Variations of gravity anomaly roughness in Chugoku district, Japan: Relationship with distributions of topographic lineaments

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Tectonic movement may disturb lateral continuities of crustal structures at weak zones. These lateral discontinuities of density structure cause undulations of the gravity anomaly field whose complexity can be an indicator of past crustal instability. On the other hand, topographic lineaments are formed along weak crustal zones. We would expect therefore that gravity anomaly roughness bears some relation to the distribution of surface lineaments. We develop a statistical method by employing the Bouguer anomaly standard deviation as an index of gravity anomaly roughness in terms of which we interpret the spatial distribution of topographic lineaments in Chugoku district, Japan. Locations of the lineaments, which could be diagnostic of the heterogeneity of the previously damaged crust, tend to coincide with those of high roughness areas of gravity anomaly fields.

Key words: Gravity anomaly, roughness, standard deviation, lineament, Chugoku District, active fault.

1. Introduction

The subsurface structure is deformed where the crust is weak and these deformed density structures may cause undulations of the local gravity anomaly field. Accordingly, the complexity of the gravity anomaly field can be an indicator of crustal instability. Kudo and Furumoto (1998) applied fractal analysis to the gravity anomaly field in order to investigate the complexities of crustal structures. Several studies quantified variations of bathymetry and seismic profiles as root-mean-squared (RMS) roughness to demonstrate a negative correlation of oceanic basement roughness and spreading rates (e.g., Malinverno, 1991; Goff, 1992; Bird and Pockalny, 1994). Small and Sandwell (1992) applied the same technique to satellite gravity profiles. RMS roughness is equivalent to the standard deviation of the short-wavelength component of the profiles. This paper attempts to utilize standard deviations of Bouguer anomaly values to examine the spatial variations of roughness in the gravity anomaly field. On the other hand, "ancient" inactive faults, sedimentary basins, magmatism, accreted terrains, plutons and other geologic contacts would have great influence on the complexity of gravity anomalies, and none of these imply a damaged crust. If these occurs primarily or dominantly to produce gravity anomaly complexities, it would be difficult to detect the relationship between variations of Bouguer anomaly roughness (BAR) and surface manifestations of recent faulting. In order to discuss whether this relationship is unequivocal or not, particularly in active tectonic zones, we develop a statistical method for interpreting topographic lineament data in terms of BAR. The present method is applied to a gravity data set in Chugoku district, Japan, which is located at the back-arc side of southwest Japan (Fig. 1). Active faults in this region are sparsely distributed compared with other regions in Japan (Nakata and Imaizumi, 2002). However, as shown in Fig. 2, large numbers of apparent lineaments, which dislocate topographic features, are detected where no noteworthy active faults are found (Takada *et al.*, 2003). These topographic lineaments are most likely created along weak zones primarily formed by faulting under the regional stress field of the upper crust. In addition, these kinds of lineaments, formed by erosion along weak zones of the fault plain, do not arise below sea level. Therefore, most of the topographic lineaments in Chugoku district may be created by faulting activities after formation of elevated planation surfaces during the last few hundreds of thousand years. Although there are huge examples which have good correlation between topographic lineaments and steep gravity gradient zones in other regions in Japan, very few examples of steep, say more than 3 mgal/km, gravity gradient zones are overlapped by topographic lineaments in this study area (Fig. 2(b)). However, it seems that these lineaments tend to cluster over the area which possesses undulated gravity anomaly distributions. This study therefore focuses on the relationship between the complexity of gravity anomalies and the distribution pattern of topographic lineaments.

2. Tectonic Setting

Palaeomagnetic studies of the Japan arc indicate that southwest Japan experienced a large clockwise rotation ($>$ 45 degrees) associated with the opening of the Japan Sea at around 15 Ma (Otofuji *et al.*, 1985). Palaeoecologic and palaeogeographic evidence shows that most parts of Chugoku district were inundated during the Miocene rotation (Tai, 1975). The main highland surfaces of this region

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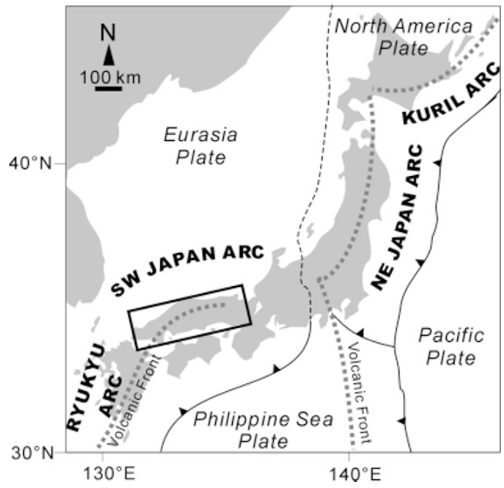
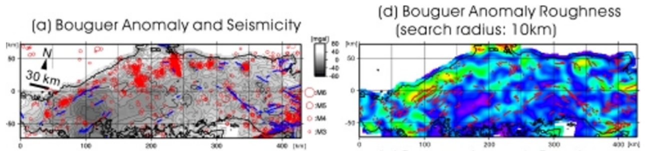
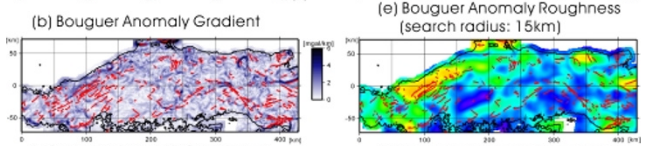


