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Horizontal Gradient Analysis for Gravity and Magnetic Data Beneath Gedongsongo Geothermal Manifestations, Ungaran, Indonesia

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ABSTRACT

Ungaran Volcano a geothermal prospect in the province of Central Java, Indonesia. The primary manifestations are located at the Gedongsongo area, which appears to be fumarole, hot spring and altered zones. The study area was covered by gravity and magnetic surveys in order to delineate the subsurface structure and its relation to the geothermal manifestations that spread through the area. An analysis using horizontal gradient (HG) interpretation techniques has been applied to gravity and magnetic data. The results indicate that the hot springs around Ungaran Volcano are structurally controlled and have depths ranging from 1 to 3 km. Moreover, the magnetic quantitative interpretation indicates that the area beneath Gedongsongo is composed of 3 layers. The first layer is sedimentary and consists of breccia, sandstone, pyroclastic deposits, alluvium, and top soil with susceptibility $7.0x10^{-5}$ cgs emu; the second layer has an alteration of andesite lava with susceptibility $-1.0x10^{-2}$ cgs emu; the third layer is composed of hornblende-augite andesite with susceptibility $1.34x10^{-2}$ cgs emu. The results of the present study allow greater understanding of the subsurface structure, and may aid in future geothermal exploration of Gedongsongo area.

1. INTRODUCTION

Faults and fractures play a significant role in the localization and evolution of hydrothermal systems. Hydrothermal activity in volcanic settings is dependent on a number of interacting factors, including: heat source, circulating fluids, and permeable pathways Curewitz and Karson (1997). Understanding the structural relationships between faults and regions of hydrothermal upwellings is important for the effective development and exploitation of geothermal resources

Ungaran is a composite andesite arc volcano located 30 km southwest of Semarang, the capital city of Central Java province, Indonesia (Fig. 1) and is still an undeveloped geothermal prospect.

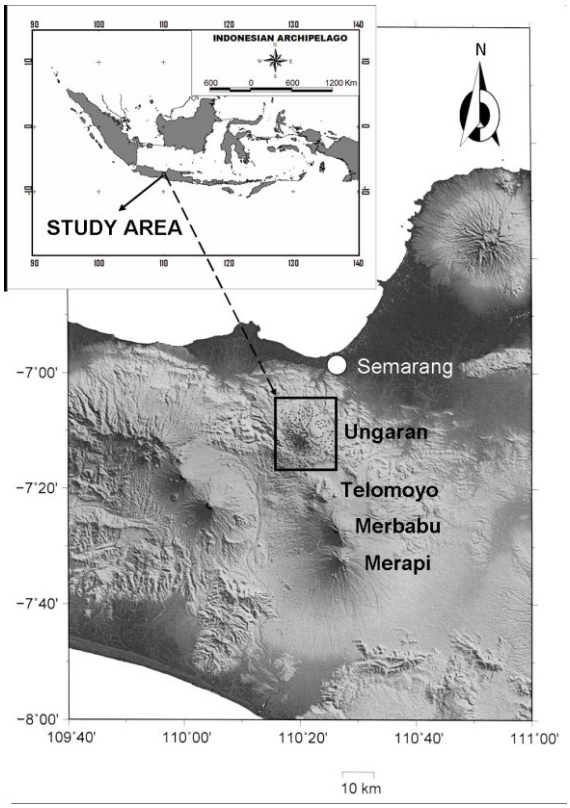


Figure 1: Location of Ungaran volcano.

There are some geothermal manifestations at the piedmont of Ungaran volcano. Gedongsongo is the main geothermal manifestation in Ungaran volcano, located in the southern part of the Ungaran volcano; several geothermal manifestations such as fumaroles, hot springs, hot acid pool and acid surface hydrothermal alteration rocks exist at this site. Geochemical and soil gas surveys presented by Phuong et al. (2012) show particularly high CO_2 concentrations (> 20%); high Hg concentrations were also detected in the vicinity of the fumaroles. Emanometries of Rn, Tn and CO_2 also conclusively identified the presence of a fracture zone for the migration of geothermal fluid. The Hg results infer that the up-flow zone of high temperature geothermal fluids may be located in the north of fumaroles in the Gedongsongo area (near the collapse wall). Chemistry of thermal springs in the up-flow zone are acid (pH = 4) and show a Ca-Mg-SO_4 composition. The thermal waters are mainly Ca-Mg-HCO_3 and Ca-(Na)-SO_4-HCO_3 types near the fumarolic area and are mixed Na-(Ca)-Cl-(HCO_3) waters in the south east of Gedongsongo. The $\delta^{18}O$ (between - 5.3 and - 8.2‰) and δ (between - 39 and - 52‰) indicate that the waters are essentially meteoric in origin. The up-flow zone, located north of fumarlo, is deduced from micro seismic and spontaneous potential by Setyawan et al (2008).

