


LETTER

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# Continuity of subsurface fault structure revealed by gravity anomaly: the eastern boundary fault zone of the Niigata plain, central Japan

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## Abstract

We have investigated gravity anomalies around the Niigata plain, which is a sedimentary basin in central Japan bounded by mountains, to examine the continuity of subsurface fault structures of a large fault zone—the eastern boundary fault zone of the Niigata plain (EBFZNP). The features of the Bouguer anomaly and its first horizontal and vertical derivatives clearly illustrate the EBFZNP. The steep first horizontal derivative and the zero isoline of the vertical derivative are clearly recognized along the entire EBFZNP over an area that shows no surface topographic features of an active fault. Two-dimensional density structure analyses also confirm a relationship between the two first derivatives and the subsurface fault structure. Therefore, we conclude that the length of the EBFZNP as an active fault extends to ~56 km, which is longer than previously estimated. This length leads to an estimation of a moment magnitude of 7.4 of an expected earthquake from the EBFZNP.

**Keywords:** Active fault, Bouguer anomaly, First horizontal derivative, First vertical derivative, Talwani's method

## Introduction

Active structures, such as faults and folds, are controlled not only by recent stress fields but also by past ones. Therefore, it is important to determine the characteristics of active structures, such as their length, dip, segmentation, and grouping in order to gain an understanding of their tectonic history. Geological and geomorphologic features provide useful information on the characteristics of active structures. Geophysical surveys of gravity anomalies and/or seismic velocities are also powerful tools for examining subsurface active structures, especially in areas where surface features related to active structures are no longer visible.

One of the most difficult problems in characterizing active structures is the segmentation and/or grouping of

active faults. It has often been observed that the rupture of a large earthquake propagates over several segments. It is, therefore, important for the evaluation of the size and the occurrence probability of a future large earthquake in a fault zone to investigate the interrelation of neighboring segments and faults. Grouping and/or segmentation has been mainly determined by the geometry of the fault distribution on the surface. For example, the 5-km rule, as a critical distance of fault grouping and/or segmentation, proposed by Matsuda (1990), is widely applied in Japan to define a fault zone that has the potential to generate a large earthquake. However, grouping and/or segmentation is not often examined from the perspective of the continuity of the subsurface structure.

The eastern boundary fault zone of the Niigata plain (EBFZNP) is about 56 km long and is distributed in the NNE-SSW direction along a boundary between the Niigata plain and the Echigo-Iide Mountains, central Japan (Fig. 1). The EBFZNP is one of the major active fault zones in central Japan and consists of the Kushigata

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Range fault zone (KRFZ) and the Tsukioka fault zone (TFZ) in the north and the south, respectively (Ikeda et al. 2002). The Headquarters for Earthquake Research Promotion of Japan (HERP) has produced a long-term evaluation of an expected large earthquake in the EBFZNP (HERP 2002, 2006). Based on the 5-km rule of Matsuda (1990), HERP considers the KRFZ and the TFZ as independent fault zones, although it points out the possibility that erosion and sedimentation of a river have caused the geomorphologic features between the two fault zones to vanish. Consequently, we have examined the continuity of subsurface structures by using a geophysical survey to evaluate the possible maximum size of an earthquake around the Niigata plain.

In this study, we have conducted a gravity survey and constructed a detailed Bouguer anomaly map of the EBFZNP, along with a compilation of previously published gravity data. We also illustrate distinct features related to the subsurface fault structure from analyses of the Bouguer anomaly and its derivatives and discuss the continuity of the KRFZ and the TFZ.

### Tectonic and geological setting

The study area extends from the northern Fossa Magna to the Niigata plain in central Japan and is characterized by a very thick sedimentary basin, up to 6000 m thick (Japan National Gas Association and Japan Offshore Petroleum Development Association 1992), accompanied by an opening into the Sea of Japan. Neogene to Quaternary sediments are thickly deposited in the basin. However, pre-Neogene granitoids and an accretionary complex are mainly exposed at the Echigo-Iide Mountains (Fig. 2). The EBFZNP is a part of the Shibata-Koide tectonic line proposed by Yamashita (1970), which is located at the eastern edge of the Niigata plain (Fig. 1a).

The KRFZ is composed of the Kajikawa fault and other faults located at the western edge of the Kushigata Range. The TFZ is composed of the Tsukioka, Anchi, and Muramatsu faults. The strikes of both fault zones are approximately NNE-SSW, and the length of the KRFZ and the TFZ is about 16 km and 30 km, respectively (HERP 2002, 2006). No evidence of a clear geomorphologic connection has been observed between the KRFZ and the TFZ, because the Kajikawa River, which flows between the KRFZ and the TFZ, might have eroded or buried terrain displacements formed by faulting (HERP 2002). The continuity of the two fault zones is, therefore, unclear at the surface.

The EBFZNP has a displacement that has raised the west side (plain side) (Active Fault Research Group 1991), but this movement contradicts the overall topography in terms of fault zone development, at the boundary between the basin and the mountains. Kato et al. (2013)

carried out a seismic survey across the TFZ in order to resolve this contradiction. According to the seismic survey, they pointed out that the EBFZNP, recognized on the surface, is a west-dipping reverse fault that is a secondary fault derived from the east-dipping main fault, which extends below the Echigo Mountains. In other words, the main fault has formed the Echigo Mountains and the EBFZNP has developed along the unconformity between the lower Neogene and the basement as a secondary west-dipping reverse fault (Kato et al. 2013).

