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Geology and Evolution of the Nakajima Islands (Toya Caldera, Hokkaido, Japan) Inferred from Aerial Laser Mapping and Geological Field Surveys

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Aerial high-resolution laser-scanner mapping and geological field surveys were performed over the Nakajima Islands within Toya caldera, southwestern Hokkaido, Japan, to study the evolutional history of the islands. The laser-scanner mapping survey covered the entirety of the Nakajima Islands, an area of 3×3 km. A three-dimensional digital map produced from the laser-scanning data revealed detailed topographic features of the islands. Geological field surveys were carried out over the whole area of the Nakajima Islands, to determine how their topography relates to the geological and lithological features. These surveys suggest that the islands consist of a tuff cone, eight lava domes, and a cryptodome. The tuff cone has a low profile and wide crater and consists of dacitic pyroclastic deposits, suggesting that the cone was produced by explosive eruptions resulting from the interaction of dacitic magma and groundwater. The lava domes are conical or pancake-shaped and composed of dacitic to andesitic lavas, suggesting that the domes formed by extrusions of high-viscosity, dacitic to andesitic magmas. The cryptodome consists of coherent dacite overlain by mudstone and sandstone, suggesting that the dome formed by the uplift of caldera-floor deposits following the intrusion of high-viscosity dacitic magma. Mudstones and sandstones are present along the northeastern and southwestern parts of the islands, implying that the caldera floor was uplifted during or prior to the volcanism, forming a bulge (small resurgent dome) at the center of the caldera. We infer that the Nakajima Islands have evolved from caldera resurgence related to the ascent of voluminous dacitic to andesitic magma, followed by subsequent formation of multiple dacitic to andesitic domes and phreatomagmatic eruptions on the resurgent dome.
Key words: laser-scanner mapping, geology, Nakajima Islands, Toya caldera, evolutional history

1. Introduction

LIDAR (light detection and ranging) is a powerful tool for those studying the morphological features of volcanoes (*e.g.*, Chiba *et al.*, 2007a, 2007b; Hunter *et al.*, 2003; Pesci *et al.*, 2007). Three-dimensional digital mapping based on high-resolution laser-scanning data provides invaluable information on the distribution and morphology of craters, lavas, domes, and pyroclastic deposits, as well as reworked deposits. Laser-scanner mapping is particularly useful for surveying topographic features in thickly vegetated areas, for which 'tree-removing' data filtering can be used to reveal the topography of the ground surface (Chiba *et al.*, 2007b; Goto *et al.*, 2011).

We conducted aerial laser-scanner mapping and geological field surveys over the Nakajima Islands within Toya caldera, southwestern Hokkaido, Japan (Fig. 1), to study the morphological and geological features of the islands. The Nakajima Islands are a silicic volcanic complex produced by post-caldera volcanism (Katsui, 1990; Ota, 1956; Soya *et al.*, 2007; Ui *et al.*, 2013; Yokoyama *et al.*, 1973), but their detailed geology remains unknown because it is obscured by the thick vegetation cover (Fig. 2). Three-dimensional digital mapping based on the laser-scanning data allowed us to study the detailed topographic features of the islands, and use them as the basis for understanding their geology. This paper describes the topographic and geological features of the Nakajima Islands and discusses the evolutional history of the islands.

2. Nakajima Islands

The Nakajima Islands are located in the central part of Toya caldera (Fig. 1). The caldera covers an area of 10×11 km, and was formed by violent silicic eruptions at approximately 110 ka (Ganzawa *et al.*, 2007; Machida and Arai, 2003; Okumura and Sangawa, 1984; Takashima *et al.*, 1992; Yokoyama *et al.*, 1973). The caldera-forming eruptions generated large-volume, rhyolitic, pyroclastic fall (Machida and Arai, 2003), and flow (Yokoyama *et al.*,

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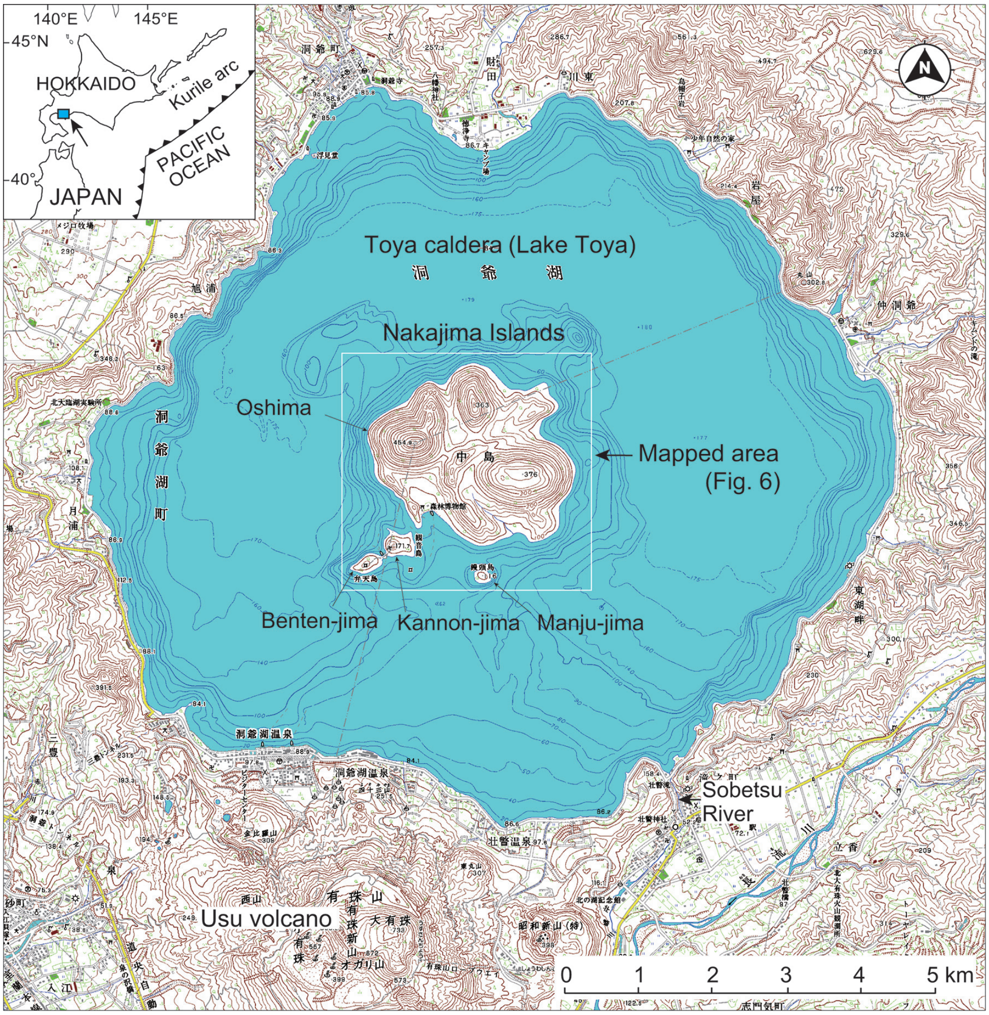

Fig. 1. Location map of the Nakajima Islands in Toya caldera, southwestern Hokkaido, Japan. The survey area (see Fig. 6) is shown by the rectangle. The location of Usu volcano is also shown. The base map was taken from the 1 : 50,000 scale topographic map *Toyako-onsen* issued by the Geospatial Information Authority of Japan (GSI). The topographic contour interval is 20 m.

1973) deposits around the caldera. The Toya caldera holds a freshwater lake (Lake Toya), which occupies the entire caldera floor (*i.e.*, 10×11 km) and has a maximum depth of 180 m. The water level of Lake Toya is 84 m above sea level (a.s.l.).

The Nakajima Islands comprise four islands: Oshima (2.5×2.8 km), Kannon-jima (380×430 m), Benten-jima (300 × 450 m), and Manju-jima (180 × 230 m; Fig. 1). Oshima Island is the largest, and its highest point is 370 m above the lake level (454 m a.s.l.). Thermoluminescence (TL) dating of lavas on the islands suggests that they formed 40–45 ka (Takashima *et al*., 1992). The Nakajima Islands host no active fumaroles, and their surfaces are widely covered with thick vegetation, mainly broadleaf trees (Fig. 2A).

A bathymetric map of Lake Toya (Fig. 3) suggests that the Nakajima Islands lie on a submerged rise that has an irregular morphology. A reef located 750 m northeast of Oshima Island (Fig. 3) consists of dacitic lava blocks, which suggests that it is a submerged lava dome (Ota, 1956; Tanakadate, 1918).

