Gravity anomalies and the geologic block structures in and around the aftershock area of the 2007 Noto Hanto Earthquake

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The 2007 Noto Hanto Earthquake occurred on 25 March. We have constructed a detailed gravity anomaly map over the Noto peninsula. Four block boundaries which are identified by morphological/geological studies are also recognized on the gravity anomaly map. Various other observations indicate that the mainshock ruptured only one of the blocks, the Kuwatsuka block, although aftershocks are distributed over two blocks, the Kuwatsuka and the Saruyama blocks. The Bouguer anomalies over the Kuwatsuka block are relatively high compared to those of the Saruyama block, i.e. the basement depth of the Kuwatsuka block is shallower than that of the Saruyama block. This difference in the basement depth is consistent with the deformation pattern observed by SAR interferometry. At the block boundary, an offset is recognized in the aftershock distribution. Based on the relationships among the gravity anomalies, the geologic structures, the aftershock distribution and the source fault, we propose that the rupture size of the earthquake was constrained by the block structure in this region.
Key words: Gravity anomaly, the 2007 Noto Hanto Earthquake, geologic block structure.

1. Introduction

The 2007 Noto Hanto (Noto Peninsula) Earthquake (M_{JMA} 6.9) occurred on 9:41, 25 March 2007. The reported focal mechanism was thrust with a right lateral slip component (Hoshiba, 2007). Seismic intensities over 6 (JMA scale) were observed around the source region, and several hundred houses were damaged. During the earthquake, one person was killed. The Noto peninsula is not a very seismically active region. This is the first M 6 class earthquake since 1993, which occurred off the north coast of Suzu city (M_{JMA} 6.6).

Katagawa *et al.* (2005) reported the acoustic stratigraphy in the Japan Sea off the west coast of the Noto peninsula obtained by single-channel seismic exploration. From the aftershock distribution, ERI (2007) proposed that the fault plane of this earthquake seems to be on a downward extension of the faults F14 and F15 reported in Katagawa *et al.* (2005).

We have compiled all of the gravity data available over the Noto peninsula (Kono *et al.*, in preparation). Here, we discuss the relationships among the gravity anomalies, geologic structures, aftershock distribution and the source fault.

2. Gravity Data

On the land area, many institutes have obtained gravity data in and around the aftershock area. We have compiled gravity data obtained by Kanazawa University (Kono and Furuse, 1989), Hokuriku Electric Co. Ltd. (unreleased), Geographical Survey Institute of Japan (GSI, 2002), Geological Survey of Japan (GSJ, 2000), Gravity Research Group for Southwestern Japan (The Gravity Research Group in Southwest Japan, 2001), our detailed observation data (Kono *et al.*, 2006) and the satellite altimetry and ship depth soundings (Smith and Sandwell, 1997). The total number of compiled data points is over 13,000 in the research area (Fig. 1). They are spaced approximately one every 2 km^2 on the land area. We show the distribution of the gravity stations in Fig. 2. Compiling all these data, we constructed a detailed Bouguer anomaly map of the Noto peninsula (Fig. 3). Many other interesting features of the Bouguer anomalies over the Noto peninsula will be described in another manuscript (Kono *et al.*, in preparation).

All of the compiled data were recalculated using the calculation routine developed by Kanazawa University (Kono and Furuse, 1989). A terrain correction using a 50-m DEM (Honda and Kono, 2005) was then adopted, assuming a density of 2,670 kg/m^3 in the calculation.

