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ORIGINAL PAPER

Gravity data analysis of Ungaran Volcano, Indonesia

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Abstract Mount Ungaran is a Quaternary volcano located in the province of Central Java, Indonesia. The study area was covered by a gravity survey in order to delineate the subsurface structure and its relation to the hot springs that are spread throughout the area. The gravity data were analyzed using gravity gradient interpretation techniques, such as the horizontal gradient and Euler deconvolution methods, and many faults were detected. The results of the present study suggest that the hot springs around Ungaran Volcano are structurally controlled and have depths ranging from 1 to 3 km. The results of the present study lead to an understanding of the relationships between the interpreted faults and the locations of hot springs and may aid in future geothermal exploration of the area.

Keywords Gravity · Ungaran Volcano · Hot springs · Structure · Interpretation techniques · Indonesia

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.

Ungaran Volcano is located at the northern part of the Java volcanic arc, Indonesia, as shown in (Fig. 1b). Ungaran was formed in a volcanic arc with three other volcanoes, namely Merapi, Merbabu, and Telomoyo. Ungaran is situated in the northern part of this volcanic chain and is believed to have formed from back-arc side magmatism associated with subduction (Katilli 1975). For example, the Gedongsongo hot spring is located in the southern part of Ungaran (Fig. 2a) and is the main geothermal manifestation in the area which includes furmaroles, hot springs, hot acid pools, and an acidic surface of hydrothermally altered rocks with inferred reservoir temperatures ranging from 120°C to 290°C (Widarto et al. 2005).

To investigate the structural relationships between faulting and hydrothermal activity at Ungaran, gravity methods have been used to identify potential subsurface structures. The

