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17. *Volcanological Survey of Indonesian Volcanoes.*
Part 5. A Gravity Survey on and around Batur Caldera, Bali.

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1. Introduction

Batur Caldera in Bali Island has been called one of the most typical calderas in the world. The caldera embraces a lake and an active central cone which last erupted lavas in January, 1968. Fundamental studies on this caldera, especially from the geological standpoints, have already been made for several decades by Indonesian and Dutch scientists. As a part of the co-operative studies of Indonesian volcanoes between Indonesian and Japanese volcanologists, we carried out a gravity survey on and around this caldera in September, 1968, in succession to the surveys in Central Java (Yokoyama, Surjo and Nazhar, 1970) and on the Krakatau Islands (Yokoyama and Hadikusumo, 1969). In this paper, the results obtained on Batur Caldera and a brief discussion on them are reported.

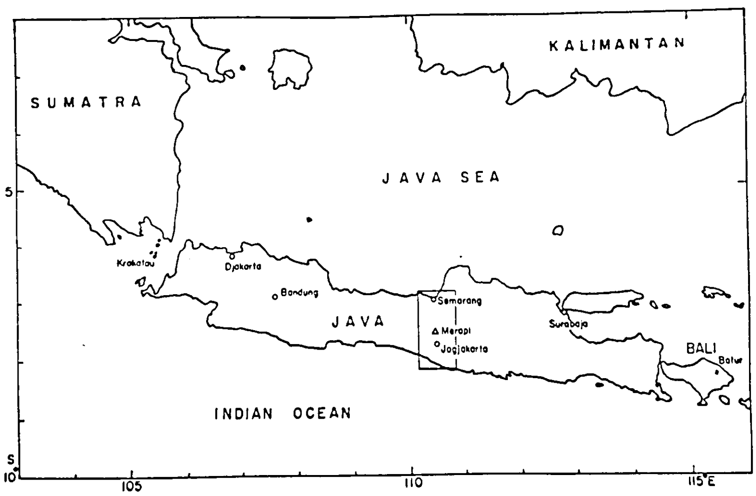

Fig. 1. Java and Bali Islands.

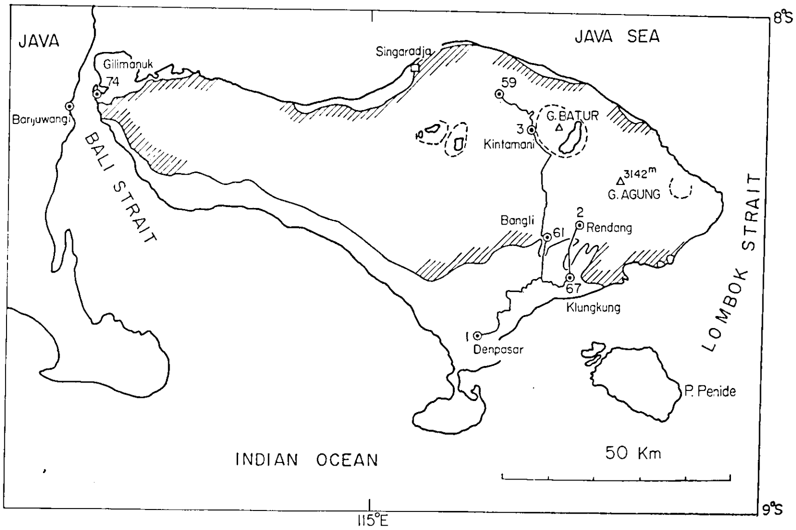

Fig. 2. Bali Island. Hatched area shows the Quaternary volcanics and the numerals denote some of the gravity points.

