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Dense Clustering of Latest Cenozoic Caldera-like Basins of Central Hokkaido, Japan, Evidenced by Gravimetric Study

Akihiko Yamamoto

Institute of Seismology and Volcanology, Graduate School of Science, Hokkaido University, Sapporo, Japan

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Abstract

This paper examines gravity structures of the central Hokkaido using new gravity data, and attempts to present preliminary interpretations of their characteristic features, particularly with special attention to the numerous sedimentary basins of latest Cenozoic age (late Miocene to Quaternary). We compile more than 6,000 gravity data of the study area and produce a new gravity anomaly map. The new map in the central Hokkaido delineates two characteristic features that are divided by a boundary which falls approximately along the Tokoro Tectonic Line (TTL) of the map area. To the east of TTL, the Bouguer anomaly field is characterized by the high-amplitude gravity ridge attributable to Mesozoic sequences associated with several ellipsoidal gravity depressions having an almost NE-SW major axis of 15～20 km, whereas to the west, anomaly relief is much lower with several closed gravity depressions relative to the region to the east of TTL. It is quite intriguing that these remarkable lows, dominant over the mountainous area to the west of TTL, clearly form a dense cluster of closed depression with a diameter of about 10 km, which well correlates with the distributions of the known basins. These features are much strengthened by a relief-shaded Bouguer image. Gravity analysis by horizontal derivatives and high-pass filtering of the gravity field shows that the major high Bouguer gradient zones, found to be nearly closed in a ring-shaped or oval-shaped form, are remarkable in the central part of the map area. Several of them indicate a better coincidence between the basin rims and the location of a steep gravity change. This implies that they have caldera-like collapse structure, and that the subsurface part of these basins accords with a steep-sided depression, with a flat bottom, probably filled with low-density volcanic materials. The Bouguer anomaly contours around these caldera-like basins are likely those of the thickness contours of the basin fill, which yields significant constraints on the subsurface structure beneath the basin. Assuming the average density of the basin fill to be 2.2 g/cm^3 (a density contrast of 0.47 g/cm^3) in one of the typical Cenozoic basins in the central Hokkaido, we obtain the result that an apparent maximum thickness of the basin fill amounts to be 750 m ～1,000 m, which corresponds to a gravity attraction with a relative amplitude of 15 and 20 mgal, respectively.

1. Introduction

The central Hokkaido, Japan, is characterized by large mountainous areas with notable calderas and volcanic plateau underlain by tuffs and lavas, as well as numerous small-scale sedimentary basins (e.g., *Yamagishi, 1976* ; *Oka, 1986* ; *Kato et al., 1990*) which have continuously undergone tectonic movements of east-west compression (*Miyasaka and Matsui, 1986*). Recent studies show that these sedimentary basins have been formed during late Cenozoic (late Miocene to Quaternary) age and their tectonic evolution is roughly explained in terms of plate tectonics (*Oka, 1986*). Gravimetric studies are becoming widely acknowledged as a powerful and useful tool for studying the distributions of subsurface masses that may be associated with tectonic or volcanic activity to form such basins or calderas. The gravity field prevailing over the central Hokkaido, particularly around the Cenozoic basins, is best reflected on Bouguer gravity anomalies that are most sensitive to the subsurface mass distributions and are influenced by the nature of underlying geological formations.

A number of gravity studies have given significant constraints on basins or calderas around volcanic areas. *Healey* (*1968*) described the gravity anomaly at Pahute Mesa, located north of Timber Mountain, and attributed the anomaly to the volcanic rocks of the Silent Canyon caldera complex. The gravity anomaly he described is roughly circular and its overall appearance has probably affected the thinking of many regarding the geometry of the caldera complex. Later *Ferguson et al.* (*1994*), based on gravity and seismic travel time data, showed that the Silent Canyon caldera complex is actually a nested set of buried calderas, and that abrupt changes in the subsurface thickness of the caldera-forming units occur across the faults, indicating that these linear features served as caldera boundaries. *Gettings and Griscom* (*1988*) draw a conclusion that a ring dyke of mafic composition is inferred to intrude to near-surface levels along the caldera ring fractures, and low-density fill of the caldera floor probably has a thickness of 0.7-0.9 km from gravity modeling study of Newberry Volcano in U.S.A. *Eaton et al.* (*1975*) and *Kane et al.* (*1976*) gave interpretations of gravity anomalies over a young volcanic center in connection with Yellowstone and Long Valley Caldera in U.S.A., respectively. The presence of five major centers in the Taupo Volcanic Zone (New Zealand), each associated with an approximately circular negative anomaly, was revealed by gravity analysis (*Rogan, 1982*). *Carle* (*1988*) suggested that Long Valley Caldera has a piston-shaped collapse structure based on three-dimensional

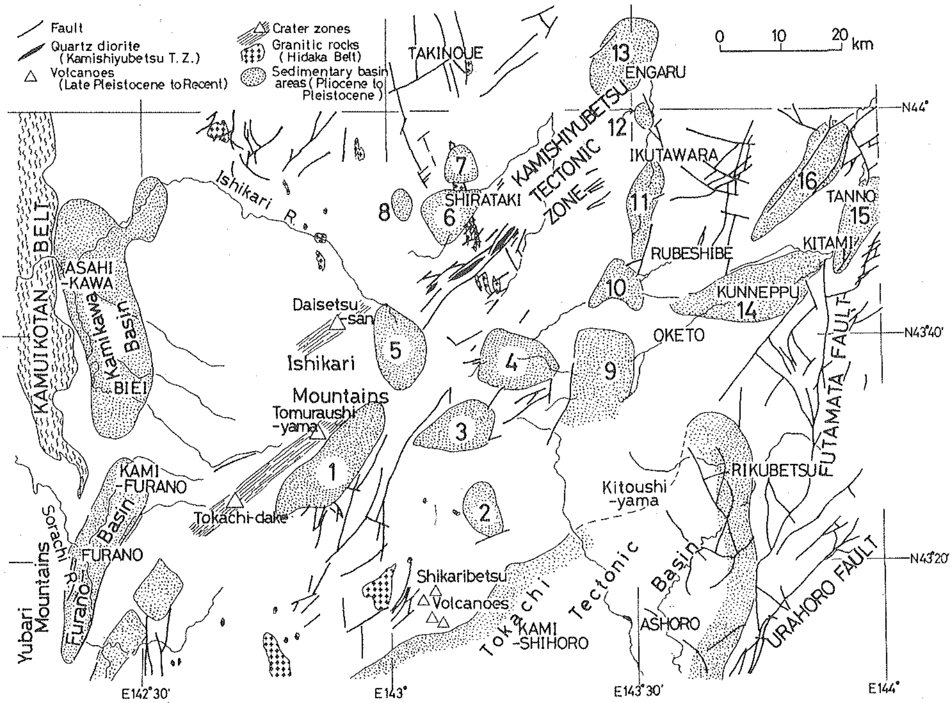


Fig. 1. Distributions of the latest Cenozoic basins around the Kitami Mountain area, central Hokkaido (After Oka, 1986). The perimeters of these sixteen basins are digitized and used in relation to gravimetric investigation in this study.

gravity modeling. Iterative 3-D modeling using gravity data also placed significant constraints on the structure and volcanic evolution of Tenerife, Canary Islands (*Ablay and Kearey, 2000*). Recently, *Komuro et al.* (*2002*) reported that the subsurface structure of the Teragi Cauldron in Sw Japan may be square shaped, with a steep rim and a flat floor, based on the fact that the low gravity anomaly over the cauldron shows a pan-shaped gravity depression.

