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A QUANTITATIVE CONSIDERATION OF SEVERAL CALDERAS FOR STUDY OF THEIR FORMATION

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RESUMEN

Se han acumulado datos gravimétricos acerca de 22 calderas, la mayoría de ellas en Japón. Para algunas de dichas calderas se dispone también de datos sísmicos por explosión o mediante resultados de perforaciones. Sintetizando estos datos se deducen algunas configuraciones comunes a su estructura subsuperficial.

Si bien todas las calderas japonesas son relativamente recientes, fluctuando su edad entre 6 000 y 100 000 años (B.P.), se intenta una discusión general acerca de ellas en conjunto: las deficiencias de masa obtenidas mediante anomalías gravimétricas sobre las calderas presentan una estrecha correlación con sus diámetros. Esta correlación es similar a la de los cráteres originados por meteoritos en Canadá, lo que implica la similitud de la estructura subsuperficial entre las calderas y dichos cráteres.

ABSTRACT

Gravimetric data have been accumulated on 22 calderas mainly in Japan. For some, explosion-seismic data or drilling results are also available. Synthesizing these data, some common features of their subsurface structure are deduced.

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Although all Japanese calderas are relatively young, ranging in age from 6 000 to 100 000 Y.B.P., a general discussion on them as a whole is tried: the mass deficiencies obtained by gravity anomalies over the calderas have a close correlation with their diameters. This correlation is similar to that of the meteorite craters in Canada, implying the similarity in the subsurface structure between the calderas and the meteorite craters.

INTRODUCTION

In order to discuss the formation of calderas, it should be indispensable to study the existing subsurface structure of various calderas as well as the surface geology at and around them.

Many calderas have been surveyed by gravimetric methods which prove to be effective in study of caldera structure because the caldera deposits (or fills) are products of explosions. A few calderas were observed by explosion seismic methods and recently drillings on and around calderas are increasing in number and depth. Their results are useful to cross-check the structure obtained by gravimetric methods.

Hitherto, specific features of each caldera have been reported. In this paper a general discussion mainly on Japanese calderas as a whole will be made.

SUBSURFACE STRUCTURE OF CALDERAS

Gravimetric methods

At most calderas, gravity anomalies, whether high or low, are conformable to their rims. This means that the calderas have structural contrasts against the surrounding basements.

Gravimetric data on 22 calderas mainly in Japan are summarized in Table 1. The calderas are classified into 2 types, one characterized by high gravity anomaly and the other by low gravity anomaly. High gravity anomalies originate from mafic caldera deposits, and more common, low ones from siliceous caldera deposits. Calderas of high anomaly type are generally small in diameter and may have been formed by subsidence of massive mafic lavas: an example of this type, Ooshima caldera (Fig. 1) was discussed by Yokoyama (1969) on a geophysical basis. Other examples may be the calderas on Galápagos Islands though no detailed gravity survey has been carried out there. The present paper is mainly concerned with calderas of low anomaly type. The following are general features of calderas of low anomaly type:

