Stratigraphy and Lithofacies of the Toya Ignimbrite in Southwestern Hokkaido, Japan: Insights into the Caldera-forming Eruption at Toya Caldera

Yoshihiko GOTO*, Kazuya SUZUKI*, Takashi SHINYA*, Atsuki YAMAUCHI*, Masaaki MIYOSHI*, Tohru DANHARA** and Akihiko TOMIYA***

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Abstract
A stratigraphic study of the Toya Ignimbrite in southwestern Hokkaido, Japan, was performed to clarify the sequence of caldera-forming eruption at Toya caldera. The Toya Ignimbrite (thickness < 80 m) is rhyolitic in composition and comprises six stratigraphic units: (1) a fine-grained ash-fall deposit at the base; (2) a base surge deposit and an overlying, voluminous, pumiceous pyroclastic flow deposit, both of which contain accretionary lapilli; (3) a number of base surge deposits and associated ash-fall deposits; (4) a pumiceous pyroclastic flow deposit that contains large lithic clasts up to 50 cm in diameter; (5) a pumiceous pyroclastic flow deposit with a basal lithic-rich layer (lag breccia); and (6) a pumiceous pyroclastic flow deposit at the top. The stratigraphy suggests that the caldera-forming eruption at Toya caldera commenced with a phreatomagmatic explosive eruption (forming unit 1), followed by violent phreatomagmatic eruptions that generated a voluminous pyroclastic flow (unit 2), and small-scale phreatomagmatic eruptions that generated a number of base surges (unit 3). The next phreatomagmatic eruption triggered caldera collapse (unit 4), which reached the climax with a violent phreatomagmatic eruption (unit 5) and ended with a magmatic eruption (unit 6). These eruptions occurred continuously without any significant time breaks. Component analysis of non-juvenile lithic clasts suggests that the vent-opening phase of the caldera-forming eruption involved a single vent. Pyroclastic flows during the caldera collapse may have erupted from multiple vents. Textural studies of pumice clasts suggest that white pumice was ejected during the initial to final stages, while banded pumice and grey pumice were ejected during the final stage. Geochemical data indicate that there was no significant change in magma composition during the caldera-forming eruption, with the exception of a small amount of mafic magma was mixed into the rhyolitic magma during the final stage.

Key words: caldera-forming eruption, Toya caldera, pyroclastic flow deposit, stratigraphy, lithofacies
I. Introduction

Calderas are circular volcanic depressions with diameters larger than those of explosive vents (Williams, 1941). Most calderas are the product of subsidence due to rupture and the collapse of magma chamber roof rock induced by rapid chamber decompression during or following a large-scale eruption (Lipman, 1984; Cole et al., 2005; Acocella, 2007). This model of caldera formation is supported by the presence of large-volume pyroclastic deposits around silicic calderas (e.g., Bishop Tuff, Wilson and Hildreth, 1997; Campanian Ignimbrite, Rosi et al., 1999; Taupo Ignimbrite, Wilson and Walker, 1985; Kos Plateau Tuff, Allen and Cas, 1998), the structures of eroded calderas (e.g., Lipman, 1984; Brannen and Kokelaar, 1994; Miura, 1999), direct observations of caldera formation (e.g., Geshi et al., 2002), and numerous laboratory experiments (e.g., Komuro, 1987; Roche et al., 2000; Acocella, 2007).

Previous geological studies of large-volume pyroclastic deposits (e.g., Barberi et al., 1978; Self and Sparks, 1978; Bacon, 1983; Aramaki, 1984; Sparks et al., 1985; Self et al., 1986; Bacon and Drütt, 1988; Orsi et al., 1992; Allen and Cas, 1998; Allen, 2001; Milner et al., 2003; de Silva et al., 2006; Hildreth and Wilson, 2007; Maeno and Taniguchi, 2007; Carey et al., 2009, 2010; Houghton et al., 2010; Hasegawa et al., 2016) suggest that caldera-forming eruptions vary in eruption style, intensity, and degree of interaction with external water. As the rarity of caldera-forming eruptions, the processes leading to caldera formation remain poorly understood. Additional geological surveys and interpretation of the pyroclastic deposits around individual calderas are required to gain a better understanding of the processes of caldera formation.

Toya caldera in southwest Hokkaido is one of the major Quaternary calderas in Japan (Fig. 1). Previous geological studies (Suzuki et al., 1970; Machida et al., 1987) suggest that Toya caldera was formed at ca. 110 ka by explosive rhyolitic eruptions that generated large-volume pyroclastic flow deposits. The deposits are identified as either the Toya pyroclastic flow deposit (Yokoyama et al., 1973) or the Toya Ignimbrite (Feebrey and Nakagawa, 1995). We have performed stratigraphic surveys of the Toya Ignimbrite to clarify the sequence of the caldera-forming eruption. Published stratigraphic data for the Toya Ignimbrite are sparse (Suzuki et al., 1970; Lee, 1996; Machida and Yamagata, 1996), and further stratigraphic study may provide invaluable information with which to constrain the processes involved during formation of the Toya caldera. This paper describes the stratigraphy and lithofacies of the Toya Ignimbrite and discusses the processes of caldera formation.

II. Geological outline of Toya caldera

Toya caldera has 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 and water level of 84 m above sea level. Lake Toya is drained by the Sobetsu River, which exits from the southeastern caldera rim. Bathymetric data (Fig. 2) indicate that the caldera floor is relatively flat and surrounded by a steep wall of ~9 km in diameter and 160 m above the caldera floor. Geophysical studies show that the caldera is defined by a negative gravity anomaly, with an 11-milligal low at the caldera center (Yokoyama, 1964).

Geological mapping shows that the rim of Toya caldera consists of Tertiary to Quaternary volcanic and sedimentary rocks (Fig. 2; Ota, 1956; Yokoyama et al., 1973; Yahata and Norota, 2003; Soya et al., 2007). The eastern and northeastern caldera rims comprise rhyolitic breccia of the Tertiary Osarugawa Formation (labeled OR in Fig. 2). 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 (AL) lavas (Fig. 2). The southwestern caldera rim comprises Tertiary to Quaternary andesite lavas of the Poromoi volcanics (PV; or the Abuta vol-
canics of Yahata and Norota, 2003). 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 (TP) pyroclastic flow deposits. Drilling data indicate that Tertiary plutonic rocks (mainly 7 Ma granodiorite) are present beneath the caldera rim at 800–1500 m depth (Wada et al., 1988; Yahata et al., 2014). These Tertiary plutonic rocks are not exposed on the surface of the caldera rim.

The Toya Ignimbrite (TI in Fig. 2) overlies the Tertiary to Quaternary volcanic and sedimentary rocks, forming a pyroclastic plateau at the northwestern and southeastern sides of Lake Toya. The Toya Ignimbrite is up to 80–100 m thick and comprises rhyolitic pumice, lithic fragments, and volcanic ash. Geochronological studies suggest that the Toya Ignimbrite was erupted at ca. 110 ka (Okumura and Sangawa, 1984; Machida et al., 1987; Takashima et al., 1992; Shirai et al., 1997; Ganzawa et al., 2007; Ito, 2014; Matsuura et al., 2014). Further details of the Toya Ignimbrite are provided in Sections III–VI.

Toya caldera contains two post-caldera volcanoes: Nakajima and Usu (Fig. 2). Nakajima volcano is located within Lake Toya and com-
prises an andesitic to dacitic dome complex (Ota, 1956; Katui, 1990; Goto et al., 2015). Thermoluminescence (TL) dating suggests that Nakajima volcano formed at 40–45 ka (Takashima et al., 1992). Usu volcano is located at the southern rim of Toya caldera and comprises a basaltic to andesitic stratovolcano with dacitic lava domes and cryptodomes (Yokoyama et al., 1973). Eruptive activity commenced at 18–19 ka (Goto et al., 2013) and the volcano is still
active today, with at least nine eruptions since AD 1663 (e.g., Tomiya et al., 2001; Ui et al., 2002; Tomiya and Miyagi, 2002; Nakagawa et al., 2005; Soya et al., 2007).

III. Toya Ignimbrite

The Toya Ignimbrite is widely distributed around Toya caldera. Geological studies (e.g., Okumura et al., 1984; Machida et al., 1987; Machida and Arai, 2003) indicate that the Toya Ignimbrite extends for 42 km to the north (Iwanai; Location 16 in Fig. 1) and 35 km to the west (Neppu; Location 17). The ‘Toya ash’, a widespread tephra associated with the Toya Ignimbrite, has been identified in eastern Hokkaido and in the Tohoku district in northeast Japan (e.g., Ooma on Shimokita Peninsula; Location 18 in Fig. 1). The total volume of the Toya Ignimbrite, including the Toya ash, is > 150 km$^3$ (Machida et al., 1987). The Toya Ignimbrite is easily identifiable because it contains eulite (Fe-rich orthopyroxene), which is uncommon in Quaternary pyroclastic deposits in Japan (Machida et al., 1987).

