Euler deconvolution of gravity data in Geothermal Reconnaissance; the Obama geothermal area, Japan

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ABSTRACT

Obama geothermal area is located on the western side of Kyushu Island, southwestern Japan. This area is characterized by high potential geothermal resources that attract most of researchers to study the subsurface structure of the area. Euler deconvolution is applied to newly acquired gravity data to image the subsurface structures thereby aiding the geothermal exploration. The results were compared with the available geologic and geothermal information in order to get a relationship between structures and geothermal resources. These analyses indicate that the dominant subsurface faults trend E-W, but N-S trending faults also exist. The dominant orientation of these faults provides a geothermal relation between subsurface structures and geothermal resources in the Obama geothermal field.

Key words: Bouguer gravity, Obama geothermal area, Euler deconvolution

1. INTRODUCTION

The Obama geothermal area, Kyushu Island, is one of the most promising geothermal fields in Japan, and therefore study of its structure contributes to a good understanding of the geothermal reservoir characteristics.

Heat discharge from the water is the highest in Japan, 23.72 J/s, which exceeds even 16.88 J/s reported at Beppu Spa (NEDO, 1988). The water flowing out on the seashore was used historically for a hot spring cure during ebb tides. The water quality is classed as hyperthermal common salt. The Obama geothermal field is a dynamic system, and its coastal location allows the incorporation of seawater into the circulating waters (Saibi et al., 2004).

In order to delineate the subsurface structure and its relation to the geothermal reservoir, gravity variations have been used since 2003, as a good economic technique for this area. Two gravity surveys were carried out in the Obama geothermal area in 2003 and 2004 using Scintrex CG-3 and CG-3M gravimeters. The total number of gravity stations is 203 over the survey area covering approximately 4 square km. In addition, Periodic gravity measurements through time provide useful information on the longevity of the geothermal resources (Torge, 1989).

In this paper, we present a new perspective to the

subsurface structural setting at the Obama geothermal area by applying a technique of Euler deconvolution to the available gravity data.

2. GEOLOGIC SETTING

The Obama geothermal field is located in the western part of Kyushu Island, in southwestern Japan (Fig. 1) and exactly on the western foot of Unzen volcano and on the front of Chijiwa Bay. The Obama spa is historically noted for the abundance and high temperature of its hot spring waters. The Obama field could be originated from magmatic emanations derived from a magmatic reservoir, at about 10 km depth beneath Chijiwa Bay (NEDO, 1988).

The Obama geothermal area is located within a volcano-tectonic depression zone, which is controlled by both tectonic and volcanic processes (Tamanyu and Wood, 2003). The Obama area is considered to be in the southwestern part of the larger Beppu-Shimabara graben. Abundant geothermal manifestations discharged at the surface are aligned along the faults and lie at the junction of the Southwest Japan Arc and the Ryukyu Arc, where a Beppu-Shimabara graben has been formed by the rifting tectonic movement that is associated with the subduction of the Philippine Sea Plate beneath the Eurasian Plate (Kamata and Kodama, 1993), or a right-lateral shear zone caused by oblique subduction of the Philippine Sea plate beneath the Kyushu island of Japan

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Fig. 1 Location map of Obama geothermal area, Japan.

Fig. 2 Beppu-Shimabara Graben and regional tectonic. Black triangles indicate active volcanoes.

Fig. 3 Regional structure of Shimabara peninsula (Nakada et al., 2001). σ_1 is the first stress field, σ_2 is the second stress field.

(Tsukuda, 1993). Within that graben, there are many Quaternary volcanoes, including active volcanoes such as Yufu, Tsurumi, Garan, Kuju, Aso and Unzen (east to west), which are accompanied by active geothermal manifestations.

The Beppu-Shimabara graben (Fig. 2) is a large depressional zone crossing the middle Kyushu island from ENE to WSW. The crustal movement around the graben is therefore very active, characterized by the N-S extensional stress field (Tada, 1993).

The Obama graben is in marginal depression zone affected by regional and local stress fields (Fig. 3). The first extensional stress field is in the N-S direction and the second compressional stress field is in the E-W direction (Nakada et al., 2001).