3. Laser-scanner mapping survey

The laser-scanner mapping survey covered the whole of the Nakajima Islands, encompassing an area extending 3 km N–S and 3 km E–W (Fig. 1). The survey was carried out by Tanaka Consultant Co. Ltd, using a Develo LISA3 instrument (Fig. 4). Under typical conditions, the scanner

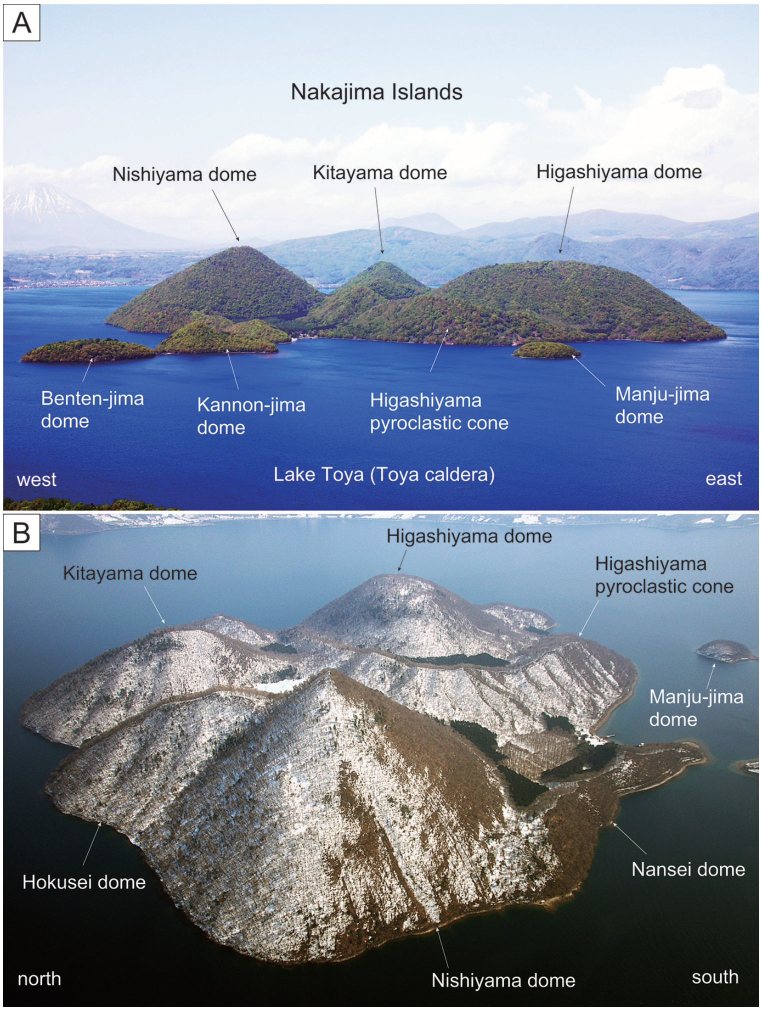

Fig. 2. (A) View of the Nakajima Islands from the south. (B) Oblique aerial photograph of Oshima Island from the west. The photograph was taken from a helicopter during the laser-scanner survey on 13 March 2011, when the islands had a thin covering of snow (<30 cm thick).

is able to measure distances of up to 1000 m with an accuracy of ±10 mm (Table 1). The lightweight instrument (Fig. 4B) can be mounted on an airplane, a manned helicopter, or a radio-controlled helicopter. In the present survey, the LISA3 was mounted on a manned Robinson R44 helicopter (Fig. 4A).

The survey was performed on 13 March 2011. The considerations involved in setting the date of the survey were: (1) the timing (between the end of leaf fall and the onset of leaf budding to minimize tree noise); (2) good ground conditions (little or no snow cover); (3) the number of available GPS NAVISTAR satellites (to minimize positioning error); and (4) good flight conditions. On 13 March, the broadleaf trees on the Nakajima Islands were bare, and the weather was fair. The ground was thinly covered with snow (<30 cm; Fig. 2B).

Fig. 5 shows the helicopter flight route of the laser-scanner mapping survey. The helicopter flew at a height between 400 and 750 m above the lake level (*i.e.*, 484–834 m a.s.l.), and remained about 400 m above the ground surface over the Nakajima Islands. The measurement duration was 1 h (11:30–12:30 local time). The position of the helicopter was recorded at 1-s intervals using a Global Positioning System (GPS) and at 0.01-s intervals using an inertial measurement unit (IMU). After the flight, the three-dimensional flight route was reconstructed from the GPS and IMU data.

The laser-scanning data were cleaned to remove noise and then filtered to produce a digital terrain model (DTM), which shows the bare ground surface. As part of the

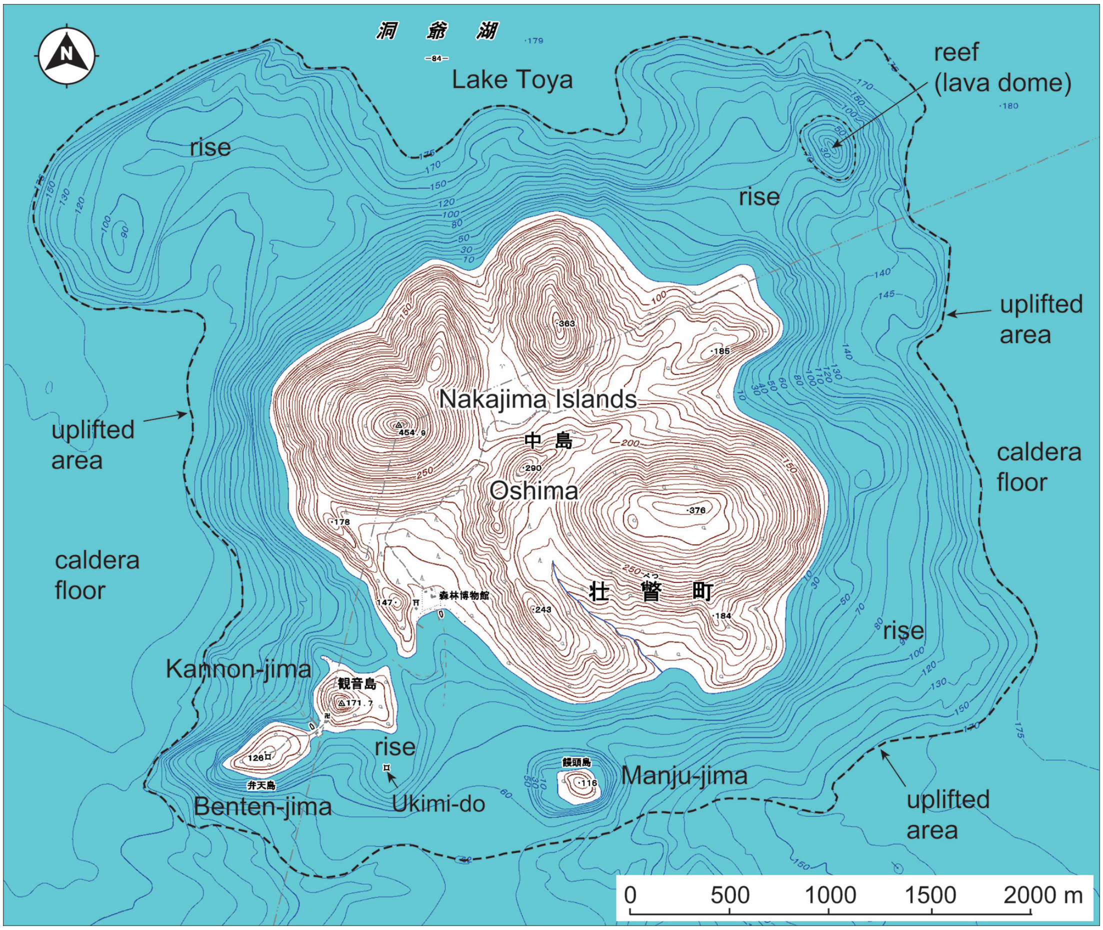

Fig. 3. Bathymetric map around the Nakajima Islands. The uplifted area is outlined by a dashed line. The location of a submerged lava dome (reef) is also shown. The base map was taken from the 1 : 25,000 scale topographic map *Toya* issued by the Geospatial Information Authority of Japan (GSI). The topographic contour interval is 10 m.

filtering process, trees and buildings were carefully removed using the TerraScan application (Terrasolid Co. Ltd). Both automatic and handpicking methods were used during this process to avoid the unintentional removal of useful information. The automatic method was applied to the whole survey area, whereas the handpicking method was applied to local bumpy areas. No correction was made for the snow on the ground; therefore, the DTM includes the thickness of the snow. As the snow was <30 cm thick, it did not adversely influence the mapping results.

After filtering, a triangulated irregular network (TIN) was produced from the ground data. The size of the TIN (*i.e.*, one side of the triangle) was 1–2 m. The TIN was then converted to grid elevation data (grid size of 1 × 1 m) using the linear-approximation interpolation method. The applications TerraScan and Terramodel (Terrasolid Co. Ltd) were used for this conversion. Finally, a three-dimensional, digital topographic map was produced from the grid elevation data (Fig. 6).

The map (Fig. 6) has contour lines with 2-m intervals, which allows the angle of inclination of the ground surface to be expressed by shading: gentle slopes appear pale grey, whereas steep slopes appear dark grey. Compared with previous topographic maps at scales of 1 : 50,000 (Fig. 1) or 1 : 25,000 (Fig. 3), this new digital topographic map (Fig. 6) has a much higher resolution and allows detailed investigation of the topography to aid geological interpretations (Fig. 7).

The digital topographic map (Fig. 7) shows that the northern slopes of volcanoes on the islands generally have rough surfaces, whereas the southern slopes have smooth surfaces (*e.g.*, the Higashiyma and Nishiyama domes). This difference reflects real topography. Field surveys revealed that the northern slopes of the volcanoes commonly have small U-shaped gullies (5–20 m wide, 20–40 m long, 5–10 m deep), whereas the southern slopes are covered

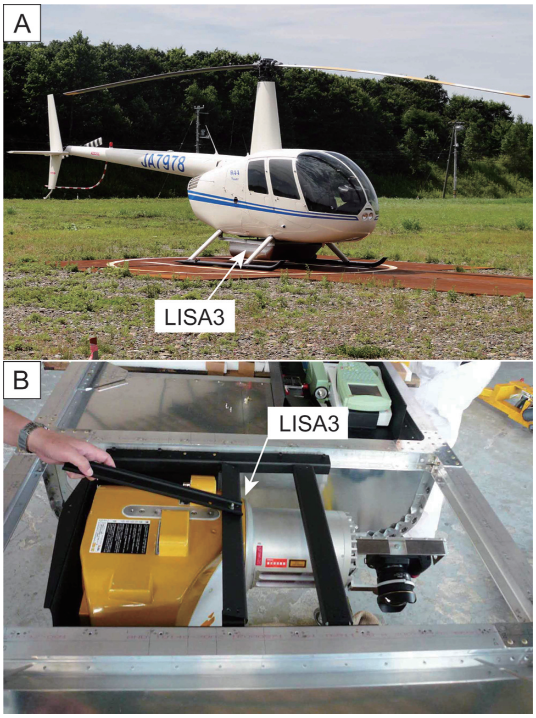

Fig. 4. (A) Photograph of the LISA3 instrument mounted on a manned helicopter. (B) Close-up photograph of the LISA3 instrument.

