SUBSURFACE STRUCTURE OF TOYA CALDERA, JAPAN AS REVEALED BY DETAILED MAGNETIC SURVEY

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(Received March 28, 1984; Revised September 14, 1984)

Shipborne and ground magnetic surveys were conducted using a proton precession magnetometer on and around Toya caldera, Hokkaido, Japan. Modeling of the noticeable magnetic anomaly indicates the presence of highly magnetized rocks filling a basement depression. Considering the low gravity anomaly on the caldera, the magnetized infill is identified as low density caldera deposits. The proposed diameter of the depression is only about half that of the present caldera. The evidence suggests that the original caldera wall has been eroded away.

Analysis of the magnetic anomalies reveals that the andesitic central cones of Toya caldera are magnetized in a normally polarized direction and with magnetizations of 3–4 A/m. Exceptionally, a magnetization of 9 A/m is estimated for two lava domes. The origin of the strong magnetization is possibly attributed to the rich content in Fe$_3$O$_4$, on the basis of the chemical analysis of rock samples. Two topographic highs of the lake floor are identified as sunken lava domes because of the considerably high magnetic anomalies.

1. Introduction

There are several theories on the mechanism of caldera formation. The engulfment theory is widely known. According to the theory, the "Crater Lake type caldera" is formed as a consequence of collapse of a mountain body into a big magma reservoir which has at least the same diameter as that of the caldera (e.g., WILLIAMS, 1942). If the initial mountain body is relatively small, the magma reservoir may still remain beneath the caldera. On the other hand, YOKOYAMA (1963, 1981) has objected to the theory. He has insisted on the basis of gravity data obtained in the caldera regions that the Crater Lake type caldera is formed by big explosions. The explosion theory does not necessarily require the presence of a big magma reservoir at shallow depths under the caldera. In any case, the detailed subsurface structure of the caldera is necessary to clarify the mechanism of caldera formation.

Lake Toya, situated in the southwestern part of Hokkaido, Japan, is a nearly circular caldera lake about 10 km in diameter. An outline of the geologic history in this region is as follows (e.g., Ota, 1956; Oba, 1966; KATSUI, 1981). The sur-
face rocks in the Toya region overlie the basement rocks, Osaru-gawa formation, formed in middle Miocene. The formation includes andesitic tuff-breccia, mudstone, dacite, and so on. The volcanic depression was formed in late Pleistocene (30,000 years or so B.P.), accompanied by ejection of a huge amount of dacite pumice. After the formation of caldera, probably in latest Pleistocene time, the Naka-jima lava dome group was formed at the center of Toya caldera as central cones. Then, in the early Holocene age, Usu volcano started its activity on the southern rim of the caldera. Figure 1 shows the geologic cross section of Toya caldera proposed by OTA (1956).

Since the environment of the caldera is widely covered with thick volcanic ejecta originating from the caldera itself and its main part is under deep water, geophysical method is very useful for obtaining the present subsurface structure of the caldera. Then, the magnetic total force intensity was measured on and around Toya caldera. The main goal of this study is to interpret the magnetic data on Toya caldera.

2. Observation

A shipborne magnetic survey was conducted on Lake Toya using a proton precession magnetometer (GEOMETRICS G-815 with 1 nT indication). The ship tracks are shown in Fig. 2. The total length of the tracklines amounts to about 80 km. Magnetic stations were also established on land including the Naka-jima lava domes (Figs. 2 and 7); they total 272 in number. NISHIDA and MIYAJIMA (1984) have already established about 1,000 magnetic stations in the Usu volcanic region. For simplicity, these stations are excluded from Fig. 2.

