Fluid Flow Direction Beneath Geothermal Area Based on Self–Potential Data (A Case Study at Mount Patuha, West Java, Indonesia)

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Abstract**—** The purpose of this research is to estimate the fluid flow movement beneath geothermal area by self-potential (SP) data analysis. The value of SP, such as curve shape, contour, and positive-negative value are used to achieve the aims of this research. The study was conducted in the area of Mount Patuha, West Java, Indonesia. This area is estimated as a prospect of geothermal energy. Measurements were conducted by using the amplitude of potential at the position of reference point in the Kawah Putih, with a height of 2213 m above sea level. Electrode moves with the observation point of 10 m distance. The results of this study are shown in the form of estimation of ground water movement to the northeast toward the Kawah Putih area.

*Key words***—**curve shape**,** self potential, contour, positive-negative value, geothermal energy, amplitude of potential.

I. Introduction

Self-Potential is a passive geophysical method that measures the natural potential of the earth (Nyquist, 2003). This method is called passive because it does not give any disturbance to the earth. Potential measurements are made between two points on the surface of earth's surface. First, self-potential method was proposed by Robert Fox in 1830 (Reynolds, 1997) by using a copper plate electrode with a measuring device for detecting the galvanometer copper-sulfide deposits in Cornwall, England. Self-potential method has been used since 1920 as a complementary application in the exploration of metal deposits.

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The main factor affecting the value of self-potential variation is the presence of ground water. Potential flow is caused by ground water, either as a solvent of the electrolyte or other minerals.

The natural potential of the earth surface consists of two components, one is constant and the other is time varying. Constant component is caused by electrochemical processes, and by components that change due to variations of the potential difference of alternating current (ac) induction, i.e. by an electrical storm and the variation of Earth's magnetic field. Each component of the self-potential is called mineral potential and the background potential.

II. BASIC THEORY

Electrokinetic's Potential (E_k) arises as a result of the electrolyte movement through a porous or capillary slit. Potential is measured along the capillary. Generated potential from this process are usually categorized as electro filtration, electro mechanics, and streaming potential which can be expressed as follows:

$$E_k = \frac{\varepsilon \mu C_E \delta P}{4\pi\eta} \tag{1}$$

In which ε, μ, η, δP, and C_E are the dielectric constant, resistivity, dynamic viscosity of the electrolyte response, the changes of pressure, and the coupling coefficient of electro filtration respectively. C_E represents the physical and electrical properties of the electrolyte which passes through the medium.

The electric current occurs because of the hydraulic gradient and the quantity of electro filtration coupling coefficient (C_E). This current shows the physical and electrical properties of the electrolyte. The movement of fluid through a medium will generate a potential gradient along the flow path as a result of the interaction between pore fluid movement and two layers (Overbeek, 1952). This potential is called the streaming potential.

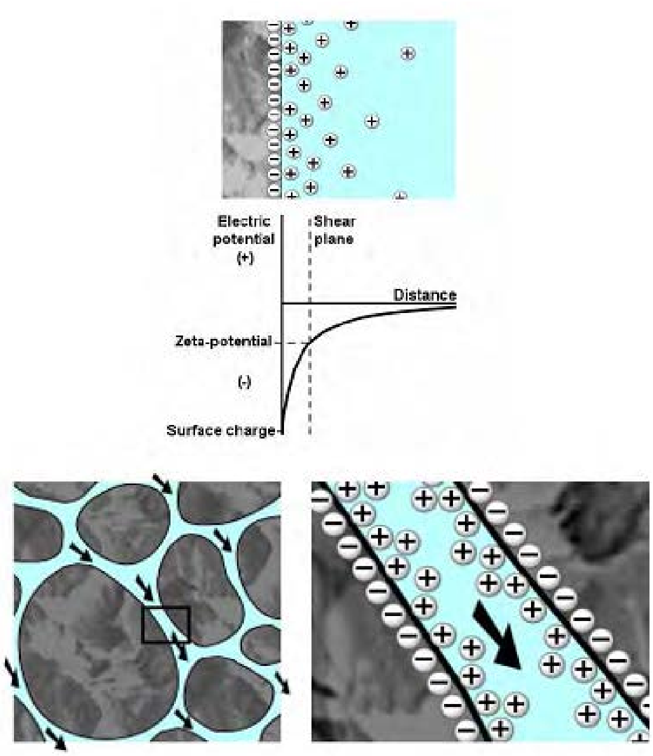

Fig. 1 Formation mechanism of the streaming potential

The amount of electrical potential difference is caused by water infiltration that depend on the pressure gradient and conductivity of pore water called coupled conductivity which is negative (Friborg, 1997). Coupled conductivity does not look so different from different ground surfaces. Although some data indicates that there is a relationship between ore minerals coupled with conductivity as a result of pore space on the ground with the ore minerals that produce an electric double layer. Soil material is affected by internal erosion in the overall pore space which then showed an increase compared to the streaming potential of materials that have no effect.