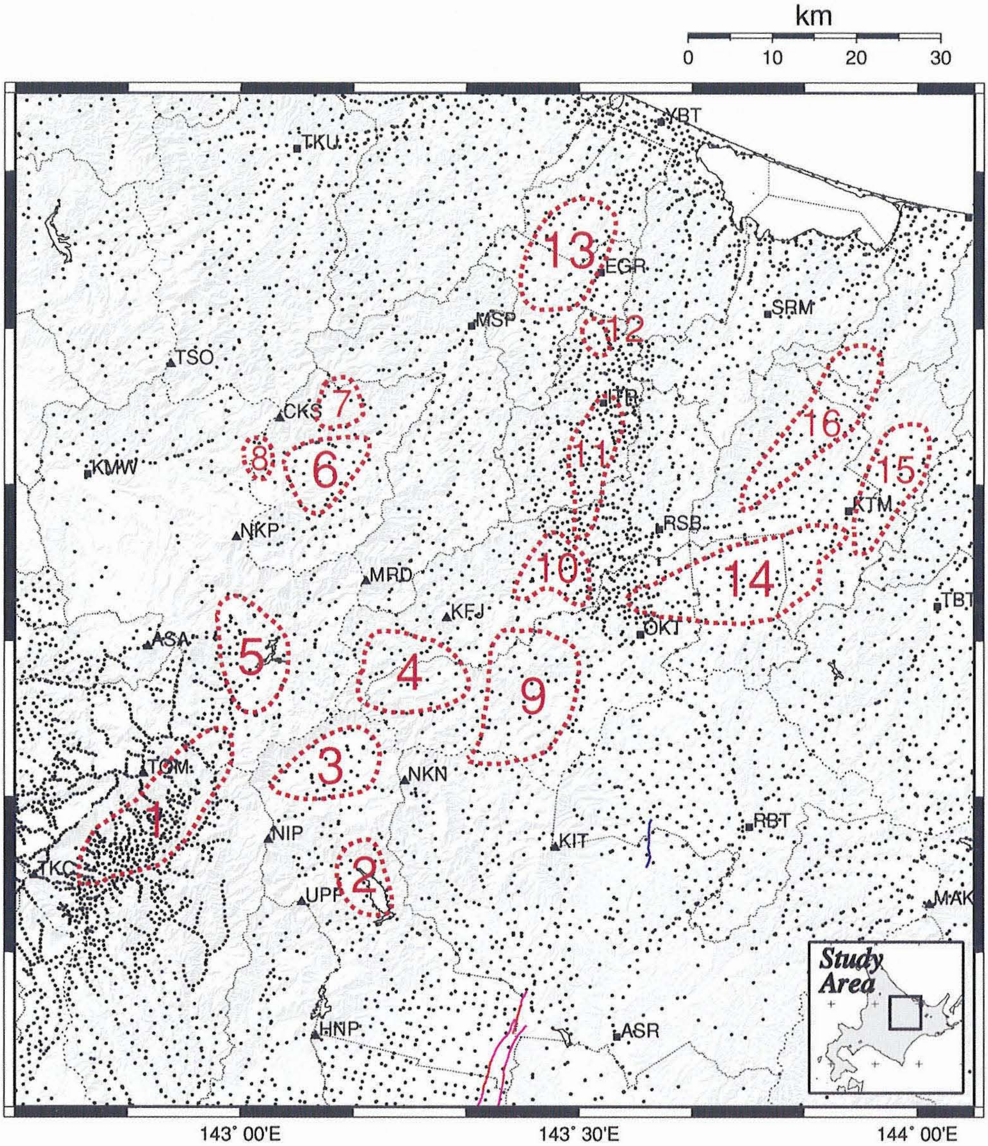
Understanding tectonic basins or volcanic calderas requires passive geophysical study, as well as detailed geological and petrological studies. The less seismicity and the absence of ongoing eruptions around the areas of the late Cenozoic caldera-like basins (Figs. 1 and 2) have precluded geophysical interpretations or investigations. Although a general view of Bouguer anomaly in the central Hokkaido shows that (1) low anomalies corresponding to Quaternary mafic volcanic rocks that are dominant over the mountainous areas (the Ishikari Mountains), and (2) Mesozoic high-density rocks (late Jurassic volcanics and late Cretaceous plutonic rocks) are characterized by high Bouguer anomalies, detailed gravity structure particularly around the basins in the central Hokkaido has not been studied so far.

The aim of this paper is to present preliminary interpretations of gravity structures of north-eastern part of the central Hokkaido with special reference to the numerous small-scale sedimentary basins formed during latest Cenozoic age (late Miocene to Quaternary). We also attempt to constrain the geometry of subsurface structures by integrating geophysical data (Bouguer anomaly).

2. Geological Background

Fig. 4 illustrates the generalized geology of the central Hokkaido area with the gravity anomaly of Fig. 3 at a 5 mgal contour interval superimposed for reference. The distributions of the latest Cenozoic sedimentary basins (Fig. 1) of the central Hokkaido are redrawn in Fig. 2 with gravity stations, where sixteen basins are sequentially numbered according to Fig. 4 of *Oka* (*1986*). The map area in this study is geologically and tectonophysically divided into three zones: the Hidaka Zone, the Tokoro Zone and the Nemuro Zone (from left to right in Fig. 4), each of which runs almost in NWN-SES direction across Hokkaido. It is intriguing that the sedimentary basins of our interest cluster in the northeastern part of the Ishikari Mountains (Daisetsu and Tokachi volcanic areas) and the southern part of the Kitami Mountains, and that their linear dimension as a whole is about 10 km in diameter. As shown in Figs. 2 and 4, most of the basins (#2∼#4, #9∼#12 and #14∼#16) distribute in the Tokoro Zone