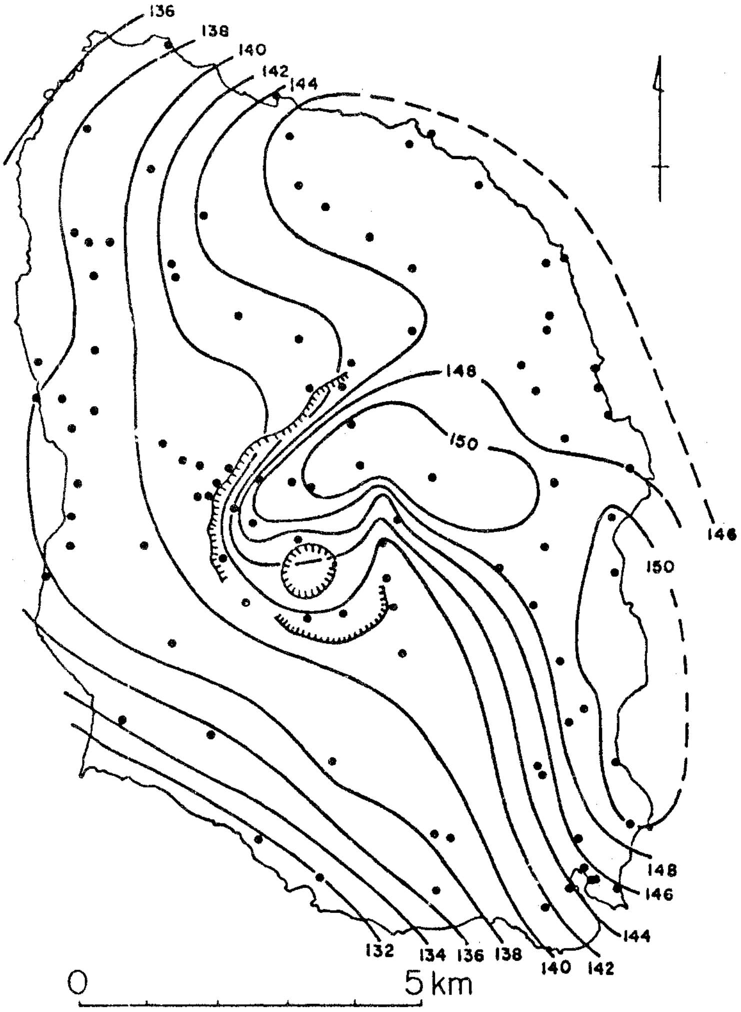

Fig. 1. Distribution of Bouguer gravity anomalies on Ooshima volcano island, Japan. Unit is mgal.

The patterns of gravity anomalies on calderas are conformable to caldera rims and, in many cases, the anomalies gradually increase towards the centers of the calderas. On calderas of the larger diameter, the larger gravity anomalies are observed.

Caldera depressions containing caldera deposits are of funnel shape, not of piston shape because of the above patterns of gravity anomalies and of the available drilling results (Yokoyama, 1984). At some calderas, the boundaries of gravity anomalies are found inside the present rims: at such calderas, the present caldera rims have resulted from dissections, and are not significant in discussion of caldera structure.

Density contrasts between caldera deposits and basement rocks may be assumed as 0.3 ~ 0.5 g/cc in average. They are exemplified in the results of drilling of 1 000 m deep at Kuttyaro caldera, Hokkaido (Yokoyama, 1983) where the core density increases linearly from 1.5 to 2.3 g/cc with depth, in contrast to the surrounding country rocks. The maximum limits of gravity anomalies on calderas of low anomaly type are 40 ~ 50 mgal. In these cases, the maximum depths of caldera deposits are estimated as 2 ~ 4 km. In general, gravity anomalies observed at calderas are so large that they may be reasonably attributed to the calderas and that we can not easily distinguish the small anomalies of deeper origin, if any.

Seismometric methods

Seismometric studies are very few on the calderas of Table 1. The Geological Survey of Japan (Ono *et al.*, 1978) has repeated a series of explosion seismic observations from 1972 to 1977 to study subsurface structure and possible anomaly in wave propagation beneath and around Aira caldera and its post-caldera cone, Saku-

TABLE 1. Geophysical aspects of calderas mainly in Japan.
ΔM is estimated by surface integral of gravity anomalies on a caldera.

