RELATIONSHIP BETWEEN THE LOCATIONS OF HOT SPRINGS AND THE DEDUCED SUBSURFACE STRUCTURE FROM GRAVITY DATA ANALYSIS IN UNGARAN VOLCANO (INDONESIA)

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SUMMARY - Mount Ungaran is a Quaternary volcano located in Central Java, Indonesia. We used gravity data in order to understand the subsurface structure at Ungaran volcano and its relationship with the locations of hot springs. We analyzed the gravity data using integrated gradient interpretation techniques, such as the Horizontal Gradient (HGM) and Vertical Derivatives (VDM) methods and detected many faults. The results of the present study will hopefully lead to an understanding of the relationships between interpreted faults and the locations of hot springs and may aid in future geothermal exploration of the area.

1 INTRODUCTION

Ungaran is a volcano located about 30 km southwest of Semarang, the capital city of Central Java province, Indonesia, as shown in Figure 1. It is a still undeveloped geothermal prospect. Ungaran is a Quaternary volcano that can be divided into young and old Ungaran. The young Ungaran body seems to have been constructed inside a caldera formed after old Ungaran. Ungaran formed in a volcanic arc with three other volcanoes, Merapi, Merbabu, and Telomoyo. It is situated in the northern part of this volcanic chain, and it is believed to be constructed of back-arc magmatism associated with subduction (Kohno et al., 2006). Gedongsongo, located in the southern part of Ungaran, is the volcano's main geothermal manifestation, and it includes fumaroles, hot springs, hot acid pools and an acidic surface of hydrothermally altered rocks. Unfortunately, published studies on Ungaran are rare. A geochemical model developed by Phuong et al. (2005) showed that the thermal water in the Ungaran volcanic area is divided into two distinct types: sulphate water, Ca-(Na)-Mg-SO_4-HCO_3, in Gedongsongo and bicarbonate waters, such as Ca-Mg-HCO_3 and Na-(Ca)-HCO_3-Cl, in the surrounding areas, e.g., Banaran, Kendalisodo, Diwak and Kaliulo. Widarto et al. (2005) suggested that the subsurface temperature of the reservoir system ranges from 120 to 290^{o}C and that a hot water-dominated hydrothermal system has developed in the study area. Many geophysical methods have been applied to Ungaran (Fujimitsu et al., 2007), but the deep structure has not been clarified. We therefore carried out a gravity study to determine the subsurface structural geology of Ungaran and study the relationship between the locations of hot springs and deduced faults.

2 GENERAL GEOLOGICAL SETTING

Gertisser and Keller (2003) summarized the geology of Central Java as being divided into several structural units: the southern coast, including the Karangbolong Mountains, the southern Serayu chains and the western Progo Mountains, the southern mountains, the western foothills of the Solo Zone, the northern Serayu, and the northern coastline. Geothermal areas in Central

Java, including Ungaran, are located in the Quaternary Volcano Belt (Solo Zone). This belt is situated between the North Serayu Mountains and the Kendeng Zone, and it hosts young Quaternary eruption centers: Dieng, Sindoro, Sumbing, Ungaran, Soropati, Telomoyo, Merapi, Muria, and Lawu (Bemmelen, 1970). The Ungaran volcanic area is composed of andesitic lava, perlitic lava and volcanic breccia from the post-Ungaran caldera stages, as shown in Figure 2 (Thanden et al., 1996). There are geothermal manifestations at the piedmont of Ungaran, namely, Gedongsongo, Banaran, Kendalisodo, Diwak, Kaliulo and Nglimut. Gedongsongo is the main geothermal manifestation associated with the Quaternary andesitic volcanic complex of Ungaran.

