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原　著

Gravity Anomaly and Subsurface Structure in the Kaga Hot Springs Area

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加賀温泉郷地域の重力異常と地下構造

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要　旨

石川県南部の温泉群がある地域（加賀温泉郷）の地下構造を調べることを目的として重力探査を行った．これまでに得られていた重力測定値と合わせて，当該地域における精密なブーゲー重力異常分布図を作成し，逆解法により地下構造を推定した．加賀温泉郷の付近は相対的に 15 mgal 程度負の重力異常となっており，基盤の大きな陥没を示している．負の重力異常域は直径が 10 km 強のほぼ円形をしている．基盤の最大の陥没量は 2.6 km と見積もられる．付近の岩石が中新世の火山岩であることから，この構造は埋没したカルデラである可能性がある．加賀温泉郷の内，片山津，粟津，そして山代温泉はこのカルデラ状構造の内側にあり，山代温泉はその縁付近にある．これらの温泉の熱源は中新世の火山体という可能性がある．

キーワード：重力異常，基盤構造，埋没カルデラ，加賀温泉郷

Abstract

To study the structure beneath the Kaga hot spring area of southern Ishikawa prefecture, a gravity survey was conducted in and around the area. Combining these data with those obtained previously, we obtained a high-resolution Bouguer gravity anomaly map of the study

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region. We then estimated the structure from the map using an inversion method. The relative gravity anomaly of the area is negative by about 15 mgal, suggesting that the basement beneath the area is deeply depressed. The region with the negative gravity anomaly has a nearly circular shape with diameter greater than 10 km. The maximum value of the basement depression was estimated as 2.6 km using inversion analysis. Because younger layers overlying the granitic basement are mainly Miocene volcanic rocks, the possibility exists that the circular structure is a buried Miocene caldera volcano. The Katayamazu, Yamashiro, and Awazu hot springs are inside the caldera-like structure, and the Yamanaka hot spring appears near its margin. It is probable that the hot springs heat source is a buried volcanic edifice that was created during the Miocene.

Key words : Gravity anomaly, Basement structure, Buried caldera, Kaga hot spring area

1. Introduction

The Japanese islands have many hot springs that are regarded as formed by activities of volcanoes and faults (e.g., Nishimura *et al.,* 2006). In and around the southern Kaga plain, Ishikawa prefecture, there are many hot springs such as Awazu, Katayamazu, Yamashiro, and Yamanaka. The area is therefore called the Kaga hot springs area (Fig. 1). These hot springs have been known and used through the ages, for example Awazu hot spring, opened in 712, has a long history of about 1,300 years. The salient feature of these hot springs is the outwelling of abundant hot water. However, geological understandings of heat sources and underground paths of hot waters have not been clarified yet. No volcanoes and no major active faults are related to the heat sources and the underground paths of the hot waters in and around the Kaga hot springs area. To reveal them, it is important to obtain information related to the subsurface

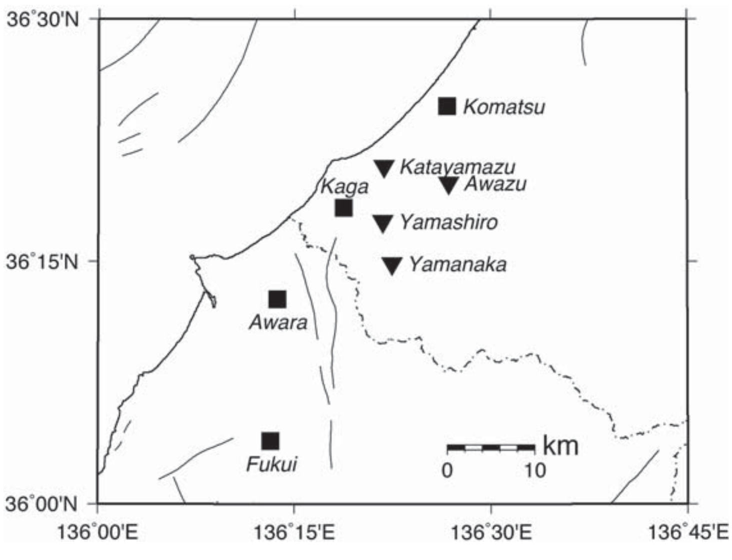

Fig. 1 Topographic map of the Kaga hot springs area. Squares, triangles, solid lines and broken lines respectively represent major towns, major hot springs, Quaternary active faults (Research Group for Active Faults in Japan, 1991) and the prefecture boundary.

structure, from the surface to several kilometers' depth.

