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Gravity-Based Active Fault Mapping around the Eastern Margin of the Ishikari Lowland, Hokkaido, Japan

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Abstract

The Ishikari Plain is characterized by the largest alluvial lowland (the Ishikari Lowland) in Hokkaido, Japan. In the eastern margin of this plain lies the Ishikari Teichi Touen Fault Zone (ITTFZ) which borders on the Miocene hill belts (Iwamizawa, Kurisawa and Umaoi hills). Past gravity studies in the Ishikari Lowland showed that low anomalies corresponding to Quaternary sediments are dominant over the plain, whereas detailed gravity structure particularly across the ITTFZ in the eastern margin of the plain has not been reported so far. This paper examines gravity structures of the Ishikari Lowland by focusing relief-shaded Bouguer gravity, specifically to relocate the faults (the ITTFZ), and to present a gravity-based active fault mapping for correct determination of fault segmentation. Gravity analyses are based on dense gravity data measured by various institutes. Bouguer anomaly relief is produced by illuminating the artificial light from eight directions to effectively display the detailed gravity features varying laterally along the azimuth direction. The active fault distribution in the region is mapped through the relief-shaded Bouguer anomaly. A striking linearity of the relief-shaded Bouguer gravity along the ITTFZ is found on most of the relief maps, particularly on the maps for the azimuth of the due east and west direction. This lineament shows a good agreement with both distributions of the old and new active faults in the northern and southern parts of the ITTFZ. In the central segment of the ITTFZ, however, the lineament in the relief-shaded Bouguer map does not bear a good correlation with the active fault distributions. It is also shown that the ITTFZ as a whole consists of two parallel fault strands, both of which run approximately in the same trend and step each other by 1~2 km, along the western margin of the Miocene hill belts. In addition, the gravity relief for the azimuth of the due north (or south) direction exhibits a remarkable lineament, extending southward from near Bibai, whose southward continuation can be traced to the south-east until 20~25 km south of Atsuma along the western-most boundaries of pre-Neogene volcanics. This implies that the geometry of the southern end of the known fault system (the ITTFZ) provides continuity along the relief-shaded Bouguer lineament roughly to the south-east.

1. Introduction

Hokkaido, the northernmost of Japan's four major islands, covers 32,224 square miles (83,454 square kilometers). Much of the island consists of forested mountains and hills. A hilly and curved peninsula extends from southwestern Hokkaido. Northeast of this peninsula lies the Ishikari Plain, Hokkaido's largest lowland. The Ishikari Plain is chief industrial region and characterized by the largest alluvial lowland (the Ishikari Lowland) in Hokkaido. Geophysically, seismic activity of the felt earthquakes in densely-populated Sapporo area, located in the northern part of the plain, was very high in 1930's but low in the recent 20~30 years (Kasahara and Miyazaki, 1998). It is now clear that we have several active fault zones around the plain. Fault-bounded plains or basins often accompany a variety of tectonic motions such as reverse faulting. Specifically in Hokkaido, these motions are associated with the plate movements and the secondary tectonics. In the eastern margin of this lowland lies the Ishikari Teichi Touen Fault Zone (ITTFZ) which borders on the Miocene hill belts (Iwamizawa, Kurisawa and Umaoi hills). The ITTFZ has arcuate-shaped en echelon features and strikes in a direction roughly between N20°E (northern part) and N20°W (southern part), protruding toward west in the central part, and is classified as reverse fault system. In the southern part of the ITTFZ, particularly south of 42°50'N, its nearly single fault line character begins to vanish and splays into several closely-spaced strands, which roughly parallel the trend of the ITTFZ and become less continuous. Past studies showed the tectonic evolution and active movements of the active faults around the Ishikari Plain (Research Group for Active Faults of Japan, 1980, 1991 ; Oka, 1986 ; Oka et al., 2001). The gravity field prevailing over the Ishikari Plain is best reflected on the Bouguer anomaly map. Bouguer gravity anomalies are most sensitive to the subsurface mass distributions, and are influenced by the nature of underlying geological formations. Yamamoto and Ishikawa (2002) made a gravimetric study in southwestern Hokkaido, covering the area of Neogene mountains which dominate west part of the Ishikari Plain. Although a general view of Bouguer anomaly in the Ishikari Lowland shows that (1) low anomalies corresponding to Quaternary sediments are dominant over the plain, and (2) Neogene high-density rocks are characterized by high Bouguer anomalies, detailed gravity structure particularly across the ITTFZ in the eastern margin of the plain has not been reported so far. Recently, Yamamoto (2003) gave detailed examination of Bouguer anomalies over the plain and discussed about their important features. This paper examines gravity structures of the Ishikari

Lowland related to fault dynamics of the eastern margin of the Ishikari Lowland by focusing Bouguer gravity reliefs, specifically (1) to relocate the faults (the ITTFZ), comparing the new active fault distributions with the older ones, and (2) to present a gravity-based active fault mapping for correct determination of fault segmentation or strands.

2. Regional Geologic Setting

West Hokkaido covers the area from the Okushiri Ridge to the west margin of the Kitakami-Ishikari-Rebun Belt, each of them is the N-S trending tectonic zone. In general, N-S oriented tectonic zones of Hokkaido are formed by the Mesozoic arc-trench subduction kinematics between the Eurasian and Paleo-Pacific plates, and the Latest Mesozoic to Miocene oblique collision kinematics between the Okhotsk and Eurasian plates (Oka, 1986). Fig. 1 shows a 3-D perspective view of topography with known faults (Fig. 1a), and a simplified geologic map (Fig. 1b) around the Ishikari Lowland, where Bouguer anomaly isolines are superimposed. Geology information in Fig. 1b is based on the digital version of 1:1,000,000 scale geological map of Japan (3rd edition) by Geological Survey of Japan (1995). Thick colored lines and dotted red lines in Fig. 1b denote known active faults by Nakata and Imaizumi (2002) and the Research Group for Active Faults of Japan (1991), respectively. Their fault pattern in the lowland is displayed in detail in Fig. 1b. Thick color-coded faults in Fig. 1 through Fig. 10 indicate, red: certainly exist and location is accurately determined, magenta: certainly exist and location is not accurate, green: possibly exist (invisible), and blue: estimated fault lying at depths, respectively. As shown in Fig. 1, the Ishikari Plain is characterized by the largest late-Cenozoic lowland (the Ishikari Lowland) in west Hokkaido. Wide-spread deposition of alluvial deposits constitutes a large part of the overall sedimentary sequence around the plain. The thickness of the Ishikari Plain is considered to be 1,500 to 2,000 m which is continuous to Quaternary. The basins in west Hokkaido were formed mainly by the N-S trending ridges and NW-SE trending Quaternary upheavals. Tectonic evolution of the basins developed in west Hokkaido is interpreted largely by the rotational tectonics of the Northeast Japan Arc. Neogene rugged mountains dominate west part of the plain (W. Sapporo Mountains, see Fig. 1a), and in the eastern margin of this plain lies the ITTFZ which borders on the Miocene hill belts, the Iwamizawa Hill (IH), Kurisawa Hill (KH), Umaoi Hill (UHN, UHC, UHS), as shown in Fig. 1. East of the hill belts spread Yubari Mountains and the Yubari Coal area mainly