We have performed a stratigraphic survey of the Toya Ignimbrite in both the proximal and distal areas of Toya caldera (Figs. 1 and 3). Survey locations were mainly located to the south and north of Toya caldera (Fig. 1), as these areas are relatively flat and have many exposures. Survey locations in the distal areas include Iwanai (Location 16), Neppu (Location 17), and Ooma (Location 18). Stratigraphic sections at representative locations are shown.
The Toya Ignimbrite is best exposed in subvertical cliffs along the Osarugawa River to the south of Toya caldera (Locations 1–6 in Fig. 3), where it has been deeply eroded by the river. The geological sequence along the Osarugawa River (Locations 1–6 in Fig. 4) consists of: (1) the Quaternary Kaminagawa Formation (conglomerate with a thickness of > 4 m; Suzuki et al., 1970) at the base, (2) the Osarugawa pyroclastic fall deposit (Osr-pfa; 40 cm thick, source volcano unknown; Machida et al., 1987), (3)
the Osarugawa pyroclastic flow deposit (Osr-pfl; 3.6 m thick, source volcano unknown; Machida et al., 1987), (4) a soil layer (10 cm thick), (5) the Toya Ignimbrite (< 80 m thick), (6) the Kt-2 tephra (1.3 m thick, erupted from Kuttara volcano in southwestern Hokkaido; Fig. 1; Yamagata, 1994), and (7) tephras from the Nakajima Islands and Usu volcano (total thickness < 12 m; omitted from Fig. 4; for further details see Soya et al., 2007; Goto et al., 2013) at the top.

At the western side of Toya caldera, the Toya Ignimbrite is sporadically exposed along the Nukkibetsugawa River (Location 8). The geological sequence exposed in a large cliff along the Nukkibetsugawa River (Location 8 in Fig. 4) consists of the Osarugawa pyroclastic flow deposit (Osr-pfl; thickness > 8 m) and the over-

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lying Toya Ignimbrite (30 m thick).

At the northern side of Toya caldera (Locations 10–14), the Toya Ignimbrite is poorly exposed, as several widely distributed pyroclastic flow deposits erupted from other volcanoes occur in this area. For example, the geological sequence at a quarry in Suzukawa (Location 14 in Fig. 4) consists of: (1) the Kimobetsu pyroclastic flow deposit 2 (Km-pfl2; erupted from Shiribetsu volcano; thickness > 20 m; Nakagawa et al., 2011) at the base, (2) the Toya Ignimbrite (1 m thick), (3) the Kimobetsu pyroclastic flow deposit 1 (Km-pfl1; erupted from Shiribetsu volcano; 20 m thick; Nakagawa et al., 2011), and (4) the Shikotsu pyroclastic flow deposit (Spfl; erupted from Shikotsu caldera; 7 m thick; Katsui, 1959) at the top. The thick Km-pfl1 deposit covers the Toya Ignimbrite in this area (Locations 10, 12, and 13), and therefore hampers stratigraphic surveys of the Toya Ignimbrite.

At the eastern side of Toya caldera, the Toya Ignimbrite is poorly exposed because of high elevations (< 880 m) and rugged topography (Fig. 1). The geological sequence at a road cut in Kounai (Location 15 in Fig. 4) consists of: the Toya Ignimbrite (thickness > 10 m) at the base, the Kt-2 tephra (1.5 m thick; Yamagata, 1994), and the Us-b tephra (erupted from Usu volcano; 0.3 m thick; Yokoyama et al., 1973) at the top.

At distal areas, the Toya Ignimbrite (> 12 m) is well exposed at several small quarries in Iwanai (Location 16 in Fig. 4). At Neppu (Location
17 in Fig. 4), the Toya Ignimbrite (thickness > 13 m) is exposed solely in subvertical cliffs along the Neppu River. The Toya Ignimbrite (15 cm thick) occurs on a coastal terrace deposit at Ooma (Location 18 in Fig. 4).

IV. Stratigraphy of the Toya Ignimbrite

We performed stratigraphic surveys of the Toya Ignimbrite along the Osarugawa River to the south of Toya caldera (Locations 1–6 in Fig. 3), where subvertical exposures up to 80 m high are common. Other locations (i.e., to the north, east, and west of Toya caldera) are not suitable for detailed descriptive studies, as the stratigraphic sequence of the Toya Ignimbrite is poorly exposed and discontinuous.

Stratigraphic sections along the Osarugawa River (Locations 1–6 in Fig. 4) suggest that the Toya Ignimbrite can be divided into several textually distinct, mappable stratigraphic units. A stratigraphic section through the Toya Ignimbrite (Fig. 5) was produced by assembling several stratigraphic sections from exposures along the Osarugawa River. The reconstructed section shows that the Toya Ignimbrite comprises six stratigraphic units (units 1 to 6 in ascending order; Figs. 6–9). These units are also exposed in stratigraphic sections at the northern, eastern, and western sides of Toya caldera (Locations 7–18 in Fig. 4).

The lithofacies of units 1 to 6 are described here and summarized in Table 1. The distribution area of each unit is shown in Fig. 10. Correlations between the stratigraphic units proposed in this paper (units 1 to 6) and those proposed by previous studies are shown in Fig. 11. The mineral assemblage of each unit is listed in Table 2. Photomicrographs of volcanic ash from unit 1 and photographs of pumice clasts in units 2 to 6 are shown in Fig. 12. The lithology of each unit, including variations in the texture of pumice clasts (Fig. 13), density of pumice clasts (Fig. 14), variations in lithic clasts (Fig. 15), refractive index data (Fig. 16), and chemical compositions (Table 3; Fig. 17), are described in Section VI.

The Toya Ignimbrite comprises various types of pyroclastic deposits, and the terms used to describe each unit are outlined here. The term 'ignimbrites' is used for non-welded or welded pumiceous pyroclastic flow deposits (e.g., Sparks et al., 1973; Cas and Wright, 1986). The 'Toya Ignimbrite' consists mainly of non-welded pumiceous pyroclastic flow deposits, but is accompanied with minor ash-fall, base surge and pyroclastic surge deposits. Although these minor deposits are beyond the definition of ignimbrites, they have close relationships with
Fig. 6 Photographs of the Toya Ignimbrite. (A) Units 2, 3, 5, and 6 at Location 6. Unit 4 is not exposed at this location. Each unit is characterized by a different color: unit 2 is pale reddish grey; unit 3 is dark brown; unit 5 is pale yellowish grey; and unit 6 is pale reddish grey. (B) Detailed view of (A), showing units 2c, 3a, 3b, 5a (lag breccia), and 5b. The scale ruler (in the white circle) is 2.5 m long. The red and white segments of the scale ruler are 50 cm long.

Fig. 7 (A) Units 1, 2a, and 2b at Location 3. Unit 1 directly overlies the Kaminagawa Formation (conglomerate). The soil layer between the Kaminagawa Formation and unit 1 is not developed at this location. The red and white segments of the scale ruler are 10 cm long. (B) Units 2c, 2d, and 3a at Location 6. The red and white segments of the scale ruler are 10 cm long.
Fig. 8  (A) Ash-fall deposit of unit 3 at Location 2. The deposit contains abundant accretionary lapilli. The red and white segments of the scale ruler are 10 cm long. (B) Pyroclastic flow deposit of unit 4 at Location 1. Note that large lithic clasts occur in the deposit. The red and white segments of the scale ruler are 10 cm long.

Fig. 9  (A) Lag breccia of unit 5a at Location 6. The red and white segments of the scale ruler are 10 cm long. (B) Pyroclastic flow deposits of units 5 and 6 at Location 3. Unit 5 is pale yellowish grey in color, whereas unit 6 is pale reddish grey. Person for scale.
the pumiceous pyroclastic flow deposits. We therefore use 'Toya Ignimbrite' for the assemblage of these pyroclastic deposits. The term 'base surge deposit' refers to dark brown, thinly bedded, very fine-grained, pumice-poor deposits (cf., Cas and Wright, 1986). These deposits are typically clay-rich, well consolidated, and commonly contain accretionary lapilli. The term 'pyroclastic surge deposit' is used for cross-laminated, pale grey, fine- to coarse-grained, pumiceous deposits. It corresponds to ground surge or ash-cloud surge deposits (Cas and Wright, 1986) and excludes base surge deposits. The pyroclastic surge deposit studied is clay-poor, poorly consolidated, and lacks accretionary lapilli. The term 'pyroclastic flow deposit' is used for pale reddish-grey, massive (non-laminated) deposits that contain abundant pumice clasts up to 20 cm in diameter.

The lithology and mineralogy of each unit (units 1–6, in ascending order) are described below.