From the point of investigation of the subsurface structure, in addition to a geological survey of the surface, various geophysical and geochemical surveys are necessary. We can expect that a gravity anomaly is a useful tool to provide information about the subsurface structure, especially for the basement structure, in the Kaga hot springs area. Herein, we present a detailed gravity anomaly map based on a dense gravity survey and discuss the subsurface structure in and around the Kaga hot springs area and heat sources beneath the area.

2. Geological features in and around the Kaga hot springs area

Figure 2 presents a geological structure in and around the Kaga hot springs area (Geological Survey of Japan, 2003). The basement in this area consists primarily of Hida metamorphic rocks (middle to late Palaeozoic), the Tedori Group (Mesozoic sedimentary rocks, middle Jurassic to early Cretaceous), and early rhyolite pyroclastic rocks (Mesozoic volcanic rocks). The basement rocks were covered with Miocene volcanic rocks (Tertiary volcanic rocks, about 15–20 Ma). These Miocene volcanic rocks are known as the Green Tuff and consist of andesitic, dacitic, and rhyolitic volcanic/pyroclastic rocks that were not formed from recent volcanism but from ancient volcanism. The volcanic activities of this area are regarded as intense. It is possible that the heat source and the chemical components of the Kaga hot springs come from the body of the Miocene volcanic rocks (Fuji and Itakura, 1992). In the Hokuriku region, including this study area, the Miocene volcanic rocks exist along the coast and extend from southwest to

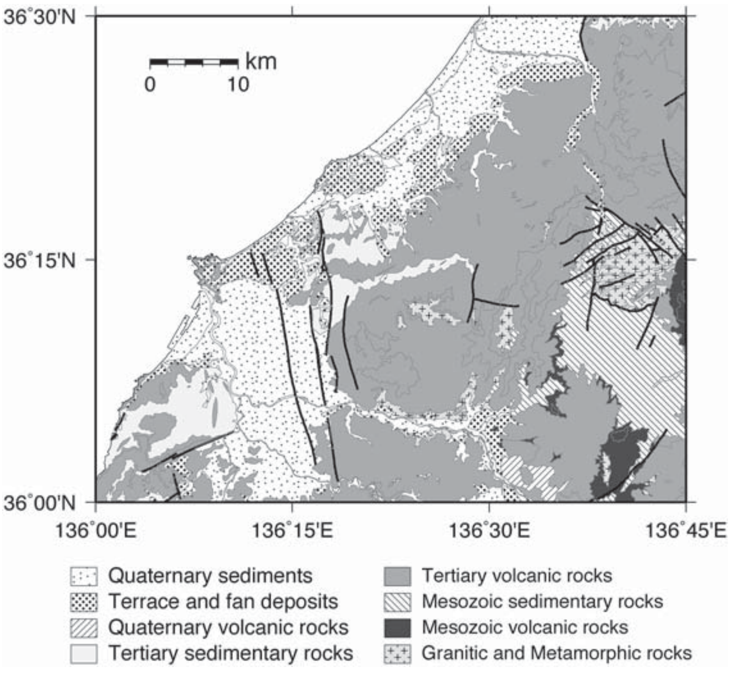

Fig. 2 Geological map of the Kaga hot springs area (modified from Geological Survey of Japan, AIST, 2003).

northeast between Fukui prefecture and Toyama prefecture. The middle Miocene to Quaternary sediments are distributed between the Miocene volcanic rocks and the coast (Fig. 2). The Kaga hot springs, excluding the Yamanaka hot spring, are on the plain or terraces formed during the Quaternary.

Regarding the chemical components of hot springs, salt-water springs are found mainly near the coast, for example the Katayamazu hot spring. However, sulfate springs are found mainly in inland areas. The Yamashiro and Awazu hot springs are sodium sulfate springs, and the Yamanaka hot spring, located in the most inland area, is a sodium sulfate and calcium sulfate spring (Fuji and Itakura, 1992).

3. Gravity survey

The gravity values in this study area were measured using a LaCoste-Lomberg gravimeter and another gravimeter (CG-3 ; Scintrex Ltd.). The gravity anomaly dataset includes measurement data obtained by Kanazawa University with 122 new measurement data measured in this study and data measured by other institutes (Geospatial Information Authority of Japan, 2006, Geological Survey of Japan, 2004, Gravity Research Group in Southwest Japan, 2001). The total number of gravity measurement points used for this study was 3,628 (Fig. 3).