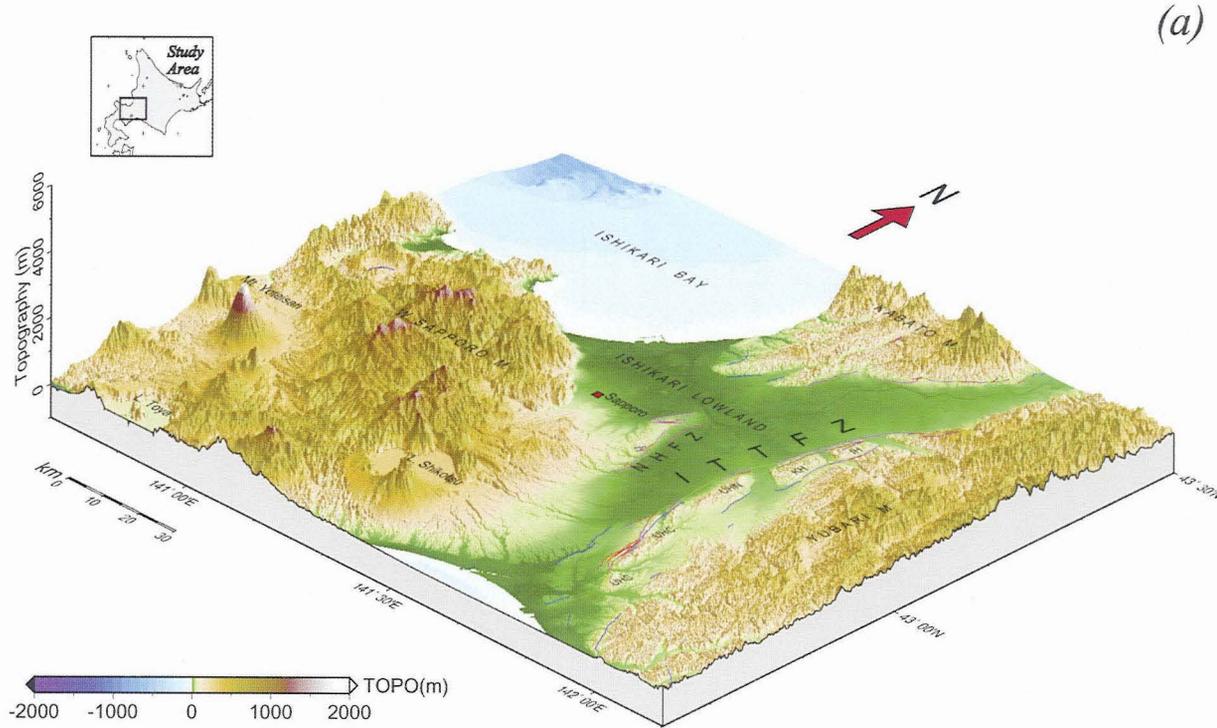


Fig. 1. (a) A 3-D perspective map showing topography and known faults around the Ishikari Lowland. Active faults are taken from Nakata and Imaizumi (2002), where colored faults indicate, red: certainly exist and location is accurately determined, magenta: certainly exist and location is not accurate, green: possibly exist (invisible), and blue: estimated fault lying at depths, respectively. Azimuth and elevation of the view point of 3-D image are 135° from north clockwise and 30°, respectively. Vertical exaggeration is about 5 times. ITTFZ: the Ishikari Teichi Touen Fault Zone, IH: Iwamizawa Hill, KH: Kurisawa Hill, UHN: Umaoi Hill (Northern Block), UHC: Umaoi Hill (Central Block), UHS: Umaoi Hill (Southern Block), NHFZ: the Noppo Hill Fault Zone.

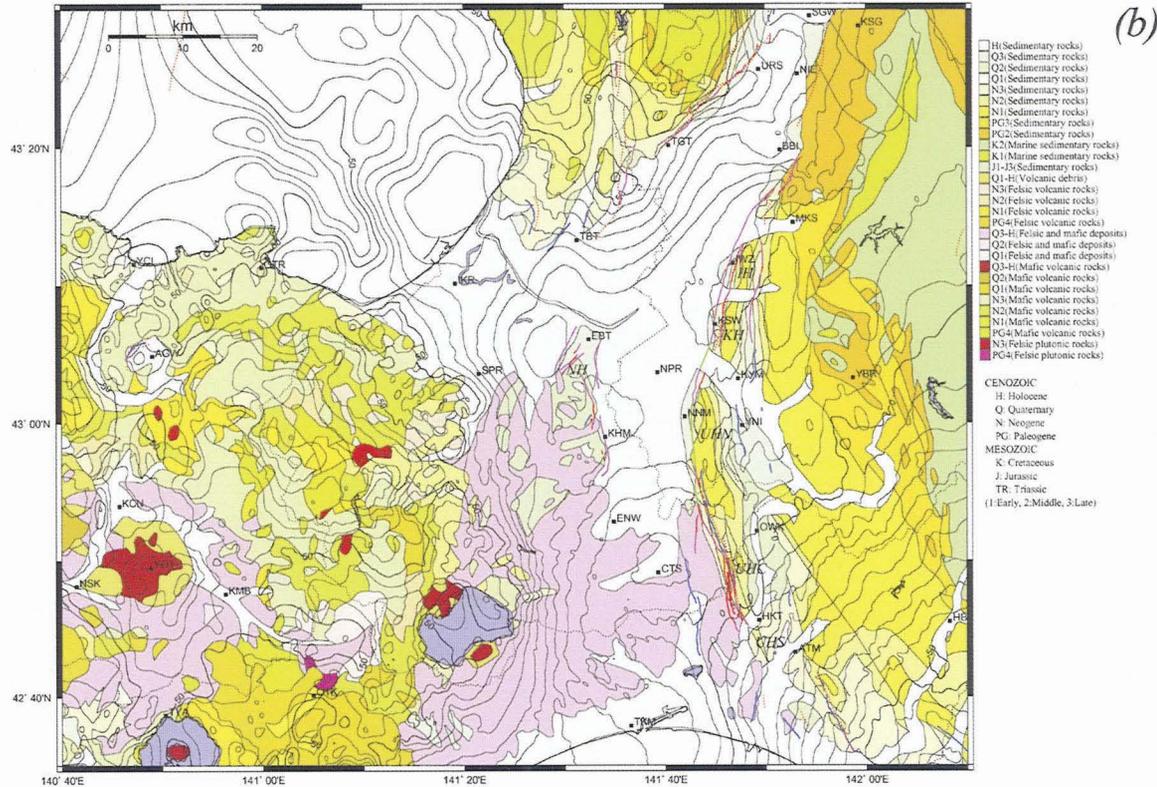


Fig. 1. (b) Map showing simplified geology around the Ishikari Lowland. Bouguer anomaly isolines are superimposed with a contour interval of 5 mgal. Assumed density is 2.67 g/cm^3 . Geology information is based on the digital version of 1 : 1,000,000 scale geological map of Japan (3rd edition) by Geological Survey of Japan (1995). Heavy colored lines and dotted red lines demonstrate known active faults by Nakata and Imaizumi (2002) and the Research Group for Active Faults of Japan (1991), respectively. Large closed triangles and squares, followed by three letters, show geographical locations of major named summits and cities (towns), respectively. Location of hill belts in the eastern margin of the Ishikari Plain is also shown. AGW : Akaigawa, ATM : Atsuma, BBI : Bibai, CTS : Chitose, EBT : Ebetsu, ENW : Eniwa, HBT : Hobetsu, HKT : Hayakita, IKR : Ishikari, IWZ : Iwamizawa, KCN : Kucchan, KHM : Kitahiroshima, KMB : Kimobetsu, KSG : Kamisunagawa, KSW : Kurisawa, KYM : Kuriyama, MKS : Mikasa, NH : Nopporo Hill, NIE : Naie, NNM : Naganuma, NPR : Nanporo, NSK : Niseko, OTK : Ohtaki, OTR : Otaru, OWK : Oiwake, SGW : Sunagawa, SPR : Sapporo, TBT : Tobetsu, TGT : Tsukigata, TKM : Tomakomai, TYA : Toya, URS : Urausu, YBR : Yubari, YCI : Yoichi, YNI : Yuni, YOT : Mt. Yotei.

composed of pre-Neogene volcanic formations. The ITTFZ runs nearly in the N-S direction along the westernmost part of the hill belts, bending toward west around NNM (Naganuma, see Fig. 1b), and is classified as reverse fault system. The ITTFZ, having 55 km length, consists of several active faults, the Iwamizawa Fault, the Kurisawa Fault, the Naganuma Tilted Belt, the Izumisato Fault, the Umaoi Fault, and the Kenbuchi Fault (Research Group for Active Faults of Japan, 1980, 1991). These faults develop in the western margin of the Miocene hill belts. East of the hill belts also prevail several lowlands such as the Yuni Lowland. IH and KH have N-S oriented anticline structures whose eastward and westward flanks are characterized by steeply declined Neogene formations.

3. Gravity Data

Land gravity data were taken in the whole part of the Ishikari Lowland and adjacent areas from various institutes and companies to make gravity stations as uniform and dense as possible. In total, about 25,000 gravity data from Hokkaido University, Geological Survey of Hokkaido (hereafter referred to as GSH), the Japan Petroleum Exploration, Co., Ltd. (hereafter referred to as JAPEX), etc. were collected for gravity study around the lowland. Particularly, gravity data measured by JAPEX number more than 20,000 in the lowland and its vicinity. Komazawa et al. (1998) published a Bouguer anomaly map around the Ishikari Plain assuming a reduction density of 2.3 g/cm^3 on the basis of land gravity data by JAPEX.