Almost all the inland area of Bali Island is composed of Quaternary volcanics (andesite and basalt) as shown by the hatched area in Fig. 2. Batur Caldera is situated at the eastern part of Bali Island and about 20 km from Agung (3142 m) or the Peak of Bali. It is a large oval cauldron with a NW-SE axis of 10 km and closed on all sides. Its rim varies in height from 1267 m to 2152 m (the summit of Abang). This cauldron contains a second, concentric and more circular cauldron with a diameter of 7 km. The inner one is younger and separated by the terrace of Kintamani (ranging from 1400 to 1100 m in height) from the outer caldera rim in its western part. Both caldera rims are indicated in Fig. 4, the NW half of the inner caldera rim approximately coinciding with the contour-line of 1250 m in Fig. 3. On the escarpment of the inner caldera, there are the two past eruption centres, Pajang and Bunbulan. The floor of the inner caldera lies 120～300 m lower than the terrace of Kintamani, and coincides with the level of Lake Batur in the SE part of the outer caldera. The depression of the lake might originate together with the inner cauldron. At the common centre of both the calderas, the central cone Batur (1717 m) has been built. According to Kemmerling (1918) and Stehn (1928), the outline of geology of Batur Caldera is as follows:

The eruption centre of Batur repeatedly shifted along the NE-SW line between Bunbulan and Pajang, both of which would be active during the interval between the first and the second caldera formations. Moreover, a number of parasitic craters were formed at its foot. There

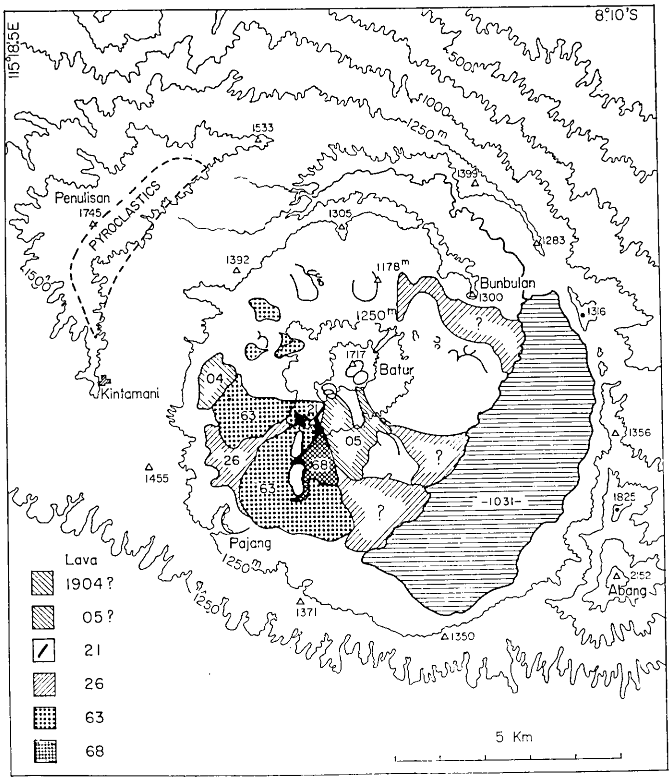

Fig. 3. Distribution of the lava flows from Batur (partly after Stehn).

is a difference in composition between the eruption products of the older and the younger Batur. The outer caldera rim and the terrace of Kintamani consist of glass-rich to normal andesites. The rocks of Abang are already basaltic. The young central cone and all parasitic eruption centres have produced basaltic rocks, the older basalts being poor in olivine and the younger ones rich in olivine. The differentiation has apparently followed the reverse course of the normal succession. The volcano may have passed through several successive cycles of differentiation, from basic to acid, each one ending with a Plinian outburst of acid magma and the collapse of the top part, while only a few of the stages have been found in the field. The outer caldera rim and the terrace of Kintamani are covered by pumiceous efflatta of an acid composition (64.70% of SiO_2). These products are probably related to a Plinian outburst at the end of a differentiation cycle, causing the collapse of the inner caldera. But in the older initial stages of Batur complex, more basic lavas might be present, which are not exposed. The youngest cycle of activity has started again with basaltic, olivine-bearing andesites with 50.45~53.68% of SiO_2.