3 GEOTHERMAL SYSTEM AT UNGARAN

Budiardjo et al. (1997) stated that the Ungaran geothermal prospect is a hot water-dominated system associated with a young Quaternary volcanic system. The field falls in a low resistivity zone extending over approximately 5 km^2. The reservoir is inferred to be capped in the upper part by near-impermeable post-caldera Upper Quaternary volcanic rocks. The reservoir fluid is composed of high-temperature sodium-chloride water that is most likely to occupy pre-caldera fractured lower Quaternary volcanic rocks and Tertiary volcanic rocks. The main source of heat emanating through the system comes from the intrusive body of andesitic to dioritic rocks of Ungaran volcano. This body heats the system to reach a reservoir temperature of approximately 220^{o}C, based on an application of a geothermometer to gases taken from the Gedongsongo fumaroles (Phuong et al., 2005). The upper level of the Ungaran geothermal reservoir is estimated to be situated at a depth of approximately 2000 m.

Geothermal manifestations

The geothermal surface manifestations in the Ungaran geothermal field consist of fumaroles, neutral pH bicarbonate warm/hot springs, relatively dilute steam-heated (or thermal-meteoric) springs and hydrothermal alteration (Figure 3). The temperatures of these manifestations range from 36–38^{o}C in diluted hot spring fluids to 80^{o}C in fumaroles occurring on the southern and northern flanks of Ungaran volcano. The fumaroles of the Ungaran prospect are located only in the Gedongsongo area. The warm/hot spring occurs in Banaran, Kendalisodo, Diwak and Kaliulo, located approximately 3, 5, 10 and 15 km, respectively, away from the Gedongsongo fumarolic area. According to Budiardjo et al. (1997), the compositions of the thermal spring waters can be divided into two water types. The hot water at Gedongsongo originates as steam-heated meteoric water characterized by low chloride content (similar to local surface water), high sulphate content (up to 1000 ppm), and low pH (up to 5). The hot spring water in other areas falls into neutral bicarbonate-sodium chloride water diluted by flowing water from the Ungaran volcano geothermal reservoir. The anomalously high concentrations of sodium, chloride and boron in hot spring water in Kaliulo indicate an influence of connate water trapped in the Tertiary marine volcanic rocks, as suggested by Budiardjo et al. (1997).

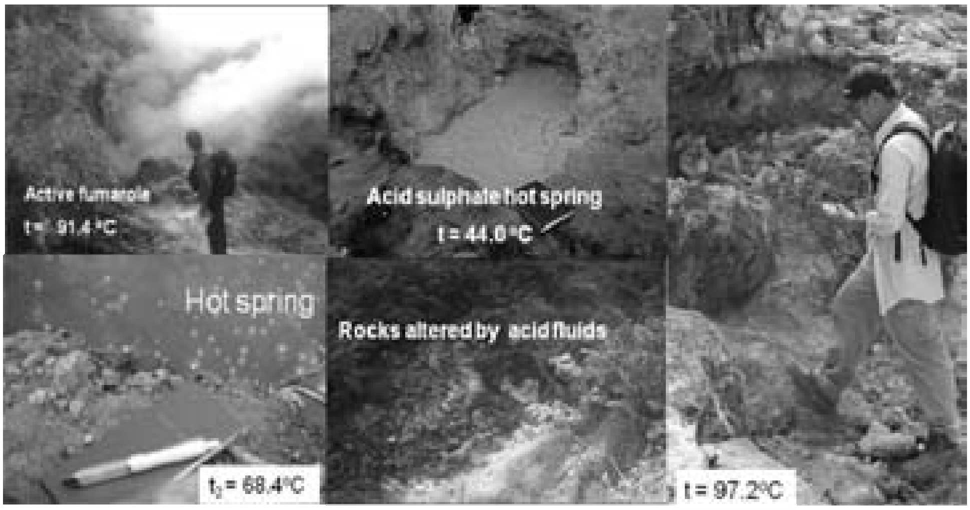

Figure 3: Geothermal manifestations at Ungaran volcano.

