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# 45. Volcanological Survey of Indonesian Volcanoes. Part 3. A Gravity Survey on the Krakatau Islands, Indonesia.

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## 1. Introduction

As a part of the co-operative studies of Indonesian volcanoes between Indonesian and Japanese volcanologists, gravimetric surveys were carried out during the period August to October, 1968. The authors planned to make gravity surveys in three volcanic districts of the country: central Java around Merapi which is a typical stratovolcano, the Krakatau Islands in the Sunda Straits, and Batur Caldera in Bali. The second contains Krakatau Caldera which was formed by the gigantic eruption in 1883 and has been supposed to belong to the type of low gravity anomaly, and the last to the type of high gravity anomaly according to the classification by one of the authors (I. Y.)[1]. The gravity measurements in central Java were made at 100 points in co-operation with Messrs. I. Surjo and B. Nazar, and those on Batur Caldera at 73 points with assistance from Mr. S. Suparto. In this paper, preliminary results obtained on the Krakatau Islands are reported. More detailed discussions together with the results obtained in the other two districts will be given elsewhere.

The gravity meter used for the surveys is Model "G" Geodetic Gravity Meter No. 31 of the LaCoste & Romberg type, belonging to Hokkaido University. The total of measurements were referred to the gravity station at the Earthquake Research Institute, University of Tokyo, of which the gravity value was 979.80205 gal. The base point at Hotel Indonesia, Djakarta was connected with the E. R. I. twice, on arrival and return both in a day: The differences of gravity values

1) I. YOKOYAMA, "Structure of caldera and gravity amomaly." *Bull. Volcanol.*, [ii] **26** (1963), 67–72.

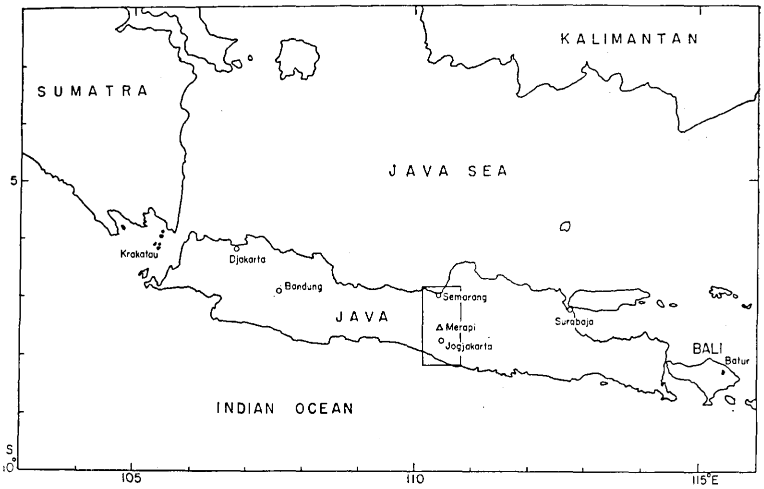



Fig. 1. Java, Bali and Krakatau.

Table 1. Gravity values at 16 principal points of the survey.

| Gravity point | | Longitude (east) | Latitude (south) | Observed gravity value (mgal) |
|---|---|---|---|---|
| No. 1. | Hotel Indonesia, Djakarta | 106°48'.4 | 6°10' | 978,160.13 |
| 2. | Kemayoran Airport, Djakarta | 106 50.7 | 6 09 | 978,163.44 |
| 3. | Hotel Savoy Homann, Bandung | 107 37.1 | 6 55.1 | 978,321.69 |
| 4. | Geological Survey, Seism. Room, Bandung | 107 37.9 | 6 53.9 | 978,328.78 |
| 5. | Wisma Merbabu, Kaliurang | 110 25.8 | 7 35.7 | 977,996.25 |
| 6. | P. P. M., Jogjakarta | 110 23.3 | 7 48.0 | 978,217.25 |
| 7. | Ambarrukmo Palace Hotel, Jogjakarta | 110 24.3 | 7 46.9 | 978,213.78 |
| 8. | Local Government, Bojolali | 110 35.8 | 7 31.9 | 978,064.06 |
| 9. | Djrakah Observatory | 110 25.4 | 7 29.9 | 977,888.59 |
| 10. | Babadan Observatory | 110 24.6 | 7 31.6 | 977,890.74 |
| 11. | Crossroads, Bawen | 110 26.0 | 7 14.7 | 978,037.02 |
| 12. | Hotel Dibya Puri, Semarang | 110 25.3 | 6 58.3 | 978,133.01 |
| 13. | Bali Hotel, Denpasar | 115 13.0 | 8 39.4 | 978,234.11 |
| 14. | Crossroads, Klungkung | 115 24.2 | 8 32.1 | 978,254.62 |
| 15. | Rendung Observatory | 115 25.8 | 8 25.5 | 978,165.63 |
| 16. | Quay at Labuan | 105 47.1 | 6 21.4 | 978,180.43 |

