Subsurface Structural Mapping Using Gravity Data of Hohi Geothermal Area, Central Kyushu, Japan

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ABSTRACT

Hohi area is located in central Kyushu island of Japan and is known as a volcano-tectonic depression region. The area is characterized by its potential geothermal resources. In this study, we attempt to delineate the subsurface structures of the area using integrated interpretation of existing gravity data. The gravity survey of Hohi area is about 500 km^2. The total number of gravity stations was up to 1500 and average distribution of stations was approximately 3 per km^2. Interpretation of horizontal gradient of the gravity data indicated that the area is characterized by the existence of high gradient anomalies associated with existing geothermal fields and manifestations. Horizontal gradient analysis also enabled tracing several faults that are mainly striking in the S-N, NW-SE, and NE-SW directions. Euler deconvolution method has been applied to the gravity data and provided fast information about both the depth and trends of the shallower subsurface structures in the area. Depth to deeper structures, based on modeling of the gravity data, is found to be about 5.4 km.

1. INTRODUCTION

The northeastern part of Central Kyushu, known as the Hohi region (Figure 1), is one of the most active geothermal areas in Japan. The Hohi region provides abundant geothermal resources. There are several hot springs and three power plants: 12.5 MW, Otake, 110 MW Hatchobaru, and 25 MW, Takigami (Hayashi, 2000). A large scale of geological and geophysical surveys has been carried out in the Hohi area to delineate the subsurface structure and its relation to existing geothermal reservoirs (Hase et al. 1985). Gravity method is one of the best geophysical techniques for delineating subsurface structures and monitoring subsidence as well as estimating mass recharge, which is reduced by fluid withdrawal in the reservoir during long-term exploitation. Because of the appeal of the method, several precise gravimetric surveys were carried out in the Hohi area. These surveys have been studied by several researchers (e.g., Komazawa and Kamata, 1985; Kusumoto et al., 1999a and 1999b).

In this paper, we present a new look on the subsurface structure setting of the Hohi area using the existing gravity data. We show definite relation between the deep structure pattern obtained from the horizontal gradient of the gravity data and the existing geothermal fields. This relation is useful for locating new prospects for further geothermal exploration. On the other hand, application of Euler method to the gravity data of the Hohi geothermal area provides useful information about the locations and trends of the shallower subsurface structures.

Results of the horizontal gradient and Euler method and available geological information were used to build a 2D conceptual structural model in the area of study.
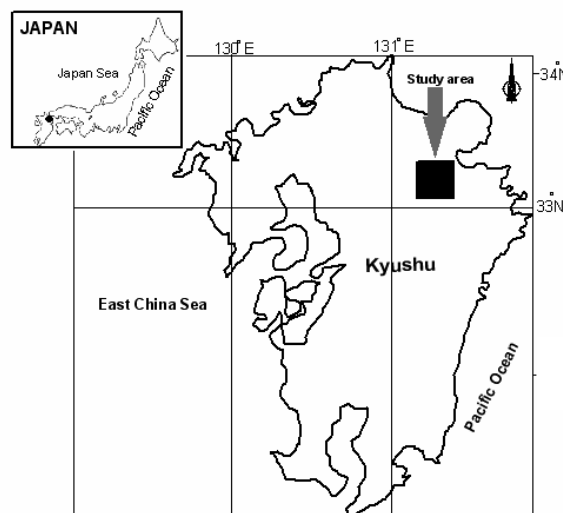

Figure 1: Location map of the Hohi geothermal area

2. GEOLOGICAL SETTING

The surface geology of the Hohi area is characterized by Tertiary and Quaternary volcanics, partly intercalated with lake sediments, and their bed rocks (Tamanyu, 1985). Tertiary rocks are composed of the Miocene and Pliocene strata. Miocene strata are the Ishiba conglomerate, which unconformably overlies the bed rocks with basal conglomerate. The Pliocene strata are made up of Taio Group and Pre-Kusu Altered Volcanics. Taio Group is divided into two formations of tuff and Andesitic Pyroclastics. The Pre-Kusu Altered Volcanics is divided into three formations of the Dacitic Pyroclastics, Andesitic Pyroclastics, and the Green Tuffs in ascending order. Quaternary rocks are composed of the Pleistocene strata and the Holocene fan and talus deposits. Pleistocene strata is composed of Hohi volcanics, Kusu Group and Young volcanics. Surface and air-photo survey revealed many lineaments with east-west trend.

