MODELING A 3-D SUBSURFACE STRUCTURE AROUND DAMAGED AREA DUE TO THE RECENT EARTHQUAKES IN NIIGATA, JAPAN USING GRAVITY SURVEY

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ABSTRACT:

Many active foldings are found and it is known that the subsurface structure is complex in the Niigata-ken Chuetsu area, Japan, where two destructive earthquakes were occurred on 2004 and 2007. In a case where we want to simulate the earthquake ground motions during the main shock in this area, detailed information is required with respect to the subsurface structure. This kind of information, however, is not provided enough in this time. We, thus, carried out the gravity survey around Chuetsu area at 517 sites and estimate a 3-D shape of the upper boundary for the gravity basement. For this, we develop a new technique to estimate the 3-D structure of ground with some different densities. Applying the technique, we obtain a model of subsurface structure. Through the comparison of the proposed model and the results from some previous researches, we can conclude that the proposed model provides more accurate and detailed information than previous ones.

KEYWORDS: gravity survey, subsurface structure, bedrock, Niigata, Moving Window Poisson (MWP) analysis

1. INTRODUCTION

Characteristics of strong motion are affected by 3-D subsurface structure. Thus, it is important to estimate the subsurface structure in order to consider the earthquake disaster and its mitigation. Many researchers have applied various geophysical survey techniques to estimate ground structures, such as seismic refraction and reflection, microtremor, gravity, magnetic surveys, and so on. The gravity survey, especially, is useful to estimate the structure of large area with appropriate accuracy.

The analysis of the bedrock structure based on the gravity survey requires some assumptions to obtain a stable solutions, because there are many unknown parameters and trade-offs among the parameters. Thus, usually, we assume a two-layered medium with homogeneous density. This type of structure can explain the many of observed gravity data and agree with different type of information such as borehole data. We, however, have a few cases where we cannot explain physical phenomena using such simple model; for example, a medium which has a vertical boundary of density in media.

To solve the above problems, Chandler *et al.* (1981) have proposed a technique to detect vertical boundaries, which are called Moving Window Poisson analysis (MWP) method. They combined the first vertical derivative of the gravity anomaly with total field magnetic intensity anomaly reduced to the pole. They, furthermore, discussed quantitatively the relationships between the structural boundary and the properties of the anomalies through some model studies.

Since their analytical model has less reality of the ground structure, we consider more realistic model and discuss the applicability of the MWP method to real structures. We point out some problems of Chandler's MWP method (Chandler *et al.*, 1981). To solve these problems, we have developed a new technique to detect a vertical boundary of ground, media with different densities, using gravity and magnetism simultaneously. We, furthermore, extend

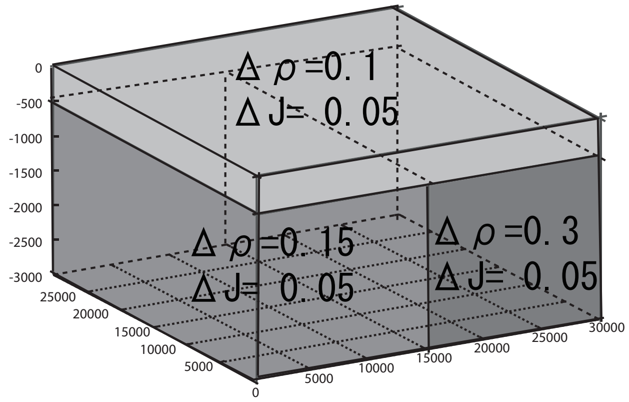


Figure 1 A model of ground.

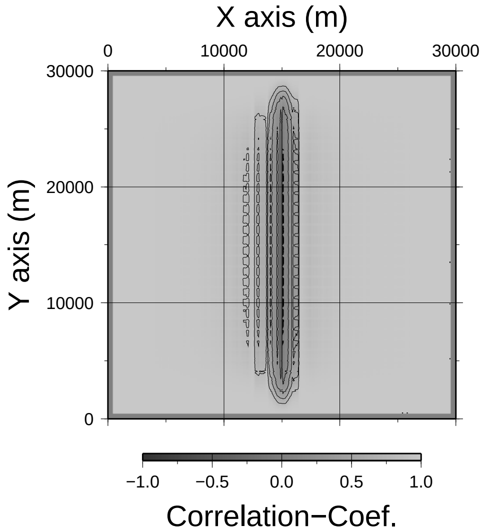


Figure 2 Distribution of correlation coefficients between gravity and magnetic anomaly.

a method, which estimates a 3-dimensional density structure by means of an inversion technique, to obtain a multi-layered ground model with more than two different densities using the vertical boundaries obtained from the proposed method. These methods are applied to data observed in Niigata-ken Chuetsu region, Japan.

