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Gravity anomalies of the central Flores Island, Indonesia

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Abstract: Gravity survey in the geothermal area including Mataloko, Nage and Mengeruda, the central Flores Island, eastern Indonesia, was conducted in 1999 to 2001. And the biggest town in the survey area is Bajawa Town. The total number of measurement points amounted to about 800, and about 170 stations were taken at the very short intervals, about 200-meter, in the Mataloko geothermal area. The location and altitude were decided by differential GPS and the accuracy is thought to be within 1-meter accuracy or better. All measured gravity data were referred to the International Gravity Standardization Net 1971 (IGSN71) and the normal gravity values were estimated according to the gravity formula 1980. Terrain corrections were conducted with respect to the distance range up to 60km, by approximating the real topography to an assemblage of annular prisms interpolated by mesh terrain data and random terrain data of gravity points. The effect of the topographic sinking from horizon due to the earth's curvature was taken into consideration. Bouguer corrections within the range of 60km in arc-distances were made using a spherical cap crust formula. The density for both terrain correction and Bouguer corrections is chosen to be 2.0 g/cm^3 according to the result of surface density estimation. This estimated density is reasonable compared to the geological setting. Because whole measurement area is covered with volcanic sediment or pyroclastic flow and surface layer density is estimated to be low from geological consideration.

The features of Bouguer anomalies is characterized by a low anomaly around Mengeruda compared to volcanic sediment or pyroclastic flow of depression area, a steep gradient structure in the west near of Mataloko and a elongated high anomaly area from Bena to Dona were found.

1. Introduction

Gravity survey was carried out in and around Bajawa Town, including Mataloko, Nage and Mengeruda, geothermal area, the central Flores Island, the eastern Indonesia. There are three big volcanoes, Keli Inerie, Keli Inelika and Keli Ebulobo. Keli Inerie has a typical conic feature, and Keli Ebulobo is one of the most active volcanoes in Indonesia. Though Keli Inelika has no clarifying peak as a result of erosion, there are some still craters in it. Within the area surrounded by three volcanoes the geothermal potential is very high.

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To delineate the underground structure of the area, this gravity survey was carried out on August and September of 1999, July and August of 2000, and July of 2001, and geological survey, MT survey, SP survey, geochemical surveys etc., were performed at the same time.

2. Gravity survey in the central Flores Island

Three gravity meters, LaCoste & Romberg G-type gravity meter G-304, ZLS Burris gravity meter B-001 of Geological Survey of Japan and LaCoste & Romberg G-type gravity meter G-236 of Mitsubishi Metal Resources Co. Ltd., were used in this survey. They are all used for the nation-wide gravity survey of Japan. As for the accuracy, these gravity meters were calibrated at the calibration route of Mt. Tsukuba, and it was found that there were a few problem with the instrument factor, so three

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gravimeters are suitably adjusted by recycling the gravimeter constant. For the decision of position and altitude of measurement points, the differential GPS system was adopted. Although barometric altimeters of TOMMEN are also used for easy and instant way of getting height at real time, the data of barometric altimeters were never used for data processing. Ones of the differential GPS devices are manufactured by Magellan Systems Corporation and portable one, and the other are of Trimble Corporation. They weigh only 2 or 3 kg. The position and altitude were decided within the accuracy of 1 meter, or several centimeters at best, from the base station. The base stations were established almost in the central area of gravity survey. The coordinates of base station were decided by the long-term averaging of the differential GPS device, therefore, the errors of absolute coordinate of base station were estimated to be less than 3 meters. The altitude of one base station, Elizabeth Hotel, was fixed to be 1176.65 m above sea level after the adjustment for the sea level, and the other, Hotel Ariesta, to be 1207.76 m above sea level. The WGS-84 system was adopted for the geodetic system for this survey.

Gravity measurement stations were taken almost along the road except for the precise survey in the Mataloko geothermal area, Inerie Volcano and Inelika Volcano. On the gravity measurement, the loop-closing method was taken, because the gravimeter with spring has drift. The gravity base station was established at the same site of GPS base. The total number of gravity stations amounted to about 800, and about 170 stations are taken at the Mataloko geothermal area of precise survey. The locations of gravity stations are shown in Fig.1 with cross marks on the relief topography map is also shown.

