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Spatial Correlation Model between Resistivity Data and Subsurface Permeable Zones to Optimize the Existence of a Geothermal Reservoir

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ABSTRACT

Indonesia as a country that is crossed by the tectonic paths has potential disasters related to the presence of volcanic and earthquake zones. It also has natural resources potential, one of which is the presence of the geothermal potential. One location that has potential geothermal resources is Mt. Patuha, located in the south of Bandung, West Java, Indonesia. Although the geothermal potential that exists in these locations has been partially produced, it is suspected that there are still other parts of the location that have the potential for increasing the production targets in the future. One parameter that can be used as an indication of the geothermal prospect area is the presence of surface manifestations i.e. hot springs and fumaroles. Hot springs occur due to the fractures that carry hot fluids from the subsurface. Areas with high fracture intensity in subsurface will certainly be the main target in geothermal exploration. High fracture intensity shows high permeability in the presence of fluid and hot steam from the influence of magmatism. In addition, the heat effects of fluids and vapours caused the alteration of rocks as caprocks which are usually characterized by the very low resistivity zones. The geothermal reservoir itself will be characterized by relatively low to moderate resistivity zones. Distribution of the subsurface resistivity is generally obtained from the results of geophysical surveys such as the MT (magneto-telluric) method carried out in the fairly regular grids and covered wide area. The surface fracture zones could be identified from the satellite images or the digital terrain model data, while the subsurface permeability data in the study site were obtained from the results of exploration drilling in term of the presence of TLC (total lost circulation) data. The drilling in geothermal exploration commonly was carried out in irregular grids and only covered specific area due to its high cost. Multivariate geostatistical method with conditional co-simulation such as Sequential Gaussian Co-Simulation could generate 3-dimensional model of subsurface permeable zones by considering their spatial correlation with the resistivity data as secondary variable. This method was effective to optimize the existence of geothermal reservoir in the Patuha geothermal field.

1. INTRODUCTION

Geothermal resources in Indonesia are distributed at 256 sites and among of them, 40 sites are located in West Java. The capacity of geothermal power plant installed in West Java is 839 MWe out of 1197 MWe of all geothermal capacity in Indonesia (Fauzi et al., 2015), therefore West Java is the most interesting and favorable study site. At this moment, Indonesia only uses 4-5 % of its geothermal capacity and expected to utilize the energy by 10 % of total energy per year (Syafii et al., 2018).

The economical level of the reservoir is more controlled by permeable zones than temperature. Natural fractures in geothermal is the main path for reservoir fluids to flow into the production well. Therefore, the presence of large fractures affects the total lost circulation (TLC) case, where the drilling fluid does not return to the surface because it enters through the fracture cracks. Thus, it is noticeably an economic determinant of geothermal factors (Lavrov, 2016). The large fluid losses and entry into the rock formations are a good indication of the presence of permeable fractures (Dyke et al, 1995). Natural fracture correlates with the results of geophysical and mud-logging logs that could prove the natural permeability while drilling and after drilling. The temperature anomalies, lost drilling fluids and gas emissions are indicators of the permeability structures in wells where the spatial corroded inside the wells shown in the images of log calipers and acoustics (Vidal et al., 2017).

One parameter that could be used as an indication of the geothermal prospect area is the presence of surface manifestations. The areas with high subsurface fracture intensity will certainly be the main target in geothermal exploration. High fracture intensity shows high permeability in the presence of fluids and hot steam from the influence of magmatism. In addition, the heat effects of fluids and vapors caused the alteration of rocks as a caprock which are usually characterized by the low resistivity.

The TLC data which indicate the existence of subsurface permeable zones are usually very few and limited because they are only obtained from the drilling results. While geophysical data, such as Magnetotelluric (MT) are very broad and the results could be associated with the subsurface permeable rocks. Multivariate geostatistics method is suitable for combining two variables that fairly high correlated to be co-variables to estimate/simulate the variables sought by looking at the spatial aspects (Syafii et al., 2018; Al-Mudhafar, 2018). The purpose of this study is to model the probability of permeable zones from TLC data using conditional co-simulation method by utilizing the high correlation between TLC and the low to moderate resistivity from MT data. This approach was applied to the Patuha geothermal field, West Java, Indonesia.