2. MWP METHOD AND ITS REFINEMENTS

Poisson's equation provides liner relationship between gravity and magnetic potential as

$$\phi_M = \frac{\Delta J}{G\Delta\rho}\frac{\partial \phi_g}{\partial i}, \tag{1}$$

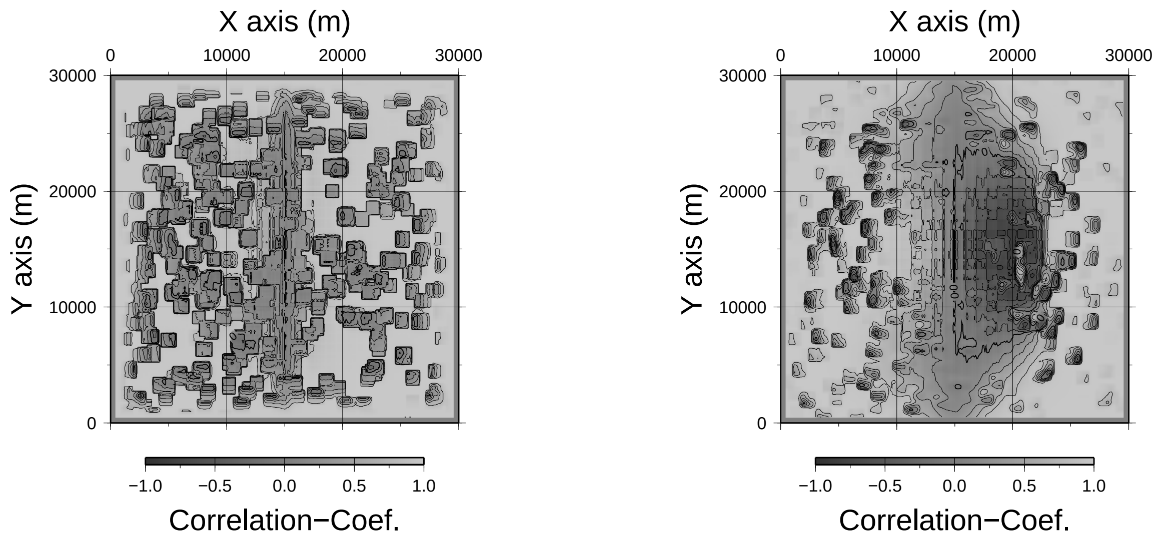
where ϕ_M and ϕ_g stand for magnetic and gravity potentials, respectively, G for universal gravitational constant, ΔJ for magnetization of dominant source, $\Delta\rho$ for density contrast of the dominant source, and $\partial/\partial i$ denotes gradient with respect to a magnetized direction (Garland, 1951). Chandler et al. (1981) have differentiate Equation (1) with respect to the vertically downward direction and extended it to include a trend component by local anomaly as

$$T_z \quad = \quad A + \frac{\Delta J}{G\Delta\rho}\frac{dg}{dz}, \tag{2}$$

where T_z stands for total magnetic intensity anomaly reduced to vertical polarization, dg/dz for the first vertical derivative of the gravity anomaly, and A for an intercept parameter that reflects regional properties in apparent base levels due to anomaly interference.

Three unknown parameters can be determined from the linear regression of observed data, which are T_z and dg/dz, applying the least squared method to Equation (2): the slope corresponds to $\Delta J/\Delta\rho$, intercept to A, and correlation coefficient between T_z and dg/dz. For the linear regression, the observed data are limited in a spatial window function and analyzed inside the small window. Then, the window can be moved over the target area and we can analyze the coherency between T_z and dg/dz for each small windowed area. Chandler *et al.* pointed out that these three parameters fluctuate spatially in a case where the medium includes density contrast. This means that we can find location of density contrast to calculate the correlation between T_z and dg/dz. Chandler *et al.* (1981) called this technique "moving window Poisson (MWP) analysis method."