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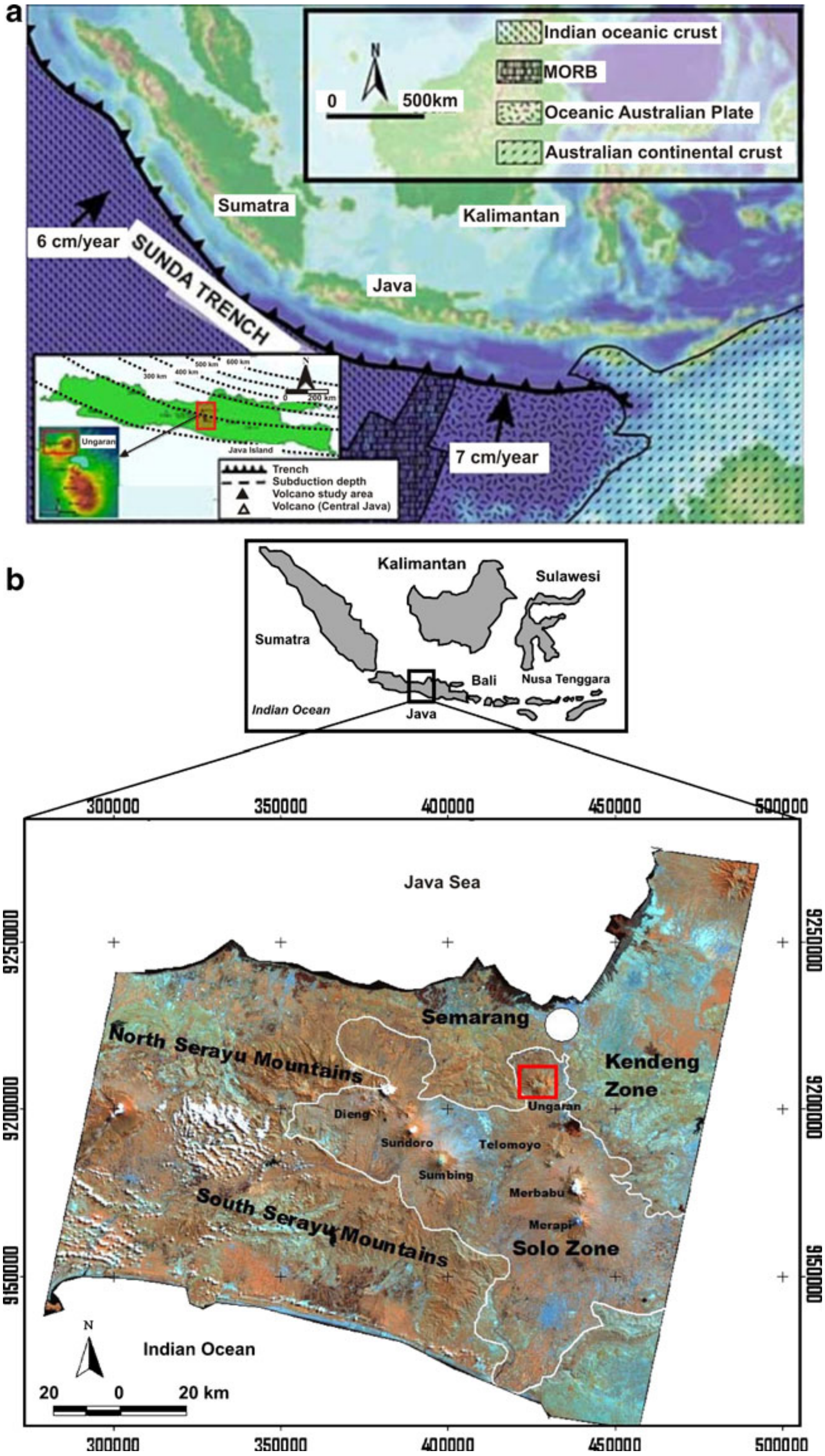
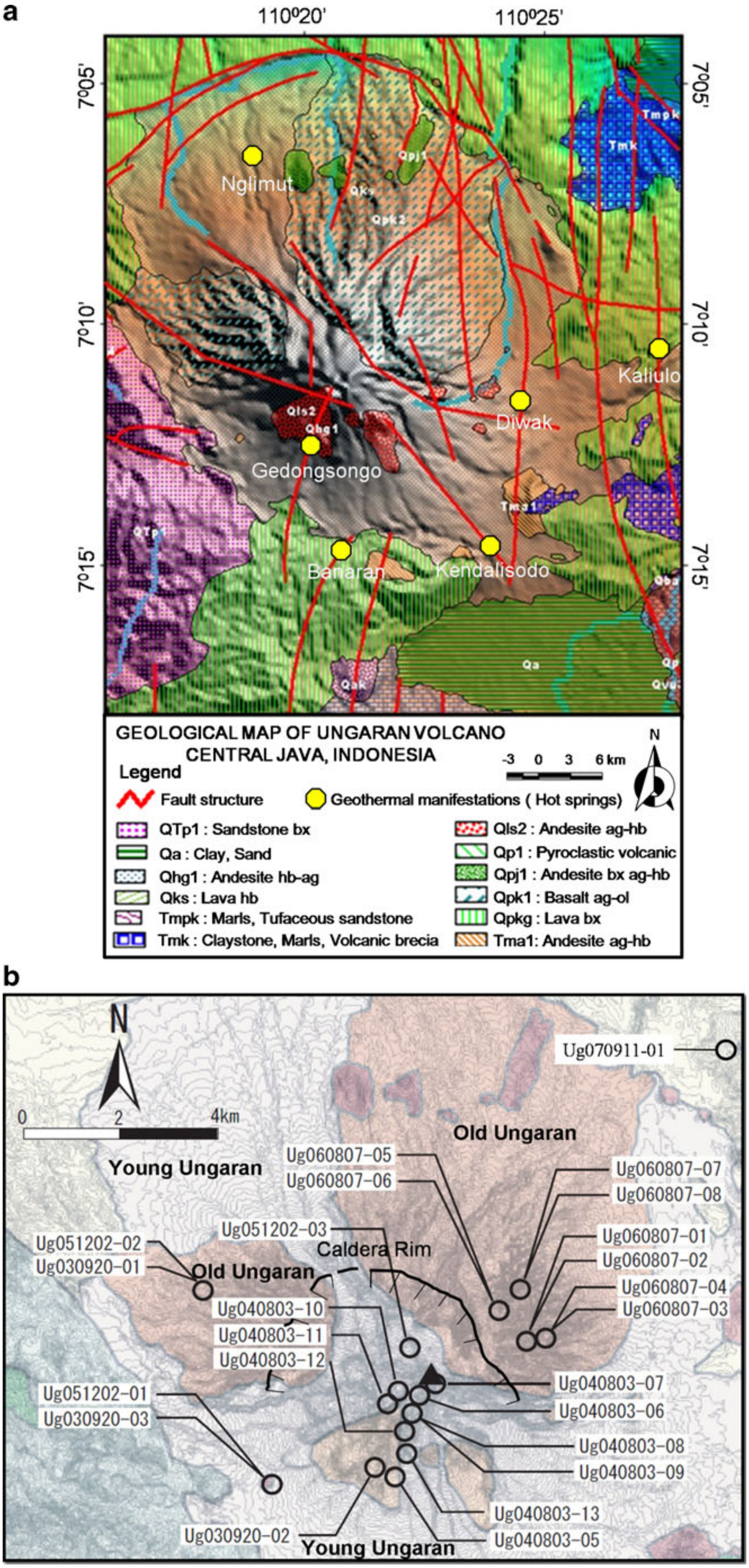