Tectonically, the Hohi area (Figure 2) is located at the intersection of three tectonic lines, i.e., Median Tectonic Line MTL, Oita-Kumamoto Tectonic Line OKTL and Kurume-Hiji Line KHL (Kusumoto et al., 1999). Generally, the eastern part of central Kyushu, Japan, is the junction

between the Honshu-arc and Ryukyu-arc. There are several explanations for the formation of this region. Most of them attach importance to the depression structure associated with volcanism and/or right-lateral motion of the MTL and other tectonic lines (Kusumoto et al., 1999).
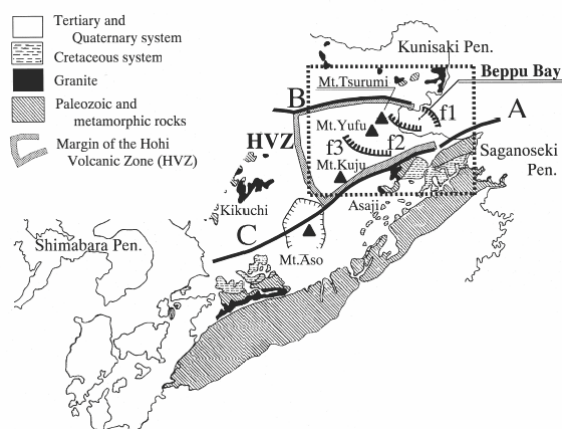

Figure 2: Geological map in central Kyushu. The rectangle shown by a broken line is the study area. HVZ: Hohi volcanic zone. A: Median Tectonic Line. B: Kurume-Hiji Line. C: Oita-Kumamoto. Tectonic Line. f1: Beppu Bay Cross Fault. f2: Asamigawa Fault. f3: Tsuzura-Shonai Fault (modified from Sasada, 1984; NEDO, 1990).

3. GRAVITY AND WELL DATA

A gravity survey covering the Hohi area. has been carried out in 1987 by Sumiko Consultants Co., Ltd under the contract with Idemitsu Geothermal Company Limited. The Hohi area is about 500 km^2. The total number of gravity station was up to 1500, and average distribution of stations was approximately 3 per km^2. A density of 2.3 g/cm^3 was used to yield the Bouguer anomaly map shown in Figure 3. The map is characterized by a closed negative contour (less than 30 mGal, named as Shishimuta low anomaly) in the central part of this area, and a high north-to-south trending contour (greater than 20 mGal, named Mizuwake-touge). Another characteristic is high trending along a flank of the central region separated from other gravity low known as Shonai low. These anomalies are involved in so-called Hohi low gravity zone, which may reflect volcano tectonic depression zone.

Burial depth of Pre-Tertiary basement rocks is comparatively shallow at the south with abruptly increasing depth to the north of the area. The basement rocks in the study area were reached by three drill holes (, HT-5-1, N1-0I-3). These depths are listed in Table 1 (Komazawa and Kamata, 1985;New Energy Development Organization, 1991). Dry density data were measured from N1-0I-3 wells. Density measurements were made only in the basement rocks and found to be 2.67 g/cm^3 at depth of 1795 m and 2.68 g/cm^3 at depth of 2303 m from the surface. N1-0I-3 is located on the southwestern corner of the study area (Figure 3). About 60 density samples (Table 2) were measured in the sedimentary section and 24 density samples from the basement rock. Generally, there is a gradual increase in the density for the pyroclastic rocks. The density of the andesite lava is almost the same and seems to not depend on the depth. Basement rocks and dyke rocks show highest density in the field.
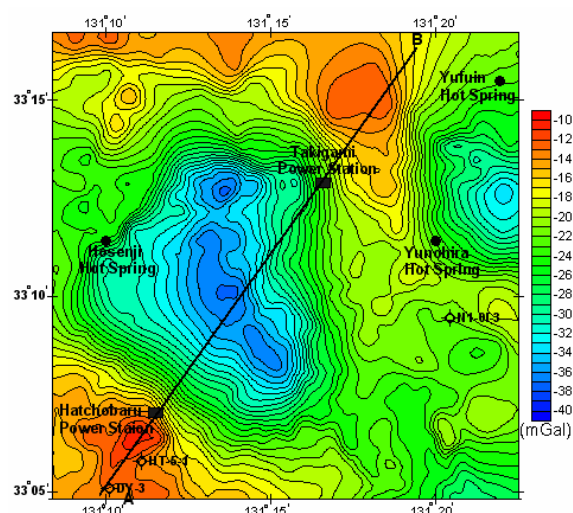

Figure 3: Compiled Bouguer anomalies of the Hohi geothermal area (density=2.3 g/cm^3), ✧ Well.