1) Unit 1

Unit 1 is a fine-grained ash-fall deposit that is 1–2 cm thick (Fig. 7A). Detailed isopach data on the deposit are not available due to the limited number of exposures. The thickness of the deposit is 2 cm at Location 3, and 1 cm at Locations 4, 5 and 14 (Fig. 10). There are no thickness data from localities to the east and west of Toya caldera. The deposit is white in color, non-laminated, non-graded, and poorly consolidated. No accretionary lapilli was identified within the ash. The ash consists of rhyolitic glass shards (87% of total grains), crystals of plagioclase, quartz, orthopyroxene, clinopyroxene, and opaque minerals (9%), and minor lithic fragments (4%), all of which are < 0.3 mm in diameter (Table 2). The glass shards (Fig. 12A) are blocky, colorless, have low vesicularity, and contain microcrystals. The presence of eulite in the ash (Fig. 16) strongly suggests that unit 1 belongs to the Toya Ignimbrite, although previous workers (e.g., Suzuki et al.,

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**Table 1** Summary of the geological units of the Toya Ignimbrite.

| Unit | Thickness (m) | Lithofacies | Eruption style |
|------|---------------|-------------|----------------|
| 6    | 6.4–6.5       | Pumiceous pyroclastic flow deposit, consisting of a lower lithic-rich layer (unit 6a; 0.4–0.5 m thick) and an upper pumice-rich layer (unit 6b; 6.0–6.4 m thick). The pumice-rich layer contains white pumice, banded pumice, and grey pumice. No accretionary lapilli. | magmatic eruption |
| 5    | 7.5–24.0      | Pumiceous pyroclastic flow deposit, consisting of a lower lithic-rich layer (unit 5a; 2–4 m thick) and an upper pumice-rich layer (unit 5b; 3.5–21 m thick). The lithic-rich layer contains large lithic clasts (< 3 m across). The pumice-rich layer contains white pumice and banded pumice. No accretionary lapilli. | phreatomagmatic eruption |
| 4    | 3.4–3.9       | Pumiceous pyroclastic flow deposit, containing white pumice (< 7 cm across) and large lithic clasts (< 50 cm across). No accretionary lapilli. | phreatomagmatic eruption |
| 3    | 4.4–7.7       | Base surge and ash-fall deposits. The lower part (unit 3a; 1–3.6 m thick) consists of a number of thin, base surge and ash-fall deposits, both of which contain accretionary lapilli. The middle part (unit 3b; 2.5–3.6 m thick) consists of a thick base surge deposit. The upper part (unit 3c; 0.2–1.3 m thick) consists of several base surge deposits. | phreatomagmatic eruption |
| 2    | 28.2–34.0     | Base surge deposit (unit 2a; thickness 10–20 cm) and overlying thick pumiceous pyroclastic flow deposit (units 2b–d; 28–34 m). The pyroclastic flow deposit consists of a ground surge layer (2b), a massive layer (2c), and an ash-cloud surge layer (2d). Units 2a and 2c contain accretionary lapilli. | phreatomagmatic eruption |
| 1    | 0.01–0.02     | Fine-grained ash-fall deposit, consisting of blocky rhyolitic glass shards, crystals (plagioclase, quartz, orthopyroxene, clinopyroxene, and opaque minerals), and minor lithic fragments. No accretionary lapilli. | phreatomagmatic eruption |
10 cm thick; Fig. 7A

...consist of rhyolitic volcanic glass and minor ice clasts... Figure 15

...grey in color, and is poorly consolidated. It consists of rhyolitic glass shards, crystals of plagioclase, quartz, and rare accretionary lapilli... Figure 11

...The deposit is grey and consists of rhyolitic glass shards, crystals of plagioclase, quartz, and opaque minerals... Figure 7A

...The pumice clasts are white and consist of rhyolitic volcanic glass and minor amounts of plagioclase, quartz, orthopyroxene, and opaque minerals... Table 2

...The pumice clasts are white and consist of rhyolitic volcanic glass and minor amounts of plagioclase, quartz, orthopyroxene, and opaque minerals... Figure 12C

...The pumice clasts are white and consist of rhyolitic volcanic glass and minor amounts of plagioclase, quartz, orthopyroxene, and opaque minerals... Table 2

...The pumice clasts are white and consist of rhyolitic volcanic glass and minor amounts of plagioclase, quartz, orthopyroxene, and opaque minerals... Figure 15

...The pumice clasts are white and consist of rhyolitic volcanic glass and minor amounts of plagioclase, quartz, orthopyroxene, and opaque minerals... Figure 7B

...The pumice clasts are white and consist of rhyolitic volcanic glass and minor amounts of plagioclase, quartz, orthopyroxene, and opaque minerals... Figure 7B

...The pumice clasts are white and consist of rhyolitic volcanic glass and minor amounts of plagioclase, quartz, orthopyroxene, and opaque minerals... Figure 7B
Fig. 10  Maps showing the distribution and thickness (m) of each unit (1-6) of the Toya Ignimbrite. Note that unit 2 is the most extensive of the six units.
clinopyroxene, hornblende, biotite, and opaque minerals, and minor lithic fragments. No accretionary lapilli was identified in unit 2d.

3) Unit 3
Unit 3 (4.4–7.7 m thick) directly overlies unit 2. We could not find reworked deposits or erosion surfaces between these units (Fig. 7B). Unit 3 comprises a number of thin (mostly <30 cm) base surge and ash-fall deposits (Figs. 6 and 7B). Unit 3 is brown, displays a thinly bedded texture, and is coarse- to fine-grained with minor pumice clasts and abundant accretionary lapilli. Unit 3 corresponds to the ‘Karasawa tuff’ of Suzuki et al. (1970), ‘Toya pyroclastic fall deposit (Tpfa)’ of Ikeda and Katsui (1986), ‘pyroclastic fall deposit’ of Lee (1993), and ‘Tpfa’ of Machida and Yamagata (1996) (Fig. 11).

Unit 3 is divided into three subunits (3a–3c in ascending order; Fig. 5). Unit 3a (1.0–3.6 m thick; Fig. 7B) comprises several thin base surge and ash-fall deposits, each of which is < 40 cm thick. The base surge deposits are brown to brownish grey, thinly bedded, coarse-grained (1–2 mm), relatively consolidated, and consist of volcanic ash that contains a small amount of pumice (< 20 mm in diameter; < 1 vol.%; Fig. 12D). The volcanic ash comprises lithic fragments, crystals of plagioclase, quartz, orthopyroxene, clinopyroxene, hornblende, biotite, and opaque minerals, and glass shards. The pumice clasts (Fig. 12D) are white and consist of rhyolitic volcanic glass and minor amounts of plagioclase, quartz, orthopyroxene,
and opaque minerals (Table 2). The base surge deposits contain abundant accretionary lapilli (< 5 mm in diameter). The ash-fall deposits (Fig. 8A) are brown, laminated, fine-grained (< 1 mm across), poorly consolidated, and composed of lithic fragments, crystal of plagioclase, quartz, orthopyroxene, clinopyroxene, hornblende, biotite, and opaque minerals, and glass shards. The ash-fall deposits contain abundant accretionary lapilli (< 5 mm in diameter; Fig. 8A).

Unit 3b (2.5–3.6 m thick) directly overlies unit 3a and comprises a thick base surge deposit (Fig. 9A). The deposit is brownish grey, massive (non-laminated), coarse-grained (1–2 mm), and poorly consolidated. The deposit consists of lithic fragments, crystals of plagioclase, quartz, orthopyroxene, clinopyroxene, hornblende, and opaque minerals, and glass shards. The contact between them is parallel to the bedding of unit 3c. We could not find reworked deposits or erosion surfaces between these units. Unit 4 occurs only at locations 1 and 2, suggesting that unit 4 is distributed in areas proximal to Toya caldera (Fig. 10D). Unit 4 corresponds to the 'Toya caldera pyroclastic deposit III' of Suzuki et al. (1970), ‘Toya pyroclastic flow

### Table 2

| Unit | Subunit | Pumice type | Mineral assemblage of pumice | Mineral assemblage of matrix |
|------|---------|-------------|-----------------------------|-----------------------------|
| 6    | 6b      | white pumice| Pl, Qz, Opx, Opq            | Qz, Pl, Opx, Opq           |
|      |         | banded pumice| Pl, Qz, Opx, Hb, Cum, Cpx, Opq| Qz, Pl, Opx, Hb, Opq       |
|      |         | grey pumice| Pl, Qz, Opx, Opq            | Qz, Pl, Opx, Hb, Opq       |
| 5    | 5b      | white pumice| Pl, Qz, Opx, Opq            | Qz, Pl, Opx, Opq           |
|      |         | banded pumice| Pl, Qz, Opx, Opq            | Qz, Pl, Opx, Opq           |
| 4    | 4       | white pumice| Pl, Qz, Opx, Opq            | Qz, Pl, Opx, Opq           |
| 3    | 3c      | no pumice  | –                           | Pl, Qz, Opx, Opq           |
| 3b   |         | white pumice| Pl, Qz, Opx, Opq            | Pl, Qz, Opx, Cpx, Hb, Opq  |
| 3a   |         | white pumice| Pl, Qz, Opx, Opq            | Pl, Qz, Opx, Cpx, Hb, Opq  |
| 2    | 2d      | no pumice  | –                           | Pl, Qz, Opx, Cpx, Hb, Opq  |
| 2b   |         | white pumice| Pl, Qz, Opx, Opq            | Pl, Qz, Opx, Cpx, Hb, Opq  |
| 2a   |         | white pumice| Pl, Qz, Opx, Opq            | Pl, Qz, Opx, Cpx, Hb, Opq  |
| 1    | 1       | no pumice  | –                           | Pl, Qz, Opx, Cpx, Hb, Opq  |

Abbreviations are as follows: Qz, quartz; Pl, Plagioclase; Kf, Alkali feldspar; Opx, Orthopyroxene; Cpx, Clinopyroxene; Hb, Hornblende; Cum, Cummingtonite; Bt, Biotite; Opq, Opaque Fe-minerals.

Unit 3b lacks accretionary lapilli.

Unit 3c (0.2–1.3 m thick) directly overlies unit 3b and comprises several base surge deposits, each of which is <50 cm thick (Fig. 9A). The deposits are brownish grey, thinly bedded, coarse-grained (1–2 mm), and poorly consolidated. The unit consists of lithic fragments, crystals of plagioclase, quartz, biotite, orthopyroxene, hornblende, and opaque minerals, and glass shards. Unit 3c lacks accretionary lapilli.

