Subsurface Structure of Toya Caldera, Hokkaido, Japan, as Inferred from CSAMT Resistivity Survey

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Abstract

A controlled-source audio-frequency magnetotelluric (CSAMT) survey was conducted over Toya caldera, Hokkaido, Japan, to investigate its subsurface structure. The caldera is 10–11 km in diameter and contains a freshwater lake, Lake Toya, that occupies the entire caldera floor. A post-caldera dacitic dome complex, the Nakajima Islands, is present within Lake Toya. The CSAMT survey was carried out along a 16-km-long line that crosses Toya caldera in a NE-SW direction, passing over the Nakajima Islands. The 17 receiver stations (7 stations located outside of Lake Toya, 5 stations within Lake Toya, and 5 stations on the Nakajima Islands) were distributed along the survey line. Unique on-boat measurements were performed at the stations on Lake Toya. Two-dimensional inversion of the CSAMT data revealed the resistivity structure for the upper 1500 m beneath the caldera. The resistivity structure indicates the existences of high-resistivity (> 100 Ω·m) and low-resistivity (< 30 Ω·m) domains at the northeastern and southwestern sides of Lake Toya, respectively, a medium-resistivity (30–50 Ω·m) domain beneath Lake Toya, a high-resistivity (> 100 Ω·m) layer at the Nakajima Islands, and a low-resistivity (< 10 Ω·m) domain beneath the Nakajima Islands. This resistivity structure, combined with geological and bathymetric data, suggests that the subsurface structure of Toya caldera comprises altered Tertiary to Quaternary volcanic/sedimentary rocks outside of the caldera, and a homogeneous caldera-fill deposit beneath the caldera floor. A 9-km-diameter ring fault may occur along the caldera rim. There is a conspicuous hydrothermal alteration zone beneath the Nakajima Islands that may have formed in response to heating of the caldera-fill deposit by the underlying magma during the volcanic activity that formed the Nakajima Islands.

Key words: Toya caldera, subsurface structure, resistivity, CSAMT survey, Nakajima Islands

I. Introduction

Calderas are subcircular volcanic depressions whose diameters are larger than those of explosive vents (Williams, 1941). Most calderas are the product of subsidence in response to the emptying of a magma chamber during or following a large-scale eruption (Lipman, 1997, 2000; Cole et al., 2005; Acocella, 2006). Direct observations of caldera formation (Geshi et al., 2002) and numerous laboratory experiments (e.g., Komuro, 1987; Roche et al., 2000; Walter and Troll, 2001; Kennedy et al., 2004; Geyer et al., 2006; Acocella, 2007) support this caldera-forming model. However, our knowledge of caldera formation is still speculative, as the subsurface
structures of individual Quaternary calderas are largely unknown. Current models of caldera formation are based primarily on geological mapping of eroded calderas (e.g., Lipman, 1984; Branney and Kokelaar, 1994; Miura, 1999), the distributions of intra-caldera volcanoes (Smith and Bailey, 1968; Walker, 1984), drilling observations from small calderas (Kurozumi and Doi, 2003), and laboratory experiments (Acocella, 2007 and references therein). Detailed geological surveys of Quaternary calderas are commonly hampered by thick caldera-fill deposits, intra-caldera volcanoes, and caldera lakes. Thus, characterizing the subsurface structures of individual Quaternary calderas using geophysical methods is critical to gain a better understanding of caldera evolution.

Resistivity surveying is a powerful tool for studying subsurface geological structures (e.g., Ogawa et al., 1998; Matsushima et al., 2001; Srigutomo et al., 2008; Aizawa et al., 2008, 2009; Yamaya et al. 2009; Fikos et al., 2012). We conducted a controlled-source audio-frequency magnetotelluric (CSAMT) survey (Sandberg and Hohmann, 1982; Milsom, 2003) over Toya caldera, southwestern Hokkaido, Japan, to investigate its subsurface structures (Fig. 1). Toya caldera is one of the major Quaternary