3. Geological Background

The geology of the Noto peninsula is characterized by large density contrast between Pre-Tertiary basement rocks and Tertiary formations. The basement rocks are composed of Hida Metamorphic rocks and Funatsu Granitic rocks. These basement rocks outcrop widely around the Mt. Hodatsu and Sekidoh mountainous regions (Kaseno, 1993). Some basement outcrops are also found in the source re-
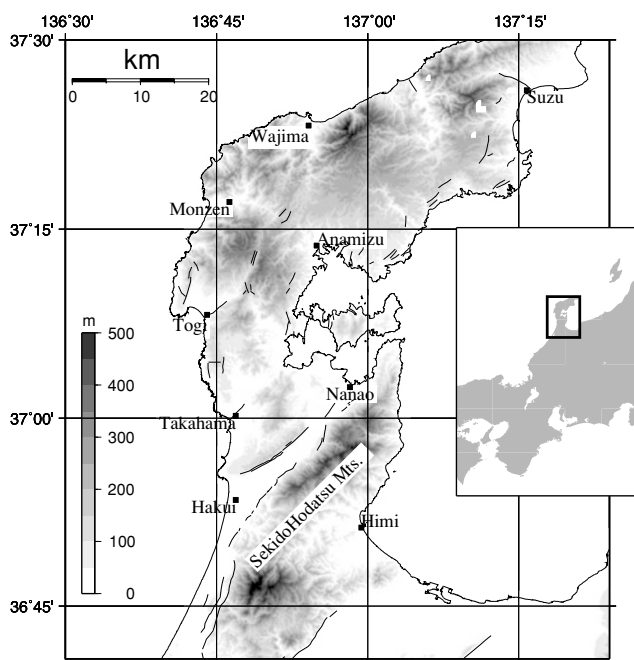
Fig. 1.   Topography of the Noto Peninsula. Solid squares indicate the location of major towns, the names of which are described beside. Active faults (Active Fault Research Group, 1991) are indicated with black lines.
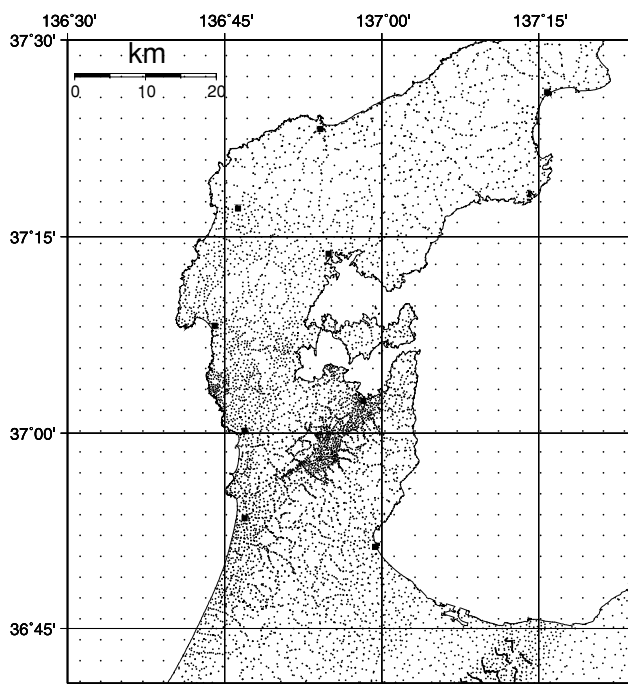

Fig. 2.   Distribution of the gravity stations. Black solid circles indicate the locations of all the gravity data compiled in this work. Solid squares indicate the locations of major towns.

gion of the Noto Hanto Earthquake. Generally, the southern part of the Noto peninsula is characterized by outcropping basement rocks, while the middle and the northern parts are covered with Neogene formations. These are mainly composed of hyaloclastic rocks, andesite lava, sandstone and conglomerate. The geologic structure in and around the source region is very complicated, but no large dislocations have been reported. Quaternary sediments are distributed around Togi, Anamizu, Wajima and Takahama.

4. Gravity Anomalies

As shown in Fig. 3, the northern and the middle parts of the Noto peninsula show relatively high-gravity anomalies, while the southernmost part shows relatively low anomalies. It is obvious that there is a trend in gravity anomaly over the Noto peninsula. This long wavelength component in the gravity anomaly is attributed to deep structures, such as the subducting plate and undulations of the Moho and/or Conrad discontinuities. For the purpose of focusing on and discussing the shallow structure, we should eliminate this long wavelength component. As it may be difficult to describe the gravity trend as a simple linear plane, we used the "grdtrend" command on Generic Mapping Tools (Wessel and Smith, 1998) to describe the regional trend as a cubic surface. We then subtracted the trend from the observed gravity anomaly (Fig. 4). It is still ambiguous whether the calculated trend correctly simulates the gravity effect from the deep structures. However, it is obvious from Fig. 4 that the major trend shown in Fig. 3 has been removed and that local Bouguer anomalies, such as positive anomalies around the Sekidoh Mountains and northern Togi and negative anomalies around southern Takahama are now emphasized. The positive anomalies show a good correspondence

with the distribution of outcropping basement rocks.