Fig. 2. Locations of gravity stations used in this study with shaded image of digital topography. Thick and red-dotted polygons with specific sequential numbers (#1∼#16) indicate the rims of the Cenozoic basins (see Fig. 1) in the central Hokkaido by Oka (1986). Heavy colored lines demonstrate known active faults by Nakata and Imaizumi (2002) which 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. Location of the study region is shown in the bottom right corner on a map of Hokkaido. Large closed triangles and squares, followed by three letters, indicate geographical locations of major summits and cities (towns), respectively. ASA: Mt. Asahidake, ASR: Ashoro, CKS: Mt. Chitokaniushi, EGR: Engaru, HNP: Mt. Higashi-nupukaushinupuri, ITR: Ikutahara, KFJ: Mt. Kitamifuji, KIT: Mt. Kitoushi, KMW: Kamikawa, KTM: Kitami, MAK: Mt. Meakan, MRD: Mt. Muridake, MSP: Maruseppu, NIP: Mt. Nipesotsu, NKN: Mt. Nishi-kumaneshiri, NKP: Mt. Niseikaushuppe, OKT: Oketo, RBT: Rikubetsu, RSB: Rubeshibe, SRM: Saroma, TBT: Tsubetsu, TKC: Mt. Tokachidake, TKU: Takinoue, TOM: Mt. Tomuraushi, TSO: Mt. Teshiodake, UPP: Mt. Upepesanke, YBT: Yubetsu.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which largely consists of Mesozoic rocks, that is, Late Cretaceous deposits-conglomerate and Late Jurassic dismembered ophiolite sequence. In contrast, the remainder of the basins (#1, #5~#8, and #13) belongs to the Hidaka Zone which is characterized by Late Cretaceous deposits resting on an undated basement and Oligocene-Miocene metamorphic rocks. There are no conspicuous faults present around the basins (Figs. 2 and 4), which would contribute to the shape or structure of the basins. In the eastern part of these basins, Mesozoic rocks are extensively dominant. East of these basins lies the Nemuro Zone whose westernmost boundary is abruptly cut by the Abashiri Tectonic Line (ATL) which runs through Kitami (KTM) to Rikubetsu (RBT) in Fig. 4. The Kamishiyubetsu Tectonic Line sharply bounds these basins in their northernmost part. Several basins (#11~#13) are sharply bounded on the east by the Tokoro Tectonic Line (TTL) which runs in NWN-SES direction passing through Yubetsu (YBT), Engaru (EGR), Ikutahara (ITR), Rubeshibe (RSB) and Rikubetsu (RBT). Also three basins (#14~#16) are located in Tokoro belt which largely consists of Mesozoic rocks (Late Cretaceous deposits and Late Jurassic ophiolite sequence), whose easternmost margin is bounded by ATL (*Kimura, 1981*).

Yamagishi (*1976*) pointed out that most of these basins show a closed polygon with a diameter of about 10 km associated with large-scale volcanic activity. Stratigraphic study indicates that normal sediments of the basins contain fair amount of volcanic products that are chiefly rhyolitic pumice flow deposits subsequent to the accumulation of the basal conglomerates, and also abut against the basement at high angle (*Yamagishi, 1976*). Consequently, *Yamagishi* (*1976*) and *Moriya* (*1983*) draw a similar conclusion that those basins possess caldera-like collapse structure that was formed during the age from Neogene Tertiary to Pleistocene. Recently, *Ishii* (*2001*) and *Ishii et al.* (*2002*) argued about the characteristic features of one of these basins, the Tokachi-Mitsumata Basin (#3 in Fig. 2), and they concluded on the basis of detailed geological study that the Tokachi-Mitsumata Basin is an oval-shaped caldera (about 13 km by 10 km), formed by effusion of Muka pyroclastic flow in latest Cenozoic age (487±17 ka). These geological interpretations with well-established evidences suggest that other basins may also be considered as late Cenozoic "caldera or cauldron". The evidence to define them as "caldera", however, is not discussed here since it is beyond the scope of this paper. One of the chief objectives of this paper is to delineate gravity features and present reliable evidence to constrain the geometry of subsurface structures by gravity analysis.

3. Gravity Data and Reductions

Recent gravimetric studies such as *Geographical Survey Institute* (*GSI*) (*1985*), *Komazawa et al.* (*1987*), *Kono and Furuse* (*1989*), *Geological Survey of Japan* (*GSJ*) (*1992*), and *Komazawa et al.* (*1999*) have presented gravity anomaly maps of Hokkaido district or whole Japanese Islands and delineated characteristic features of Bouguer gravity. These maps, however, do not illustrate detailed features of late Cenozoic basins in the central Hokkaido due to lack of gravity data and/or the nonuniformity of station coverage. To overcome this disadvantage we compiled gravity data from many institutes such that station coverage would be as uniform and dense as possible. Gravity data used in this paper consists of the gravity database by *GSJ* (*2000*) and land gravity data measured by Hokkaido University. In total, about 6,100 gravity data are collected for gravity study around the central Hokkaido. Fig. 2 shows the distribution of gravity data used in this study. Gravity data by *GSJ* (*2000*) are reprocessed in a uniform manner used in this study. 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, instrumental 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. On a mature active, volcanic areas such as the central Hokkaido, where the topography is extreme and elevation varies in excess of 2.3 km above and below sea level, terrain effects are large and show considerable spatial variations. Accordingly, in this study, we compute terrain corrections using digital elevation model spaced at every 50 m, provided by the *GSI* (*2001*), to a radius of 80 km according to the method by *Yamamoto* (*2002*). In all reductions the earth's sphericity is taken into consideration.

Quantitative analysis of gravity anomalies relies heavily on the accuracy of Bouguer reduction density about which we need a priori information. An error of 0.1 g/cm^3 in the reduction density, corresponding to an error of nearly 0.42 mgal in Bouguer anomaly for every 100 m, is not a very large error in itself but an error of 0.1 g/cm^3 in the density may have a large effect on the interpretations of Bouguer anomalies (*Yamamoto, 1999*). However, selection of an optimum reduction density for the Bouguer and terrain corrections is problematic because of the variability in density of the lithologies present. Also we note that there is not a unique solution for the problem. First, we applied the simple Nettleton's method (*Nettleton, 1939*) to the central Hokkaido to estimate an optimum reduction density. The obtained result is 2.68 g/cm^3 which is somewhat a larger estimate. Secondly, we applied the F-H method (*Fukao et al., 1981*; *Yamamoto et al., 1982*) to the same study area to estimate an appropriate reduction density, and obtained an approximately constant value of 2.61 g/cm^3 for mesh size 4′ (~6.4 km) to 10′ (~16 km). Then, ABIC method (*Murata, 1993*) was applied to the same study area and an optimum reduction density was estimated to be 2.4912 g/cm^3. Bouguer anomaly maps produced by using these optimum densities do not cause considerable changes of amplitudes or patterns of Bouguer gravity (not shown here). Consequently, we use a conventional value (2.67 g/cm^3) for a gravity reduction density.

Thus Bouguer anomaly values were determined to produce a new gravity map of the central Hokkaido and adjoining areas. After an overall revision and reduction for these gravity data, a Bouguer anomaly map, a high-pass filtered anomaly map, and a first horizontal derivative map of the region were constructed.

4. Bouguer Anomaly

4.1 Regional-Scale Gravity Anomaly Features

According to the procedures described in the previous sections, we produced the color-coded new gravity anomaly map in the central Hokkaido and vicinity (Fig. 3a), where Bouguer gravity is contoured at 2 mgal interval and grid size for automatic machine-contouring is 0.025 arc-minutes (~40 m). In addition, in order to emphasize (and isolate) short-wavelength gravity depression and bulge more fully, Bouguer anomaly fields are high-pass filtered with a cut-off wavelength of 20 km (Fig. 3b). Thick and red-dotted polygons in Fig. 3 indicate the rims of the Cenozoic basins defined by *Oka* (*1986*). See Fig. 2 for their sequential numbers (#1~#16). Note that shaded relief of Bouguer gravity in Fig. 3 is generated by illuminating the artificial light from the north-west direction in order to highlight gravity structures in much more detail.