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**Fig. 1** Topographic map of Toya caldera, Hokkaido, Japan. The caldera contains Lake Toya, a circular freshwater lake of 10 km in diameter. The red line shows the location of the CSAMT survey. The 16-km-long survey line is oriented NE–SW and crosses Toya caldera. The locations of the bipole sources (A1 and A2) and receiver stations (red circles; M1–M17) are also shown. For the bipole sources, the solid black circles are the ends of the grounded wire (black lines) that are connected to the transmitter. The base map is from the 1:50,000 scale topographic map ‘Toyako-onsen’, issued by the Geospatial Information Authority of Japan. The topographic contour interval is 10 m.
calderas in Japan. The subsurface structure of the caldera has previously been studied by gravimetric (Yokoyama, 1964) and magnetic (Matsuzaki and Utashiro, 1966; Nishida, 1984) surveys, but its structure remains poorly constrained. The CSAMT survey was performed along a NE−SW survey line crossing Toya caldera. Unique on-boat CSAMT measurements (Suzuki et al., 2009; Goto and Johmori, 2015) were also conducted on Lake Toya, a deep freshwater lake that occupies the caldera. Two-dimensional inversion of the CSAMT data captured the resistivity structure of the upper 1500 m beneath the caldera. This paper presents the results of the resistivity survey and discusses the subsurface geological structure of Toya caldera.

II. Geological outline of Toya caldera

Toya caldera is defined by a subcircular (or polygonal) caldera rim that ranges in diameter from 10 km (N−S) to 11 km (E−W; Fig. 2). Lake Toya fills the caldera, with an average water depth of 140−180 m. The water level of Lake Toya is 84 m above sea level. Lake Toya is drained by the Sobetsu River, which exits from the southeastern caldera rim. Bathymetric data (Fig. 2) reveal that the caldera floor is quite

Fig. 2 Three-dimensional digital elevation map of Toya caldera, showing the bathymetry of Lake Toya. The locations of the receiver stations (yellow circles; M1−M17) are also shown. The base map is from a Red Relief Image Map (Chiba et al., 2007) acquired by Asia Air Survey using bathymetric data from Team Beluga (within Lake Toya), aerial laser mapping data from Asia Air Survey (around Usu volcano), and 10 m DEM data from the Geospatial Information Authority of Japan (around Toya caldera).
flat and surrounded by a steep wall that is ~9 km in diameter and ~160 m above the caldera floor. Geophysical studies (Yokoyama, 1964) indicate that the caldera is defined by a negative gravity anomaly, with an 11-milligal low observed at the caldera center.

Geological mapping (Ota, 1956; Yokoyama et al., 1973; Yahata and Norota, 2003; Soya et al., 2007) suggests that the rim of Toya caldera consists of Tertiary to Quaternary volcanic and sedimentary rocks (Fig. 3). The eastern and northeastern caldera rims comprise silicified rhyolitic breccia of the Tertiary Osarugawa Formation (OR in Fig. 3). The northern and northwestern caldera rims consist of altered tuff of the Osarugawa Formation (OT) and overlying Tertiary to Quaternary andesite lavas, such as the Muko-Toya (M) and Asahiura (AS) lavas. The southwestern caldera rim comprises Tertiary to Quaternary andesite lavas and breccia of the Poromoi volcanics (or the Abuta volcanics of Yahata and Norota, 2003) that includes the Abuta (PA) and Nottoko (PN) lavas. The southern caldera rim is buried by a post-caldera volcano, Usu. The southeastern caldera rim comprises tuffaceous sandstone and mudstone of the Osarugawa Formation (OM) and overlying Quaternary Sobetsu (S) and Takinoue (TU) pyroclastic flow deposits. Drilling data (Wada et al., 1988; Yahata et al., 2014) indicate that Tertiary plutonic rocks (mainly 7 Ma granodiorite) are present beneath the caldera rim. These Tertiary plutonic rocks are not exposed on the surface of the caldera rim.