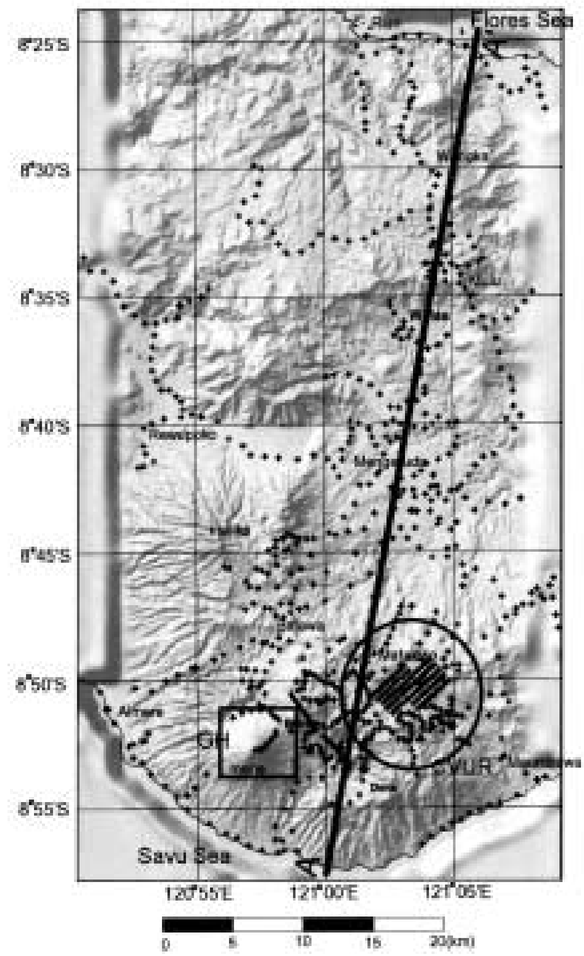

Fig. 1 Distribution of Gravity Station. Shaded relief topography is made from 50 m mesh. AA' is the 2-D analysis line. GH and CVUR denote the area of GH correlation of Inerie volcano and the area of CVUR method, respectively.

3. Data processing of measured gravity data

All measured gravity data were referred to the International Gravity Standardization Net 1971 (IGSN71) and normal gravity values were calculated according to the gravity formula 1980, Geodetic Reference System 1980. Bouguer corrections within the range of 60 km in arc-distances were made using a spherical cap crust formula. Terrain corrections were performed within the same range of Bouguer correction, by approximating real topography to an assemblage of annular prisms with the height interpolated from mesh terrain data and random terrain data at gravity stations (Komazawa, 1988). The effect of the topographic sinking from horizon due to the earth's curvature was also taken into consideration. As no detailed digital terrain data for terrain correction were available, the detailed terrain data were created through the digitization of the contours of 1:25,000 scale topographic. The $50m \times 50m$ mesh data were made from the digitized contour data maps except outer area, and the relief map of Fig. 1 was made from this data. Of course, the accuracy is sufficient for the terrain correction of the close zone (0 - 500 m) and the near zone (500 m - 4 km). As for the middle zone (4 - 16 km) and the far zone (16 - 60 km), the "gtopo30"(30"×30") mesh data were used. Here the actual distance of 30" is less than 1km. But the terrain correction of sea is not performed, because bathymetric maps of this area could not be prepared.

The density for both terrain correction and Bouguer corrections is chosen to be 2.0 g/cm^3 according to the result of the surface density estimation, CVUR, Comparison of Variance of Upward-continuation Residual method (Fig. 2). And, the estimated density is reasonable compared to the

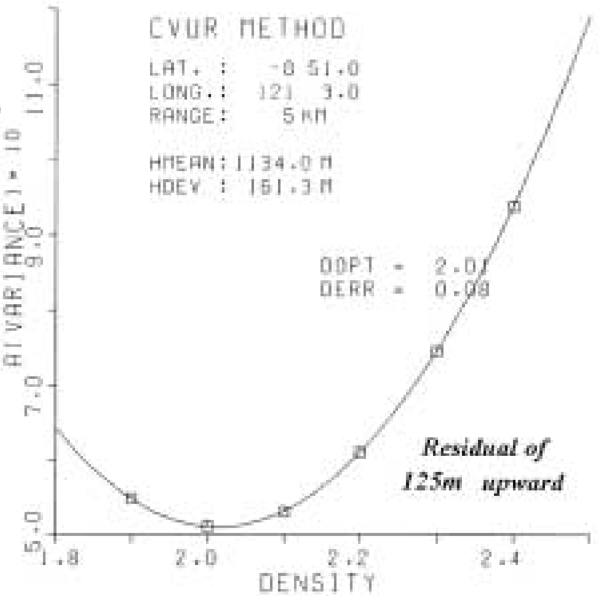

Fig. 2 Surface density estimation with CUVR method. In this case, analysis is conducted for a circular area with a radius of 5 km. Upward-continuation heights h1 and h2 are taken to be 0 m and 125 m.