Caldera	Locality	Dia (km)	Max Δg (mgal)	ΔM (ton)	Ejecta mass (ton)	Drilling	Remarks	References (gravity anomaly)
Kuttyaro	Hokkaido	22	- 46	7.8×10^{10}	3×10^{11}	1000^{m}	partly lake	Yokoyama (1958)
Mashu	"	6.5	- 10	1.1×10^{9}	2×10^{10}		mainly lake	Yokoyama (1970)
Akan	"	24x13	- 21	3.8×10^{10}	1.5×10^{11}		partly lake	Ohkawa & Yokoyama (1979)
Shikotsu	"	15	- 20	3.2×10^{10}	2×10^{11}		mainly lake	Yokoyama & Aota (1965)
Toya	"	12	- 15	6.6×10^{9}	4×10^{10}		mainly lake	Yokoyama (1964)
Kuttara	"	3.5	- 1.5	7.0×10^{7}	6×10^{9}		mainly lake	Yokoyama et al. (1967)
Nigorikawa	"	3	- 4	2.1×10^{8}	?	$736\sim2400^{m}\times26$		Ando (1981)
Towada	Tohoku	12	- 15	1.4×10^{10}	6×10^{10}		mainly lake	Yokoyama & Maki (1964)
Onikobe	"	13	- 24	2.2×10^{10}	?			Rikitake et al. (1965)
Haruna	Kwanto	2.6	- 1	2.4×10^{7}	?		partly lake	Yokoyama & Maekawa (1983)
Hakone	"	9	- 10	4.1×10^{9}	2×10^{10}	$>500^{m}\times20$		Yokoyama (1983)
Aso	kyushu	22	- 23	4.0×10^{10}	3.6×10^{11}	170^{m} & 600^{m}		Yokoyama (1983)
kakuto	"	20x12	- 10	1.1×10^{10}	1×10^{11}			Yokoyama & Ohkawa (1986)
Aira	"	25	- 35	1.2×10^{11}	$>3\times10^{11}$		mainly submarine	Yokoyama (1961)
Ata (Ibusuki)	"	15	- 25	?	6×10^{10}		partly submarine	Yokoyama & Ohkawa (1986)
Kikai	Osumi Ids	20x15	- 25	2.6×10^{10}	2×10^{11}		mainly submarine	Ishihara (1977)
Thera	Greece	10	- 10	4.0×10^{9}	?		mainly submarine	Yokoyama & Bonasia (1978)
Toba	Sumatra	100x30	- 45	1.3×10^{12}	2×10^{12}		partly lake	Yokoyama & Ohkawa (1986)
Krakatau	Sunda Straits	9	- 10	2.8×10^{9}	3×10^{10}		mainly submarine	Yokoyama & Hadikusumo (1969)
Ooshima	Seven Izu Ids	3	+ 7					Yokoyama (1960)
Kilauea	Hawaii	4	+ 9					Kinoshita (1965)
Batur	Bali	10	+ 10				partly lake	Yokoyama & Suparto (1970)

rajima volcano in Kyushu. By the refraction seismic observations, regional crustal structure of the south Kyushu was determined and by two fan-shooting observations, a large attenuation of the amplitude of seismic waves was found under Aira caldera and Sakurajima volcano. The physical state causing the attenuation is not definitely determined yet.

Shikotsu caldera in Hokkaido was studied by Yokoyama and Aota (1965): a land gravity survey along the shore of the caldera lake and a shipborne geomagnetic total force survey on the lake were carried out. The distribution of Bouguer gravity anomalies is reproduced in Fig. 2, where topographic corrections for lake water are neglected because they are estimated at only 0.3 mgal at their maximum. The Geological Survey of Japan (Ito *et al.*, 1983) made explosion seismic observations on and around the caldera in 1980 and 1982: the observation line was about 36 km long in the direction of the major axis of the lake (Fig. 2) and the shot-points were 2 at the east and one at the west of the lake. The observation points were 24 in total, 14 seismometers on land and 10 hydrophones at the lake bottom, about 360 m