### Unit 4

Unit 4 (3.0–3.4 m thick) directly overlies unit 3 and consists of a massive, pumiceous, pyroclastic flow deposit. The contact between units 3 and 4 is sharp and is marked by a manganese layer (5 mm thick; produced by precipitation after the emplacement of unit 4). The contact between them is parallel to the bedding of unit 3c. We could not find reworked deposits or erosion surfaces between these units. Unit 4 occurs only at locations 1 and 2, suggesting that unit 4 is distributed in areas proximal to Toya caldera (Fig. 10D). Unit 4 corresponds to the 'Toya caldera pyroclastic deposit III' of Suzuki et al. (1970), ‘Toya pyroclastic flow
Fig. 12  Photographs of glass shards and pumice clasts from units 1 to 6.
deposit (Tpfl III’ of Ikeda and Katsui (1986), and Tpfl II’ of Machida and Yamagata (1996) (Fig. 11).

Unit 4 is pale reddish grey, massive (non-laminated), matrix-supported, and consolidated (but non-welded) (Fig. 8B). It consists of rhyolite pumice (1–2 vol.%) and lithic clasts (2–3 vol.%) in a fine- to coarse-grained matrix (> 95 vol.%). The pumice clasts (< 7 cm in diameter; mostly < 2 cm in diameter; Fig. 12E) are white and consist of rhyolitic volcanic glass and crystals of plagioclase, quartz, orthopyroxene, clinopyroxene, and opaque minerals (Table 2). The lithic clasts (< 50 cm in diameter; Fig. 8B) comprise andesite, rhyolite, sedimentary rocks (volcanic sandstone, greenish altered tuff), and plutonic rocks (granodiorite) (Fig. 15). The lithic clasts are distributed sporadically within the deposit but tend to concentrate at the base of unit 4. The matrix of unit 4 is pale yellowish-grey, coarse-grained, and composed of rhyolitic glass shards, crystals of quartz, plagioclase, K-feldspar, orthopyroxene, clinopyroxene, hornblende, and opaque minerals, and lithic fragments. Some glass shards show polyhedral-crack texture (Büttner et al., 1999). Unit 4 lacks accretionary lapilli.

5) Unit 5

Unit 5 (7.5–24.0 m thick) directly overlies unit 4 and comprises a pumiceous pyroclastic flow deposit that is characterized by a basal lithic-rich layer (lag breccia; Figs. 6B and 9A). The contact between the units 4 and 5 is unclear. Unit 5 corresponds to the ‘volcanic breccia’ and the lower part of the ‘Toya caldera pyroclastic deposit IV’ of Suzuki et al. (1970), the lower part of the ‘Toya pyroclastic flow deposit (Tpfl) IV’ of Ikeda and Katsui (1986), and to the ‘Tpfl III’ of Machida and Yamagata (1996).

Unit 5 comprises a lower lithic-rich layer (unit 5a; 2.0–4.0 m thick) and an upper pumice-rich layer (unit 5b; 3.5–21.0 m thick) (Fig. 6B). Unit 5a (Fig. 9A) is massive, matrix-supported (but non-welded), and consists of lithic clasts (70 vol.%) and minor pumice clasts (< 1 vol.%) in a coarse-grained matrix (30 vol.%). The lithic clasts are angular to subangular, up to 3 m in diameter, and vary in color, rock type, and degree of alteration. The lithic clasts comprise rhyolite, andesite, plutonic rocks (fine- to coarse-grained granodiorite), sedimentary rocks (volcanic sandstone, mudstone, and greenish altered tuff), and welded tuff. The clasts of greenish, altered tuff are soft and < 1 m in diameter. The matrix of unit 5a is pale yellowish grey and consists mainly of lithic fragments with minor crystals and glass shards. Unit 5a contains no accretionary lapilli. Unit 5a grades upwards into unit 5b.

Unit 5b (Fig. 9B) is massive, matrix-supported, poorly consolidated (non-welded), and consists of pumice clasts (5–8 vol.%) and minor lithic clasts (1–2 vol.%) in a fine-grained matrix (> 90 vol.%). The pumice clasts comprise white pumice (Fig. 12F) and minor banded pumice (Fig. 12G). The white pumice (< 20 cm in diameter) and banded pumice (< 10 cm in diameter) both consist of rhyolitic volcanic glass and crystals of plagioclase, quartz, orthopyroxene, and opaque minerals. The lithic clasts comprise rhyolite, andesite, plutonic rocks (fine- to coarse-grained granodiorite),
and sedimentary rocks (volcanic sandstone). The matrix of unit 5b is coarse-grained, pale yellowish grey in color, and consists of rhyolitic glass shards, crystals of quartz, plagioclase, K-feldspar, orthopyroxene, hornblende, and opaque minerals. Some glass shards show polyhedral-crack textures. The K-feldspar and hornblende in the matrix may be xenocrysts. Unit 5b lacks accretionary lapilli. At Location 6, large gas-segregation pipes (Cas and Wright, 1986) (10–30 cm in diameter, 5–10 m long) are present from the base to the middle part of unit 5b.

6) Unit 6

Unit 6 (6.4–6.5 m thick) directly overlies unit 5b and comprises a pumiceous pyroclastic flow deposit (Fig. 9B). The contact between them is unclear. Unit 6 is pale reddish grey in color, and is therefore distinguishable from the underlying unit 5, which is pale yellowish grey (Fig. 9B). Unit 6 corresponds to the upper part of the ‘Toya caldera pyroclastic deposit IV’ of Suzuki et al. (1970), the upper part of the ‘Toya pyroclastic flow deposit (Tpfl) IV’ of Ikeda and Katsui (1986), and to the ‘Tpfl IV’ of Machida and Yamagata (1996).

Unit 6 comprises a lower lithic-rich layer (unit 6a; 0.4–0.5 m thick) and an upper pumice-rich layer (unit 6b; 6.0–6.4 m thick) (Fig. 9B). Unit 6a is massive, matrix-supported, and poorly consolidated (non-welded). It consists of lithic clasts (30–40 vol.% and minor pumice clasts (< 2 vol.%) in a coarse-grained matrix (60–70 vol.%). The lithic clasts (5–30 cm in diameter) are subangular and vary in color, lithology, and degree of alteration. The lithic clasts are rhyolite, andesite, sedimentary rocks (volcanic sandstone, greenish altered tuff), plutonic rocks (coarse-grained granodiorite), and welded tuff. The matrix of unit 6a is pale reddish grey, fine-grained, and consists of rhyolitic volcanic glass and crystals. Unit 6a lacks accretionary lapilli. Unit 6a grades upwards into unit 6b.

Unit 6b is massive (non-stratified), matrix-supported, and poorly consolidated (non-welded). It consists of pumice clasts (5–10 vol.) in a fine-grained matrix (> 90 vol.%), with no lithic clasts. The pumice clasts are white (Fig. 12H), banded (Fig. 12I), and grey (Fig. 12J). The white pumice (< 20 cm in diameter) consists of rhyolitic volcanic glass and crystals of plagioclase, quartz, orthopyroxene, and opaque minerals (Table 2). The banded pumice (< 20 cm in diameter) consists of rhyolitic volcanic glass and crystals of plagioclase, quartz, orthopyroxene, hornblende, minor cummingtonite, minor clinopyroxene, and opaque minerals. The grey pumice (< 20 cm across) consists of rhyolitic volcanic glass and crystals of plagioclase, quartz, orthopyroxene, clinopyroxene, hornblende, and opaque minerals. The matrix
of unit 6b is fine-grained, pale reddish grey in color, and consists of rhyolitic glass shards, crystals of quartz, plagioclase, orthopyroxene, hornblende, biotite, and opaque minerals, and lithic fragments (Table 2). The biotite in the matrix may be xenocrysts. Unit 6b lacks accretionary lapilli.

The uppermost portion of unit 6b grades upwards into its weathered equivalent (5 cm thick), which is capped by a dark brown humus soil layer (1 cm thick). The soil layer is covered by the Kt-2 tephra, which was erupted from Kuttara volcano in southwestern Hokkaido, Japan (Fig. 1). The teprostratigraphy above the Kt-2 tephra at Location 2 is described by Goto et al. (2013).

V. Distribution and volume of the Toya Ignimbrite

The distributions of units 1 to 6 of the Toya Ignimbrite are shown in Fig. 10. The distribution of the Toya Ignimbrite within the Pacific Ocean is not presented, as offshore data were not collected as part of this study. The distributions suggest that unit 2 (Fig. 10B) is the most extensive of the six units. The geological sections at Iwanai (Location 16 in Fig. 4; thickness > 12 m; pumice clast < 6 cm across) and Neppu (Location 17; thickness > 13 m; pumice clast < 6 cm across) indicate that the Toya Ignimbrite at these locations consists only of unit 2c. The Toya Ignimbrite at Ooma (Location 18; thickness 15 cm) is probably the co-ignimbrite ash (Sparks and Walker, 1977; Cas and Wright, 1986) of unit 2, as pumice clast (< 5 mm across) consists only of white pumice. The extensive distribution of unit 2 is consistent with the low density of its pumice clasts (Fig. 14). The distributions of units 3 and 4 are smaller than those of units 5 and 6.