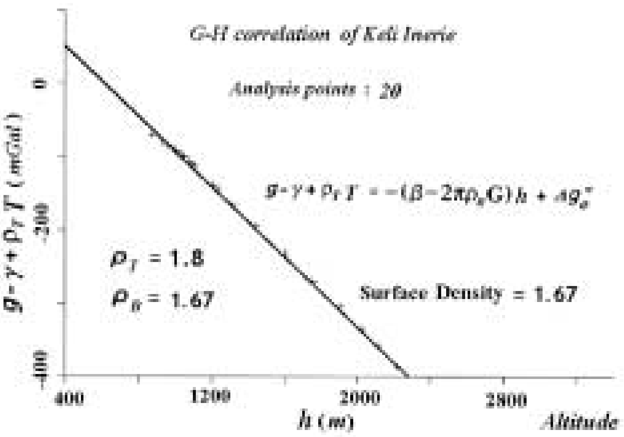

Fig. 3 GH correlation of Inerie volcano.

geological setting (VSI, 1995). As the whole measurement area is covered with volcanic sediment or pyroclastic flow, which are related to Quaternary volcanoes, the surface layer density is estimated to be low from geological consideration. But, the bulk density of Keli Inerie, which analysis area is shown in Fig. 1, is estimated to be about 1.7 g/cm^3 from G-H relation (Fig. 3), as the CVUR method is not applicable to the data of only one route. This estimated density is very low compared to other volcanoes and it must be a very unique example. For example, the bulk density of Mt. Fuji, the shape of which is similar to Inerie, is about 2.3 g/cm^3 and the central cone of Aso volcano is about 2.2 g/cm^3 (Komazawa, 1995). It is quite probable that the volcanic edifice is composed mainly of volcanic ashes and scoria, and little of welded lava. Other interpretation may be that the local vertical gravity gradient (dg/dz) around Inerie is a little bigger than 0.3086 mGal/m, which is the vertical gravity gradient of normal field and commonly used. That is, the surface density will be set to bigger than 2.18 g/cm^3, if the value of dg/dz can be assumed to be bigger than 0.33 mGal/m. But this probability is thought to be little.

Bouguer anomaly map with an assumed density of 2.0 g/cm^3 is shown in Fig. 4, and Inerie volcano shows an unnatural low gravity anomaly. Another Bouguer anomaly map with an assumed density of 1.7 g/cm^3 is shown in Fig. 5, and it is proven that the contour pattern is smoother. The density of 1.7 g/cm^3 may be suitable for surface density around Inerie volcano. And a photograph of Inerie volcano is shown in Photo. 1.

4. Characteristic of Bouguer gravity anomalies

The features of Bouguer anomalies are characterized by a low anomaly around the Mengeruda geothermal field and they are compared to volcanic sediment or pyroclastic flow of depression area. And the low gravity anomaly zone or belt extends east to west. To the south of this area, a steep gradient structure in the west near of Mataloko and an elongated high anomaly area from Bena to Dona were found and these anomalies are considered to correspond to the shallow hot bedrock with remarkable geothermal potential.

A gradient structure steep is found a little around Welas and its anomaly is infered to correspond to a caldera named Welas Caldera (Muraoka *et al.*, 2000). It is understood that the steep gradient structure with a shape of semicircle/horseshoe of northern half corresponds to the caldera structure. But, it is unclear whether the caldera has the similar structure as the Aso caldera, one of piston-cylinder type volcanoes, having a very steep gravity gradient (Williams, 1941; Smith and Bailey, 1968; Komazawa, 1995), because the distribution of gravity stations here is not sufficient. The steep gradient structure of the southern semicircle area is unclear not only in Bouguer anomalies but also in topographical feature on caldera wall. The low gravity zone from the east to the west including Mengeruda geothermal area to Rewupoko is thought to be a new graven structure and the graven was generated by tectonic depression. The structure of horseshoe with northern steep gradient is inferred from the incline toward to south and the sedimentation in the southern area of the caldera, so the graven is a newly formed structure compared to Welas Caldera.