Figure 4 also shows a comparison between aftershock distributions provided by Japan Meteorological Agency (2007/03/25, 0:00–24:00) and the gravity anomalies. Between Monzen and Wajima, we recognize a NE-SW trending linear distribution of the sharp gradient of the gravity anomaly, along the shallow aftershock distribution. The gravity anomaly is relatively low in the northwestern side and relatively high in the southeastern side. This linear gravity anomaly seems to extend along the northern shore northeast of Wajima. In the sea area, however, the distribution of the data is not dense enough to discuss in detail. The extension to the western sea area is also uncertain for the same reason.

5. Discussion

Since one of the largest geologic characteristics of the Noto peninsula is the large density contrast between basement rocks and Tertiary formations, we are able to approximately use the Bouguer anomaly map as an indication of relative basement depth. Fig. 5 shows the geologic block structures over the northern Noto Peninsula (after Ohta *et al.*, 1976) and the Bouguer anomalies. The classification of the block boundaries is based on the height discontinuities of former shorelines of marine terraces. According to the analyses, the northern Noto peninsula is divided into four major bocks: Kuwatsuka (KT), Saruyama (SY), Hachibuse (HB), Houryu (HR). The SY block was reported to show no clear sign of uplift along the coastline between Monzen and Wajima, the other blocks show relatively active uplift. The southern end of the KT block coincides with the northern end of the low anomalies in Takahama. The boundary between HB and the HR is obscure. The linear gravity gra-
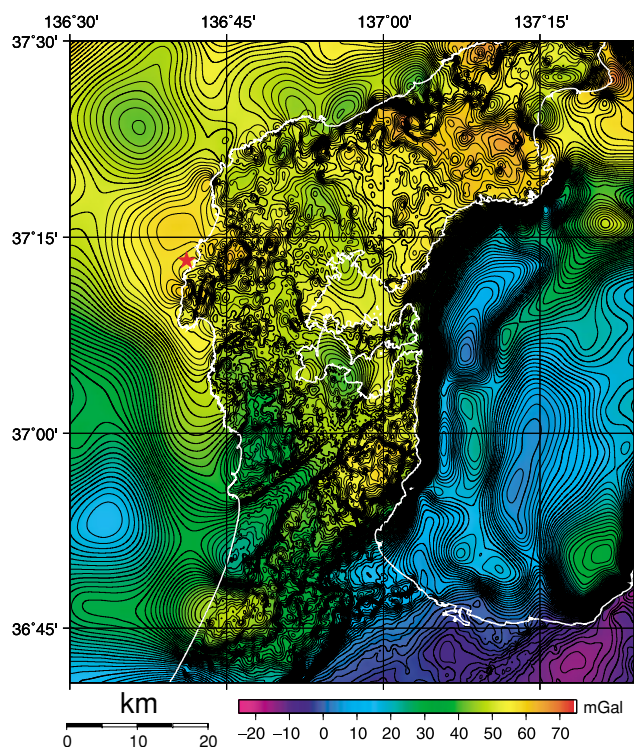
Fig. 3. Bouguer Anomaly map of the Noto Peninsula (Kono *et al.*, in preparation). All data shown in Fig. 2 are compiled. Assumed density is 2,670 kg/m^3. Contour interval is 1 mGal. Red solid star indicates the epicenter of the mainshock.
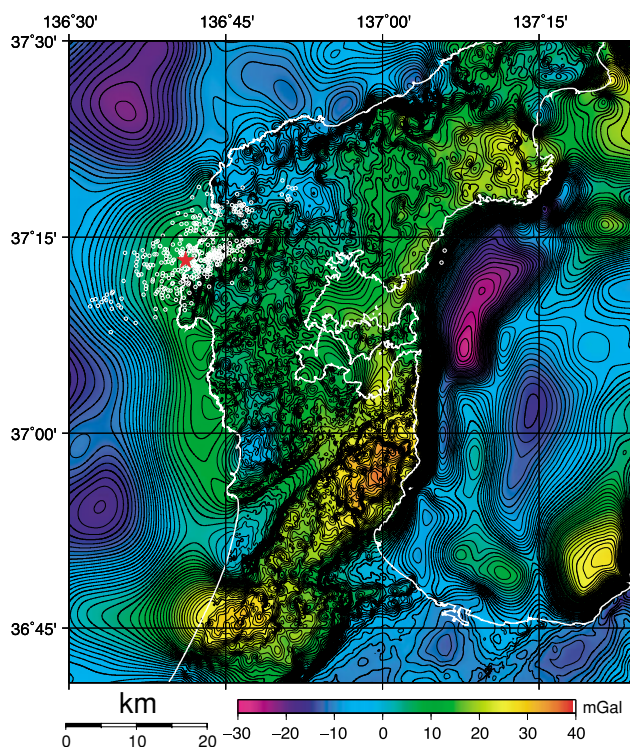

