Volcanic Hazard Implication Based on Magnetic Signatures Study of Seulawah Agam Geothermal System, Indonesia

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Abstract. Geothermal is a natural phenomenon of the Earth. Magma flows from earth crust through thinned and fractured area as lava while trapped magma heats underground rocks and groundwater. Crustal rocks lose their magnetization at the Curie point temperature. Geothermal region is characterized as high temperature gradient with heat flow and the region will be associated with Curie point isotherm. Almost all volcanic rocks are magnetic because they contain small amounts of primary magnetic minerals. Ground magnetic study was conducted at Seulawah Agam (Aceh, Indonesia) and its vicinity where the flow of the geothermal is suspected from south-east to north-west from Seulawah Agam. Ground magnetic data was acquired in line mode consisting of few stations crossing the suspected geothermal flow using GEM-GSM19T system with 30-50 m station spacing and ~500 m line spacing. Magnetic residual shows the value of 0-110 nT interpreted as hot water, flowing from west to east and south to north while the value of >170 nT interpreted as hot mud/fumaroles flowing from north to south. This study shows that magnetic residual of hot water and hot mud/fumaroles generally decreases with depth.

Keywords: Seulawah Agam, geothermal, hazard, magnetic residual, faults, fracture

1. Introduction
Geothermal is a natural process which are involve the recovering heat from beneath the earth. Magma flows from earth crust through thinned and fractured area as lava. Trapped magma heats the surrounding underground rocks and groundwater (Figure 1). The heated groundwater (trapped in permeable and porous rocks under a layer of impermeable rock) could be manifested as a geothermal reservoir or it returns to ground surface as fumaroles, hot springs, mud pots and other interesting phenomena [1] [2]. This type of geothermal system is the most important but not the only one. There exists a great variety of different geothermal systems. Depending on their geological, hydrological and heat transfer characteristics, viz. structure, stratigraphy and type of rocks, presence or absence of permeable reservoirs and insulating cap-rocks, chemistry and distribution of fluids, temperature range, etc. [3] [4].

Crustal rocks lose their magnetization at the Curie point temperature where ferromagnetic rocks become paramagnetic, and their ability to generate detectable magnetic anomalies are disappeared [5].
A geothermal region is characterized by an anomalously high temperature gradient and heat flow, therefore to be expected that regardless the composition of the rocks, the region will be associated with Curie point isotherm relating to the isotherm regions [6].

![Figure 1. Schematic representation of an ideal geothermal system [1].](image)

Almost all volcanic rocks are magnetic caused by the content of small amounts of primary magnetic minerals (mainly magnetite and titanomagnetite). The total magnetization of volcanic rocks (0.5-10 A/m) is given by the vector sum of induced and remnant magnetization. Induced magnetization depends on the magnetic susceptibility of the rocks and the magnitude of the earth’s magnetizing field. The levels of magnetic susceptibility are showing the characteristics for certain rock types and this information was used in conjunction with a magnetic survey to determine the thickness of layers and their rock types that characterized with different susceptibilities. In many liquids dominated geothermal fields, hydrothermal processes alter magnetite and titanomagnetite to almost nonmagnetic minerals, such as pyrite, leucoxene, or hematite [7]. Such processes cause the volcanic rocks to become partly or completely demagnetized and a significant magnetization contrast exists between the reservoir rocks and the unaltered volcanic rocks.

Large volcanic fields associated with active margins. Regional effects of deeper-seated magnetic bodies can cause a shift of residual magnetic anomalies. Regional field is required to obtain “zero level” value for the residual bipolar anomalies; this can be obtained from the analysis topographic anomalies outside the prospect, or by simultaneous analysis of first order residual anomalies observed at a higher level and extended to non-magnetic basement rocks [8].

Demagnetization of volcanic rocks by fluid/rock interaction is a complex process which depends on parameters controlling the stability of the primary magnetic minerals (pH, fluids temperature, joint permeability, fluid movement, etc.). In an oxidizing environment, magnetite can be stable which explains why volcanic rocks on top of a high temperature reservoir and at levels above shallow boiling can retain their magnetization [8] [7a]. Elsewhere the same rocks forming topographic highs (volcanic domes) may be completely demagnetized by interaction with shallow, acid condensates as hematite and limonite replace primary magnetic minerals.