Geothermal fracture modeling has been carried out using different methods and software. Vidal et al. (2017) modeled a permeable zone using MOVE™ from Midland Valley Exploration to analyze the geometry of fractures that are interconnected and correlate them within two geothermal wells. GEOFRAC is an application made using MATLAB to model the 3-dimensional fractures aided by geostatistical simulations (Kubo et al., 2015; Koike et al., 2001; Koike et al., 2012). TOUGH2 software is used to simulate the reservoirs through an analysis of discrete fractures network (DFN) (McClure, 2009; Juliusson and Horne, 2010). The indicator kriging method for geological and fracture modeling has been applied by previous researcher (Pyrcz and Deutsch, 2014). The permeable zones in a geothermal reservoir are containers for the fluid flow in rocks and could be connected with the rock conductivity. So that electromagnetic data is suitable for identifying the permeable zones from the resistivity values (Barkaoui, 2011; Campanyà et al., 2015).

2. STUDY SITE AND TECTONIC SETTING

Indonesia is controlled by three large plates, i.e. Pacific, Eurasia, and Indo-Australia Plates. The Pacific Plate moves toward west-northwest to the Eurasian and Indo-Australian Plates which is moving toward north to the Eurasian Plate as well. Subduction zones occurred in the Sunda and Java Trench formations (see Figure 1a) (Hall, 2012). Volcanic bows in the western zone of Sumatra have an orientation to the southeast of the Sunda Trench. The Java Trench which followed by the Sunda Trench moved from west to east, so this zone is active and asymmetric with the dip of 700 km into the mantle. The volcanic formation in Java is above the seismic zones within 100 and 200 km depth. The results of this volcanic arc was followed by the convergent plates as boundaries (Schotanus, 2013).

The active plate makes the volcanic and intrusion zones since Oligocene along the Sunda Arc. The plate meeting along the subduction zone is divided into the oblique subduction in the western part of Sumatra and in front of the subduction zone which is located in the eastern part of the plate meeting on Java, Bali and Sumbawa Islands. West Java is in the transition zone between the west and the east of the subduction zone of the Indian-Australian Plate which moves 6-7 cm per year. There is a northeast-southwest line from the western part of Java Island to the Meratus mountain range in the southeastern part of Borneo which is the limestone crustal continental crust. The eastern part of this boundary is a complex of high-pressure and low-temperature metamorphic rocks (Schotanus, 2013).

Patuha geothermal field is located about 50 km southeast of the Bandung City, West Java which is one of several well-known active geothermal fields such as Wayang Windu, Darajat, and Kamojang (see Figure 1b). Patuha field is a vapor-dominated with steam zone underlying deep liquid reservoir. The reservoir temperature about 215 – 230ºC covering area of 20 km^2 (Ashat et al., 2019). It is surrounded by a volcanic center or vents which are distributed along a west to northwest trending structure (see Figure 2). Based on the field mapping reports, major structure trends that develop in this field are in NE-SW and NW-SE directions (Elfina, 2017). According to the resistivity survey, Patuha geothermal system consists of three reservoirs which are associated with the area of Kawah Putih, Kawah Ciwidey and Kawah Cibuni (see Figure 2). It is also confirmed by the thermal gradient measured at 150 m depth which shows three anomaly areas of high temperature. Additionally, the ALOS PALSAR satellite imagery analysis shows three lineament trending features which are probably identified as reservoir zones (Ashat et al., 2019).