### Data and methods

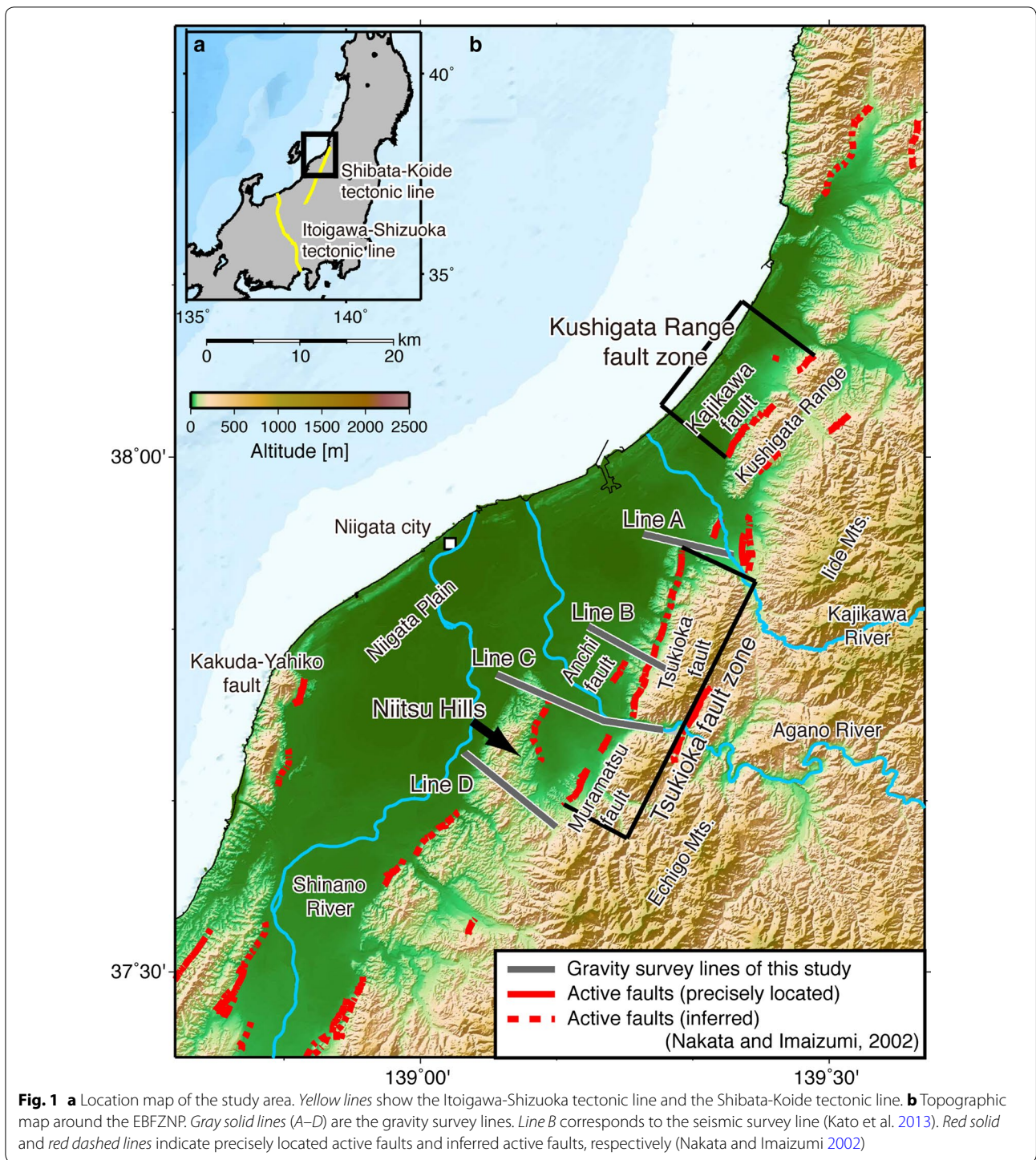
#### Measurement and compilation of gravity data

We conducted a gravity survey with a Scintrex CG-3M gravimeter from September 1 to 9, 2014, and from March 6 to 7, 2015, in and around the EBFZNP. A loop-closing method was adopted for the correction of gravimeter drift. We also conducted a GNSS (Global Navigation Satellite System) observation at each gravity measurement point and determined the position from a baseline analysis of GNSS. For some points where positions were poorly located, maps and a digital elevation model (5-m mesh DEM), published by the Geospatial Information Authority of Japan, were used to obtain the positions. We set four gravity survey lines, one of which corresponds to a seismic survey line (Kato et al. 2013) across the TFZ and the Niitsu Hills (Figs. 1, 3). An interval of gravity measurement on each survey line is about 100 m in the area near the faults and about 200–300 m outside that area. The total number of measurement points in this study was 216 (Fig. 3). Together with the above data, the gravity data, published by the Geographical Survey Institute (2006), Yamamoto et al. (2011), Honda et al. (2012), and the Geological Survey of Japan (2013), are also compiled. The total number of gravity data around the study area was over 5100 (Fig. 3).

#### Gravity correction and derivative filtering

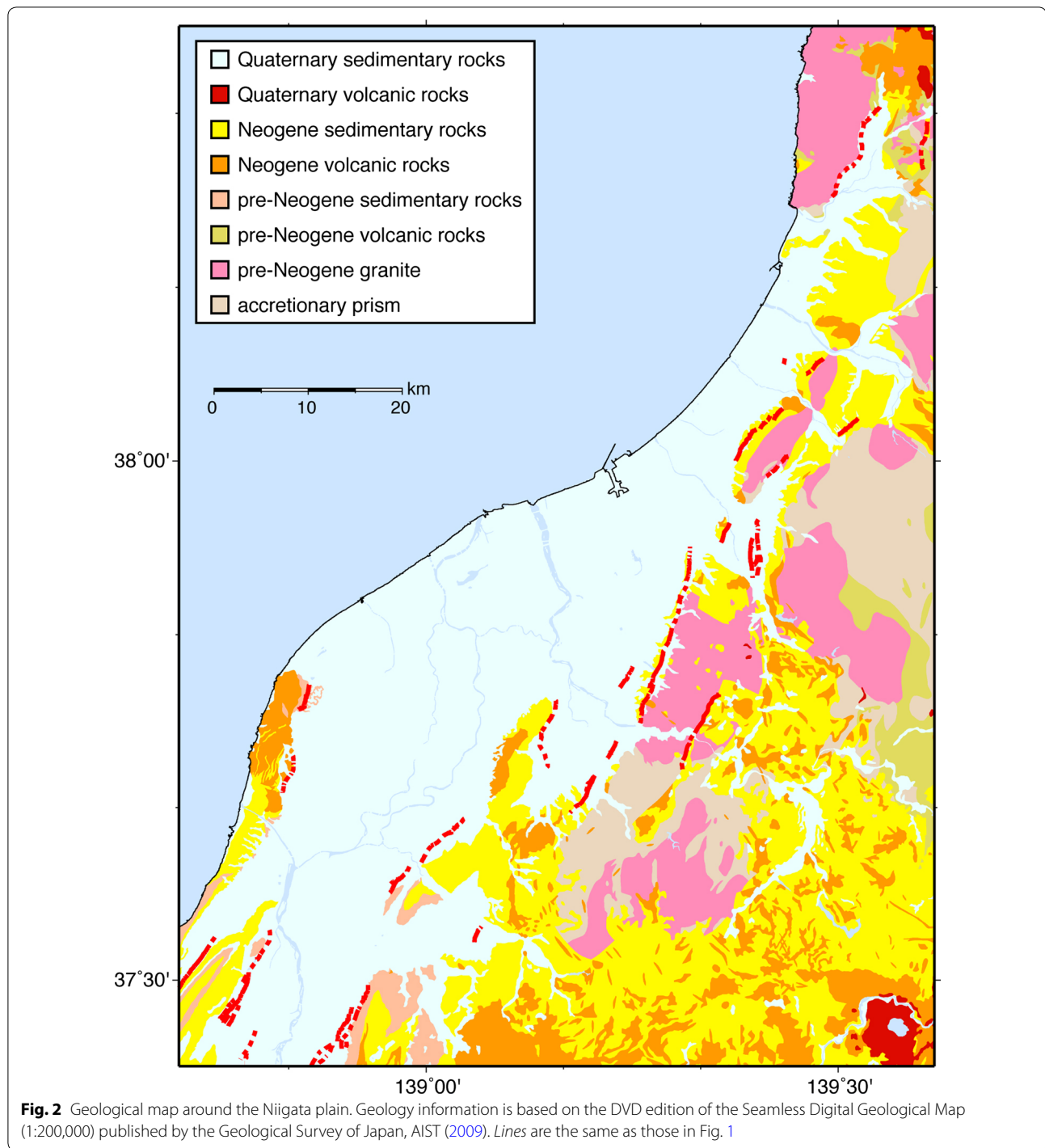
We applied a terrain correction with a 10-m DEM released by the Geographical Survey Institute (Sawada et al. 2015), a slab correction (Furuse and Kono 2003), and a plain trend correction, in addition to normal correction procedures (e.g., tide, drift, free-air, and Bouguer corrections), to the compiled gravity data. Afterward, we calculated the Bouguer gravity anomalies. The assumed density for the terrain and the Bouguer corrections is 2670 kg/m<sup>3</sup>, as pre-Neogene granite and Jurassic accretionary prism are exposed widely in the mountain area of this study (Fig. 2).