Around Batur within the inner caldera, there are many lava flows as shown in Fig. 3, some of which are doubtful in their ages, say 1804, 1821, 1849, 1888, 1897, 1904, and 1905. During the eruption of 1926, lavas of $21 \times 10^6 m^3$ were extruded from southern part of the NE-SW fissure across Batur, and the large village of Batur at the foot of Pajang was buried by the lava flows. The activities of Batur after 1926 are as follows:

1963, Sept. 5 The outpouring of basaltic lavas continued until Sept. 26 from three separate fissures accompanied by minor explosions and lava-fountains from several spots.

1965, Aug. 18 Eruptions occurred at the southernmost crater. No lava flows.

1966, April 28 Eruptions took place at the 1965 crater. No lava flows.

1968, Jan. 23 Lava outpoured from the 1966 crater until Feb. 15 accompanied by minor explosions.

2. Gravity survey

A gravity survey on Batur Caldera was carried out in the middle of September, 1968 and the gravity meter used for the survey was a Model "G" of LaCoste & Romberg type. On Sept. 9 we left Kaliurang near Jogjakarta, Central Java with the gravity meter by bus and arrived at Denpasar after 24 hours' travel. After the survey on Batur Caldera we returned to Kaliurang on Sept. 19. During these 10 days, the drift of the gravity meter reading was about 0.1 mgal. The base in Bali Island was at Denpasar (Bali Hotel). The total of measurements were referred to the gravity station at the Earthquake Research Institute, the University of Tokyo, of which the gravity value was 979.80205 gal. The connecting route with Tokyo was extended to Djakarta, Bandung, Kaliurang and Denpasar in order, respectively within a day. The difference of gravity between the bases at Kaliurang and Denpasar was determined twice as 237.97 and 237.75 mgal: we adopt their mean value 237.86 mgal as the most probable value. As reported in the previous paper (Yokoyama, Surjo and Nazhar, 1970), the connecting error between Kaliurang and Tokyo was approximately 0.1 mgal, and therefore the accuracy of all measurements in Bali Island is about 0.2 mgal in reference to the E. R. I., Tokyo.

The observation points were 74 in number including the points outside of Batur Caldera, such as Gilimanuk (the western end of the island), Bangli, Klungkung and Rendang, as shown Figs. 2 and 4. The photos of some observation points, Nos. 1, 2 and 67, were shown in Fig. 8 of the previous report (Yokoyama and Hadikusumo, 1969). In the survey, we tried to occupy the triangulation points and the spot heights as far as possible, of which heights were indicated in the unit of meter on the topographic maps. Besides these points, many other points were occupied and their heights were determined by barometric and interpolation method between the known heights. During the survey on and around Batur Caldera, a base barograph was operated at Kintamani in order to make corrections for atmospheric variations. The barometers were those of American Paulin System, by which one could read the heights at 0.5 m intervals, but the accuracy of height determination usually depends on the atmospheric conditions. It is not so reliable between distant points even if atmospheric variations are corrected by the barographic observations at the base. In this respect, the interpolation method may be more practical. In the present survey, the error of height determination may be less than 5 m corresponding to about 1 mgal in the Bouguer anomaly.

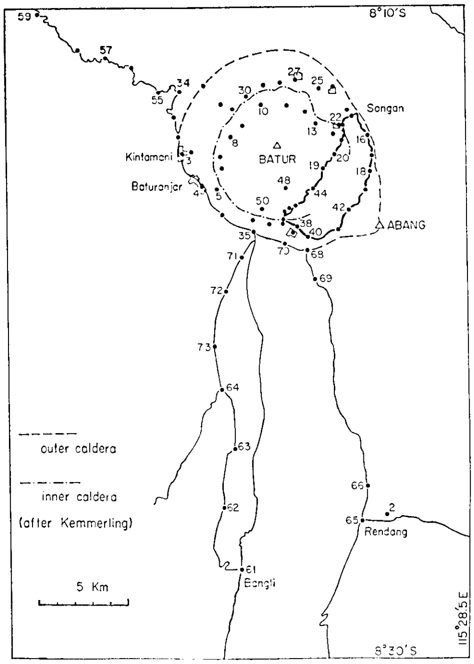

Fig. 4. Gravity points on and around Batur Caldera.