The surface of the ore mineral has always a negative electrical charge, so that it pulls the positive ionic charge around the pore water and formed electrical double layer. The layer will be cut off if the pore water moves due to pressure gradient. The result is a separation of charge and electrical potential difference between the upstream and downstream in the pore. The number of electrical potential difference is caused by water absorption that depends on the potential gradient and conductivity of pore water pressure. Some data indicate that there is a relationship between ore minerals coupled and the conductivity as a result of pore space in soil with ore mineral that produces electrical double layer. The earth material is influenced by internal erosion in the overall of pore space. The streaming potential is increased by increasing influenced material.

The case of coupled electrokinetic, coupled fluid flux, and current induced density can be expressed as follows (Meilawati, 2011 and Sill, 1983):

$$J_E = -(\kappa\varepsilon\zeta/\eta)\nabla\phi - (K/\eta)\nabla P \quad (2)$$

$$I_E = -\kappa\sigma\nabla\phi - (\kappa\varepsilon\zeta/\eta)\nabla P \quad (3)$$

The formula above shows that J_E is the current density and I_E is the fluid flux couple. $\nabla\phi$ is the electric potential gradient and ∇P is the pressure gradient. The parameters σ, ε, and η are the electrical conductivity, dielectric constant, and viscosity of the fluid respectively. κ and K are the porosity and permeability of the medium. ζ is the zeta potential that shows the voltage across the double layer. The first and the second component of equation (2) shows the flux of fluid flow from electro-osmotic effect and Darcy's law, whereas in the first and second component of equation (3) shows the electrical current density and potential resulting from Ohm's law.

In an equilibrium state ($I_E = 0$), equation (3) can be simplified as follows:

$$\frac{\nabla\phi}{\nabla P} = -\frac{\varepsilon\zeta}{\sigma\eta} \quad (4)$$

$\nabla\phi/\nabla P$ are called coupled electrokinetic coefficient. ζ (zeta potential) is an important parameter for electrokinetic coupled. Some minerals and rocks show that ζ is negative in water with pH > 2, and increase negatively with increasing of pH. The experiments also indicated that the value ζ increase with decreasing of the electrolyte concentration and increasing of the temperature.

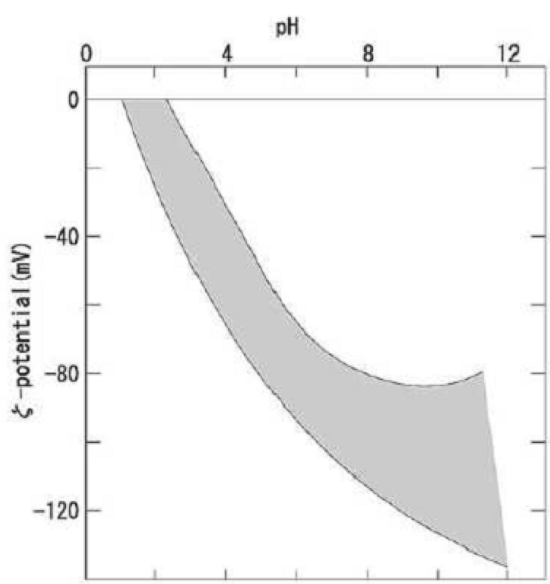

Fig. 2 The relationship between pH of the zeta potential review on morphological insights of self-potential anomalies on Volcanoes (Zlotnicki and Nishida, 2003)

The temperature gradient through the rock sample will generate an electric field. This phenomenon is called the thermoelectric effect, and is usually caused by differences in thermal diffusion of ions in the pore fluid and by influence of ions donor in the rock. This process is called as the Seebeck Effect.

Coupled of heat flow (J_T) and electric current density (I_T) which caused by controlling force (driving force), namely the temperature gradient and electrical potential gradient, can be formulated as follows:

$$J_T = -\sigma\pi\nabla\phi - \lambda\nabla T \quad (5)$$

$$I_T = -\sigma\nabla\phi - \theta\,\nabla T \quad (6)$$

In which σ, λ, π, and θ are the electrical conductivity, thermal conductivity, Peltier coefficient and thermoelectric coefficient respectively.

2.1 Electrochemical Potential

a. Diffusion Potential

The diffusion potential by electrochemical process can be expressed as follows:

$$E_d = \frac{RT(I_a - I_c)}{nF(I_a + I_c)}\ln(\frac{C_1}{C_2}) \ , \quad (7)$$

where I_a and I_c are the movement of anions (+ *ve*) and cautions (- *ve*) respectively. R is the gas constant, T is the absolute temperature (K), n is the valence of ion, F is the Faraday constant, C_1 and C_2 are the concentration of the solution.

Diffusion potential can reach tens of mV, which is caused by differences of mobility in ground water.

b. Nernst Potential

Nernst Potential (E_N) occurs when there is a potential difference between two electrodes that are immersed in a homogeneous solution where the concentration of the solution is different. Nernst Potential is a special case of diffusion potential, which can be expressed as follows:

$$E_d = \frac{RT}{nF}\ln(\frac{C_1}{C_2}) \quad (8)$$

The changes of transient diffusion potential can reach over tens of mV. This happens due to differences in mobility of electrolytes with different concentrations in ground water. Equation (8) shows that electrochemical potential depends on concentration and temperature. High concentration ratio of electrolyte (C_1/C_2) and temperatures will increase the potential value. For this reason, self-potential measurements are very important in the exploration of geothermal resources, where actually temperature and salt concentration in soil is very high.