The high anomaly around Wangka corresponds to

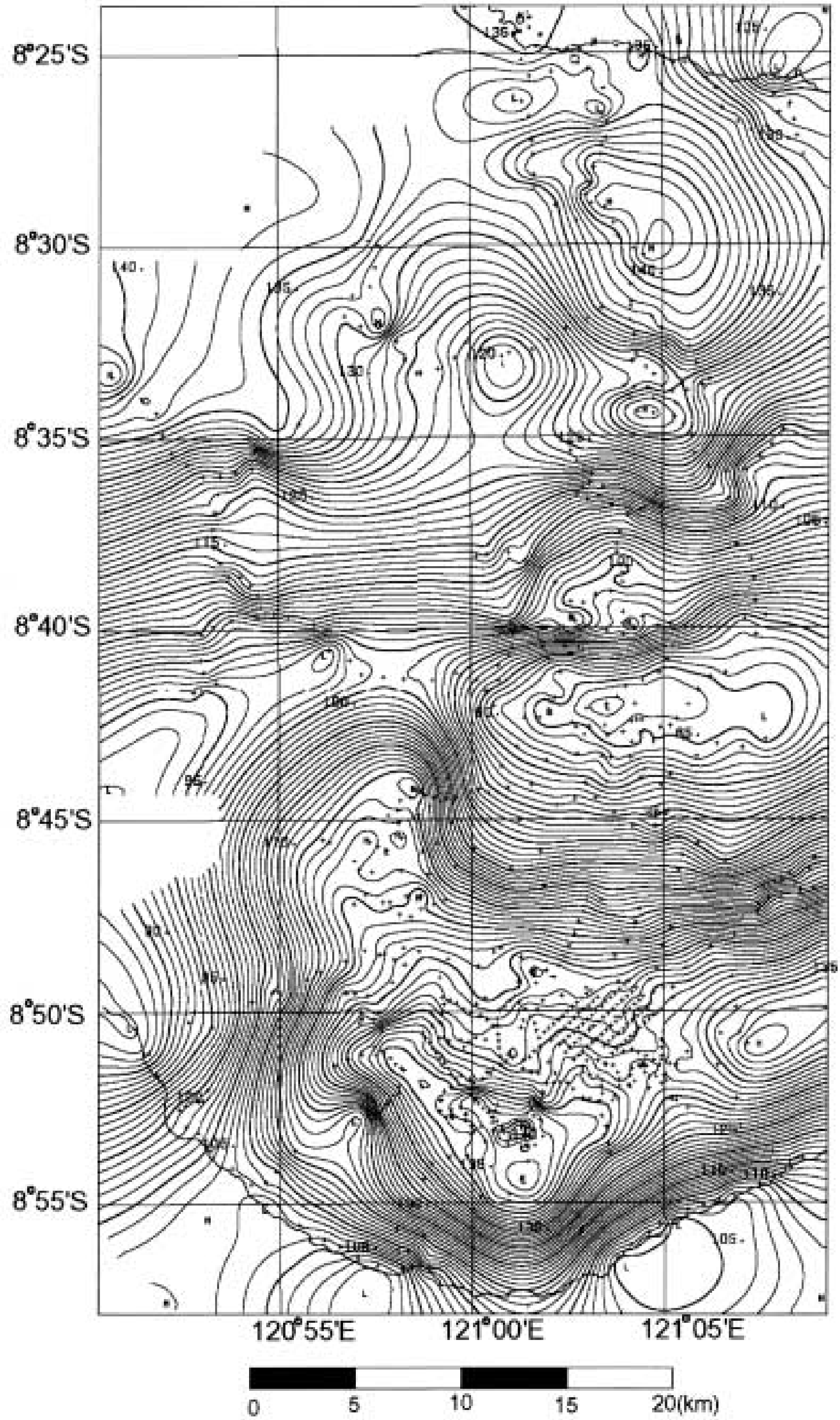

Fig. 4 Bouguer anomalies with assumed density of 2.0 g/cm³. Contour interval is 1 mGal.