Deep structures such as faults and fractures needed clarification; therefore, gravity and magnetic data was evaluated using gradient analysis techniques in order to estimate the relationships between stucture and geothermal manifestations on the surface area.

2.GEOLOGY

Geothermal areas in Central Java, including Ungaran volcano, are located in the Quaternary Volcanic Belt (Solo Zone). This belt is located between the North Serayu Mountains and the Kendeng Zone, and contains young Quaternary centers of eruption, including Dieng, Sindoro, Sumbing, Ungaran, Soropati, Telomoyo, Merapi, Muria, and Lawu (Bemmelen, 1949).Ungaran volcanic area is composed of andesitic lava, perlitic lava, and volcanic breccia from the post Ungaran caldera stages (Thanden et al., 1996), as shown in Fig. 2.

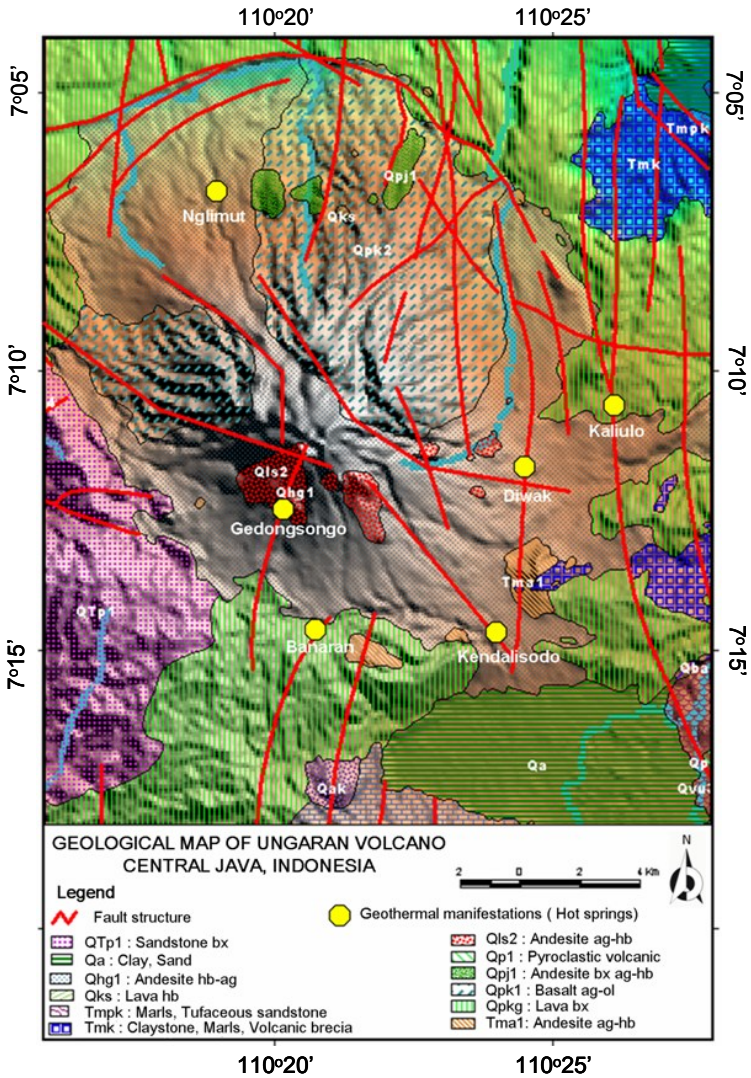


Figure 2: Geology map of Ungaran volcano (Modified from Thanden et al., 1996).

Ungaran is a complex volcano consisting of a younger body, which was formed by the most recent volcanic activity, and an older body formed by prior volcanic activity**.** The Young Ungaran body seems to have been constructed inside a caldera formed during the older Ungaran activity. According to Kohno et al. (2006), the Old Ungaran body formed prior to 500,000 years ago, and the Young Ungaran volcano did not form until 300,000 years ago. The volcanic rocks are rich in alkali elements and are classified as trachyandesite to trachybasaltic andesite.