between them were determined as 1,641.96 and 1,641.89 mgal respectively. Therefore, the accuracy of all our measurements is about 0.1 mgal in reference to the E. R. I. The gravity values at 16 principal points covered by our survey are listed in Table 1, their photographs being shown in Fig. 8.

## 2. Gravity measurements on the Krakatau Islands

The great eruption of Krakatau in 1883 was an unparalleled one on record, and well described together with subsequent phenomena in the Report of the Krakatoa Committee[2]. In 1927 the submarine eruption of Anak Krakatau occurred in the midst of the three island relics of the 1883 eruption. One of the authors (D. H.) and others[3), 4)] carried out the seismic observations of the eruptions in 1960 and have repeated topographic surveys on Anak Krakatau. One of the purposes of the present expedition to the Krakatau Islands was a resurvey of topography of Anak Krakatau.

The gravity survey on the Krakatau Islands was carried out within the period Sept. 28 to Oct. 2, 1968. We hired a fishing boat at Labuan on the western coast of Java and set sail for the Krakatau Islands which are composed of Rakata, Anak Krakatau, Lang and Verlaten Island, and set a base camp at Anak Krakatau. At the end of the survey, we proceeded to Sebesi and Sebuku Island, both being situated at the north of the Krakatau Islands, to make a single observation on each island. All measurements were made at the mean shore lines of these islands and therefore the error of height determination may be less than 1 meter because the spring range at the harbour of Djakarta is known as being as small as 0.2 meters. At every observa-

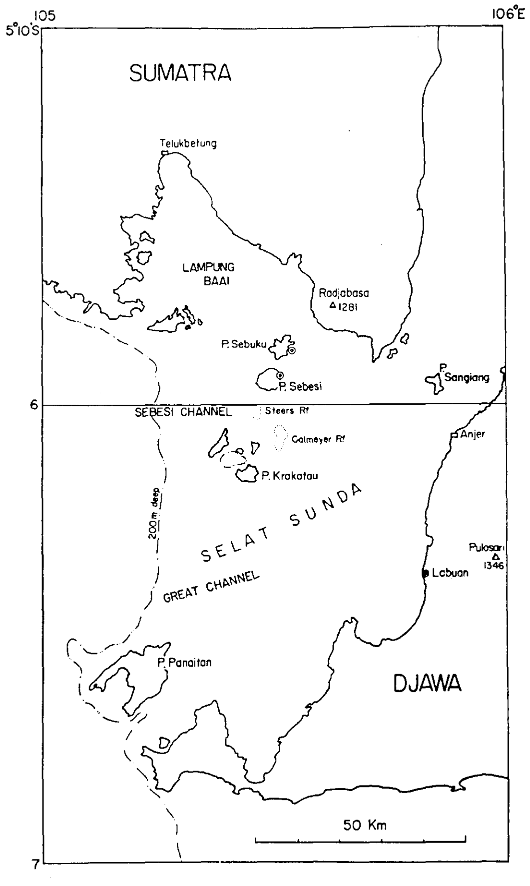



Fig. 2. Sunda Straits.

2) G. J. SYMONS edit. "The Eruption of Krakatoa, and Subsequent Phenomena." 1888, London.

3) R. W. DECKER and D. HADIKUSUMO, "Results of the 1960 expedition to Krakatau." *Jour. Geophys. Res.*, **66** (1961), 3497-3511.

4) M. T. ZEN and D. HADIKUSUMO, "Recent changes in the Anak-Krakatau volcano." *Bull. Volcanol.*, [ii], **27** (1964), 259-268.