In the present study, gravity values for land stations obtained by JAPEX were first recalculated to determine absolute values based on the Japan Gravity Standardization Net 1975 (JGSN75, Suzuki, 1976), because most of them were tied to the Potsdam network. To find the exact difference between the Potsdam-based and JGSN75-based values, gravity stations measured at close geographical proximity were reoccupied and compared, where their elevations are accurately controlled. Then, JGSN75-based values were converted to those based on the Japan Gravity Standardization Net 1996 (JGSN96, Nakai et al., 1997; Yamaguchi et al., 1997). Land gravity data by GSH were compiled and also recalculated, referring to the values of JGSN96, so as to fit the reference gravity data by Hokkaido University to which the absolute gravity values were already assigned. Gravity data by Hokkaido University were obtained by a LaCoste & Romberg Model G land gravity meter and a Scintrex gravity meter. These data were fully corrected for latitudinal and elevation effects, instrumen-

tal height, earth tide, and secular drift of the spring. Characteristic features and behaviors of the above gravity meters are described by Yamamoto et al. (2001a, 2001b). These gravity data were then reduced for free-air and Bouguer corrections, as well as for terrain effects, where spherical terrain corrections were applied to a radius of 80 km according to the method by Yamamoto (2002). See Yamamoto (2003) for locations of these gravity data used in this study. In addition, to supplement regional coverage, we used the 1 km-spacing gridded Bouguer data by Geological Survey of Japan (2000) in the area where gravity data are not closely-spaced. It should be noted that the area is a very small part of the mountainous regions prevailing east and west of the plain, as well as the oceanic region in the Ishikari Bay. In all reductions the earth's sphericity is taken into consideration. Thus Bouguer anomaly values were determined to produce a new gravity map of the Ishikari Plain and adjoining areas. After an overall revision and reduction for these gravity data, a Bouguer anomaly map, a residual anomaly map, and a first horizontal derivative map of the region were constructed.

4. Bouguer Anomaly

According to the procedures described in the previous section, Yamamoto (2003) constructed a new gravity anomaly atlas (Bouguer anomaly map and a first horizontal derivative/gradient map) of the Ishikari Plain and its vicinity and argued about their features. Basic ideas of Bouguer gradient are given by Yamamoto et al. (1986). In this paper we take another approach to present a gravity-based fault mapping around the eastern margin of the Ishikari Lowland using the same data described in Yamamoto (2003). To accomplish this purpose, we constructed a Bouguer gravity relief map as well as a Bouguer anomaly map around the Ishikari Lowland. In Fig.2 we show a colored Bouguer anomaly map around the Ishikari Lowland and its vicinity, where Bouguer anomaly is low-pass filtered with a cut-off wavelength of 1 km. Grid size for automatic machine-contouring is 0.025 arc-minutes (~ 40 m). Relief-shaded Bouguer anomaly map was produced by illuminating the artificial light from the east direction against non-filtered Bouguer distributions. Gravity features in the Ishikari Lowland are summarized according to Yamamoto (2003) as follows. Gravity field over the Ishikari Plain is distinctly low as compared to its surroundings. This low anomaly is mostly associated with significant Quaternary sediments spreading extensively over the area. Bouguer anomaly value of the plain ranges from 0 mgal in its southern part to 40 mgal in its

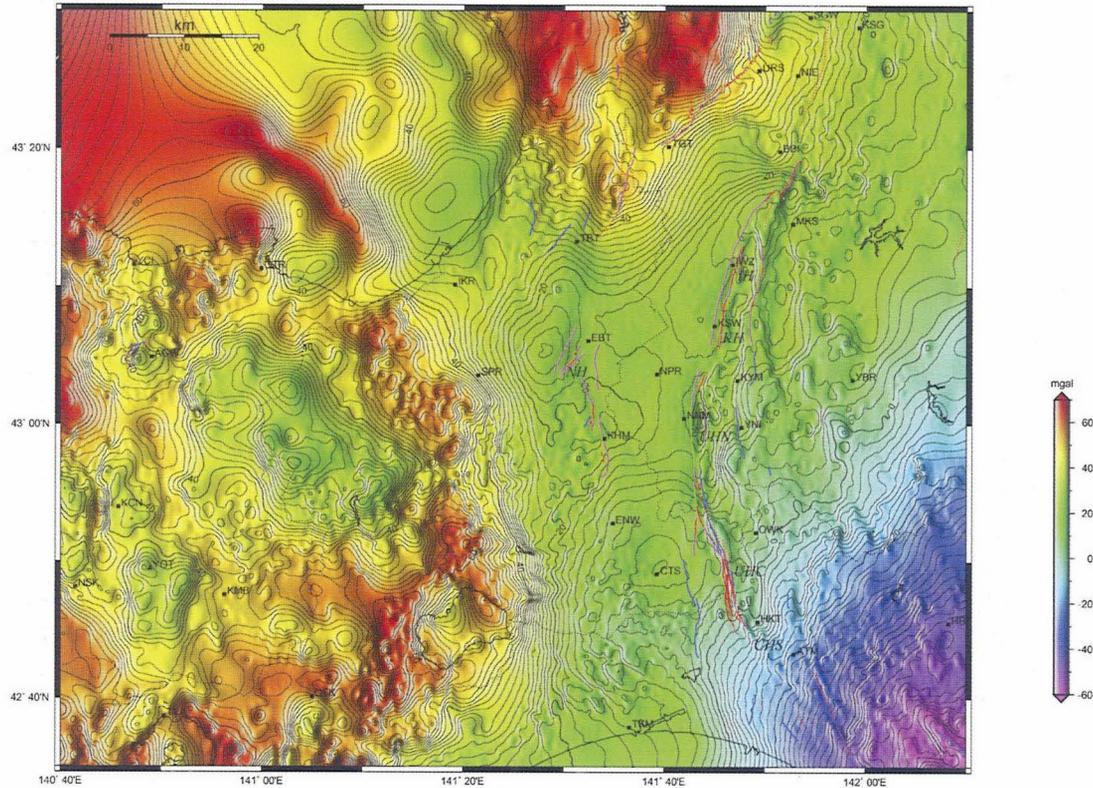


Fig. 2. Colored Bouguer anomaly map of the Ishikari Lowland and its adjacent areas with a contour interval of 2 mgal. Assumed density is 2.67 g/cm^3 . Bouguer anomaly is low-pass filtered with a cut-off wavelength of 1 km. Grid size for automatic machine-contouring is 0.025 arc-minutes ($\sim 40 \text{ m}$). Shaded relief of Bouguer anomaly is superimposed by illuminating the light from the due east direction. Heavy colored lines and dotted red lines demonstrate known active faults by Nakata and Imaizumi (2002) and the Research Group for Active Faults of Japan (1991), respectively. Large closed triangles and squares, followed by three letters, show locations of major named summits and cities (towns), respectively. Locations of hill belts in the eastern margin of the Ishikari Plain are also shown. See the caption of Fig. 1 for the abbreviations.

northern part. The boundary between the plain and the (pre-)Neogene surroundings is characterized by an iso-contour line of 40 mgal on its north and west sides. To the west of the plain, high anomalies corresponding to the mountain regions of Neogene high-density volcanics dominate almost whole parts in the mountain regions. Arcuate-shaped gravity highs clearly develop in the eastern part of these volcanics, forming a belt-like structure of 10~15 km width. In the easternmost margin of the Neogene volcanics, gravity highs are bordered by a sharp gravity gradient stretching south from Sapporo City (SPR), whose southward continuation is passing through the Eniwa Lake and can be traced a few kilometers east of the Shikotsu Lake. While gravity anomalies around the Nopporo Hill (NH), where the Nopporo Hill Fault Zone (see Fig. 1a) is newly identified as an active fault system in the newly-compiled fault mapping (Nakata and Imaizumi, 2002), are small in amplitude and are associated with no abrupt gravity changes compared to its topography and surrounding fault distributions, implying that no sharp density contrast is appreciable at depths. Steep gravity gradients are also observed along the ITTFZ in the eastern margin of the plain. They are trending almost in the N-S direction, which is closely correlated with that of the active fault distributions (Figs. 1 and 2). As shown in Figs. 1 and 2, most of the Miocene hill belts (IH, KH, UHN, UHC, UHS) of the eastern margin of the Ishikari Lowland accompany locally high gravity ridges that are well correlated with Miocene formations. In contrast, Bouguer gravity low is associated on both (west and east) sides of the hill belts, which is corresponding to light sediments of the lowland. Also, the map is characterized by the conspicuous presence of several gravity highs, with several closed local maxima, along the ITTFZ. These local maxima do not bear close correlation with surface geology (see Figs. 1 and 2). These local gravity anomalies are extending from the northern portion near Iwamizawa (IWZ) to the southern portion near Hayakita (HKT), passing through the western margin of the Naganuma Tilted Belt near Naganuma (NNM), and illustrate the prominent lineament protruding westward. This N-S oriented lineament can be found along the western margin of the Miocene hills. Thus dense gravity data led to success that the conspicuous lineament corresponding to the ITTFZ was detected from Bouguer anomaly map.