4 GRAVITY DATA

Gravity data for this study are public domain data provided by Gadjah Mada University. The

data were taken during two periods: February 14-22, 2001 and March 19-25, 2001, and cover 143.85 km^2 using 163 gravity stations (Figure 4). The Bouguer gravity map is shown in Figure 5, and it shows a positive Bouguer anomaly ranging from 20.5 to 56 mGals. A high Bouguer anomaly was found in the northern part of Ungaran volcano. Considering the geological setting,

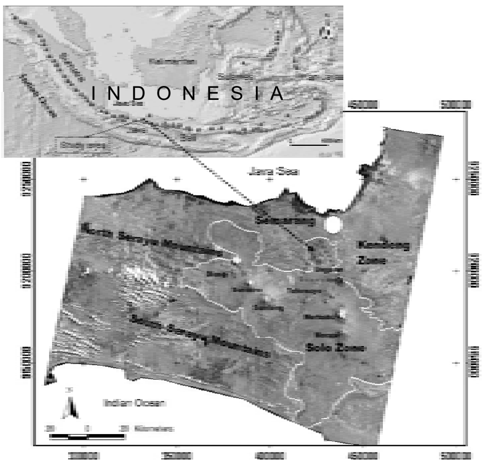

Figure 1: Location of the study area.

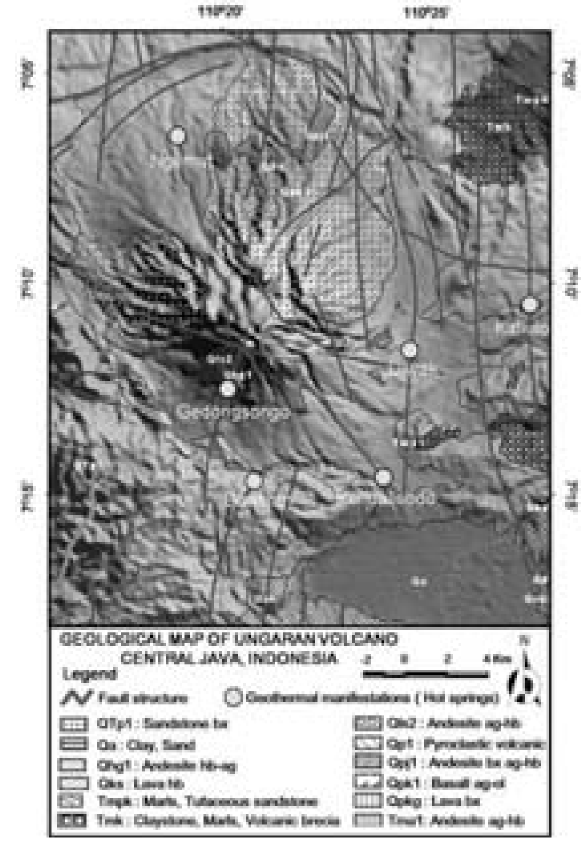

Figure 2: Geologic map.

the high Bouguer anomaly correlates with the old Ungaran volcano.

5 METHODOLOGY

We used two gravity interpretation techniques: HGM and VDM. The combination of the two methods enhanced the structural definition of the study area. The VDR method has the advantage that its zero quantity represents the ridges or contacts of the gravity sources. The location of the maximum HGM can be used as an indicator of the locations of edges of the source. The HGM and VDM techniques are illustrated in Figure 6.

Vertical derivative method (FVD and SVD)

The first (FVD) and second order vertical derivatives (SVD) are expressed as:

$$FVD = \partial g / \partial z \quad (1)$$

$$SVD = \partial^2 g / \partial z^2 \quad (2)$$

where ($\partial g/\partial z$) and ($\partial^2 g/\partial z^2$) are the first and second vertical derivatives of the gravity field in the z direction, respectively.

Maps of the FVD and SVD are shown in Figs. 7 and 8, respectively. The SVD map tends to emphasize local anomalies and isolate them from the regional background, while the SVD enhances near-surface effects at the expense of deeper anomalies. The quantity 0 mGal/m^2 should indicate the edges of local geological features. The hot springs are located exactly on the zero contour line of the first and second vertical derivatives, which is interpreted as a contact.