Late Quaternary rhyolitic pyroclastic flow and fall deposits are widely distributed around Toya caldera, covering the Tertiary to Quaternary volcanic and sedimentary rocks (Ota, 1956; Suzuki et al., 1970; TI in Fig 3). These deposits are identified as either the Tertiary pyroclastic flow deposit (Yokoyama et al., 1973) or Toya Ignimbrite (Feebrey and Nakagawa, 1995). The Toya Ignimbrite was produced by the 110 ka caldera-forming eruption at Toya caldera (Yokoyama et al., 1973; Okumura and Sangawa, 1984; Machida et al., 1987; Takashima et al., 1992; Ganzawa et al., 2007). The Toya Ignimbrite is up to 80–100 m thick and comprises rhyolitic pumice, lithic fragments, and volcanic ash. The Toya Ignimbrite forms a pyroclastic plateau at the northwestern and southeastern sides of Lake Toya (Figs. 2 and 3).

Toya caldera contains two post-caldera volcanoes, Nakajima and Usu. Nakajima is located within Lake Toya and comprises an andesitic to dacitic dome complex that consists of a tuff cone, nine lava domes, and two cryptodomes (Nishida, 1984; Goto et al., 2015). Bathymetric data from Lake Toya (Fig. 2) suggest that Nakajima volcano lies on a submerged rise with an irregular morphology of mudstone and sandstone (Katsui, 1990; Goto et al., 2015). Goto et al. (2015) inferred that Nakajima volcano evolved by uplift of the caldera floor (small-scale resurgent doming; cf. Smith and Bailey, 1968) and subsequent extrusions of dacitic to andesitic lavas onto the uplifted caldera floor. Thermoluminescence (TL) dating suggests that Nakajima volcano formed at 40–45 ka (Takashima et al., 1992). No geothermal manifestations (e.g., active fumaroles, hot springs, hydrothermal alteration zones) are observed on the surface of Nakajima volcano.

Usu volcano is located at the southern rim of Toya caldera (Fig. 2). It comprises a basaltic to andesitic stratovolcano surmounted by dacitic lava domes and cryptodomes (Yokoyama et al., 1973; Soya et al., 2007). The volcano became active at 18–19 ka (Goto et al., 2013) and is still active today, with at least nine eruptions since AD 1663 (Yokoyama et al., 1973; Ui et al., 2002; Nakagawa et al., 2005; Soya et al., 2007).

III. CSAMT survey

The CSAMT survey was undertaken to obtain the resistivity structure of the upper 1500 m beneath Toya caldera. The survey was carried out along a 16-km-long line, crossing Toya caldera in a NE–SW direction (Fig. 1). The CSAMT survey followed the 'scalar CSAMT' method (Matsuoka, 2005; Yokokawa, 1984), whereby a transmitter emits electrical currents into the ground at audio and near-audio fre-
The geology of Toya caldera is asymmetric. The northeastern caldera rim mainly comprises silicified rhyolite (OR), and the southwestern caldera rim comprises altered andesitic lavas (PN and others). The locations of the receiver stations (black circles; M1–M17) are also shown.

Fig. 3  Simplified geological map of Toya caldera, modified from Ota (1956) and Soya et al. (2007).
quencies via a grounded wire (bipole source), and a receiver records both the electric field, parallel to the grounded wire, and the magnetic field, perpendicular to the grounded wire (Fig. 4A).

The CSAMT survey was conducted by Neo-science, Osaka, Japan, using a high-resolution electromagnetic system (Geo-SEM). The system consists of a transmitter and a receiver (Fig. 5). The transmitter (Fig. 5A) consists of a transformer, rectifier, switching circuit, global positioning system (GPS) clock, and generator (Fig. 5B). An 8.7-km-long grounded wire, with 30 electrodes at each termination, was connected to the transmitter (Fig. 5C). A 600-mm-long, 13-mm-diameter stainless steel rod was used for each transmitter electrode. The receiver consists of an amplifier, filter, data logger, GPS clock, and set of sensors (Fig. 5D). The sensors consist of a pair of electrodes and a coil. A 280-mm-long and 15-mm-diameter copper rod was used for each receiver electrode (Fig. 5D). The transmitter and receiver were synchronized with a high-precision quartz clock system using GPS to an accuracy of $1 \times 10^{-6}$ s. The specifications of the Geo-SEM system are given in Table 1, and further details of the system are provided by Johmori et al. (2010).