Geologically, the Obama area is composed of Quaternary-Neogene volcanic formations (Fig. 4). The basement rock is composed of Pliocene (Neogene) formations and the sedimentary rock is composed essentially of Quaternary formations. Previous geological studies indicated the existence of faults striking mainly in E-W direction (NEDO, 1988). However, N-S trend could be observed in the area, named Obama fault that bordering western coast of the Obama area (Ōta, 1973).

3. GRAVITY DATA

A gravity network was established in 2003 and 2004 over the Obama geothermal area to monitor the geothermal reservoir. A density of $2,300 \text{ kg/m}^3$ was used to yield the Bouguer anomaly map of the study area as shown in Fig. 5. Visual inspection in Fig. 5, the area is characterized by positive gravity values, covered whole the area, ranging between 11.2 and 13.5 mGal, increasing in the eastern and southern parts of the map area. This could be related to the low gradient in the subsurface structure. The depth to the basement from the drillhole data is 500 m (NEDO, 1988). The observed variations in the anomalies reflect the half graben structure associated with the volcano-tectonic depression

Fig. 4 Geologic map of Obama geothermal area modified from NEDO (1988). The black rectangle indicates the study area corresponding to Figs. 5 through 8.

zone of Shimabara peninsula.

4. EULER DECONVOLUTION

Euler deconvolution is used to estimate depth and location of the gravity source anomalies. The method was established by Thompson (1982) and applied essentially for real magnetic data along profiles. Reid et al. (1990) followed up a suggestion in Thompson's paper and developed the equivalent method operating on gridded magnetic data. The application of Euler deconvolution to gravity data has been carried out by several authors, e.g., Wilsher (1987), Corner and Wilsher (1989), Klingele et al. (1991), Marson and Klingele (1993), Fairhead et al. (1994), and Huang et al. (1995).

Fig. 5 A Bouguer anomaly map of Obama area, contour interval is 0.2 mGal, $\rho=2,300 \text{ kg/m}^3$. The black line indicates the coastline. The black rectangle indicates the area of Figs. 11 (A) and 11 (B).

The 3D equation of Euler deconvolution given by Reid et al. (1990) is:

$$(x-x_0) \frac{\partial g}{\partial x} + (y-y_0) \frac{\partial g}{\partial y} + (z-z_0) \frac{\partial g}{\partial z} = \eta (\beta - g) \quad (1)$$

Equation (1) can be rewritten as:

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

where (x_0, y_0, z_0) are the position of a source whose total gravity is detected at (x, y, z) , β is the regional value of the gravity, and η is the structural index (SI) which can be defined as the rate of attenuation of the anomaly with distance. SI must be chosen according to a prior knowledge of the source geometry. For example, in gravity case, 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 vertical ($\partial g / \partial z$) derivatives (Fig. 6 (A), (B) and (C)) are used to compute the anomaly source locations.

By considering four or more neighboring observations at a time (an operating window), source location (x_0, y_0, z_0) and β can be computed by solving a linear system of equations generated from the equation (2). Then by moving the operating window from one location to the next over the anomaly, multiple solutions for the same source are obtained. In our study, a technique of Euler deconvolution has been applied to the gravity data using

Fig. 6 First derivatives of Gravity: Fig. 6 (A) in x direction, Fig. 6(B) in y direction and Fig. 6(C) in z direction. The black line indicates the coastline.

Fig. 7 Euler solutions for a structural index of zero, 0.1 km $\times$ 0.1 km window and a maximum relative error of 15%. The 16,157 best solutions are shown. Solutions selected using standard criteria. The black line indicates the coastline of Obama.

a moving window of 0.1 km $\times$ 0.1 km (grid spacing is 10 m). We have assigned several structural indices values and found that SI of (0) gives good clustering solutions. Reid et al. (1990; 2003), and Reid (2003) presented a structural index equal to zero for the gravity field for detecting faults. Results of the Euler deconvolution for gravity data are shown in Fig. 7.

Some Euler solutions are located outside the area of gravity measurement (in the bay) (Fig. 7). This phenomenon is due to instability of Euler solution derived from the moving of the window. The solutions can be taken into account in our interpretation, as they show good clustering.

The interpretation of Euler solutions (Fig. 8) indicates that the N-S and E-W trends characterize the shallower structural setting of the Obama geothermal area. The depth of faults ranges between 100 m and 600 m (DF: deep fault). The depth of the Obama fault (OF) is around 200 m and its location agrees with the results of Ōta (1973).

