Magnetic Imaging of Ultramafic Bodies on the Site of the Ohi Nuclear Power Station, Central Japan

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SUMMARY

The Ohi nuclear power station is located at the northern Oshima Peninsula in the Wakasa Bay on the coast of Japan Sea, central Japan. The geology of the site of the power station is composed mainly of shales, diabases, gabbros and ultramafic rocks of the Palaeozoic Yakuno Ophiolite. Ultramafic rock is a key geology since fracture zones in the study area can be found only in the ultramafic bodies.
To map the distribution of ultramafic bodies, we conducted magnetic surveys on ground and at sea around Daibahama beach. A ground magnetic survey was carried out on a grid and along specified lines on a small peninsula and some reefs by using a proton magnetometer. A seaborne magnetic survey was also conducted by a small rubber boat on which a Cesium magnetometer was mounted. Both measured data were merged and IGRF residual magnetic anomalies were reduced onto a smoothed surface at an altitude of 2.5 m above ground and above sea level at sea assuming equivalent anomalies below the observation surface.
3D magnetic imaging has been applied to the magnetic anomalies and the resultant magnetic structure is generally associated with a dipping-dike by a previous 2D modelling. A reversely magnetized body was imaged with a seaward dip below the surface along the 2D profile but has a horizontal limitation. This means the magnetic imaging is helpful to reveal the three-dimensional subsurface structure of the area.

Key words: Ohi nuclear power station, 3D magnetic imaging, magnetization, magnetic anomalies, magnetic survey

INTRODUCTION

The Ohi nuclear power station is located at the northern Oshima Peninsula in the Wakasa Bay on the coast of Japan Sea, central Japan (Figure 1). The geology of the site of the power station is composed mainly of shales, diabases, gabbros and ultramafic rocks of the Palaeozoic Yakuno Ophiolite. An evaluation of the power station on conformity to the new regulatory requirements for nuclear power plants has been conducted. Various surveys such as tectonic geomorphological, trenching and drilling were conducted to better understand the fracture zones in the gabbro and ultramafic complex (Kudo et al, 2016). As a result, the fracture zones can be classified into two types: faults found only in the complex and landslides seen in the upper parts of the ultramafic bodies. Whereas, magnetic susceptibilities were measured for whole cores from drilling and the upper parts of the ultramafic bodies showed high magnetic susceptibilities (> 10^{-2} SI).

SEABORNE AND GROUND MAGNETIC SURVEYS

To map the distribution of ultramafic bodies, we conducted magnetic surveys on ground and at sea around Daibahama beach in December 2015 (Okuma et al., 2016). A ground magnetic survey was carried out on a grid and along a specified line on a small peninsula and some reefs by using a proton magnetometer. A seaborne magnetic survey was also conducted by a small rubber boat on which a Cesium magnetometer was mounted (Photo 1). Both measured data were merged and IGRF residual magnetic anomalies were reduced onto a smoothed surface at an altitude of 2.5 m above ground and above sea level at sea assuming equivalent anomalies below the observation surface (Nakatsuka and Okuma, 2006). Figure 2 indicates total magnetic intensity anomaly map of the study area. According to the map, several positive magnetic anomalies lie over the southeastern edge of the estimated distribution area of