Table 2. Gravity values observed on the Krakatau Islands.

| Gravity point | Long. 105°E | Lat. 6°S | Height (meter) | Normal value (mgal) 978, | Observed value (mgal) 978, | Free-air anomaly (mgal) | Bouguer anomaly (mgal) | B. A. Corrected for Topog. (mgal) |
|---|---|---|---|---|---|---|---|---|
| Labuan | 47′.1 | 21′.4 | 1.6 | 112.1 | 180.43 | 68.8 | 68.7 | — |
| 1. Anak Krakatau | 22.3 | 06.2 | 1 | 107.2 | 180.17 | 73.3 | 73.2 | 74 |
| 2. Lang Island | 23.6 | 05.5 | 0 | 107.0 | 182.77 | 75.8 | 75.8 | 76 |
| 3. 〃 | 23.5 | 04.8 | 0 | 106.7 | 177.71 | 71.0 | 71.0 | 71 |
| 4. 〃 | 24.3 | 05.2 | 0 | 106.9 | 175.47 | 68.5 | 68.5 | 69 |
| 5. Rakata | 24.3 | 08.9 | 0 | 108.1 | 176.11 | 68.0 | 68.0 | 71 |
| 6. 〃 | 24.0 | 10.0 | 0 | 108.4 | 174.49 | 66.1 | 66.1 | 69 |
| 7. 〃 | 21.8 | 08.6 | 1 | 108.0 | 181.45 | 73.8 | 73.6 | 83 |
| 8. 〃 | 22.5 | 08.6 | 1 | 108.0 | 178.75 | 71.1 | 71.0 | 86 |
| 9. 〃 | 22.2 | 08.8 | 0 | 108.0 | 179.97 | 72.0 | 72.0 | 84 |
| 10. 〃 | 23.4 | 08.2 | 0.5 | 107.9 | 179.80 | 72.0 | 72.0 | 80 |
| 11. Verlaten Is. | 20.4 | 05.3 | 2 | 106.9 | 182.78 | 76.5 | 76.3 | 77 |
| 12. 〃 | 20.5 | 04.8 | 1 | 106.7 | 183.82 | 77.4 | 77.3 | 78 |
| 13. 〃 | 20.4 | 03.4 | 1 | 106.3 | 177.30 | 71.3 | 71.2 | 72 |
| 14. 〃 | 18.6 | 06.7 | 1 | 107.4 | 184.02 | 76.9 | 76.8 | 78 |
| 15. 〃 | 19.3 | 06.2 | 2 | 107.2 | 185.71 | 79.1 | 78.9 | 81 |
| 16. Lang Is. | 23.6 | 06.5 | 0 | 107.3 | 184.70 | 77.4 | 77.4 | 78 |
| 17. Anak K. | 21.8 | 05.6 | 1 | 107.0 | 177.04 | 70.4 | 70.2 | 71 |
| 18. 〃 | 21.6 | 06.0 | 1 | 107.1 | 174.01 | 67.2 | 67.1 | 69 |
| 19. 〃 | 22.1 | 05.7 | 1 | 107.0 | 179.03 | 72.3 | 72.2 | 73 |
| 20. 〃 | 22.3 | 06.0 | 1 | 107.1 | 179.70 | 72.9 | 72.8 | 74 |
| 21. 〃 | 21.9 | 06.3 | 1 | 107.2 | 174.28 | 67.4 | 67.3 | 69 |
| 22. 〃 | 22.2 | 06.4 | 1 | 107.3 | 179.63 | 72.6 | 72.5 | 74 |
| 23. Verlaten Is. | 19.6 | 04.1 | 2 | 106.5 | 178.37 | 72.5 | 72.3 | 72 |
| 24. 〃 | 19.2 | 04.8 | 1 | 106.7 | 182.77 | 76.4 | 76.3 | 77 |
| 25. 〃 | 19.9 | 03.5 | 2 | 106.4 | 177.38 | 71.6 | 71.4 | 72 |
| Sebesi | 29.1 | 5°58′.6 | 1 | 104.8 | 165.74 | 61.2 | 61.1 | — |
| Sebuku | 30.3 | 5 50.4 | 1 | 102.3 | 177.69 | 75.7 | 75.6 | — |

tion point, the observer (I. Y.) left the boat with the gravity meter and landed on the shores of the islands by a small canoe. Due to the roughness of the open sea, it was not always possible for the observer to land everywhere he wished. But, fortunately, the survey was fairly successful as will be seen later.