First horizontal derivative filtering (e.g., Blakely and Simpson, 1986; Yamamoto et al. 1986; Yamamoto 2003; Kusumoto 2016) and first vertical derivative filtering (e.g., Sawada et al. 2012; Matsumoto et al. 2016) of Bouguer



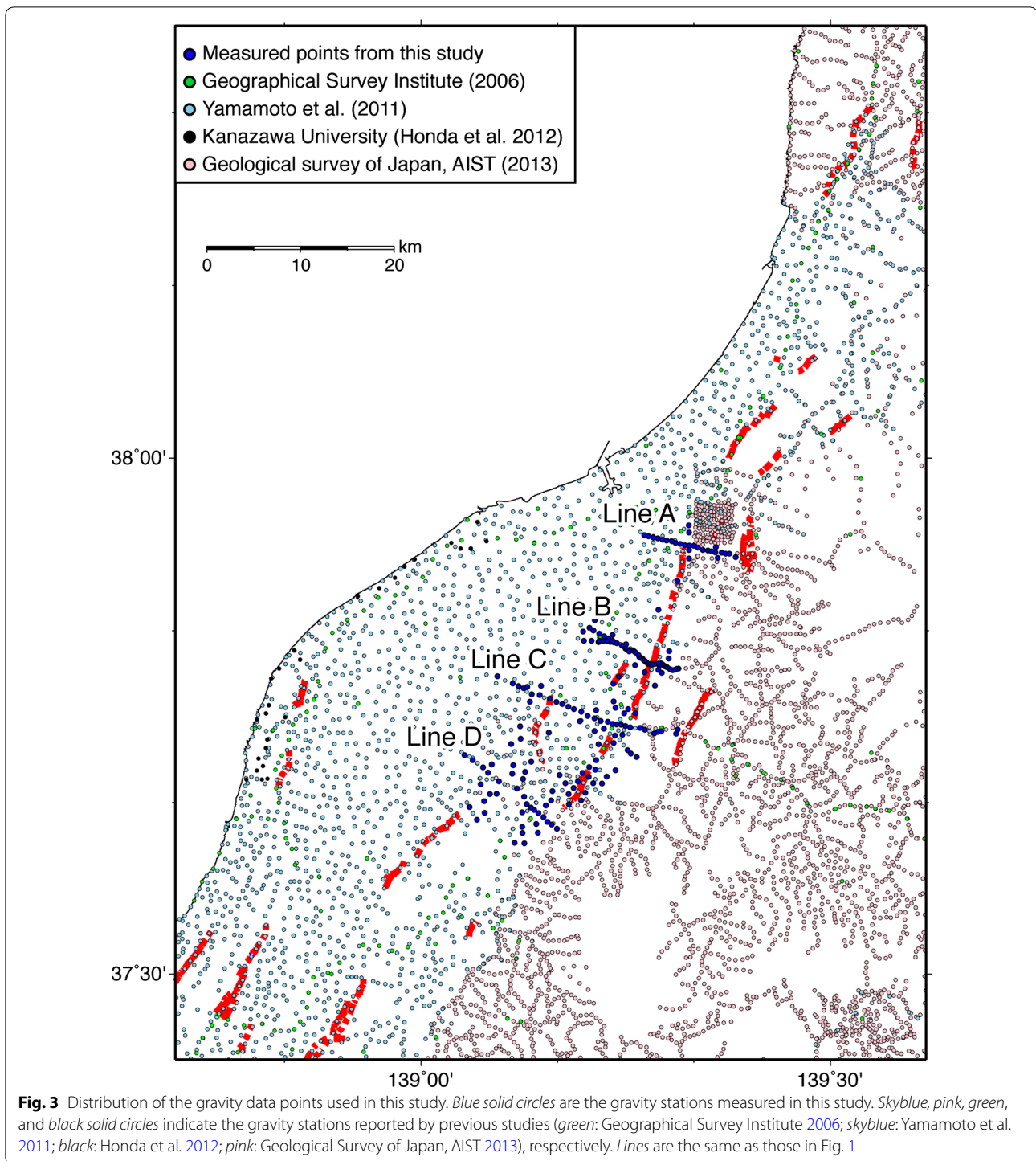
anomalies are useful for estimating a subsurface structure. Steep changes in the subsurface structures, such as faults and/or geological boundaries, are recognized as large absolute values of the first horizontal derivative and the 0 mGal/km isoline (zero isoline) of the first vertical derivative of Bouguer anomalies (Society of Exploration

Geophysicists of Japan 1998). It is important that the difference in the dip angle of a fault can be distinguished between the location of the maximum value of the first horizontal derivative (HD) and the zero value of the first vertical derivative (VD) (Society of Exploration Geophysicists of Japan 1998). To investigate the continuity



of the subsurface structures of the EBFZNP, we applied these filtering processes to the Bouguer anomalies. Here, HD is calculated as  $\sqrt{(\partial g/\partial x)^2 + (\partial g/\partial y)^2}$ , where  $g$  is the Bouguer anomaly and  $x$  and  $y$  represent the two orthogonal directions. VD is approximately calculated by subtracting the 1000-m upward-continued Bouguer anomalies from the original Bouguer anomalies. Before

the derivative filtering, we applied a low-pass filter with a cutoff wavelength of 1500 m to the Bouguer anomalies. We confirm that the elevation of the upward continuation and the cutoff wavelength of the low-pass filter have little effect on the discussion of this study because the location of the steep HD and the zero isoline are independent of the selection of elevation and cutoff wavelength.