Fig. 1 **a** The Quartenary volcanism of the Sunda arc is connected to the northward subduction of the Indo-Australia plate beneath the Eurasian plate at a rate of 7 cm/year near Java (after Kohno et al. 2006). **b** Location of the study area

Laboratory of Geothermics of Kyushu University in Japan had conducted many geophysical investigations of the hydrothermal system of Ungaran Volcano with the collaboration of Gadjah Mada University, Indonesia, since 2004. These methods are infrared imagery, seismic observation, and SP surveys at the Gedongsongo fumarolic area of Ungaran Volcano (Fujimitsu et al. 2007). The gravity data were analyzed using integrated gradient interpretation techniques, such as the horizontal gradient (HG) and Euler deconvolution (ED) methods. Saibi et al. 2006a, 2008 used gravity data and Euler deconvolution technique in order to image faults for geothermal prospection.

Fig. 2 **a** Geologic map. **b** Ungaran volcano can be divided into two bodies: Old Ungaran and Young Ungaran (Kohno et al. 2006). *Black circles* show the locations of rock samples



Geologic setting

The active volcanoes of the Indonesian archipelago are connected to several distinct subduction zone systems, namely the Sunda, Banda, Sangihe, and Halmahera arc systems (Edward 1988; Bogie et al. 1998; Camus et al. 2000). The tectonic evolution of the Indonesian archipelago from the Late Paleozoic to the Pliocene proceeded with subduction and accompanied volcanism spreading systematically in ever-widening areas from the continent toward the ocean. The Java arc-trench system was formed by subduction of an oceanic plate under the continental crust. The Quaternary volcanism of the Sunda arc is connected to the northward subduction of the Indo-Australian plate beneath the Eurasian plate at a rate of 6 cm/year near Sumatra and 7 cm/year near Java (Hamilton 1979; Kohno et al. 2006). The north–south alignment of Quaternary arc volcanoes from Ungaran to Merapi occupies the western part of the Solo Zone in Central Java (Van Bemmelen et al. 1970). The Solo Zone is a geothermally active volcano-tectonic depression which has been progressively infilled by extensive Quaternary volcanism originating in Central and East Java (Van Bemmelen et al. 1970; Fig. 1b). Geographically, Van Bemmelen et al. (1970) mentioned that the row of volcanoes, from Merapi to Ungaran, occupies the western part of the Solo Zone. This zone is a depression that consists of the Quaternary product of substantial volcanism in Central to East Java. Geothermal areas in Central Java, including Ungaran, are located in the Quaternary Volcano Belt (Solo Zone). The old Ungaran body was formed more than 500,000 years ago, and the young Ungaran body did not form until 300,000 years ago (Kohno et al. 2006).

Some rock density measurements were carried out at the Laboratory of Geothermics (Kyushu University, Japan). The samples were collected from both areas (old Ungaran and young Ungaran rocks). The density of each rock, in wet and dry conditions, was calculated (Setyawan et al. 2009). The location of the rock sampling is presented in Fig. 2b. The results show that the older Ungaran had a slightly more basaltic composition than those from the Young Ungaran, which is composed of andesitic volcanic rocks. The density contrast between the Young and Old Ungaran rocks is 250 kg/m^3 (Setyawan et al. 2009). Ungaran volcanic area is composed of andesitic lava, perlitic lava, and volcanic breccia from the post-Ungaran caldera stages, as shown in Fig. 2a (Thanden et al. 1996).