Most gravity values were measured on spot elevations marked on topographic maps. If an appropriate spot elevation was not found, then we measured a gravity value on a point where the elevation can be estimated easily, such as the intersection of a road and a contour line. The error of the estimated height of the measurement points is less than a few meters in almost all cases. The errors of gravity values are therefore estimated as less than 1 mgal.

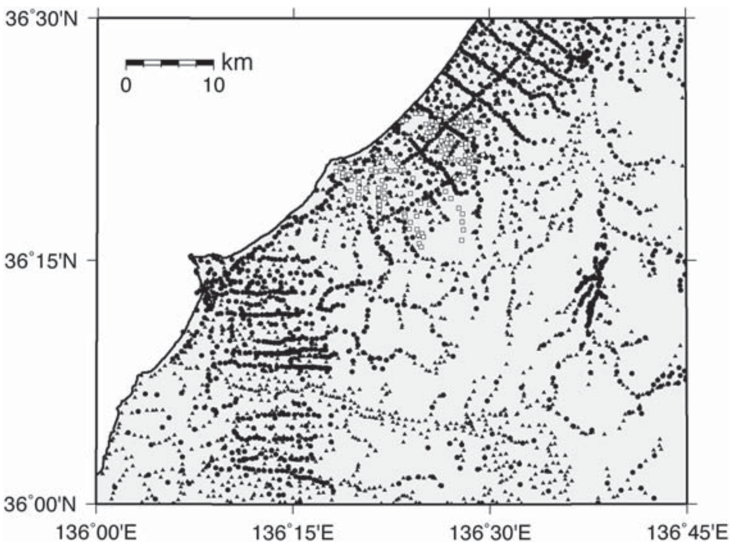

Fig. 3 Distribution map of measurement points. Squares show new measurement points, circles show points measured by Kanazawa University, and triangles show points measured by other institutes.

The gravity anomaly map used for this study portrays a distribution of the Bouguer anomaly with terrain correction. We calculate the terrain correction using the method of Honda and Kono (2005) with 50 m mesh digital elevation map data. The hills around the Kaga hot springs consist of rhyolite pyroclastic rocks and lavas in the early Miocene (Kano *et al.,* 1999). The mean density of Miocene felsic rocks is 2,440 kg/m^3. The mean density of the pyroclastic rocks is less than that of rhyolite rocks, of which the density was between 2,000 and 2,300 kg/m^3 (Iwatani and Kano, 2005). We therefore adopt the density of 2,300 kg/m^3 for the Bouguer correction and terrain correction.

4. Remarkable features of the gravity anomaly

Figure 4 depicts a gravity anomaly map for a wide area around the Kaga hot springs. An enlarged gravity anomaly map of the target area is presented in Fig. 5. A positive gravity anomaly is apparent in the coastal area. A negative one extends to the inland area (Fig. 4). The values of the gravity anomaly decrease southeastward. The negative gravity anomaly means that the average density of the crust is less than that of surrounding areas. The observed trend, decreasing southeastward, is caused mainly by the crust thickening towards the central part of Honshu (Zhao *et al.,* 1992 ; Iidaka *et al.,* 2003).

The most striking features of the distribution of the gravity anomaly in and around the Kaga hot springs area is the existence of a negative gravity anomaly that cuts off the positive gravity anomaly trending from northeast to southwest along the coast (Fig. 5). The negative gravity anomaly is more than 10 km wide and extends to the southeast from the coast. This negative gravity anomaly zone suggests that the depth of the basement rocks beneath this zone is deeper than the surrounding area, i.e., this is a depression structure. From the contour line of the gravity anomaly, this depression structure appears to consist of two near-circular depressions aligned in a northwest-southeast orientation (a buried caldera structure), or alternatively, a depression zone extending in a northwest-southeast orientation (a graben structure). The most negative gravity anomaly is found not at the central part but at the northeastern side of the depression area, indicating that the basement becomes steeply deeper in the northeastern side. Fault structures related to this depression structure have not been reported in the relevant literature.