Our gravity meter had to be thermostated by a battery. However, in and around Batur Caldera, there was no commercial electric supply to charge the batteries. Bangli is the nearest city where one can use commercial electricity. We took a car battery to Kintamani and had to finish the survey using small Cd·Ni batteries inside the caldera within 3 days, from Kintamani to Kintamani.

The present survey was not satisfactory in the distribution of the gravity points because of the difficulties in topographies and keeping the batteries: we could not set any gravity points on the new lava flows. However, the results of the survey may afford us a clue for discussing the regional subsurface structure of Batur Caldera.

All observed gravity values are listed in Table 1 where we missed a gravity measurement at gravity point No. 52 at Kintamani.

3. Gravity anomalies on Batur Caldera

The Bouguer gravity anomalies in this area are calculated as shown

Table 1. Gravity values observed on and around Batur Caldera.

Gravity point	Long. 115°E	Lat. 8°S	Height (meter)	Normal value (mgal) 978,	Observed value (mgal) 978,	Free-air anomaly (mgal)	Bouguer anomaly (mgal)
1. Denpasar (Bali Hotel)	13.0	39.4	25	165.7	234.11	76.1	73.5
2. Rendang Observatory	25.8	25.5	532.55	159.6	165.63	170.4	114.6
2. Kintamani	19.6	14.4	1479	154.8	*936.94	238.6	83.7
4. △ T417	20.1	15.4	1455	155.2	*943.82	237.6	85.3
5. Slope	20.7	15.5	1286	155.2	*990.83	232.5	97.8
6. Caldera bottom	20.8	14.9	1110	155.0	039.93	227.5	111.3
7. 〃	20.8	14.5	1094	154.8	041.48	224.3	109.7
8. Jehmampeh	21.1	13.9	1088	154.6	043.09	224.2	110.3
9. Caldera bottom	21.5	13.6	1098	154.4	045.23	229.7	114.7
10. near S.H. 1123	22.1	13.0	1128	154.2	040.32	234.2	116.1
11. Caldera bottom	23.0	13.0	1129	154.2	039.86	234.1	115.9
12. near S.H. 1116	23.5	13.2	1143	154.3	041.74	240.2	120.5
13. Caldera bottom	23.8	13.5	1163	154.4	038.64	243.1	121.4
14. Lake shore	24.6	13.6	1031	154.4	067.22	231.0	123.0
15. S.H. 1031	24.9	13.4	1031	154.4	069.78	233.5	125.6
16. Lake shore	25.4	14.1	1031	154.6	071.05	234.6	126.7
17. 〃	25.5	14.7	1031	154.9	074.14	237.4	129.5
18. Troenjan	25.4	15.2	1031	155.1	072.42	235.5	127.5
19. Hot spring (Jeh Bungkah)	24.0	15.0	1031	155.0	059.81	223.0	115.0
20. Lake shore	24.4	14.6	1031	154.8	062.60	226.0	118.0
21. 〃	24.7	14.1	1031	154.6	066.20	223.0	121.8
22. Songan	24.5	13.7	1037	154.5	063.36	228.9	123.0
23. near Songan	24.4	13.9	1050	154.6	059.86	229.3	119.4
24. Road to Pinggan	24.8	13.2	1038	154.3	063.68	229.7	121.0
25. Valley	23.9	12.4	1116	154.0	039.43	229.8	113.0

(to be continued)