The results observed on these islands are tabulated in Table 2, where the mean density of the land is assumed to be 2.5 g/cc, the topographic corrections being calculated graphically by using a topographic

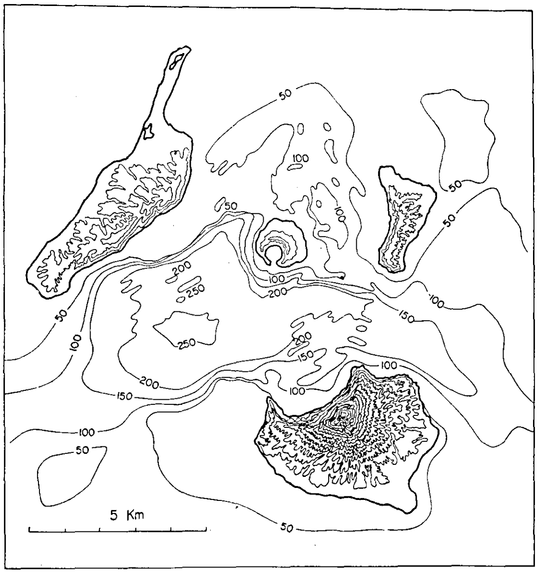



Fig. 3. Topographic and bathymetric chart of the Krakatau Islands surveyed in Dec. 1940. The contour-intervals are 50 meters.

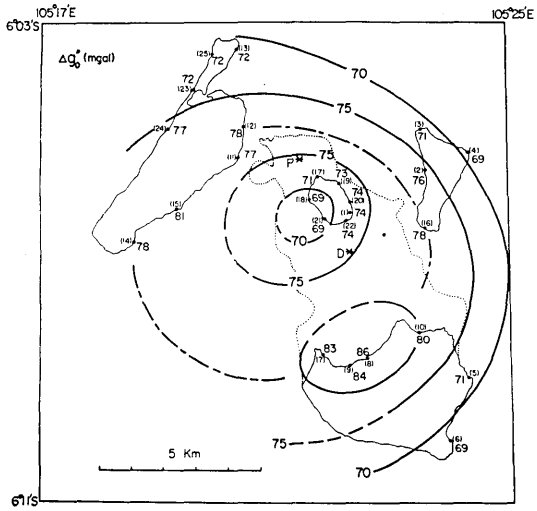



Fig. 4. Distribution of the Bouguer gravity anomalies. Unit is mgal. P and D denote the former vents of Perboewatan and Danan respectively.

and bathymetric chart shown in Fig. 3 which was surveyed in Dec. 1940. The final results of the Bouguer anomalies are accurate within the error of a unit of mgal because the calculation of topographic corrections is more or less erroneous. The distribution of the Bouguer anomalies corrected for topography is shown in Fig. 4.

## 3. Some remarks on the gravity anomalies

First, two subjects will be mentioned as fundamental bases for discussion of gravity anomalies and then followed by the examples of the Krakatau Islands.

### Gravity anomalies due to a subterranean mass of circular disc.

Gravity anomalies due to a thin homogeneous circular disc of radius $a$, of which mass is $\Delta M$, can be derived from the following potential:

$$\Delta V=\frac{2\Delta M}{a}\left[\frac{1}{2}\frac{a}{r}-\frac{1}{2}\cdot\frac{1}{4}\frac{a^3}{r^3}P_2(\cos\theta)+\frac{1}{2}\cdot\frac{1}{4}\cdot\frac{3}{6}\frac{a^5}{r^5}P_4(\cos\theta)\right.$$
$$\left.-\frac{1}{2}\cdot\frac{1}{4}\frac{3}{6}\cdot\frac{5}{8}\frac{a^7}{r^7}P_6(\cos\theta)+\cdots\right], \qquad (1)$$

where $P_n(\cos\theta)$ is a Legendre polynomial of the $n$-th order and $r$ the distance between the disc and an external point. The gravity values at the earth surface due to a circular mass deficiency of depth $d$, are numerically calculated by means of the Table of Legendre Polynomials by G. C. Clark and S. W. Churchill[5]. The variation of a quantity being proportional to $\Delta g$ with various depths of the disc of $a$ and $\Delta M$, is shown in Fig. 5, where it is realized that distinguishing of the anomaly from the background is very difficult when the origin is situated rather deep. In other words, it may be generally said that the sources must lie near the earth surface if the anomalies are to be conspicuous or of short wave-length.