As shown in Fig. 3a, the Bouguer anomaly field is characterized by two markedly difference textures divided by a boundary which falls approximately along the Tokoro Tectonic Line (TTL) of the map area. To the east of TTL, the Bouguer anomaly field is characterized by the high-amplitude gravity ridge which is attributable to Mesozoic sequences, whereas to the west, anomaly relief is much lower with several closed depressions relative to the region to the west of TTL. Note that these high and low anomaly zones are sharply separated by

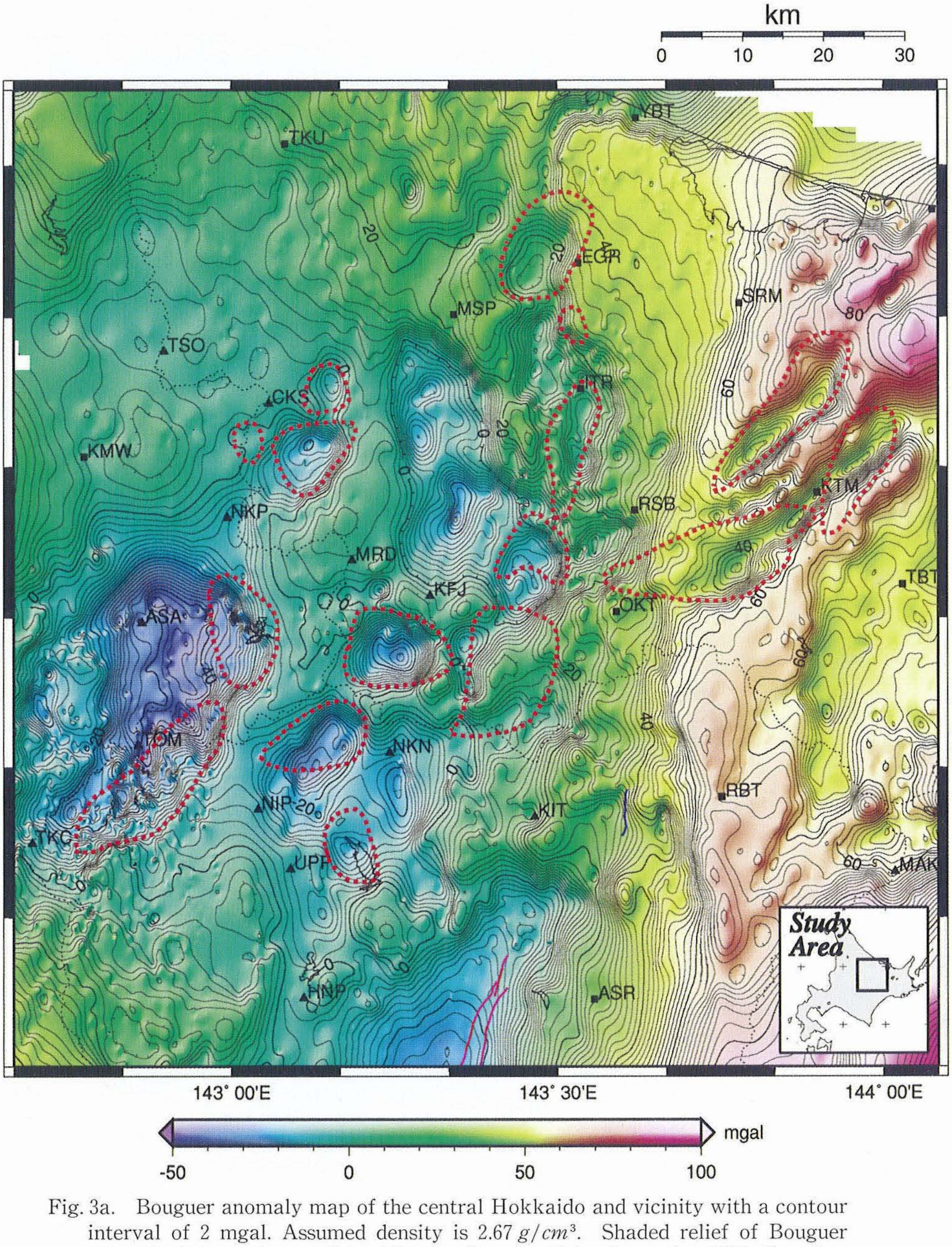

Fig. 3a. Bouguer anomaly map of the central Hokkaido and vicinity with a contour interval of 2 mgal. Assumed density is 2.67 g/cm^3. Shaded relief of Bouguer anomaly is superimposed by illuminating the light from the NW direction. Thick and red-dotted polygons indicate the rims of the Cenozoic basins by Oka (1986). See Fig. 2 for their sequential numbers (#1～#16). See also the caption of Fig. 2 for the abbreviations and colored faults.