To verify applicability of the MWP method, some simple numerical calculations are carried out using more realistic models than Chandler's models. An assumed ground model is shown in Figure 1. The gravity and magnetic anomalies are calculated analytically at grid points of 100 x 100 m on the surface (Komazawa, 1995 and Kato,



(a) for Equation (2) (b) for integral of Equation (2)

Figure 3 Distribution of correlation coefficients between gravity and magnetic anomaly.

1987), and they are used as observed data. Applying the MWP method to the pseudo-observation data and the correlation coefficients between T_z and dg/dz are obtained under 1 x 1 km spatial windows as shown in Figure 2. From this figure, we can recognize the location of the density contrast where the center of the ground model.

For the ground in real world, however, the material of the ground is not homogeneous and includes many various anomalies. Thus, we set many small anomalies randomly in the sediment of Figure 1. In this case, the correlation coefficients are shown as Figure 3 (a). It is noted that the fluctuations of the correlation coefficients are shown not only at the location of density contrast but also at the locations of the small and random anomalies. It is very difficult to find appropriately the location of the density contrast from Figure 3 (a).

Through the above numerical studies, we found that to recognize a vertical boundary using MWP method is difficult in a case where there are many anomalous sources in the sediment. This comes from the high sensitivity of MWP method to the anomalies. To avoid this difficulty, we consider the relationships between the pseudo gravity anomaly and the gravity anomaly, which is called Method B hereafter, instead of the vertical derivative of the gravity anomaly and total field magnetic intensity anomaly reduced to the pole. The Method B treats the correlation coefficients between the integrals of T_z and dg/dz.

The results of the Method B is shown in Figure 3 (b) for the same ground model of Figure 3 (a). Although Method B can find roughly position of the vertical boundary, it is very difficult to point out its exact position. This is caused by a less sensitivity of Method B to the anomaly of the medium.

Then, we propose a new method to use simultaneously the both Chandler's method and Method B: we pick up area with high correlation coefficients for both Chandler's method and Method B, in which we use -0.5 to 0.5 for the range of high correlation in this study. Using this new method, which is called "modified MWP (MMWP) method," we can detect a vertical boundary exactly with less ambiguity. Applying MMWP method to the pseudo-observation data obtained numerically from the ground model including random anomalies in the sediment, the vertical boundary of the media is found as shown in Figure 4.

3. ESTIMATION OF GROUND STRUCTURE WITH THREE DIFFERENT DENSITIES

Komazawa (1995) has proposed a technique to estimate a 3-dimensional density structure with two-layered media, which consist of sediment and basement, using an inversion technique. We extend this method to multi-layered media with known density boundaries. To consider the boundary, we set some control points, whose depth should be 0 m at the outside of a target medium. The location of the control points depends on the information on the

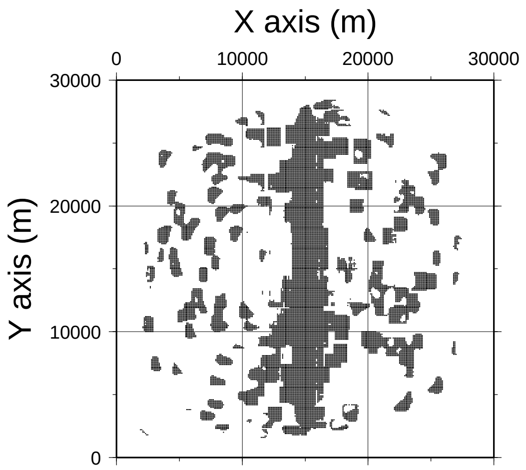


Figure 4 The location of estimated structural boundaries.