3. METHODOLOGY

We used the horizontal gradient technique for gravity and magnetic data interpretation. These methods were used successfully to image the subsurface structure of the study area. Saibi et al. (2006a, b, 2008) mentioned the relationship between the locations of the hot springs and the results of the integrated gravity interpretation techniques. The horizontal gradient method was used extensively to locate the boundaries of density contrast from gravity data. The greatest advantage of the horizontal gradient method is that it is least susceptible to noise in the data; it requires only the calculation of the two first-order horizontal derivatives of the field and the horizontal gradient filter, which can be estimated by Phillips et al (1998). The amplitude of the horizontal gradient Cordell and Grauch (1987) is expressed as equation (1) and (2):

$$HG\ (x, y) = \left[\left(\frac{\delta g}{\delta x} \right)^2 + \left(\frac{\delta g}{\delta y} \right)^2 \right]^{1/2} \quad (1)$$

$$HG\ (x, y) = \left[\left(\frac{\delta H}{\delta x} \right)^2 + \left(\frac{\delta H}{\delta y} \right)^2 \right]^{1/2} \quad (2)$$

where ($\partial g/\partial x$) and ($\partial g/\partial y$) are the horizontal derivatives of the gravity field in the x and y directions, and ($\partial H/\partial x$) and ($\partial H/\partial y$) are the horizontal derivatives of the magnetic field in the x and y directions, respectively.

4. RESULT AND DISCUSSION

4.1 Gravity

Gravity data for the study area was issued from the public domain data provided by Gadjah Mada University, Indonesia. The data was taken during two periods, 14–22 February 2001 and 19–25 March 2001, and covers 144 km^2 that consists of 163 gravity stations. Fig. 3 shows the Bouguer anomaly map of the study area. It is characterized by positive gravity values ranging from 20.5 to 56 mGal (Setyawan et al, 2006). A high gravity anomaly was found in the northern part of Ungaran Volcano. Compared with geologic information, this high anomaly correlates with the old Ungaran Volcano. A density of 2.47 g/cm3 (Murata 1993) was used to produce the Bouguer anomaly map of the study area (Fig. 3). The mesh size is 200 m in the x and y directions. The gravity data was corrected for free air, terrain, tides, and Bouguer effects.

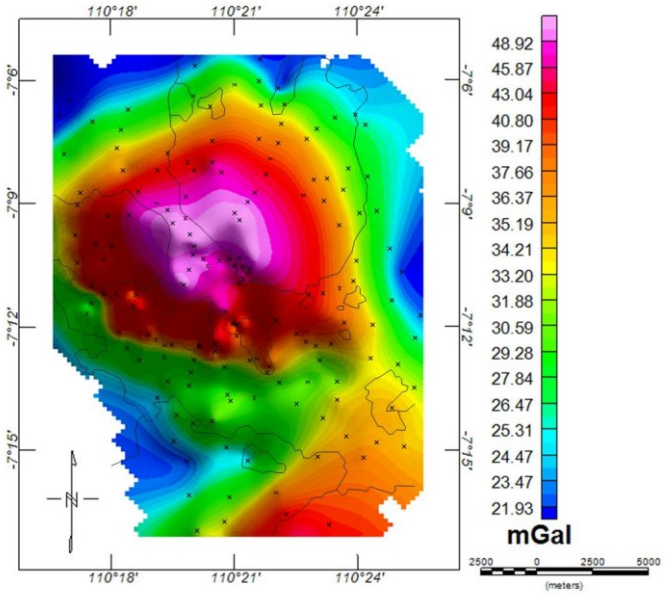


Figure 3: The Bouguer anomaly map of Ungaran volcano which is overlied with the geologic map.

The horizontal gradient magnitude (HGM) for Ungaran was calculated in the frequency domain. The HGM of gravity data is calculated using Fast Fourier Transform (FFT). Grauch and Cordell (1987) discussed the limitations of the horizontal gradient magnitude for gravity data. They concluded the horizontal gradient magnitude maxima can be offset from a position directly over the boundaries, if the boundaries are not near-vertical and close to each other. The horizontal gradient map of gravity data for Ungaran is presented in Fig. 4. There are two possibilities of interpretation of the maxima value; one is correlated with the edge of

the mountain body or intrusive of rock, and the other is correlated with the fault structure. Generally, the study area may be dissected by major faults striking in the east to west and northwest to southeast directions.