Table (1) Drill hole depths at the Hohi geothermal area

Well name	Altitude above sea level (m)	Depth Below sea level (m)
DY-3	954	506
HT-5-1	1170	774
N1-0I-3	637	584

Table (2) Formation and Density measurements in well N1-0I-3

No	Formation Name and rock type	Depth (m)	Density gm/cm^3
1	Asono (Silt, unconsolidated mud)	90	0.9
2	Hanamure-yama (Andesite lava, tuff breccia,lapilli tuff)	204	2.4
3	Nakatouge pumice flow (Pumice tuff)	301	1.3
4	Ayukawa pyroclastic flow (Lapilli tuff,welded tuff,tuff breccia)	545	2
5	Shonai (Sand-silt,tuff,volcanic breccia)	592	2.2
6	Pre-Kusu (Tuff, conglomerate, tuff breccia)	694	1.9
7	Taio group (Andesite lava, Tuff, Conglomerate)	1220	2.3
8	Ryouke granite (Granodiorite, Andesite, dyke),	1700	2.6

4. DATA ANALYSIS AND INTERPRETATION

The present study is based on qualitative and quantitative analysis of the gravity data to delineate both shallow and deep basement structures. In that regard, the gravity data were first digitized at an interval of 250 m and were subjected to spectral analysis (Spector and Grant, 1970) to isolate deep source from shallow sources. The gravity data were transformed to the frequency domain and regional/residual separation was made based on the power spectra (Figure 4).

Figure 5 shows the regional field of the gravity data. Meanwhile, the residual component is displayed in Figure 6. Generally, the regional structure of the Hohi area is characterized by a broad negative gravity low indicating a basin structure, which may correspond to graben structure. This basin is known as Shishimuta caldera. Komazawa and Kamata, (1985) showed that this caldera was formed mainly by volcano-tectonic depression. In addition to the gravity anomaly of Shishimuta caldera, there are two high anomalies striking mainly to the north direction and separating the low anomaly of Shishimuta caldera from Shonai gravity low in the eastern part of the study area. On the other side, the residual map shows several local anomalies striking in the N-S, NW-SE, and E-W directions. Some of these anomalies are associated with the existing geothermal field (e.g., Otake and Hatchoubaru geothermal area). The residual gravity values around the Otake and Hatchoubaru geothermal area are relatively high, which may indicate that there is a basement uplift and/or lateral difference in the density from causative rocks. Unlike Otake and Hatchoubaru area, the Takigami area is located at the edge of a local gravity low. Thus, the residual gravity data indicate that the shallower structure systems of the Takigami area and Otake and Hatchoubaru geothermal area are different. Other observed anomalies may indicate promising areas for future geothermal exploration. Detailed studies are highly recommended to understand the geothermal potentialities for the areas associated with these anomalies.
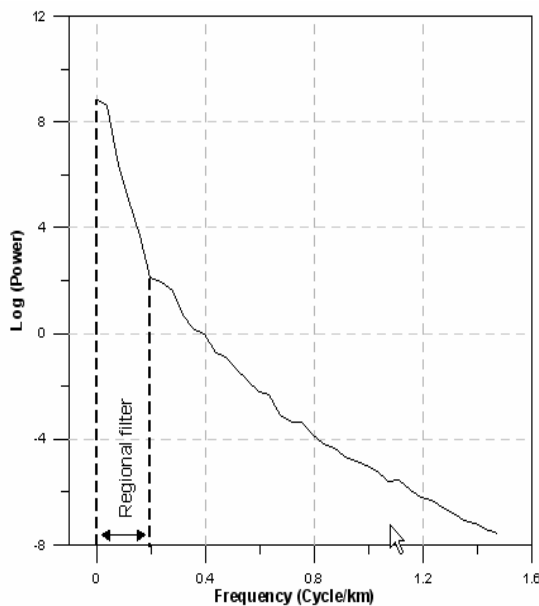

Figure 4: Power spectrum of the Bouguer anomalies of the Hohi geothermal area.