Figure 2a shows a circular structure which could be related to the vertical collapse structure discussed in this section. It is clearly observed in the northern part of the volcano (Fig. 2a) as delineated by normal faults. However, its southern location is not clearly observed. The possible relation between this collapse structure and the gravity results is discussed in the last section of this paper.

Ungaran is a stratovolcano that consists of a series of andesitic to basaltic lavas and breccia with occasional tuff interbedding. The product of Ungaran stratovolcano overlies the Tertiary marine sedimentary rock formation (Budiardjo et al. 1997). According to Van Bemmelen et al. (1970), the volcanism started on Lower Pleistocene, represented by the Middle Damar Beds (the oldest Ungaran). The volcano continued to grow and produced the Old Ungaran and Young Ungaran.

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 some prior volcanic activity. The Young Ungaran body seems to have been constructed inside a caldera formed during the older Ungaran activity (Setyawan et al. 2009).

Geothermal system at Ungaran Volcano

The Ungaran geothermal prospect is a hot water-dominated system associated with the Upper Quaternary volcanism of Ungaran Mountain (Budiardjo et al. 1997). The field falls into low resistivity zone extending across approximately 5 km^2

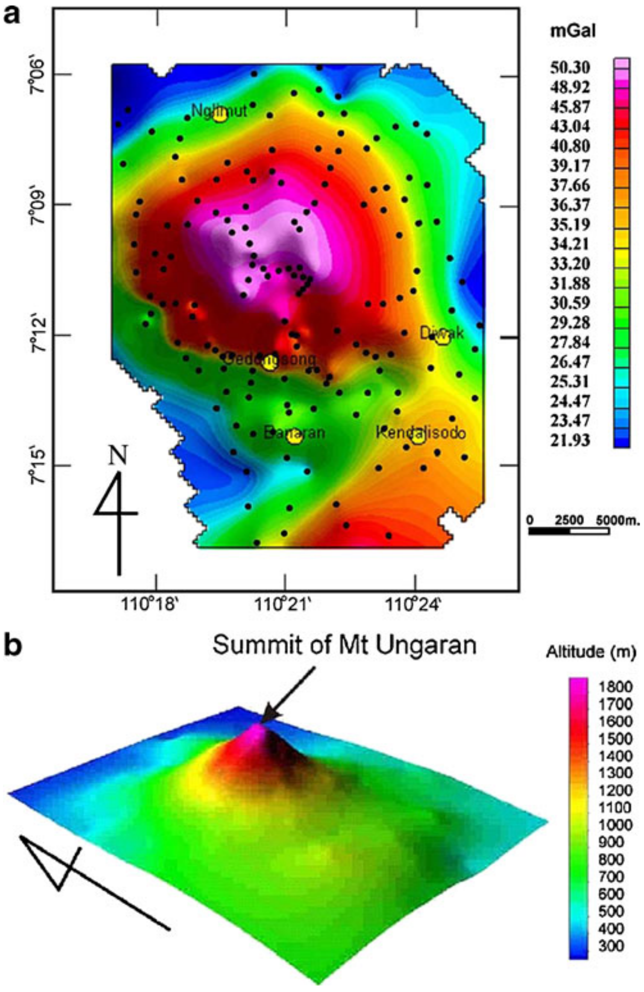


Fig. 3 **a** Bouguer gravity map of Ungaran Volcano. *Black points* show the gravity stations. *Yellow circles* indicate the locations of the hot springs around the volcano. **b** Topography map of Ungaran Volcano in meters