The survey line for the CSAMT survey was 16 km long and oriented N50°E (Fig. 1). The 17 receiver stations (M1–M17) were horizontally spaced at an average interval of 910 m, ranging from 325 m to 1425 m along the survey line. Stations M1–M3 and M14–M17 were located outside of Lake Toya. The Stations M4–M13 were located within Lake Toya, with stations M6–M10 located on the Nakajima Islands. The positions of the receiver stations were confirmed using GPS. The bipole source (grounded wire) was placed along the Osarugawa River (Fig. 1). The source was 8.7 km long and oriented N45°E. The distance between the bipole sources and the receiver stations was 6–7 km, which is 4–4.7 times larger than the depth of interest (1500 m).

The resistivity measurements were carried out in two different ways, dependent on whether the receiver station was on land or water (Fig. 4). At the land stations (M1–M3, M6–M10, and M14–M17; Fig. 1), the electrodes and a coil were placed on the ground surface (Fig. 4A). A pair of electrodes was separated by 20 m and set parallel to the bipole source to measure the electric field, whereas the coil was set perpendicular to the bipole source to measure the magnetic field. At the water stations (M4–M5 and M11–M13), a manned fiberglass boat (4.8 m long, 1.5 m wide) was floated on the lake (Figs. 5E and F) and fixed to the measuring location by an anchor (Fig. 4B). A pair of electrodes, consisting of two 390-mm-long, 10-mm-across iron rods that were separated by 5.5 m (Fig. 5G), was mounted at either end of a surveying pole that extended from the boat. The pole was adjusted to keep the electrodes parallel to the bipole source using an azimuth compass (Fig. 5F) and to ensure that the electrodes measured the electric field correctly. The coil was not carried on the boat but placed on the ground surface of the lakeshore near the boat (at locations M3, M6, M10, and M14; Fig. 1) and set perpendicular to the bipole source (Fig. 5H). We substituted the magnetic field at M3 for the field at M4, M6 for M5, M10 for M11, the average of M10 and M14 for M12, and M14 for M13. This boating method is based on the fact that small waves on the lake have only a minor effect on the electric field measurements but a significant influence the magnetic field measurements. The magnetic field substitutions are based on the theory that the magnetic fields at a particular distance from a bipole source are almost identical if the resistivity structure is one- or two-dimensional (2-D). This boating method is superior to lake-bottom CSAMT surveys in terms of environmental loading, and is thus suitable for caldera studies in national parks.

The CSAMT measurements were acquired between 20 May and 1 June 2015. The transmitter injected 1–8 A electrical currents into the ground at two series of frequencies ($f$): $f = 2^n$ (where $n = 0–13$) and $f = 20 \times 2^n$ (where $n = 0–8$), to minimize the noise related to the
commercially used frequency of 50 Hz and its associated higher harmonics. The receiver recorded the electric and magnetic fields, parallel and perpendicular to the grounded wire, respectively. The total measurement time at each receiver station was 1 hr, with the mea-
Fig. 5 Photographs of the electromagnetic system (Geo-SEM) used for the CSAMT survey. (A) Transmitter of the Geo-SEM. (B) Generator for the transmitter. (C) Electrodes for the bipole source. (D) Receiver of the Geo-SEM. The coil is 72 cm long. (E) CSAMT survey on Lake Toya. A manned fiberglass boat was used to measure the electric field. A pair of electrodes, separated by 5.5 m, was set at either end of the surveying poles that extended from the boat. (F) Boating survey at station M13 on Lake Toya. An azimuth compass was used to measure the electric field. (G) Electrode used for the boating survey. (H) Coil set on the lakeshore to measure the magnetic field (station M14).
surement times at each frequency ranging from 2 min at 8192 Hz to 8 min at 1 Hz. The CSAMT data were then processed (band-pass filtering, Fourier transform, and stacking) to remove noise. The number of waves for stacking ranged from >400,000 at 8192 Hz to >300 at 1 Hz. The apparent resistivity and phase were then calculated from the electric and magnetic fields.