To delineate the subsurface structure of the area, we have taken two approaches. These approaches are horizontal gradient analysis to delineate the deep structures and the Euler method to delineate shallower structures. Results of these methods, together with available geological information and well data, are used to build 2D conceptual structural model to help in understanding the geothermal potentiality of the study area.
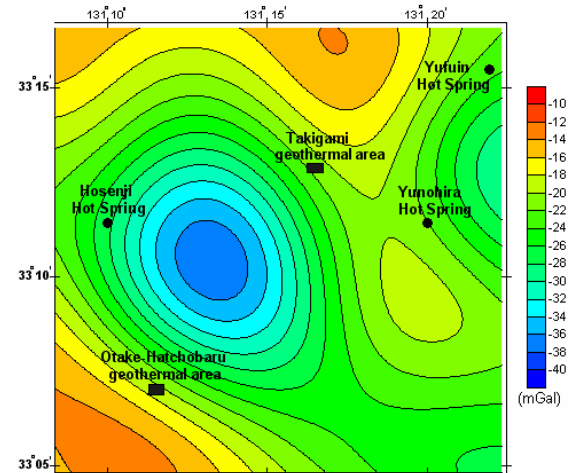

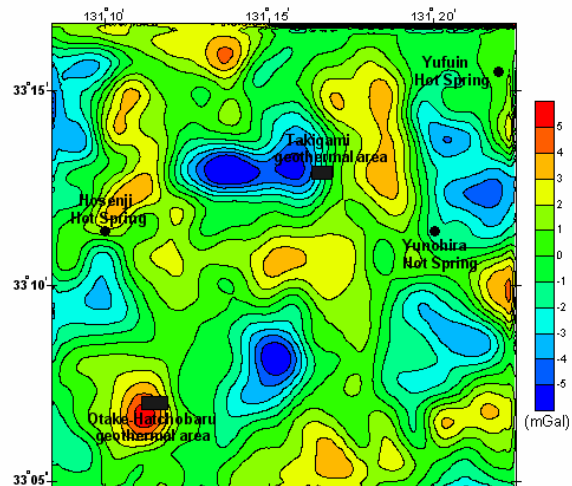**Figure 5: Regional gravity anomaly map of the Hohi geothermal area.**

Figure 6: Residual gravity anomaly map of the Hohi geothermal area.

4.1 Horizontal Gradient

The horizontal gradient method has been used intensively to locate contacts of density contrast from gravity data (Cordell, 1979) or pseudogravity data (Cordell and Grauch, 1985). Blakely (1995) stated that the horizontal gradient of gravity anomaly caused by a tabular body tends to overlie the edges of the body if the edges are vertical and well separated from each other. The biggest advantage of the horizontal gradient method was its least susceptibility to the noise in the data because it only required the calculations of the two first-order horizontal derivatives of the field (Phillips, 1998). The method is also robust to delineation either shallow or deep in comparison with the vertical gradient, which is useful only for the shallower structures. The amplitude of the horizontal gradient (Cordell and Grauch, 1985) is expressed as:

$$HG = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2} \quad , \qquad (1)$$

where $(\dfrac{\partial g}{\partial x}$ and $\dfrac{\partial g}{\partial y})$ are the horizontal derivatives of the gravity field in the x and y directions. The amplitude of the horizontal gradient of the regional data of the Hohi area was calculated in the frequency domain and is illustrated in Figure 7. High gradient values were observed around the gravity low of Shishimuta caldera. It is observed that the pattern of the high gradient anomalies is broad, not like sharp ones of ideal vertical boundaries of density contrast. One explanation of this pattern is that the boundaries in the Hohi area are not vertical and relatively deep and/or the anomalies are produced by several boundaries. Grauch and Cordell (1987) discussed the limitations of the horizontal gradient methods for gravity data and concluded that, 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. Figure 8 shows a tentative qualitative interpretation of the horizontal gradient data. Generally, the area may be dissected by major faults striking in the NW-SE, N-S direction. The most interesting result is that the locations of the geothermal fields as well as the hot springs are well correlated with the horizontal gradient anomalies. This indicates that the geothermal areas in Hohi area are structurally controlled, especially for the deep sources. This result is important as a selection of new areas for geothermal exploration can be made based on the horizontal gradient map.
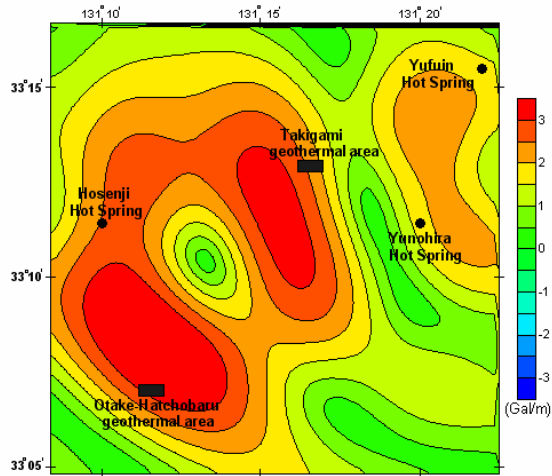