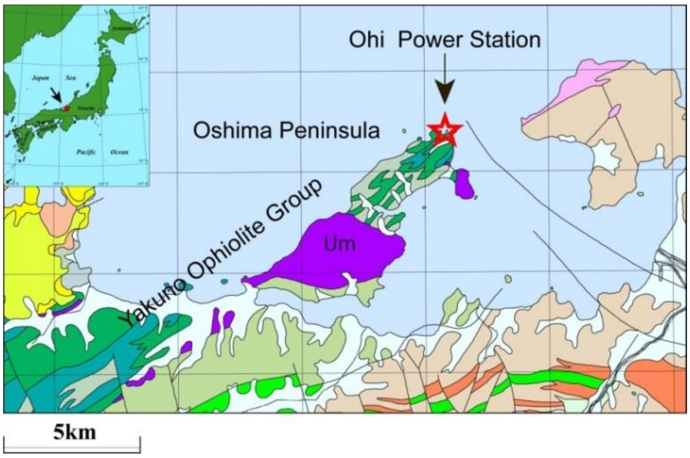

Figure 1 Regional geologic map of the Ohi nuclear power station and it surrounddings (Modified from Wakita et al. (2009)).
U_m means ultramafic rocks. The study area is located at the northeastern edge of the Oshima Peninsula.

Photo 1 Photo of the seaborne magnetic survey in shallow water conducted in Decedmber 2015.
A seaborne magnetic survey was coducted by a small rubber boat on which a Cesium magnetometer was mounted. Trackline paths were recovered by post differential GPS.

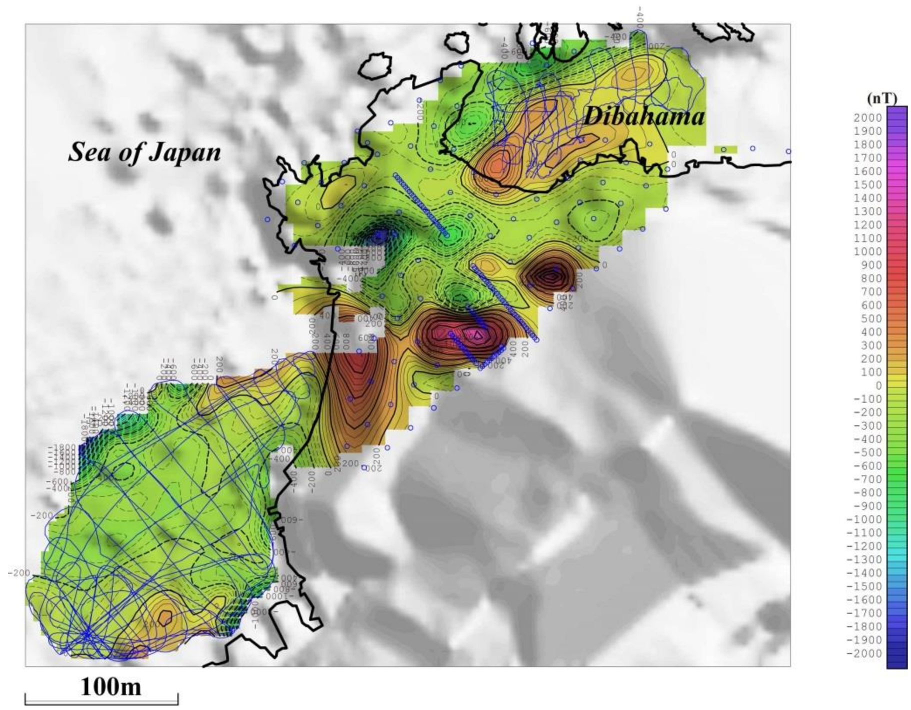

Figure 2 Total magnetic intensity anomalies at an altitude of 2.5 m above ground and above sea level at sea.
The magnetic anomalies were reduced onto the surface by using a method assuming equivalent anomalies below the observation surface (Nakatsuka and Okuma, 2006). Blue open circles and blue solid line indicate magnetic stations on ground and seaborne survey lines at sea, respectively. Topographic shading was superimposed.

ultramafic bodies on land, while negative magnetic anomalies are dominant at the northwestern edge. Magnetic susceptibility and NRM measurements were carried out for columnar specimens sampled from drill cores (Okuma et al., 2016). As a preliminary analysis, we conducted 2D modelling of the specific survey line on a basis of the rock magnetic measurements. A thin dipping-dike with a reverse magnetization can account for the observed magnetic anomalies.