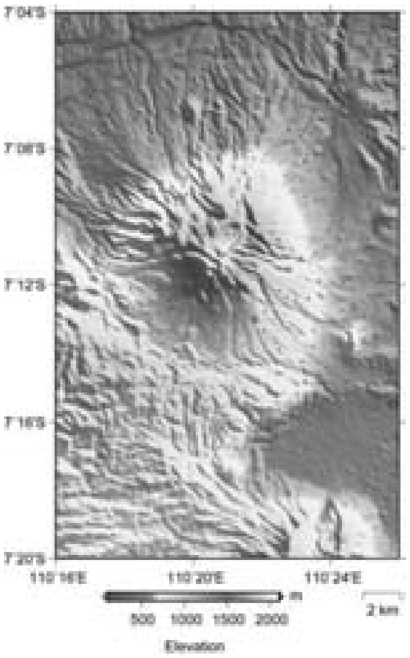

Figure 4: Topography of study area and distribution of gravity stations.

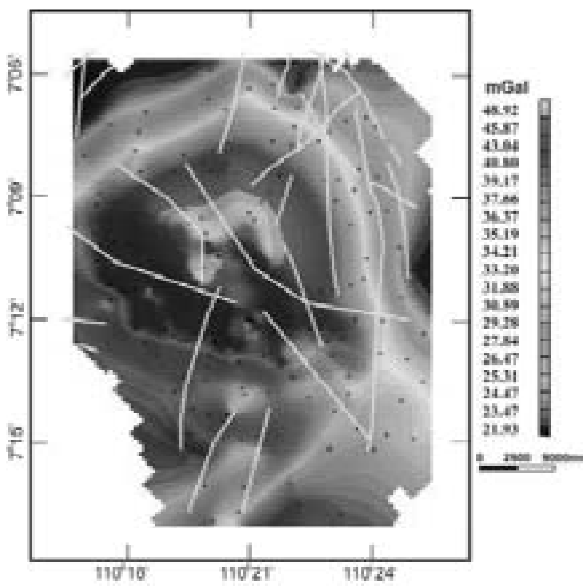

Figure 5: Bouguer gravity map.

Horizontal gradient method (HGM)

This method effectively delineates both shallow and deep sources, in comparison with the vertical gradient method, which is useful only for identifying shallower structures. The amplitude of the horizontal gradient (Cordell & Grauch, 1985) is expressed as:

$$HGM = [(\partial g/\partial x)^2 + (\partial g/\partial y)^2]^{1/2} \qquad (3)$$

where ($\partial g/\partial x$) and ($\partial g/\partial y$) are the horizontal derivatives of the gravity field in the x and y directions, respectively. The amplitude of the horizontal gradient in the Ungaran volcano was calculated in the frequency domain and is illustrated in Figure 9. The area may be dissected by major faults striking N-S and E-W.

6 CONCLUSIONS

We present an interpretation of the gravity anomalies in Ungaran caused by the distribution of subsurface geological formations and their structures. We show that geothermal manifestations such as Gedongsongo, Gonoharjo, Diwak, and Kaliulo, located on the young Ungaran volcano, correlate well with the horizontal gradient anomalies interpreted as faults. This indicates that the geothermal manifestations of Ungaran are structurally controlled, especially by deep gravity sources. Integrating the different gravity gradient interpretation techniques is necessary to improve our understanding of the subsurface structure.

