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Volcanic Calderas and Meteorite Craters with the Special Relation to Their Gravity Anomalies

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Abstract

The subterranean structures of volcanic calderas in Japan have been studied by means of gravimetric methods, while those of meteorite craters in Canada were independently discussed by M.J.S. Innes of the Dominion Observatory, Ottawa who employed the same methods. Combining the two sets of results, one can prove that volcanic calderas and meteorite craters have been formed by similar physical processes in the sense of explosive formation. Of course, the energy of explosion of meteorite craters was provided by the falling meteorites and that of calderas was supplied from the depths of the earth. In the formation of volcanic calderas, subsidence of fore-caldera volcanoes was caused simultaneously with the repeated explosions which accompanied ejection of voluminous pumice or ignimbrite, while a meteorite crater is the simple result of impact and explosion of a meteorite. It is very suggestive that extrapolations from energies released in small TNT explosions to the tremendous energies that produced the meteorite craters and the volcanic calderas of larger dimensions are valid.

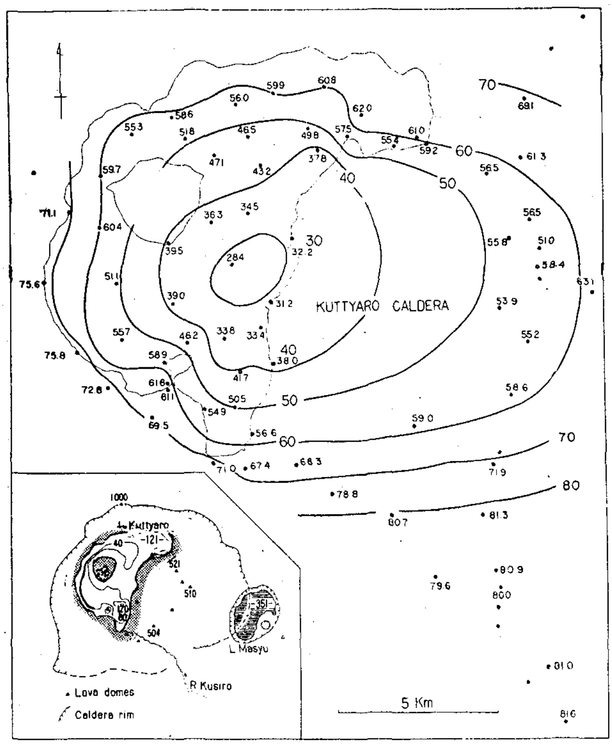
1. Introduction

Formation of both volcanic calderas and meteorite craters are much-disputed problems. The former has been discussed only from the standpoint of volcanogeology, while the latter has been progressively studied by analytical and experimental methods from standpoint of cratering. In the course of systematic studies on the subterranean structures of volcanic regions, the writer has made gravimetric surveys on several calderas in Japan and succeeded in classification of the calderas into two types which have respective characteristics in relation to their subterranean structures. For the formation of meteorite craters, Innes[1] published a valuable report of gravimetric surveys on three Canadian meteorite craters, i.e., Brent, Holleford, and Deep Bay, in which he estimated energy of crushing required to form the craters. In the present paper, some comparisons between volcanic calderas and meteorite craters are made and a theory concerning the origin of volcanic caldera formation is presented.

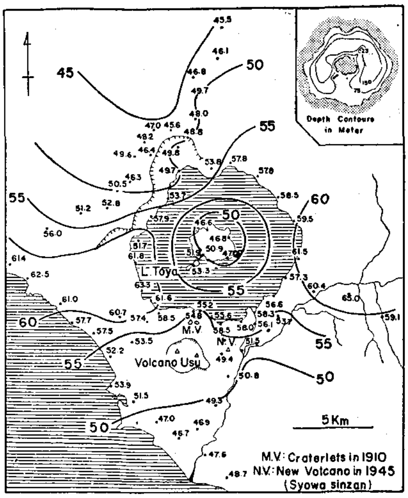
2. Subterranean structures of volcanic calderas and meteorite craters deduced from gravity data