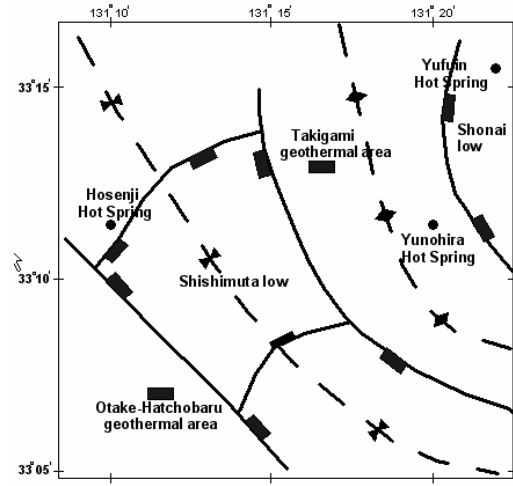**Figure 7: Horizontal gradient of the regional gravity data of the Hohi geothermal area.**

Figure 8: Tentative deep structure interpretation of the Hohi geothermal area.

4.2 Euler Method

3D form of Euler's equation can be defined (Reid, 1990) as

$$x\frac{\partial g}{\partial x}+y\frac{\partial g}{\partial y}+z\frac{\partial g}{\partial z}+\eta g = x_0\frac{\partial g}{\partial x}+y_0\frac{\partial g}{\partial y}+z_0\frac{\partial g}{\partial z}+\eta b \qquad (2)$$

where $\dfrac{\partial g}{\partial x}$, $\dfrac{\partial g}{\partial y}$, and $\dfrac{\partial g}{\partial z}$ are the derivatives of the field in the x, y, and z directions, η is the structural index value that needs to be chosen according to a prior knowledge of the source geometry. By considering four or more neighboring observations at a time (an operated window), source location (x_0, y_0, and z_0) and b can be computed by solving a linear system of equations generated from equation (2). Then by moving the operated window from one location to the next over the anomaly, multiple solutions for the same source are obtained.

The Euler method has been applied to the residual data using a moving window of 2.5 km x 2.5 km. We have assigned several structural index values and found that structural index of (0.5) gives good clustering solutions. Figure 9 shows the results of the Euler method from the residual data. The Euler solutions (Figure 9) indicate that the N-S and E-W trends characterize the shallower structure setting of the Hohi geothermal area. Near the Takigami area, the N-S trend is known as Noine fault zone and is important (Furuya et al., 2000). The vertical displacement of this fault zone is about 1000 m. This result agrees very well with the results of the Euler method, where solutions around this zone are found to be about 750 to 1250 m. The E-W trend is confirmed by surface lineaments (Furuya et al., 2000). Depth solutions associated with this trend are relatively shallower than those associated with the N-S trend.
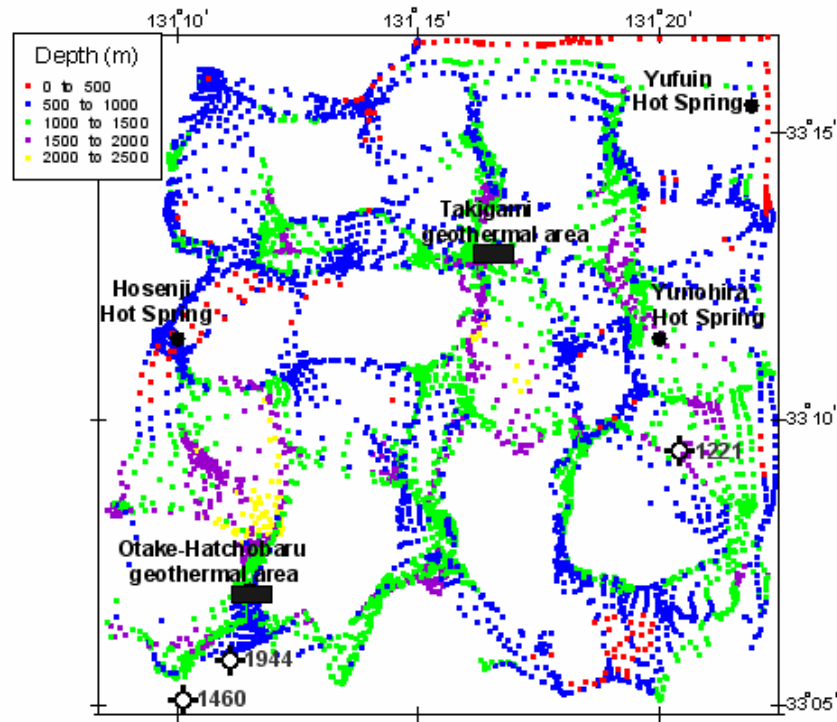
Figure 9: Euler solutions from the residual gravity data of the Hohi geothermal area.