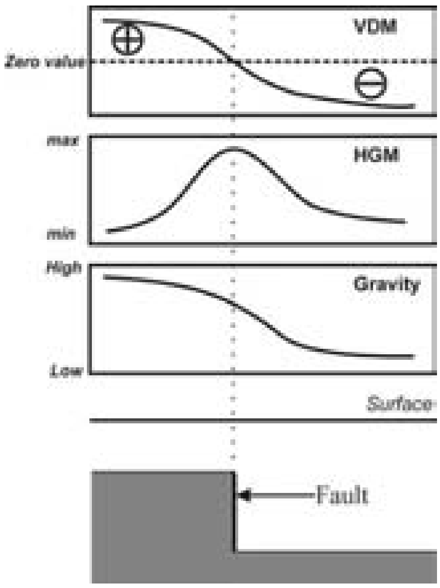

Figure 6: Gravity anomaly over a fault.

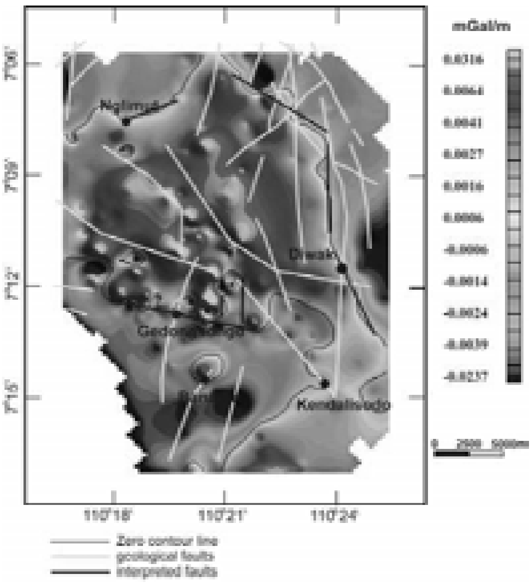

Figure 7: FVD of the gravity data.

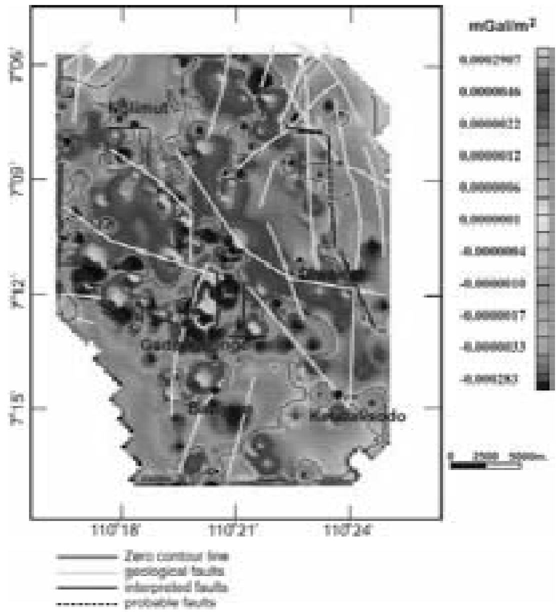

Figure 8: SVD of the gravity data.

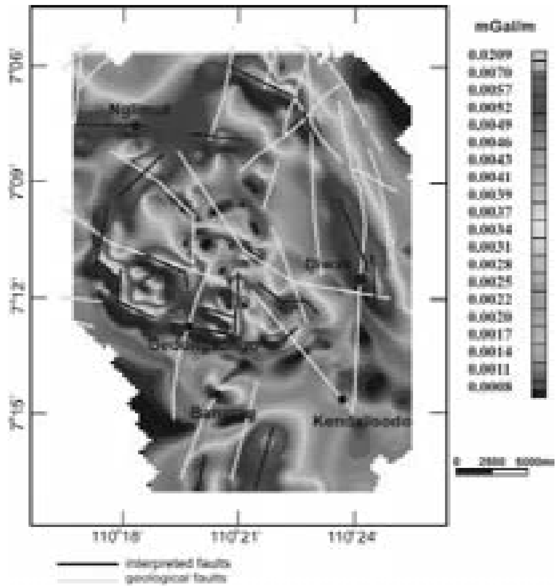

Figure 9: Horizontal gradient map of the gravity.

7 ACKNOWLEDGEMENTS

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