Summarizing the results of gravity surveys on several calderas in Japan, one may group them, according to the residual values of Bouguer gravity anomalies, into the two categories, the high anomaly type and the low anomaly type. The high gravity anomaly is observed only on the Oosima caldera in Japan and the only other example is the Kilauea caldera in Hawaii so far as the writer knows. In the present case attention is to be confined to the low anomaly type: low gravity anomalies are observed on the calderas in Japan, Kuttyaro, Akan, Toya, Hakone, Aso and Aira, and the Mono Basin in U.S.A. Some of them are illustrated in Fig. 1. These were all formed during gigantic eruptions of tremendous amounts of pumice. The prominent features of calderas deduced from the gravity anomalies are summarized as follows:

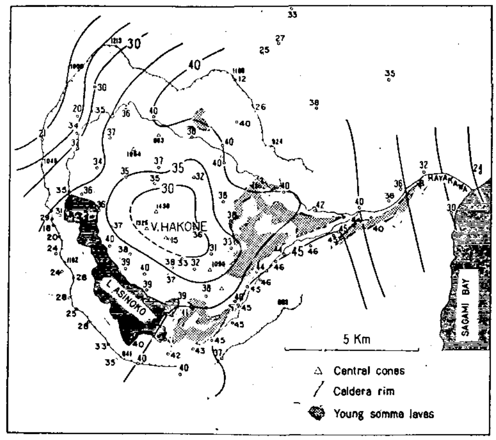
1. Low gravity anomalies amounting to a few score of *milligals* over 10



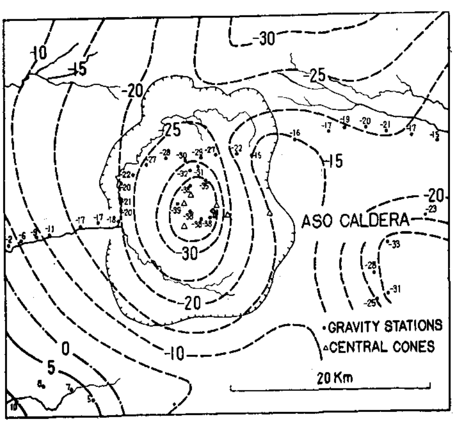
a) Kuttyaro



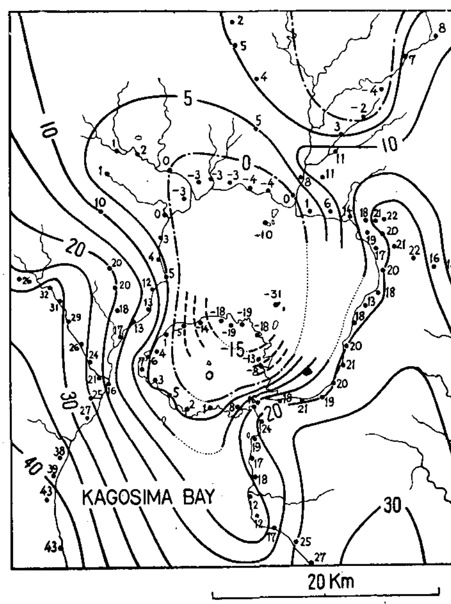
b) Toya



c) Hakone



d) Aso (after C. Tsuboi *et al.* and the Geographical Survey Institute)



e) Aira

Fig. 1. Distribution of the Bouguer anomalies in *milligal* on several calderas in Japan. Topographic corrections are made only on the central part of the Aso caldera. On the other calderas, these do not affect the contour distributions of the Bouguer anomaly.

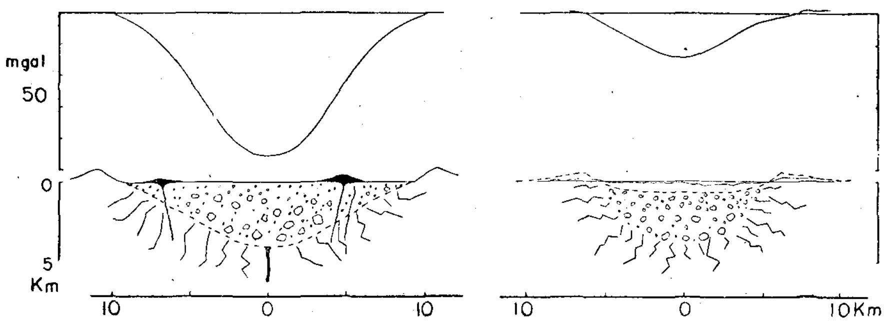
or 29 *km.* in diameter are almost concentric with the centres of the calderas and indicate existence of coarse material to a depth of a few kilometers beneath the calderas: this material might perhaps be fall back of fragmented fore-caldera volcanoes and ejected pumice.