4.3 MODELING

With the help of the available drilling information, we present a conceptual structure model (Figure 10) between Hatchobaru and Takigami fields (location of the model is labeled A-B in Figure 3).

In this model, only two layers were used representing the basement and its overlapping volcanic zone. A uniform density contrast of 0.3 g/cm^3 was used and the model was constrained with the well data of DY-1 and HT-5-1. Interpretation results of the horizontal gradient helped also to get this model in a few numbers of iterations. Generally, the depth to the basement in the south-west and north-west of the Shishimuta caldera is about 1 km. Also the model shows that the maximum depth at the trough of the Shishimuta caldera is about 5.4 km. Kamata and Kodama (1993) proposed a similar structural model in the hohi area. They considered the subsidence of the basement caused by large-scale volcanism and the formation of the half-graben as contributing to the evolution of this regional structure.

It should be stated as we used only two layers with a uniform density contrast, the confidence of the above model is limited. In modeling gravity data in volcanic areas, assumption of a uniform density contrast may lead to depth errors. Thus, the above model just gives an approximate image of the subsurface. More depth and density
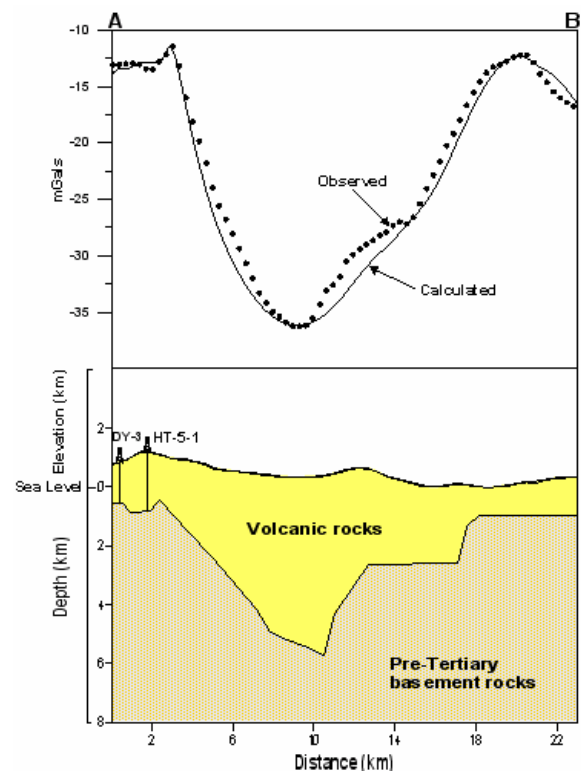

Figure 10: 2D Conceptual structure model based on inversion of the gravity data.

information will help greatly in constructing more accurate model of the subsurface structure of the Hohi area.

5. CONCLUSION

In this paper, we attempted to give a new insight on the structural setting of the Hohi area using existing gravity data. Regional and residual components were separated using the FFT technique. Then horizontal gradient analysis

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was applied to the regional component and residual data were studied using the Euler method. The regional structure setting of the area is characterized by two major faults striking mainly in the NW-SE and N-S direction. Horizontal gradient analysis indicates that the existing geothermal areas in the Hohi area are structurally controlled. As results, the horizontal gradient of the regional field is useful for locating new areas for further geothermal exploration. Results of the Euler method show that the N-S and E-W trends characterize the shallower structure setting of the Hohi area. 2D Modeling of the gravity indicates the depth basement is about 1 km near the border of Shishimuta basin and gets deeper at its trough to reach 5.4 km.

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