In the case of electrochemical concentration gradient and potential gradient as driving force, the gradient of temperature and pressure can be neglected. J_C as the flux flow of a substance *m* is described by the Nernst-Planck, namely:

$$J_{C,m} = -\left(D_m Z_m C_m F/RT\right)\nabla\phi - D_m\nabla C_m \quad (9)$$

in which suffix *m* determine the nature of the ions namely the charge number and diffusion coefficient of the ion concentration. *F, R, T* are the Faraday constant, gas constant and absolute temperature respectively. The first and the second part of the above equations describe the flux of each substance flow caused by effects of electrophoretic and Fick 's law.

Electrical current (I_C) was observed as a result of Faraday's constant and the sum of the charge and the flux flow of substances:

$$I_C = -F\left\{\sum\left(D_m Z_m^2 C_m F/RT\right)\nabla\phi + D_m Z_m \nabla C_m\right\} \quad (10)$$

It can be define that $\nabla\phi/\nabla C_m$ as the diffusion coefficient of electrochemically coupled to *m*-ion.

Further electrochemical potential caused by anion adsorption by the surface layer of quartz and pegmatite is known as the adsorption potential. In addition, the adsorption potential can be calculated for the observation of anomalies in the upper clay of layer in the solid-liquid potential.

2.2 Self-Potential Data Correction

a. Thermoelectric Effects

Thermoelectric effects influence the thermal conduction mechanism. Thermoelectric coefficient with an average of 0.2 mV/^{0}C usually show a self-potential anomalies 100 mV with changes in temperature 500^o C. These events are not always apparent in the field except when there is a very hot gas flux.

1) Thermoelectric effects are purely due to mechanism of conduction which only applies to areas where the temperature of gas changes.

2) Flux of gas, the circulation of ground water and rain water show the changes of thermal convection component to the conduction component, which indicates as the thermoelectric effect.

3) The amount of gas is generally positive but less appropriate than the measurement of self-potential observations in the field.

Electrokinetics Effect

Anomaly is associated with fracture zones, the summit crater, or a mountain top. Anomaly is offset by the linear relationship between potential and height. The main source associated with fluid flow through porous medium produces electrical current.

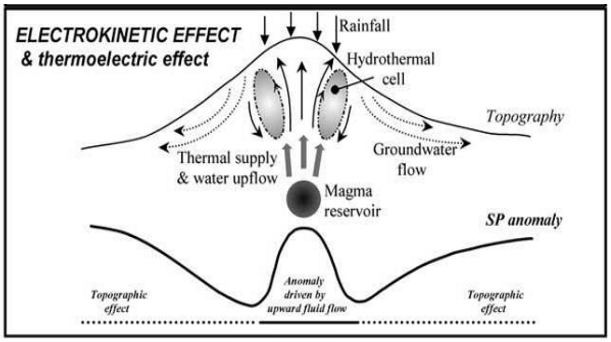

Fig. 3 Sketch of self-potential anomalies on volcanoes: Combined with electrokinetic effects *(Zlotnicki, 2003)*

Electrokinetic phenomena on a volcano and in geothermal filed area occur due to the rise of hot fluid (hydrothermal upflow) in permeable media that is controlled by magnetic heat and is measured as self-potential at the surface (Hase, 2005), The positive SP anomalies will be found around active craters. The anomalies are associated with the pressure of subsurface hydrothermal upflow. SP anomalies are also influenced by topography affect that directly control the flow of fluid (Srigutomo, 2010)

Topographic Effects

In some mountainous areas, the rain water can seep in every different geological layers, it is depending on the value of permeability. The downward flow is usually interrupted by impermeable layers. Geological topographic influences the flow of water due to gravity where the potential increases when the topographic height decreases. Usually it is written as a negative relationship (mV/m) or (mV/MPa) as a coupled electrokinetic coefficient. The coefficient has a value ranging between -1 and 10 mV, with an average -2mV.

Circulation

Heat exchange triggers the hydrothermal circulation of impermeable rock as ground water reservoir beneath earth's surface. Heat source produces fluid flow over the top bag along the surface of the magma and tectonic (crater walls, cracks, etc.) while it is also offset by the downward flow of circulation.

Each of the hydrothermal system has unique characteristics as results of various interactions, including size and shape of the heat source rocks, geological structure, permeability, topography, surface hydrology (temperature and infiltration).

Geothermal fluid is derived from water surface (meteoric water) into the rock below the surface through cracks or permeable rock. In reservoir, water from surface will contact with the hot rocks. Because hot water is lighter than cold water, then hot water will tend to move upwards through cracks or permeable rock, and then be appeared on the surface as hot springs, geysers, etc.