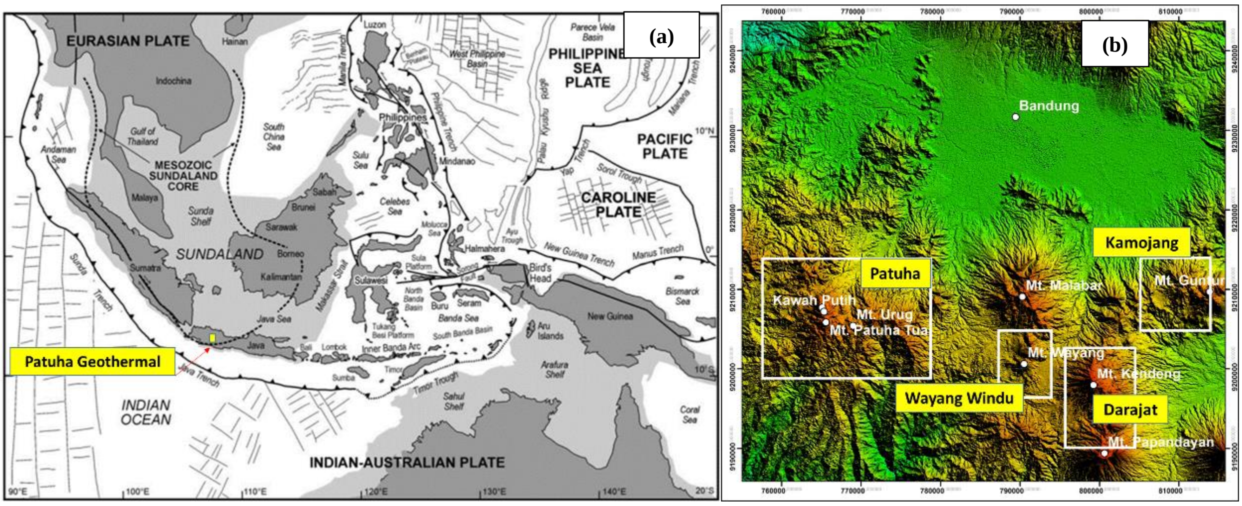

Figure 1: (a) The tectonic setting in Indonesia (Hall, 2012); (b) The eastern part of Patuha geothermal field is the Wayang-Windu, Darajat and Kamojang geothermal fields.

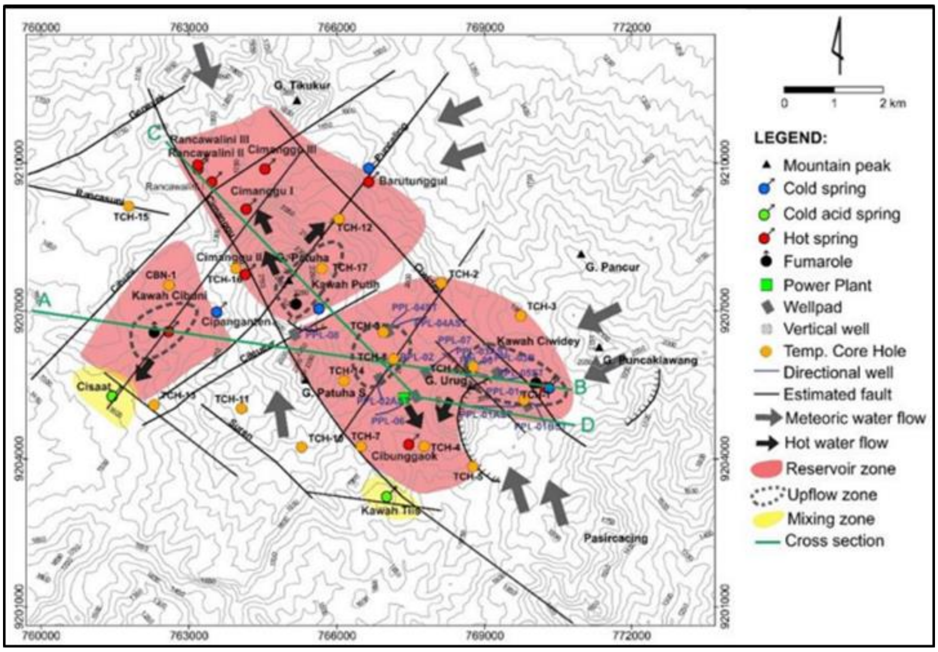

Figure 2: The lateral fluid flow pattern in the geothermal system at Patuha (Amelia, 2014; Ashat et al., 2019).

3. GEOSTATISTICAL MODELING AND ANALYSIS

3.1 Markov Model (MM)

Markov Model (MM) was introduced by Almaeda and Journel (1994) and has been widely applied in the geostatistical field (Shmaryan and Journel, 1999). Stochastic simulation represents a powerful tool for the description of phenomena which cannot be described deterministically because of their complexity. Estimation of the primary variables using secondary variables could use MM1 and MM2. The MM1 has received acceptance in practice because it does not call for a full linear model of coregionalization (LMC). The MM1 is a reasonable model if primary variable $Z_1(\mathbf{u})$ is defined on the same or a larger volume support than secondary variable, while MM2 was developed for the case where the volume support of the secondary variable is larger than that of the primary variable. This is often the case with remote sensing and seismic-related data (Remy et al., 2009). The resulting MM2 coregionalization model is:

$$\left.\begin{aligned} \rho_{11}(h) &= \frac{C_{11}(h)}{C_{11}(0)} \\ \rho_{22}(h) &= \frac{C_{22}(h)}{C_{22}(0)} \\ \rho_{11}(h) &= \rho_{12}^2 . \rho_{22}(h) + (1-\rho_{12}^2)\rho_R(h) \end{aligned}\right\} \qquad (1)$$

where ρ_{11}(h), C_{11}(h), and C_{11}(0) are the correlogram, covariance, and variance of primary variable respectively, ρ_{22}(h), C_{22}(h), and C_{22}(0) are the correlogram, covariance, and variance of secondary variable respectively, ρ_{12} and ρ_R(h) are the co-located coefficient of correlation between primary and secondary variables, and residual correlation, respectively.