Fig. 4. Filtered Bouguer anomaly map of the Noto peninsula (Kono *et al.*, in preparation). Regional trend of the Bouguer Anomaly was subtracted from the observed anomaly shown in Fig. 3. Assumed density is 2,670 kg/m^3. Contour interval is 1 mGal. White open circles indicate aftershocks provided by Japan Meteorological Agency (2007/03/25, 0:00–24:00). Red solid star indicates the epicenter of the mainshock.

dient distribution mentioned in the previous section is recognized in the SY block. The aftershock area spreads over two of these four blocks, the KT and the SY blocks. In the gravity anomaly distribution, the KT and the SY blocks are clearly recognized by relatively high and low anomalies, respectively. As noted above, this means that the basement depth of the KT block is shallower than that of the SY block. The gap of the former shoreline (0.12 Ma) is at least 50 m between the SY and the neighboring two blocks, and the difference in the uplift rate is at least 0.42 m/1 ky (Ohta *et al.*, 1976). It can be said that the uplift movement of the KT block, at least for these 120,000 years, has been relatively active compared to that of the SY block. This is consistent with the fact that the Bouguer anomalies of the SY block are lower than those of the KT block. Thus, we assume that the uplift movement of the KT block has been relatively active compared to that of the SY block.

The region of large crustal movement shown in SAR interferometric images (JAXA, 2007; GSI, 2007; Fukushima *et al.*, 2007) corresponds well to the KT block. Additionally, the slip distributions inferred from SAR interferometry indicates a large slip beneath the western sea area (GSI, 2007). AIST (2007) and Hiramatsu *et al.* (2007) surveyed the uplift and the subsidence along the coastline based on the distribution of midlittoral and infralittoral organisms. They constructed fault models that ruptured only the KT block and found a good match to the observed uplift well. Slip distributions estimated from strong motion data also indicate a large slip area near the mainshock (e.g. Horikawa, 2007) and little slip in the shallow part of the SY block.
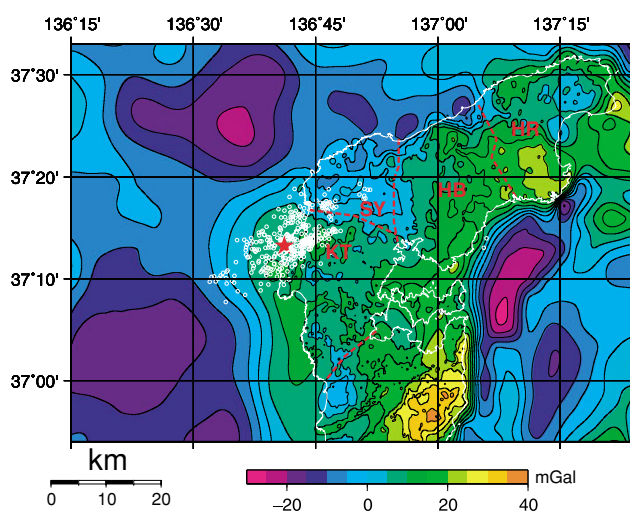

Fig. 5. Filtered Bouguer Anomaly map over the northern Noto peninsula (Kono *et al.*, in preparation) and the block structure of the northern Noto peninsula. Red solid star indicates the epicenter of the mainshock. White open circles indicate aftershocks provided by Japan Meteorological Agency (2007/03/25, 0:00–24:00). Red dashed lines indicate geologic block boundaries proposed by Ohta *et al.* (1976). Geologic blocks indicated by initials are as follows. KT: Kuwatsuka, SY: Saruyama, HB: Hachibuse and HR: Houryu blocks.