5. Relief-Shaded Bouguer Gravity

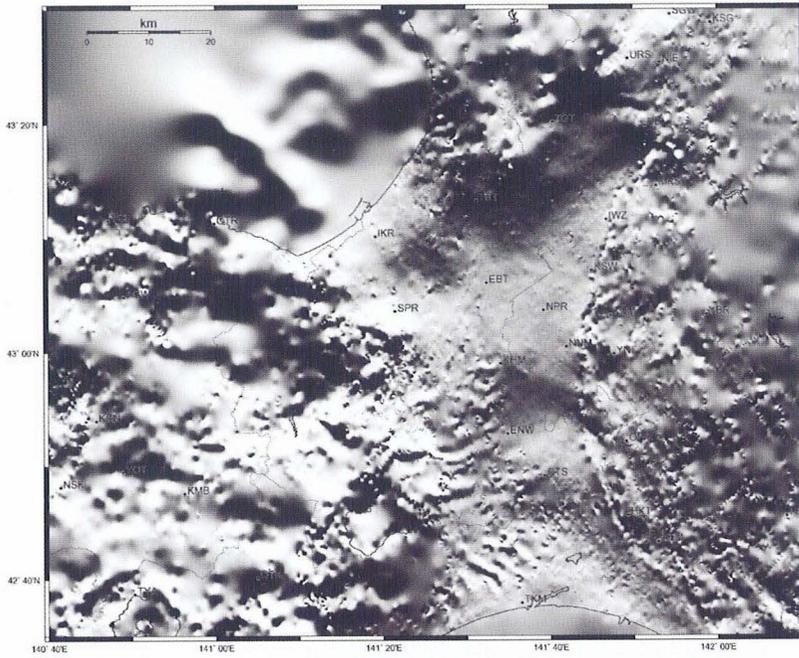
Planimetric gravity anomaly relief of Japan (Geographical Survey Institute, 1993, 2000) or southwest Japan (Shichi and Yamamoto, 2001a) were previously

constructed on the basis of dense gravity database (e.g. Geological Survey of Japan, 2000; Shichi and Yamamoto, 2001b). However, the detailed gravity relief around the Ishikari Lowland has not been given. As shown in the previous section, the Ishikari Lowland is characterized by the conspicuous presence of low gravity anomalies associated with abrupt gravity changes in the eastern margin of the plain, corresponding to the ITTFZ. Also, local gravity anomalies are forming the prominent lineament protruding westward around the ITTFZ. To clearly show the gravity structure around the Ishikari Lowland, particularly the sharp and fine linearity corresponding well to the ITTFZ, we discuss here relief-shaded gravity anomaly illuminated by the artificial light from various directions.

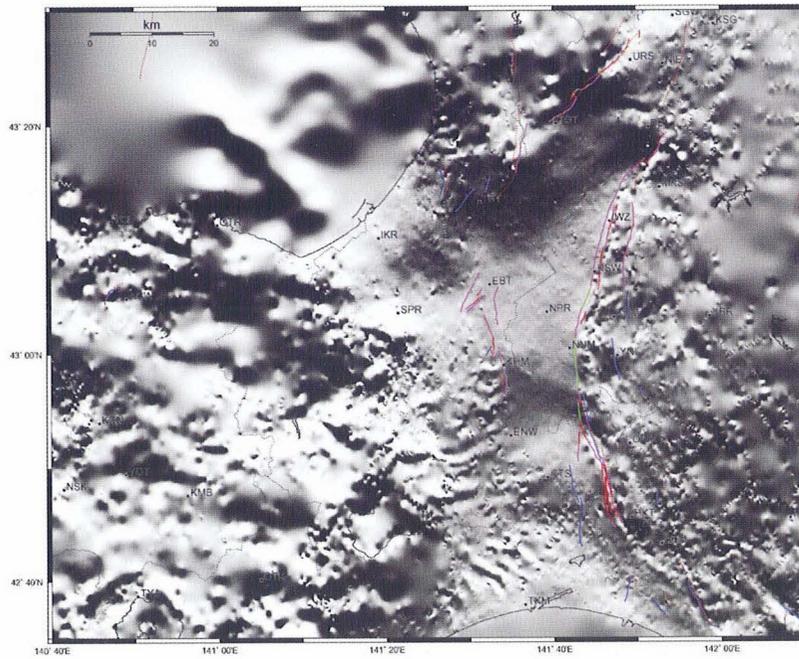
In general, Bouguer anomaly can be shaded by giving illumination to highlight gravity structures laterally varying along the azimuth direction (the direction of illumination). Therefore, gravity structures with lateral variations along the azimuth direction display striking contrast and also show striking difference as compared with those with lateral variations perpendicular to the azimuth direction. This means that gravity structures with lateral variations perfectly perpendicular to the azimuth direction never appear in gravity relief map shown in shades of white and black. In this paper we first take a horizontal derivative of non-filtered Bouguer anomaly along the azimuth direction. Then we normalize the derivative such that their values range from -1 (black) to 1 (white). This procedure makes brighter the areas whose Bouguer values increase along the illumination vector, while the areas with decreasing values along the vector are shown gloomily (blackish color in the figure). Note that we simply change the azimuth of view point and use the fixed elevation of 0 degree (horizontal view) in this study. In this way relief-shaded Bouguer gravity maps were produced for eight directions of illumination.

Fig. 3a illustrates the relief-shaded Bouguer gravity map in a planimetric view illuminated by the light from the due north direction. Note that the

Fig. 3. (a) Planimetric map showing the relief-shaded Bouguer gravity of the Ishikari Lowland and surrounding areas, illuminated by the light from the due north direction (azimuth: $N0^{\circ}E$, elevation: 0°). Azimuth direction is shown on the upper-right side of the figure. No filtering is applied to Bouguer anomaly. (b) Same as (a), but known active faults are superimposed in bright colors. Heavy colored lines and dotted red lines denote known active faults by Nakata and Imaizumi (2002) and the Research Group for Active Faults of Japan (1991), respectively. Colored faults indicate, red: certainly exist and location is accurately determined, magenta: certainly exist and location is not accurate, green: possibly exist (invisible), and blue: estimated fault lying at depths, respectively.



(a)



(b)



illumination vector is shown on the upper-right side of the figure. Fig. 3b is the same as Fig. 3a, but known active faults are superimposed in bright colors. Heavy colored lines and dotted red lines in Fig. 3b depict known active faults by Nakata and Imaizumi (2002) and the Research Group for Active Faults of Japan (1991), respectively. Colored faults in Fig. 3b indicate, red: certainly exist and location is accurately determined, magenta: certainly exist and location is not accurate, green: possibly exist (invisible), and blue: estimated fault lying at depths, respectively. In this manner we constructed the relief-shaded gravity maps illuminated by the artificial light from the eight directions (N, NE, E, SE, S, SW, W, NW), and each of them is corresponding to Figs. 3~10, respectively. As shown in Figs. 3 and 4, it is quite intriguing that a pronounced linearity of shaded relief along the ITTFZ is uncovered, although the azimuth direction is due north or NE that is nearly parallel to the trend of the ITTFZ. This lineament extends from at least 5 km north of IWZ (Iwamizawa) to several kilometers west portion of HKT (Hayakita) and ATM (Atsuma), and also shows a good agreement with distributions of the old (dotted red line) and new (thick colored line) active faults in northern and southern parts of the ITTFZ (Fig. 3b). Whereas, in central part near NNM (Naganuma), the lineament of relief-shaded gravity does not agree with the trend of active faults. These features can be found in Figs. 6 and 7 for the azimuth of NE and the due south, respectively. However, gravity shaded relief, running in almost the same trend with new active faults, continues about several kilometers east of NNM.