Table 1. Specifications of the Develo LISA3 laser scanner.

Laser scannar (Develo LISA3)	
Laser class	Class 1
Measuring distance	Maximum 1000 m
	Minimum 2 m
Accuracy	±10 mm
Measuring rate	8333 points/second
Laser frequency	Near-infrared light
Beam divergence	0.25 mrad
Scanning range	80° (vertical), 360° (horizontal)
Line number	1–20/second
Weight	25 kg (without battery)

The laser class is based on the safety classification of laser devices according to Japan Industrial Standard (JIS) C6802. Note that the beam divergence of the LISA3 is 0.25 mrad (*i.e.*, a beam diameter of 25 mm at a distance of 100 m).

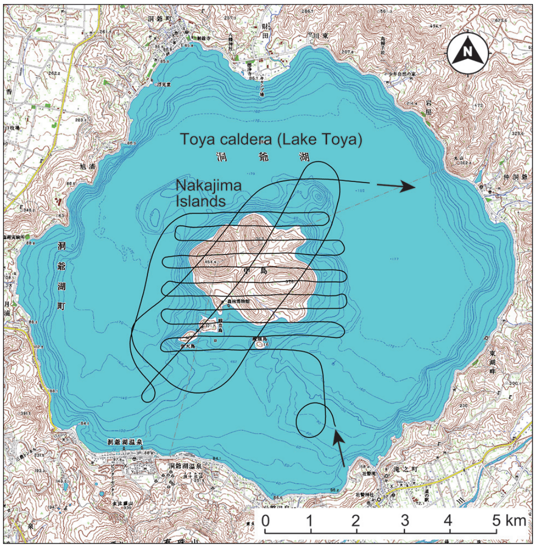

Fig. 5. Flight route of the helicopter for the laser-scanner mapping survey. The arrows indicate the flight directions of the helicopter.

with thick surface soil and lack such gullies. We infer that the gullies on the northern slopes formed in response to erosion by snow (or ice).

Oblique, three-dimensional images of the islands from various viewpoints were also produced from the grid elevation data (Fig. 8). These images are visually superior to the topographic map, and helped to improve our understanding of the three-dimensional morphology of volcanic edifices.

4. Geological field surveys

Geological field surveys of the Nakajima Islands (Oshima, Kannon-jima, Benten-jima, and Manju-jima) were performed from October 2010 to September 2014. Detailed field investigations were conducted along the lakeshore, ridges, and valleys, as well as on the peaks of the islands. We found several outcrops of dacitic to andesitic lavas, dacitic pyroclastic deposits, and mudstones from the islands (Fig. 9; locations are shown in Fig. 7). The sizes of these outcrops vary from 1 × 1 m to 5 × 20 m. Rock samples were collected from these outcrops. For the field sites where no outcrops were found (*e. g.*, the Hokusei and Kitayama domes; Fig. 7), rock samples were collected from relatively large (>50 cm in size) angular rocks scattered on the surface. Petrographical observations and whole-rock major-element chemical analysis were also performed on the rock samples (Tables 2 and 3).

A lake-bottom geological field survey was also carried out 150 m southeast of Kannon-jima Island (Ukimi-do; Fig. 3) in June 2012, using a small manned boat. We found an outcrop of volcanic sandstone and mudstone (larger than 10 × 20 m in area) at a water depth of 1 m. Rock samples of the volcanic sandstone and mudstone (each 10–20 cm in size) were collected from the lake bottom using a hand rake (described in section 13).

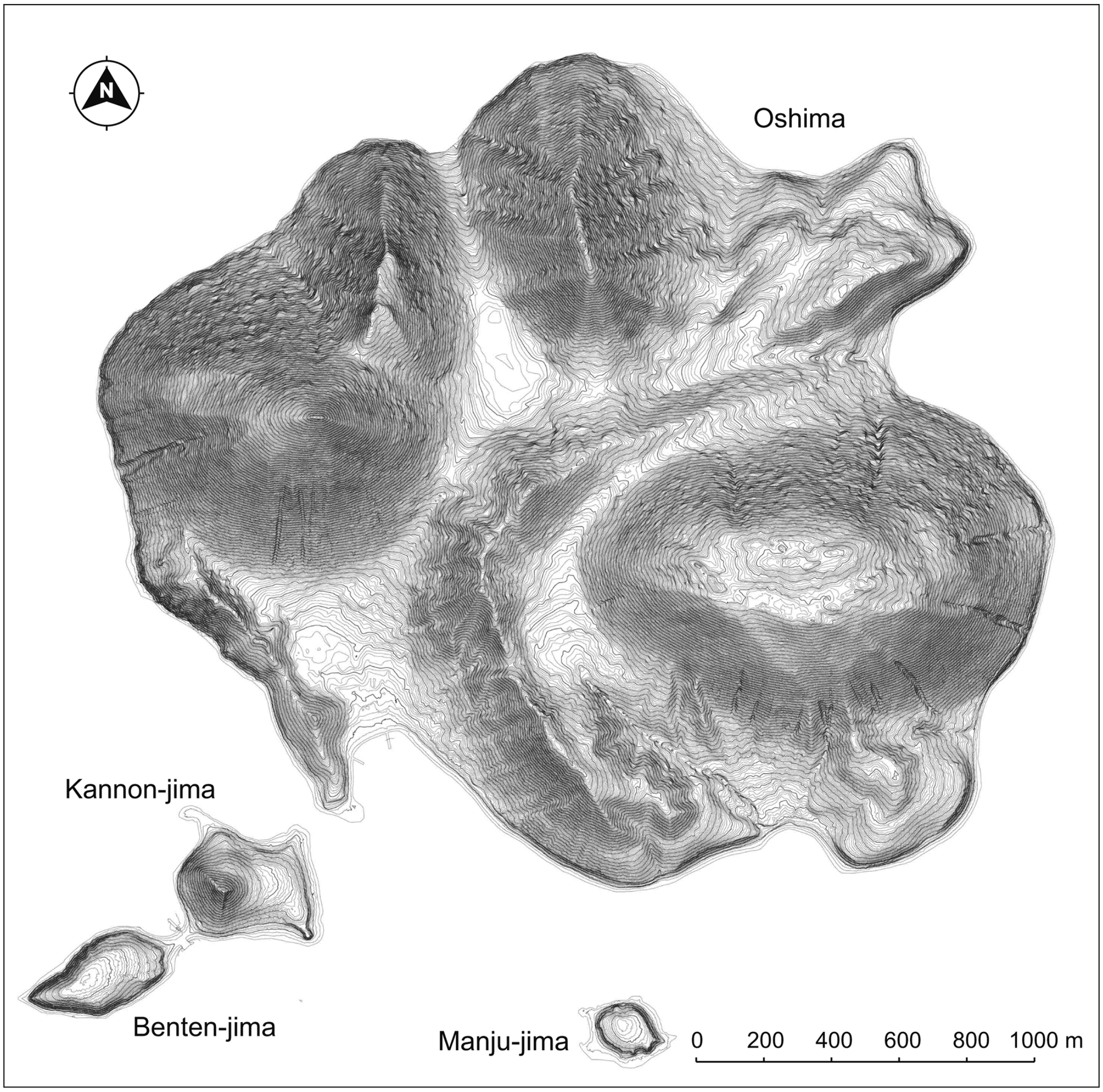

Fig. 6. Three-dimensional digital topographic map of the Nakajima Islands generated from the aerial laser-scanner mapping survey. The topographic contour interval is 2 m.

5. Topographic and geological features of the Nakajima Islands

The three-dimensional digital topographic map (Fig. 6) and images (Fig. 8) reveal the detailed topographic features of the Nakajima Islands (Fig. 7). The notable features are a pyroclastic cone (Higashiyama), eight lava domes (Higashiyama, Nishiyama, Hokusei, Kitayama, Nansei, Kannon-jima, Benten-jima, and Manju-jima), and a cryptodome (Hokutou-misaki). These features, and their interpretations, along with the results of the geological field survey, are described in the following sections and summarized in Table 2. We named each of the volcanic edifices identified in this study following local geographical names.