The bulk volume of each unit is listed in Table 4. The volumes of units 1 to 6 were calculated by using their distribution areas multiplied by their average thicknesses. The distribution of each unit was determined using field mapping data. As we have not collected thickness-distribution data from the Pacific Ocean, the volumes in the sea are not included in this calculation. The calculated results (Table 4) indicate that unit 2 has the largest volume (> 27.2 km$^3$) of the six units. The total bulk volume of the units 1 to 6 is > 36.8 km$^3$. This volume is a minimum estimate for the Toya Ignimbrite, as the volume of the widespread ‘Toya ash’ (Machida et al., 1987) is not included in this calculation.

VI. Lithology of the Toya Ignimbrite

1) Textural variations in pumice clasts

Pumice clasts in units 2 to 6 of the Toya Ignimbrite can be classified into three textural
Fig. 16 Components of the matrix of the Toya Ignimbrite, and refractive indices of volcanic glass, plagioclase, and orthopyroxene, determined using the RIMS2000 instrument. The relationship between refractive indices and components of plagioclase is after Tsuboi (1923). The relationship between refractive indices and components of orthopyroxene is after Leake (1968).
types: (1) white pumice that is homogenous in texture (B–F and H in Fig. 12), (2) banded pumice that is composed of alternating white and grey pumice layers (G and I in Fig. 12), and (3) grey pumice that is homogenous to weakly banded in texture (J in Fig. 12). Quantitative data on proportions in pumice types were determined for each unit. Pumice samples collected from locations 1, 3, and 6 (11–34 samples for each unit; larger than 30 mm across) were washed in water in the laboratory and classified into the three types. After classification, the volume of each pumice type was measured using the glass-bead method of Sasaki and Katsui (1981).

The results (Fig. 13) indicate that the Toya Ignimbrite exhibits changes in pumice type with stratigraphic position. Units 2–4 consist solely of white pumice. Unit 5 comprises white pumice (94 vol.%) and banded pumice (6 vol.%). Unit 6 comprises white pumice (42 vol.%), banded pumice (46 vol.%), and grey pumice (12 vol.%).

2) Density of pumice clasts
The apparent density of pumice clasts in units 2–6 was determined using the glass-bead method of Sasaki and Katsui (1981). Pumice samples collected from locations 1, 3, and 6 (11–34 samples for each unit; larger than 30 mm across) including white pumice, banded pumice and grey pumice were washed in water, dried at room temperature for more than 3 weeks, and weighed to an accuracy of 0.01 g. The bulk volume of each pumice sample was then measured using glass-beads in a graduated cylinder (cf., Sasaki and Katsui, 1981).

The results indicate that the pumice clasts from each unit have slightly different values of apparent density (Fig. 14). Pumice clasts in unit 2 vary in apparent density, with relatively low apparent density in unit 2c. Pumice clasts in unit 3 have high apparent density. There is an increase in apparent density from units 4 to 6. This result is consistent with the result of a preliminary experiment using a water bath: pumice clasts in units 4 and 5 mostly float on

| Name | Unit 1 | Unit 2 | Unit 2 | Unit 3 | Unit 4 | Unit 5 | Unit 5 | Unit 6 | Unit 6 | Unit 6 |
|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|      | (2a)   | (2b)   | (2c)   | (3a)   | (3b)   | (5a)   | (5b)   | (6a)   | (6b)   | (6b)   |
|      | volcanic | white | white | white | white | white | white | white | white | white |
| Sample No. | TY-501 | TY-500 | TY-343 | TY-358A | TY-359A | TY-671-39 | TY-324-a | TY-673-3 | TY-303-b | TY-673-33 |
| SiO₂ | 76.20 | 76.41 | 76.43 | 76.72 | 76.15 | 76.29 | 76.59 | 76.65 | 76.25 | 75.36 |
| TiO₂ | 0.10 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.06 | 0.07 | 0.13 |
| Al₂O₃ | 13.33 | 12.98 | 12.68 | 13.07 | 12.99 | 13.20 | 13.35 | 13.25 | 13.15 | 13.39 |
| Fe₂O₃* | 1.57 | 1.13 | 1.12 | 1.11 | 1.10 | 1.07 | 1.10 | 1.07 | 1.20 | 1.55 |
| MnO | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| MgO | 0.19 | 0.10 | 0.10 | 0.10 | 0.10 | 0.09 | 0.10 | 0.09 | 0.14 | 0.24 |
| CaO | 0.64 | 0.45 | 0.42 | 0.45 | 0.46 | 0.46 | 0.61 | 0.47 | 0.55 | 1.03 |
| Na₂O | 4.77 | 4.66 | 4.72 | 5.06 | 4.59 | 5.09 | 5.06 | 5.16 | 4.97 | 4.86 |
| K₂O | 2.85 | 3.01 | 2.97 | 2.99 | 3.16 | 2.94 | 2.88 | 2.84 | 2.84 | 2.57 |
| P₂O₅ | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 |
| Total | 99.76 | 98.91 | 98.60 | 99.67 | 98.72 | 99.29 | 99.85 | 99.70 | 99.28 | 99.25 |
| L.O.I. | 3.85 | 4.27 | 4.25 | 3.87 | 3.86 | 3.18 | 2.89 | 2.55 | 2.63 | 2.66 |

Compositions were determined by X-ray fluorescence (Rigaku RIX-2000) at Shimane University, Japan, following Kimura and Yamada (1996). Fe₂O₃* = total iron as Fe₂O₃. L.O.I. = loss on ignition. The sample of unit 1 was prepared by pulverizing a bulk sample of the ash-fall deposit using an agate mortar.
water, whereas those in unit 6 mostly sink. Banded pumice and grey pumice in units 5 and 6 have a higher apparent density than white pumice in all units.

3) Chemical composition of pumice clasts

Whole-rock major element chemical compositions of pumice clasts were determined by X-ray fluorescence spectrometry (XRF) (Rigaku RIX-2000 at Shimane University, Japan) following the analytical methods described by Kimura and Yamada (1996). Analyses were performed for the following samples: six samples of white pumice from units 2a, 2c, 3a, 4, 5b, and 6b; two samples of banded pumice from units 5b and 6b; and one sample of grey pumice from unit 6b (Table 3). These pumice samples were washed in distilled water, dried in an oven at 110°C for 24 hours, and pulverized using a tungsten carbide mill. The ash-fall deposit of unit 1 (bulk sample, milled using an agate mortar) was also analyzed by XRF.

The results indicate that white pumice clasts in units 2 to 6 have almost identical chemical composition (SiO₂ = 76–77 wt.%, Fe₂O₃ = 1.1 wt.%, and MgO = 0.10 wt.%; Table 3). Banded pumice in unit 5 shows similar geochemistry to the white pumice. Banded pumice in unit 6 contains almost identical SiO₂ (77 wt.%) contents to white pumice, and slightly higher Fe₂O₃ (1.2 wt.%) and MgO (0.14 wt.%) contents. Grey pumice in unit 6 is characterized by slightly lower SiO₂ (75 wt.%), and higher Fe₂O₃ (1.55 wt.%) and MgO (0.24 wt.%) contents than the white pumice. The geochemistry of unit 1 (bulk sample of volcanic ash) closely resembles that of the pumice clasts from units 2–6, which is consistent with the conclusion that unit 1 is part of the Toya Ignimbrite. The geochemistry of pumice clasts (Table 3) suggests that there was no significant change in magma composition from unit 1 to unit 6, although slightly mafic magma (high Mg and Fe, and low K) was involved during the formation of unit 6.

4) Variations in the lithology of non-juvenile lithic clasts

Component analysis of non-juvenile lithic clasts (cf., Suzuki-Kamata et al., 1993; Suzuki-Kamata, 2010; Cole et al., 1998) for units 2–6 was performed to obtain quantitative data on lithological variations. A total of 20–190 samples were collected from each unit from locations 1, 3, and 6, and used for the analysis. The number of samples collected from each unit was dependent on the size and abundance of lithic clasts. For example, 20 rock samples (210 g in total) were collected from unit 2a, as lithic clasts in this unit are small (< 2 cm in diameter) and rare (< 1 vol.% of the total deposit).

In contrast, 190 rock samples (24 kg in total) were collected from unit 5a, as lithic clasts from this unit are large (> 3 m in diameter) and abundant (70 vol.% of the total deposit). The lithic clasts were classified into nine rock types (granodiorite, greenish altered tuff, volcanic sandstone, mudstone, rhyolite, andesite, pyroclastic flow deposit, welded tuff, and ‘others’). After classification, the volume of each lithic type was measured using water in a graduated cylinder.

The results were summarized into five rock types, corresponding to the geological units associated with Toya caldera (Ota, 1956), as follows: (1) plutonic rocks (mainly granodiorite; intrusives beneath the caldera rim); (2) sedimentary rocks including tuff, volcanic sandstone, and mudstone (Osarugawa Formation); (3) rhyolites (Osarugawa Formation); (4) andesites (Asahiura and Tsukiura lavas, etc.); and (5) others (welded tuff, etc.). The results are presented in Fig. 15 and indicate that the lithic clasts in unit 2a are mostly plutonic rocks (95 vol.%). The proportion of plutonic rocks decreases from unit 1 (95 vol.%) to unit 6 (8 vol.%), although unit 5 has a slightly higher proportion than units 4 and 6. Sedimentary rocks are rare in units 2 and 3, but common in units 4–6.