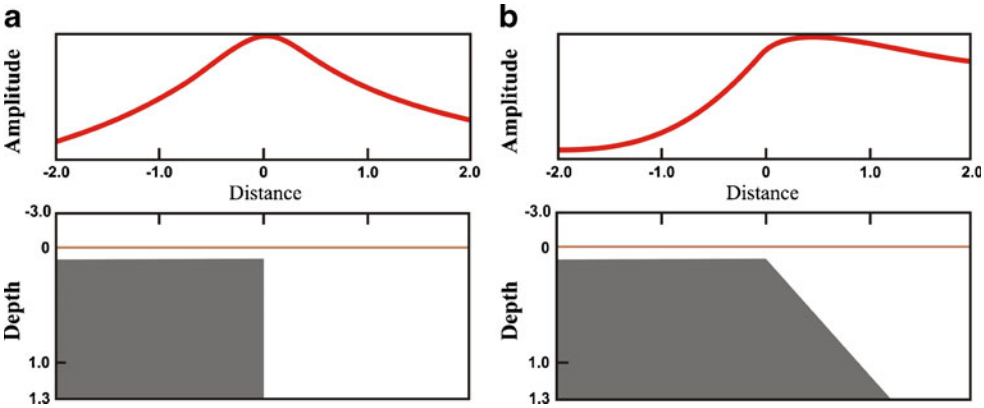


Fig. 4 Horizontal gradient magnitude over two models: a vertical contact (**a**) and a dipping contact (**b**) (Phillips et al. 2000)

(Widarto et al. 2005). Gedongsongo is the main geothermal resource area of the Ungaran prospect with the Quaternary andesitic volcanic complex of Ungaran Mountain. The reservoir is inferred to be capped in the upper part by near impermeable Upper Quaternary volcanic rocks of post-caldera. The reservoir fluid is composed of high-temperature sodium chloride water, most likely occupying fractured lower Quaternary pre-caldera volcanic rocks and Tertiary volcanic rocks. The main source of heat is the intrusive body of andesitic and dioritic rocks of Ungaran Volcano. This body heats the system up to a reservoir temperature of approximately 220°C, based on geothermometer measurements of gases taken from the Gedongsongo fumaroles. The upper level of the Ungaran geothermal reservoir is estimated to be at a depth of approximately 2,000 m (Phuong et al. 2005). 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 (Phuong et al. 2005). The temperature of these manifestations ranges from 36–38°C in diluted hot spring fluids to 80°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 (Fig. 2a). The warm/hot springs occur at Banaran, Kendalisodo, Diwak, and Kaliulo, located approximately 3, 5, 10, and 15 km away from the Gedongsongo fumarolic area, respectively.

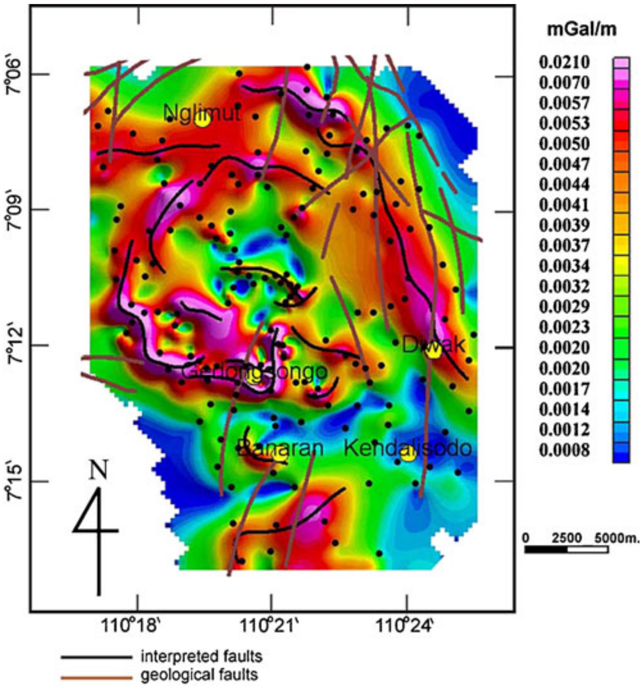


Fig. 5 Horizontal gradient map of the study area. *Black lines* are the interpreted faults from HG. *Brown lines* indicate the faults from the surface geology (Thanden et al. 1996). *Yellow circles* show the locations of the hot springs around the volcano. *Black points* show the gravity stations