### Modeling of a two-dimensional density structure

We have constructed two-dimensional (2D) density structures across the EBFZNP, using forward modeling. In this study, we applied the 2D method of Talwani et al. (1959) to estimate 2D density structures along the four gravity

survey lines (Figs. 1, 3). The purpose of 2D density structure analysis is to evaluate the subsurface structure of the EBFZNP and to verify that the locations of the maximum of HD and the zero value of VD from the Bouguer anomalies correspond to the subsurface fault structures.

## Results

### Characteristics of the Bouguer Anomaly and its derivatives

Figure 4 shows the Bouguer anomalies around the Niigata plain with the topography of the area. Compared to the geological map (Fig. 2), the observed Bouguer anomalies coincide well with the geological makeup of this region. The Bouguer anomalies show higher values near the Echigo and Iide Mountains, where high-density rocks, such as Neogene volcanic rocks and pre-Neogene basement rocks, are well distributed. The low anomalies in most of the Niigata plain reflect the thick Neogene to Quaternary sediments. We recognize that the Bouguer anomalies change rapidly at the eastern and western edge of the Niigata plain. The eastern and western edges correspond to the EBFZNP and the Kakuda-Yahiko fault, respectively.

Figure 5 shows the HD and VD of the Bouguer anomalies around the Niigata plain. Both the large value of the HD ( $>4.5$  mGal/km) and the zero isoline of the VD, which represent the tectonic discontinuities in the subsurface, are clearly continuous along the EBFZNP, including an area between the KRFZ and the TFZ. On the other hand, at both ends of the EBFZNP, the zone where HD values are large decreases and the zero isoline of VD deviates from the extension of the surface fault trace.

In addition, slightly higher Bouguer anomalies (about 30–40 mGal higher than the plain side), a steep horizontal gradient, and the zero isoline of the VD exist in the southwestern part of the Niitsu Hills. Except for these locally high anomalies, the spatial variation of the Bouguer anomalies is poor in and around the Niitsu Hills, although the Niitsu Hills show a distinct topographic high. According to Ikeda et al. (2002), the Niitsu Hills are characterized by an anticline structure, which is formed by the folding of sedimentary layers that have a small density difference and are deposited in the Niigata sedimentary basin. This anticline structure may be the cause of the inconsistency between the high Bouguer anomalies and the topography. We discuss this later in “Line C” and “Line D” sections based on the results of two-dimensional density structure analysis.

### Two-dimensional density structure analysis

We performed two-dimensional (2D) density structure analysis by applying the 2D Talwani et al. method along the four gravity survey lines in this study (Lines A to D in Figs. 1 and 3). Line B corresponds to the reflection seismic survey line of Kato et al. (2013). The Niigata sedimentary basin consists of Miocene to Quaternary sedimentary and volcanic rocks. The Niigata oilfield standard stratigraphy divides the basin into the Mikawa, Tsugawa, Nanatani, Shiya (Miocene), Nishiyama, Haizume (Pliocene), and Unuma Formations (Pleistocene), along with

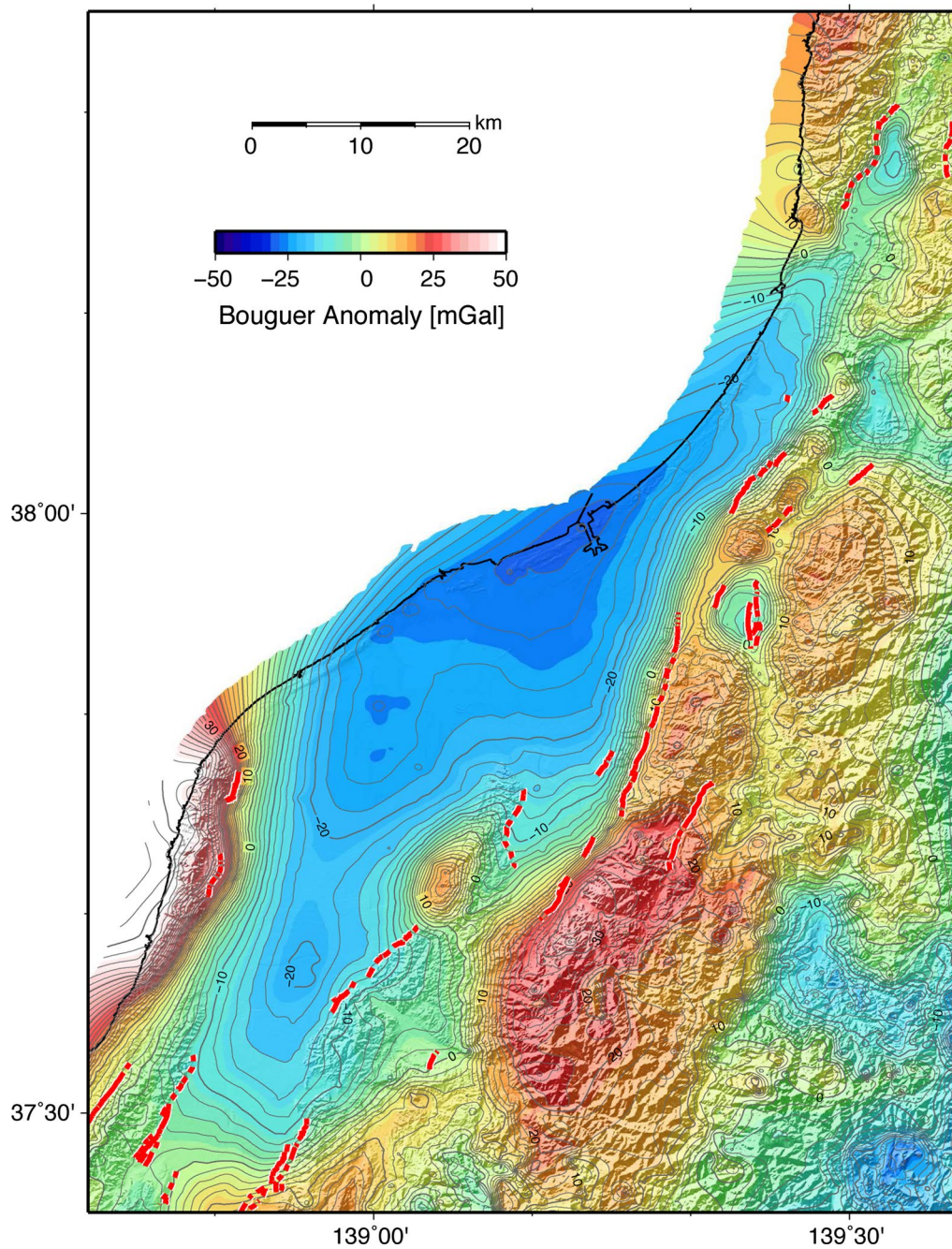
terrace deposits and alluvium from the lower layer (Collaborative Research Group for the Sasagami Hills 1980). In this 2D density structure analysis, we divided the subsurface structures into four layers shown in Table 1, based on the geological classification mentioned above. We constructed, by trial and error, the 2D density structure of each profile to reproduce the observed Bouguer anomalies and the HD and VD. In the case of difficulty in fitting these three quantities, we emphasized the fitting of the Bouguer anomaly and the VD rather than the HD. We summarize the results of the 2D density structure analysis of each profile in subsequent sections.