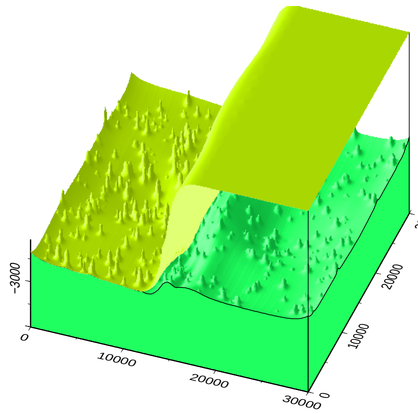


Figure 5 Estimated model of Figure 1 using the proposed method. The yellow and green surfaces are lower surfaces of the media with $\Delta\rho = 0.15$ and $\Delta\rho = 0.3$, respectively.

shape of the boundary. Furthermore, to obtain a realistic model of gravity basement, we consider constraint with respect to depth to the bedrock. For this, some other control points are given.

Using these control points, firstly, the initial model for the depth of lower surface of m-th medium, $H_{m,1}$ is determined and gravity anomaly $g_{m,n}$ is calculated analytically on the basis of $H_{m,1}$. Secondly, the n-th step model of the surface, $H_{m,n}$ is modified to (n+1)-th model $H_{m,n+1}$ using the following equations:

$$D_{m,n} = H_{m-1,n} - H_{m,n}, \tag{3}$$

$$\rho_{adv} = \frac{\sum^M D_{m,n}^2 \rho_m}{\sum^M D_{m,n}^2}, \tag{4}$$

$$H_{m,n+1} = H_{m,n} + \left(g^{res} - \sum^M g_{m,n} \right) \cdot \frac{\sum^m D_{m,n}^2}{\rho_{adv} \sum^M D_{m,n}^2}, \tag{5}$$

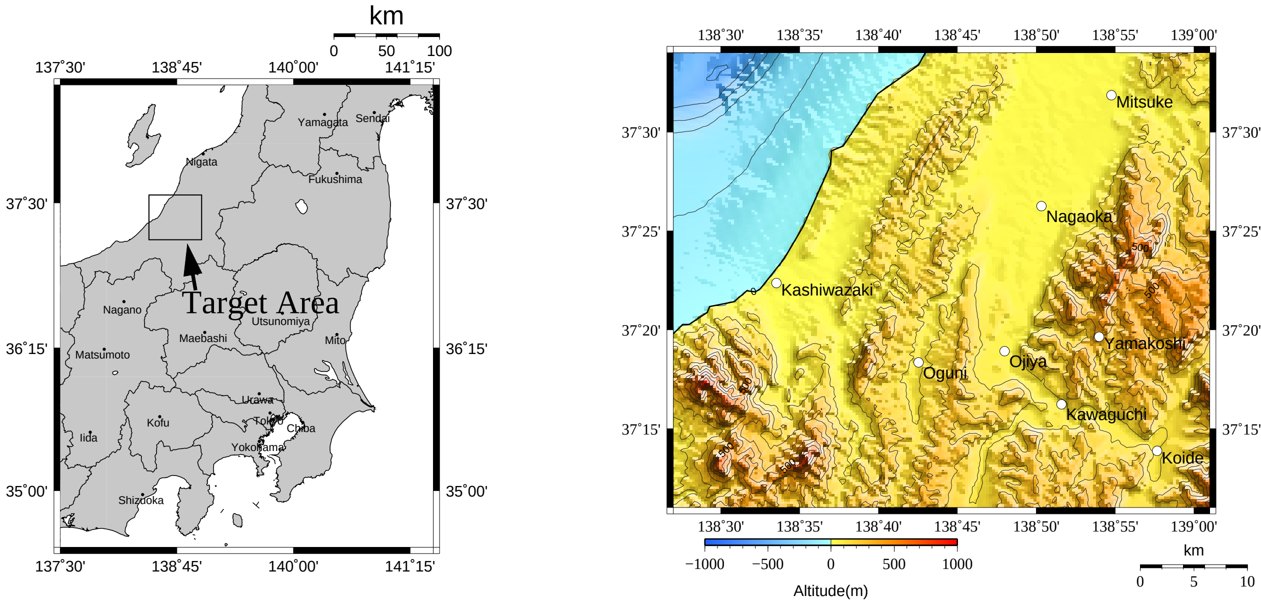
where $D_{m,n}$ is thickness of the m-th medium, ρ_m density contrast of m-th medium, $g_{m,n}$ gravity anomaly obtained analytically from the model $H_{m,n}$, and g^{res} gravity anomaly obtained after applying band-pass filter. In the following calculations, we apply the band-pass filter between 50 to 6000 m to the observed gravity data. The value of gravity anomaly is calculated analytically from (n+1)-th model $H_{m,n+1}$ and the $H_{m,n+1}$ is updated by using obtained anomaly. To reduce the difference between analytical and observed gravity anomaly, the iteration is performed five times. Using this procedure, the ground model for Figure 1, which include the small random anomalies, is estimated as shown in Figure 5. Although we can see small fluctuations of the boundaries of different media which come from the random anomalies, it is observed that the obtained model agrees with the given one.