2. The faults or discontinuous boundaries at the caldera rim do not stand vertically but gently incline aslant towards the centre of the caldera. This suggests that explosion was an important factor in formation of the calderas.

3. Mass deficiency observed at a caldera has a certain relation with the total mass of ignimbrite found in vicinity of the caldera.

4. In order to account for the transportation of ignimbrite as far as 60 *km.* from the calderas, one must suppose extraordinary and, in some cases, lateral explosive energy whether the material was carried in the air or flowed over the earth-surface.

As an example, a gravity anomaly profile on the Kuttyaro caldera and its deduced subterranean structure are shown in Fig. 2. Some of the above conclusions cast doubts on the customary geological theory that volcanic calderas of the low gravity anomaly type were produced by simple collapse under gravitational stress during rapid effusion of pumice.



a) Kuttyaro caldera b) Deep Bay crater (after Innes)

Fig. 2. Gravity anomaly profile and subterranean structure.

As for the subterranean structures of the Canadian meteorite craters, Innes gave detailed discussion on the basis of gravity surveys and drillings there. In Fig. 2, for example, a gravity anomaly profile and structure of Deep Bay after Innes are shown for comparison with similar features of volcanic calderas. Density contrasts between country rocks and volcanic calderas and meteorite craters are taken as 0.3 and 0.26 *gr./cc.* respectively, the former being rather arbitrary because no drilling has been undertaken at the calderas. Therefore, the depth of ruptured zone at the volcanic caldera may possibly be larger than that shown in the figure. Anyway, similarity in their structures is surprising and suggests that these depressions have been formed essentially by similar physical processes.

To advance a more quantitative comparison, mass deficiencies and crushing energies at both the depressions will be discussed in the following.

3. Mass deficiencies at volcanic calderas and meteorite craters

Subterranean mass anomaly is estimated by Gauss's theorem which relates the integrated anomaly over a horizontal plane to the limit of the detectable gravity anomaly, while its distribution is indeterminate. Innes estimated mass deficiencies ΔM at three Canadian meteorite craters as shown in Table I and examined how ΔM varies with crater diameter. He obtained the relation

$$\Delta M = 6.52 \times 10^4 D^{2.50} \text{ grams} \tag{1}$$

where D is the crater diameter in feet. This means that the third-power rule is not strictly true and suggests that ΔM increases with diameter at a rate somewhat smaller than D^3.

Table I. Volcanic Calderas, Meteorite Craters, and Nuclear Craters.

	Diameter *km.*	Mass Deficiency *ton*	Energy of Crushing *erg*	Remarks
Aira	25	12×10^{10}	1.2×10^{26}	after Yokoyama[2]
Kuttyaro	22	7.8×10^{10}	7.8×10^{25}	〃 [3]
Aso	22	4.0×10^{10}	4.0×10^{25}	〃 [4]
Toya	12	6.6×10^{9}	6.6×10^{24}	〃
Hakone	11	6.6×10^{9}	6.6×10^{24}	〃
Holleford	2.4	3.4×10^{8}	2.5×10^{23}	after Innes[1]
Brent	3.5	9.2×10^{8}	8.7×10^{23}	〃
Deep Bay	12.2	2.1×10^{10}	2.0×10^{25}	〃
Barringer	1.3	—	4.4×10^{22}	〃
New Quebec	3.9	—	9.1×10^{23}	〃
Odessa	0.17	—	1.0×10^{20}	〃
	Diameter *km.*	**Total Yield** *kt.* of TNT	**Energy of Crushing** *erg* (47% of total yield)	**Remarks**
Jangle U	0.079	1.2	2.4×10^{19}	after Nordyke[6]
Teapot Ess	0.089	1.2	2.4×10^{19}	〃
Neptune	0.061	0.115	2.3×10^{18}	〃
Rainier	0.080	1.7	3.4×10^{19}	after Johnson *et al.*[5]

Similar analyses to estimate mass deficiencies at five Japanese calderas were made by the present author with results also listed in Table I. The relationship between mass deficiency and diameter of depression which is valid for both Japanese calderas and Canadian meteorite craters, is obtained as follows:

$$\varDelta M = (4 \pm 1) \times 10^7 D^{2.3 \pm 0.1} \ tons \tag{2}$$

where D is the diameter in *km*. The relation is represented in Fig. 3.