These observations and analyses support the conclusion that the mainshock ruptured only the KT block and that the major crustal uplift occurred in the KT block as well. In other words, the block structures presumably limited the source
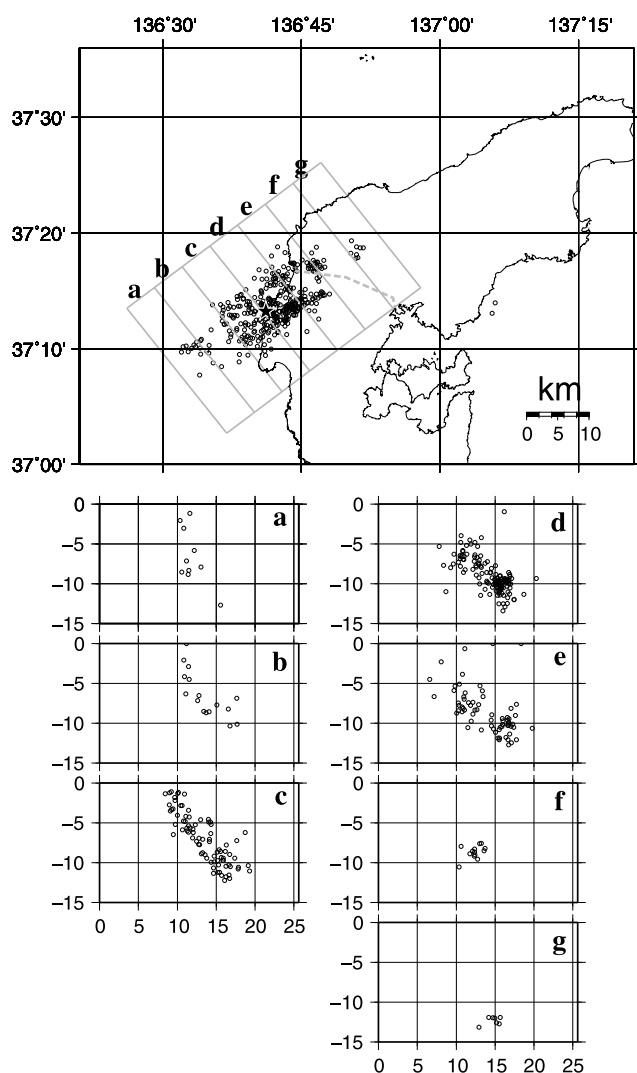
Fig. 6.   Aftershocks provided by Japan Meteorological Agency (2007/03/25, 0:00–24:00) and their profiles approximately perpendicular to the strike of the source fault. Side views (a–g) correspond to the profiles of the bounded boxes in the map view. Black solid star with white rim in the map view indicates the epicenter of the mainshock. Gray dashed line in the map indicates the boundary between the KT and the SY block.

size of the Noto Hanto earthquake.

Figure 6 shows aftershock distributions provided by Japan Meteorological Agency, and its vertical cross-sections projected approximately perpendicular to the earthquake fault. In plan view, a gap of the aftershock is recognized in the KT block along the KT-SY boundary. In the cross-sectional views, linear distributions are shown in the KT block side. On the other hand, the SY block side does not show linear distribution. At any rate, the aftershock distribution seems to change its pattern near the KT-SY block boundary. This suggests again that the block structure affects the distribution of the aftershocks. This characteristic is also shown in the more accurate aftershock distribution obtain by "Group for the aftershock observations of the 2007 Noto Hanto Earthquake" (Sakai *et al.*, 2007).

As mentioned above, the Bouguer anomalies reflect the density heterogeneity of the shallow crust, probably as a result of cumulative crustal deformation. Gravity anoma-

lies support the block boundaries over the northern Noto peninsula which were proposed based on geological and geographical observations. As mentioned previously, geodetic and seismological analyses also suggested that the rupture had occurred within the KT block. Combining the results of these studies and those of the geological and geomorphological studies cited above, we propose that the rupture size of the 2007 Noto Hanto Earthquake was constrained by the block structure of the northern Noto Peninsula. We believe that detailed investigations of gravity anomaly and geologic structure, as shown in this paper, provide useful information on the size of a typical earthquake in a region.

6.   Summary

We have constructed a detailed Bouguer anomaly map by compiling all available data. The Bouguer anomaly distribution is closely related to the geologic block structures in the northern Noto peninsula. By relating this to other data, it is probable that the rupture of the mainshock was constrained by the old block structure in the northern Noto peninsula (Ohta *et al.*, 1976).

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