6. Higashiyama pyroclastic cone

The Higashiyama pyroclastic cone, located in the southeast of Oshima Island (Fig. 7), is elliptical in plan view, ranging in basal diameter from 1500 m (N–S) to 2200 m (E–W). In east–west cross section, it has a low profile with the highest point being 206 m above the lake level (Fig. 8A). The cone has a large-diameter crater, which is 1400–2000 m across (elongated E–W) and open to the east. Its crater floor is flat and mostly occupied by a lava dome (Higashiyama dome). The cone largely retains its primary morphology except for a missing section of the eastern part. The outer slope of the cone is slightly eroded and has radial gullies and a horizontal terrace (Figs. 7 and

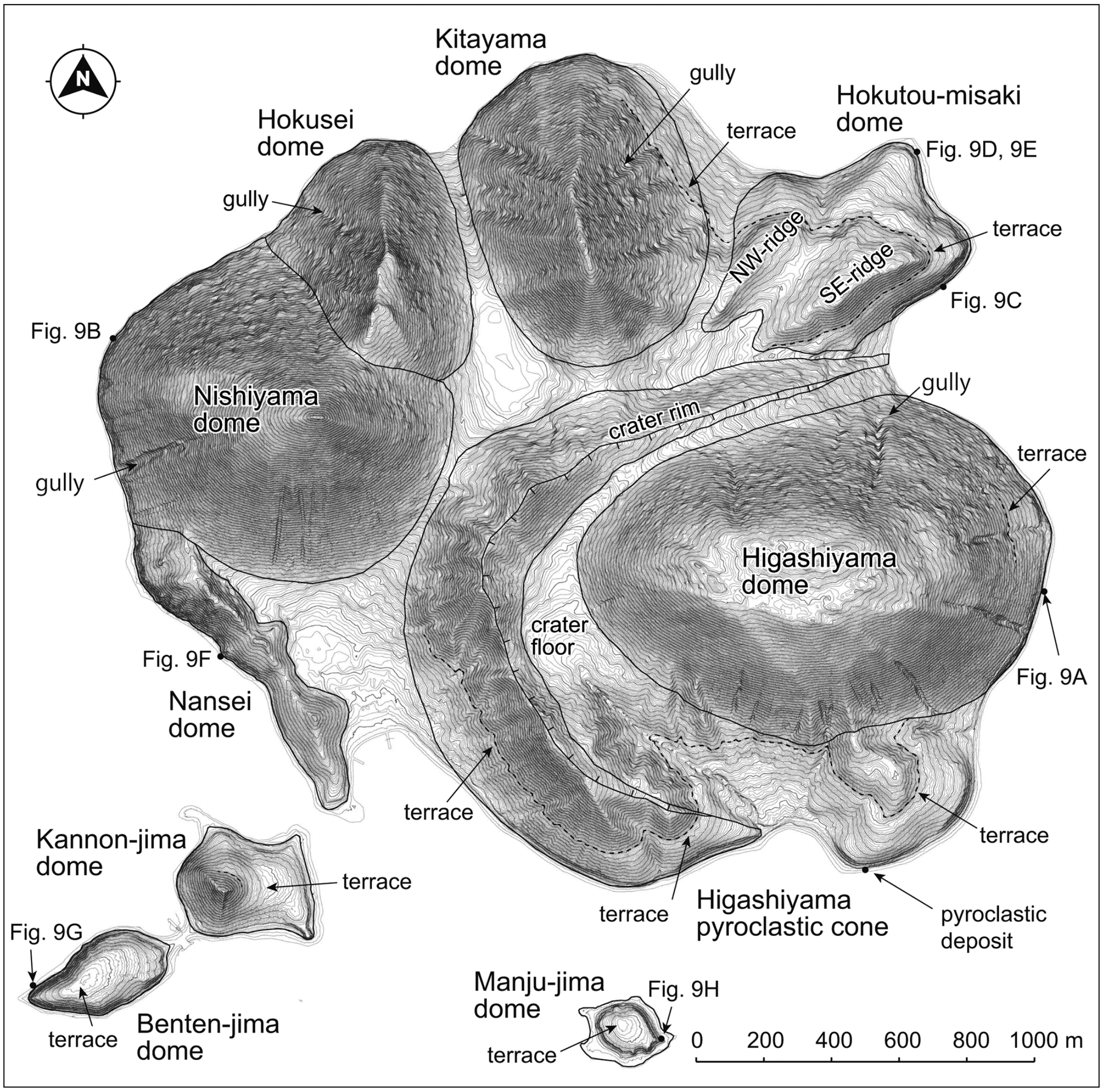

Fig. 7. Interpretation of the map shown in Fig. 6. Bold lines show the boundaries of the volcanic edifices. Dashed lines indicate the location of the horizontal terrace (56 m above the lake level). The locations of Fig. 9A–H, and an outcrop of pyroclastic deposit at the Higashiyama pyroclastic cone are also shown.

8A). The horizontal terrace occurs at 56 m above the lake level (140 m a.s.l.), and overprints the radial gullies (Fig. 7). The northern slope of the cone partially covers the Hokutou-misaki dome, suggesting the cone formed after the dome. A lobate mound at the southeastern tip of Oshima Island (pyroclastic deposit in Fig. 7) is inferred to be a remnant of the crater floor of the Higashiyama pyroclastic cone, because the mound has similar morphological features observed along the southern part of the Higashiyama pyroclastic cone (both have a well-developed terrace at 56 m above the lake level).

Field surveys suggest that the outer slope of the Higashiyama pyroclastic cone has no outcrops. The outer slope of the cone is covered with humus soil, and scattered dacitic lava blocks, which are up to 2 m in size. The dacitic lava blocks are composed of grey, poorly vesicular dacite and minor pale grey, vesicular dacite. The poorly vesicular dacite contains phenocrysts of plagioclase, hornblende, hypersthene, quartz, opaque minerals, and minor augite, whereas the vesicular dacite contains phenocrysts of plagioclase, hornblende, hypersthene, quartz, and opaque minerals. The horizontal terrace is 5–20 m wide, and covered with a thick soil.

The field surveys also suggest that the crater floor of the

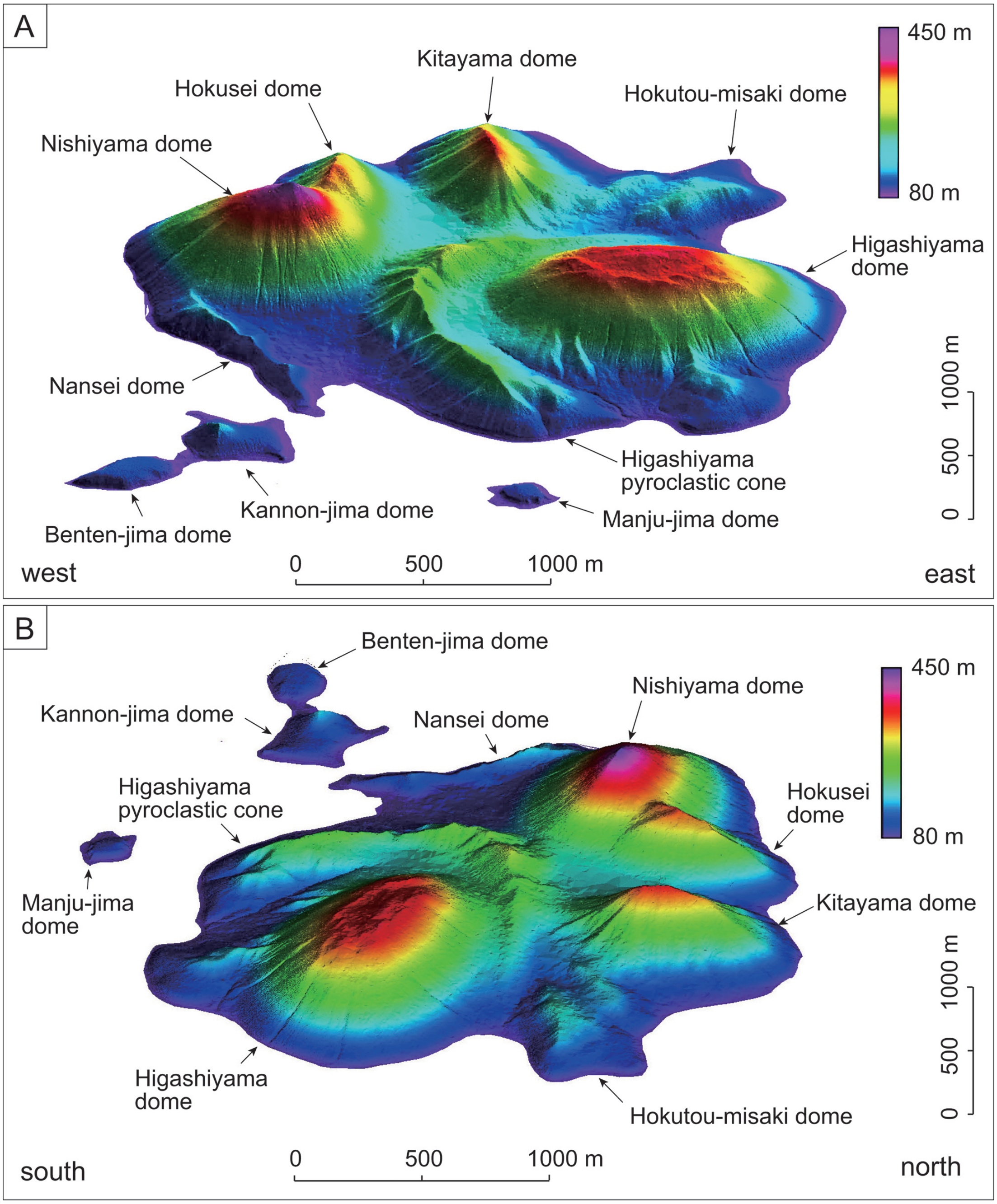

Fig. 8. Oblique three-dimensional digital images, produced by laser-scanner survey, of the Nakajima Islands viewed from the south (A) and east (B).

Higashiyama pyroclastic cone consists of pyroclastic deposits. A dacitic pyroclastic deposit occurs at the lakeshore of the lobate mound (pyroclastic deposit in Fig. 7). The deposit is pale reddish grey and composed of pale grey, vesicular dacite clasts (<50 cm in size) and minor grey, poorly vesicular dacite clasts (<50 cm in size) set in a coarse- to fine-grained matrix. The vesicular dacite (probably juvenile pyroclasts) contains phenocrysts of plagioclase, hornblende, hypersthene, quartz, and opaque minerals (65–66 wt.% SiO_2; Table 3). The matrix of the

Table 2. Properties of volcanic edifices on the Nakajima Islands.