3.2 Primary Variable

Patuha geothermal field has 40 locations of TLC from 14 wells (see Figure 3a), which are assumed to be the location of permeable zones. The TLC data are only indicated by the location of points, so in order to perform geostatistical estimation those data are considered as indicator (binary) data. This study used the TLC data as the primary variable and resistivity data from Magnetotelluric (MT) survey as the secondary variable. TLC data is only available as an indicator 1 if there is TLC and 0 otherwise. One way to quantify the indicator data is to use the Indicator Kriging (IK) method. The probability value of TLC data produced by IK method is attempted to correlate with the low to moderate resistivity zones (15 – 100 Ωm) where in general they indicate the existence of a geothermal reservoir.

A key concept in any geostatistical approach is the assumption of stationarity, which is defined as invariance by translation of spatial statistics and is required for the inference of a probabilistic model. The most commonly used tool in geostatistics for a measurement of the relation between two random variables is the variogram and its equivalent, the covariance. The omnidirectional indicator variogram of TLC data is fitted using the Spherical model with distance of influence 100 m as shown in Figure 3b. The probability of permeable zones (0.10 – 0.90) produced by IK method is depicted in Figure 3c, while the histogram of high probability of TLC (0.50 – 0.90) is seen in Figure 3d, with mean 0.653 and median 0.647.

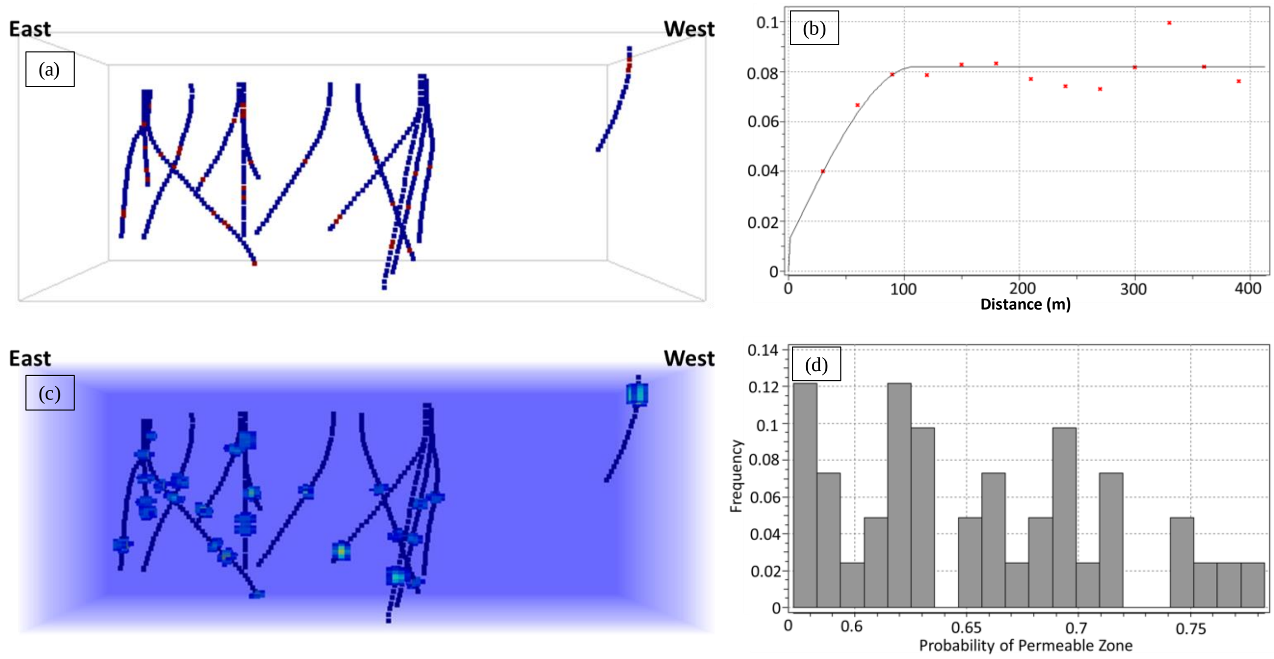

Figure 3: (a) The presence of TLC data (red) in 14 wells in Patuha geothermal field; (b) The variogram fitted by Spherical model with range 100 m, sill 0.70, and nugget 0.10; (c) The probability model of TLC by IK method with probability 0.10 –0.90; (d) The histogram of high probability of TLC (0.50 – 0.90).