The quality of data at each measuring station was checked by examining the $\rho_a - f$ curve ($\rho_a =$ apparent resistivity). The $\rho_a - f$ curves for stations M1–M15 are smooth and generally possessed higher apparent resistivities at higher frequencies, exhibiting a gentle S-shape. The smooth curves imply that the data from these stations (M1–M15) are acceptable for resistivity calculations. However, the $\rho_a - f$ curves for stations M16–M17 are relatively irregular, likely due to the heterogeneous geological structure near these stations (i.e., silicified domains in rhyolitic breccia; Ota, 1956). We performed re-measurements at stations M16–M17 but did not obtain smoothly curving data. Since stations M16–M17 are located far from the caldera floor, the differing values should not adversely influence the resistivity structure beneath the Toya caldera. We therefore included the M16–M17 data in our analysis.

The distance between the bipole source and receivers (6–7 km) is sufficient to obtain the resistivity structure at depths of up to 1000 m in the far-field region (e.g., Sandberg and Hohmann, 1982). However, this distance (6–7 km) is not enough to obtain the resistivity structure at depths of up to 1500 m, which is our focus. Therefore, after ensuring that the CSAMT data were complete, near-field corrections were applied to the data, following the method of Sasaki (1988). The corrected CSAMT data (apparent resistivity and phase angles) are shown in Fig. 6.

IV. Data analysis

The resistivity structure beneath Toya caldera was modeled from a 2-D inversion of the CSAMT data using a finite element method, following Sasaki (1986). The initial model for the 2-D inversion consisted of a uniform resistivity ($50 \, \Omega \cdot m$) model, with the value of $50 \, \Omega \cdot m$ based on the mean value of the low-frequency data. The inversion was performed under the assumption that the electric and magnetic fields were measured at the same location for the Lake Toya stations (M4–M5 and M11–M13).

The 2-D inversion was carried out in transverse magnetic (TM) mode (Sasaki, 1986) along the 16-km-long survey line, oriented N50°E (survey line in Fig. 1). Since the computational needs of the entire 2-D inversion were beyond the capacity of our equipment, we divided the
Fig. 6 Apparent resistivity and phase angles of the observed CSAMT responses (blue lines) and modeled responses (red lines) for receiver stations M1–M17 (See Fig. 1 for station locations).
16-km-long section into five datasets (M1–M5, M4–M9, M9–M13, M12–M17, and M6–M11), and modeled each part separately. Dataset M6–M11 was specifically selected, as these stations are located in the central part of caldera floor, including the Nakajima Islands. The modeled 2-D inversion results for the five datasets were then integrated to form the 16-km-long section. No apparent discrepancies were observed in the modeled resistivity structure from the overlapping segments of the five datasets.

The 2-D inversion was performed using a topographic model derived from the 1:25,000 scale topographic map (‘Toyako-onsen’) of the region, issued by the Geospatial Information Authority of Japan. The mesh size (element size) from the finite element method was 50 m wide and 30 m high at the ground surface. Each ‘inversion block’, representing the unit used to model resistivity in the 2-D inversion (Sasaki, 1986), consisted of four elements (two vertical and two horizontal). The 2-D inversion was carried out by comparing the observed CSAMT responses (apparent resistivity and phase angles) with the modeled responses, using the non-linear least-squares method. Eight iterations were run for M1–M5 and M12–17, and five for M4–M9, M9–M13, and M6–M11 in the inversion.