The roundness and degree of alteration of lithic clasts from each unit were then examined. Lithic clasts in units 5a and 6a showed distinct differences: lithic clasts in unit 5a are generally angular and fresh, whereas those in unit 6a are mostly rounded and hydrothermally altered. This characteristic was most obvious.
5) **Refractive index of glass shards and minerals in the matrix**

Refractive indices of glass shards \(n\), feldspar \(n_1\), and orthopyroxenes \(\gamma\) in unit 1 (volcanic ash) and the matrix of units 2 to 6 of the Toya Ignimbrite were measured using a RIMS2000 analyzer at Kyoto Fission-Track, Japan, following the analytical methods described by Danhara et al. (1992). Samples were collected from locations 1 and 3. The measured grains (from the 63–125 \(\mu\)m grain size fraction) were...
as follows: 60 glass shards, 35 plagioclase feldspar crystals, and 50 orthopyroxene crystals.

The results of refractive index analysis (Fig. 16) indicate that glass shards, plagioclase, and orthopyroxene in units 1 to 6 are almost identical in terms of refractive index values with the exception of glass shards from unit 6b (Sample TY-304), which show a bimodal pattern in histograms. This result is consistent with the presence of grey pumice in unit 6 (Fig. 13) and the variable chemical compositions of white, banded, and grey pumice in this unit (Table 3). Refractive index analysis of orthopyroxene shows that eulite (Fe-rich orthopyroxene) is present in all units.

6) Chemical composition of matrix glass shards

Major and trace element chemical compositions (58 elements) of matrix glass shards from units 1 to 6 of the Toya Ignimbrite (collected from Locations 1 and 3) and from the Osarugawa pyroclastic flow deposit (collected from Location 4) were determined by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS), following the procedure of Maruyama et al. (2016). The samples for units 1, 2b, 2d, 3c, 4, 5b, and 6b were analyzed using a Thermo Fisher Scientific iCAP Qc quadrupole ICP-MS instrument at Kyoto University, Japan. Samples from unit 2a and the Osarugawa pyroclastic flow deposit (sample TY-109) were analyzed using the same model of instrument at the University of Tokyo, Japan.

The results indicate that glass shards in units 1 to 5 have almost identical chemical compositions and contain 77–80 wt.% SiO₂ (Table 5). The patterns of 58 elements relative to the crustal abundances (Taylor and McLennan, 1985; Rudnick and Fountain, 1995; McLennan and Taylor, 1996; McLennan, 2001) are shown in Fig. 17A. The chemical compositions of glass shards in unit 6 are slightly inhomogeneous and can be divided into type I, which is characterized by lower light rare earth element (LREE) and higher heavy rare earth element (HREE) contents, and type II, which is characterized by higher LREE and lower HREE (Fig. 17B).

The trace element patterns of the volcanic glass shards from the Osarugawa pyroclastic flow deposit (TY-109 in Fig. 17C) differ from those of the Toya Ignimbrite samples. This result is consistent with the presence of a 10-cm-thick soil layer between the two deposits, which suggests a significant time break between the two eruptions. However, elements heavier than La show similar element patterns, implying that both eruptive units were sourced from a similar parental magma.

VII. Discussion

1) Stratigraphy of the Toya Ignimbrite

Suzuki et al. (1970) first surveyed in detail the Toya Ignimbrite and described that the stratigraphic sequence of the Toya Ignimbrite comprises four stratigraphic units: the Toya caldera pyroclastic deposits I, II, III, and IV (Fig. 11). They also recognized the Karasawa Tuff between the deposits II and III, and volcanic breccia between the deposits III and IV (Fig. 11). Ikeda and Katsui (1986) have modified this stratigraphy and proposed that the stratigraphic sequence comprises five units: the Tpfl I, Tpfl II, Tpfa, Tpfl III, and Tpfl IV. Later publications (Lee, 1993; Machida and Yamagata, 1996; Ganzawa et al., 2007) have followed or simplified this stratigraphy (Fig. 11).

Our stratigraphy (units 1–6) differs from Ikeda and Katsui (1986) in that we have newly
Table 5  Major- and trace-element chemical compositions of glass shards in the matrix of the Toya Ignimbrite (TY-397, 100, 103, 310, 321, 346, 302, and 304) and the Osaragawa pyroclastic flow deposit (TY-109). The volcanic glass shards from unit 6b (TY-304) can be divided into two types: type I and type II.

| Unit Sample Type | Osr-pfl TY-109 | Unit 1 TY-397 | Unit 2a TY-100 | Unit 2b TY-103 | Unit 2d TY-310 | Unit 3c TY-321 | Unit 4 TY-346 | Unit 5b TY-302 | Unit 6b TY-304 Type I | Unit 6b TY-304 Type II |
|------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|------------------------|------------------------|
|                  |                |                |                |                |                |                |                |                |                        |                        |
|                  |                |                |                |                |                |                |                |                |                        |                        |
|                  |                |                |                |                |                |                |                |                |                        |                        |

(wt.%)  

| Element | Unit 6b TY-304 Type I | Unit 6b TY-304 Type II |
|---------|------------------------|-------------------------|
| SiO2    | 138.0                  | 131.0                   |
| TiO2    | 0.06                   | 0.05                    |
| Al2O3   | 14.0                   | 13.5                    |
| FeO     | 0.12                   | 0.11                    |
| Cr       | 1.0                    | 1.0                     |
| Co      | 0.1                    | 0.1                     |
| Ni      | 0.2                    | 0.2                     |
| Cu      | 0.1                    | 0.1                     |
| Zn      | 0.6                    | 0.6                     |
| Ga      | 1.0                    | 1.0                     |
| Ge      | 2.0                    | 2.0                     |
| As      | 5.0                    | 5.0                     |
| Rb      | 20.0                   | 20.0                    |
| Sr      | 50.0                   | 50.0                    |
| Y       | 10.0                   | 10.0                    |
| Zr      | 90.0                   | 90.0                    |
| Nb      | 7.0                    | 7.0                     |
| Mo      | 2.0                    | 2.0                     |
| Ag      | 0.1                    | 0.1                     |
| Cd      | 0.0                    | 0.0                     |
| In      | 0.0                    | 0.0                     |
| Sn      | 0.1                    | 0.1                     |
| Sb      | 0.1                    | 0.1                     |
| Cs      | 1.0                    | 1.0                     |
| Ba      | 100.0                  | 100.0                   |
| La      | 12.0                   | 12.0                    |
| Ce      | 30.0                   | 30.0                    |
| Pr      | 1.0                    | 1.0                     |
| Sm      | 2.0                    | 2.0                     |
| Eu      | 0.1                    | 0.1                     |
| Gd      | 1.0                    | 1.0                     |
| Tb      | 0.1                    | 0.1                     |
| Dy      | 1.0                    | 1.0                     |
| Ho      | 0.1                    | 0.1                     |
| Er      | 1.0                    | 1.0                     |
| Tm      | 0.1                    | 0.1                     |
| Yb      | 1.0                    | 1.0                     |
| Lu      | 0.1                    | 0.1                     |
| Hf      | 1.0                    | 1.0                     |
| Ta      | 0.1                    | 0.1                     |
| W       | 1.0                    | 1.0                     |
| Ti      | 0.1                    | 0.1                     |
| Pb      | 1.0                    | 1.0                     |
| Bi      | 0.1                    | 0.1                     |
| Th      | 1.0                    | 1.0                     |
| U       | 0.1                    | 0.1                     |

Mean values of analyzed data are shown. N.O.A., number of analyses. The number of analyzed glass shards is shown in parentheses.
identified unit 1 (ash-fall deposit) at the base, and unit 6 (pyroclastic flow deposit) at the top. The identifying of unit 1 is important because this unit is the product of vent-opening phase of the caldera-forming eruption. The identifying of unit 6 is also important as unit 6 differs from other units in component (Fig. 13), in chemical composition (Fig. 17), and in eruption style (described later). Machida and Yamagata (1996) have recognized unit 6 (their Tpfl IV; Fig. 11), but also followed the stratigraphic sequence of Ikeda and Katsui’s (1986); therefore there was inconsistency in their stratigraphic sequence.

Ikeda and Katsui (1986) suggested that the widespread tephra, Toya ash is the co-ignimbrite ash of the Tpfl IV (i.e., units 5 and 6). However, we infer that the Toya ash is the co-ignimbrite ash of unit 2 because: (1) unit 2 is the most extensive of the six units (Fig. 10B); (2) unit 2 contains abundant low-density pumice clasts (Fig. 14); (3) the Toya Ignimbrite (Toya ash) at Ooma (Location 18; thickness 15 cm) contains only white pumice; (4) pumice clasts in units 5 and 6 have relatively high densities (Fig. 14).

2) Period of the caldera-forming eruption

The six units of the Toya Ignimbrite are inferred to have formed by a continuous eruption without any significant time breaks, because no soil layers are interbedded within units 1 to 6. Furthermore, we could not find reworked deposits or erosion surfaces among these units, implying that the six units were emplaced within a short time period. This inference is also supported by the following observations. (1) Unit 1 is well preserved, consisting of 1–2 cm of soft volcanic ash (Fig. 7A), suggesting it was covered by unit 2 immediately after its deposition. (2) Unit 2d is well preserved without erosion, consisting of a 10–20 cm thick soft pyroclastic surge deposit (Fig. 7B), suggesting it was covered by unit 3 immediately after its deposition. (3) The contact between units 3 and 4 is sharp and parallel to bedding planes in unit 3, suggesting that no erosion occurred after the deposition of unit 3. (4) Unit 4 is covered directly by unit 5. (5) Unit 5 grades upward into unit 6 (Fig. 9B). We thus infer that the caldera-forming eruption of Toya caldera occurred as a single eruptive event. Although we have no quantitative data for the eruption duration, we presume that the caldera-forming eruption occurred within a year.