3.3 Secondary Variable

The electromagnetic fields vary from one host rock to another depending on the petrophysical properties of the host rock and other factors. The intensity of rocks alteration is furthermore dependent on the temperature, time and the texture of the host rocks (Barkaoui, 2011). The MT survey in the study site was conducted in 1983 by CGG/GEOCO with 139 MT points. Furthermore, in 1995 and 1997 additional MT was carried out by Geosystem and PT Tri Bawana Utama with 35 and 85 points respectively. All MT lines in the study site is depicted in Figure 4a. The data used in this study is the result of 2D inversion data, modeled by Elnusa in 2013. Twenty-one inversion lines of resistivity were analyzed and modeled in 3D using Voxler with Inverse Distance interpolator (see Figure 4b). The cross-section that describes the resistivity distribution and crossing Kawah Ciwidey is shown in Figure 4c. The red color refers to the very low resistivity (< 15 Ωm) is interpreted as caprock zones, while the yellow to green color which refers to the low to moderate resistivity (15 – 100 Ωm) and just below the caprock is interpreted as reservoir zones.

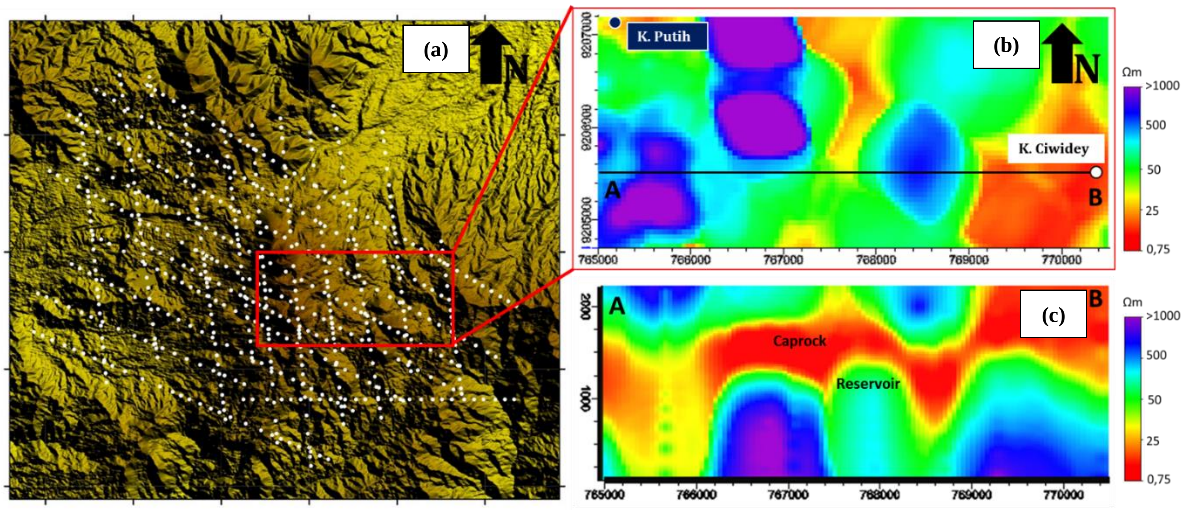

Figure 4: (a) Regional distribution of MT lines survey at Patuha geothermal field, the red rectangle is local study site; (b) Plan view of resistivity map; (c) Cross-section A-B of resistivity distribution shows the caprock and reservoir zones.

3.4 Sequential Gaussian Co-Simulation Method

The principle behind a geostatistical simulation is to build the random variables that reproduces the statistical and spatial continuity of the regionalized variable. The idea is to generate a set of realizations of the random function. In linear geostatistics, ordinary or simple kriging produces a smoothed model of variability, because the target is to minimize the error variance. While the conditional simulation has the target to reproduce the dispersion variance by generating some different realizations of $Z(x)$ which is presenting the same statistics (histogram) and spatial variability (covariance) of the actual regionalized variable.