These contacts, interpreted as faults, are plotted and statistically analyzed (Fig. 9).

The rose diagram (Fig. 9) indicates that, there are

four major faults patterns ($N0^{\circ}E$, $N30^{\circ}E$, $N90^{\circ}E$ and $N45^{\circ}W$) characterized the study area; the main direction is $N87^{\circ}E$, which confirm the direction obtained from previous studies in Obama area by Ōta (1973). In general, the regional structure setting of the Obama area is characterized by four major faults striking in E-W, N-S, NE-SW and NW-SE directions.

Fig. 8 Faults interpretation of the Obama geothermal area from Fig. 7. The black line indicates the coastline of Obama.

Fig. 9 Rose diagram of faults of Obama geothermal area. The gray line indicates the vector mean.

Fig. 10 Tectonic model of Shimabara peninsula (Nakada et al., 1995).

Fig. 10 shows the tectonic model of Shimabara peninsula, the N-S stress field is dominant and extensional tectonic feature which generate normal faults striking in E-W direction. The E-W stress field, caused by the subduction of the Philippine Sea Plate, is subdominant compressional tectonic that able to create reverse faults striking N-S direction, especially at the boundaries of Shimabara graben.

5. RELATIONSHIP BETWEEN MARINE GEOTHERMAL ACTIVITY AND STRUCTURES

The Obama geothermal area is divided into two different parts; the northern and southern parts. The northern part has high surface and reservoir temperatures and the southern part has low ones. These results based on the surface temperature of hot springs (Fig. 11 (A)) and the estimated subsurface reservoir temperature from chemistry geothermometers (Na-K-Ca) as shown in Fig. 11 (B) (Saibi et al., 2004). Herein, we want to give a tentative explanation of the geothermal anomaly, by combining surface/reservoir temperature with the location of submarine hot spring (Fig. 12), which might have relation with the Obama spa.

The northern part of Obama might be supplied by submarine hot spring through the deep fault and the

Fig. 11 (A): Surface temperature of Obama hot springs in 2001 (Saibi et al., 2004).

Fig. 11 (B): Isotherms of reservoir temperature of Obama hot springs calculated with Na-K-Ca geothermometer (Saibi et al., 2004).

Fig. 12 Proposed model of generation of Obama hot springs. A gray rectangle indicates the area of Figs. 11 and 12.

southern part of Obama has low temperatures because of the intrusions of sea water through the Obama fault resulting from over-exploitation of thermal water. It is worth noting that the whole system (Obama geothermal area) have a supply from deep heat source (magmatic source) located beneath Unzen volcano (eastern of Obama area and central Shimabara peninsula). The proposed model of generation of Obama hot spring is shown in Fig. 12.

6. CONCLUSION

In this paper, Euler deconvolution of gravity data gives useful information on the subsurface structures of Obama geothermal area, and can be applied to other geothermal areas. The results show a relation between the structural pattern, locations of hot springs, and the temperature of the surface hot springs.

The resulting structural map explains some geothermal anomalies: (1) the high surface and reservoir temperatures of hot springs in the northern part of Obama geothermal area relating to the supply of hot water from the submarine hot spring; (2) the low surface and reservoir temperatures of hot springs in the southern part of Obama geothermal area relating to the intrusion of sea water through the Obama fault.

The results from this work show the importance of

using Euler deconvolution in the analysis of gravity data. It also provides new insights into the structure of the study area. The structural map is a very useful document in the planning of geothermal research to be undertaken in the study area.

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長崎県地熱地域におけるオイラーデコンボリーションを用いた重力データの解析

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要 旨

小浜温泉は、長崎県島原半島西部に位置する高温の食塩泉である。本地域では、過去に大局的な温泉湧出機構モデルが考えられたが、詳細な湧出機構についてはまだ行われていない。この原因の一つとして本地域の詳細な地下構造がまだ把握されていないことが挙げられる。本研究では、小浜温泉とその周辺地域の詳細な基盤構造を把握することを目的として高密度に測定点を配置した重力測定を行った。また、得られたブーゲー異常にオイラー デコンボリーションを適用することにより断層構造の推定も行った。この結果、地質調査から推定されている東西方向の断層のほか、南北方向の断層も存在することが明らかになった。