The magnetic susceptibility of a rock and the temperature at which it disappears depend strongly on the rock components, the more or less magnetic minerals [8] [9]. Demagnetization by hot fluid/rock
interaction is cumulative and irreversible. Demagnetized rocks therefore occur in extinct geothermal systems, a phenomenon now used to explore for epithermal mineral deposits. Cumulative demagnetization of active systems may also reflect the control of paleo-permeability and paleo-subsurface fluid flow patterns. In some cases demagnetization can affect large areas outside the present-day high temperature reservoir, thus causing some rather indistinct magnetic anomaly patterns [8] [9] [10]. Magnetic surveys are capable of detecting differences in magnetic susceptibility within subsurface structures through changes in the Earth’s primary magnetic field. The aim of the magnetics survey was to qualify the subsurface structures, type of rock and the existence of fracture. The magnetic method is also employed to find any obvious geothermal outflow under the survey area. Knowledge of subsurface magnetic characteristics in the area could help to qualify the geothermal source of the hot springs as well as the local geology. Seulawah Agam geothermal systems conjecturable related with the fault in the geothermal resources area. Therefore, it is necessary to study the existence of the faults in this geothermal systems area and its implication for volcanic hazard.

2. Geology Settings
Seulawah Agam volcano, one of three active stratovolcanoes in the Aceh province, is located at the northwest end of Sumatra (Figure 2). Seulawah Agam has two craters, van Heutsz (Heszt), the most active crater at an elevation of 714 m on the north side, and Simpago on the south side. The lithology of the study area is dominated by Lam Teuba volcanic composed of andesitic to dacitic volcanic,

Figure 2. Map of geology of the study area [11]
pumiceous breccia, tuffaceous, calcareous sometimes cross-bedded sandstones, conglomerates, agglomerate, minor mudstones and ash flows which intruded of the Seulimeum formation. The Seulimeum formation is composed of tuffaceous and calcareous sandstones, conglomerates and minor mudstones [12]. The geological formation formed a topographic depression, occupied with alluvial flat and low flat-topped hills within Barisan Range. The adjacent Sumatra in the west coast constitutes volcanic arc with many Quaternary volcanoes such as Pulau Weh and Seulawah Agam. The volcanic belt is extended along the tectonically weak SFS and this tectonic weakness is supposed to have triggered volcanism [13]. In the northern most Sumatra, the Sumatran Fault System (SFS) splits into two major dextral strike-slip faults which are the Seulimeum and the Aceh Fault [12]. Sumatran Fault system occurs from the Middle Miocene and the opening of the Andaman Sea. Pre-Tertiary basement rocks outcrop mainly along the central spine of the Barisan Mountains, which extend the length of the island parallel to the southwest coast.

The area from northeast and southwest is overlain by Tertiary sedimentary and volcanic rocks. From upstream of the Jantho region to downstream of Indrapuri, the Pleistocene coarse-grained partly volcanic sands and gravels form a prominent terrace surface on both sides of the Krueng Aceh. Downstream of Indrapuri, the alluvial deposits can be subdivided into a shallow aquifer system and a deep aquifer system. Upstream of Indrapuri, the alluvial sandy-gravelly deposits in the vicinity of the river courses, the older terrace sand-gravel deposits and the semi-consolidated sandstones are assumed to constitute the main aquifers of the upper part of the Krueng Aceh valley [14].

3. Study Area and Methods
Magnetic method is widely used in geothermal exploration and gives an effective presentation of the subsurface structures. Thus, a detailed land magnetic survey has been carried out for the total component of geomagnetic field. Ground magnetic study was conducted at Seulawah Agam, Aceh, Indonesia and its vicinity. The reason the magnetic survey focused on the geothermal manifestation was it has specific geologic features in the area that generally have a high magnetic susceptibility. Seulawah Agam is an active volcano with geothermal sources such as Herz, Ie Jue and Ie Seu’um. Flow of the geothermal is suspected from south-east to north-west from Seulawah Agam. Ground magnetic data was acquired in line mode consisting of few stations crossing the suspected geothermal flow using two GEM-GSM19T system, and Global Positioning System (GPS) navigation for real-time measurements. One instrument is used as a base station for the diurnal correction and the other is used to measure the magnetic field along the study area. A base station with magnetic homogeneity is carefully selected to record magnetic reading at time interval 60 seconds for diurnal correction affected by the Earth's field. The measurement is setting with 30-50 m station spacing and ~500 m line spacing, depending on the topography and land conditions (Figure 3). The measurements for local structures such as individual faults are done on the ground by regular measurements along parallel profiles or in a grid. The magnetic measurements generally aim at locating hidden intrusive or it may also at finding areas of reduced magnetization due to geothermal activity. All necessary corrections for the measured magnetic data have been performed for diurnal variation and IGRF correction to obtain a corrected magnetic anomaly data for mapping the residual magnetic contour map. In these surveys, variation of magnetic values would be used to help interpret the layers of subsurface as well as faults that may affect the hot water flow within the Seulawah Agam geothermal system.