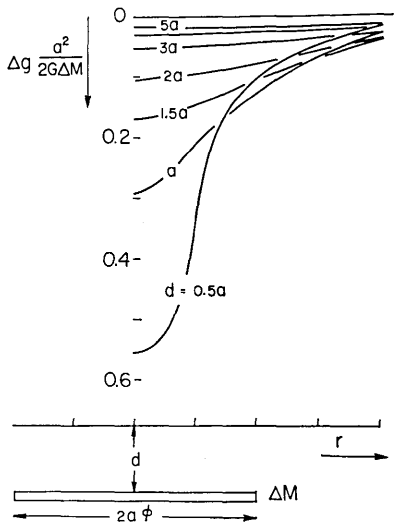



Fig. 5. Radial distribution of gravity anomaly due to a subterranean disc of which the mass deficiency is $\Delta M$.

### Estimation of anomalous mass by surface integral of gravity anomalies

The total anomalous mass responsible for a gravity anomaly is given by Gauss's theorem which relates the integrated anomaly over a horizontal plane

5) G. C. CLARK and S. W. CHURCHILL, "Table of Legendre Polynomials." Engineering Research Institute, Univ. Michigan, 1957.

to the limit of the detectable gravity anomaly in the following form:

$$M=\frac{1}{2\pi G}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Delta g(x, y)dxdy \ , \qquad (2)$$

where $G$ is the gravitational constant. This formula can give no direct information on the shape, depth, or density of the anomalous mass, but only an estimate of the order of its total magnitude. The error of the estimation by the above formula mainly derives from limited coverage and the difficulty of distinguishing the anomaly of interest from other gravity variations. A detailed discussion of the application of this formula was made by T. R. LaFehr[6] mentioning Kuttyaro Caldera, Japan as an example. To fulfil the corrections proposed by LaFehr, it is necessary to assume the depth and shape of the anomalous mass. He obtained the amount of anomalous mass responsible for the Kuttyaro anomaly as being between $9\times10^{10}$ ton (for a model of point source) and $13\times10^{10}$ ton (for a model of prism, depth zero and the ratio width/thickness 4). At the calderas the anomalous mass is usually situated at the uppermost part of the crust, while its shape is not prismatic but circular conical. One of the present authors (I. Y.)[7] calculated the anomalous mass at Kuttyaro Caldera as being $7.8\times10^{10}$ tons applying no corrections. If we are concerned with the order of magnitude of mass deficiency at the calderas, the corrections may not be so important.

### Residual anomaly due to "Krakatau Caldera"

The Bouguer anomalies on and around the Krakatau Islands prove concentric centering at Anak Krakatau though there is no observation on the south-western sea. In Fig. 4, the chain-line shows the crest of the anomaly which is nearly equal to 78 mgal. From the outside, the anomaly increases up to 78 mgal and then decreases towards the centre reaching 69 mgal. The residual anomaly amidst the islands is about 9 mgal low relative to the above-mentioned crest of which the diameter is about 8 km. Since these anomalies are already corrected for topography, they reflect the subterranean structure. The increasing tendency at the outer skirts may be due to the volcanic structure which pre-existed at this area. The island before the 1883 eruption is shown by a dotted line in Fig. 4 and also the old map is reproduced in Fig. 6 from the Report of the Krakatoa Committee[2]. In the figure, dashed lines indicate

6) T. R. LaFehr, "The Estimation of the Total Amount of Anomalous Mass by Gauss's Theorem." *Jour. Geophys. Res.*, **70** (1965), 1911-1919.

7) I. Yokoyama, "Gravity survey on Kuttyaro Caldera Lake." *Jour. Phys. Earth*, **6** (1958), 75-79.

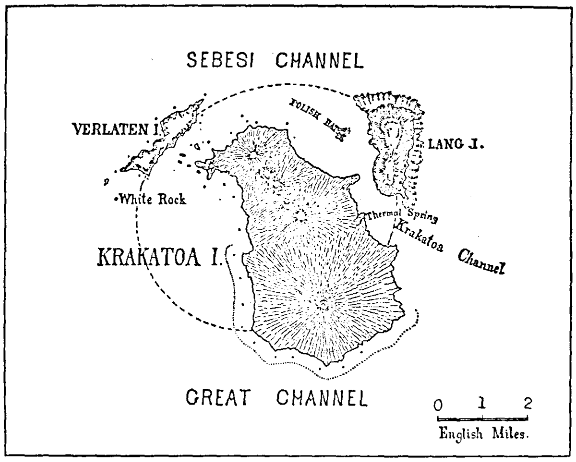



Fig. 6. Map of the islands of the Krakatau group before the 1883 eruption from the Report of Krakatoa Committee.

approximately the submerged edge of the great crater which is a basal wreck of the great Krakatau volcano. According to the above Report, this volcano must have originally been a cone of considerable dimensions and almost entirely built up of lava-streams of enstatite-dacite.