4. APPLICATION AND DISCUSSIONS

We applied the proposed method to gravity and magnetic data observed around Niigata-ken Chuetsu region, Japan, where we can use the dense data of gravity and magnetism, and tried to find some possible boundaries in this area.

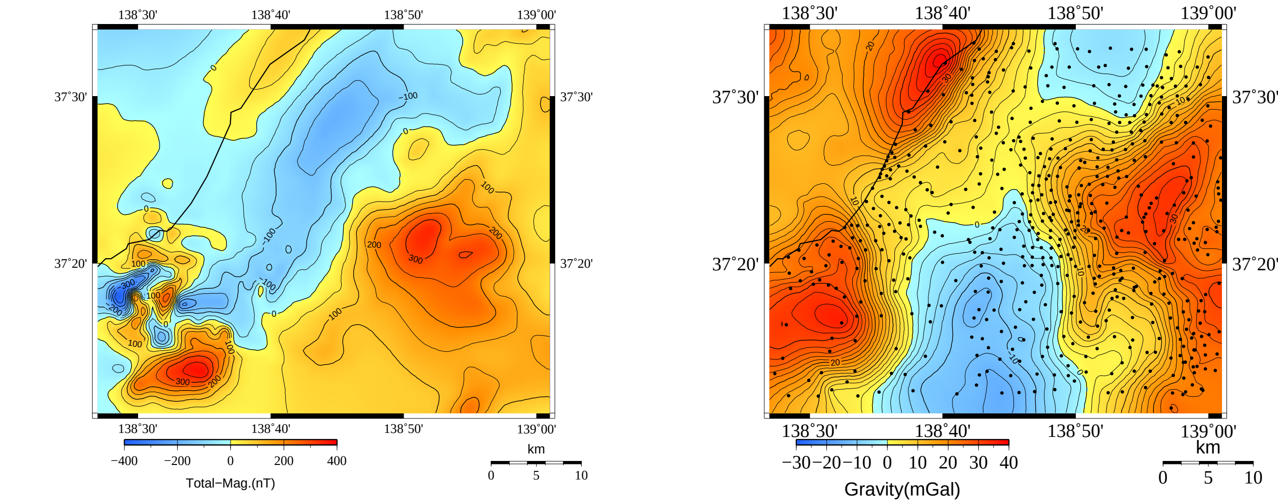
The target area is located in 37°11'N to 37°34'N and 138°27'E to 139°01'E: 52km EW × 45km NS. Thus, the area includes Nagaoka, Ojiya, Kashiwazaki and a part of Uonuma. The location of the target area and the topographical map are shown in Figure 6.

We use the magnetism data from CD-ROM published by Geological Survey of Japan (Geological Survey of Japan, 2005).



(a) Location of the target area (b) Topographical map of the target area

Figure 6 Location and topography of the target area.