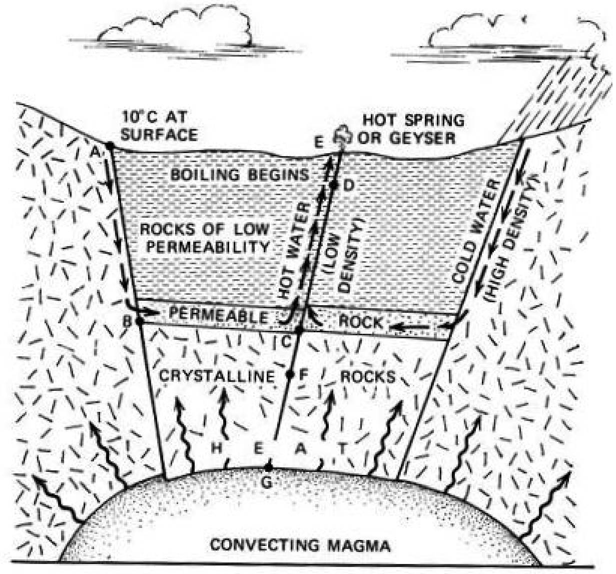

Fig. 4 Hydrothermal Circulation *(White, 1967)*

Self-potential anomalies data can be interpreted qualitatively and quantitatively, depending on the purpose of the research. The number and quality of data, the additional data structure which contains information of geology and hydrology, as well as the available computing facilities determine the self-potential. Self-potential anomalies are often interpreted qualitatively by the shape of the profile, amplitude, polarity, and contours pattern. General qualitative self-potential is indicated by some of parameter of physics.

III. APPLICATION OF SELF-POTENTIAL METHOD IN GEOTHERMAL EXPLORATION

3.1 Geological Review

a. The structure of geology

In this study, the area under study is mountain Patuha. The Patuha is located about 50 km southwest of the city Bandung. The field is situated within a northwest-trending volcanic mountain range, including the nearby peaks of North Patuha (Layman, 2003). Based on the results of field analysis and interpretation of Landsat imagery, the structure of this region is in the form of normal fault with a general northwest-southeast direction in addition to other faults trending east-west and north-south. Based on these observations, at least 9 pieces were found to be normal fault, the fault Geneyek, Cibuni, Ciwidey Cimanggu, Suren, Cileueur, Cikidang, Rancasuni and fault Punceling (Sutawidjaja, 2000)

3.2 Morphology

In general, the mountain has the appearance of geomorphology Patuha as follows (Sutawidjaja, 2000):

a. Old Hills Volcano morphology (spread across parts of northern, northwestern, southwestern, eastern, northeastern and southeastern areas of research).
b. The complex morphology of volcanic cones and craters Patuha concentrated mainly in central and western areas of research.
c. Cone and crater morphology Eruption Side scattered in the southwestern sector, east-southeast, southeastern and northeastern mountain Patuha.
d. Morphology Hills Berelief-ramps are occupying the west-northwest, and Sinumbra Rancasuni area.
e. Leveling located in the northwest region including Cimanggu, Plantation Patuha, Rancabali and Rancawalini.

3.3 Stratigraphy

Based on observations made directly in the field and analysis of aerial photographs, we obtained a picture of the stratigraphic study, which can define the area from old to young as follows (Sutawidjaja, 2000):

a. Sumbul mountain product
b. Kunti mountain product
c. Masigit mountain product
d. Patuha-2 mountain product
e. Patuha mountain product
f. Kawah Putih products
g. Secondary deposit

3.4 Surface Appearance

Based on observations made directly on site obtained a picture of the surface appearance / manifestation of geothermal research areas are as follows (Fig. 3) (Sutawidjaja, 2000):

a. Areas of cold gas discharges
b. Hot springs (30^o – 82^o C)
c. Fumaroles (93^o – 100^o C)
d. Mud pool (60^o – 93^o C)
e. Steaming ground (60^o – 83^o C)
f. Hydrothermal alteration, hydrothermal epidote, typically associated with quartz, calcite and chlorite

At first, self-potential method is used to determine the areas of mining prospects (Sato, 1960, Telford, 1990). But along with the development of science and technology, the self-potential can be used to investigate the prospects of geothermal areas (Corwin, 1976, 1979, 1990).

Application of self-potential method in geothermal exploration is based on electrokinetic process mechanism where an electrolyte fluid flowing in porous media are experiencing separation and accumulation of electric charge. Measurement of self-potential from electrokinetic potential for geothermal exploration has been done in the flow mapping of hydrothermal circulation zones below the earth’s surface (Yasukawa, 2000), which attempts to describe the fracture and fault zones. In addition, self-potential method has been widely used for monitoring of geothermal production and injection wells. It is also used in the study of the process of hydraulic fracturing in geothermal reservoir through the monitoring of self-potential anomalies (Kawakami, 1994).

Geothermal energy is stored in the earth layers, whereby a layer of earth can be solid or semi-liquid. At this, geothermal energy has been successfully utilized as a source of power. It is the heat energy contained in rocks and fluids in the crust layer. In geothermal systems, the technical term is geothermal reservoir. Reservoir states to store reserves of water, fuel oil, and so on. Thus the term geothermal reservoir having an understanding as a place that stores of geothermal energy. This energy is heat energy stored in rocks and fluid filling the pores or rock fractures. The components contained in the geothermal reservoir consists of a hot porous rock, water (electrolyte solution), and steam heat. The application of SP methods in geothermal exploration is based on electrokinetic mechanism, where the fluid-containing electrolyte to flow in a porous medium, giving rise to the potential difference.