#### Line A

Figure 6a shows an enlarged map along Line A. The western part of Line A stretches into the Niigata plain. Line A crosses the northern edge of the Sasagami Hill and the Tsukioka fault around a point, 4 km from the western end of Line A. The thickness of the sedimentary layer is about 3.5 km from the western end and becomes thinnest around the 6-km point. A depression of the basement depth is recognized in the eastern part of the profile. The surface position of the Tsukioka fault is around the 4.5-km point. This position corresponds approximately to the maximum point of the HD and the zero point of the VD. The Tsukioka fault is considered to be an intraformational slip in the Miocene layer (Kato et al. 2013). The 2D density structure obtained here is consistent with the Tsukioka fault being formed by an intraformational slip. However, the discrepancy between the observation and the calculation is large for distances  $>10$  km. This may be induced by active faults located around the SE end.

#### Line B

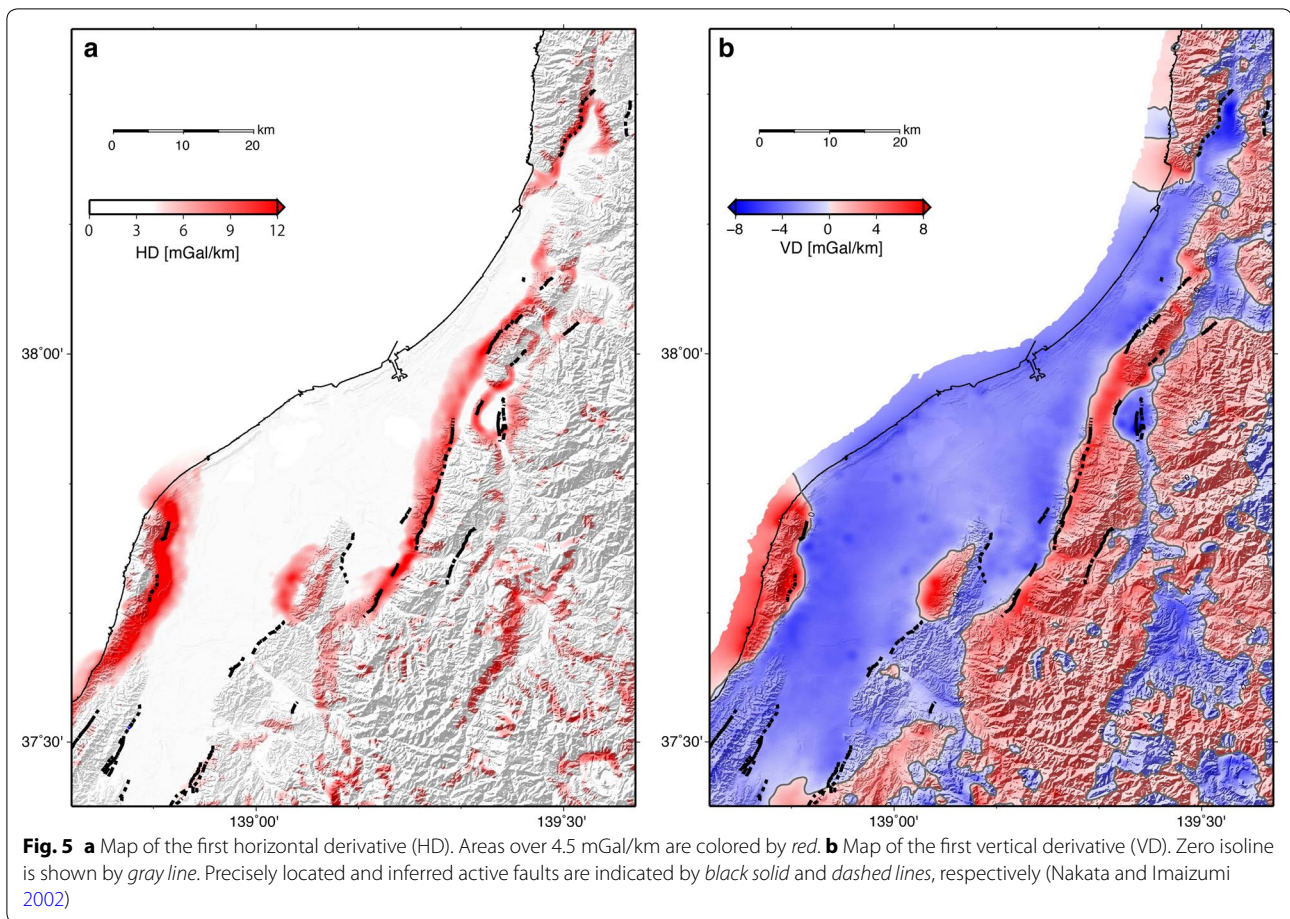
Figure 6b shows an enlarged map along Line B. The western part of Line B stretches into the Niigata plain, and the eastern part stretches into the mountain side. Line B crosses the Sasagami Hill around the 4- to 6.5-km region and the Tsukioka fault at the 6-km point from the western end of the reflection seismic survey line from Kato et al. (2013). We used the seismic reflection profile from Kato et al. (2013) as the initial model of the 2D density structure and constructed a density structure that coincides with the seismic reflection profile. The thickness of the Quaternary–Miocene layers is 3–3.5 km in the western part and becomes thinner in the eastern part of Line B. Kato et al. (2013) reported that the east-dipping main fault exists below the Echigo Mountains and connects with the west-dipping Tsukioka fault at a depth of 2 km, forming a wedge configuration with the fault and the pre-Neogene basement. The observed Bouguer anomalies and the first derivatives are well reproduced by these structures. The maximum point of the HD and the zero