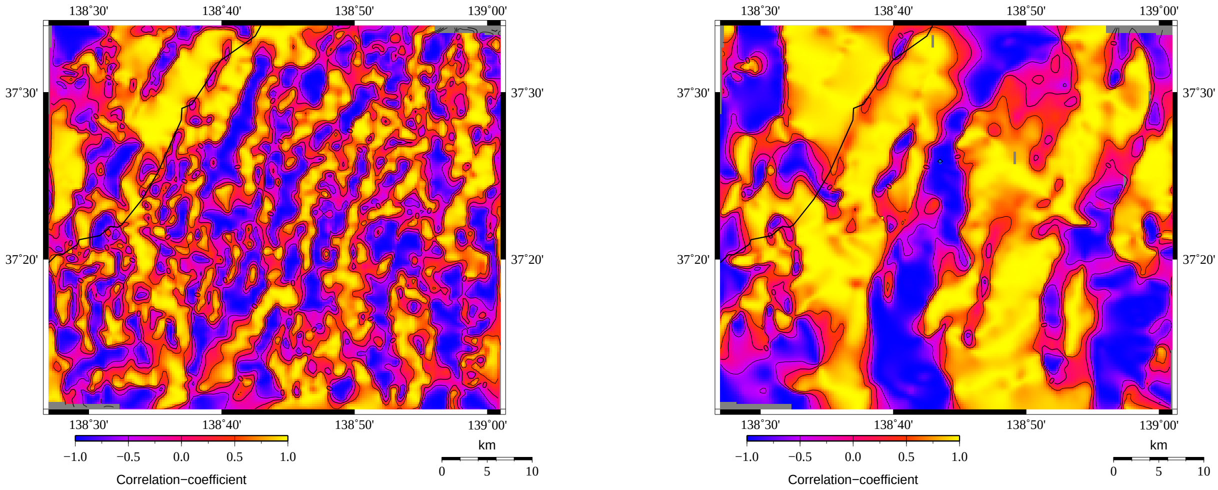


(a) Total magnetic anomaly (contour interval: 50 nT) (b) Bouguer anomaly (contour interval: 2 mGal)

Figure 7 Anomaly maps of magnetic and gravity.

The gravity survey has been carried out in this area (Takahashi *et al.*, 2007). The observation sites of gravity with 2km intervals were set and some part was filled by 1km intervals. We spent 47 days for the observation during June to November, 2005 and July 2007, and we obtained gravity values at 517 sites. We used Automated Burris Gravity Meter made from ZLS Corp., automatic gravimeter CG-3M from Scintrex, and LaCoste & Romberg Gravimeter model G from Micro-g LaCoste Inc. for the survey. Positions of the observation sites were determined by the differential survey of GPS with errors less than 1m in vertical and horizontal distances.

On the basis of some methods, the assumed density is determined as 2.40 t/m^3. After some corrections of the gravity data such as the terrain correction, the Bouguer anomaly map is estimated. The obtained anomalies of the magnetic and gravity are shown in Figure 7. Small dots in Figure 7 (b) show the observation sites of the gravity. Applying the conventional MWP method and Method B to anomaly maps, correlation coefficients for Equation (2) and its integrals are obtained as shown in Figure 8.



(a) from conventional MWP method (b) from Method B

Figure 8 Distribution of correlation coefficient obtained from conventional MWP method and Method B (contour interval: 0.5).

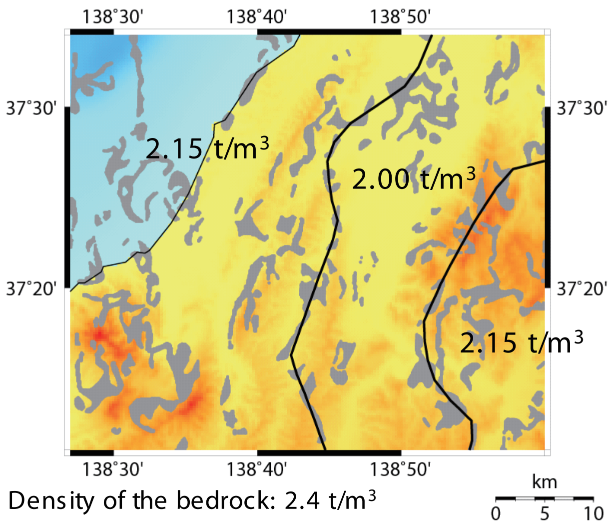


Figure 9 Structural boundaries in the target area.

Using the MMWP method, the location of the boundary of the media is shown as grayish areas in Figure 9. From this figure, the mountainous area in the south-western part of target area is picked out as vertical boundaries because of its complicated structure which consists of sediment and volcanic rock. Furthermore, the mountainous area in the central and eastern parts of target area are also detected. These areas seem to correspond to the boundaries between the formation of the late and early Pliocene from surface geological map.