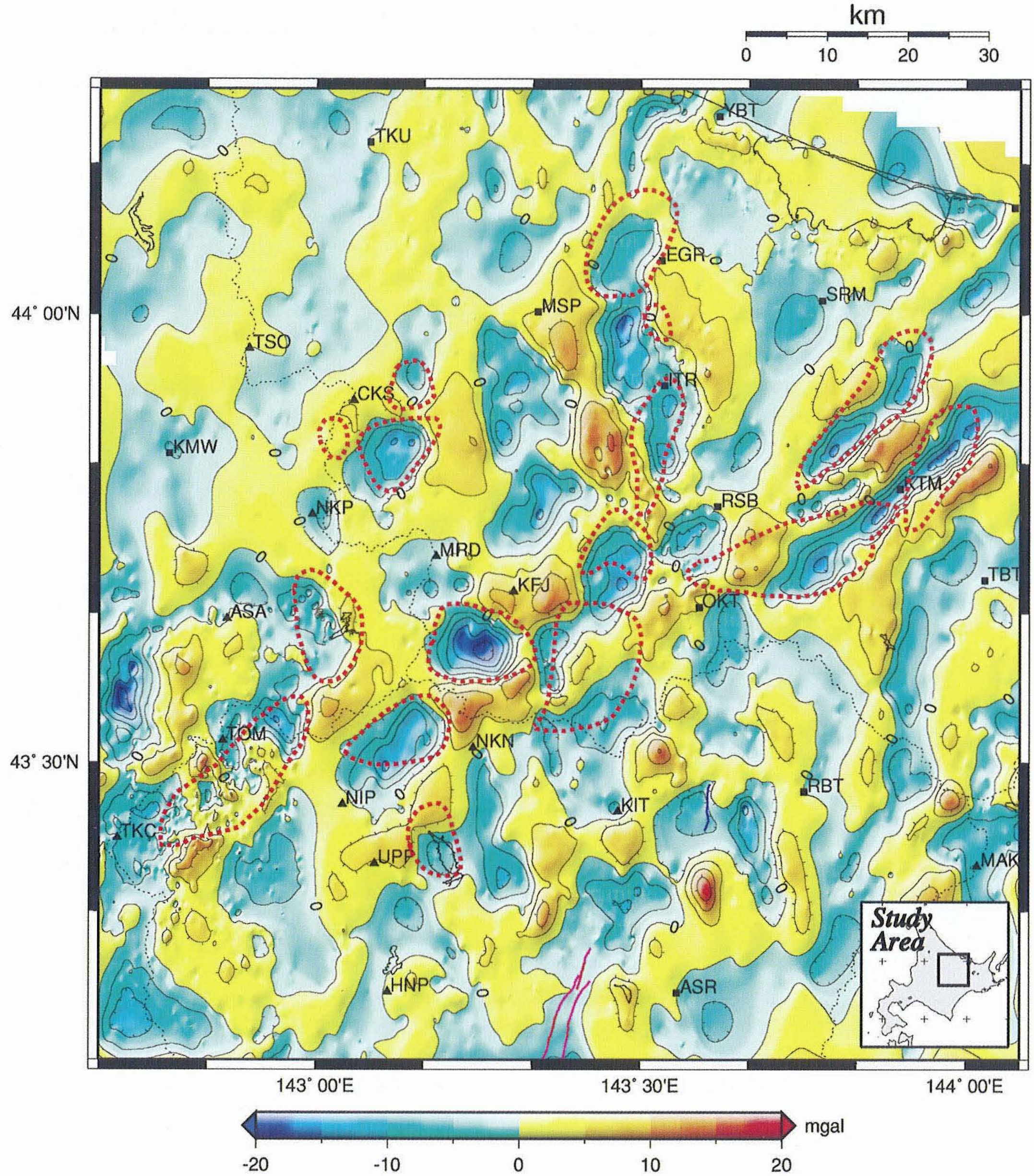

Fig. 3b. Same as Fig. 3a, but Bouguer anomalies, with a contour interval of 5 mgal, are high-pass filtered with a cut-off wavelength of 20 km, where short-wave-length gravity depression and bulge are isolated more fully.

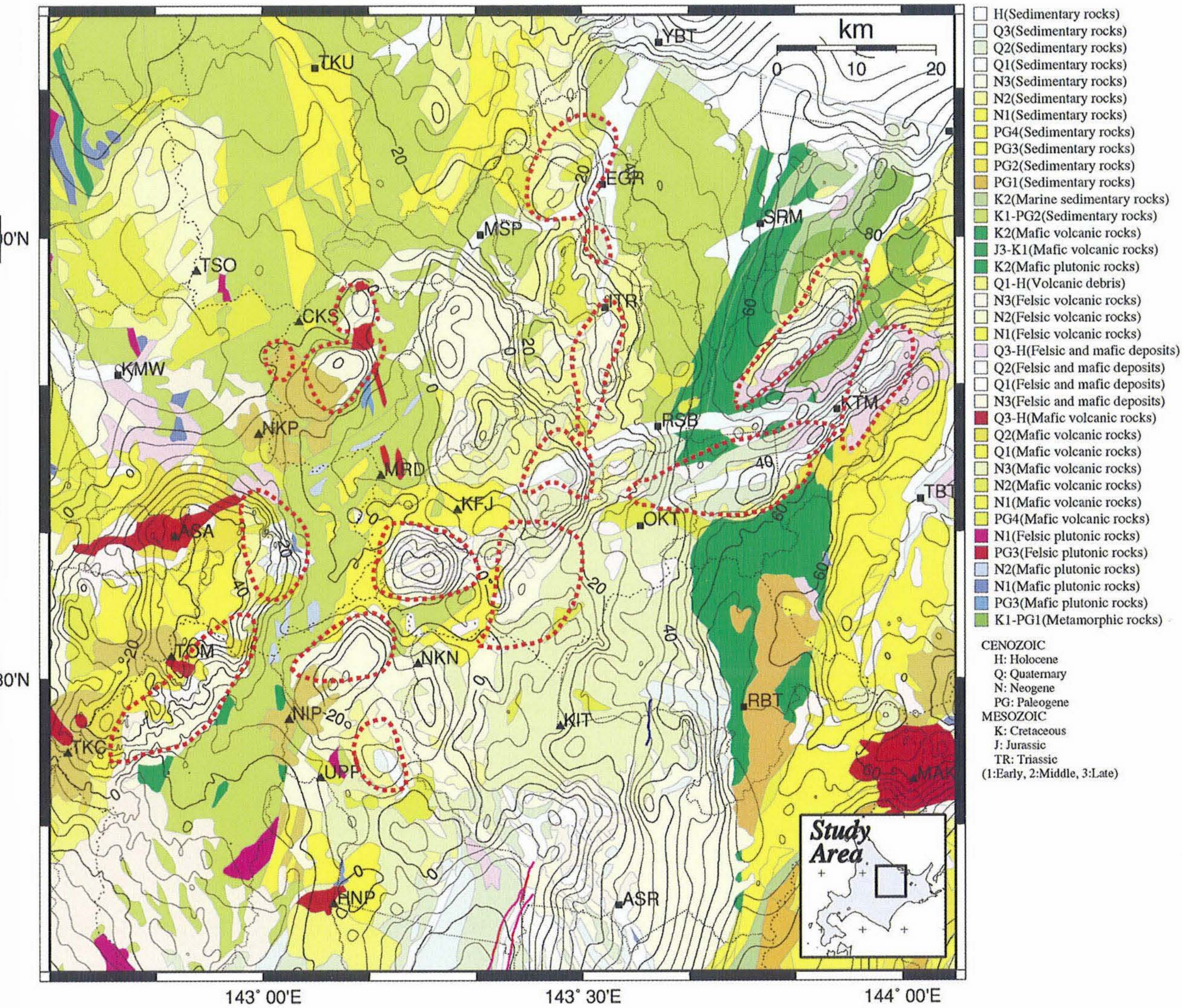

Fig. 4. Simplified geological map of the central Hokkaido and vicinity. Bouguer anomaly isolines are superimposed for reference with a contour interval of 5 mgal. Geology information is based on Geological Survey of Japan (1995). Thick and red-dotted polygons indicate the rims of the Cenozoic basins by Oka (1986). See Fig. 2 for their sequential numbers (#1～#16). See also the caption of Fig. 2 for the abbreviations and colored faults.

TTL running in NWN-SES direction. The Bouguer anomaly ridge to the east of TTL dominates extensively in the Mesozoic sequences around the eastern part of the map area whose easternmost and westernmost boundaries are almost coincident with the Abashiri Tectonic Line (ATL) and TTL, respectively. Apparent gravity anomaly depressions in ellipsoidal shape with almost NE-SW major axis of 15～20 km sharply penetrate this gravity ridge to the eastern edge of the map area (Fig. 3a).