3) Eruption styles of the caldera-forming eruption

Textural and lithological characteristics of the Toya Ignimbrite suggest that the caldera-forming eruption at Toya caldera comprises a series of explosive eruptions that vary in eruption style, as follows.

Unit 1 is composed of volcanic ash, consisting mainly of poorly vesicular, blocky volcanic glass (Fig. 12A), implying that magma fragmentation was driven by contact with water rather than by vesiculation (cf., Heiken and Wohletz, 1985). We therefore infer that unit 1 was produced by a phreatomagmatic eruption. The caldera-forming eruption at Toya caldera thus commenced with a phreatomagmatic eruption. The eruption could be phreatoplinian, as unit 1 seems to be widely dispersed. Initial phreatomagmatic fallout ash has also been reported from other caldera-forming eruptions; the 1875 eruption of Askja volcano in Iceland (Self and Sparks, 1978; Sparks et al., 1981; Carey et al., 2010), the 1.8 ka Taupo eruption in New Zealand (Houghton et al., 2010), the 161 ka Kos Plateau Tuff in eastern Aegean Sea (Allen, 2001), and the 120 ka eruption at Kutcharo caldera in Japan (Hasegawa et al., 2016).

Unit 2a is a base surge deposit consisting mainly of fine-grained ash and containing accretionary lapilli, suggesting that it was produced by a phreatomagmatic eruption. Units 2b–2d are interpreted to have been formed during a single pyroclastic flow. We interpret unit 2b as a ground surge (Cas and Wright, 1986) of the pyroclastic flow, 2c as the main part of the flow, and 2d as the ash-cloud surge (Cas and Wright, 1986) associated with the pyroclastic flow. Unit 2 contains abundant pumice clasts and accretionary lapilli, suggesting that it was
produced by a magma-dominant phreatomagmatic eruption. Unit 2b contains carbonized wood fragments in its basal part, suggesting a relatively high temperature of emplacement.

Unit 3 comprises thin layers of base surge and ash-fall deposits, both of which contain abundant accretionary lapilli, suggesting that unit 3 was produced by multiple small-scale phreatomagmatic eruptions. The presence of polyhedral-cracked glass shards in the matrix, in addition to the relatively high density of pumice clasts, is consistent with formation during phreatomagmatic eruptions. The presence of polyhedral-cracked glass shards in the matrix in unit 5b, suggest that the phreatomagmatic eruptions involved a high water/magma ratio (e.g., Tomiya et al., 2001; Yamamoto, 2001).

Unit 4 comprises a pumiceous pyroclastic flow deposit that contains no accretionary lapilli, suggesting that the eruption style of unit 4 was mainly magmatic. However, the matrix of unit 4 contains polyhedral-cracked glass shards, implying contact with water. We thus infer that it was produced by a magma-dominant phreatomagmatic eruption.

Unit 5 comprises a pumiceous pyroclastic flow deposit, consisting a lower lithic-rich layer (unit 5a) and an upper pumice-rich layer (unit 5b). We interpret unit 5a as co-ignimbrite lag breccia (Druitt and Sparks, 1982; Cas and Wright, 1986). The presence of abundant pumice clasts, the absence of accretionary lapilli, and the presence of polyhedral-cracked glass shards in the matrix in unit 5b, suggest that unit 5 was also produced by a magma-dominant phreatomagmatic eruption.

Unit 6 comprises a pumiceous pyroclastic flow deposit, consisting a lower, thin lithic-rich layer (unit 6a) and an upper pumice-rich layer (unit 6b). We interpret unit 6a as co-ignimbrite lag breccia (Druitt and Sparks, 1982; Cas and Wright, 1986). We infer that unit 6 was produced by a magmatic eruption, as evidenced by the presence of abundant pumice clasts, absence of accretionary lapilli, and lack of polyhedral-cracked glass shards in the matrix. There are no indicators of a phreatomagmatic eruption origin for unit 6. Unit 6 is pale reddish grey in color due to thermal oxidation, suggesting a relatively hot temperature of emplacement.

In conclusion, units 1 to 5 are the products of phreatomagmatic eruptions, whereas unit 6 is the product of a magmatic eruption. The eruption styles of the caldera-forming eruption at Toya caldera thus changed from dominantly ‘wet’ (units 1 to 5) to ‘dry’ (unit 6) explosive styles. The influence of external water must have been eliminated. The early ‘wet’ explosive style can be explained by the presence of a lake at the time of eruption (Machida et al., 1987). We speculate that a pre-Toya caldera (or a large crater) existed, which was filled with a lake, because several pyroclastic flow deposits are distributed around the rim of Toya caldera; namely, the Sobetsu (1.6 Ma; Takashima et al., 1992), Takinoue (0.9 Ma; Takashima et al., 1992), and Osarugawa (120–125 ka; Machida and Arai, 2003) pyroclastic flow deposits (Figs. 2 and 4).

The shift from ‘wet’ to ‘dry’ explosive style may be explained in several ways: (1) depletion of the water source; (2) shift of the vent position to a new (dry) location; (3) uplifting of the vent area; (4) domination of magmatic-volatile-driven explosion over phreatomagmatic explosion (e.g., Allen, 2001); or (5) caldera collapse that caused environmental changes. We favor (5), because caldera collapse mainly occurred during the eruption of unit 5, as discussed later.

4) Vent systems of the caldera-forming eruption

Component analysis of non-juvenile lithic clasts indicates that units 2 to 6 contain different proportions of rock types (Fig. 15). Therefore, the eruptive vents for these units were not fixed in terms of location and depth. Vent-migration, vent-widening, changing of explosion depths, or caldera collapse may have occurred during the eruption of units 2 to 6, resulting in the incorporation of lithic clasts with different lithologies from the vent area. Detailed vent lo-
cations for each eruption were not determined due to the limitations of the lithic clast data. However, it is emphasized that vents were not stable during the caldera-forming eruption. We exclude the possibility of gradual vent-deepening during the eruptions that generated units 1 to 6, based on the observation that plutonic rocks decrease in proportion from unit 1 (95 vol.%) to unit 6 (8 vol.%).

The lithic clasts in unit 2a mostly comprise plutonic rocks (95 vol.%; Fig. 15), which are presently not exposed on the surface of the caldera rim. We thus infer that the eruption of unit 2a occurred in a restricted area, and that initial vent-opening phase of the caldera-forming eruption involved a single vent. Plutonic rocks above the magma chamber were fragmented during the initial stage of the caldera-forming eruption, and the plutonic rock fragments were then incorporated into the pyroclasts of unit 2a. Drilling data (Yahata et al., 2014) indicate that Tertiary plutonic rocks (mainly 7 Ma granodiorite) are present beneath the caldera rim at depths of 955–1300 m at the northern rim, and 805–1500 m at the western rim. The vent for initial vent-opening phase could be located somewhere at the northern, western or central part of the present Toya caldera area.

The lithic clasts in units 2c and 3 consist of plutonic rocks, andesites, rhyolites, and sedimentary rocks (Fig. 15), the latter three of which are exposed at the caldera rim. The large-scale explosive eruptions that formed unit 2 may have opened a large vent and destroyed surface rocks. The lithic clasts in units 4–6 have similar lithological assemblages to those of units 2c and 3, but differ in size and proportion. The lithic clasts in units 4–6 (< 3 m in diameter) are much larger than those in units 1–3 (< 10 cm in diameter). Of note, units 4–6 contain abundant sedimentary rocks (19–22 vol.%; Fig. 15). We therefore infer that a relatively large eruptive event (involving vent-migration, significant vent-widening, or caldera collapse) occurred at the beginning of the eruption that generated unit 4. The vent could have moved or extended to the southeastern part of the present Toya caldera area, as sedimentary rocks occur widely at the southeastern caldera rim of Toya caldera (Fig. 2).

Lee (1996) performed component analysis of lithic clasts from the lag breccia of unit 5a at 12 locations around Toya caldera and concluded that the Toya Ignimbrite was derived from a system involving multiple vents. Therefore, the vent systems of the caldera-forming eruption may have changed from single vent (units 1 and 2) to multiple vents (at least unit 5). The timing for the shift could be at the beginning of the eruption that generated unit 4, as the lithic clasts in units 4–6 differ in proportion and sizes from those in units 2–3.

5) Timing of caldera collapse

Previous geological studies of pyroclastic deposits around calderas (e.g., Druitt and Sparks, 1982; Aramaki, 1984; Druitt and Bacon, 1986; Hildreth and Mahood, 1986; Suzuki-Kamata et al., 1993, Lee, 1996; Allen, 2001; Suzuki-Kamata, 2010) suggest that caldera subsidence accompanies an extrusion of large-volume pumiceous pyroclastic flow that contains large-diameter non-juvenile lithic clasts (co-ignimbrite lag breccia; Druitt and Sparks, 1982; Cas and Wright, 1986).