Name	Diameter (m)	Height (m)	Volume (m^3)	Lithology (phenocryst assemblage)	Interpretation
Higashiyama pyroclastic cone	1500–2200	206	1.7×10^8	dacite (Pl, Ho, Opx, Qz, Opq, ±Cpx)	tuff cone
Higashiyama dome	1000–1350	292	1.4×10^{10}	dacite (Pl, Ho, Opx, Cpx, Opq)	lava dome
Nishiyama dome	900–1050	370	9.2×10^8	dacite (Pl, Ho, Opx, Opq)	lava dome
Hokusei dome	500–800	256	3.2×10^7	dacite (Pl, Ho, Opx, Qz, Opq)	lava dome
Kitayama dome	600–900	279	4.1×10^7	dacite (Pl, Ho, Opx, Qz, Opq)	lava dome
Hokutou-misaki dome	550–750	101	1.2×10^7	dacite (Pl, Ho, Opx, Opq), mudstone, sandstone	cryptodome
Nansei dome	200–900	94	3.6×10^6	dacite (Pl, Ho, Opx, Qz, Opq, ±Ol, ±Cpx)	lava dome
Kannon-jima dome	380–430	88	3.7×10^6	andesite (Pl, Ho, Opx, Opq)	lava dome
Benten-jima dome	250–500	42	3.3×10^6	dacite (Pl, Ho, Opx, Qz, Opq, ±Cpx)	lava dome
Manju-jima dome	350–450	82	6.1×10^6	andesite (Pl, Ho, Opx, Qz, Cpx, Ol, Opq)	lava dome

The height is relative to the lake level. The volume of each volcanic edifice was calculated by approximating each to a polyhedron above the lake level. The height and volume of Manju-jima dome is relative to the lake bottom. Abbreviations: Pl, plagioclase; Ho, hornblende; Opx, orthopyroxene; Qz, quartz; Cpx, clinopyroxene; Ol, olivine; Opq, opaque minerals.

Table 3. Whole-rock major-element chemical compositions of volcanic rocks from the Nakajima Islands.

Name	Higashiyama pyroclastic cone	Higashiyama pyroclastic cone	Higashiyama dome	Higashiyama dome	Nishiyama dome	Hokusei dome
Sample No.	NJ-03-L2A	NJ-03-L2B	NJ-01	NJ-02	NJ-34	NJ-32
SiO_2 (wt. %)	65.80	64.61	63.65	63.09	64.06	62.81
TiO_2	0.52	0.55	0.64	0.64	0.61	0.67
Al_2O_3	15.96	16.02	16.09	16.36	16.13	16.87
Fe_2O_3*	5.44	5.83	6.60	6.66	6.37	6.91
MnO	0.14	0.15	0.18	0.19	0.17	0.17
MgO	1.86	2.00	2.05	2.04	1.96	2.17
CaO	4.99	5.09	5.53	5.56	5.63	5.93
Na_2O	3.63	3.64	3.66	3.57	3.38	3.37
K_2O	1.34	1.36	1.00	0.99	0.92	0.84
P_2O_5	0.11	0.11	0.14	0.14	0.14	0.15
Total	99.80	99.38	99.54	99.24	99.37	99.89
L.O.I.	1.14	1.25	-0.04	0.07	-0.06	0.15

Name	Kitayama dome	Hokutou-misaki dome	Nansei dome	Kannon-jima dome	Benten-jima dome	Manju-jima dome
Sample No.	NJ-31	NJ-80	NJ-37	KJ-03	BJ-02	MJ-03
SiO_2 (wt. %)	64.61	64.44	65.90	60.23	64.00	59.01
TiO_2	0.62	0.59	0.51	0.69	0.55	0.68
Al_2O_3	16.25	16.06	16.12	16.66	16.12	17.32
Fe_2O_3*	6.56	6.36	5.56	8.34	6.22	7.34
MnO	0.15	0.15	0.13	0.18	0.15	0.16
MgO	2.07	1.98	1.92	2.78	2.24	4.13
CaO	5.53	5.46	5.09	6.45	5.55	7.23
Na_2O	3.28	3.26	3.32	3.23	3.36	3.01
K_2O	1.05	1.07	1.24	0.82	1.10	1.00
P_2O_5	0.12	0.11	0.08	0.11	0.10	0.15
Total	100.24	99.48	99.87	99.49	99.39	100.04
L.O.I.	0.00	-0.04	0.63	0.04	0.14	1.22

Compositions were determined by X-ray fluorescence (Rigaku RIX-2000) at Shimane University, Japan, following Kimura and Yamada (1996). $Fe_2O_3^*$ = total iron as Fe_2O_3. L. O. I. = loss on ignition.

deposit is inhomogeneous and consists of crystals of plagioclase, hornblende, hypersthene, quartz, opaque minerals, and blocky-shaped volcanic glass. This deposit may be debris from primary dacitic pyroclastic deposits.

The morphology and components of the Higashiyama pyroclastic cone suggest that it is a tuff cone or tuff ring (Cas and Wright, 1987; Vespermann and Schmincke, 2000) produced by phreatomagmatic explosions resulting from

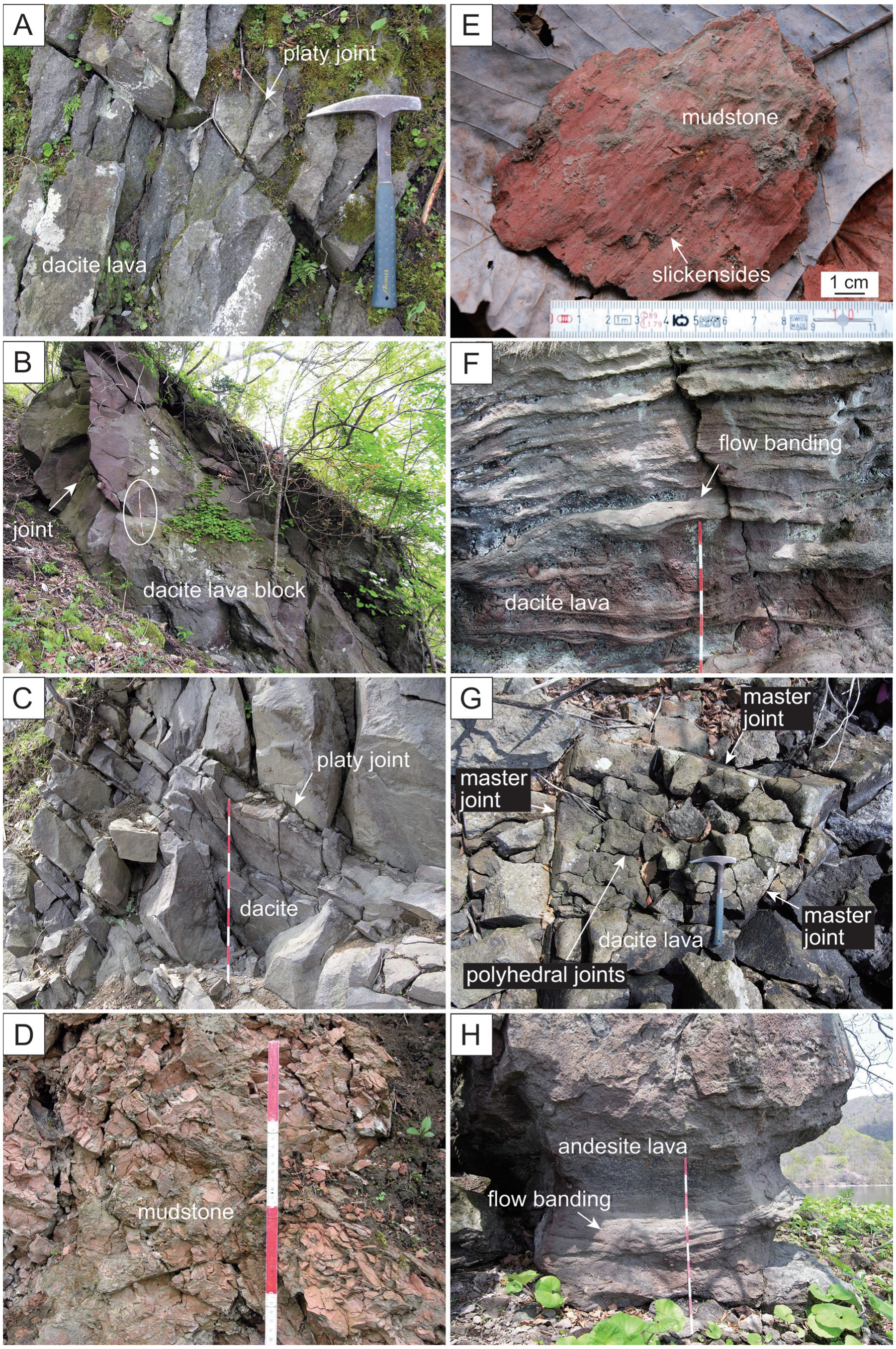

Fig. 9. Field photographs showing the lithofacies of volcanic domes on the Nakajima Islands. (A) Dacite lava of the Higashiyama dome. The hammer is 33 cm long. (B) Large dacite lava block (20 m in size) of the Nishiyama dome. The scale ruler (in the white circle) is 1 m long. (C) Coherent dacite of the Hokutou-misaki dome. The scale ruler is 1 m long. (D) Indurated mudstone of the Hokutou-misaki dome. The red and white segments of the scale ruler are 10 cm long. (E) Indurated mudstone showing slickensides from the Hokutou-misaki dome. (F) Flow-banded dacite lava of the Nansei dome. The red and white segments of the scale ruler are 10 cm long. (G) Polyhedral-jointed dacite lava of the Benten-jima dome. The hammer is 33 cm long. (H) Flow-banded andesite lava of the Manju-jima dome. The scale ruler is 1 m long. The locations of Fig. 9A–H are shown in Fig. 7.

the interaction of magma and groundwater. Such activity is to be expected because the Nakajima Islands are located within the Toya caldera, which is filled with water. We infer that the Higashiyama pyroclastic cone formed during the late stages of activity on the Nakajima Islands, as the cone largely retains its primary morphology. The horizontal terrace on the cone may have formed by erosion following a rise in the lake water level after formation of the cone.