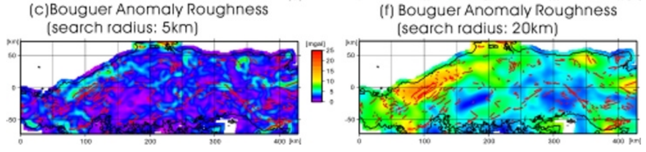
Fig. 1. Map illustrating the tectonic setting around the Japanese Islands. The survey area (Chugoku district) is shown by a rectangle. Dashed line indicates location of the volcanic front.


(a) Bouguer Anomaly and Seismicity

(d) Bouguer Anomaly Roughness (search radius: 10km)


(b) Bouguer Anomaly Gradient

(e) Bouguer Anomaly Roughness (search radius: 15km)


(c)Bouguer Anomaly Roughness (search radius: 5km)

(f) Bouguer Anomaly Roughness (search radius: 20km)

Fig. 2. (a) Bouguer anomaly map in the survey area with a contour interval of 5 mgal. Open red circles indicate epicentral distribution of shallow earthquakes (depth $\leq$ 15 km and M $\geq$ 3) during 1980–2003 determined by the Japan Meteorological Agency. (b) Bouguer anomaly gradient map. (c)–(f) Bouguer anomaly roughness (BAR) maps for a search radius of (c) 5 km, (d) 10 km, (e) 15 km, and (f) 20 km, respectively. Use the color scale bar of (c) to interpret (d)–(f). Thick blue lines in (a) represent locations of active faults by Nakata and Imaizumi (2002). Thick red lines in (b)–(f) represent locations of topographic lineaments derived from Takada *et al*. (2003).

were formed by the post-Miocene peneplanation with thrust faults which continued until the Quaternary. Recent major regressions are recorded as planation surfaces which were produced at about 0.5 Ma (Fujiwara, 1996). Traces of recent faulting after these regressions can be detected as lineament-like structures of topographic undulations.

3. Lineament and Gravity Data

Nakata and Imaizumi (2002) provided a digital active fault map of Japan (see the blue lines in Fig. 2(a)). Active faults, based on fault-related landform created during the late Quaternary, were derived from a topographic lineament survey by aerial-photo interpretation and image analysis. Takada *et al.* (2003) carried out further detailed mapping of the topographic lineaments in Chugoku district (see the red lines in Figs. 2(b)–(f)). They proposed new active fault candidates in addition to those proposed by Nakata and Imaizumi (2002). Although their technique is based on the same approach used in Nakata and Imaizumi (2002), they treated the lineaments, which accompany a series of apparent lateral gaps of ridges, linear hills and stream drainages, as active even if they are not associated with fault-related geologic features. Significant elevation gaps indicating recent faulting are also counted as lineaments. Thus, they extracted 508 new lineaments in total, 204 of which had already been assumed to be active faults by former studies in the survey area. We use these 508 lineaments after converting them into a computer-readable form. The original lineament samples are an ensemble of points that were given such that the contiguous points keep the line-segment property as straight as possible. Therefore, each distance between the contiguous points is not constant. A simple calculation shows that their average distance and standard deviation are 186 and 294 m, respectively. These deviations of the distances from a constant value would cause undesired results because equidistance properties are essentially required in point array datasets for each lineament in order to import them into our statistic analysis. Finally, we interpolated new samples at 10 m intervals along straight-line segments between the original contiguous points.

Two large gravity databases in Japan have been issued for public use. One is the "Gravity CD-ROM of Japan" published by the Geological Survey of Japan (2000). The other is the "Gravity Database of Southwest Japan" published by the Gravity Research Group in Southwest Japan (2001). Both databases have been constructed to be complementary to each other to reduce nonuniformity. In order to discuss the complexity of the density structures beneath Chugoku district, we use these Bouguer gravity anomaly data. We generate 1 km mesh grid data which cover the rectangular area indicated in Fig. 1. The Bouguer anomaly shown in Fig. 2(a) is calculated by using a topographic density of 2.67 g/cm^3. We also interpret the results obtained by using the topographic density of 2.4 g/cm^3 to check the influence of the uncertainty of the topographic density.