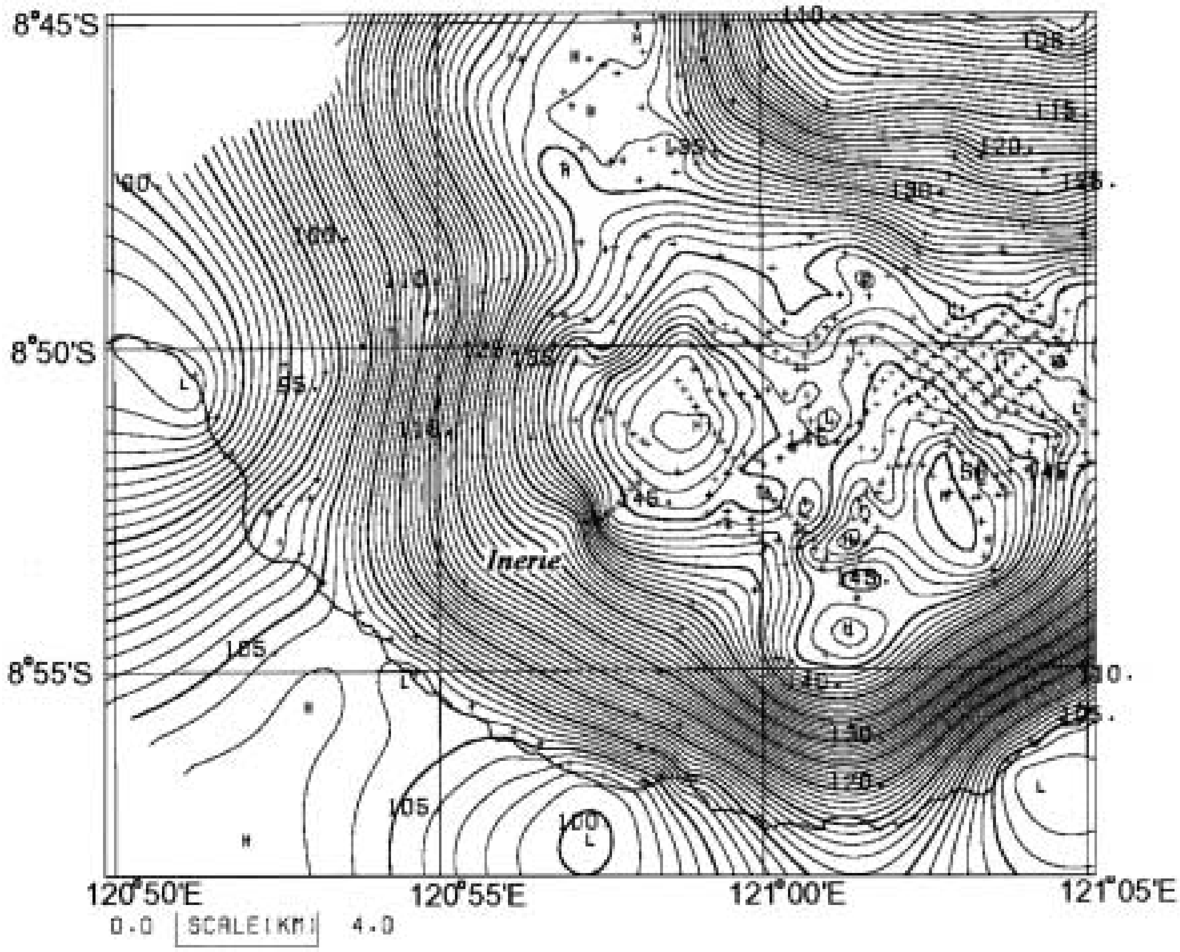

Fig. 5 Bouguer anomalies around Inerie volcano with assumed density of 1.7 g/cm^3. Contour interval is 1 mGal.

Photo. 1 Inerie volcano viewed from Inerika volcano. Shape of Inerie is almost cone.

a anticline and the outcrop of limestone is distributed (VSI, 1995). The low gravity anomaly in 10 km southwest of Wangka is not a caldera, but it may correspond to the basement depression deeply filled with the volcanic sediment or pyroclastic flow of low density. The other low gravity anomaly in west of Riun corresponds to the outcrop of intrusive granite (VSI, 1995), so the density of the rock widely distributed in northern coastal area is estimated to be higher compared to granite.

The feature is clearer by the upward continuation residual map (Fig. 6) with filtering processing. The areas shaded by the horizontal lines are those of minus residual values. The residual anomalies related to the structure shallower than 2 to 3 km are extracted by a band-pass filter designed with two upward-continuation filters (Komazawa, 1995), this case the regional trend is calculated from 2 km upward continuation. To avoid repeating general features of Bouguer anomalies already mentioned, only one conspicuous point is commented here that the local negative anomaly with a diameter less than 5 km around Welas Caldera becomes clearer.