In Figs. 5 and 9 Bouguer anomaly relief was produced by illuminating the light from the due east and west directions, respectively. This is quite effective to delineate trends in the laterally heterogeneous gravity structure varying along E-W direction around the ITTFZ. In these two figures, two high gravity belts, running almost in the fault-parallel (N-S) direction, can be found distinctly. These striking two belts, running from near Iwamizawa (IWZ) to near Hayakita (HKT), are depicted as a pair of white and black shades which is protruding westward. Note that each of these two belts consists of a pair of Bouguer high and low extremes. Both of these two belts develop and are mapped in the western margin of the Miocene hill belts. These two belts have nearly the same orientation ($\sim N20^\circ E$ near IWZ) but are stepped each other by 1~2 km along much of the ITTFZ, both of which coincide approximately with the new active fault distributions at least north of KSW (Kurisawa). It should be noted that topographic relief may not be attributed to such two high anomaly belts. We interpret these results to reflect that the ITTFZ as a whole consists of two parallel fault strands, both of which run approximately in the same trend

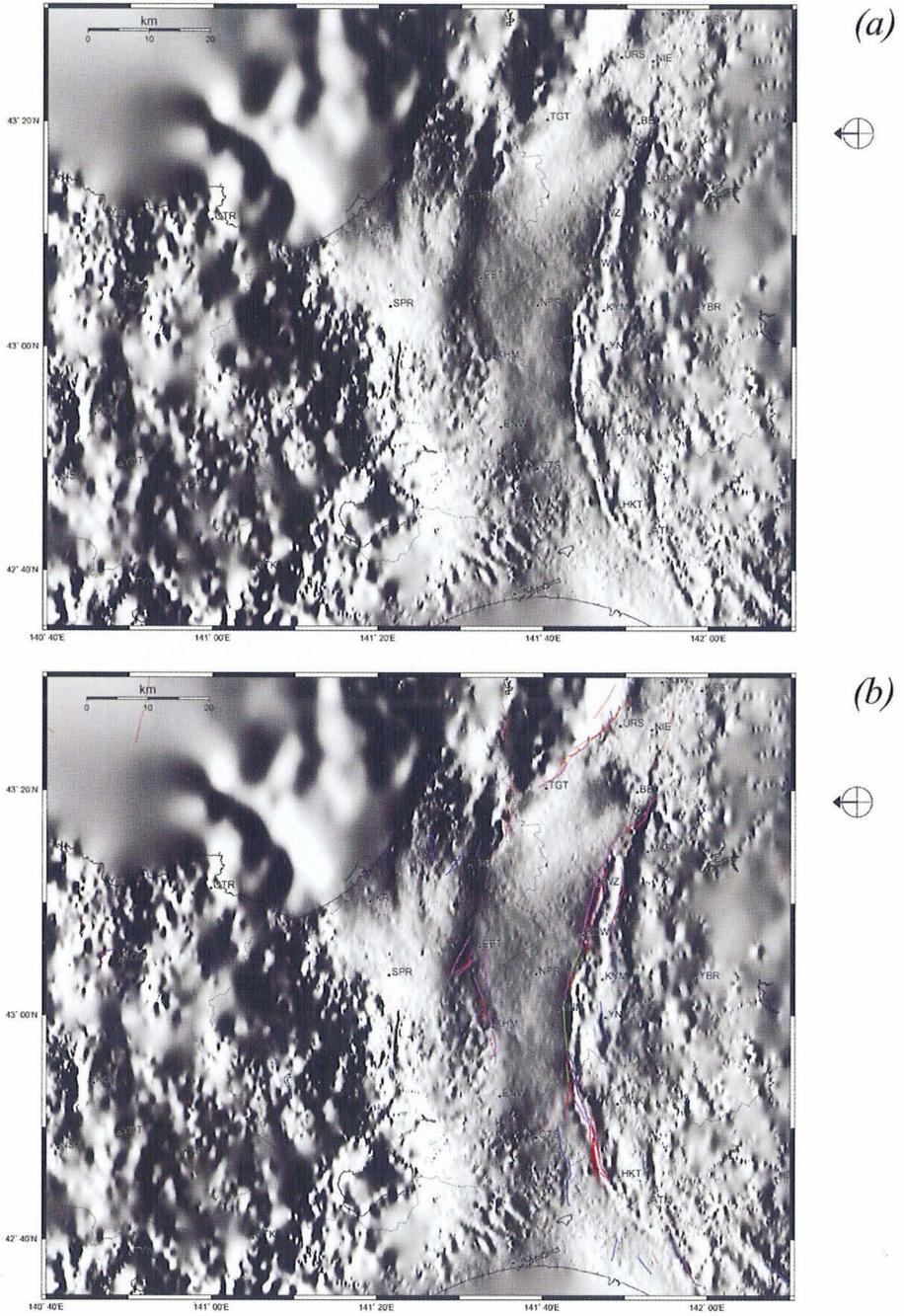


Fig. 5. Same as Fig. 3, but artificial illumination is from the east (azimuth: $N90^{\circ}E$, elevation: 0°).

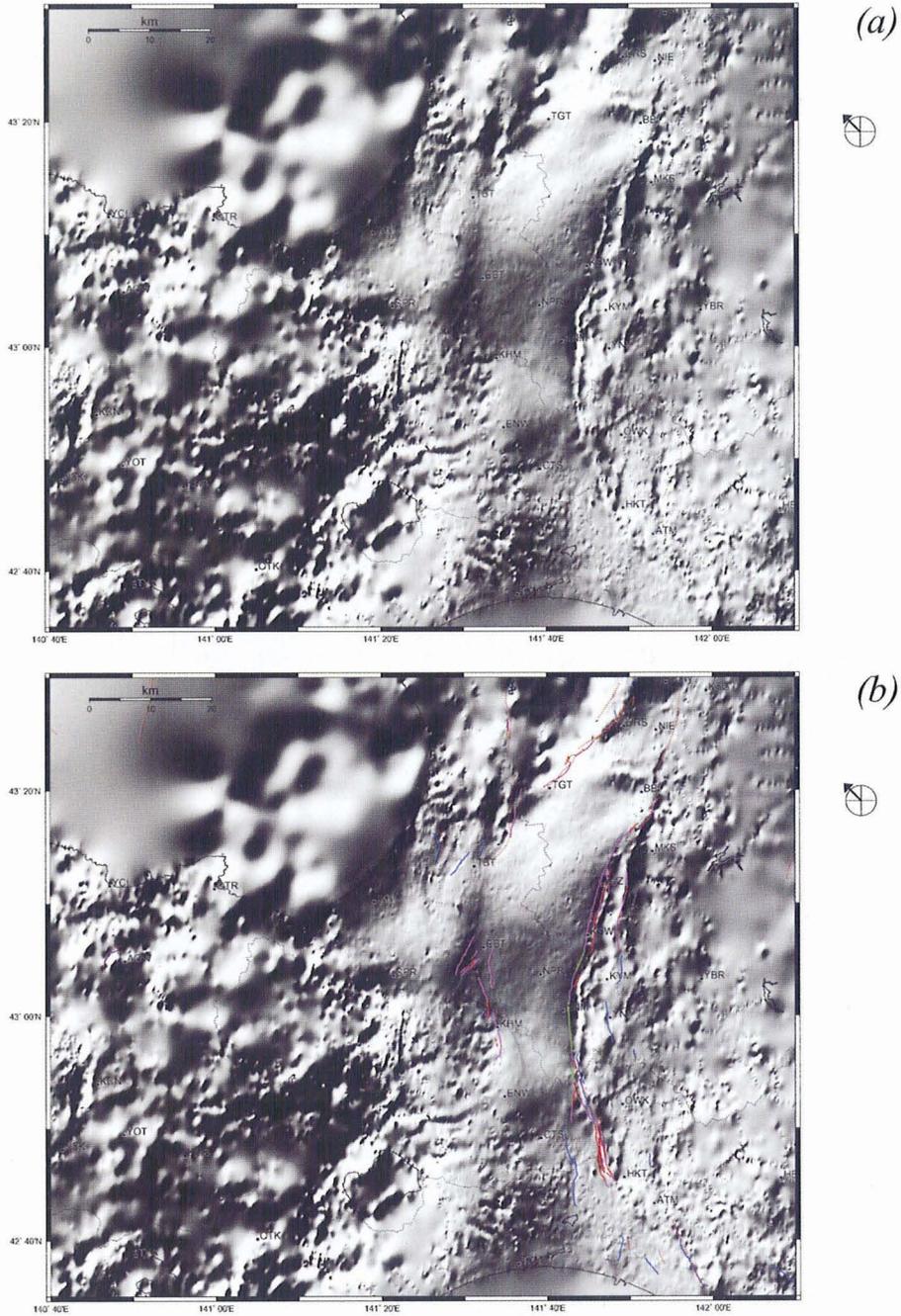


Fig. 6. Same as Fig. 3, but artificial illumination is from the south-east (azimuth : N135°E, elevation : 0°).