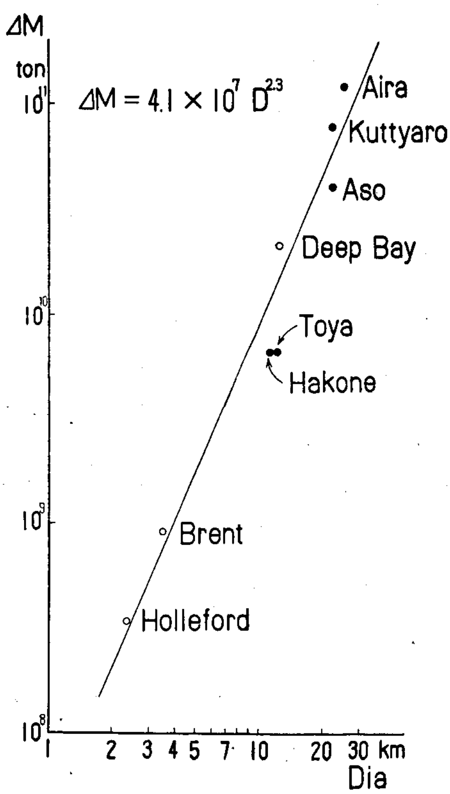


Fig. 3. Relationship between mass deficiency and diameter.

Innes estimated the total mass of the breccia and sedimentary rocks responsible for the gravity anomalies on the meteorite craters by the following relation:

$$M_1 = \varDelta M \cdot \rho_b / (\rho_c - \rho_b) \tag{3}$$

where ρ_b and ρ_c denote the mean densities of the fragmental and sedimentary rocks, and the country rocks respectively. Innes took the average values of ρ_b and ρ_c as 2.53 and 2.79 *gr./cc.* respectively. Therefore, one gets approximately

$$M_1 = 9.7\,\Delta M. \tag{4}$$

In the case of caldera formation, ejection of voluminous material plays an important role: by violent volcanic eruptions, magmatic material ejected as pumice and simultaneously fore-caldera volcano, which was generally not very large, was fragmented and fell back within the caldera compensating the space which had been occupied by ejecta. Hence, caldera deposits are mainly consist of pumice and fragments of fore-caldera volcanoes. The condition that lithic fragments from the fore-caldera volcano are not scattered distant from the caldera, depends on the depth of explosion as will be discussed later. In drawing a balance sheet of ejecta from a volcanic caldera, one may assume, without a serious error, the values of densities of various material as shown in Table II, where both ejecta are defined as found outside the calderas. Hence, density of caldera deposit ρ_d is expressed as follows:

$$\rho_d = (V_m - V_l)\,\rho_m/(V_e\,\rho_e/\rho_m - V_l)\,.$$

Table II. Ejecta from Volcanic Calderas.

	Volume	Density (*gr./cc.*)	
Original ejecta	V_e	ρ_e pumice	1.3
		ρ_e ignimbrite	2.0
Lithic ejecta	V_l	ρ_l	2.5
Fore-caldera volcano	V_m	ρ_m	2.5
Caldera deposit	$V_d = V_m - V_l$	ρ_d	2.2

Then one gets

$$V_m = V_e\,\rho_e\,\rho_d/\rho_m^2 + V_l\,(1 - \rho_e/\rho_m)\,.$$

Information from geological observations at volcanic calderas generally shows that V_l is remarkably small compared with V_e: this is probably because fragmented lithic material would fall back into the calderas. Anyhow, one gets

$$V_m = V_e\,\rho_e\,\rho_d/\rho_m^2\,.$$

On the other hand, mass deficiency at a caldera which may be deduced from gravity anomaly, is represented by the differences between mass of ejecta from the caldera and that of fall back into the caldera. Therefore one gets

$$\Delta M = V_e \rho_e - (V_m - V_l) \rho_m .$$

Assuming that $V_l \ll V_m$ and $\rho_m - \rho_d = 0.3$ as before, one gets

$$\Delta M = 0.3 V_e \rho_e / \rho_m. \tag{5}$$

This means that mass deficiency is equal to three-tenths of the mass of original ejecta recalculated as magma.