In contrast, the gravity low field to the west of TTL is divided into two parts: one occurs around the Tokachi Tectonic Basin (TTB) which is morphologically bordered around the portion passing through Rikubetsu (RBT), Mt. Kitoushi (KIT), and Mt. Higashi-nupukaushinupuri (HNP), the other consists of the vast gravity depression area situated north of TTB. These gravity lows, extending northward of TTB, take their minimum (about -46 mgal) near Mt. Asahidake around the Daisetsu and Tokachi volcanic areas (Fig. 3a). Unequivocally, these remarkable lows form a cluster of closed depression in a linear dimension of about 10 km in diameter (Fig. 3b). These salient features are strengthened by a relief-shaded Bouguer image in Figs. 3a and 3b. It is quite remarkable that Bouguer anomaly contours of these marked lows tend to become dense at a rim of each closed depression, which is discussed later.

4.2 Gravity Anomaly around the Basin Area

As shown in Figs. 1, 2 and 3, most of these Bouguer lows also coincide with the distributions of late Cenozoic basins. This is the most surprising feature which yields constraints on the geometry of underground structures of the basins. Although the basins #1 and #5 (Figs. 2 and 3) do not show a closed Bouguer depression where distinct basin topography does not develop (Fig. 5), trend-reduced Bouguer map shows a low anomaly whose anomaly relief is more gentle. As shown in Fig. 3b, several gravity high-low transitions can be observed inside the basin #1, while around the basin #5 occurs a gentle gravity low. We found a good correlation between closed low anomalies and the location of the Cenozoic basins #6～#8. Particularly, the basin #6, which is known as "the Shirataki Basin", displays a surprising coincidence between its rim and the location of the steep gravity change (maximum in horizontal gravity gradient, see Fig. 6). Similar coincidence appears in the basin #7 while Bouguer anomaly changes around the basin rim are not so steep and Bouguer gravity decreases gently, not abruptly, toward the basin center, reaching a minimum near the center. Also the basin #8 appears to have a closed depression of gravity field.

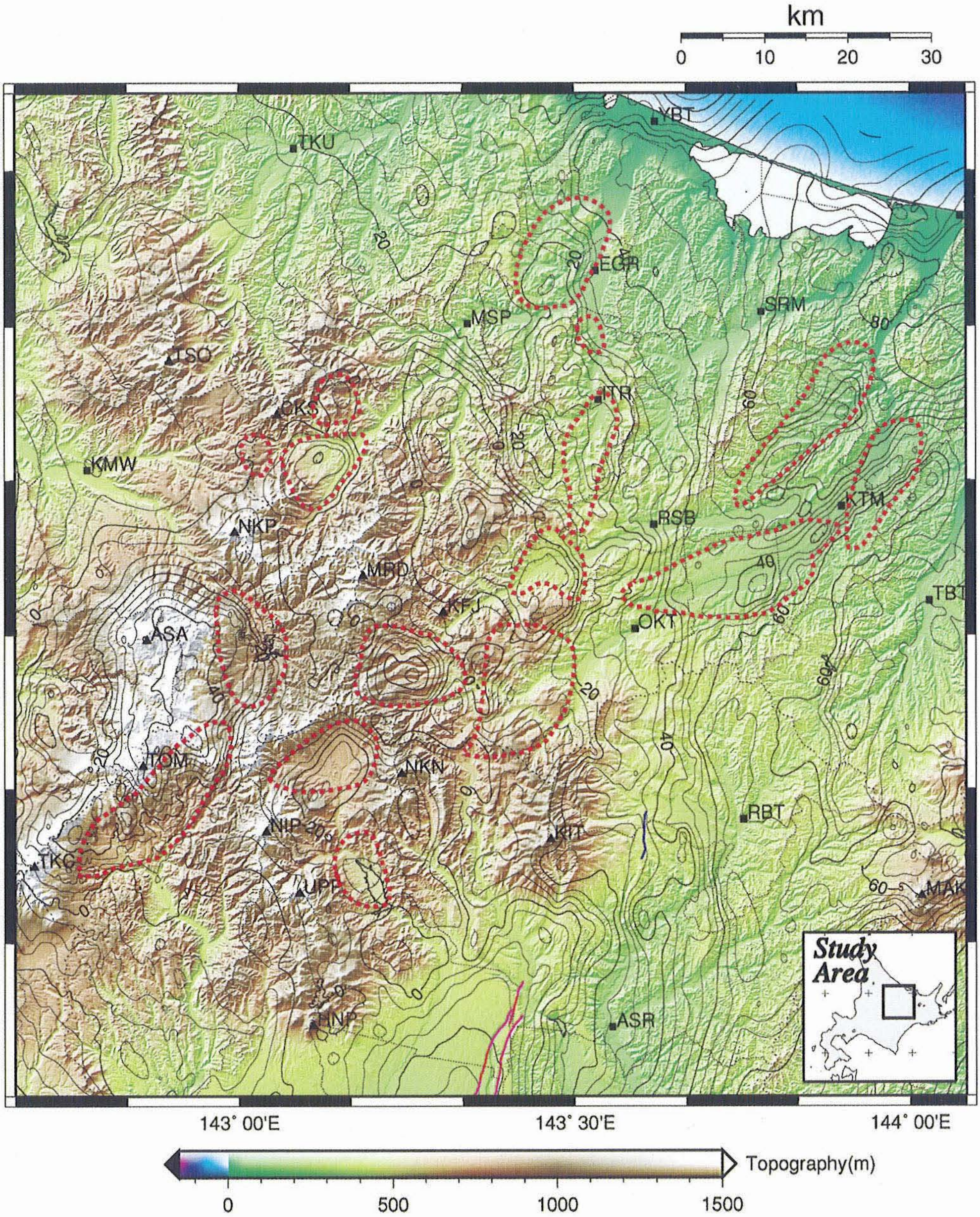

Fig. 5. Digital topography and known faults in the central part of Hokkaido, illuminated by the light from the NW direction. Bouguer anomalies are contoured at 5 mgal interval for reference. See the caption of Fig. 2 for the abbreviations and colored faults.

Gravity field of the Cenozoic basins #2～#4 is also characterized by a sharp and closed dent whose relative amplitude amounts to be 10～20 mgal (Figs. 2 and 3). In particular, the Cenozoic basins #4 forms an almost ring-shaped Bouguer low with characteristically steep rim which indicates nearly the same location of the basin perimeter. Similarly, the basin #3, known as the Tokachi-Mitsumata Basin, is clearly outlined by the gravity depression associated with a steep-gradient rim (see Fig. 6), where generalized topography around the basin also shows that the edifice is almost ring-shaped (Fig. 5). Interestingly, low Bouguer anomaly of the basin #2 seems to be stressed in trend-reduced Bouguer gravity as shown in Fig. 3b.