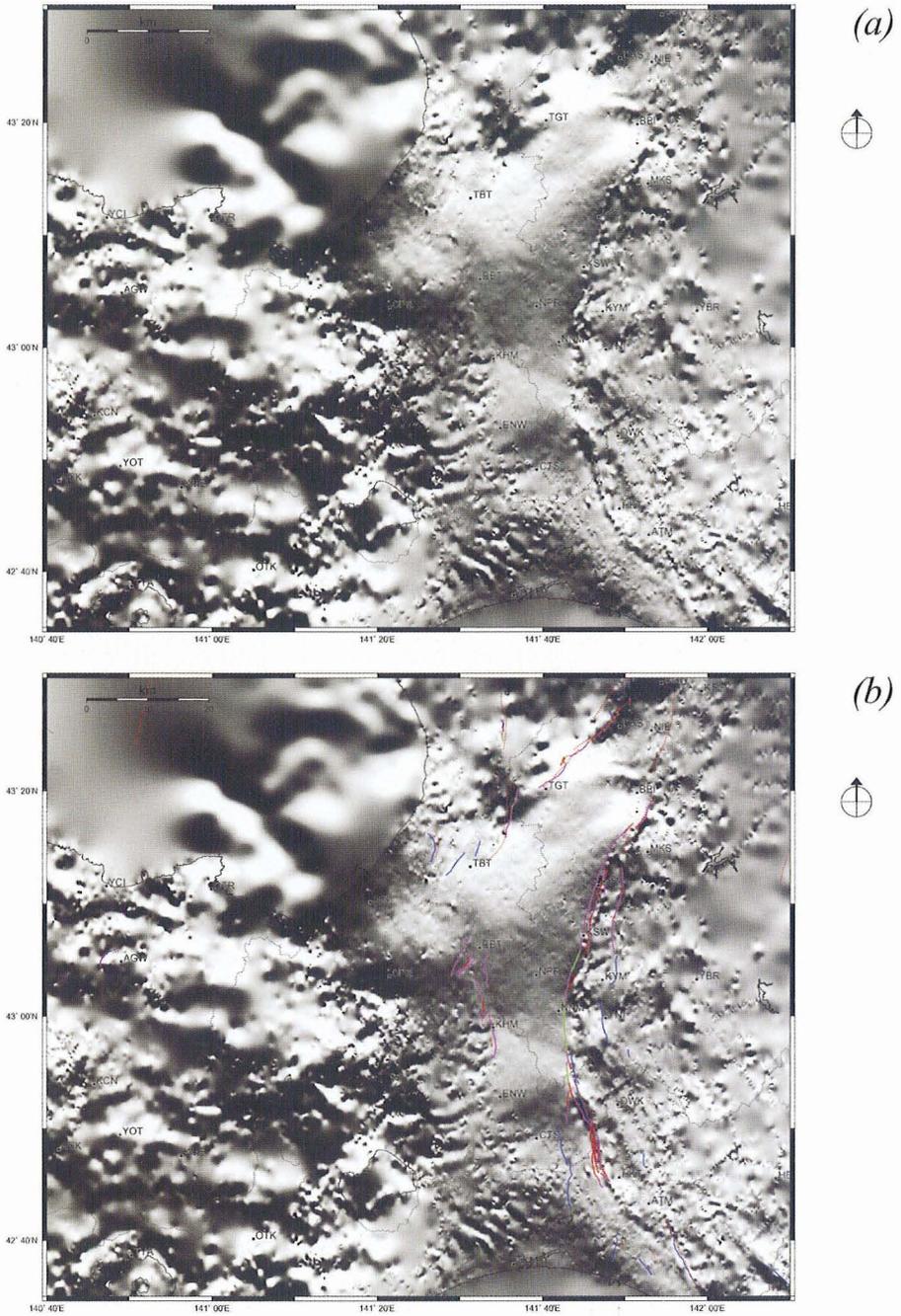


Fig. 7. Same as Fig. 3, but artificial illumination is from the south (azimuth : N180°E, elevation : 0°).

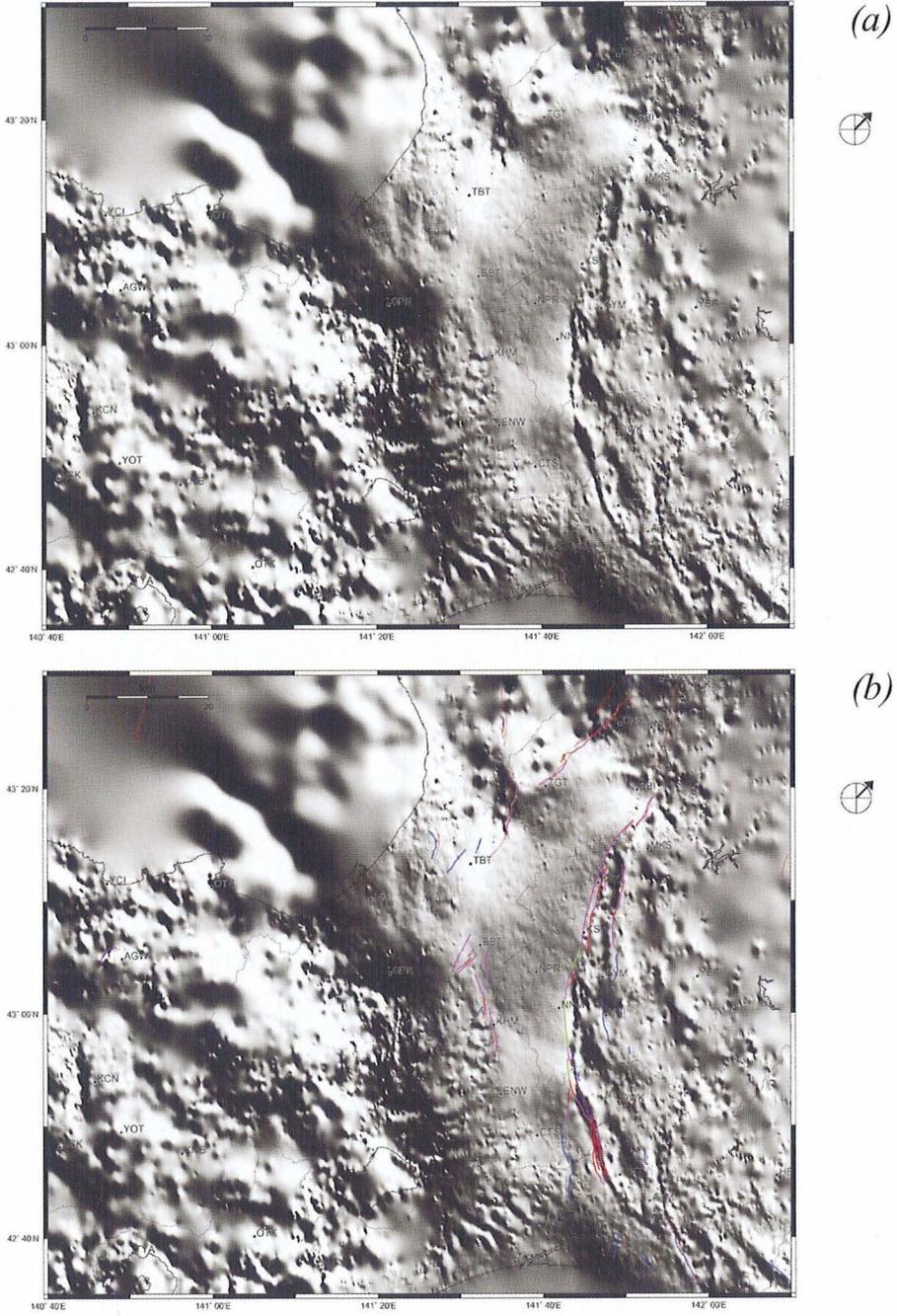


Fig. 8. Same as Fig. 3, but artificial illumination is from the south-west (azimuth: N135°W, elevation: 0°).