Figure 6 compares the observed CSAMT responses (apparent resistivity and phase angles) with the modeled responses, which shows overall agreement, except for stations M16–M17. A root mean square (RMS) value was obtained from the observed CSAMT (apparent resistivity) and modeled responses to quantitatively investigate the degree of agreement between them. The RMS value (δ) is defined as 

\[ \delta = \sqrt[2]{\frac{1}{n} \sum (\ln(\rho_{af}) - \ln(\rho_{am}))^2} \]

where \( \rho_{af} \) is the observed CSAMT response (apparent resistivity), \( \rho_{am} \) is the modeled response, and \( n \) is the number of measurements. This equation highlights that when \( \delta = 0 \), the modeled responses perfectly match the observed CSAMT responses, whereas when \( \delta = 0.1, 90\% \) of the modeled responses match the observed CSAMT responses (i.e., 10\% error). The RMS values for the five datasets are 0.08 for M1–M5, 0.08 for M4–M9, 0.08 for M9–M13, 0.18 for M12–M17, and 0.08 for M6–M11. These low values indicate good agreement between the observed CSAMT responses and the modeled responses, except for M12–M17. The higher RMS value for M12–M17 is due primarily to the irregular observed CSAMT responses at stations M16–M17.

The penetration depth was determined from the skin depth (Cagniard, 1953) and the Bostick depth (Murakami, 1987). The skin depth is defined as the depth at which the amplitude of electromagnetic waves decreases to 1/e (where e is the base of the natural logarithm). The Bostick depth is defined as 1/√2 of the skin depth, and is considered to be a more accurate representation of the penetration depth than the skin depth. The skin depth calculated from the frequency of electric currents for the deepest layer (1 Hz) and its observed apparent resistivity (mostly in the 10–100Ω·m range) yields penetration depths of 1500–5000 m, whereas the Bostick depth calculation yields penetration depths of 1000–3000 m. Since the geometric mean of the Bostick depth is ~2000 m, the maximum penetration depth from our CSAMT survey is taken to extend 1500 m below the ground surface.

V. Results and discussion

Processing of the CSAMT data has revealed the subsurface resistivity structure of the upper 1500 m beneath Toya caldera (Fig. 7A). The prominent features of the resistivity structure are outlined in Fig. 7B, and are separated into four zones (A–D) as follows: Zone A is the southwestern part of Toya caldera (0–3000 m along the survey line), Zone B is the northeastern part (12,000–16,000 m), Zone C is within Lake Toya (3000–5500 and 10,000–12,000 m), and Zone D covers the Nakajima Islands and the submerged rise around the islands (5500–10,000 m).

In addition to the four zones (A–D), a horizontal layer of high resistivity (> 50Ω·m) was detected immediately below the lake surface, corresponding to lake water (Fig. 7B). The
Fig. 7  (A) Resistivity section beneath Toya caldera obtained by the CSAMT survey. (B) Annotated version of the resistivity section, showing Zones A to D. Zone A is interpreted to represent altered Tertiary andesitic lavas and breccia. Zone B corresponds to Tertiary silicified rhyolites. Zone C is inferred to be a caldera-fill deposit consisting of pumice, lithic fragments, and volcanic ash. Zone D1 is inferred to be dacitic lavas on the Nakajima Islands. Zone D2 is inferred to be a hydrothermally altered zone.
layer is 150–200 m thick and confined to Lake Toya, which possesses a water depth of 150–180 m. The high resistivity (> 50 Ωm) is consistent with fresh lake water. The resistivity of the lake water, sampled from the southern lakeshore in July 2015 and measured in our laboratory, is 60 Ωm, consistent with our interpretation. The correspondence between the lake depth (150–180 m) and the thickness of this thin horizontal layer above Zone B (150–200 m) indicates that the on-board CSAMT survey at Lake Toya is reliable.

The geological interpretations for the four zones (A–D in Fig. 7B) are presented below. In general, the resistivity of rocks and sediments is lowered by the presence of conductive minerals (e.g., alteration minerals such as smectite-series clays), thermal waters in pores and fractures, and high temperatures (e.g., Takakura, 1998; Milsom, 2003). The resistivity data should thus show marked changes when intersecting hydrothermal alteration zones or faults (e.g., Martyn et al., 1997; Risk et al., 2003). Our geological interpretations of Zones A–D are based on a combination of this knowledge, bathymetric data (Fig. 2), and geological data (Fig. 3).