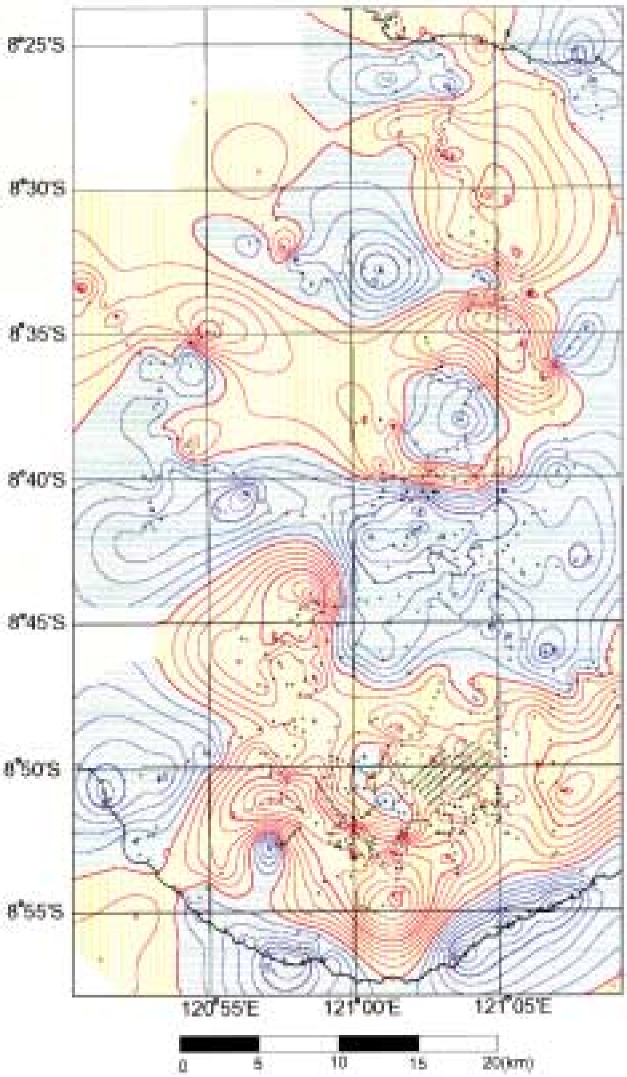

Fig. 6 Residual anomalies of shallow structure. Regional trend is removed with 2 km upward-continuation.

5. Three-dimensional (3-D) Analysis with 2 Layer Model

A three-dimensional analysis of density structure of the whole area was performed using two layers model composed of a surface layer with the density of 2.0 g/cm^3 and a basement with the density of 2.5 g/cm^3.

The procedure of the analysis (Komazawa, 1995) is as follows, (1) Removal of the regional component with a large wavelength from the gravity anomaly by using an upward continuation filter. The filter is achieved to be continued to a height of 5 km, to deal with the depth range shallower than about several km. In this depth range, shallower than several km, the difference in density is largest between the soil-sediments and the basement. Therefore, it is highly probable that the filtered anomaly reflects the configuration of basement. (2) Minimizing the difference between the observed residuals and the calculated anomalies. The model consists of the soil layer and the basement with an assumed density-contrast of 0.5 g/cm^3. A boundary condition was given that the basement is close to the ground surface at high residual areas (6 control points), around Dona, Nage, Mulu and Wangka. The 3-D gravity-basement model thus obtained and shown in Fig. 7. It is easy to imagine the geologic setting with this basement configuration.

The basement model (Fig. 7) shows three depressions of the basement: (1) a central E-W trending depression deeper than −1,500 m above sea level around Mengeruda, (2) a circular depression about −1,000 m above sea level in Welas caldera, and (3) a circular depression about −500 m above sea level in 10 km southwest of Wangka. Between the depressions (1) and (2), a narrow rise of the basement up to around sea level lies. The basement of northern part, from Wangka to Riun, is very shallow and same as ground surface. It is reasonable that the northern coastal area is the basement uplifting area, because basement rocks such as limestone or granite are distributed. The basement of high geothermal potential area or volcanic area, Inerie, Mataloko, Inelika etc., is uplifted. But the basement in Mataloko is a little deep compared to the southern geothermal area and its shape may be similar to a caldera, so the geothermal potential there may be a little lower compared to Nage. The elongated high anomaly from Bena to Dona and the steep gradient structure in the northeast of the high anomaly area may be the southwest edge of caldera wall.