Distribution of the total force intensity is shown in Fig. 3 with contour interval of 200 nT. Magnetic anomalies on the Naka-jima lava domes are separately
Fig. 2. Topographic map of Toya caldera, magnetic stations, and tracklines of the shipborne magnetic survey. Contours in meters.

shown in Fig. 8 with contour interval of 400 nT. Corrections for diurnal variations and geomagnetic storms were made on the basis of continuous magnetic records obtained at about 10 km southeast of Usu volcano. It is generally difficult to determine the reference value of field intensity in volcanic regions because the distribution of magnetic anomalies is complicated. In the present case, a field intensity of 49,200 nT is adopted as a reference value from a mean value at the eastern part of Lake Toya where is magnetically undisturbed. Dot-dashed contours represent isomagnetic lines of the reference value, while solid and dotted contours represent the positive and the negative anomalies, respectively.

An airborne magnetic survey was conducted by Matsuzaki and Utashiro (1966) over the Toya caldera region at altitudes of 1,100 and 1,600 m a.s.l. These important results are applicable and will be referred in the present discussions.
3. Interpretation of Magnetic Anomalies

3.1 Main structure of Toya caldera

The present survey confirms a detailed picture of the magnetic field over the entire Toya caldera, showing a number of high amplitude anomalies in the central part of the caldera and a relatively quite anomaly pattern in the surroundings (Fig. 3). Besides short-wavelength anomalies, the positive and the negative anomalies remarkably extend in pairs to the south and the north of Naka-jima Island, respectively. The result of the airborne magnetic survey at an altitude of 1,100 m is shown in Fig. 4 (MATSUZAKI and UTASHIRO, 1966). Since the disturbing influence of short-wavelength components is filtered in the airborne magnetic survey, the dipole-like anomaly in the central part of the caldera would more clearly appear. The anomaly may be closely related to the main structure of Toya caldera. The observed north-south profile is shown in Fig. 5 by solid curves for various altitudes. As the figure indicates, the dipole-like anomaly obtained by the present survey is hampered by the striking anomalies of short
wavelength on Naka-jima Island. Then, the anomaly is enhanced by a simple smoothing procedure as shown by a bold dashed curve. The amplitude of the anomaly attenuates with altitude; peak-to-peak amplitude of about 1,200, 500, and 230 nT for 84 (water level of Lake Toya), 1,100 and 1,600 m a.s.l., respectively. The anomaly indicates the presence of a considerable amount of normally magnetized materials under Toya caldera (magnetic inclination is 56°).

We can estimate the depth of the causative material from the relationship between the amplitude of the observed magnetic anomaly and altitude. Also, we can determine the lateral dimension of the causative material from spatial wavelength of the anomaly. Prior to detailed modeling of the anomaly, a rough estimation of these factors was made by assuming the presence of a normally magnetized circular disk beneath the lake bottom. The calculated result can explain an attenuation rate of the observed amplitude with altitude when we assume that the disk 4.5 km in diameter and 1 km thick is situated at very shallow depths of the caldera.

Rikitake (1959) studied the conduction of heat inside and outside magma on the assumption that the hot magma intruded suddenly in a spherical cavity in the Earth's crust. We apply his result on condition that the magma intruded 30,000 years ago and the diameter of the sphere, the depth of its center, the thermal
Fig. 5. Magnetic anomalies and a model structure of Toya caldera along the N-S profile shown in Fig. 3. Solid curves represent the magnetic anomalies derived from the shipborne (present study) and the airborne (MATSUZAKI and UTASHIRO, 1966) magnetic surveys while thin dashed curves represent the anomalies calculated on the basis of a normally magnetized inverted cone (shaded part). Hatched part represents the Naka-jima lava domes.

The diffusivity of rocks, and the initial temperature of the magma are 10 km, which is almost the same as the diameter of Toya caldera, 7.5 km, 0.01 c.g.s., and 1,200°C, respectively. Then, the calculated result indicates that most parts of the magma have kept the temperature above the Curie point of the ferromagnetic minerals up to the present (≈600°C). In this case, a local magnetic anomaly derived from the sphere with apparently reversed magnetization is expected when the surrounding crust is assumed to be normally magnetized, contrary to the present observed anomaly. The wavelength of the magnetic anomaly due to a big magma
reservoir, if any, should be at least the same as the diameter of the caldera. However, the observed anomaly is only about half the diameter of Toya caldera. Considering these problems, it is hard to conclude that the observed magnetic anomaly is caused by a big magma reservoir.