Zone A is located outside Lake Toya and is characterized by low-resistivity materials (< 30 Ωm). The surface geology of this area consists of Tertiary to Quaternary hydrothermally altered andesitic lavas and breccia (the Noto-toko lava; Ota, 1956; PN in Fig. 3), suggesting that zone A corresponds to these rocks. The low resistivity of Zone A may also be attributed to hydrothermal alteration due to recent geothermal activity, as this zone is located west of the geothermal area produced by the 2000 eruption at Usu volcano (Ui et al., 2002; Soya et al., 2007).

Zone B is also located outside Lake Toya and is characterized by high resistivities (> 100 Ωm), in contrast to Zone A. The surface geology of this area consists of Tertiary rhyolitic breccia that is partly silicified (the Osarugawa Formation; Ota, 1956; Fig. 3), suggesting that Zone B corresponds to this rock. The high resistivity of Zone B is likely attributed to an abundance of quartz in the silicified rhyolitic breccia. The asymmetry of the resistivity between Zones B (high resistivity) and A (low resistivity) is attributed to the geological heterogeneity of Toya caldera, whereby the north-eastern caldera rim mainly comprises silicified rhyolitic breccia, and the southeastern caldera rim comprises altered andesitic lavas and breccia (Fig. 3).

Zone C is located below the caldera floor, indicating caldera subsidence in this zone. The two domains of Zone C (3000–5500 m and 10,000–12,000 m from the western termination) possess almost identical resistivities, consistent with caldera subsidence. Zone C possesses a largely homogeneous resistivity (30–40 Ωm), except for the uppermost low-resistivity layer (< 10 Ωm) that extends along the lake bottom. Since Zone C is positioned below the caldera floor and possesses a homogeneous medium resistivity (30–40 Ωm), we infer that Zone C comprises a caldera-fill deposit that consists of pumice, lithic fragments, and volcanic ash, all of which are slightly altered. The uppermost low-resistivity layer (< 10 Ωm) of Zone C may be the hydrothermal alteration zone of the caldera-fill deposit, which would be rich in clay minerals. This low-resistivity layer possibly reflects the distribution of the smectite stability field (< 200°C; Hyndman et al., 1997; Takakura et al., 2000; Aizawa et al., 2009; Aizawa, 2010; Lee et al., 2010). We infer that the hydrothermal alteration zone was produced at the interface between the warmer caldera-fill deposit and the colder lake water.

A marked resistivity contrast occurs between Zones C and B, likely due to the presence of a ring fault (Lipman, 2000; Cole et al., 2005) that formed during caldera subsidence. The boundary between Zones C and A is more obscure, but a discontinuity in resistivity is still observed. Zone C is represented by a homogeneous medium-resistivity domain with a thin (< 100 m thick) low-resistivity layer along the lake bottom, whereas Zone A is represented by a large low-resistivity domain extending
through the upper 1000 m of the subsurface. We therefore infer that the ring fault also occurs between Zones C and A. This inferred ring fault is 9 km in diameter. The location of the inferred ring fault is consistent with the bathymetric data (Fig. 2), which indicates the existence of a circular steep wall along the caldera rim. We thus infer that the original diameter of Toya caldera was 9 km. The larger on-land caldera morphology (10–11 km diameter) may be due to enlargement by erosion.

Zone D is located beneath the Nakajima Islands and the submerged rise around the islands. This zone comprises an upper high-resistivity layer (D1; > 100 Ω·m; upper 100–300 m of the subsurface) and a lower low-resistivity domain (D2; < 10 Ω·m; depths greater than 100–300 m). The Nakajima Islands consist primarily of fresh dacitic to andesitic lavas (Ota, 1956; Goto et al., 2015), suggesting that Zone D1 corresponds to these rocks. Zone D2 is up to 4500 m wide and < 1000 m thick. Zone D2 may be a hydrothermal alteration zone that is rich in clay minerals. We discount the possibility that zone D2 is a high-temperature zone, as no geothermal manifestations (e.g., hot springs) are observed at the surface of the Nakajima Islands. Since the Nakajima Islands were formed by uplift of the caldera floor (small-scale resurgent doming) and subsequent extrusions of dacitic to andesitic lavas (Goto et al., 2015), we infer that the hydrothermal alteration zone resulted from heating of the caldera-fill deposit by underlying magma that caused uplift of the caldera floor during the formation of the Nakajima Islands. Since the Nakajima Islands were formed by uplift of the caldera floor (small-scale resurgent doming) and subsequent extrusions of dacitic to andesitic lavas (Goto et al., 2015), we infer that the hydrothermal alteration zone resulted from heating of the caldera-fill deposit by the underlying magma that caused uplift of the caldera floor during the formation of the Nakajima Islands. The depth of the intrusion is unknown.