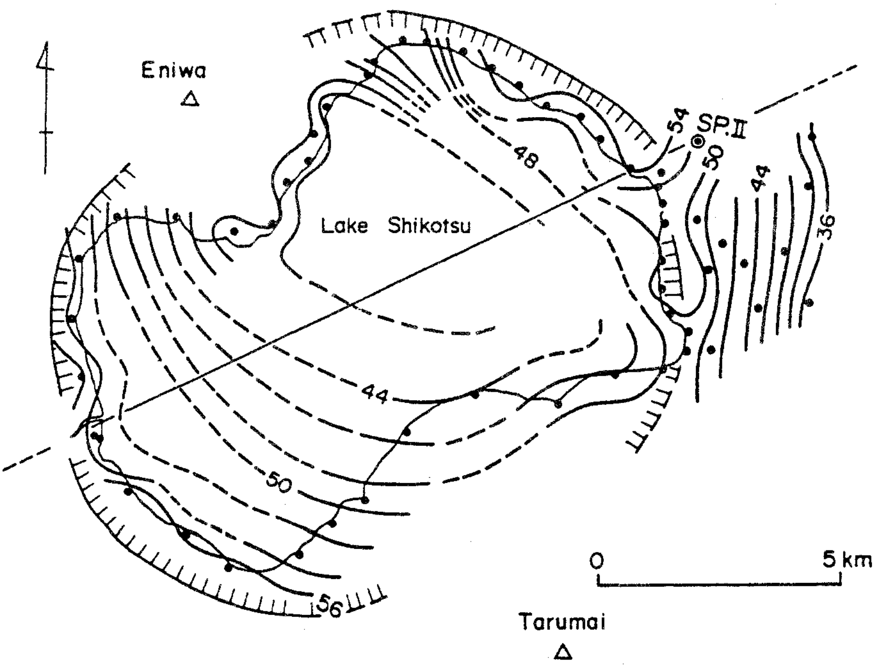

Fig. 2. Distribution of Bouguer gravity anomalies around Shikotsu caldera lake, Japan. Unit is mgal. A NE-SW line through the lake represents the explosion seismic observation line by the Geological Survey of Japan. SP. II is one of three shotpoints on the line.

deep. The present author (1984) analyzed the data obtained by the Geological Survey of Japan: from the travel time of the direct waves, the P-wave velocity of the uppermost layer was estimated at 3.5 km/s and the configuration of the basement along the observation line was determined by the method of differences (e.g. Heiland, 1951, p. 548) as shown in Fig. 3 where the result is consistent with that of the gravimetric discussion. Also, the Geological Survey of Japan (1983) carried out acoustic reflection profiling along nine courses on Shikotsu caldera lake in 1981: the substratum beneath the lake bottom is nearly horizontally layered, and no post-caldera cones are found there.

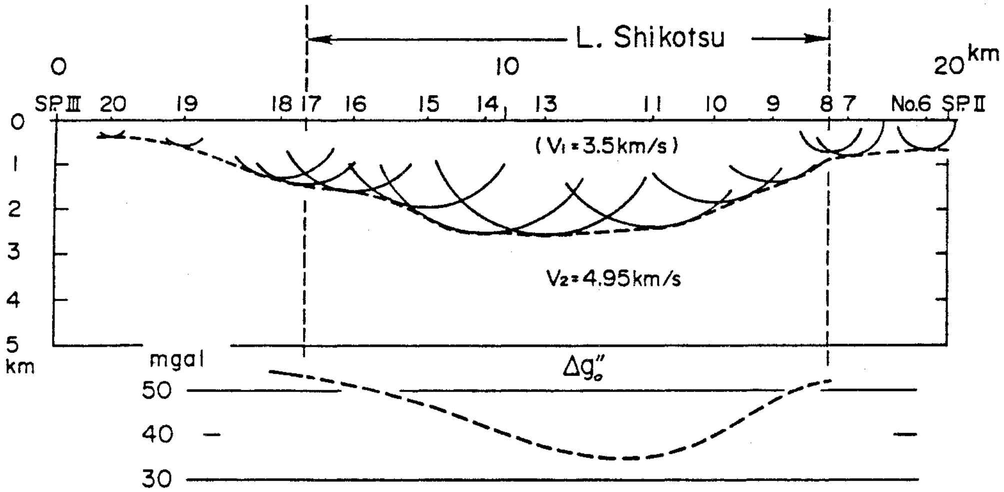

Fig. 3. Seismic velocity profile beneath Shikotsu caldera lake, obtained by the method of differences. Nos. 6 ~ 20 represent the observation points of the explosions. The bottom shows a gravity anomaly profile. Post-caldera volcanoes Tarumai and Eniwa stand on the caldera rim.