Considering the geological conditions, the location of vertical boundaries of the media are decided as the solid lines of Figure 9. Densities of the sediment are determined 2.15 t/m^3 in the western and eastern areas and 2.0 t/m^3 in the central area, and 2.4 t/m^3 for the bedrock. Using these boundaries as constraints of the inversion to estimate the ground structure, we obtain the a 3-D shape of the bedrock structure as shown in Figure 10.

To discuss proposed model about the validity, we compare proposed model with the borehole, microtremor array data, and other previously proposed model (Takahashi *et al.*, 2007), which is obtained under an assumption that the ground consists of two layers: bedrock and sediment, their densities are used as 2.4 t/m^3 and 2.0 t/m^3, respectively, that are homogeneous media. The model by Takahashi *et al.* (2007) is shown in Figure 11.

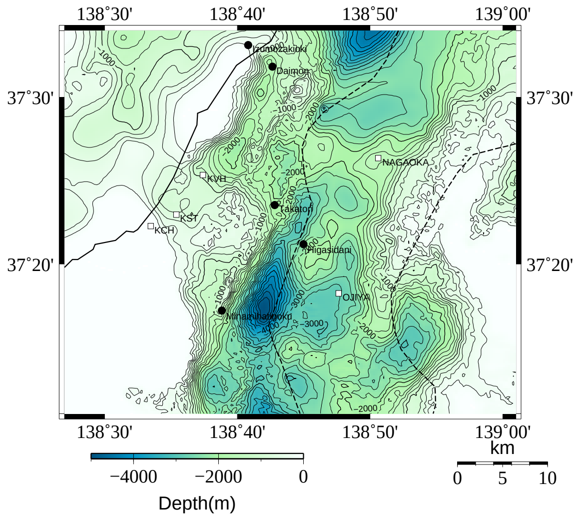


Figure 10 An estimated model of depth to the bedrock in this study.

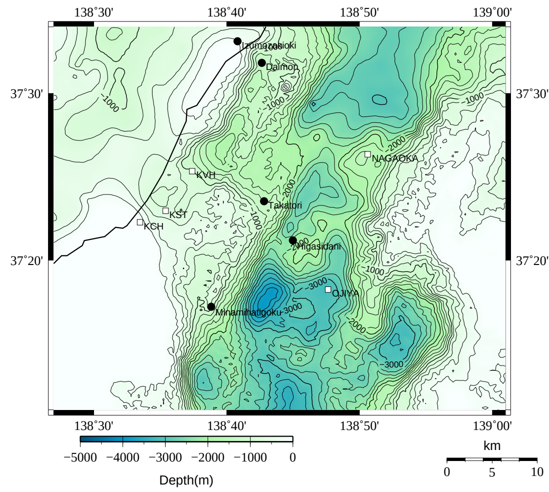


Figure 11 A model proposed previously by Takahashi *et al.* (2007).

We list depth to the bedrock at some borehole and microtremor array sites in Table 1 (Japan National Oil Corp., 1970, 1997, 1999; Kobayashi *et al.*, 1986, 1989, 1991, 1995; Yamanaka *et al.*, 2006; Yanagisawa *et al.*, 1986; Goto *et al.*, 2007). The listed sites are shown in Figures 10 and 11 as closed circles for borehole sites and open squares for microtremor array sites. From this table, it is observed that the model proposed in this study provides generally better results than the model obtained by Takahashi *et al.* (2007).

5. CONCLUSIONS

We have developed a new technique to estimate a vertical boundary of density of ground using gravity and magnetism simultaneously, in which this technique is named “Modified Moving Window Poisson (MMWP) method.” Furthermore, an inversion method to estimate a 3-D density structure with multi-layered media is developed.