### A preliminary model of subsurface structure of Krakatau

Applying formula (2) to the residual anomalies at the Krakatau Islands, the authors graphically calculate the mass deficiency as $2.8 \times 10^9$ ton. If the density contrast is chosen as 0.3 g/cc being most probable on the other calderas, its volume amounts to $9.3 \times 10^9\ m^3$ which equals the volume of a reversed circular cone (or a funnel) 3 km in radius and 1 km in depth as shown in Fig. 7. At the centre of the upper bottom of this model, the gravity anomaly proves to be about 8 mgal being almost equal to the observed value. In Fig. 7, beneath the lower bottom, there may exist a vertical and deep vent but its effect on the gravity at the earth surface is scarcely detectable even if its diameter were as large as 1 km, in agreement with a conclusion from the previous discussion.

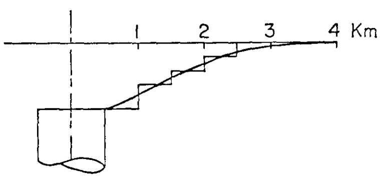
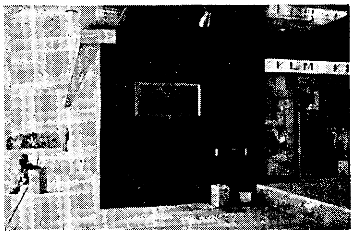



Fig. 7. A model which is responsible for the observed gravity anomaly.

The above is a provisional model of subsurface structure of Krakatau only from the standpoint of gravity anomalies. Further discussion about origin of the caldera formation needs the consideration of a balance-sheet of ejecta and will be made elsewhere.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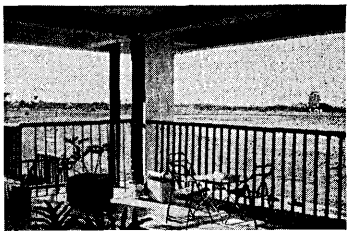
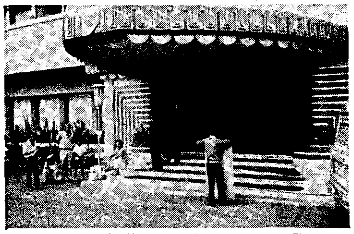

No. 2. Kemayoran Airport, Djakarta.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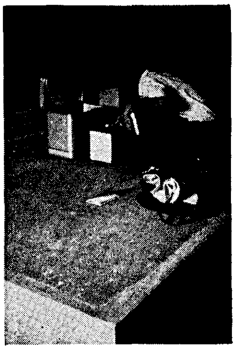
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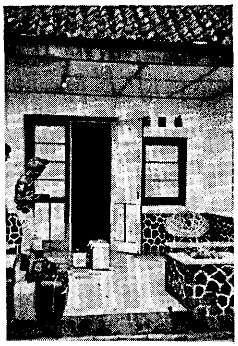
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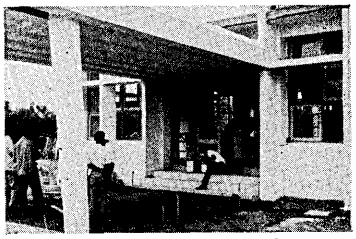
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No. 7. Ambarrukmo Palace Hotel, Jogjakarta.

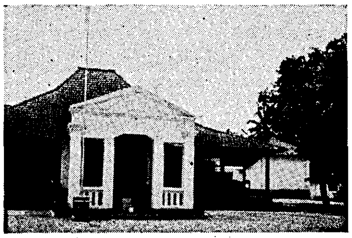
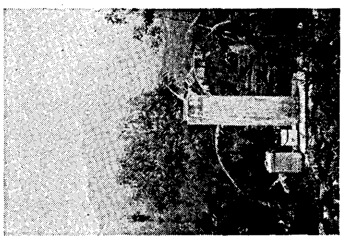

No. 8. Local Government, Bojolali.