Table 1. (continued)

Gravity point	Long. 115°E	Lat. 8°S	Height (meter)	Normal value (mgal) 978,	Observed value (mgal) 978,	Free-air anomaly (mgal)	Bouguer anomaly (mgal)
26. Blandingan	24.4	12.4	1175	154.0	022.39	231.0	108.0
27. Pinggan S.H. 1238	23.2	12.2	1238	153.9	008.43	236.0	107.0
28. Terrace	22.8	12.3	1278	153.9	*997.59	238.1	104.3
29. 〃	22.2	12.4	1275	154.0	*999.54	239.0	105.5
30. 〃	21.7	12.7	1309	154.1	*990.78	240.6	103.6
31. ◬ T428	21.2	13.0	1392	154.2	*968.12	243.5	97.7
32. Paketan	20.8	12.8	1397	154.1	*968.67	245.7	99.4
33. Slope	20.3	12.3	1524	153.9	*939.01	255.4	95.9
34. Penoelisan	19.6	12.6	1680	154.0	*889.49	253.9	78.0
35. Penelokan	21.8	16.9	1344	155.9	*974.07	232.9	92.2
36. Slope	22.2	16.7	1219	155.8	010.25	230.6	103.0
37. near lake	22.7	16.7	1068	155.8	046.27	220.1	108.2
38. S.H. 1032	23.2	16.8	1031	155.8	054.41	216.8	108.8
39. Boeahan	23.1	16.9	1045	155.9	050.68	217.3	107.9
40. Lake shore	23.5	17.2	1031	156.0	056.69	218.9	110.9
41. 〃	24.4	16.9	1031	155.9	058.76	221.0	113.1
42. Abang	24.7	16.3	1031	155.6	063.92	226.5	118.5
43. Lake shore	25.3	15.7	1031	155.4	067.54	230.3	122.4
44. 〃	23.6	15.6	1031	155.3	060.65	223.5	115.6
45. 〃	23.0	17.5	1031	156.1	054.41	216.5	108.5
46. 〃	22.7	18.0	1031	156.3	052.40	214.3	106.3
47. near lake	22.9	16.2	1046	155.6	052.59	219.8	110.3
48. S.H. 1097	22.8	15.6	1090	155.3	043.43	224.5	110.4
49. near lake	22.8	16.3	1056	155.6	049.01	219.3	108.7
50. Caldera bottom	22.0	16.2	1077	155.6	042.68	219.4	105.7

(to be continued)

Table 1. (continued)

Gravity point	Long. 115°E	Lat. 8°S	Height (meter)	Normal value (mgal) 978,	Observed value (mgal) 978,	Free-air anomaly (mgal)	Bouguer anomaly (mgal)
51. Slope	21.7	16.6	1227	155.7	008.09	231.0	102.6
52. Kintamani	19.9	14.4	1489	154.8	—	—	—
53. Crossroads	19.4	13.3	1595	154.3	*909.27	247.2	80.2
54. △ T416	19.5	13.9	1539	154.6	*922.38	242.7	81.6
55. Crossroads	18.9	12.6	1576	154.0	*913.88	246.2	81.2
56. near △T142	18.1	11.8	1414	153.7	*951.72	234.4	86.3
57. near △T141	17.2	11.6	1338	153.6	*969.92	229.2	89.1
58. Road corner	16.4	11.3	1206	153.5	003.42	222.1	95.8
59. Road to Singaradja (Penginjahan)	15.2	10.2	914	153.0	078.63	207.7	112.0
60. near △ T417	20.8	16.3	1372	155.6	*961.76	229.6	85.9
61. Bangli	21.4	27.3	442	160.3	172.88	149.0	102.7
62. Soesoet	20.8	25.3	633	159.5	125.78	161.6	95.3
63. S.H. 708	21.2	23.5	709	158.7	107.47	167.6	93.3
64. S.H. 856	20.8	21.8	856	157.9	069.11	175.4	85.7
65. S.H. 532	25.1	25.7	532	159.7	163.90	168.4	112.7
66. S.H. 587	25.3	24.7	587	159.2	157.39	179.3	117.9
67. Klungkung	24.2	32.1	93	162.4	254.62	120.9	111.2
68. Road corner	23.5	17.5	1316	156.1	*980.09	230.1	92.3
69. △ T517	23.7	18.5	1218	156.5	008.27	227.6	100.1
70. S.H. 1360	22.7	17.3	1360	156.0	*972.45	236.1	93.8
71. Road to Bangli	21.5	17.7	1179	156.2	002.00	209.6	86.2
72. 〃	20.9	18.8	1056	156.5	025.19	194.6	84.0
73. △ T488	20.6	20.4	955	157.3	047.04	184.5	84.5
74. Gilimanuk	114° 25.1	9.9	2	152.9	174.02	21.7	21.5