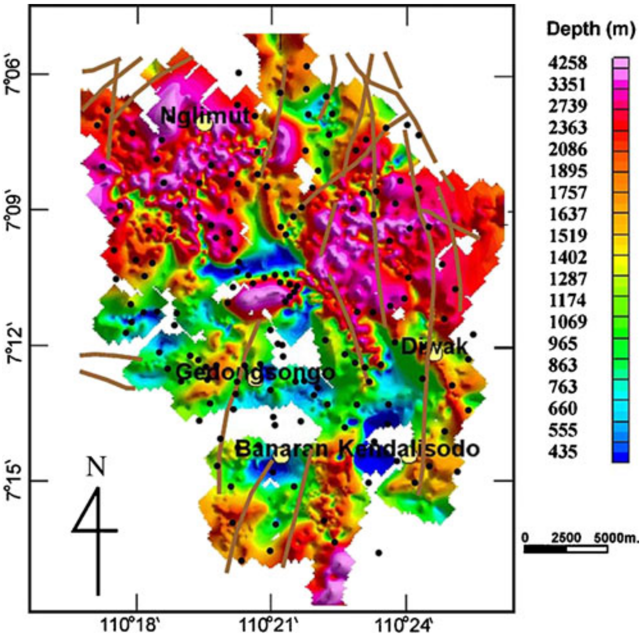


Fig. 6 Euler solutions using a structural index of 0. The maximum relative error is 10%. Solutions were selected using standard criteria. *Brown lines* indicate the faults from the surface geology (Thanden et al. 1996). *Black points* show the gravity stations

Table 1 Gravity source depths at the different hot springs at Ungaran Volcano

Hot spring	Gravity source depth (m)
Banaran	500
Gedongsongo	750
Kendalisodo	1,200
Diwak	1,750
Nglimut	3,750

Gravity data

Gravity data for the study area are issued from the public domain data provided by Gadjah Mada University, Indonesia. The data were taken during two periods, 14–22 February 2001 and 19–25 March 2001, and cover 144 km^2 that consists of 163 gravity stations. Figure 3a shows the Bouguer anomaly map of the study area. It is characterized by positive gravity values ranging from 20.5 to 56 mGal. 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/cm^3 (Murata 1993) was used to produce the Bouguer anomaly map of the study area (Fig. 3a). The mesh size is 200 m in the x and y directions. The gravity data were corrected for free air, terrain, tides, and Bouguer effects. Unfortunately, we do not have information on instrumentation (gravimeters), data precision, and localization (GPS) of the gravity stations.

Methodology

We used two gravity interpretation techniques: the HG and the Euler deconvolution. The combination of these two methods was 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 because it requires only the calculation of the two first-order horizontal derivatives of the field (Phillips et al. 1998). The method is also robust in delineating both shallow and deep sources, in comparison with the vertical gradient method which is useful only in identifying shallower structures. The horizontal gradient filter can be estimated by (Phillips et al. 1998):

$$|H\,(x,\,y)| = \sqrt{\left(\frac{\partial G}{\partial x}\right)^2 + \left(\frac{\partial G}{\partial y}\right)^2} \qquad (1)$$

where $\partial G/\partial x$ and $\partial G/\partial y$ are the derivatives of gravity field in the x and y directions, respectively. The method is based on the principle that a near vertical, fault-like boundary produces a gravity anomaly whose horizontal gradient is largest directly over the top edge of the boundary (Grauch 1987). The HG is illustrated in Fig. 4.

Once the boundaries are delineated using the HG filter, the ED is applied to the data to estimate the depths of such boundaries. Euler deconvolution was used to estimate the depth and location of the anomalous gravity source. The Euler deconvolution can be estimated by (Reid et al. 1990):

$$(x - x_0)\frac{\partial G}{\partial x} + (y - y_0)\frac{\partial G}{\partial y} + (z - z_0)\frac{\partial G}{\partial z} = N(B - G) \qquad (2)$$

where G is the observed field, x_0, y_0, and z_0 are the source anomaly locations, B is the base level of the observed field, and N is a structure index (SI), which can be defined as the rate of attenuation of the anomaly with distance. SI must be chosen according to prior knowledge of the source geometry.