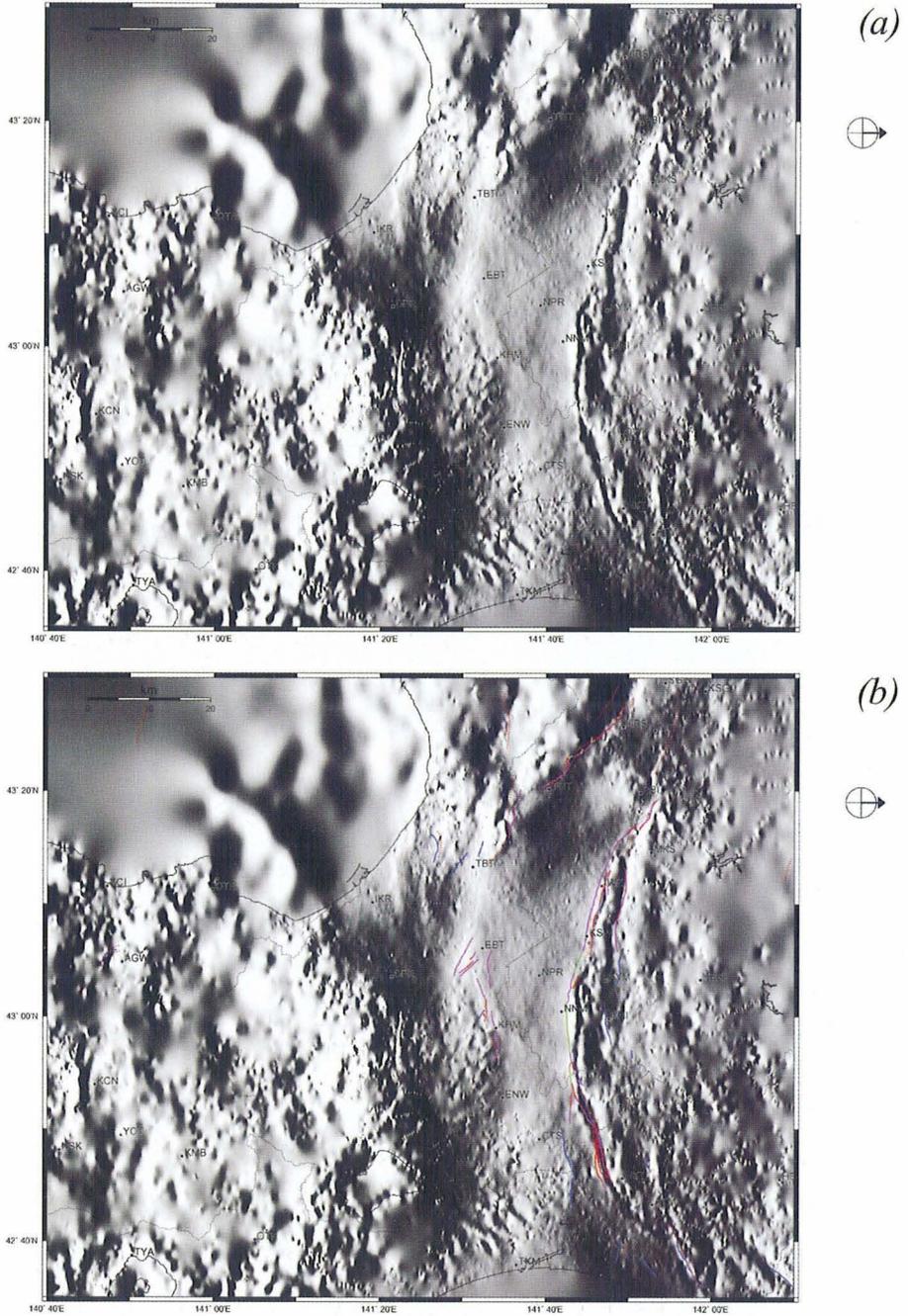


Fig. 9. Same as Fig. 3, but artificial illumination is from the west (azimuth : N90°W, elevation : 0°).

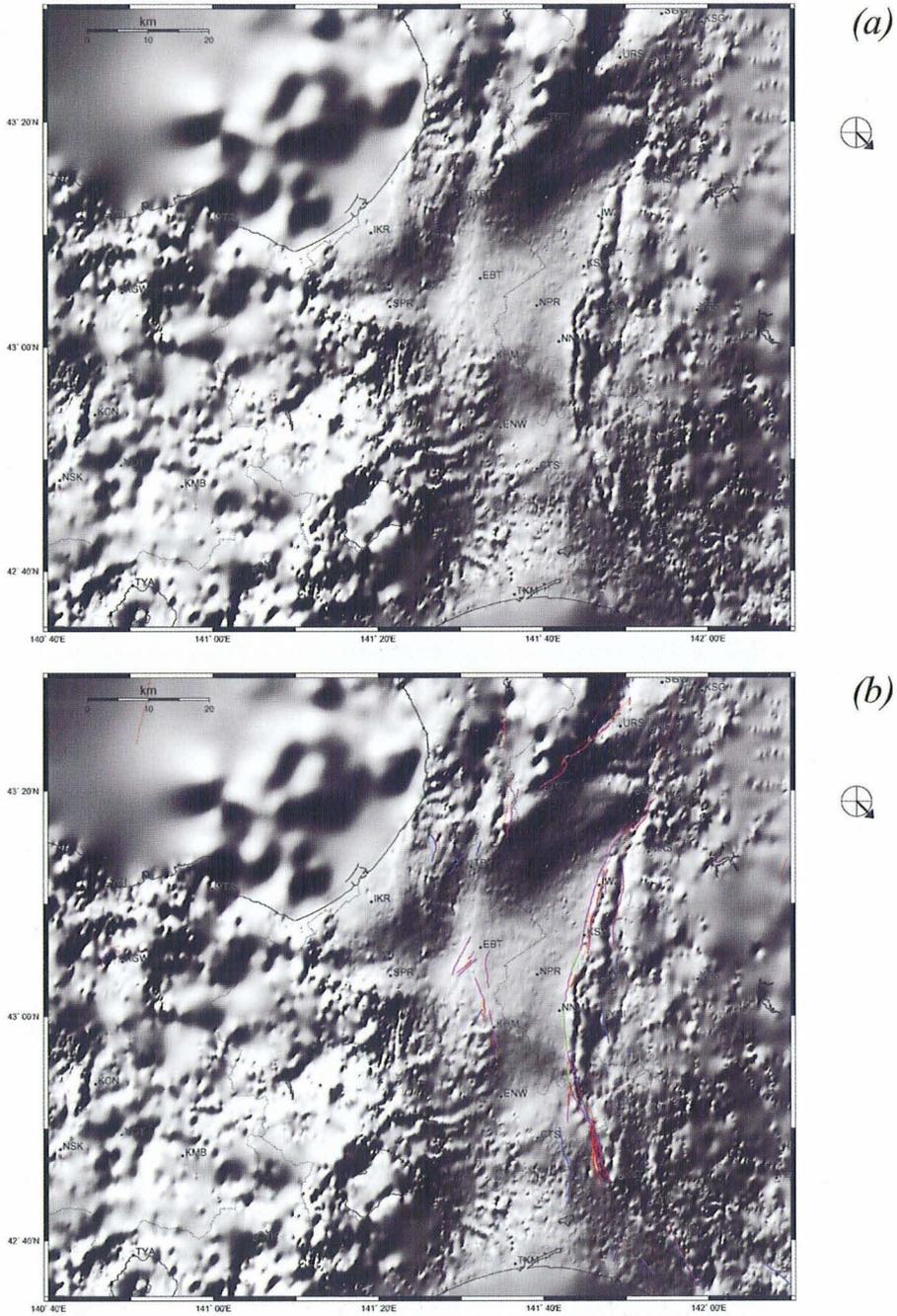


Fig. 10. Same as Fig. 3, but artificial illumination is from the north-west (azimuth : $N45^{\circ}W$, elevation : 0°).

and step each other by 1~2 km, along the western margin of the Miocene hill belts. In contrast, as illustrated well in Figs. 6, 8 and 10, gravity low is clearly observed along the new active fault extending northward from near KYM (Kuriyama) to near BBI (Bibai). This low anomaly runs along the eastern margin of the Iwamizawa Hill (IH) and the Kurisawa Hill (KH). However, it does not continue southward from KYM, implying that a sharp gravity change does not extend toward south along the eastern margin of the Umaoi Hill (UHN, UHC, UHS).

In addition, relief-shaded gravity for the azimuth direction of 0° (due north) or 180° (due south) from north clockwise exhibits a remarkable lineament extending southward from near BBI (Figs. 3~7). The southernmost tip of this lineament reaches about 5 km south of ATM (Atsuma). This fact suggests that active fault zone along the ITTFZ is spatially distributed over a distance of more than 80 km, whose southward extension can be mapped until about 20 km south of ATM along the boundaries of pre-Neogene volcanic rocks. Thus the southward extension of the ITTFZ can be well defined and mapped by gravity relief analysis, where no noteworthy faults are distributed. From this result we infer that the geometry of the southern end of the known fault system (the ITTFZ) provides continuity over a distance of 20~25 km along the relief-shaded Bouguer lineament roughly to the south-east. Consequently, our results suggest that the relief-shaded Bouguer gravity analysis, using closely-spaced Bouguer data, is quite effective in demarcating the extension of the pre-existed (or invisible) faults for correct estimates of their location and segmentation.

