure 7 show 3D visualization which across Padang Baru - Takis - Sungai Limau - Kambahan hot springs (A - B - C). The low resistivity below Takis, Sungai Limau, Kambahan, and Padang Baru hot springs interpreted as alteration rock that indicate the interaction of thermal fluid with rocks at the depth and serves as a cap rock of Bonjol geothermal system. This low resistivity as if continuously from the northern to southern part of the area and assumed as response of depression zone. The conductive layer as altered zone correlated with shallow gradient thermal drilling result. Altered rocks with argillic type founded from 41.6 meter until 250.8 meter depth which is dominated by montmorillonite and smectite [9].

The distribution of low resistivity shows that Bonjol geothermal area has two promising zones (Figure 7). Firstly, in the northern part area around Takis, Sungai Limau, and Kambahan hot springs, and secondly, in the southern part area around Padang Baru hot spring. The promising zones in the northern part assumed as alteration rock and interpreted as top reservoir at 1000 m depth. The promising zones in the southern part has shallower of top reservoir at 800 m depth, although Padang Baru hot spring is lowest temperature.
Figure 5. 2D Model section of line 2, 3, and 5
Figure 6. 2D Model section of line 6, 7, and 8
Figure 7. 3D visualization
7. Conclusion

By combining of MT data survey in 2009 and 2018, the author get more clearly the promising area of Bonjol geothermal system. In processing data using 75 MT data stations, where 25 MT data in 2009 measurement and 50 MT data in 2018 measurement. The low resistivity zone in the northern part around Takis, Sungai Limau, and Kambahan hot springs interpreted as alteration zone, and top reservoir assumed at 1000 m depth. The low resistivity zone in the southern part around Padang Baru hot spring also interpreted as alteration zone, and has shallower of top reservoir at 800 m depth. The low resistivity zone indicates two promising zones, there are in the northern part around Takis, Sungai Limau, and Kambahan hot springs, and in the southern part around Padang Baru hot spring.

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