A qualitative study of self-potential anomalies due to water flow in soil has also been done (Vichabian, 2002). Their prediction results indicate that the presence of water movement in soil can lead to self-potential phenomenon. The vertical movement of water that seeps generate positive value of self-potential can lead to greater self-potential change for the greater distance. Various application of SP methods in geothermal exploration is namely to map the flow of hydrothermal circulation zones below the surface. Hydrothermal exploration is to delineate the zone of fracture and fault zones. Besides the SP method has been widely used for monitoring the injection wells and geothermal wells. Studies have also been carried out by Vichabian and Morgan (2002) concerning the flow of water in the soil. The results of their predictions indicate that the presence of water movement in soil may cause the SP. The movement of water vertically raises SP positive, while the horizontal movement of water can pose a greater SP to change the distance increases.

IV. SELF-POTENTIAL DATA ACQUISITION

In this study, measurements were conducted at the Kawah Putih, Mount Patuha, West Java. Kawah Putih is at altitude of approximately 2200 meters above sea level. Patuha is an andesitic stratovolcano mountain type. Geologically, the mountain is part of the Patuha active Sunda arc, which is formed from India-Australia plate subdued beneath the Eurasian plate (Layman, 2003). Volcanism in this region originated from the Upper Pliocene and Lower Pleistocene that gave a unique system of volcanoes and crater lakes. Placement of observation points is shown in Fig. 5. Kawah Putih has a width of approximately 300 m to the water lake with temperature about 26-34^o C. This crater contains acid with pH 0.5-1.3, 2500-4600 ppm of sulfur and 5300-12600 ppm of Cl content.

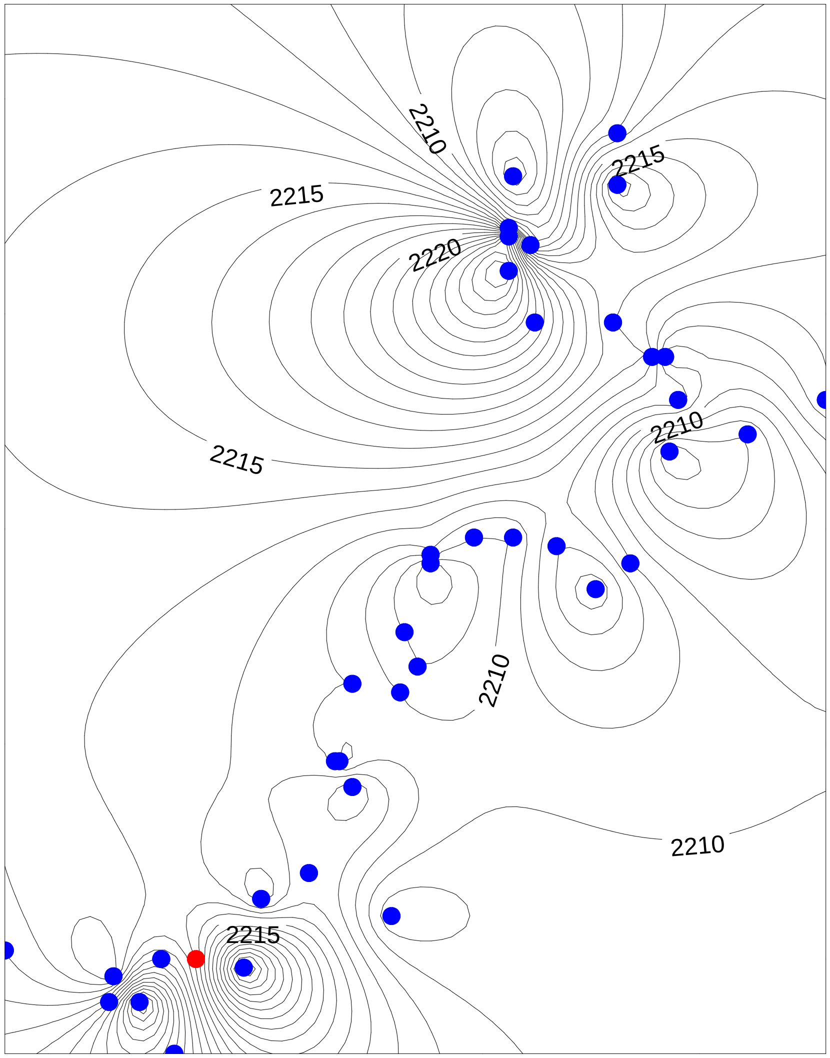

Fig. 5 The point of self-potential measurement: Base (red) and observation point (blue).

The potential gradient method uses two electrodes to move the fixed distance approximately 5 m or 10 m. The observation point is the midpoint between two electrodes with units of mV/m unit. In this study, the used method is the potential amplitude method. Measurement of self-potential at Kawah Putih has about 41 points. The used Equipment in the data acquisition is a digital multi meter, porous pots, copper electrodes, cables, CuSO4, GPS and spades.