Matsuzaki and Utashiro (1966) and Nishida (1984) performed magnetic surveys over Toya caldera, with both detecting a strong magnetic anomaly beneath the Nakajima Islands. Matsuzaki and Utashiro (1966) interpreted the magnetic anomaly as an andesite intrusion beneath the Nakajima Islands, whereas Nishida (1984) interpreted it as a funnel-shaped caldera (4.5 km across, 1 km deep) beneath the islands. We do not favor the Nishida (1984) model, since our resistivity observations suggest that an alteration zone is present here, even though the proposed funnel-shaped caldera matches the location and size of Zone D2. We thus infer that the magnetic anomaly beneath the Nakajima Islands is attributed to the inferred dacitic to andesitic intrusion beneath Zone D2.

Tomiya and Miyagi (2002) analyzed petrological and experimental data of volcanic rocks from Usu volcano and concluded that two magma chambers occur at different depths beneath Usu. The deeper magma chamber (10 km depth) is compositionally zoned and consists of lower basaltic and upper rhyolitic magmas, whereas the shallower magma chamber (4–5 km depth) consists solely of dacitic magma. Since Usu is another post-caldera volcano of Toya caldera, we consider it likely that a shallow dacitic to andesitic intrusion occurs beneath the Nakajima Islands. Further geophysical and geological studies are required to fully understand the subsurface structures of Toya caldera.

VI. Conclusions

A CSAMT survey has revealed the subsurface resistivity structure of the upper 1500 m beneath Toya caldera. The resistivity structure suggests the existence of a 9-km-diameter ring fault and a homogeneous caldera-fill deposit beneath the caldera floor. A hydrothermal alteration zone is present beneath the Nakajima Islands, inferred to have resulted from heating of the caldera-fill deposit by the underlying magma that caused the uplift of the caldera floor during the formation of the Nakajima Islands.

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北海道洞爺カルデラの地下構造の解明

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北海道南西部に位置する洞爺カルデラは日本有数の陥没カルデラである。このカルデラの地下構造を解明するため、CSAMT法による比抵抗構造探査を行った。探査は洞爺カルデラを北東〜南西方向に横断する測線上（測線長16 km、受信点17か所）で行った。カルデラ内の洞爺湖では小型ボートを用いた湖上測定を行った。データ解析は有限要素法を用いた2次元逆解析を用いた。その結果、洞爺カルデラの深度1500 mまでの比抵抗構造が得られた。洞爺カルデラの南西側には低比抵抗領域が存在し、新第三紀〜第四紀の変質した安山岩であると推定される。カルデラの北東側には高比抵抗領域が存在し、新第三紀の珪化した流紋岩であると推定される。カルデラ内には均質な中比抵抗領域が存在し、軽石や石質岩片などの火山碎屑物からなるカルデラフィル堆積物であると推定される。カルデラ中央部の中島は高比抵抗領域からなり、中島がデイサイト質の溶岩ドーム群からなることと調和的である。中島とその周囲の隆起域の地下深部には低比抵抗領域（幅4500 m、厚さ1000 m）が存在する。この低比抵抗領域は、中島とその周囲の隆起域を形成した地下的マグマによりカルデラフィル堆積物が加熱され、熱水変質して形成されたと考えられる。

キーワード：洞爺カルデラ、地下構造、比抵抗、CSAMT探査、中島

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