7. Higashiyama dome

The Higashiyama dome, located within the Higashiyama pyroclastic cone (Fig. 7), is elliptical in plan view, ranging in basal diameter from 1000 m (N–S) to 1350 m (E–W). In east–west cross section, the dome has a flat top with steeply sloping sides, and rises 292 m above the lake level (Fig. 8A). The dome retains its primary morphology except for the presence of several narrow gullies on the sides, and an indistinct horizontal terrace at 56 m above the lake level (Fig. 7).

Field surveys revealed that the dome consists of massive dacite with platy joints spaced at intervals of 5–30 cm (Fig. 9A). The dacite is grey, non-vesicular, and contains phenocrysts of plagioclase, hornblende, hypersthene, opaque minerals, and minor augite (63–64 wt.% SiO_2; Table 3).

The morphology and chemical composition of the Higashiyama dome suggest that it was produced by extrusion of high-viscosity dacitic magma. The low degree of erosion suggests that the dome was emplaced during the late stages of activity at the Nakajima Islands. The dome and the Higashiyama pyroclastic cone probably comprise a ‘tuff cone-dome complex’ that was produced by progressive activity that began with phreatomagmatic explosions and ended with the effusive emplacement of the lava dome, as commonly reported in water-rich environments (Zimmer *et al*., 2010).

8. Nishiyama dome

The Nishiyama dome, located at the western end of Oshima Island (Fig. 7), is almost circular in plan view, ranging in basal diameter from 900 m (N–S) to 1050 m (E–W). In cross section, it has a pointed top with steeply sloping sides, and rises 370 m above the lake level (Figs. 2B and 8A). The dome largely retains its primary morphology, except for the presence of several narrow gullies (Fig. 7) and an indistinct horizontal terrace at 56 m above the lake level. The Nishiyama dome partly covers the Hokusei dome and the Nansei dome (Fig. 7).

Field surveys suggest that the Nishiyama dome has no exposures. The surface of the dome is covered with humus soil and a scattering of angular dacite lava blocks up to 10 m in size (mostly <2 m across; Fig. 9B). The dacite is reddish grey, poorly vesicular, and contains phenocrysts of plagioclase, hornblende, hypersthene, and opaque minerals (64 wt.% SiO_2; Table 3).

The morphology and chemical composition of the Nishiyama dome suggest it was produced by the extrusion of high-viscosity dacitic magma. The dome differs in morphology from the Higashiyama dome in terms of lacking a flat top. This difference may be attributed to the higher viscosity and/or smaller volume of lava at the Nishiyama dome. The low degree of erosion suggests that the Nishiyama dome was emplaced during the late stages of activity at the Nakajima Islands.

9. Hokusei dome

The Hokusei dome, located in the northwest of Oshima Island (Fig. 7), is elliptical in plan view, ranging in basal diameter from 500 m (E–W) to >800 m (N–S). In north–south cross section, it has a ridged top (elongated N–S) with steeply sloping sides, and rises 256 m above the lake level (Fig. 7). The dome has been moderately eroded, and gullies are developed on its surface (Fig. 7). It is unclear whether or not a horizontal terrace occurs at 56 m above the lake level. The southern part of the Hokusei dome is partly covered by the Nishiyama dome (Fig. 8B).

Field surveys suggest that the Hokusei dome has no outcrops. The surface of the dome is covered with humus soil and a scattering of angular to subangular, dacite lava blocks up to 1 m across. The dacite is reddish grey, poorly vesicular, and contains phenocrysts of plagioclase, hornblende, hypersthene, quartz, and opaque minerals (63 wt.% SiO_2; Table 3).

The morphology and chemical composition of the Hokusei dome suggest it was formed by the extrusion of high-viscosity dacitic magma. Judging from the degree of erosion, the Hokusei dome was emplaced during the early stages of activity at the Nakajima Islands. The Hokusei dome differs from the Nishiyama dome in phenocryst assemblage (*e.g*., quartz is present; Table 2) and degree of erosion, suggesting that they are independent domes that were emplaced during different stages of activity.

10. Kitayama dome

The Kitayama dome, located in the northern part of Oshima Island (Fig. 7), is elliptical in plan view, ranging in basal diameter from 600 m (E–W) to 900 m (N–S). In north–south cross section, it has a ridged top (elongated N–S) with steeply sloping sides, and rises 279 m above the lake level (Fig. 7). The dome has been moderately eroded, and radial gullies are developed on its surface (Fig. 7). The eastern and western slopes of the dome possess different morphologies. The eastern slope has a gentle foot with a horizontal terrace at 56 m above the lake level, whereas the western slope does not have a gentle foot. The eastern foot of the Kitayama dome grades to the Hokutou-misaki dome (Fig. 7).

Field surveys suggest that the Kitayama dome has no outcrops. The surface of the dome is covered with humus soil and angular to subangular dacite lava blocks up to 1 m across. The dacite is grey, poorly vesicular, and contains phenocrysts of plagioclase, hornblende, hypersthene, opaque minerals, and minor quartz (65 wt.% SiO_2; Table 3).

The morphology and chemical composition of the Kitayama dome suggest it was produced by the extrusion of high-viscosity dacitic magma. The eastern slope of the dome has a gentle foot with a horizontal terrace, implying that the eastern foot consists of relatively soft sediments. Therefore, the dome could be a partly extrusive cryptodome (McPhie *et al*., 1993) formed by the partial extrusion of dacite magma from a cryptodome. Judging from the degree of erosion, the Kitayama dome was emplaced during the early stages of activity at the Nakajima Islands. The Kitayama dome resembles the Hokusei dome in its degree of erosion and phenocryst assemblage, suggesting that these domes were emplaced during a similar stage of activity.

11. Hokutou-misaki dome

The Hokutou-misaki dome, located in the northeast of Oshima Island, has a unique morphology (Fig. 7), being amoeboid or semi-rectangular in plan view, ranging in basal diameter from 550 m (NW–SE) to $>$750 m (NE–SW). In north–south cross section, it gently rises 101 m above the lake level (Fig. 7). In detail, the dome comprises two broad ridges, both of which trend NE–SW (Fig. 7). The southeastern ridge is 650 m long, 300 m wide, and rises 101 m above the lake level. The ridge consists of a gentle northwestern slope that dips 5–20° (interpreted to form part of the original dome surface) and a steep southeastern slope that dips 40–45° (interpreted to be a fault surface). The southwestern part of this ridge is covered by the Higashiyama pyroclastic cone. The northwestern ridge is 450 m long, 150 m wide, and rises 91 m above the lake level. The ridge resembles the southeastern ridge in morphology, and consists of a gentle northwestern slope and steep southeastern slope. The western part of this ridge grades into the Kitayama dome. Both the southeastern and northwestern ridges have a horizontal terrace ($<$20 m wide) at 56 m above the lake level.

Field surveys revealed that the Hokutou-misaki dome consists of coherent dacite and mudstone. The dacite is exposed on the southeastern slope of the southeastern ridge (Fig. 9C; see the location in Fig. 7). Here, the dacite contains platy joints spaced at intervals of 10–80 cm (Fig. 9C). The dacite is grey and contains phenocrysts of plagioclase, hornblende, hypersthene, and opaque minerals (64 wt.% SiO_2; Table 3). The mudstone is exposed on the northwestern slope of the southeastern ridge (Fig. 9D; see the location in Fig. 7). Here, the mudstone ($>$ 5 m thick) overlies the coherent dacite ($>$2 m thick). The mudstone is reddish grey, massive, indurated, and in places contains slickensides on sheared planes (Fig. 9E). The mudstone consists of lithic fragments, crystals of plagioclase, quartz, hypersthene, trace hornblende, opaque minerals, and volcanic glass. The refractive index of the volcanic glass ranges from 1.4930 to 1.4952 (mean, 1.4941; mode, 1.494; number of grains measured, 30; as determined using an RIMS2000 instrument at Kyoto Fission-Track Co. Ltd), suggesting that the volcanic glass originated from the Toya pyroclastic flow deposits (Machida and Arai, 2003; Yokoyama *et al*., 1973). The mudstone is thus interpreted to have originated from the uplifted floor deposits of the Toya caldera. We have also found many pebbles of red indurated sandstone along the lakeshore. Therefore, the Hokutou-misaki dome probably consists of coherent dacite overlain by mudstone and sandstone.

The morphology and components of the Hokutou-misaki dome suggest it is a cryptodome (Minakami *et al*., 1951) formed by the uplifting of caldera-floor deposits following the intrusion of dacitic magma, or a partially extrusive cryptodome (McPhie *et al*., 1993) formed by the partial extrusion of dacite magma from a cryptodome. The indurated mudstone with slickensides (Fig. 9E) is interpreted to have formed by heating and shearing of the caldera-floor deposits caused by the intrusion of hot dacitic magma. Similar indurated mudstone with slickensides has been reported from the Showa-Shinzan cryptodome at Usu volcano, Japan ('natural brick'; Mimatsu, 1962). The asymmetric ridge morphology of the Hokutou-misaki dome could reflect hinge-like uplifting of the overlying sediment during dome growth. We infer that the faults (steep southeastern slopes) of the Hokutou-misaki dome were produced during the hinge-like dome growth. Similar hinge-like dome growth has been reported from the Usu–Shinzan cryptodome at Usu volcano, Japan (Katsui *et al*., 1985). The Hokutou-misaki dome probably formed during the early stages of activity, because it does not deform the Higashiyama pyroclastic cone.