V. DATA PROCESSING

The data is made in the coordinates (longitude and latitude) form. The measured data is corrected with base point (reference) and elevation. In the self-potential data collection for this study, the used method is the method of potential amplitude with the position of the reference point (base) located on a white crater, with the position coordinates on 9207050 765 384 east longitude and south latitude with an altitude of 2213 m above sea level. While the moving electrode (the rover) as figure 3.2 with the distance between the observation point 10 m.

The gridding data process is carried out using kriging. The results are arranged in three slicing (A, B and C) as shown in Fig. 6. The line A have the SP value between - 107,49 and 35.77 mV. There is SP value less then - 100 mV. Water movement and sulfid deposit exist in this area, For line B, the SP Values are between -107,49 and 47.16 mV. The SP value less then -100 mV also obtain in this line.The SP values in line C are between - 47.8 and 57.51 mV. The decreasing SP value in this line due to fluids fracture zone.

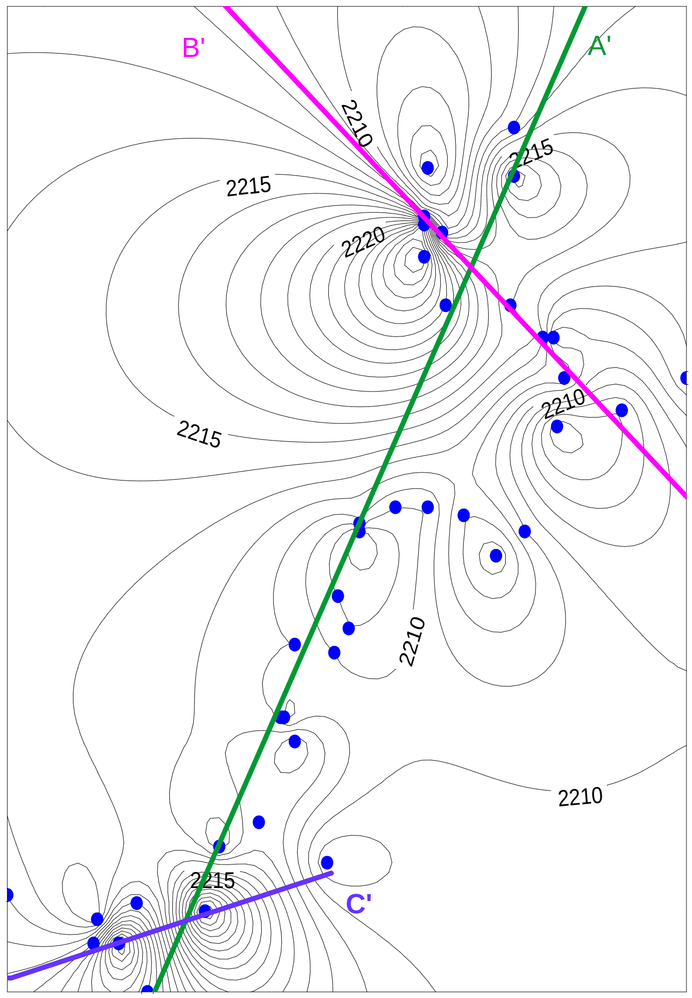

Fig. 6 Licing line A, line B and line C

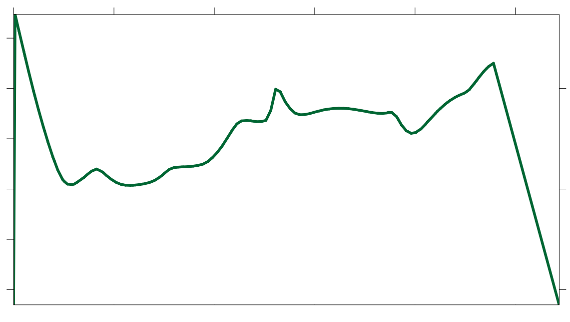

Fig. 7 The graph line A after correction. The SP value between - 107.49 and 35.77 mV. There is SP value less then - 100 mV. Water movement and sulfid deposit exist in this area.

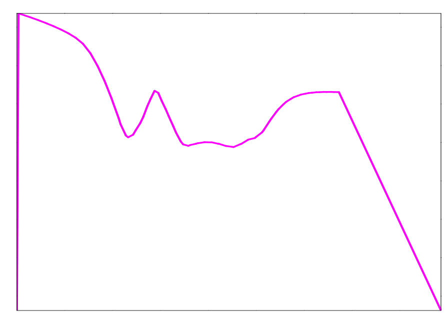

Fig.8 The graph line B after correction. The SP Values are between -107.49 and 47.16 mV. The SP value less then -100 mV also obtain in this line.