5. Inversion analysis of gravity anomaly

The Bouguer anomaly features suggest two possibilities of the subsurface structure : a buried caldera structure and a graben structure. To examine these possibilities, we performed a three-dimensional inversion analysis of gravity anomaly (Rama Rao *et al.,* 1999) and estimated the lateral variation of the basement depth. Two layers were assumed in the inversion analysis so that the interface depth, the depth of the upper surface of the lower layer, is the fitting parameter. Geological information shows that the upper layer consists of rhyolite lavas and pyroclastic rocks and the lower layer, which is the basement, consists of granite. We therefore set the upper layer density as 2,300 kg/m^3 and that of the lower layer as 2,670 kg/m^3. In other words, the density

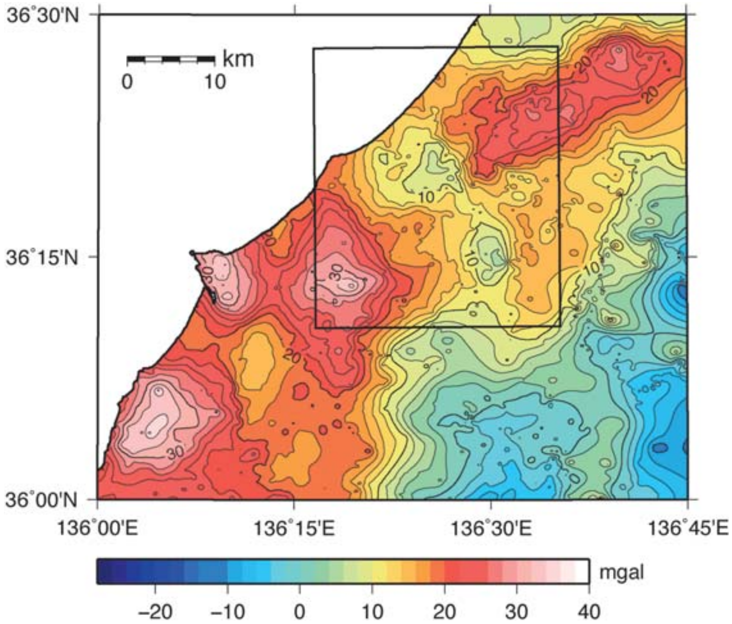

Fig. 4　Bouguer anomaly map. The assumed density is 2,300 kg/m^3. The contour interval is 2 mgal.

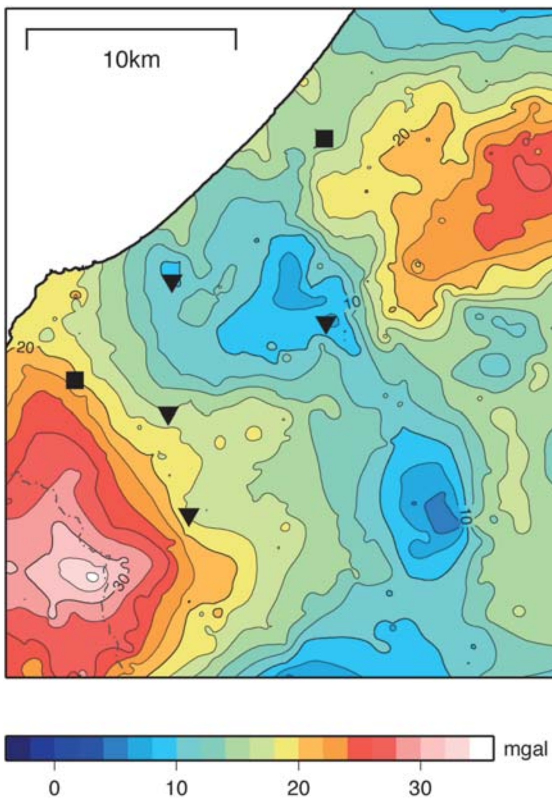

Fig. 5　Detailed Bouguer anomaly map. The assumed density is 2,300 kg/m^3. The contour interval is 2 mgal. Squares show major towns and inverted triangles show major hot springs (refer Fig. 1).

difference between the two layers is 370 kg/m^3.

We applied a band-pass filter of 8 km to 25 km to the Bouguer anomaly for the inversion analysis to remove trends with long wavelength, which reflected much deeper structure than the subsurface structure, on which we focus here, and to remove fluctuations with short wavelength that might have been introduced by measurement errors and slight heterogeneities near the surface (Fig. 6a). The blocks for the inversion are set as 2 km × 2 km and the analyzed area is covered with 19 × 21 blocks. We set the initial depth of the interface of 1 km that provides the minimum residual between the band-pass filtered and the calculated gravity anomalies. In fact, we tried various values as the initial depth and confirmed that the depth of 1 km provides the minimum residual.