Drilling

A few results of drilling at and around the calderas of Table 1 are available for cross-checking the gravimetric discussions. The results at the four calderas – Kuttyaro, Nigorikawa, Hakone and Aso – were already discussed by the present author (1983). The conclusion is summarized as follows:

1) Within the calderas, coarse material is usually accumulated a few kilometers in depth. The caldera deposits consist of pumice, tuff and rocks of pre-caldera cones (all are named "fall-back"). Hitherto, a traditional idea has assumed that the caldera

deposits were mainly fragments of pre-caldera cones. At some calderas, there remain scarcely caldera deposits because of erosion by rivers.

2) The caldera boundaries are not always faults, and dip inward at low angles with a few exceptions of rather steep angles: the configuration of the basements beneath calderas is funnel-shape.

3) It is concluded that pre-caldera volcanoes could not collapse into magma reservoirs, if any, through narrow vents at the centers of the calderas.

The conclusions on subsurface structure of calderas deduced from gravity anomalies do not contradict the seismometric results and are supported by the drilling results.

DISCUSSION

Individual studies of particular calderas in the world from the standpoints of geology or geophysics have provided us with valuable information about calderas. However, from another standpoint, a general discussion dealing them as a mass should be also useful to understand the caldera formation.

In Table 1, mass deficiency ΔM at a caldera is defined as the mass that would have to be added to eliminate a residual Bouguer anomaly, and is estimated by applying Gauss' theorem which relates the integrated anomaly over a horizontal plane extending to the limits of the detectable anomaly, to the residual anomalies observed there. The surface integral is proportional to the mass only and is independent of its form and shape, and furthermore no assumptions are needed about the densities of the mass. Ohkawa (1975) discussed the accuracy of the practical estimations which depend on assumed subsurface models whether a point mass (or a sphere), a circular cylinder or a funnel shape, etc. Although we should assume funnel-shape models for most calderas, all the mass deficiencies in the table are estimated on the assumption of a point mass only for the sake of simplicity. The true values would be systematically a little larger than those listed in the table. The mass deficiency at Kikai caldera is reestimated by the present author. The masses of ejecta from the calderas are calculated from their volumes which are found in the literature and sometimes are not reliable. In this paper the author will not discuss these quantities any more.

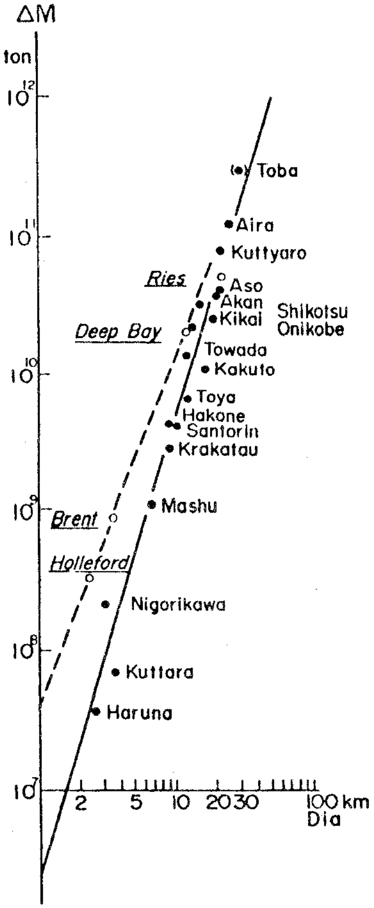

Fig. 4. Relationship between mass deficiency and diameter at volcanic calderas (solid circles) and meteorite craters (hollow circles). Toba depression is not used to get the best-fit line for calderas, nor is Rieskessel used for meteorite craters.

Mass deficiencies deduced by gravity anomalies on the calderas of low anomaly type are plotted against their diameters in Fig. 4 where the correlation is determined by the method of least squares as