YOKOYAMA (1964) observed the gravity field on and around Toya caldera as shown in Fig. 6. The low gravity anomaly amounting to -11 mgal is concentric centering at Naka-jima Island, suggesting the presence of coarse materials beneath the caldera. The wavelength of the low gravity anomaly is considerably short in comparison with the diameter of Toya caldera as in case of the magnetic anomaly. A drill hole through the floor of Kuttyaro caldera, Hokkaido, penetrated 1,000 m of caldera deposits composed of a fragmented fore-caldera volcano, pumice and volcanic ashes having a density ($\rho \sim 2.2$ g/cm$^3$) lower than that of the surrounding crust ($\rho \sim 2.5$ g/cm$^3$) (NISHIDA and YOKOYAMA, 1965). While no density measurement has been made at Toya caldera, comparable fillings must be common to the usual Crater Lake type case. The gravity anomaly calculated on the basis of the above-mentioned circular disk filled with such low density materials can approximately account for the amplitude of the observed low gravity anomaly. Therefore, the magnetic and gravity anomalies on Toya caldera are probably caused by the same material—thick accumulations of caldera deposits. The magnetic and gravity anomalies caused by highly magnetized and low density rocks are often observed in the caldera regions such as e.g., Taupo Volcanic Zone, New Zealand (ROGAN, 1982).

The calculated magnetic anomaly based on the circular disk is not exactly
coincident with the observed one; the amplitude of the calculated anomaly sharply changes with distance in the neighborhood of the disk margin while the observed one changes gradually. The observed gravity anomaly begins to decrease inwardly as in other calderas. Therefore, it is difficult to assume the vertically inclined boundary as in the case of a circular disk. The discontinuous boundary at the caldera rim may slope downward towards the center of the caldera. Then, modeling of the dipole-like anomaly was made by assuming the presence of a funnel-shaped basement depression filled with highly magnetized caldera deposits. The calculation was made by using the method given by Rikitake and Hagiwara (1965). Figure 5 shows a model for the magnetic structure of Toya caldera, although the model is by no means unique. The diameter and the thickness of the depression are estimated as approximately 5 km and 1 km, respectively. The intensity of magnetization of the fillings is assumed to be 4 A/m ($4 \times 10^{-3}$ emu/cm$^3$). The calculated magnetic anomalies at various altitudes are shown in Fig. 5 by thin dashed curves, indicating close approximation to the observed anomalies. The observed gravity anomaly can also be explained by the inverted cone, if we assume a density contrast of 0.3 g/cm$^3$ between the caldera deposits and the basement rocks. The proposed diameter of the caldera is about half that of the present caldera. The present topographic rim is presumably a false one, perhaps because the original caldera wall has been eroded away.

The calculated intensity of magnetization of the fillings (4 A/m) is a value relative to that of the surrounding basement rocks, but the value may approximate to an intrinsic one because five samples of the basement rocks, Osaru-gawa formation, have negligible remanent magnetizations less than $10^{-3}$ A/m and have low susceptibilities of the order of $10^{-4}$ SI units (Nishida, unpublished). An intensity of 4 A/m seems to be too strong for induced magnetization of usual dacitic rocks (e.g., Dobrin, 1976; Telford et al., 1976). In fact, the induced magnetization of dacitic rocks of Usu volcano shows only an intensity of the order of 0.1 A/m (Nemoto et al., 1957). However the total intensity of induced and remanent magnetization (Nemoto et al., 1957; Nishida and Miyajima, 1984) shows much the same value (3 A/m or so) as the calculated one. Therefore, it is probable that the thermal remanent component acquired in the course of cooling of hot ash deposits dominates the induced magnetization in the present case.