Next, the total mass of crushed material to volcanic calderas is composed of the mass of a fore-caldera volcano and that of subsidence caused by ejection of voluminous pumice. Therefore, the total mass of crushed material is represented as follows:

$$\begin{aligned} M_2 &= V_m \rho_m + V_e \rho_e = V_e \rho_e / \rho_m (2.2+2.5) \\ &= 4.7 V_e \rho_e / \rho_m . \end{aligned} \tag{6}$$

From (5) and (6), one gets

$$M_2 = 15.7 \Delta M . \tag{7}$$

The difference between the values of the multiplier in equations (4) and (7) is due to the differences in selected values of density and in mechanisms of formation.

4. Energy considerations

The energy consumed in crushing was estimated, by the observation of the Rainier event at the Nevada test site (Johnson, Higgins, and Violet[5]), to be about 47 per cent. of the total prompt energy released, equivalent to about 6.4×10^{17} *ergs/gr*. This, combined with the total mass of fragmental rock estimated from the gravity data, should provide a firm estimate of the minimum energies required to form the meteorite craters and volcanic calderas. Application of the above value of crushing energy to the volcanic calderas is independent of the assumption that they were formed by some explosive actions.

Innes already obtained the relationships between energy of crushing and crater diameter in order to examine whether extended extrapolations are valid over the whole range of energies — from those released in small TNT explosions to the tremendous energies that must have been required to produce large meteorite craters. In nuclear explosions and meteorite impacts, the stress waves of high pressure as high as 10^6 *atm.* are characteristic while small TNT explosions and volcanic explosions would not yield such high pressure. But pressure is not a unique factor in the energy considerations. Following Innes, the present author would like to add some examples of larger diameters and, at the same time, to consider the mechanism of caldera formation. The relationship between energy of crushing and diameter is shown in Fig. 4 which includes experimental underground explosions, six North American craters of probable meteorite origin and Japanese volcanic calderas. The relation is expressed by

$$E_{\text{(crushing)}} = (1.6 \pm 0.2) \times 10^{22} D^{2.69 \pm 0.05} \ ergs$$

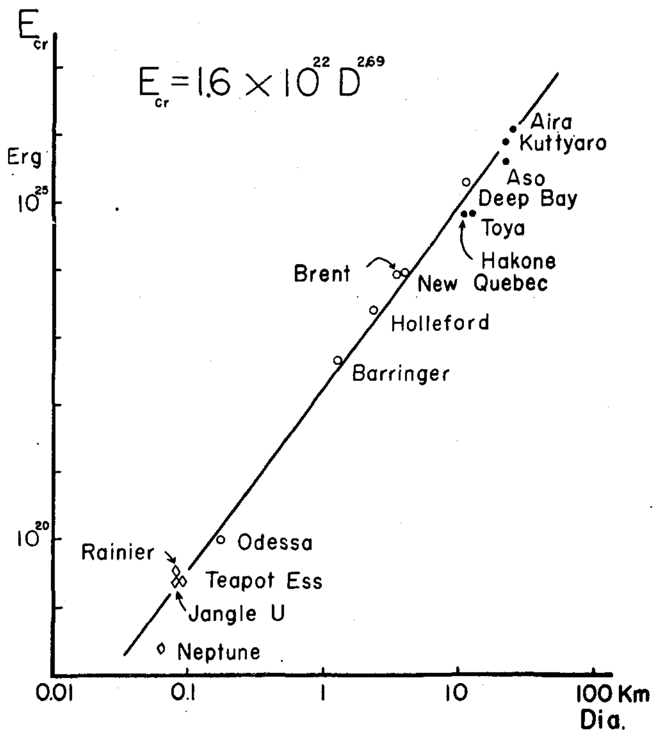


Fig. 4. Relationship between energy of crushing and diameter.