$$\Delta M = 2.0 \times 10^{6} D^{3.3} \qquad \text{(ton)}$$

where D denotes diameters in km. From the calculation, Toba depression (100 km x 30 km) is excluded. Yokoyama and Ohkawa (1986) discussed the gravity anomalies observed on and around Lake Toba and concluded that it had resulted from an amalgamation of a few caldera depressions. In Fig. 4, the author plots Toba depression for reference, assuming that it is composed of four calderas, each of which is 30 km in diameter and accompanied with a mass deficiency of 3×10^{11} tons. In Fig. 4, estimations of mass deficiency ΔM from gravity anomalies at the smaller calderas such as Nigorikawa, Kuttara and Haruna are not necessarily accurate because their residual gravity anomalies are small. Accidentally, there is a volcanic crater of about 1 km in diameter near Naples. It is Lake Averno, where Oliveri Del Castillo *et al.* (1964) carried out a subwater gravity survey and observed a very small residual low anomaly less than 0.5 mgal at the center of the lake. According to the above formula, the mass deficiency should be 3.5×10^{6} ton and the average gravity anomaly is expected to be about 0.2 mgal. This example does not contradict the above experimental relation. Distinction of calderas and craters by diameters is not genetically significant. Fig. 4 shows that the larger the diameter of depressions, the larger the explosions within them. Calderas may have been formed by violent magmatic explosions, and craters are of similar origin but of smaller scale.

On the other hand, Innes (1961) gave detailed discussion about subsurface structures of the Canadian meteorite craters on a basis of gravity surveys and drillings there. According to his results, their subsurface structures are surprisingly similar to those of volcanic calderas deduced by the present author (Yokoyama, 1958, Yokoyama and Aota, 1965). The three Canadian meteorite craters, Deep Bay, Brent and Holleford, are also plotted in Fig. 4 and Innes (1961) obtained the best fit correlation as

$$\Delta M = 3.9 \times 10^{7} D^{2.50} \qquad \text{(ton)}$$

In the figure, the mass deficiency at Ries in south Germany, the largest meteorite crater of the world, estimated by Jung and Schaaf (1967) is also plotted for reference.

Of course, the above depressions of the two kinds are distinctly different in their origins. Meteorite craters present clear contrast to volcanic calderas in the following points: First, the former was formed by one impact explosion while the latter usually by repeated explosions. Second, the former explosion should be far much higher pressure and temperature than the latter explosions. Third, the former would violently shatter the earth surface while the latter would eject a tremendous amount of pyroclastics. And last, the former was formed, in general, in older geological ages in comparison with the latter, e.g. the Canadian craters were formed in the Mesozoic era. The older depressions may have been eroded and expanded more than the younger ones.

In spite of the above contrast, their relations between mass deficiencies and diameters are nearly similar each other as shown in Fig. 4 where it is rather peculiar that volcanic calderas better satisfy the third-power rule in cratering theory (cf. Innes, 1961) than meteorite craters. If calderas were formed by subsidence of caldera bottoms amounting to a few hundred meters regardless of diameter, as conventionally stated, mass deficiencies should be in proportion to the second power of their diameters. Although one cannot deny the possibility of statistical errors due to the small number of the Canadian craters or of underestimation of their original diameters, it may be said that the mass deficiencies at meteorite craters are usually, more or less, greater than those at calderas. This is due to larger density contrast of the deposits at meteorite craters than that of the caldera deposits. In fact, in the range of smaller diameter, meteorite craters have larger mass deficiencies than calderas while larger meteorite craters are roughly equal to calderas of the same diameter in mass deficiency. This situation may be interpreted as follows: with an increase of diameters, the effect of explosivity of meteorite craters is gradually overtaken by the effect of ejections of magmatic material at calderas.

CONCLUDING REMARKS

The mass deficiencies at 17 calderas of low gravity anomaly type are arranged against their diameters. At the same time those at 3 Canadian meteorite craters are plotted on the same diagram. Both approximate the third-power rule in cratering theory.

The mass deficiencies at calderas should depend on density contrasts of caldera deposits and on their volumes. The former does not diverge so much, and the latter would be the results of destructive explosions not by 2-dimensional subsidences.

The substantial difference between calderas and craters is not magnitude of their diameters but whether their formations were accompanied with ejections of large amounts of magmatic material. The different diameters should be the results of the different magnitude of their eruptions.

Hitherto, an explosion factor has been ignored in the discussions of caldera formation. In this paper, importance is attached to the volume of calderas and consequently to an explosion factor.

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