Figure 8 shows the gravity basement and the surface topography along the line-AA' indicated in Fig. 1. The two-dimensional analysis was conducted by Komazawa (1995). The section AA' crosses Dona, Mataloko, Mengeruda, Welas Caldera, Wangka and the east of Riun. Figure 8 shows that the depth of gravity basement increases gradually towards north, so the source of hot spring around Mengeruda may be the southern geothermal area around Inerie to Mataloko.

6. Conclusion

Although measured points are not so many, some steep gradient structures, a high anomaly area elongated in NW-SE from Bena to Dona and some low anomaly areas were found. The steep gradient structure between Inerie and Bena may be the west edge of caldera wall. The high anomaly area corresponds to the shallow basement uplift or the high-density intrusion rock.

Of course, in order to investigate the detailed subsurface structure, it is necessary to carry out more

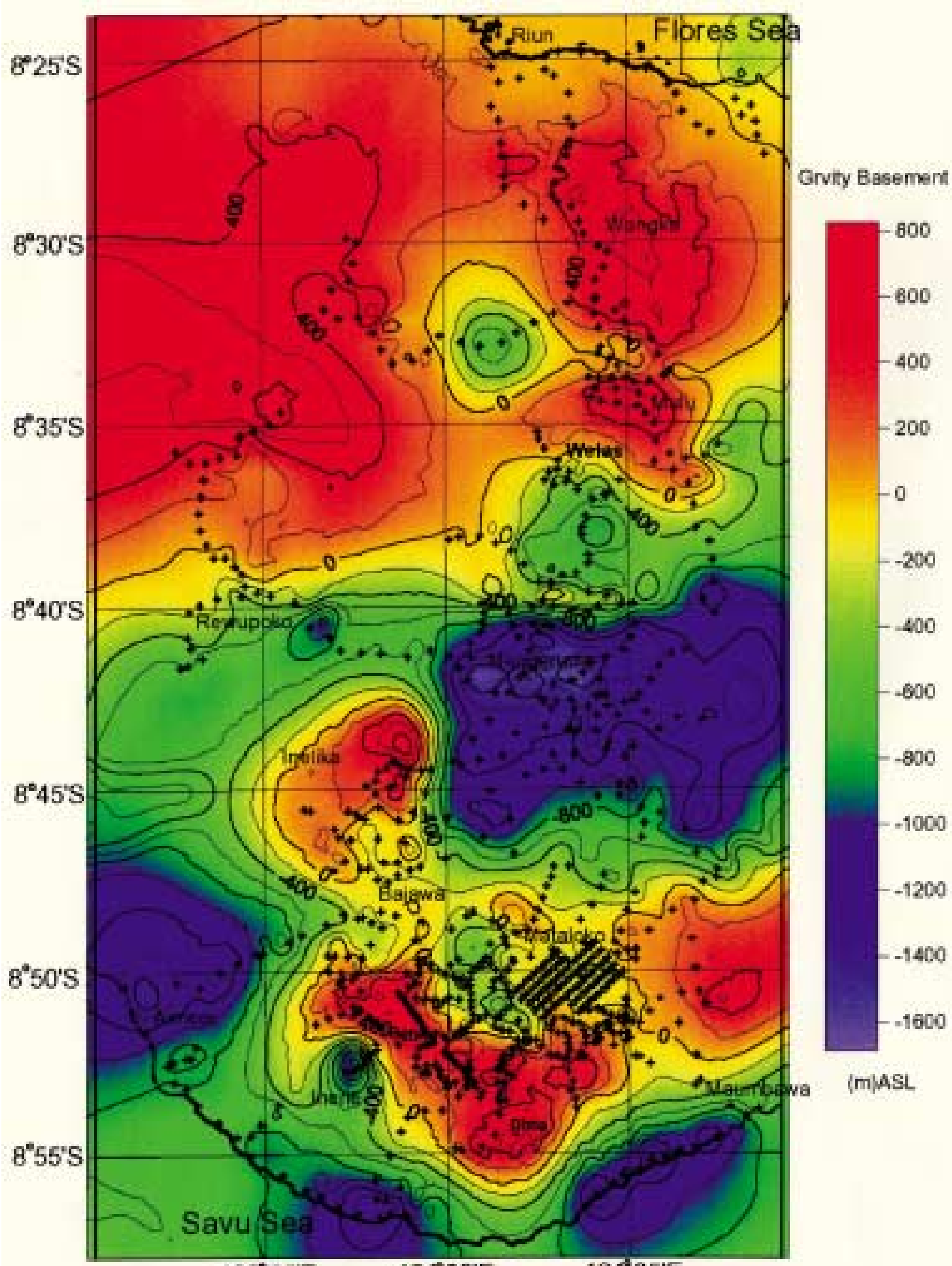