12. Nansei dome

The Nansei dome, located in the southwest of Oshima Island (Fig. 7), exhibits a narrow ridge extending NW–SE (200 m wide, 900 m long, highest point 94 m above the lake level). The dome is severely eroded, and its primary morphology is poorly preserved. The highest point of the dome is located in its northwestern part. It is possible that the Nansei dome occurs above a feeder dyke oriented NW–SE. It is also possible, however, that the Nansei dome is a thick lava flow, whose flow direction was from northwest to southeast.

Field surveys revealed that the Nansei dome consists of a lower, flow-banded unit (Fig. 9F) and an upper, massive (non-flow-banded) unit. The lower flow-banded unit (Fig. 9F) is reddish grey and comprises alternating bands of highly vesicular dacite and poorly vesicular dacite, both of which contain phenocrysts of plagioclase, hornblende, hypersthene, quartz, and opaque minerals (66 wt.% SiO_2; Table 3). The upper unit consists of grey, poorly vesicular dacite that contains phenocrysts of plagioclase, hornblende, hypersthene, quartz, opaque minerals, and minor olivine and augite. The contact between the lower and upper units is not exposed. Field surveys on the ridge of the Nansei dome revealed that the dome has a small horizontal terrace at 56 m above the lake level (140 m a.s.l.).

The morphology and chemical composition of the Nansei dome suggest it was produced by the extrusion of high-viscosity dacitic magma. Judging from the degree of erosion, the Nansei dome was emplaced during the early stages of activity at the Nakajima Islands. The Nansei dome has been TL dated to 45±13 ka (Takashima *et al*., 1992). Ui *et al.* (2013) interpreted the Nansei dome to be a remnant pyroclastic cone that consists of pyroclastic surge deposits. However, they misinterpreted the lower flow-banded unit (Fig. 9F) as surge deposits; no pyroclastic deposits were observed at Nansei dome during our field surveys.

13. Kannon-jima dome

The Kannon-jima dome on Kannon-jima Island (Fig. 7) is elliptical in plan view, ranging in basal diameter from 380 m (N–S) to 430 m (E–W). In east–west cross section, the dome has a pointed top with gently sloping sides, and rises 88 m above the lake level (Fig. 8A). The dome has been severely eroded, and its primary morphology is poorly preserved. The dome has several subhorizontal terraces at 20–56 m above the lake level (Fig. 7), suggesting that the lake level rose after emplacement of the dome, causing erosion of the lower half of the dome. Field surveys revealed that the Kannon-jima dome comprises massive andesite with platy joints spaced at intervals of 50–200 cm. The andesite is grey, and contains phenocrysts of plagioclase, hornblende, hypersthene, and opaque minerals (60 wt.% SiO_2; Table 3).

The bathymetric map (Fig. 3) suggests that the Kannon-jima dome lies on a submerged rise that extends NW–SE. This rise has a flat top (450×900 m in area) located 1–5 m below the surface of the lake. On-ship field surveys 150 m southeast of the Kannon-jima dome (Ukimi-do; Fig. 3) revealed that the rise consists of volcanic sandstone and mudstone. The volcanic sandstone is brown, thinly bedded, and consists of mineral fragments (<3 mm) of plagioclase, quartz, augite, opaque minerals, and minor hornblende. The mudstone is brown, laminated, and possesses identical components to the sandstone. The sandstone and mudstone are gently dipping, although we were unable to accurately measure dips and strikes as these units were underwater. Previous studies have noted the presence of volcanic sandstone at the Kannon-jima dome (Katsui, 1990), which is consistent with our results.

The morphology and chemical composition of the Kannon-jima dome suggest it was produced by the extrusion of high-viscosity andesitic magma. The existence of volcanic sandstone and mudstone at the submerged rise near the dome suggests that the caldera floor was uplifted during or prior to formation of the lava dome. Judging from the degree of erosion, the Kannon-jima dome was emplaced during the early stages of activity at the Nakajima Islands.

14. Benten-jima dome

The Benten-jima dome, adjacent to the Kannon-jima dome, is elliptical in plan view, ranging in basal diameter from 250 m (N–S) to 500 m (E–W; Fig. 7). In east–west cross section, the dome has a flat top with steeply sloping sides, and rises 42 m above the lake level (Fig. 2A). The dome has been severely eroded, and its primary morphology is poorly preserved. The flat top is probably a horizontal terrace produced by erosion.

Field surveys revealed that the dome comprises massive dacite (64 wt.% SiO_2; Table 3) with platy joints spaced at intervals of 20–80 cm. The dacite is grey, non-vesicular, and contains phenocrysts of plagioclase, hornblende, hypersthene, opaque minerals, and minor quartz. The dacite characteristically contains abundant mafic enclaves (<10 cm in size). At the lakeshore, the dacite contains small polyhedral joints (10–20 cm across) within master joints (Fig. 9G), suggesting that the lower part of the lava was quenched by contact with water. Such polyhedral joints were not found in the upper part of the lava.

The bathymetric map (Fig. 3) suggests that the Benten-jima dome stands on a submerged rise that extends ENE–WSW and is joined to the submerged rise beneath the Kannon-jima dome. The geology of the submerged rise beneath the Benten-jima dome is unknown.

The morphology and chemical composition of the Benten-jima dome suggest it was produced by the extrusion of high-viscosity dacitic magma. The dome differs from the Kannon-jima dome in terms of mineral assemblage (*e.g.*, quartz is present; Table 2) and chemical composition (*e. g.*, higher silica content; Table 3), suggesting these domes formed during different stages of activity. Judging from the degree of erosion, the Benten-jima dome was emplaced during the early stages of activity at the Nakajima Islands. The dome has been TL dated to 40±6 and 41±8 ka (Takashima *et al*., 1992).

15. Manju-jima dome

The Manju-jima dome, located on Manju-jima Island (Fig. 7), is elliptical in plan view, ranging in basal diameter from 180 m (N–S) to 230 m (E–W). In cross section, it has a flat top with steeply sloping sides, and rises 32 m above lake level (Fig. 2A). The dome has been severely eroded, and its primary morphology is poorly preserved. The flat top is probably a horizontal terrace produced by erosion.

Field surveys revealed that the dome comprises massive, partially flow-banded andesite lava (Fig. 9H). The andesite is reddish grey, vesicular, and contains phenocrysts of plagioclase, hornblende, hypersthene, quartz, augite, opaque minerals, and minor olivine (59 wt.% SiO_2; Table 3).

The bathymetric map (Fig. 3) suggests that the Manju-jima dome lies on a submerged mound that is subcircular in plan view. The mound is interpreted as a lower part of the lava dome (*i.e.*, andesite) or a cryptodome (*i.e.*, uplifted caldera floor). The geology of this submerged mound has not been studied, and it is unknown whether the mound comprises volcanic rocks or sediments. The whole volcanic edifice of the Manju-jima dome, including the submerged lower part, is subcircular in plan view, ranging in basal diameter from 350 m (N–S) to 450 m (E–W), and rising 82 m above the lake floor.

The morphology and chemical composition of the Manju-jima dome suggest it is a lava dome or a partly extruded cryptodome produced by the extrusion of andesite magma. Judging from the degree of erosion, the Manju-jima dome was emplaced during the early stages of activity at the Nakajima Islands.

16. Discussion

The Nakajima Islands consist of a tuff cone, dacitic to andesitic lava domes, and a dacitic cryptodome, suggesting that the islands have evolved in response to complex volcanic activity involving multiple intrusions/extrusions of dacitic to andesitic magmas and phreatomagmatic explosions. These volcanic edifices consist of various types of dacites and andesites with varying degrees of erosion, suggesting they formed over several stages of volcanic activity. We infer that the Hokutou-misaki, Hokusei, Kitayama, Nansei, Kannon-jima, Benten-jima, and Manju-jima domes formed in the early stages, whereas the Higashiyama pyroclastic cone, and the Higashiyama and Nishiyama domes, formed during the late stages of activity on the islands.

The Higashiyama pyroclastic cone is the only volcanic cone on the Nakajima Islands (Fig. 7). We infer that the cone is the source crater for the Nj–Os tephra (Kasugai *et al*., 1990; Machida and Arai, 2003), because the Nj–Os tephra is the only large-volume pyroclastic fall deposit erupted from the islands (Kasugai *et al*., 1990; Machida and Arai, 2003). Although Miyabuchi *et al.* (2014) estimated that the Us–Ka tephra (Goto *et al*., 2013) was erupted from the Nakajima Islands, the tephra is characterized by low-K chemical composition, indicating it was erupted from Usu volcano (Goto *et al*., 2013; Tomiya and Goto, 2014). The vesicular dacite of the Higashiyama pyroclastic cone is identical in phenocryst assemblage to the Nj–Os tephra, consistent with our inference. We therefore infer that the activity of the Higashiyama pyroclastic cone began with phreatomagmatic explosions, shifted to magmatic explosions (which produced the Nj–Os tephra), and ended with magmatic effusions (which produced the Higashiyama dome).