3.2 Structure of Naka-jima lava domes

Naka-jima Island, situated at the central part of Lake Toya, is composed of seven lava domes shown by triangles in Fig. 7. Three solitary islets, Kannon-jima, Benten-jima, and Manju-jima, are also lava domes. A magnetic anomaly pattern on these islands (Fig. 8) clearly indicates that the lava domes are normally magnetized because the positive anomaly is distributed on the southern flank of each lava dome and the negative one on the northern flank. Topographic highs of the lake floor are distributed at the northeast (S1 in Fig. 2) and the northwest (S2) of Naka-jima Island. Water depths to the top of upheavals S1 and S2 are
Fig. 7. Topographic map of Naka-jima lava domes (contours in meters) and magnetic stations. Triangles represent the top of the lava domes.

about 20 m and 100 m, respectively. The origin of these upheavals has been supposed to be volcanic on the basis of the geomorphic characteristics (OTA, 1956). We conclude here that the two are sunken lava domes because of the considerably high magnetic anomalies as shown in Figs. 3 and 8.

Each dome in the Naka-jima lava dome group can be approximated by a circular cone because of the simple topography as shown in Fig. 7. To estimate the intensity of magnetization of the domes, the observed anomalies were compared with the calculated ones on and over the uniformly magnetized cones. The calculation is based on the method given by RIKITAKE and HAGIWARA (1965). Figure 9 shows two examples of the observed profiles, calculated profiles and model cross sections (shaded parts) along the north-south direction. We see good agreement between the observed and the calculated anomalies in the figure. Excepting the 192M dome and the S2 dome, the range of the estimated intensity of magnetization is from 3 to 4 A/m for the lava domes. A strong magnetization of about 9 A/m is estimated for the 192M dome and the S2 dome. According to the recent geological and petrographical studies by IKEDA (1984), the Naka-jima lava domes are composed of andesitic rocks. The chemical analysis reveals that rock samples contain Fe$_3$O$_4$ of a few % in volume for almost all the lava domes and 6.9% for the 192M dome. The origin of the strong magnetization of the 192M dome can be, therefore, possibly attributed to the rich content in Fe$_3$O$_4$. The same
Fig. 8. Distribution of the total force intensity in units of 100 nT.

Fig. 9. Examples of the north-south cross section of the lava domes. Solid circles represent the observed anomalies while solid curves represent the anomalies calculated on the basis of normally magnetized cones (shaded parts).
may hold true of the S2 dome, although no analysis of rock samples has been made.

4. Conclusions

Modeling of the noticeable magnetic anomaly on the caldera suggests the presence of a funnel-shaped basement depression filled with highly magnetized rocks. Considering the low gravity anomaly on the caldera, the magnetized rocks are identified as low density caldera deposits. The proposed diameter of the depression is only about half that of the present caldera. The evidence suggests that the original caldera wall has been eroded away. No significant magnetic anomaly that suggests the existence of a big magma reservoir was observed.

Analysis of the magnetic anomalies reveals that the andesitic central cones of Toya caldera are magnetized in a normally polarized direction and with magnetizations of 3–4 A/m. Exceptionally, a magnetization of 9 A/m is estimated for two lava domes. The origin of the strong magnetization is probably attributed to the rich content in Fe₂O₃. Two topographic highs of the lake floor are identified as sunken lava domes because of the considerably high magnetic anomalies.

The author would like to express his sincere thanks to Prof. I. Yokoyama for his encouragement. Gratitude is expressed to Mr. T. Maekawa, the Usu Volcano Observatory, for his kind help in the course of observation. Field work was carried out with the aid of Messrs. M. Aida, S. Nagaura, H. Ohnishi, and H. Fukazawa. The computation was carried out on HITAC M200H at the Computing Center of Hokkaido University.

REFERENCES