Fig. 7 Gravity basement in meter above sea level with density contrast of 0.5 g/cm³. Contour interval is 200 m.

dense measurement, especially around Keli Inerie and Keli Inelika and western part of Walas Caldera.

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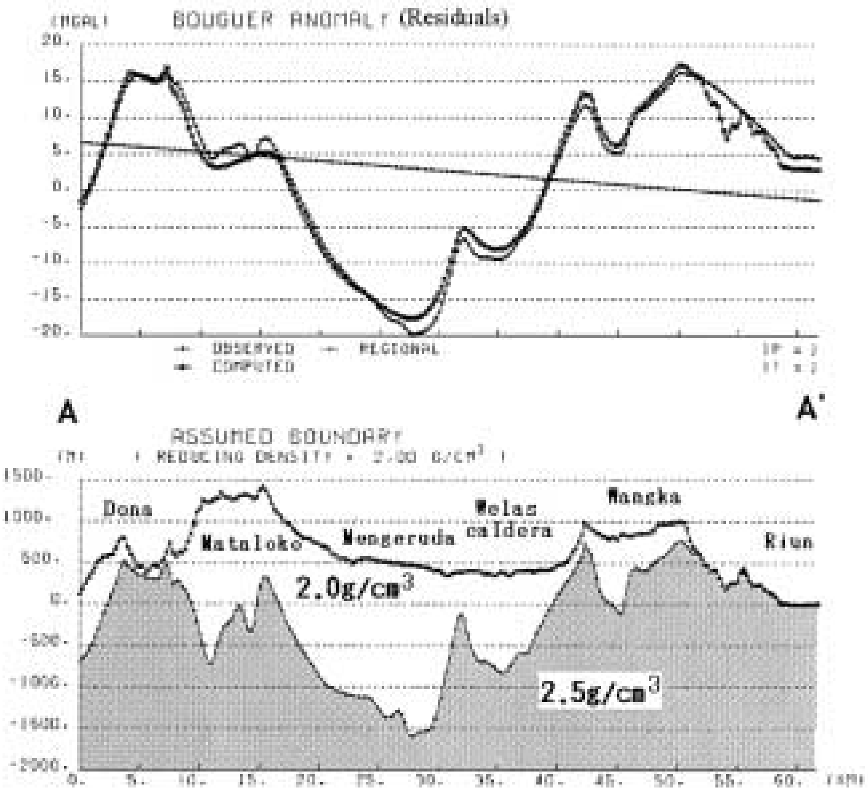

Fig. 8 2-dimensional two-layered analysis. Density contrast is 0.5 g/cm^3.

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インドネシア・フローレス島中部の重力異常

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要　旨

インドネシア・フローレス島中部で重力調査がおこなわれ，総測点数は800点に達した．イネリエ火山，イネリカ火山，マタロコ地熱地帯など火山や地熱活動の活発な調査地域南部は，高重力異常となって基盤の盛り上がりを示した．基盤構造が盛り上がっている構造は，通常の火山でも多数観測されている．但し，マタロコ地熱地帯はやや基盤が深くカルデラ状の構造が想定できる．また，イネリエ火山の表層密度は，1.7 g/cm^3 程度と解析され異常に小さい．山体自体が固結した溶岩の比率が小さいことが考えられるが，重力の鉛直勾配が局所的に1割程度大きくなっていれば，通常の火山の表層密度である 2.2 g/cm^3 程度の結果を得ることになる．現時点までの経験では，後者のケースは稀である．調査地中部のウェラスカルデラについては北側だけが確認できる馬蹄形で，南側のカルデラ壁は不鮮明である．原因としては，後に生じたメンゲルーダより西方に伸びる地溝構造に関連する造構運動により消滅したと考えられる．