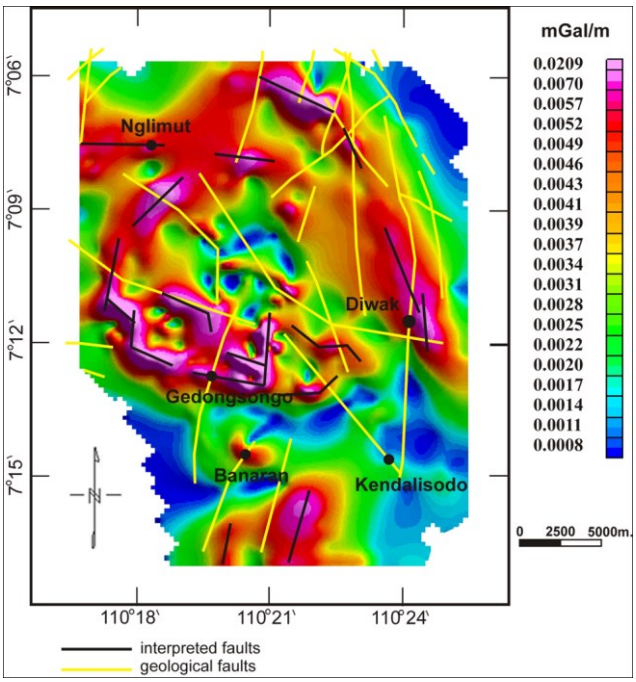


Figure 4. The horizontal gradient map of the gravity data for Ungaran. The black circles indicate the locations of geothermal manifestations. The yellow line represented of geological fault and black line is intrepeted fault from HG

Some geologic faults are confirmed and others are delineated. The interesting result is that the hot springs (e.g., Gedongsongo, Nglimut, Diwak, and Banaran) are well correlated with high horizontal gradient anomalies that are interpreted as boundaries or faults. This indicates that the geothermal manifestations for Ungaran are structurally controlled. Additionally, hot springs (e.g., kendalisodo, Gedongsongo, Diwak, and Banaran) are located at or close to the geologic faults, as shown in Figure 4. It does mean that the hot springs are controlled by the fault system. The only exception is the Kendalisodo hot spring, where there is a low magnitude of the horizontal gradient but faults close to the surface. This discrepancy could be due to the lack of gravity stations around the Kendalisodo hot spring.

4.2 Magnetic

Considering the gravity data, we continued with magnetic measurements and focused on Gedongsongo as the main hydrothermal manifestation in Ungaran Volcano. The magnetic data consisted of 143 point measurement (Fig. 5)

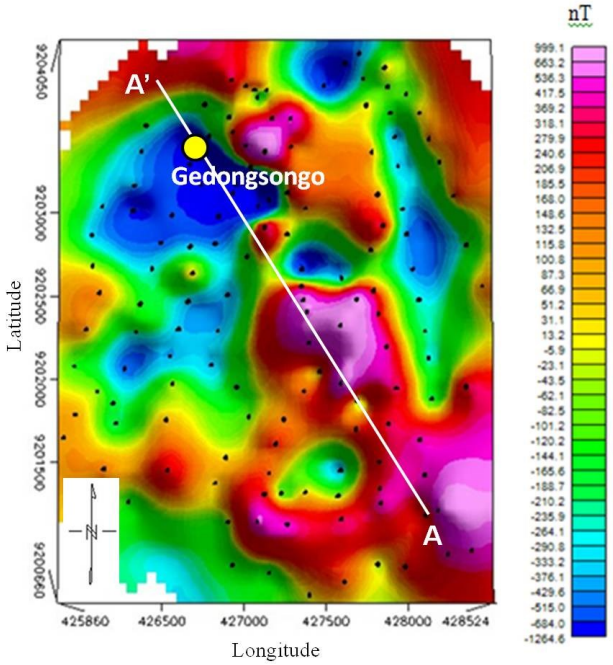


Figure 5. The total magnetic anomaly map of Southern part Ungaran volcano.

The magnetic data was corrected for IGRF, annual correction, pole reduction, and upward continuation. The total magnetic anomaly map of the southern part of Ungaran volcano shows that fumarole area in Gedongsongo has low anomaly magnetic value; this indicates an active hydrothermal system beneath the Gedongsongo area. The results correlate well with geochemistry analysis, indicating that the thermal waters are mainly Ca-Mg-HCO_3 and Ca-(Na)-SO_4-HCO_3 types near the fumarolic area and mixed Na-(Ca)-Cl-(HCO_3) waters in the south east of Gedongsongo (Phuong et al, 2012).