4. Result and Discussions
The detail magnetic data analysis and interpretations are presented by magnetic residual map. This map is produced with data processing by reduction to the magnetic north in order to overcome the undesired distortion of the shapes, sizes and locations of the magnetic anomalies in which the reduction to the north magnetic map. This step was intent to separate the residual and regional components. The Magnetic residual map is characterized by variation of characteristics anomalies which is distributed through the study area. In general, fluctuating and deformation of the rocks properties lead to sharp and strong magnetic signatures. The magnetic anomalies also display the
dominant trends that rather generally aligned along definite axes that can be used to define magnetic area.

Figure 3. Study area and its vicinity with magnetic stations (Google, 2015).
Figure 4. Magnetic residual map of the study area shows the flow of hot water and mud/fumaroles.

From the map, the high intensity magnetic signals at the southeast area of the profile mark the faults with basaltic rocks, while the northwest part shows a decay of the magnetic intensity corresponding to the end of the rock boundary. The lower intensity of magnetic signals can be associated to the presence of fluids. Magnetic residual map (Figure 4) shows the value of 0-110 nT which is interpreted as hot water. This hot water is suspected flowing with direction of west to east and south to north while the value of >170 nT interpreted as hot mud/fumaroles which is flowing from the direction of north to south. Reservoir and geothermal outflow of Seulawah Agam geothermal field is mainly controlled by fractures. The extensive dislocation from northwest part to southeast direction of study area is interpreted as geological fault. The magnetic contour indicates the presence of several fractures in some geothermal spots at the study site, that are: Ie Jue, Sumur Panas, Ie Seu’um, and Ie Busuk. Of these fracture groups that show the northwest strike to the southeast, with higher temperatures in the southeast and lower to the northwest. The subsurface temperature distribution shows an obvious and be spread evenly pattern that has a long axis from the southeast to the northwest region.

From the analysis of surface magnetic intensity map, it can be notice that, there is a local magnetic anomaly superimposed on the regional magnetic field. This anomaly is probably related to faulting structures. Some zones of high horizontal magnetic gradients, could be interpreted as locations of fault. The major local anomalies are located between high fluctuate magnetic anomalies that show locations of probable fault areas. The fault that has strike that cuts these fracture group. Hot spring gushes on the surface of the earth along with this fault. These results are shown from the characteristics of the resulting permeability values, which characterize the presence of fractures and geothermal manifestations in the study sites. This can also be an implication of the presence of volcanic hazard in the region.

Figure 5 shows magnetic residual plot against distance of all lines (L2, S and G). Magnetic residual of 0-110 nT indicates hot water while magnetic residual of >170 nT indicates hot mud/fumaroles. Generally, the magnetic content of rocks is extremely variable depending on the type of rock and the
environment surround. In a geothermal environment, due to high temperatures, the susceptibility tends to be decreased. Positive anomalies are generally interpreted to occur in demagnetized zones corresponding to heat sources with a temperature above the curie point of magnetite. This study indicated that magnetic residual of hot water and hot mud/fumaroles are generally decreased with depth. Ground magnetic measurements do provide detailed information on sub-surface structures that could act as heat sources.

![Figure 5. Magnetic residual of hot water and hot mud/fumaroles location depth (decreased with depth).](image)

(A) line L2, (B) line S and (C) line G.

5. Conclusion
The magnetic methods and data analysis procedures have been developed during study of Seulawah Agam geothermal areas. The results obtained from magnetic data showed that there are two main closures which are dominated in the study area. First, the high magnetic anomaly which is located in
the southeast part. Next is the low magnetic anomaly which is observed in the northwest part of the study area. Reservoir and geothermal outflow of Seulawah Agam geothermal field is mainly controlled by fracture, and the flow is suspected to move from southeast to northwest. The magnetic contour indicates the presence of several fracture in some geothermal spots at the study site. These results are also shown from the characteristics of the resulting permeability values, which characterize the presence of fractures and geothermal manifestations in the study sites. This can also be an implication of the presence of volcanic hazard in the region. The interpreted magnetic and geothermal data of the Seulawah Agam area have revealed new information and improved the knowledge about the internal structure beneath this area.

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