In case of the Toya Ignimbrite, large lithic clasts occur in units 4, 5 and 6. In particular, unit 5 comprises a large-volume (> 4.9 km³) pumiceous pyroclastic flow deposit that is characterized by a thick (< 4 m) lithic-rich layer (lag breccia; unit 5a) at the base. The presence of large lithic clasts (up to 3 m in diameter) in the lag breccia strongly suggests that unit 5 was produced by a catastrophic eruption during the climactic stage of caldera collapse. The lag breccia (unit 5a) includes abundant fresh plutonic rocks (22 vol.%; Fig. 15), suggesting that caldera collapse largely destroyed the plutonic rocks above the magma chamber.

Unit 6 comprises a smaller volume (> 2.6 km³) pumiceous pyroclastic flow deposit, which has a thin (< 0.5 m) lithic-rich layer (unit 6a) at its base. We infer that the explosive eruption of unit 6 occurred just after the climax of
caldera collapse, because the lithic-rich layer (unit 6a) is much thinner with smaller (mostly rounded) lithic clasts than in unit 5a. We thus infer that the lithic clasts in unit 6a were recycled from former eruption products (e.g., unit 5a) within the caldera. As discussed in Section VII-3, units 1 to 5 are the products of phreatomagmatic eruptions, whereas unit 6 is the product of magmatic eruption. This implies that the eruptions that formed units 1–5 occurred in a water-rich environment, whereas unit 6 occurred in a water-poor (dry) environment. We infer that the eruption of unit 6 occurred within a newly formed caldera, which was not filled with water at that time.

Unit 4 comprises a small volume (> 0.5 km³) pumiceous pyroclastic flow deposit that contains abundant large (≤ 50 cm in diameter) lithic clasts. We consider that caldera subsidence commenced during this eruption because: (1) unit 4 contains abundant large lithic clasts; (2) unit 4 occurs just below unit 5, which is considered to have formed by a catastrophic eruption during the climactic stage of caldera collapse; (3) component analysis of lithic clasts (Fig. 15) suggests that spatial vent migration and/or changing of the explosion depth occurred between the eruptions of units 3 and 4, as discussed in Section VII-4; and (4) units 4–6 are the products of magma-dominant phreatomagmatic eruptions, whereas units 1–3 are the products of phreatomagmatic eruptions, implying changing in degree of interaction with external water (e.g., the opening of new vent in a water-poor area) occurred between the eruption of units 3 and 4.

Unit 2 is the largest-volume (> 27.2 km³) pyroclastic deposit among the six units, implying that the eruption that generated unit 2 played an important role in emptying the magma chamber, and was therefore responsible for caldera collapse (e.g., Geshi et al., 2014). Unit 2 may correspond to the Plinian phase of caldera-forming eruptions at other calderas. Unit 2 does not show any evidence for caldera collapse, such as the presence of large lithic clasts (e.g., Druitt and Bacon, 1986; Hildreth and Mahood, 1986; Suzuki-Kamata et al., 1993). Therefore, we infer that no caldera subsidence occurred during the eruption of unit 2.

Unit 3 comprises small-volume (> 1.5 km³) base surge and ash-fall deposits that contain few pumice clasts, suggesting that the phreatomagmatic eruptions involved a high water/magma ratio (Tomiya et al., 2001; Yamamoto, 2001). The high water/magma ratio can be explained by a decrease in the eruption force in response to the emptying of the magma chamber, and/or vent migration toward a water-rich area. We favor the former explanation, as unit 3 (> 1.5 km³) is much smaller in volume than unit 2 (> 27.2 km³). Unit 3 does not contain large lithic clasts, and we therefore infer that caldera collapse did not occur during the eruption of unit 3.

6 Formation of Toya caldera

Our new geological data and interpretation allow reconstruction of the evolution of the caldera-forming eruption at Toya caldera (Fig. 18). (1) The caldera-forming eruption commenced with small-scale phreatomagmatic eruptions (that produced unit 1; Fig. 18A). A lake is assumed to have existed in the vent area at this time. (2) Subsequent violent phreatomagmatic eruptions occurred, generating large-scale pyroclastic flows (unit 2; Fig. 18B). The eruption of unit 2 was the largest among the caldera-forming eruptions and probably played an important role in emptying the underlying magma chamber. (3) The eruption then waned, and a number of small-scale phreatomagmatic eruptions occurred repeatedly and generated pulses of base surges (unit 3; Fig. 18C). This can be attributed to the reduced magma volume within the magma chamber. (4) Caldera subsidence then commenced with a magma-dominant phreatomagmatic eruption (unit 4; Fig. 18D). (5) Caldera collapse then reached a climax with a violent, magma-dominant phreatomagmatic eruption (unit 5; Fig. 18E). The magma chamber roof rocks (plutonic rocks, sedimentary rocks, rhyolites, and andesites) were largely destroyed during this eruption phase. (6) The caldera-forming
Fig. 18  Schematic model for the formation of Toya caldera. (A) The caldera-forming eruption started with a phreatomagmatic explosive eruption that produced fine-grained ash (unit 1). (B) A large phreatomagmatic eruption generated a voluminous pyroclastic flow (unit 2). (C) Phreatomagmatic eruptions occurred repeatedly, generating basal surges (unit 3). (D) Caldera collapse started with a magma-dominant phreatomagmatic eruption (unit 4). (E) Caldera collapse reached a climax with a large-scale, magma-dominant phreatomagmatic eruption (unit 5). (F) A magmatic eruption occurred during the last stage of caldera collapse (unit 6).
eruption ended with a magmatic eruption (unit 6; Fig. 18F). The volcanic eruptions producing units 1 to 6 occurred continuously without any significant time breaks. There was no significant change in magma composition during the caldera-forming eruption, although slightly mafic magma (characterized by high Mg and Fe, and low K) was involved during the latest stage. We suppose that the magma chamber beneath Toya caldera was compositionally zoned (cf., Hildreth and Wilson, 2007).

VIII. Conclusions

The Toya Ignimbrite (< 80 m thick) comprises six stratigraphic units: (1) initial fallout ash; (2) a base surge and a pumiceous pyroclastic flow deposit; (3) base surge and ash-fall deposits; (4) pumiceous pyroclastic flow deposit that contains large lithic clasts; (5) pumiceous pyroclastic flow deposit that has a basal lithic-rich layer (lag breccia); and (6) a pumiceous pyroclastic flow deposit that has a thin basal lithic-rich layer. All units (1–6) are rhyolitic in composition. No soil layers or reworked deposits occur between the units. Interpretations of these stratigraphic units suggest that the caldera-forming eruption at Toya caldera commenced with an explosive phreatomagmatic eruption (forming unit 1), followed by large-scale phreatomagmatic eruptions that generated voluminous pyroclastic flows (unit 2). The eruptive activity then temporarily weakened, and a number of base surges were generated (unit 3). The next phreatomagmatic eruption triggered caldera collapse (unit 4), and a large-scale phreatomagmatic eruption occurred during the climax of caldera collapse (unit 5). The caldera-forming eruption ended with a magmatic eruption (unit 6). These eruptions occurred continuously without any significant time breaks. There was no significant change in magma composition during the eruptions, although slightly mafic magma was involved during the final stage.

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北海道南西部，洞爺火砕流堆積物の層序と岩相記載

---洞爺カルデラの形成過程---

後藤 芳彦* 鈴木 一也* 新谷 考志*
山内 敦 貴* 三好 正晃*
檀 原 徹** 東宮 昭彦***

北海道洞爺カルデラは日本有数の陥没カルデラである。われわれは洞爺カルデラの形成過程を明らかにするため、洞爺火砕流堆積物（Toya Ignimbrite）の地質層序学的調査を行った。洞爺火砕流堆積物（層厚 80 〜 100 m）は、岩相の違いにより 6 つのユニット（ユニット 1 〜 6）に区分できる。最下位のユニット 1 は細粒な火山灰からなり、マグマ水蒸気噴火により形成された。ユニット 2 は火山豆石に富む厚い火砕流堆積物と火砕サージ堆積物からなり、大規模なマグマ水蒸気噴火により形成された。ユニット 3 は多数の薄いベースサージ堆積物とそれに伴う降下火砕堆積物からなる。ユニット 4 は小規模な火砕流堆積物からなり、粒径の大きな石質岩片（径 < 50 cm）を含む。ユニット 5 は軽石に富む厚い火砕流堆積物からなり、下部にラグブレッチャ（粒径 < 3 m）を伴う。ユニット 6 は軽石に富む火砕流堆積物からなる。ユニット 1 〜 6 は土壌層や再堆積相を挟在しない。したがって、洞爺火砕流堆積物は洞爺カルデラの形成時間間隙のない一連の噴火で形成されたと考えられる。各ユニットの組織、構成物、体積、石質岩片の岩相種などから、カルデラ陥没はユニット 4 の噴火で開始し、ユニット 5 の噴火でクライマックスに達した可能性が高い。ユニット 1 〜 6 の軽石はすべて流紋岩質であり、一連の噴火はほぼ一定の組成のマグマ噴出により行われた。ユニット 6 はやや苦鉄質な軽石を含むことから、噴火の最末期にはやや苦鉄質なマグマも噴出したと考えられる。

キーワード：カルデラ噴火，洞爺カルデラ，火砕流堆積物，層序，岩相

* 室蘭工業大学くらし環境系領域
** 京都フィッション・トラック
*** 産業技術総合研究所（AIST）地質調査総合センター