In order to clarify the subsurface structure beneath Gedongsongo area, we have done slice A – A' (Fig.5) and conducted 2D model analysis (Fig.6). From the 2D magnetic quantitative interpretation results, the area beneath Gedongsongo is composed of 3 layers. The first layer is sedimentary and consists of breccia, sandstone, pyroclastic deposits, alluvium, and top soil with susceptibility $7.0x10^{-5}$ cgs emu; the second layer is an alteration of andesite lava with susceptibility $-1.0x10^{-2}$ cgs emu; the third layer is composed of hornblende-augite andesite (andesite rock) with susceptibility $1.35x10^{-2}$ cgs emu.

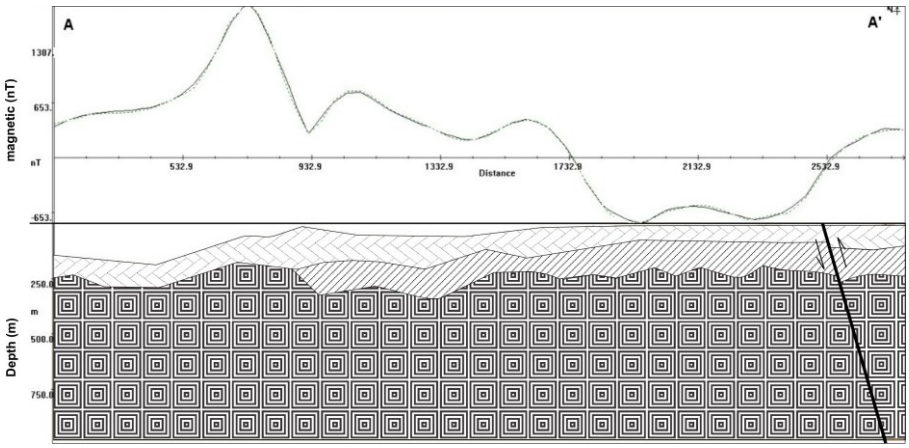


Figure 6. 2D interpretation of magnetic in Gedongsongo.

Equation 2 is applied to the magnetic data to estimate the horizontal gradient map as shown in Fig. 7. The result of the HG map is that the boundaries/faults are located at the maxima of the horizontal gradient. The most interesting result is that in the Gedongsongo area, the main geothermal manifestation area is well correlated with maxima value of horizontal gradient anomalies interpreted as belonging to a fault zone. Moreover, the geological faults are not corroborated by the horizontal gradient technique, which means that the horizontal gradient detects only the faults that have vertical extension Grauch (1987).

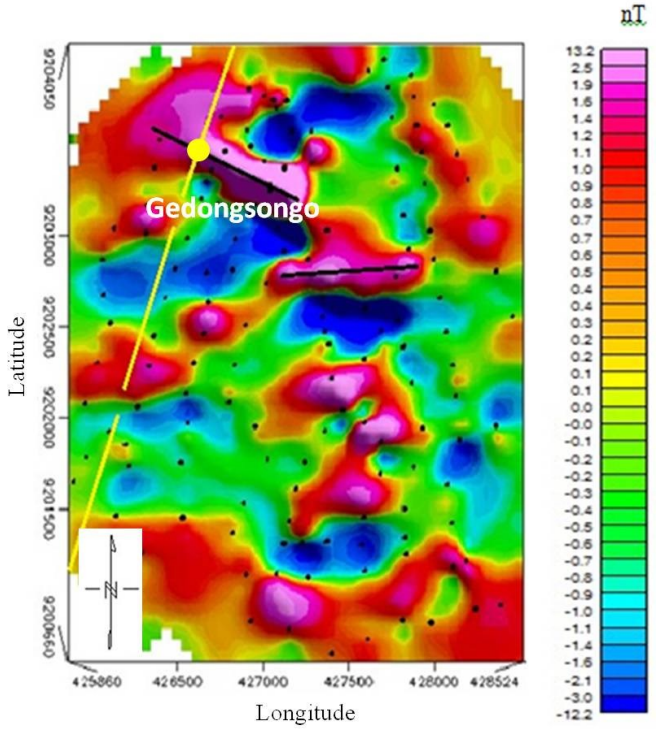


Figure 7. The horizontal gradient map of the magnetic data for Ungaran. The yellow circles indicate the locations of geothermal manifestations, yellow line represented of geological fault and black line is intrepeted fault from HG.