3D IMAGING AND RESULT

In addition to the previous 2D modelling of the specific survey line, we applied 3D magnetic imaging (Nakatsuka and Okuma, 2014) to the magnetic anomalies on the smoothed surface at an altitude of 2.5 m above ground and above sea level at sea.

Using a vector/matrix notation, the magnetic anomaly $\boldsymbol{f}$ at an observation point is expressed as follows:

$$\boldsymbol{f} = \boldsymbol{A}\boldsymbol{s} \qquad (1)$$

where $\boldsymbol{f}$ is the magnetic anomaly, $\boldsymbol{A}$ is a geometric factor, and $\boldsymbol{s}$ is magnetization of the source.

In order to regularize a simple CG method, a penalty term can be added in the minimizing function as:

$$(\boldsymbol{f} - \boldsymbol{As})^{\mathrm{T}} (\boldsymbol{f} - \boldsymbol{As}) + e\, (\boldsymbol{Bs})^{\mathrm{T}} (\boldsymbol{Bs}) \rightarrow \mathrm{Min} \qquad (2)$$

where $\boldsymbol{B}$ is the penalizing operator matrix, and e is a trade-off parameter (so-called hyper-parameter) to adjust the penalizing weight ratio between the former misfit term $(\boldsymbol{f} - \boldsymbol{As})^{\mathrm{T}} (\boldsymbol{f} - \boldsymbol{As})$ and the latter regularization term $R=(\boldsymbol{Bs})^{\mathrm{T}} (\boldsymbol{Bs})$ in (2).

In the case of a model composed of variable volume bodies, the penalizing operator and the regularizing factor should be

$$\boldsymbol{B} = \mathrm{diag}\left\{ \sqrt{\frac{v_i}{s_i^2 + \delta^2}} \right\} \qquad (3)$$

$$R = (\boldsymbol{Bs})^{\mathrm{T}} (\boldsymbol{Bs}) = \sum_i \frac{v_i \cdot s_i^2}{s_i^2 + \delta^2} \qquad (4)$$

where v_i is volume of the i-th body, and δ is critical value of magnetization.
We call the method above 3D magnetic imaging with effective source volume minimization.

We applied 3D magnetic imaging to the observed total magnetic intensity anomalies, allowing 3D variations of the magnetization intensity. The magnetic model with a flat bottom is composed of magnetic layers with a constant thicknesses varying from 10 m to 25 m, except the uppermost one, and each layer consists of an ensemble of prism models with a horizontal dimension of 5 m by 5 m. The bottom depth of the magnetic structure was assumed to be 100 m below the sea level.
Various calculations could be conducted through changing options and parameters of the imaging method. For simplicity, we, first, adopted the minimum norm inversion of CG method with automatic scaling as well as taking account of variations of a thickness of each magnetic layer. The iterative procedure of the imaging method was started using a uniform magnetization of -0.91 A/m as the initial starting value, which was derived from the average terrain magnetization. δ was set to be 0.3 A/m. It was terminated when the rms of residuals of the observed and calculated field were 2.3 nT. Figure 3 shows depth slices of the 3D imaging.
Figure 3 indicates that magnetization highs are distributed at the southeastern edge of the survey area, where ultramafic rocks are present at a shallow depth, which confirmed by drilling. Other magnetization highs extend in a direction of NE in shallow water area at the Daibahama beach, suggesting subsurface existence of ultramafic rocks. At the northwestern edge of the survey area, a reversely magnetized body was imaged with a seaward dip below the surface along the 2D profile but has a horizontal limitation.
According to rock magnetic measurements of core samples in the study area, NRM of some samples shows reverse magnetization, supporting the result of imaging.
Then, we applied 3D magnetic imaging with effective source volume minimization to the magnetic anomalies. The more condensed distribution of magnetization has been obtained. We have to compare the results of this imaging with other geological information to clarify if the distribution is too emphasized.