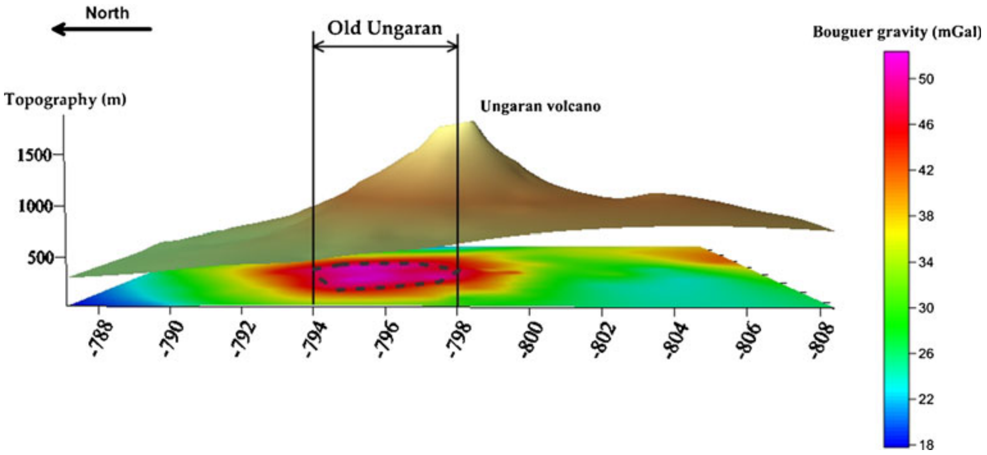


Fig. 7 Overlay of topography map and Bouguer gravity anomaly in Ungaran Volcano, Indonesia

For example, SI=2 for a sphere, SI=1 for a horizontal cylinder, SI=0 for a fault, and SI=−1 for a contact (FitzGerald et al. 2004). The two horizontal gradients ($\partial G/\partial x$, $\partial G/\partial y$) and the vertical gradient ($\partial G/\partial z$) are used to compute the anomalous source locations. We assigned several structural index values and found that an SI of zero gave good clustering solutions. Reid et al. (2003) presented a structural index equal to zero for the gravity field for detecting faults.

Application and results

Gravity data were gridded using a 200-m interval as it was the best spacing interval (after using trails) for the random distribution of the data. From the practical experiences, the grid cell size should normally be from one half to one fourth of the nominal sample interval.

Equation 1 is applied to the gravity data to estimate the horizontal gradient map as shown in Fig. 5. The result of the HG map is that the boundaries/faults are located at the maxima of the horizontal gradient. Some new faults are detected from the horizontal gradient map (shown in black color in Fig. 5). These faults are located on or near the hot springs in the area (e.g., Diwak hot spring). Moreover, most 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 et al. 1987).

Euler solutions are estimated by applying Eq. 2 to the gravity data using a SI of 0. The Euler depth map is shown in Fig. 6 and indicates that the gravity sources range from 1 to 4 km deep. The Euler method estimates the depth to the top of the source, which means that 1–4 km represents the top of the gravity source. The depths of the gravity sources at the hot springs range from 500 m at Banaran hot spring to 3750 m at Nglimut hot spring (Table 1).

Discussion and conclusions

We present an interpretation of the gravity anomalies at Ungaran caused by the distribution of subsurface geological formations and their structures. The application of the horizontal gradient and Euler deconvolution methods to the gravity 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. Additionally, hot springs (e.g., kendalisodo, Gedongsongo, Diwak, and Banaran) are located at or close to the geologic faults, as shown in Fig. 5. It does mean that the hot springs are controlled by the fault system.

The only exception is at the Kendalisodo hot spring where there is a low magnitude of the horizontal gradient but faults close to the surface (brown color). This discrepancy could be due to the lack of gravity stations around the Kendalisodo hot spring.

Figure 7 shows the relationship between gravity and elevations. The high gravity is correlated with Old Ungaran Rocks, which have low silica contents which increase the density of rocks (Setyawan et al. 2009).

The horizontal gradient method represents the lithological boundaries between volcanic units formed during the evolution of the volcano. The horizontal gradient method was able to detect a circular structure which could relate to the collapse structure of Ungaran Volcano. The Euler deconvolution method could determine the depth of the gravity sources which are almost between 1 and 4 km. Combining the different gravity gradient interpretation techniques is necessary to improve our understanding of the subsurface structure.

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