*977,

in Table 1, where the mean density of the land is assumed to be 2.5 g/cc, the vertical gradient of gravity to be 0.3086 mgal/m, the topographic corrections not being taken into consideration because we selected the gravity points at gentle topographies as far as possible. The accuracy of the anomalies is about 1 mgal except the topographic corrections which may amount to 4~5 mgal at the maximum, e.g. on the southern rim of the caldera. The distributions of the Bouguer anomalies in Bali Island and on Batur Caldera are shown in Figs. 5 and 6, respectively.

In Bali Island as a whole, the anomalies seem to increase toward the east though the present survey is not sufficient to find any tendency in gravity field there. By the way, also the results of the marine gravity surveys along the Indonesian Archipelagoes by Vening Meinesz (1932 and 1934) does not suggest any tendency on the island.

On Batur Caldera, the anomaly increases toward the east as shown in Fig. 6 where a thick broken line represents the outer caldera rim and a chained line the inner one after Kemmerling (1918). Its eastward gradient is very steep (about 30 mgal/3 km) at the terrace of Kintamani between the two caldera rims. Perhaps this may indicate the existence of an excess mass inside the outer caldera. At the central part of the caldera, a positive residual anomaly amounting to more than 5 mgal, may be superposed upon the above increasing tendency which is not so conspicuous as in the western part. At any rate, both the two concentric calderas of Batur belong to the high gravity anomaly type according to the classification of the calderas by one of the authors (Yokoyama, 1963).

Concerning the formation of Batur Caldera, Williams (1941) mentioned that its dominant process had been engulfment without any doubt because of the form of the caldera and the paucity of fragmental debris on the surrounding slopes. According to his classification of calderas,

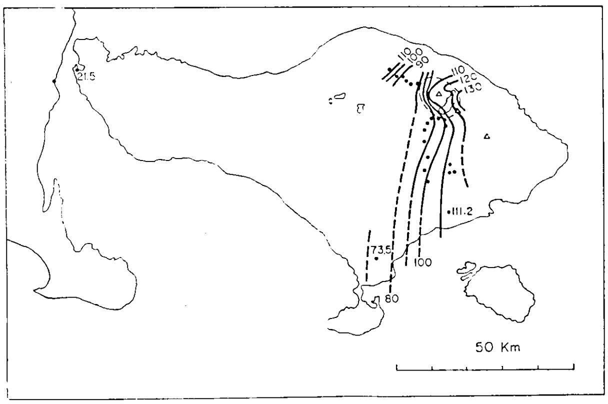

Fig. 5. Bouguer gravity anomalies around Batur Caldera. Unit is mgal.