CONCLUSION

We present an interpretation of the gravity and magnetic anomalies at Ungaran Volcano caused by the distribution of subsurface geological formations and their structure. The application of horizontal gradient methods to gravity and magnetic data clarified the subsurface structure beneath Ungaran Volcano, which could contribute to geothermal exploration. The horizontal gradient delineated subsurface faults that have no evidence on the surface and would hence not be discovered by geological mapping. Some geologic faults are confirmed and others are delineated. The interesting result is that the hot springs (e.g., Gedongsongo, Nglimut, Diwak, and Banaran) are well correlated with high horizontal gradient anomalies that are interpreted as boundaries or faults. This indicates that the geothermal manifestations for Ungaran are structurally controlled. The results of the present study lead to an understanding of subsurface structure, which may aid in future geothermal exploration of the Gedongsongo area.

REFERENCES

Bemmelen, R. W. Van. The Geology of Indonesia, **Vol. 1A**. General Geology of Indonesia and Adjacent Archipelago, 2nd Edition, Martinus Nilhoff, The Haque, Netherlands, (1970).

Cordell, L., and Grauch, V.J.S.: Mapping basement magnetization zones from aeromagnetic data in the San Juan Basin, New Mexico, in Hinze, William J. (ed), The utility of regional gravity and magnetic anomaly maps: Society of Exploration Geophysicists, Tulsa, Oklahoma, (1985). pp. 181-197

Curewitz D, Karson JA: Structural settings of hydrothermal outflow: fracture permeability maintained by fault propagation and interaction, *J. Volcanol Geotherm Res.* **79**(3–4), (1997), 149–168.

Grauch V.J.S, : A new variable-magnetization terrain correction method for aeromagnetic data, *Geophysics* **52** (1987), 94–107.

Grauch VSJ, Cordell L (1987) Limitations of determining density or magnetic boundaries from the horizontal gradient of gravity or pseudogravity data. Short note, *Geophysics* **52**(1) (1987),118–121.

Kohno, Y., Taguchi, S., Agung, H., Pri. U., Imai, A., and Watanabe, K., Geological and Geochemical Study on The Ungaran Geothermal Field, Central Java, Indonesia: an Implication in Genesis and Nature of Geothermal Water and Heat Source. *Proceedings,* 4th International Workshop on Earth Science and Technology, Fukuoka, (2006), 19-28.

Murata Y. :Estimation of optimum average surficial density from gravity data: an objective Bayesian approach, *J. Geophys Res.* **98**(B7), (1993) 12097–12109

Phillips JD : Locating magnetic contacts: a comparison of the horizontal gradient, analytic signal, and local wavenumber methods. SEG 2000 Expanded Abstracts, (2000).

Phuong N.K., Harijoko A., Itoi R., and Unoki Y.: Water geochemistry and soil gas survey at Ungaran geothermal field, central Java, Indonesia, *Journal of Volcanology and Geothermal Research*, **229**, (2012) p. 23-33.

Saibi H, Nishijima J, Aboud E, Ehara S: Euler deconvolution of gravity data in geothermal reconnaissance: the Obama geothermal area, Japan. Butsuri Tansa 59(3) (2006a):275–282

Saibi H, Nishijima J, Ehara S, Aboud E : Integrated gradient interpretation techniques for 2D and 3D gravity data interpretation. Earth Planets Space 58(7) (2006b):815–821.

Setyawan, A., Nishijima, J., Fukuoka, K., Fujimitsu, Y., and Ehara, S.: Subsurface Structure Imaging of Ungaran Volcano, Indonesia Based on Geophysical Surveys, *Annual Meeting* Geothermal Research Society of Japan, Fukusima, Japan, (2006).

Setyawan, A., Ehara, S, Fujimitsu, Y., Nishijima, J.: Fukuoka, K., and Saibi, H.: Integrated Geophysical Surveys of Ungaran Volcano: Understanding the Hydrothermal System, *Proceedings,* The 2nd International Workshop and Conference on Earth Resources Technology, Bangkok, Thailand, (2008), 9-14.

Thanden, R. E., Sumadirdja, H., Richards, P. W., Sutisna, K. and Amin, T. C.: Geological Map of the Magelang and Semarang Sheets, Java, scale 1: 100,000, Systematic Geological Map, Indonesia, Geological Research and Development Centre, Indonesia, (1996).