6. Discussion and Conclusions

We examined the Bouguer anomaly and its relief-shaded maps of the Ishikari Lowland and adjoining areas using closely-spaced gravity data. Gravity analysis delineated the detailed gravity structures around the eastern margin of the Ishikari Lowland, where the ITTFZ runs approximately in the N-S direction, bending toward west. Oka et al. (2001) summarized the tectonic evolution and formation of the ITTFZ on the basis of various geological and geophysical data. They obtained fine gravity structures around the ITTFZ in four profiles across which the Iwamizawa Fault (near IH), the Kurisawa Fault (near KH), the Izumisato Fault (near UHC) and the Umaoi and Kenbuchi Faults (near UHS) run roughly with the N-S trend. They showed that Bouguer anomaly across these four profiles exhibits two positive peaks, one of which corresponds well to the location of the above faults. While the second peak

steps to the east by 1~2 km from the other. This fact implies that these positive peaks continue along much of the ITTFZ and may be related with some specific fault movements. They also found that the Izumisato and Kenbuchi Faults show a reverse fault structure dipping toward the east from seismic reflection study. As described previously, these features around the ITTFZ can be analyzed and quantified by producing Bouguer anomaly gradient or Bouguer gravity relief shown in shades of white and black. Particularly, relief-shaded Bouguer anomaly is quite effective for such purposes because local gravity peaks along the ITTFZ can be detected easily and intuitively. Thus, Bouguer gravity relief was produced by illuminating the artificial light from eight directions to effectively depict the detailed gravity features varying laterally along the azimuth direction. Accordingly, the active fault distributions in the region were mapped from Bouguer anomaly relief.

A conspicuous linearity of shaded relief along the ITTFZ is detected from Bouguer anomaly relief maps. This lineament extends from at least 5 km north of IWZ (Iwamizawa), ending over several kilometers west of HKT (Hayakita) and ATM (Atsuma). Also, this lineament shows a good agreement with both distributions of the old (dotted red line) and new (thick colored line) active faults in northern and southern parts of the ITTFZ. Two strikingly high anomaly belts, corresponding to those pointed out by Oka et al. (2001), are observed along the ITTFZ from the present gravity relief maps. These two belts have nearly the same orientation ($\sim N20^{\circ}E$ near IWZ) but are stepped each other by 1~2 km along most of the ITTFZ, both of which coincide approximately with the new active fault distributions at least north of KSW (Kurisawa). This fact can be interpreted to reflect that the ITTFZ as a whole consists of two parallel fault strands, both of which run approximately in the same trend and step each other by 1~2 km, along the western margin of the Miocene hill belts. These results concur quite well with those of Oka et al. (2001). Furthermore, a remarkable lineament extending southward from near BBI to south of ATM is found on gravity relief map particularly for the azimuth direction of 0° (due north) or 180° (due south) from north clockwise. This fact asserts that the active fault strands along the ITTFZ is spatially distributed over a distance of more than 80 km and its southward extension can be mapped until 20~25 km south of ATM, separating the pre-Neogene volcanic rocks. Concludingly, we note that relief-shaded Bouguer gravity analysis plays an important major role in the gravity-based active fault mapping to locate and characterize the various strands and segmentation of a fault zone.

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References

- Geographical Survey Institute, 1993. Gravity anomaly relief map of the south-western Japan, 1 sheet, Geographical Survey Institute.
- Geographical Survey Institute, 2000. Gravity anomaly relief map of Japan, 3 sheets, (Technical Report, B-1-No. 28), Geographical Survey Institute.
- Geological Survey of Japan (ed.), 1995. Geological Map of Japan 1,000,000, 3rd Edition, CD-ROM Version, Digital Geoscience Map G-1 (DGM-G-1), Geological Survey of Japan.
- Geological Survey of Japan (ed.), 2000. Gravity CD-ROM of Japan, Digital Geoscience Map P-2, Geological Survey of Japan.
- Kasahara, M. and K. Miyazaki, 1998. Historical and recent seismic activities in Sapporo and vicinity, *Geophys. Bull. Hokkaido Univ.*, **61**, 239-261 (in Japanese).
- Komazawa, M., T. Hiroshima, Y. Murata, M. Makino and R. Morijiri, 1998. A gravity anomaly map of Sapporo, 1 : 200,000, Gravity Map Series, 10, Geological Survey of Japan.
- Nakai, S., K. Yamaguchi, K. Nitta, H. Yamamoto, K. Matsuo, M. Machida, M. Murakami, M. Ishihara, R. Shichi and A. Yamamoto, 1997. Data processing for the Japan Gravity Standardization Net 1996, in [Gravity, Geoid and Marine Geodesy] (GraGeoMar 96), Proceedings of the International Symposium, No. 117, Tokyo, Japan, September 30-October 5, 1996, convened and edited by J. Segawa, H. Fujimoto and S. Okubo, 228-233, Springer-Verlag Berlin Heidelberg, (pp. 746), ISBN : 3-540-63352-9.
- Nakata, T. and T. Imaizumi (ed.), 2002. Digital active fault map of Japan, University of Tokyo Press, pp 60 (in Japanese).
- Oka, T., 1986. Distribution and tectonic evolution of Late Cenozoic basins in Hokkaido, *Monograph Assoc. Geol. Collab. Japan*, **31**, 295-320 (in Japanese).
- Oka, T., J. Tajika, N. Ohtsu, W. Hirose, N. Okazaki and S. Ishimaru, 2001. The Ishikari Teichi Tounen Fault Zone, Active fault map and explanations, Geological Survey of Hokkaido (ed.), Hokkaido Government, pp 157 (in Japanese). (Japanese title was translated into English by the author)
- Research Group for Active Faults of Japan, 1980. Active faults in Japan, sheet maps and inventories, University of Tokyo Press, pp 363 (in Japanese).
- Research Group for Active Faults of Japan, 1991. Active faults in Japan, sheet maps and inventories, revised edition, University of Tokyo Press, pp 437 (in Japanese).
- Shichi, R. and A. Yamamoto (Representatives of the Gravity Research Group in Southwest Japan), 2001a. Gravity anomaly relief map of Southwest Japan (A1-size, 1 : 3,000,000, one set of two sheets), *Bull. Nagoya University Museum, Special Rept.*, **9**, Appended Maps.
- Shichi, R. and A. Yamamoto (Representatives of the Gravity Research Group in Southwest

- Japan), 2001b. Gravity Database of Southwest Japan (CD-ROM), Bull. Nagoya University Museum, Special Rept., **9**, CD-ROM.
- Suzuki, H., 1976. The International Gravity Standardization Net 1971 and the Japan Gravity Standardization Net 1975, *J. Geod. Soc. Japan*, **22**, 112-129.
- Wessel, P. and W.H.F. Smith, 1995. New version of the generic mapping tools released, *EOS, Trans. Am. Geophys. Un., Suppl.*, **Aug. 15**.
- Yamaguchi, K., K. Nitta, H. Yamamoto, K. Matsuo, M. Machida, M. Murakami, M. Ishihara, S. Nakai, R. Shichi and A. Yamamoto, 1997. The establishment of the Japan Gravity Standardization Net 1996, in [Gravity, Geoid and Marine Geodesy] (GraGeoMar96), Proceedings of the International Symposium, No. 117, Tokyo, Japan, September 30-October 5, 1996, convened and edited by J. Segawa, H. Fujimoto and S. Okubo, 241-248, Springer-Verlag Berlin Heidelberg, (pp. 746), ISBN : 3-540-63352-9.
- Yamamoto, A., 2002. Spherical terrain corrections for gravity anomaly using a digital elevation model gridded with nodes at every 50 m, *J. Fac. Sci., Hokkaido Univ., Ser. 7*, **11**, No. 6, 845-880.
- Yamamoto, A., 2003. Gravity anomaly atlas of the Ishikari Plain and its vicinity, Hokkaido, Japan, *Geophys. Bull. Hokkaido Univ.*, **66**, 33-62 (in Japanese).
- Yamamoto, A. and H. Ishikawa, 2002. Gravity anomaly and shallow crustal structure around the southernmost part of the Oshima Peninsula, Hokkaido, Japan, *Geophys. Bull. Hokkaido Univ.*, **65**, 247-290 (in Japanese).
- Yamamoto, A., Y. Fukao, M. Furumoto, R. Shichi and H. Shiraki, 1986. A Bouguer anomaly gradient belt on the Pacific side of Central Honshu, Japan, *Geophys. Res. Lett.*, **13**, 537-540.
- Yamamoto, A., M. Saito, K. Yamada and H. Ishikawa, 2001a. Gravity anomaly and crustal structure around the southern part of the Hidaka Collision Zone in Hokkaido, Japan, *Geophys. Bull. Hokkaido Univ.*, **64**, 21-49 (in Japanese).
- Yamamoto, A., K. Yamada, M. Saito and H. Ishikawa, 2001b. Gravity anomaly around the Horoman peridotite region, central Hokkaido, Japan, *Geophys. Bull. Hokkaido Univ.*, **64**, 51-80 (in Japanese).