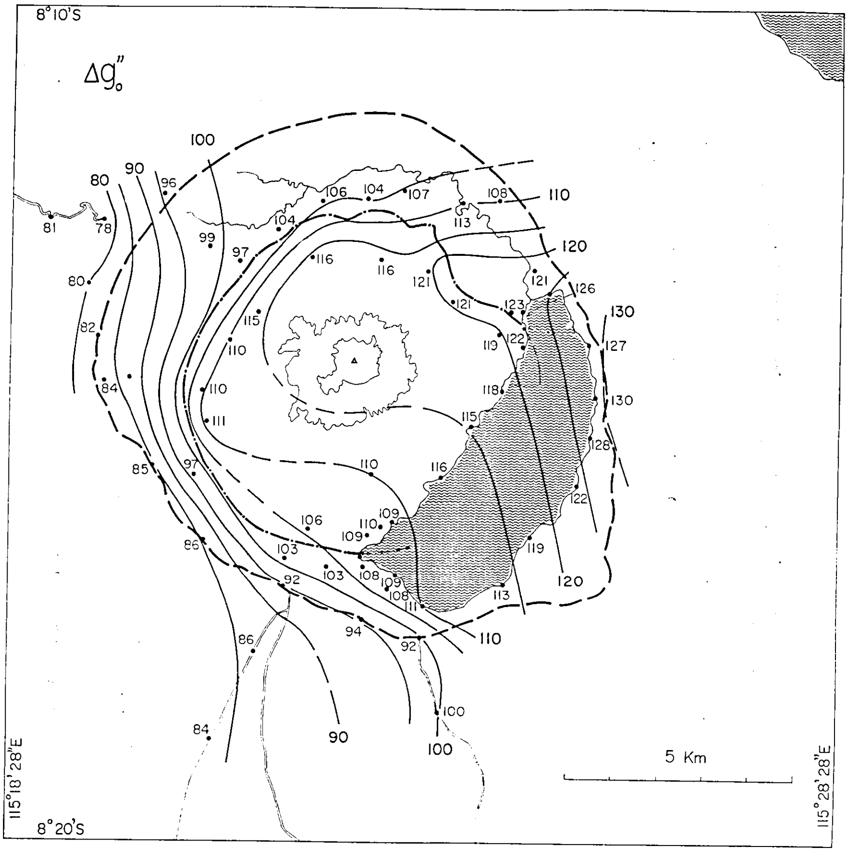

Fig. 6. Distribution of the Bouguer gravity anomalies on Batur Caldera. Unit is mgal.

Batur Caldera belongs to one of Kilauean type: the caldera-forming collapses on shield volcanoes of basalt are in large part a result of a lowering of the magma level in the central conduit by dike-injection at depth and by the opening of fissures on the flanks of the shield and the consequent discharge of subterminal and eccentric flows. This Williams' classification is clearly not accordant with the previous description of Batur Caldera by Kemmerling and Stehn.

Recently McBirney and Williams (1969) newly categorized calderas into two principal groups, one in which collapse is associated with explosive outpourings of siliceous magma and another is characterized by effusive eruption of basic lavas and piece-meal subsidence. From the previous Yokoyama's viewpoint, the former corresponds to the low gravity anomaly type and the latter to the high gravity anomaly type. McBirney and Williams subdivide the latter group into three: the Masaya type, the Hawaiian type and the Galapagos type. However, at this time, they do not mention the name of Batur. The authors suppose that none of these three is appropriate to Batur Caldera.

In Japan, there is one example of calderas of high gravity anomaly type—Oosima Caldera. Its diameter is 3～4 km, not so large compared with Batur. The Bouguer anomalies on Oosima Caldera is shown in Fig. 7. One of the authors (Yokoyama, 1969) discussed the subsurface structure of this caldera mainly from the geophysical standpoints and expressed an idea about its formation as follows: Repeating lava flows, eruptive activities and the successive accumulation of the overflowed lavas, the summit part became denser than the surroundings and hence might subside continuously or stepwise. And further, into this subsided region, the new lavas might have overflowed. The repetitions of such processes have caused the subsidence of 50～60 m at the present surface. In the case of Batur Caldera, the scale of the processes should have been far larger than those of Oosima Caldera.