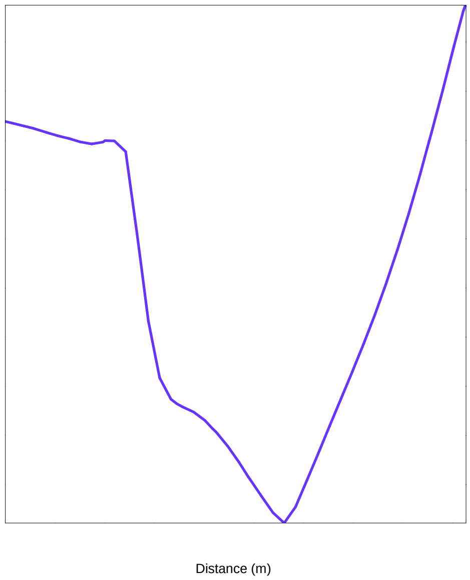

Fig. 9 The graph line C after correction. The SP values in line C are between - 47.8 and 57.51 mV. The decreasing SP value in this line due to fluids fracture zone.

VI. INTERPRETATION

After data acquisition and data processing, the SP values were corrected in elevation, 2199 m to 2228 m of -107.49 to 82.94 mV. Self-potential anomalies vary in value according to its source (Reynolds, 1997). If the value of self-potential is negative of hundreds millivolts, then the source is likely sulfide ore deposits, deposits of graphite, magnetite and conductive minerals, coal or manganese. If the self-potential positive of tens millivolts, then it is likely the source of quartz veins or pegmatite. If the self-potential value is less than 100 millivolts, it is probably due to chemical reactions. If the self-potential is positive or negative of one-hundred millivolts, the cause is the movement of ground water. If the self-potential is negative value of three hundred millivolts, the cause is bioelectric (trees and plants).

The result of this research shows that the self-potential values vary between -107.49 to 35.77 mV at a distance of approximately 270 m on line A or approximately 9,207,270 N and 765 550 E. This result can be interpreted that there is a movement of ground water due to silting of sulfur near the crater where the remnants of the sulfur production come from the crater- lake sediments.

In line B, the value of self-potential is between -107.49 to 47.16 mV. At the beginning point of line B or approximately 9207150 N -765 520 E and the end of the line B or approximately 9207270 N - 765 395 E constitutes the self-potential less than -100 mV. These results show that the movement of ground water caused by sediment sulfide similar to line A.

In line C, the value of self-potential ranged from -47.8 to 57.51 mV. For a starting point for distance of about 25 m or at position 765,340 E and 9,207,032 N to 765,363 N 9207040 E, self-potential value reduces from approximately 35 mV to 30 mV, then decreases sharply up to the -47 mV and then increases up to 57.5 mV. The range of self-potential on line C is in the normal value. Declining value of self-potential sharply indicates a possible fracture zones that are filled by fluid.

Self-potential anomalies can be seen in the base of measurement and ground water data (Fig. 10). Based on the chemical reaction due to soil water movement and also by looking at the drilling location at existing well, the movement of ground water could actually trend in all directions. However, based on the red dot and green dot, the location of existing wells and location of planned wells, the movement of ground water is estimated northeast as shown in Fig. 11. This is because there are the red dots with self-potential value less than -100 mV which shows the movement of ground water and green dots with self-potential values greater than 50 mV which indicates the existence of chemical reactions due to the movement of ground water. Sources are estimated to be in the southwest because at that point there are hot rocks. This is evidenced by the existence of another study (magnetic method) that says that the negative magnetic anomaly (Singarimbun, 2011) in point southwest point (Fig. 12).