**Fig. 4** Bouguer anomaly map around the Niigata plain. A density of  $2670 \text{ kg/m}^3$  is used for the calculation of the Bouguer anomalies. A contour interval is 2 mGal. Lines are the same as those in Fig. 1

point of the VD are located about 6 km from the western end. It may be noted that the locations of these points do not correspond to the surface boundary between the Miocene layer and pre-Neogene basement and the front edge of the basement wedge, but rather to the surface trace of the Tsukioka fault. Therefore, we consider that

the features of the gravity anomalies, especially for the first derivatives, as shown in Figs. 5, 6 and 7, are related to the fault structure of the EBFZNP. The HD discrepancy is large at distances  $>8$  km. It is difficult to reduce the discrepancy because we cannot set the sedimentary layers in this part in terms of the geological view.



**Table 1** Classification of layers and assumed densities of each layer used in the 2D density structure analysis

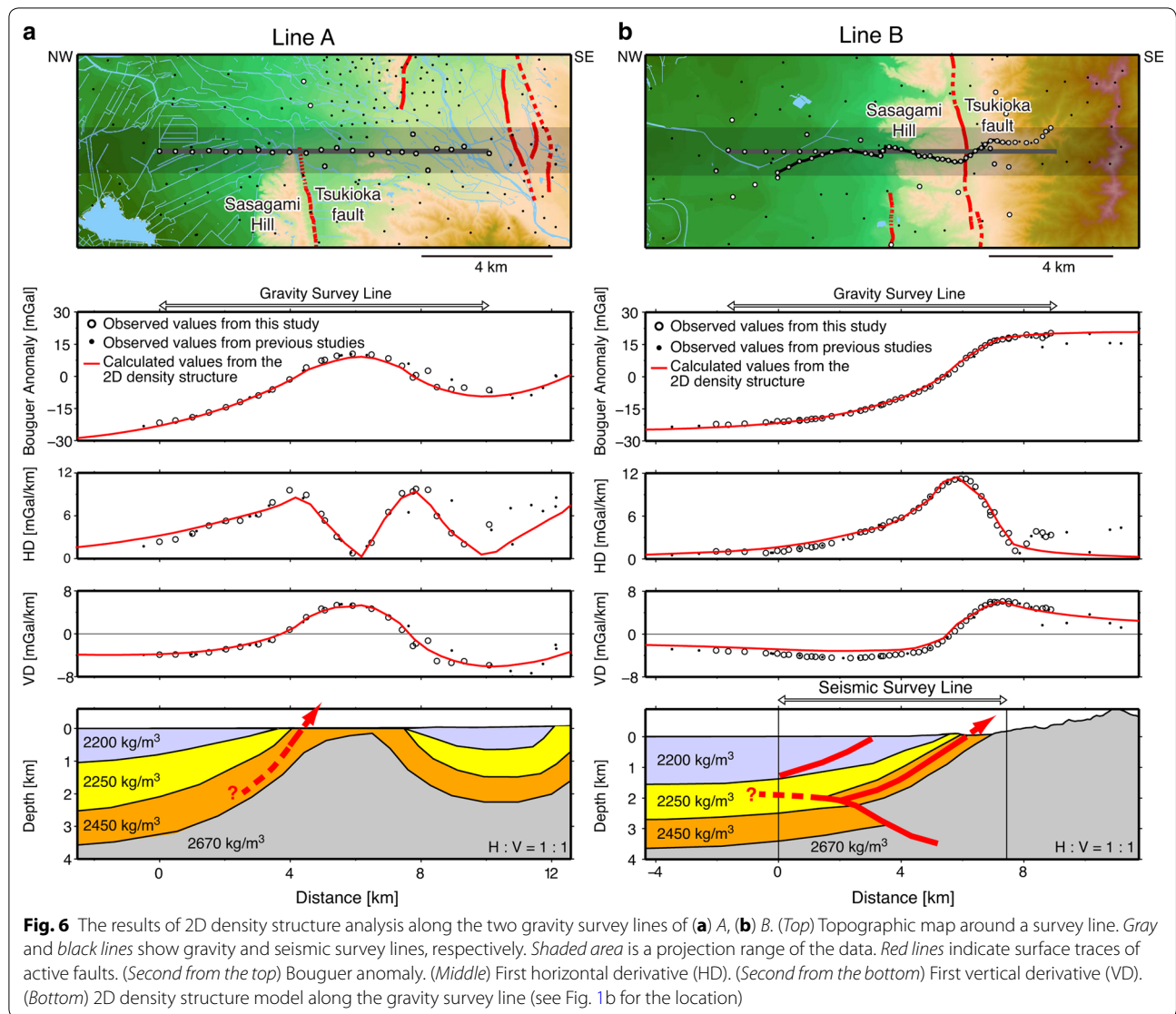
Layer no	Formation	Density (kg/m <sup>3</sup> )
1	Uonuma F. (Quaternary)	2200
2	Haizume F.–Nishiyama F. (Pliocene)	2250–2350
3	Shiyya F.–Nanatan F. (Miocene)	2450
4	Pre-Neogene basement	2670

### Line C

Figure 7a shows an enlarged map along Line C. From the western end of Line C, Line C crosses the northern part of the Niitsu Hill at about 2–6 km, lies in the plain at about 6–15 km, and stretches into the mountain side along the Agano River at >15 km. There are three boreholes near Line C (Fig. 7a), and the depths of the boundaries between the Quaternary and Pliocene layers and between the Pliocene and Miocene layers are documented (Japan National Gas Association and Japan Offshore Petroleum Development Association 1992).