4. Method

As an index of BAR, we employed standard deviations of Bouguer anomaly values. We subdivided the survey area into a series of regular grid cells with a mesh size of 1 × 1 km, to the centers of which we assigned a representative BAR value calculated from Bouguer anomalies inside a given search area. No a-priori condition is imposed on BAR in this study. The nodes are centered in the regular grid cells and we used a circular search area centering at each node. Lateral variations of the BAR values when the search radii are 5, 10, 15, and 20 km, are shown in Figs. 2(c) to (f).

Next, we performed a statistical analysis by relating the BAR values directly to the topographic lineament distributions. The following steps (I to V) were carried out on the land part of the study area. The marine area is excluded for the present investigations due to a lack of information of faults and gravity data.

(I) According to BAR distributions, we divide BAR values into 16 levels, each of which has 1 mgal width of BAR. The lowest and highest levels have a range of 0–1 and 15–16 mgal in BAR, respectively. Next, we classify each grid, where a representative BAR value has already been assigned, as one of the 16 levels of the study area.

(II) For each grid, we count the number of lineament data points in a circular region within a radius of 3 km from its node.

(III) For all grids which fall into the same level at step I, we accumulate numbers of lineament data points given for each grid at step II, and plot them against BAR values. The results are shown as thin solid lines in Fig. 3, with the scale on the right axis.

(IV) In a similar way, we also count the number of grid nodes whose BAR has the same level, and plot them against the BAR with thick dotted lines (Fig. 3), with the scale on the right axis.

(V) Next, we divide the accumulated numbers of lineament data points (results from step III) by the numbers of grid nodes (results from step IV). We call this number the "topographic lineament point frequency" which is plotted against the BAR by histograms in Fig. 3, with the scale on the left axis. The histograms in Fig. 3 should not change much for all ranges of BAR values unless lineaments distribute correlatively with the BAR.

We treat the lineament point counts per 1 grid node (i.e., results of step V) as frequencies of lineament points over the ranges of BAR values. We repeated the above steps until the search radius for the BAR determination becomes 20 km for every 5 km interval.

5. Results and Discussion

High BAR zones (e.g., larger than 4 mgal), in particular for a search radius of 5 km, tend to elongate in NE-SW or WNW-ESE directions in the BAR map (Fig. 2). The orientations of topographic lineaments of Takada *et al.* (2003) are also aligned approximately with the same trends as those of high BAR zones. These high BAR zones are similar to the lineaments in terms of trend patterns. The relationships between the topographic lineament point frequency and the BAR are presented in Fig. 3 when the search radii range from 5 to 20 km. Every result shows that the frequency of the lineament points correlates positively with the BAR (see the histograms in Fig. 3). When we put the topographic lineament point frequency values at the centers of each level of the BAR values, their linear correlation coefficients are 0.926, 0.859, 0.931 and 0.951 when the search radii are 5, 10, 15 and 20 km, respectively. Topographic lineament point frequency values at their highest BAR range are less accurate, because very few grids are counted at that range (see Fig. 3(a), (c)). In spite of the ambiguity at their highest BAR region, very high correlation coefficients are detected in every case.

We also investigate to what extent variations of the topographic density to determine Bouguer anomaly affect these results for the topographic lineament distribution. Figure 4 shows the results when the same method in the previous section was applied, except that the topographic density was assumed to be much lower (2.4 g/cm^3). In this case as well, despite lower topographic density, the result indicates that the above correlations between topographic lineament distribution and BAR are still observable. The correlation coefficients in this case are 0.860, 0.896, 0.842 and 0.782 for the search radii of 5, 10, 15 and 20 km, respectively. From these results, the fact that the BAR correlates positively with the frequency of the lineament points may not be critically affected by the assumption of the topographic density. When we use the "active fault" data of Nakata and Imaizumi (2002), instead of topographic lineaments, although the similar positive correlation can also be found, the correlation coefficients are rather lower (0.650 ∼ 0.855) for the same radii.

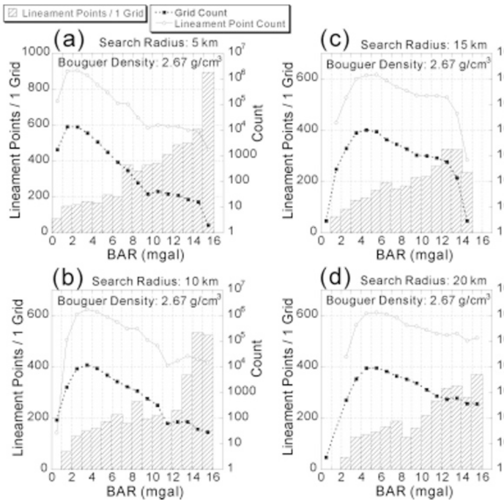


Fig. 3. Histograms (bar graphs) with the scale on the left axis showing a relationship between topographic lineament point frequency and the BAR in case of the topographic density of 2.67 g/cm^3 for a search radius of (a) 5 km, (b) 10 km, (c) 15 km, and (d) 20 km, respectively. Solid and dotted lines indicate variations of accumulated numbers of lineament data points for grids with the same BAR level and numbers of the grids, respectively. Note the different scale for the lineament point frequency (left axis).