Fig. 8. Principal points of the gravity survey in Indonesia (to be continued).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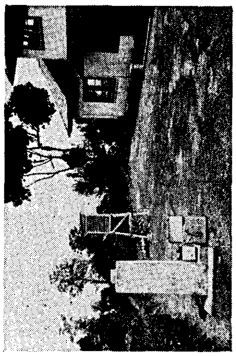
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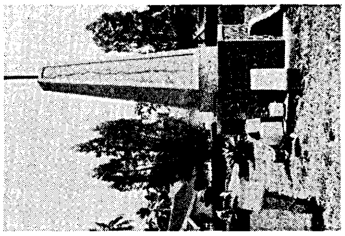
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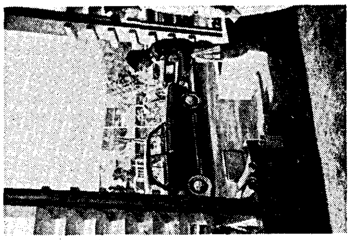
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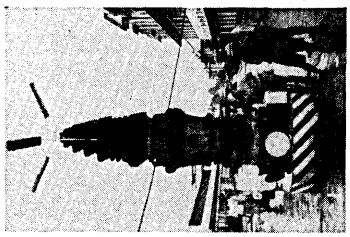
No. 13. Bali Hotel, Denpasar.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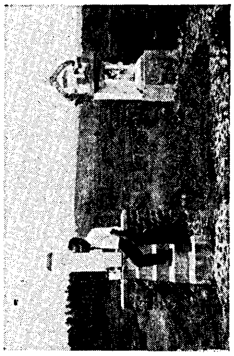
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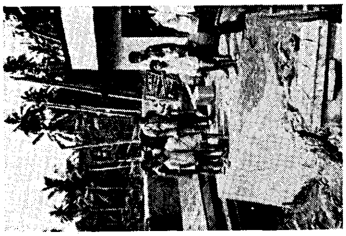
No. 16. Quay at Labuan.

Fig. 8. (continued).

**Acknowledgement**

The authors are grateful to the authorities of both Indonesian and Japanese governments who supported our co-operative studies. The authors' thanks are due to Dr. M. T. Zen who participated in the present expedition with his own theme and discussed many problems with us at the Krakatau Islands.

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# 45. インドネシア火山の調査

## その 3 インドネシア・クラカトア諸島における重力測定

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インドネシア火山の日本・インドネシア協同研究の一部として，著者らは1968年9月末にスンダ海峡のクラカトア諸島で重力測定を実施した.

クラカトア火山の1883年の大噴火は，火山学上特筆される激しいものであった．その関連現象をも含めた詳細なる記述は，クラカトア委員会の報告（1888年）として著名である．この噴火はまた，カルデラ形成の議論にも大きい示唆を与えたようである．H. Williams はカルデラの一分類として，クラカトア型なるものを提唱した．しかし，この火山に関する地球物理学的調査研究は非常に少いので，先づ重力測定をおこなった．クラカトア諸島の地下構造，ひいてはその形成の機構をも論ずる資料を得るのが目的である.

クラカトア諸島の4島で，合計25点の測定を実施した．測定点はすべて海岸である．地形補正を施して，Bouguer 異常分布を求めた．その大体の傾向は，クラカトア諸島の外周からアナク・クラカトアに向って求心的に増加し，直径約 8 km の円周上で最大値約 78 mgal に達し，更に中心に近づくと，減少し，アナク・クラカトア附近で約 69 mgal の最小値を示す．外周から増加する傾向は，この群島が大クラカトア島として 1 ケの大火山島であったときの地下構造の残りを示すものと考えられる．そして直径約 8 km の外周から中心へ向って約 9 mgal 減少する傾向は，1883年の大噴火に因る地下構造を反映しているものと考えられる.

残差重力異常値を面積的に積分して，その原因となる質量不足を推算して，密度差を仮定すると，その体積が求まる．いまカルデラ堆積物の形を逆円錐形（あるいは漏斗状）と仮定すると，重力異常分布とその体積とを，観測結果に合致するように地下構造のモデルをつくり得る.

カルデラの形成に関する議論には，この他に噴出物の量をも考慮に入れなければならぬ．これらの議論は改めておこのう筈である.

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