We used these boundary depths as constraints for the analysis. The Japan National Gas Association and Japan Offshore Petroleum Development Association 1992 provided the geological cross section across the Niitsu Hill. We also used this geological cross section for the construction of the 2D model. The sedimentary basin, the depth of which is up to 5 km, is widely distributed in the western part (<15 km). The depth of the pre-Neogene basement becomes abruptly shallower at 12–16 km. The maximum point of the HD and the zero point of the VD are located around the 15-km point. The southern end of the Tsukioka fault and the northern end of the Muramatsu fault are located around the 15-km point. Thus, the point of maximum HD and the zero point of the VD for Line C are likely to be related to the EBFZNP, although it is difficult to distinguish between the EBFZNP, which is an intraformational slip fault, and the slope of the basement from the features of the gravity anomalies. In the western part of Line C, where no distinct change in the gravity anomalies and the derivatives is observed, our 2D density analysis indicates an asymmetrically anticlinal structure, dipping gradually to the west and steeply to the





east, with a symmetrical axis at ~5 km. We suggest that this asymmetrically anticlinal structure plays an important role in the development of the Niitsu Hills.

**Line D**

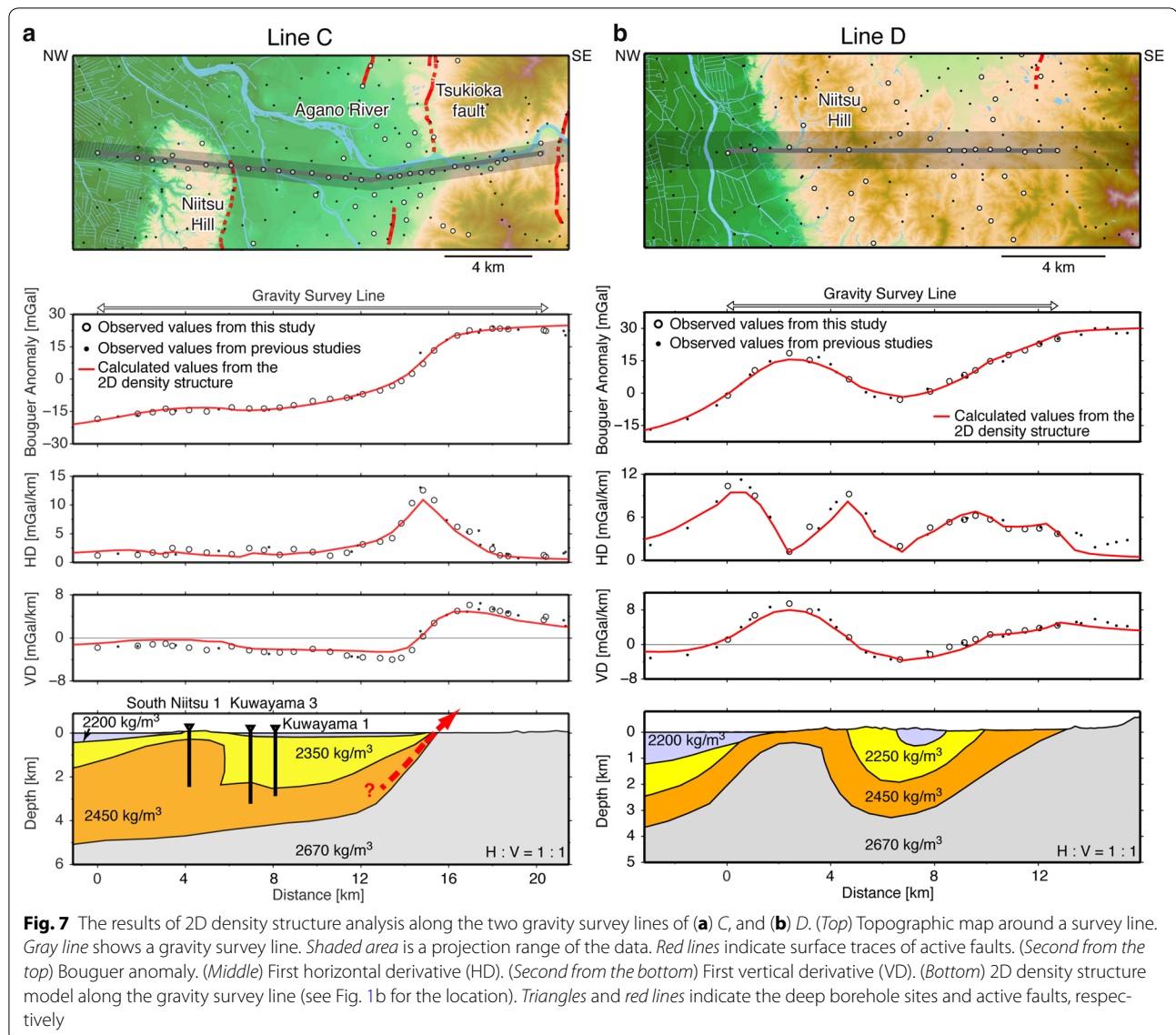
Figure 7b shows an enlarged map along Line D. Line D crosses the southwestern part of the Niitsu Hills, which is characterized by a high Bouguer anomaly in the western part, and crosses the southern extension part of the Muramatsu fault, stretching to the mountain side in the eastern part. The obtained 2D density structure shows a convex shape for the basement at -1 to 4 km with an anticlinal axis near 3 km and a concave shape for the basement at 4–13 km with a synclinal axis near 7.5 km. Therefore, we suggest that the Niitsu Hills are formed by the uplift of sedimentary layers due to a composite fold.

The maximum point of HD and the zero point of VD seem to reflect the subsurface fold structure. We recognized no distinct peak for HD and no zero point for VD on the southern extension of the Muramatsu fault, implying that the EBFZNP does not extend to Line D.

**Discussion**

**Continuity of subsurface fault structures of the EBFZNP**

The EBFZNP is divided into two fault zones, the KRFZ and the TFZ, based on the topographic features. We discuss here the continuity of these two fault zones based on the features of the gravity anomalies. The results of the 2D density structure analysis presented in the previous section show clearly that the HD and VD are good indicators of the subsurface fault structure. As we mentioned in “Characteristics of the Bouguer anomaly and its



derivatives”, both the steep HD and the zero isoline of VD are recognized along the EBFZNP (Fig. 5). It is important that these derivatives are continuous between the KRFZ and the TFZ, indicating that the EBFZNP forms a continuous fault structure below the surface, which has not been confirmed on the surface. On the other hand, at the northern end of the KRFZ and the southern end of the TFZ, it is difficult to recognize a continuous fault structure beyond the surface traces, because the steepness of HD becomes weak and the zero isoline of VD deviates from the strike of the surface fault trace of the two faults zone. Thus, we consider that the subsurface fault structure of the EBFZNP does not extend further and is restricted in the section between the northern end of the KRFZ and the southern end of the TFZ. This also

suggests that, as pointed by HERP (2002), the Kajikawa River might have eroded or buried terrain displacements formed by faulting.