where D is measured in *km*. The sense of the departure from the third-power rule suggests a less efficient transfer of energy for the larger depressions as Innes has already referred to. Although the figure is expressed by both logarithmic coördinates, the linearity seems hardly fortuitous. The linear relationship between energy of crushing and diameter would support the idea that volcanic calderas were formed by explosions and subsequent collapses similar to underground nuclear explosions contrary to the customary geological theory that they are only compensatory subsidences under gravitational stress caused by ejection of voluminous pumice or ignimbrite. Caldera formation would not be a simple static collapse but a dynamic crushing. A meteorite crater was formed by impact and explosion of a meteorite while a volcanic caldera would be formed repeatedly by the largest explosions of magmatic material. For the former, energy was supplied by meteorites, while for the latter, energy was supplied from the deeps of the earth. Total kinetic energy of caldera formation may be about twice of the energy of crushing, amounting to 10^{26} *ergs* in the order of magnitude for the largest caldera. Taking into consideration that the maximum observed kinetic energy of great earthquakes is 10^{25} *ergs* in the order of magnitude though the energy is released at once by each earthquake, one knows that volcanisms in Quaternary age which caused caldera formation were tremendously violent beyond all imagination.

5. Conclusion

To get an over-all picture of the formation of volcanic calderas, a schematic diagram drawn by Nordyke[6] affords some clue; his diagram (Fig. 5) shows

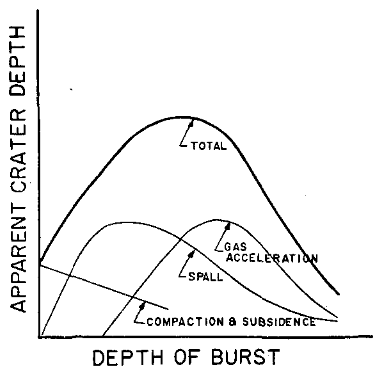


Fig. 5. Relative contributions of various mechanisms to apparent crater depth for explosion crater (after Nordyke).

the relative contributions of various elements in the explosive activity to apparent crater depth for an explosion crater. If the depth of burst is large, as in the case of caldera formation, the apparent depth of the depression may be rather small. Ejecta pass outward through the preexistent vents and simultaneously fragmented fore-caldera volcano falls back and fills space which has been occupied by ejecta. This takes account of the geological observation that lithic fragments from the fore-caldera volcano are not abundant around the caldera. In other words, the calderas were formed simultaneously with ejection of voluminous pumice: explosion and subsidence are cooperative actions in the formation of calderas. In conclusion, the subterranean configurations and energy relations at volcanic calderas both being deduced from gravity data, support a theory that volcanic calderas were formed by explosion as a leading factor and subsequently by subsidence as a secondary factor. The third-power rule proves to be approximately applicable to the extended range of volcanic calderas, strictly speaking, in a direction that suggests a less efficient transfer of energy for the depressions of larger diameter as Innes has already mentioned.

Estimation of energy of caldera formation may be, the author thinks, one step to discuss energetics of volcanisms in geological ages.

References

1) Innes, M.J.S.: The use of gravity methods to study the underground structure and impact energy of meteorite craters, J. Geophys. Research, **66** (1961), 2225–2239.
2) Yokoyama, I.: Gravity survey on the Aira caldera, Kyusyu, Japan, Nature, **191** (1961), 966–967.
3) Yokoyama, I.: Gravity survey on Kuttyaro caldera lake, J. Phys. Earth, **6** (1958), 75–79.
4) Yokoyama, I.: Gravity anomaly on the Aso caldera, Geophysical Papers Dedicated to Prof. K. Sassa (1963), 687–692.
5) Johnson, G.W., G.H. Higgins, and C.E. Violet: Underground nuclear detonations, J. Geophys. Research, **64** (1959), 1457–1469.
6) Nordyke, M.D.: Nuclear craters and preliminary theory of the mechanics of explosive crater formation, J. Geophys. Research, **66** (1961), 3439-3459.