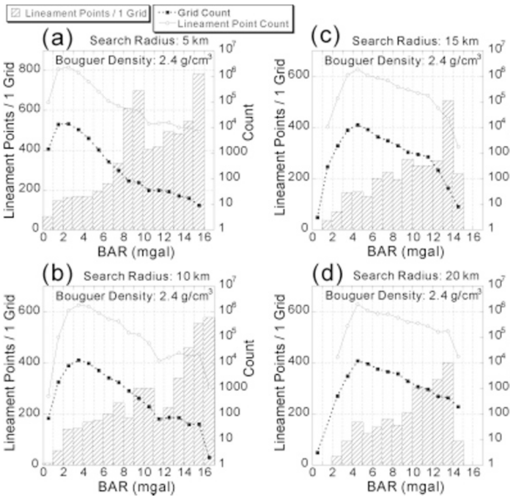


Fig. 4. Same as Fig. 3 except that a topographic density of 2.4 g/cm^3 was used.

In every case, few lineaments are detected over low (lower than 5 mgal) BAR regions. Actually, it seems likely that these low BAR values imply the simplicity and/or the homogeneity of the subsurface density structure beneath them. Although the upper crust of this region has been damaged by structural movements due to the opening of Japan Sea and the subsequent upheaval, some parts of the continental crust may be protected from such destructions. The density structure of the "preserved" crust is regarded as simple in contrast to that of the "damaged" crust. Our results imply that it is difficult for the recent faulting detected as topographic lineaments, to form over the "preserved" crust which has a simple and homogeneous density structure. The recent faulting is therefore likely to be concentrated on the previously damaged crust. Moreover, new crustal deformations associated with the recent faulting may enlarge BAR values. It seems that the crust of this region is undergoing present-day active deformation and is still in the process of separating the damaged parts from the preserved parts.

In addition, we explore the relationship between variations of BAR and the epicentral distribution of shallow ($\leq$15 km) earthquake in the same survey area by using the same technique. We use M $\geq$ 3 earthquakes, which occurred from 1980 to March 2003, from the Japan Meteorological Agency Earthquake Catalogue (see Fig. 2(a)). Several studies (e.g., Shichi *et al.*, 1992; Kudo and Kono, 1999) reported that the relationship between distributions of shallow earthquakes and horizontal gradients of the gravity anomaly field in Southwest Japan. However, no clear relationship has been found between epicentral distributions during the last two decades and BAR, when the locations of the epicenters are treated as those of the lineament points in the present investigation. This could be caused by lower crustal seismicity during 1980–2003 in the survey area. Indeed, there were only 21 earthquakes whose magnitude was 5.0 or larger within our settings of magnitude and time period. It is therefore difficult to discuss statistically the relationships of BAR with large earthquakes. The frequency of epicenter becomes unexpectedly high when some earthquake swarms occur with no spatial correlation with BAR. For such cases, our approach is not really appropriate because these swarms become obvious outliers which may lead to the contamination of the population data in our statistic analysis. Consequently, further long-term earthquake observation with a constant spatial resolution is still required for this kind of investigation.

If we could use gravity anomalies after subtracting long-wavelength anomalies caused by deep compensating masses, it would have provided even better correlation between locations of topographic lineaments with those of high roughness areas of the gravity field. However, the analysis of the coherence between the topography and gravity anomaly in the study area shows that no isostatic response has been detected, even in the long wavelength ($<$175 km) components (Kudo *et al.*, 2001). That is the reason why we do not use gravity-related physical quantities other than Bouguer anomalies. Although such long-wavelength components may not be so critical for our investigation in which the search radii are smaller than 20 km, further efforts are needed to exclude gravity contributions due to deep-seated structures which might have disturbed the present results.

6. Conclusion

We developed a method to investigate spatial distribution of topographic lineaments in relation to gravity anomaly complexities, using BAR values as an index of the complexity of the gravity anomaly field. The applicability of the present method, which is tested in a gravity data set in Chugoku District, Japan, is demonstrated by positive correlations of frequency of lineament points with BAR and by good correlations of locations of topographic lineament with those of the high BAR areas of the gravity field. Our approach using BAR is effective in quantifying major tectonic units in terms of BAR and determining the nature of crustal weakness and instability. The proposed method is useful for estimating the causes and effects of crustal behavior, even over areas covered by thick sediments and/or volcanic products, where fault-like structures are hard to detect.

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