This study area consists of fold-and-thrust fault belts, distributed in the back arc in northeast Japan. These fault belts have a dominant structure with NE-SW or NNE-SSW strikes, which have been formed in the horizontally compressional stress with E-W orientation after 3–5 Ma (Sato and Amano 1991; Sato 1994). It is to be noted that gravity anomalies reflect the cumulative displacement of a long timescale. On the other hand, the distribution of active faults reflects the near-surface displacement over several hundreds of thousands of years, at most. Therefore, there is a difference of a factor of 10 in the timescale between the information gathered from gravity anomalies

**Table 2 The length of a fault zone ( $L$ ) and the maximum earthquake size [moment magnitude ( $M_w$ )] estimated from the empirical relationship by Takemura (1998) and Hanks and Kanamori (1979)**

	Fault zone	Length (km)	$M_w$
Case 1	The Kushigata Range fault zone (KRFZ)	16	6.6 from Eq. (1) 6.2 from Eq. (2)
Case 2	The Tsukioka fault zone (TFZ)	30	7.0
Case 3	The eastern boundary fault zone of the Niigata plain (EBFZNP)	56.5	7.4

and from the active fault distribution, that is, a difference of a factor of 10 in the cumulative fault displacement. Furthermore, the amount of contraction across the fold-and-thrust fault belts is so large, reaching 10–15 km from Pliocene to Quaternary (Okada and Ikeda 2012), that the subsurface fault structure is distinctly illustrated by gravity anomalies and their derivatives. Therefore, it is useful in an area where the geological structure is not complex, to evaluate the continuity of subsurface fault structures using the first horizontal and vertical derivatives of gravity anomalies.

#### Maximum size of an expected earthquake of the EBFZNP

We estimate here the magnitude of an expected earthquake that would occur in the EBFZNP. The gravity anomalies show that the KRFZ and the TFZ have a continuous subsurface structure, indicating that these two fault zones would possibly rupture as a single event. Therefore, we consider the following three cases: (Case 1) the rupture of the KRFZ, (Case 2) the rupture of the TFZ, and (Case 3) the rupture of the entire EBFZNP, including both the KRFZ and the TFZ. To estimate the magnitude of an expected earthquake, we adopt the empirical formula that describes the relationship between fault length and seismic moment proposed by Takemura (1998),

$$\log L(\text{km}) = \frac{1}{2} \log M_o(\text{dyne} \cdot \text{cm}) - 11.82 \quad (M_o \geq M_{ot}) \quad (1)$$

$$\log L(\text{km}) = \frac{1}{3} \log M_o(\text{dyne} \cdot \text{cm}) - 7.28 \quad (M_o < M_{ot}) \quad (2)$$

where  $L$  is the length of a fault,  $M_o$  is the seismic moment, and  $M_{ot} = 7.5 \times 10^{25}$  dyne·cm. We also use the empirical scaling relationship of  $\log M_o(\text{N} \cdot \text{m}) = 1.5 M_w + 9.1$  (Hanks and Kanamori 1979) to estimate the moment magnitude ( $M_w$ ) from the seismic moment.

Table 2 summarizes the estimation of the magnitude for all three cases. For Case 1, both equations are adoptable, so two different values of  $M_w$ , 6.6 from Eq. (1) and 6.2 from Eq. (2), are given. For Case 2, the  $M_w$  of an expected earthquake is estimated to be 7.0 from Eq. (1). For Case 3, we obtain the largest  $M_w$  of 7.4 because the

length of the fault is the largest. An  $M_w$  of 7.4 is larger than the estimated magnitudes reported by HERP because the estimation of HERP considers only a single rupture of the KRFZ or the TFZ, as well as for Cases 1 and 2 of this study. We conclude that the EBFZNP may have the potential for a  $M_w = 7.4$  earthquake to occur, which is estimated from the subsurface fault length revealed by the features of the first derivatives of the gravity anomalies.

#### Conclusions

To examine the continuity of the subsurface fault structure of the eastern boundary fault zone of the Niigata plain (EBFZNP), central Japan, we have conducted a gravity survey, compiled all available gravity data, and produced a Bouguer anomaly map around the Niigata plain. We calculated the first horizontal and vertical derivatives (HD and VD) to reveal the subsurface fault structure. The HD shows large absolute values not only along the Kushigata Range fault zone (KRFZ) and the Tsukioka fault zone (TFZ), which constitute the EBFZNP, but also along the area between the two fault zones where no surface fault traces are observed. The zero isoline of VD is distributed from one end to the other end of the EBFZNP. These features suggest that a similar subsurface fault structure is continuous over the entire EBFZNP. We also performed two-dimensional density structure analysis by using the two-dimensional Talwani's method on four profiles which were perpendicular to the strike of the EBFZNP. The results of the two-dimensional density structure analysis confirm that the observed features of the derivatives are closely related to the subsurface fault structure of the EBFZNP. Furthermore, based on these features, the subsurface fault structure of the EBFZNP does not extend to the north and to the south. Therefore, we conclude that the entire length of the continuous subsurface fault structure for the EBFZNP is 56.5 km, which is longer than the sum of the lengths of the KRFZ and the TFZ. An empirical relationship between the fault length and moment magnitude gives a moment magnitude of 7.4 for an expected earthquake of the EBFZNP. This magnitude is larger than what was reported previously. We stress that gravity anomalies and their derivatives are useful in illustrating subsurface fault structures in an area

with relatively simple geological structure, such as the fold-and-thrust fault belts in northeastern Japan.

#### Abbreviations

EBFZNP: the eastern boundary fault zone of the Niigata plain; KRFZ: the Kushi-gata Range fault zone; TFZ: the Tsukioka fault zone; HD: the first horizontal derivative; VD: the first vertical derivative; 2D: two-dimensional.

#### Authors' contributions

YH, SO, TT, and RH participated in the design of this study. SW, AS, and YH performed gravity survey. SW and NM conducted the analyses. SW, TT, and RH maintained the gravity data. SW, SO, and YH drafted the manuscript. All the authors have read and approved the final manuscript.

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#### Competing interests

The authors declare that they have no competing interests.

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