Ishii (*2001*) and *Ishii et al.* (*2002*) argued about the characteristic features of the Tokachi-Mitsumata Basin and pointed out that the basin shows distinct low gravity anomalies using the same gravity dataset in this study. Finally, they concluded that the Tokachi-Mitsumata Basin, formed in late Cenozoic age, is a circular-shaped caldera from geological evidences. As shown in Figs. 2, 3 and 4, the "Tokachi-Mitsumata Caldera" morphologically has an obvious ring-shaped rim which seems to control the Bouguer contours particularly in the northern side of the caldera. The southward extension of this low anomaly continues 5 or 6 km south of this caldera and seems to adjoin the closed Bouguer low of the basin #2 whose gravity field has rather moderate gradient to the center. Gravity anomaly features around the Cenozoic basins #9～#13 are similarly expressed by an oval-shaped depression with a relative amplitude of more than 10 mgal. Particularly, in the basins #10 and #13, a good coincidence occurs between their rims and the location of a steep gravity change. On the contrary, the Cenozoic basin #9 largely indicates gravity swelling which is inversely correlated with the topographic depression associated with the basin, although the anticipated gravity feature is a Bouguer low. While the Cenozoic basins #11 and #12 does not correlate well with low gravity fields. It should be noted that immediately about 5 km west of the basin #12 occurs another remarkable gravity dent which is not correlated with any known basins. This N-S elongated gravity low, whose center is situated about 12 km ESE of Maruseppu (MSP) between the calderas #11 and #13, has almost the same diameter as the basin #13 with a relative amplitude of about 15 mgal as shown in Fig. 3b. We find the conspicuous gravity lows in the Cenozoic basins that are well-developed over the Mesozoic regions around the eastern part of the map area. These low anomalies well correlate with the distributions of the Cenozoic basins #14～#16, each of which forms an oval-shaped topographic depression controlling Bouguer contours and runs almost in NE-SW direction. It is worth noting that gravity gradients outside each basin but sloping toward it are clearly found to be rather gentle than those inside, which is interpreted as evidence of a low-density mass located below the basin. As described above, most of the Cenozoic basins indicate a good correlation with the closed depressions of gravity field, which strongly suggests that these basins possess caldera-like morphology with a piston-shaped form. This feature will be evidenced more clearly by the steep gravity gradients over nearly ring-shaped perimeter of the basins.

In addition, we point out several more gravity depressions which would not be correlated with any of known Cenozoic basins. The existence of these gravity lows suggests that there would be a hidden basin or caldera below the gravity depression areas. One of the most distinguishable hidden structures is located at the central part of the map area, entirely surrounded on three sides by the Cenozoic basins #4 and #9 (on the south side), #6~#8 (on the west side), and #10~#13 (on the east side). Maruseppu (MSP) is located near the northernmost part of this notable depression. This area shows a large-scale gravity depression about 10 km (EW) by 25 km (NS) and consists of several closed minima, each of which indicates a sharp gravity change around its rim. Another hidden structure can be found 5 km south-west of Rubeshibe (RSB) which is characterized by a circular-shaped gravity low with a relative amplitude of more than 10 mgal. The Bouguer anomaly inside or at the rim of this low, however, changes rather moderately and gradually decreases toward its center.

4.3 Horizontal Gradient

As became clear in the previous discussion, it is notable that most of the gravity depressions corresponding to the Cenozoic basins indicate a steep gravity gradient (horizontal derivative) along the basin rims. As might be expected easily, large gradient values along a basin rim infer that the walls of the basin dip with high angle (vertically of inward). The most straightforward interpretation for this feature is that the basins may have piston-shaped, not funnel-shaped, subsurface structure located beneath the basin, where the wall dips with high-angle.

Recent gravimetric analyses have shown a useful approach using horizontal derivative (horizontal component of gravity gradient) in order to help to (1) delineate remarkable zones which indicate abrupt gravity changes (steep gravity gradient) (e.g., *Yamamoto et al., 1986*), and (2) highlight gravity structures

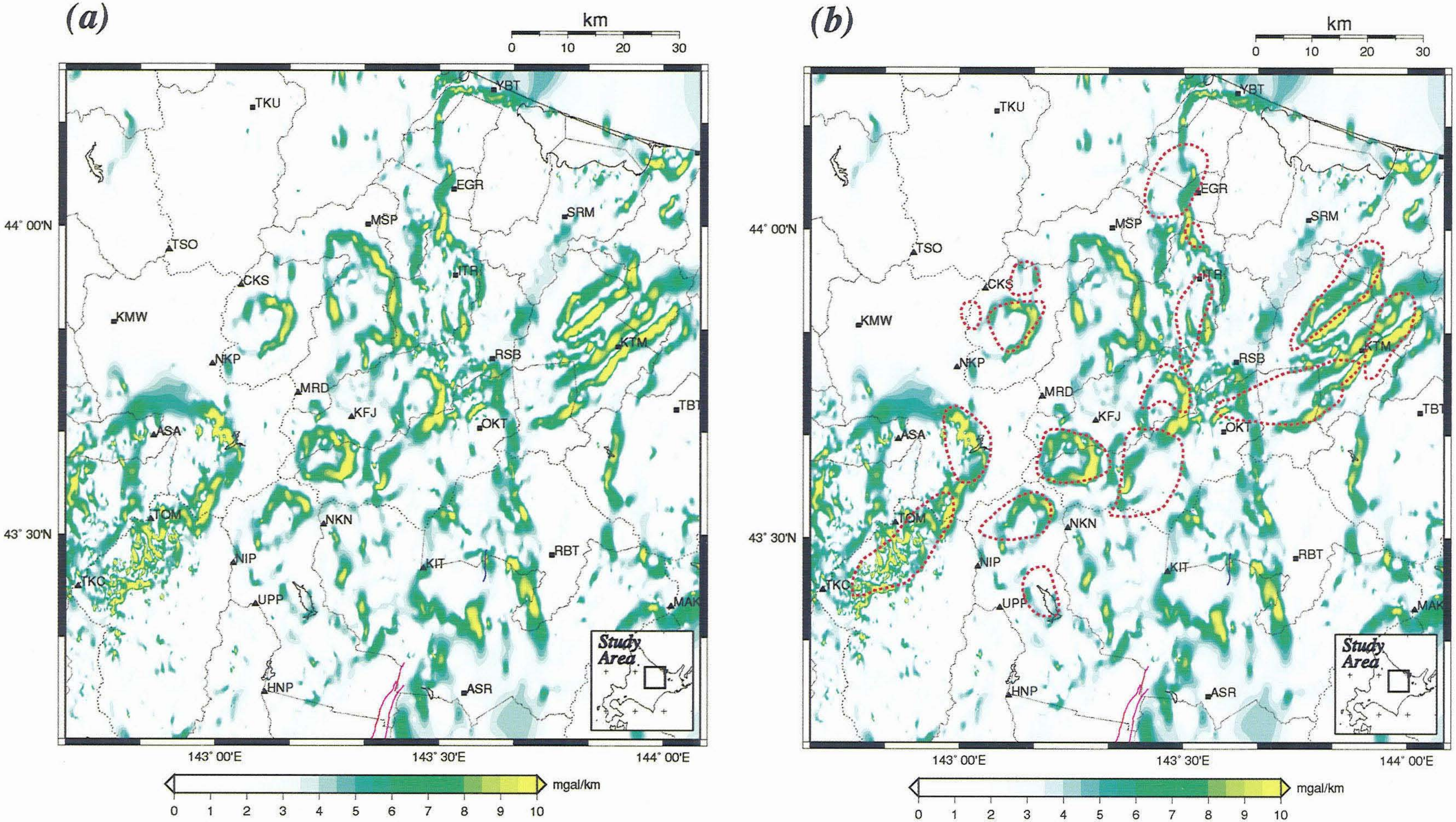

Fig. 6. (a) Bouguer anomaly gradient map around the central Hokkaido for gradient values ranging from 0 to 10 mgal/km. Yellow-coded ridge portions delineate locus of large inflection points. (b) Same as (a), but the perimeters of the Cenozoic basins by Oka (1986) are superimposed by thick and red-dotted polygons for reference. Their sequential numbers (#1～#16) are shown in Fig. 2. Note a remarkable coincidence between the perimeters of several basins and maximum inflection of gradient fields. See the caption of Fig. 2 for the abbreviations and colored faults.