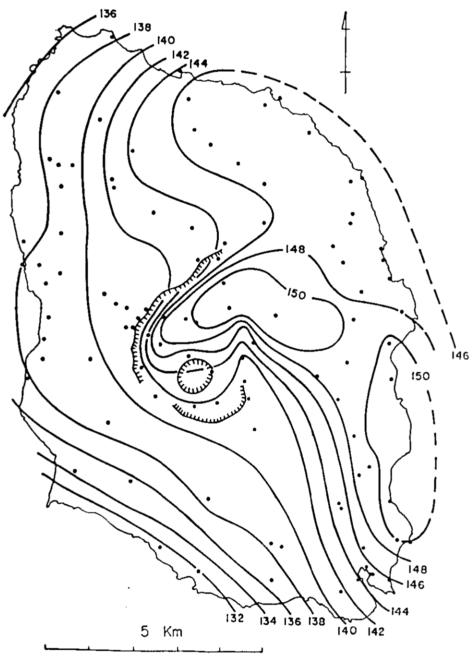

Fig. 7. Distribution of the Bouguer gravity anomalies on Oosima Volcano, Japan after Yokoyama. Unit is mgal.

In order to discuss genetics of of calderas, one should study the ejecta from the calderas. In this respect, one can refer to the paper of Marinelli and Tazieff (1968), who studied ignimbrite at the northern and the southern flanks of Batur Caldera and estimated the volume of the ignimbrite as 20 km^3 at the south of the caldera and 3 km^3 at the north of the caldera. In fact, one can easily find the loosely welded tuff ("paras") outside the caldera, especially around Gianjar at the south of Bangli, and we found some of them at the north of Songan within the caldera. More detailed discussion of the volcanic ejecta around Batur Caldera will be a future problem. Marinelli and Tazieff mentioned the ignimbrite exposed at the wall of the inner caldera. The authors collected a specimen of the ignimbrite at the cliff below triangulation point T 428 (1392 m) at the northern part of the inner rim. According to S. Aramaki (personal communication), this ignimbrite would be airfall deposits from lava fountains.

Fig. 8(a). A morning scene from Kintamani facing east. From the north, Batur, Abang (a rim cone), Agung, and village of Baturanjar on the outer rim.

Fig. 8(b). Batur Caldera seen from Penelokan. The nearest lava flow is one of the 1963 eruption.

Fig. 8(c). One of the 1963 lava flows in the north-western caldera bottom.

Fig. 8(d). An end of the 1963 lava flows which reached to the south caldera wall.

In concluding, the authors expect that the discussion on the origin of Batur Caldera, being characterized by the double cauldrons and by the high gravity anomalies, will contribute to the general theory of caldera formation.

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17. インドネシア火山の調査

その5 バリ島バツール・カルデラ周辺の重力測定

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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月バリ島のバツール・カルデラおよびその周辺で，重力測定を実施した．この火山については，すでに1920年前後から地質学的調査が行なわれており，カルデラなるものの一典型として著名である．しかしその成因に関する説は未だ確立されていないようである．H. Williams はこれを彼の「キラウェア型」に帰属させたが，これは明らかに無理である．しかしキラウェアもバツールも，塩基性溶岩を溢出したことは共通であり，その結果として，両者共に Bouguer 高異常に関係している．

バツール・カルデラの地形上の特長は，その同心二重のカルデラ壁である．重力測定の結果から，二重のカルデラそれぞれが高異常を伴つている．この形成の機巧としては，同心二重のカルデラが前後して形成されることを許すものでなければならぬ．この意味でバツール・カルデラの形成機巧は重要であるが，その解明のためには，火山地質学的，岩石学的な調査も必要である．たとえばバリ島東部に多量に産する「パラス」なる固結度の低い溶結凝灰岩の分布や，その起源を確認することが先ず必要であろう．