The correlation between primary variables (the probability of permeable zones) and secondary variable (the low to moderate resistivity) showed coefficient (ρ_{12}) 0.74 which is considered to be high (see Figure 5a). The variogram was modeled after the primary and secondary variables were transformed into gaussian, so the data becomes a standard normal distribution with mean = 0 and variance = 1. The ρ_{12} after gaussian transformation is changed to be 0.60 (see Figure 5b). The fitting result of primary variable showed a structure of Spherical model with nugget = 0.10, sill = 0.80, range = 1500 m, while the fitting result of secondary variable showed a structure of Spherical model with nugget = 0, sill = 1.05, and range = 1500 m (see Figures 5c and 5d). The Sequential Gaussian Co-Simulation (COSGSIM) method by SGeMS software used MM2 and simple kriging algorithms was performed to generate 50 realizations of probability of permeable zones (see Figure 6).

The representative simulation model was selected by dividing each block into 1st, 2nd, and 3rd quartiles from 50 realizations. Figure 7 shows the cross-section A-B in the same location as depicted in Figure 4b for the median of simulated probability of permeable zones at Patuha geothermal field. This result was validated using the location of two production wells, PPL6 and PPL1 and shows that there is high probability (> 0.75) of permeable zones beneath those wells which was interpreted as reservoir zones in the depth of 1000-1500 m. The caprock was interpreted as the low probability (< 0.60) of permeable zones.

4. CONCLUSION

The permeable zone estimated by the Indicator Kriging (IK) method produced probability values which has quantified the location of Total Lost Circulation (TLC) location. The high probability value (> 0.50) of permeable zones was correlated with the low to moderate (15 – 100 Ωm) resistivity data from MT inversion with coefficient (ρ_{12}) 0.74. The primary variables (probability of permeable zones) was conditionally simulated by considering the resistivity data as secondary variables using Sequential Gaussian Co-Simulation (COSGSIM). The permeable zones that were interpreted as a reservoir was obviously visible beneath the production wells about 1000 - 1500 m below the surface. The TLC data which was set to be the co-variable with resistivity data was effective to be used for the modeling of probability of permeable zones in a geothermal field.