laterally varying along the specific direction (e.g., *Yamamoto, 2003, 2004*). Accordingly, in order to examine the quantitative aspects of the gradient fields more closely, we take horizontal derivative of the 2-D Bouguer anomaly, particularly to investigate the variations of subsurface structure with special reference to the Cenozoic basins or caldera of the central Hokkaido. In this study, according to the past gravity works (e.g., *Cordell, 1979* ; *Cordell et al., 1985* ; *Yamamoto et al., 1986)*, horizontal derivative of 2-D Bouguer gravity field is defined by

$$[(\partial g/\partial x)^2+(\partial g/\partial y)^2]^{1/2},$$

where $g(x, y)$ is Bouguer gravity field, x and y indicate longitudinal and latitudinal directions, respectively. Units are milligals per kilometer. Note that the directional properties are completely lost in the above formula. It should be also noted that ridges in the amplitude of horizontal gradient field generally delineate the traces of gravity inflection points, by inference, the traces of basin-border or caldera-bounding faults. Using the above formula, Bouguer anomaly gradient map (Fig. 6) is produced around the central Hokkaido for gradient values ranging from 0 to 10 mgal/km. The location of the Cenozoic basins is superimposed in Fig. 6b for reference. Notice that high gradient zones are expressed distinctly by yellow colors in Fig. 6. Several major high-gradient zones can be found to be nearly closed in a ring-shaped or oval-shaped form in the central part of the map area. As shown in Fig. 6b, some of these closed extremes (maximum trace in horizontal gravity gradient) notably accord with the rim of the Cenozoic basins. Particularly in the basins #2～#4, #6, #10 and #16 a remarkable coincidence between their rims and the location of a steep gravity change can be found, whose maximum value reaches more than 13 mgal/km around the basins #4 and #10. The Bouguer contours of these basins are most likely to be those of the thickness contours of the basin fill, which places good constraints on the subsurface structure below the basin. Thus, it is quite significant that the boundary of the Cenozoic basins (calderas) seems to be defined as coinciding with the maximum trace in horizontal gradient of Bouguer anomaly gravity field (or vice versa), which may be interpreted as the result of several collapses associated with volcanic activities. These facts also imply that caldera-like collapse structure filled with a low-density material develops well beneath the Cenozoic basins of the central Hokkaido.

5. Discussion

The average density of the basin fill depends on many poorly-known factors and can only be estimated with considerable uncertainty. Much of the porous sediments probably have a density value of about 2.2 g/cm^3 or smaller. Some of the volcanic units, however, have physical densities which equal or exceed the density of the enclosing crystalline textures. Pumious or scoriacious materials, in particular, may have extreme anomalous density value considerably less than 2.0 g/cm^3. So if we assume the average density of the basin fill of the "Tokachi-Mitsumata Caldera" (the caldera #3, see Fig. 2) to be 2.2 g/cm^3, yielding a density contrast of 0.47 g/cm^3 in this study, simple calculation shows that an apparent maximum thickness (depth) of 750 m～1,000 m, which corresponds to a relative amplitude of 15 and 20 mgal. In this case several isolated closure of Bouguer contours are found within the caldera with a relative amplitude of about 2 or 3 mgal, indicating that the "Tokachi-Mitsumata Caldera" has a flat-bottom structure bounded by a steep (or high-angle) wall corresponding to the caldera-bounding rim. This feature suggests that the caldera may have originated in volcanic depression which subsided along high-angle normal fault, although generalized topographic features around this area are poorly resolved due to collapse of the caldera walls.

Similarly in the "Tokachi-Mitsumata Caldera", Bouguer anomalies of other basins, which display a surprising coincidence between their rims and the location of a steep gravity change, have a relative amplitude of about 10～20 mgal. Accordingly, this feature suggests that most of the Cenozoic basin of the central Hokkaido may possess a low-density basin fill with an apparent thickness (depth) of 500 m～1,000 m, assuming a density contrast of 0.4～0.5 g/cm^3. Although perturbations of the density contrasts and geometric configurations would improve the model fit, little new information would result without first obtaining a gravity dataset with significantly smaller station spacing to accurately define gravity anomaly. It is worth noting that the subsurface structure below these basins can be successfully constrained by Bouguer gravity anomaly, though volcanic collapse and infilling history of the Cenozoic basins in the central Hokkaido may be complicated and it is beyond the scope of this paper to deal with that matter.

6. Summary

We produced a new gravity anomaly map, as well as a Bouguer gradient map, of the central Hokkaido which enabled delineation of the main features as follows : (1) To the east of the Tokoro Tectonic Line (TTL), the gravity field is characterized by high-amplitude anomalies which outline the predominant Mesozoic sequences. These gravity ridges are bounded by steep gradients in the westernmost part. Whereas to the west of the TTL, anomaly relief is much lower, associated with several closed dents which correlate well with the distributions of the Cenozoic basins, (2) Several remarkable gravity lows form a cluster of closed depression with a diameter of about 10 km, and Bouguer anomaly contours of these marked lows tend to become dense at a rim of each closed depression, which suggests that the walls of the basin dip with high angle (vertically of inward). Thus, a gratifying aspect of this study has been emphasized by the remarkable facts that the boundary of the Cenozoic basins (calderas) seems to be well defined as coinciding with the maximum inflection in horizontal gradient of Bouguer anomaly gravity field, whereas Bouguer gradient fields inside most of the basins show considerable smaller values which implies a flat bottom. These facts corroborates that the basins possess a piston-shaped, not funnel-shaped, underground structure which may be the result of several distinct collapses, as long as the gradient field shows maximum inflection along their rims.

In addition, several more gravity depressions, none of which would be obviously correlated with known Cenozoic basins nor morphological features, are clearly observed. Most of these distinguishable hidden structures gather at the central part of the map area, entirely surrounded on three sides (east, west and south) by the Cenozoic basins. The existence of these gravity lows strongly suggests that there would be an invisible basin or caldera below the gravity depression areas.

Assuming the average density of the caldera fill to be 2.2 g/cm^3 in one of the typical calderas (the "Tokachi-Mitsumata Caldera") in the central Hokkaido, which yields a density contrast of 0.47 g/cm^3, an apparent maximum thickness of the caldera fill amounts to be approximately 750 m$\sim$1,000 m, which corresponds to a relative amplitude of 15 and 20 mgal, respectively.

We conclude that digital processing (horizontal derivatives, high-pass filtering and relief-shaded imaging) proved useful in establishing the conceptual underground model of the basins, which would be supported by 2-D or 3-D numerical modeling.

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