Table 1 Comparison estimated depth to the bedrock between Figures 10 and 11 at some borehole and microtremor array sites

Site Name	Latitude	Longitude	Depth [m]		
			Borehole or Microtremor	Figure 10	Figure 11
Borehole sites					
Minamihatigoku	37°17′11″	138°38′51″	> 2300	1256	917
Izumozakioki	37°33′08″	138°40′50″	51.8	277	205
Daimon	37°31′50″	138°42′40″	> 2000	1686	1292
Higasidani	37°21′11″	138°45′00″	2588	2192	2116
Takatori	37°23′32″	138°42′50″	> 2000	2018	1437
Microtremor array sites					
OJIYA	37°30′21″	138°44′33″	2500	2820	3128
NAGAOKA	37°30′21″	138°44′33″	2700	1514	1571
KCH	37°22′	138°34′	1685	1	83
KST	37°23′	138°35′	1575	788	754
KVH	37°25′	138°37	1945	1095	996

Applicability of the MMWP method and the proposed inversion method is confirmed through some numerical examples. These methods are applied to data observed in Niigata-ken Chuetsu region, Japan and some remarkable density boundaries are detected. The obtained boundaries agree with the known surface geology. Moreover, a model of 3-D bedrock structure with three different densities is estimated using the information about the density boundaries. The model satisfies existent information obtained from boreholes and microtremor array observations.

REFERENCES

Chandler, V.W., Koski, J.S., Hinze W.J., and Braile, L.W. (1981). Analysis of multisource gravity and magnetic anomaly data sets by moving-window application of Poisson's theorem, *Geophysics*, **46:1**, 30–39.

Garland, G.D. (1951). Combined analysis of gravity and magnetic anomalies, *Geophysics*, **16**, 51–62.

Geological Survey of Japan (2005). Aeromagnetic Database of Japan, Advanced Industrial Science and Technology, CD-ROM.

Goto, H., Miyakoshi, K., Ling, S.-Q., Sawada, S., Ishii, Y., Takabatake, D., Sato, Y., and Shingaku, Y. (2007). S-wave velocity structures on Kashiwazaki city estimated from the microtremor array observations, *Programme and Abstracts, The Seismological Society of Japan, 2007 Fall Meeting*, P1-099 (in Japanese).

Japan National Oil Corp. (1970). The Report of Borehole Mahito (in Japanese).

Japan National Oil Corp. (1997). The Report of Borehole Oguni (in Japanese).

Japan National Oil Corp. (1999). The Report of Borehole Higasiyama (in Japanese).

Kato, M. (1987). Theory of 2-D filter and analysis for gravity and magnetic data, Latice, Japan (in Japanese).

Kobayashi, I., Tateishi, M., and Uemura, T. (1986). Geology of the Izumozaki district, Geological Survey of Japan (in Japanese).

Kobayashi, I., Tateishi, M., Kurokawa, K., Yoshimura, T., and Kato, H. (1989). Geology of the Okanomachi district, Geological Survey of Japan (in Japanese).

Kobayashi, I., Tateishi, M., Yoshioka, T., and Shimazu, M. (1991). Geology of the Nagaoka district, Geological Survey of Japan (in Japanese).

Kobayashi, I., Tateishi, M., Yoshimura, N., Ueda, T. and Kato, H. (1995). Geology of the Kashiwazaki, Geological Survey of Japan (in Japanese).

Komazawa, M. (1995). Gravimetric analysis of Aso Volcano and its interpretation, *J. Geod. Soc. Japan*, **41**, 17–45.

Takahashi, C., Suzuki, Y., Akamatsu, J., and Morikawa, H. (2007). Estimation of 3D shape of the gravity bedrock structure around damaged areas by the 2007, Niigata-ken Chuetsu-oki Earthquake, *Programme and Abstracts, The Seismological Society of Japan, 2007 Fall Meeting*, P1-101 (in Japanese).

Yamanaka, H., Motoki, K., Seo, K., Fukumoto, S., Takahashi,T., Yamada, N., Asano, K., and Iwata, T. (2006). Observation of aftershocks and micro tremors in damage areas of the 2004 Mid Niigata Prefecture earthquake, *Earth extra*, **53**, 172–177 (in Japanese).

Yanagisawa, Y., Kobayashi, I., Takeuchi, K., Tateishi, M., Chihara, K., and Kato, H. (1986). Geology of the Ojiya district, Geological Survey of Japan (in Japanese).