CONCLUSIONS

We applied 3D magnetic imaging to the magnetic anomalies in the Ohi nuclear power station to better understand three-dimensional subsurface structure. The estimation on subsurface distribution of ultramafic rocks is focused since fracture zones in the study area can be found only in the ultramafic bodies. The resultant magnetic structure is generally associated with a dipping-dike by a previous 2D modelling. A reversely magnetized body was imaged with a seaward dip below the surface along the 2D profile but has a horizontal limitation. This means the magnetic imaging is helpful to reveal the three-dimensional subsurface structure of the study area.

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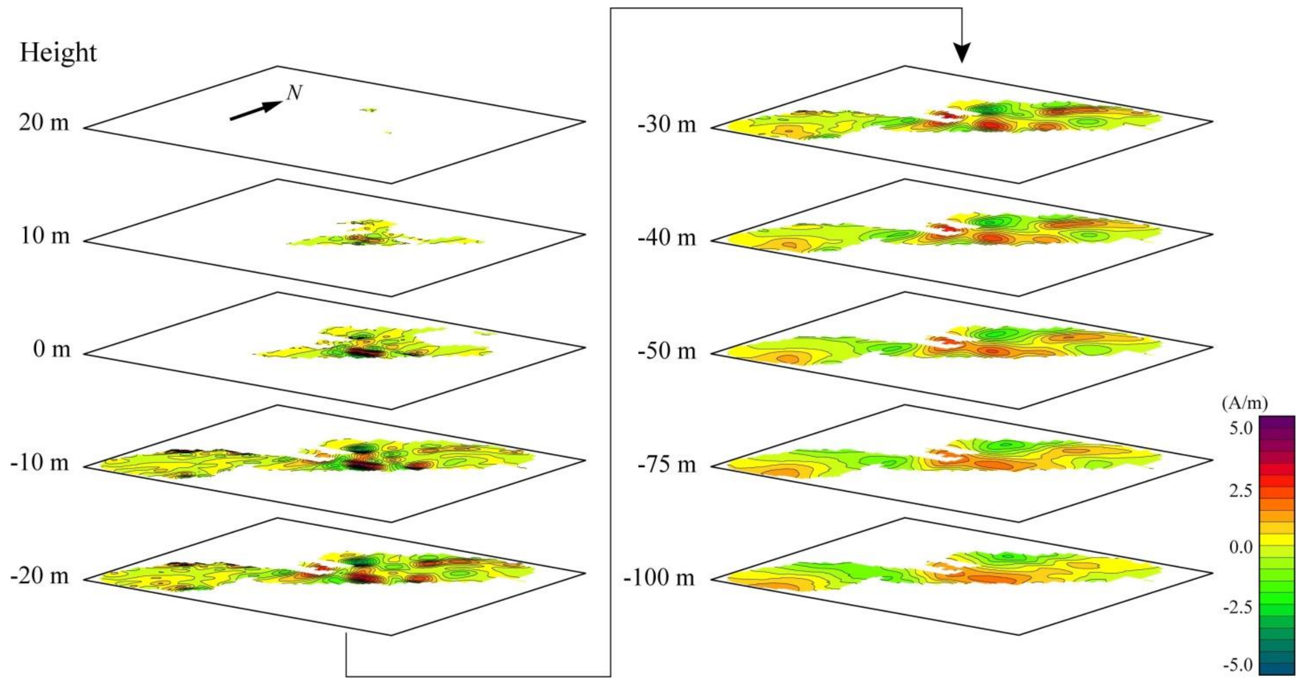

Figure 3 Depth slices of the result of 3D magnetic imaging of the study area. Minimum norm inversion of CG method was adoped with automatic scaling as well as taking account of variations of a thickness of each magnetic layer. The depths in the map represent the bottom depths of each layer. The magnetic model with a flat bottom is composed of 10 magnetic layers with a constant thickness from 10 m to 25 m for all layers except the uppermost one, and each layer consists of an ensemble of prism models with a horizontal dimension of 5 m by 5 m.

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