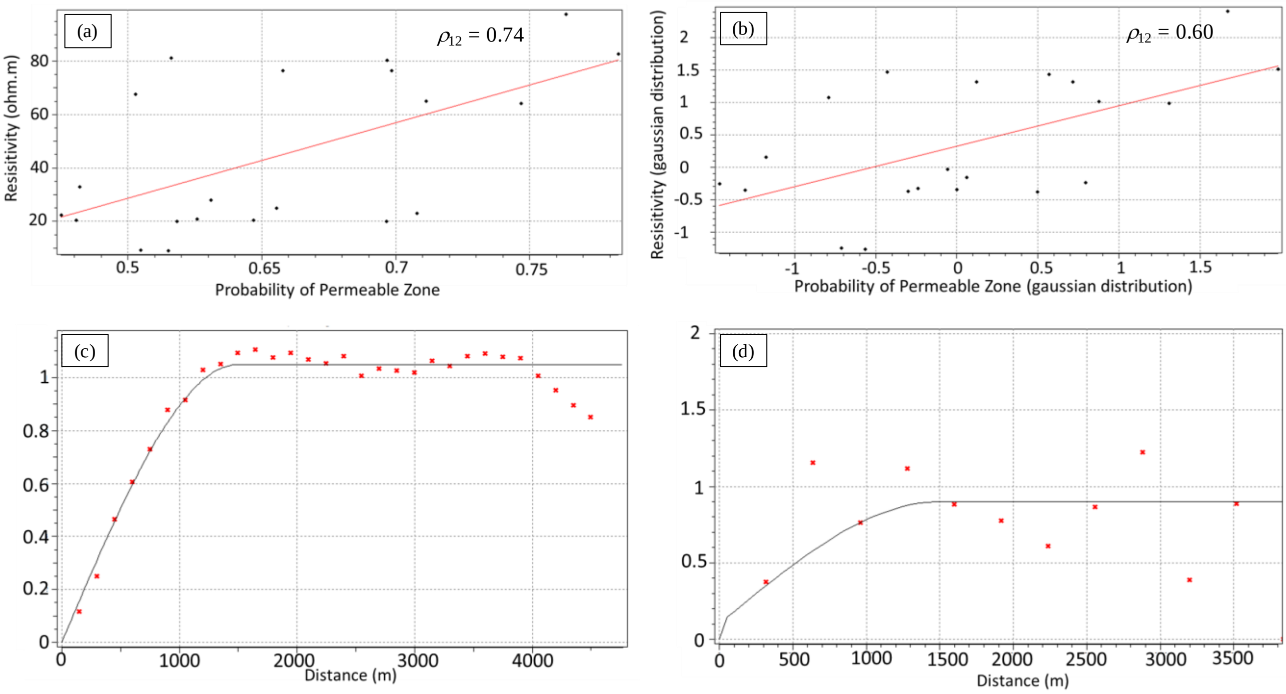

Figure 5: (a) Scatter plot between probability of TLC and low to moderate resistivity; (b) The corresponding scatter plot after gaussian transformation; (c)-(d) Variogram of probability of TLC and resistivity after transformation.

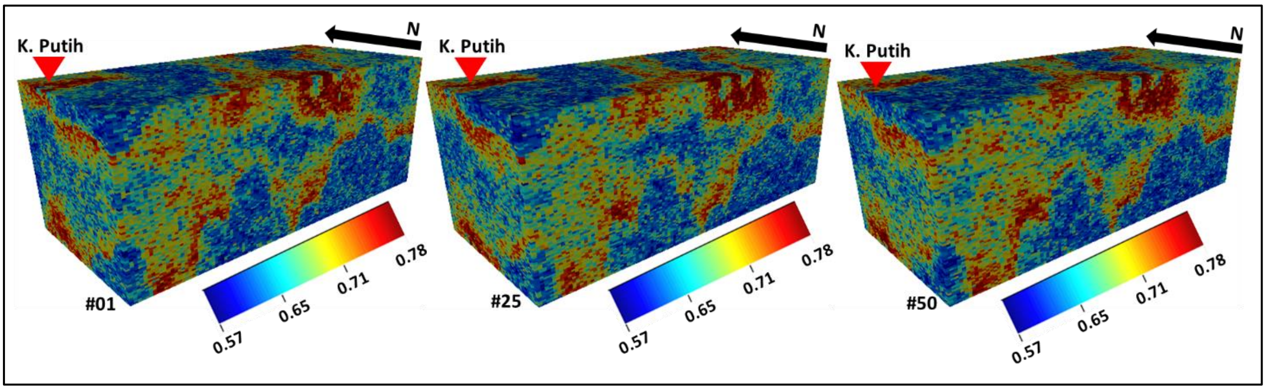

Figure 6: The realization #1, #25, #50 of the probability of permeable zones produced by COSGSIM method. In the edge of west corner is the location of Kawah Putih, the principal surface manifestation at Patuha geothermal field.

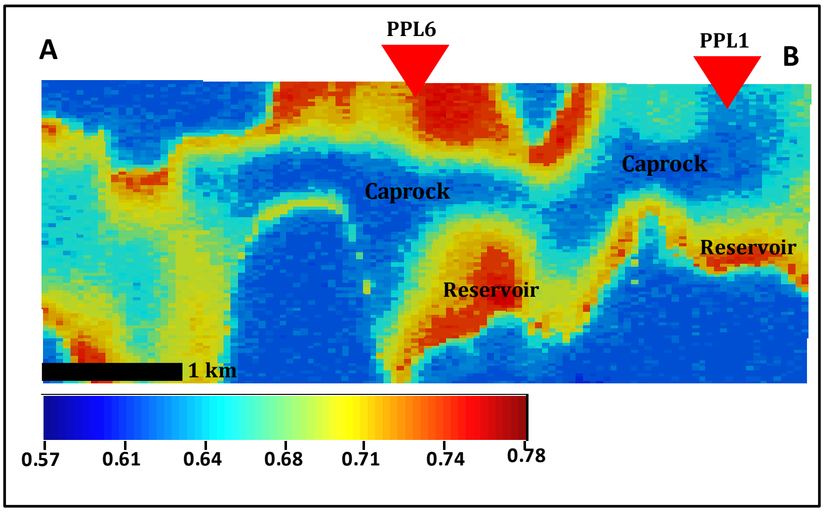

Figure 7: The simulated model of probability of permeable zones in the same location as in Figure 4b shows the interpreted reservoir and caprock which validated by the position of two production wells.

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