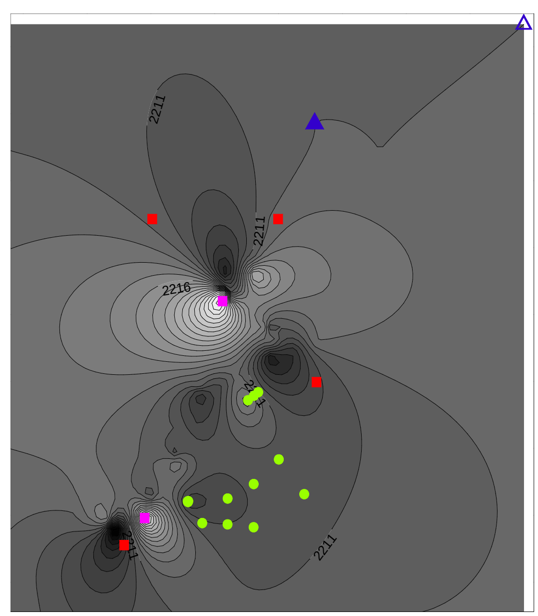

Fig. 10 Location of self-potential anomalies

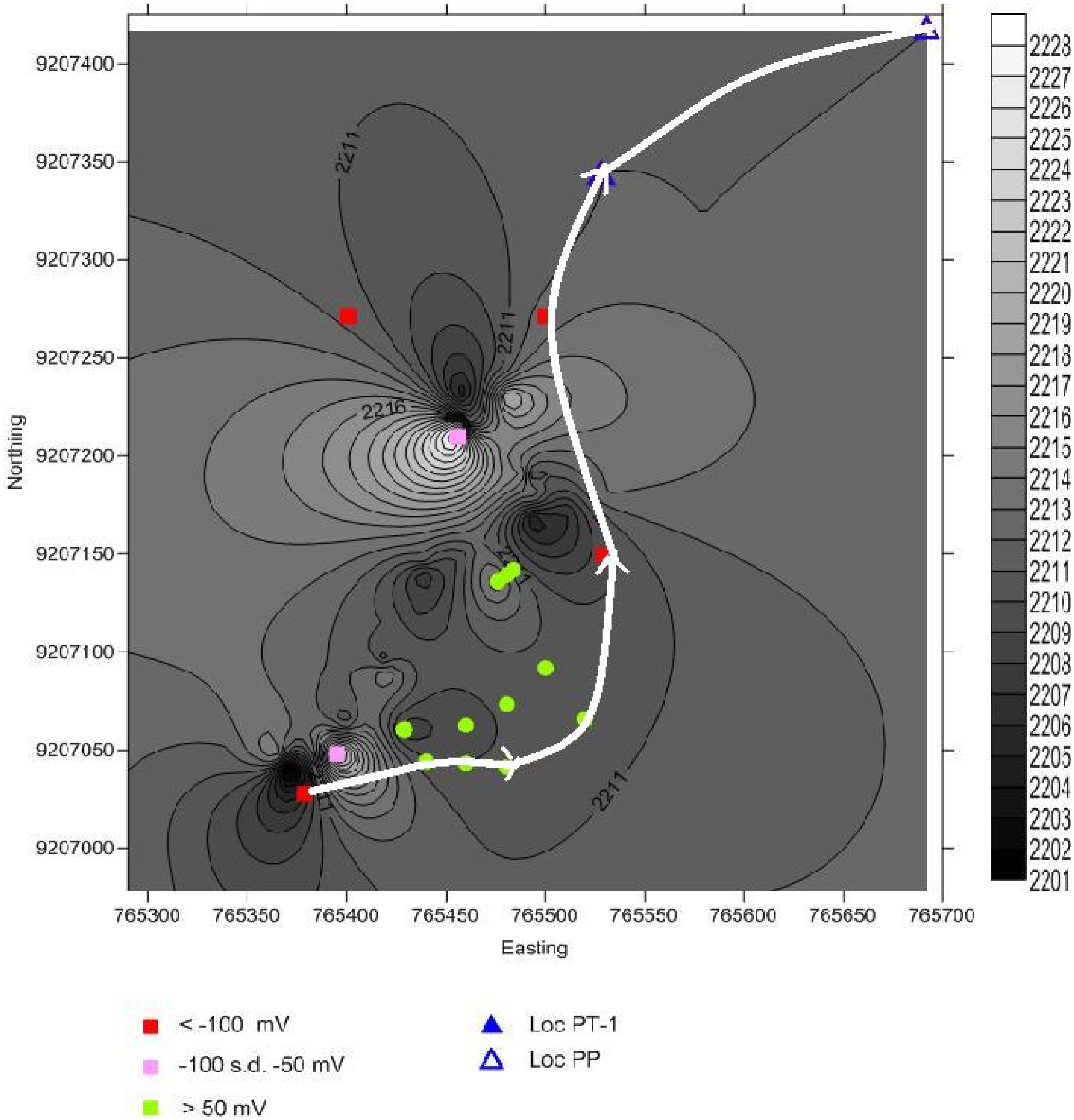

Fig. 11 The estimated direction of groundwater movement the fluid direction below the earth's surface. The direction of groundwater movement is northeast. Sources estimated to be in the southwest because at that point there are hot rocks.

Ground water moves through the pores of rock or fracture zone. This is because there are red dots with self-potential value less than -100 mV, which shows that the movement of ground water and green dots with self-potential values greater than 50 mV that indicates the existence of chemical reactions due to the movement of ground water.

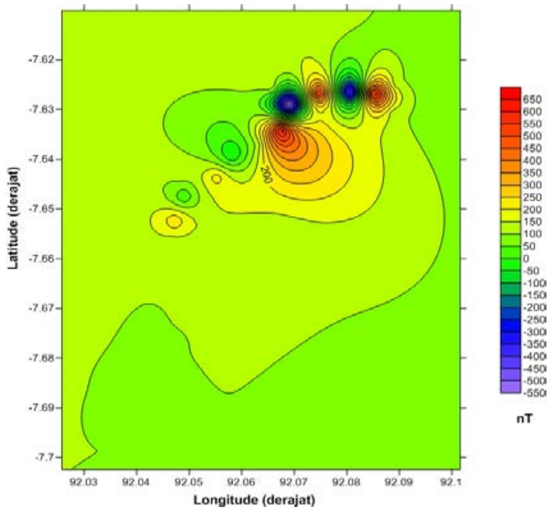

Fig. 12 Residual anomaly map after correction of regional effects

VII. CONCLUSION

Study about measurement of self-potential method can be applied in geothermal exploration to estimate the fluid direction below the earth's surface. In this study, the direction of groundwater movement in the area of Kawah Putih is northeast. Sources estimated to be in the southwest because at that point there are hot rocks. This is supported by the finding of another study that says the negative magnetic anomaly in point southwest point.

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