Figure 6c shows the optimum density structure model obtained using inversion analysis. Figure 6b is the calculated gravity anomaly from the optimum model. We recognize that the calculated gravity anomaly reproduces the band-pass filtered gravity anomaly very well. Two depression structures resembling ellipses are found beneath low anomalies in the filtered gravity anomaly. Based on the shape of these depression structures, we infer that the low-gravity anomalies are not caused by the graben structure but by the buried caldera structure. The depth of the larger one extends downward to 2.6 km. That of the smaller one extends downward to 2.0 km. The larger one is about 10 km. The smaller one is about 5 km. The Awazu, the Katayamazu,

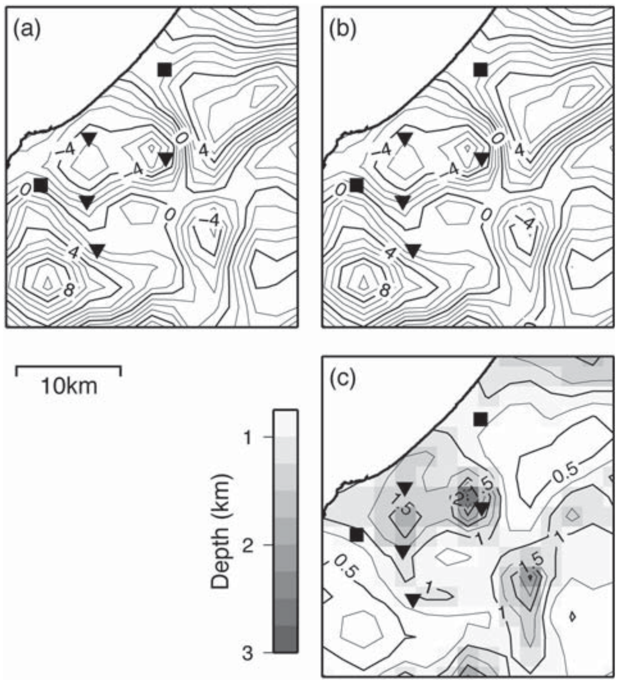

Fig. 6 (a) Band pass filtered gravity anomaly. (b) The calculated gravity anomaly from the optimum basement structure model. The contour interval is 1 mgal. (c) Optimum basement structure model. The contour interval is 0.25 km. Squares denote major towns and triangles show the major hot springs.

and the Yamashiro hot springs are located within the larger depression structure. Especially, the Awazu hot spring is located near the deepest point. However, the Yamanaka hot spring is located near the edge of the larger depression structure.

6. Implications for the origin of the Kaga hot springs

As presented in Fig. 5, the four hot springs in the Kaga hot springs area are located in or near the large depressed area. The Katayamazu, Yamashiro, and Awazu hot springs are located respectively near the northwestern, the southwestern, and the southeastern boundaries of the structure. Because the most depressed part is in the eastern part of the structure, the Awazu hot spring is located near the most depressed part. Moreover, although the Yamanaka hot spring appears outside the circular structure, it is still located near its margin. These lines of evidence suggest strongly that these hot springs have a causal link to the depression structure.

The most interesting feature of the depression structure of the basement is that it shows a nearly circular boundary. As described above, the study area is covered mainly with Miocene volcanic rocks, indicating the volcanic activity was extremely high in this region in the Miocene. It is therefore likely that the circular structure beneath the surface is a remnant of a caldera generated as a part of the volcanic activity in the relevant period.

If this is the case, we can propose another fascinating hypothesis : the heat source of the hot springs is a high-temperature body in the ancient volcanic edifice that has been buried up to the present. The ordinary interpretation of the heat source for the hot spring area is that the remnant heat of the Miocene volcanic formation might warm the underground water (Fuji and Itakura, 1992). Discovery of the buried circular structure would cast new light on the question of the heat source of the Kaga hot springs area.

7. Conclusions

We performed dense gravity measurements and compiled a database to ascertain details of the gravity anomaly in the Kaga hot springs area. We produced a Bouguer anomaly map with the Bouguer and the terrain corrections with density of 2,300 kg/m^3. The Bouguer anomaly map shows a negative gravity anomaly around the Kaga hot springs area. Inversion analysis using the two-layer model revealed the basement structure beneath the Kaga hot springs area, particularly revealing depression structures resembling calderas of which the deepest point extends downward to 2.6 km. Younger layers over the granitic basement are mainly Miocene volcanic rocks. We therefore infer the possibility that the circular structure is a buried Miocene caldera volcano. The Katayamazu, Yamashiro, and Awazu hot springs are inside the caldera-like structure, and the Yamanaka hot spring is apparently located near its margin. The possibility exists that the heat source of the hot springs is a buried volcanic edifice created during the Miocene.

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