The environment at the time of the volcanic eruptions that produced the Nakajima Islands cannot be easily determined, but it is constrained by several observations. We found no hyaloclastite on the Nakajima Islands, suggesting the eruptions mostly occurred in a subaerial environment. However, the presence of a tuff cone (Higashiyama pyroclastic cone) and quench texture in the Benten-jima dome (small polyhedral joints; Fig. 9G) suggest that the volcanic eruptions occurred in a water-rich environment. We therefore infer that the volcanic eruptions of the Nakajima Islands occurred in a water-rich subaerial environment or a shallow-water environment. We presume that the water level of the lake at the time of volcanic eruptions was similar to the present-day level, as the quench texture in the lava of Benten-jima dome (Fig. 9G) was found only at the lakeshore, and not in the upper part of the dome. The timing of the lake formation is unknown. We suppose that the lake formed just after the caldera collapse (at least until 100 ka).

The presence of mudstone and sandstone at the Hokutou-misaki dome (Fig. 9D) and at the Kannon-jima dome suggests that the caldera-floor deposits of the Toya caldera were uplifted during or prior to the volcanism, forming a bulge at the center of the caldera. This inference is supported by the fact that the Nakajima Islands lie on a submerged rise with highly irregular morphology (Fig. 3). This bulging was most probably caused by local uplift of poorly consolidated lake-floor deposits caused by the ascent of voluminous dacitic to andesitic magma. The bulge is thus interpreted to be a resurgent dome (Cole *et al*., 2005; Lipman, 2000).

The resurgent dome of the Nakajima Islands is much smaller than that of Valles caldera (Smith and Bailey, 1968). The small-scale resurgent doming at the Nakajima Islands may be attributed to the small size and/or subspherical morphology of the underlying magma chamber. Acocella *et al*. (2001) modeled caldera resurgence using layered sands to represent the crust and silicone to represent magma, and their experiments indicated two modes of resurgence that depended on the aspect ratio (magma chamber width to crustal roof thickness). At an aspect ratio of approximately one, a domical uplift with a central uplift formed in the roof. However, at low aspect ratios (<0.4; *i.e.*, shallow and wide magma chamber), a domical uplift with a central depression formed; in the case of an extensional setting, a graben formed. The laboratory experiments by Acocella *et al*. (2001), combined with the morphology of the Nakajima Islands (no central depression or graben), suggest that the resurgent dome of the Nakajima Islands was produced by the inflation of a magma chamber with a high (approximately one) aspect ratio.

The small-scale resurgent doming at the Nakajima Islands may also be attributed to the relatively soft caldera-floor deposits of the Toya caldera. Valles caldera may have a rigid caldera floor composed of densely welded tuff, which is likely to be broadly uplifted by the inflation of

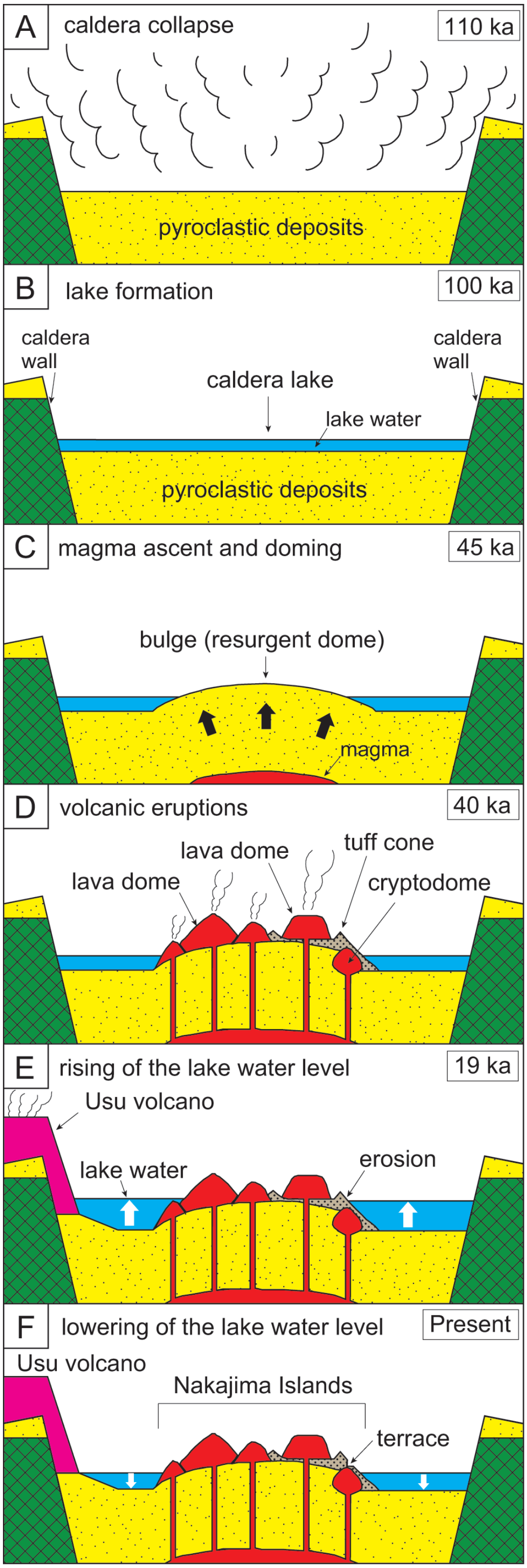

Fig. 10. Evolution of the Nakajima Islands. (A) Toya caldera formed at 110 ka by violent silicic explosive eruptions. (B) The caldera floor was filled with fresh water, forming a caldera lake. (C) A bulge (small resurgent dome) formed on the caldera floor at 45–40 ka following intrusion of silicic magma. (D) Volcanic eruptions occurred on the bulge at 45–40 ka, forming the Nakajima Islands. (E) A rise in lake level occurred at 19 ka as a result of the creation of the Usu volcano. (F) The lake level decreased to the present lake level. The ages are approximate.

underlying magma. In contrast, the Toya caldera has a softer, non-rigid caldera floor composed of non-welded pyroclastic deposits that are unlikely to be broadly uplifted. This inference is supported by the fact that the Toya pyroclastic flow deposits (Yokoyama *et al.*, 1973) are non-welded.

The existence of a horizontal terrace on the volcanic edifices on the Nakajima Islands (at 56 m above the lake level) suggests that the water level of the lake rose after the volcanism of the Nakajima Islands. The terrace is well developed on the Higashiyama pyroclastic cone and Hokutou-misaki dome, suggesting that relatively soft pyroclastic deposits and sediments were selectively eroded. The terrace is indistinct on the harder lava domes, such as the Higashiyama dome and the Nishiyama dome. A terrace at the same elevation has also been found on the inner caldera wall of Lake Toya (Ota, 1956). Ota (1956) reported four terraces (10, 25, 40, and 57 m above the lake level) from the inner caldera wall. The terrace on the volcanic edifices on the Nakajima Islands (56 m above the lake level) may correspond to the uppermost terrace (57 m) of Ota (1956). As the Nakajima Islands formed at 45–40 ka (Takashima *et al.*, 1992), the rise in water level must have occurred after 40 ka.

The rise in water level might have been driven by either climate change, such as global warming, or alternatively, a geological event in the Toya caldera area. We prefer the latter because climate change cannot readily explain such a large change in water level (the height of the terrace is 56 m above the present lake level). The largest geological event after 40 ka in this area was the formation of Usu volcano at the southern rim of the caldera at approximately 19 ka (Goto *et al.*, 2013). During this period, the caldera floor around the volcano was significantly uplifted (see the bathymetry of Lake Toya around Usu volcano in Fig. 1), and basaltic lavas entered the caldera floor, invading the caldera rim (Yokoyama *et al.*, 1973). The rise in water level can be explained by the uplifting of the caldera floor around Usu volcano, and by the basaltic lavas entering the caldera floor. Thus, we infer that the terrace was formed by a rise in the lake water level that resulted from the formation of Usu volcano at around 19 ka.

The lake water level decreased to the present level after the building of Usu volcano. The timing and cause of the lowering are unknown. One explanation is that the increase in water level at 19 ka caused the lake to overflow, forming a river that gradually incised the caldera wall while lowering the lake water level. This drain model is consistent with the fact that a small river (the Sobetsu; Fig. 1) has its source in Lake Toya and cuts the caldera rim.

Therefore, the evolution of the Nakajima Islands can be summarized as follows (Fig. 10). (1) Toya caldera was formed at approximately 110 ka by violent silicic eruptions associated with pyroclastic flows (Fig. 10A). (2) The caldera then filled with fresh water, forming a caldera lake (Fig. 10B). (3) The caldera floor was uplifted at about 45–40 ka by an intrusion of silicic magma, which formed a bulge (small resurgent dome; Fig. 10C). (4) Volcanism subsequently occurred on the bulge, producing a number of silicic lava domes, a cryptodome, and a tuff cone (Fig. 10D). (5) A rise in the lake water level caused by the creation of Usu volcano occurred at around 19 ka, and this produced a terrace on the volcanic edifices at 56 m above the present lake level (Fig. 10E). (6) The lake water level then decreased to the present level (Fig. 10F).

17. Conclusions

The aerial laser-scanner mapping and geological field surveys reported here have provided invaluable information that has improved our understanding of the geology and evolution of the Nakajima Islands. These surveys suggest that the islands consist of a tuff cone, eight lava domes, and a cryptodome. The uplifted caldera floor (mudstone and sandstone) is exposed on the northeastern and southwestern parts of the islands. The Nakajima Islands are inferred to have evolved from caldera resurgence driven by the ascent of voluminous dacitic to andesitic magma, and subsequent extrusions of the magma on the resurgent dome.

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References

Acocella, V., Cifelli, F. and Funiciello, R. (2001) The control of overburden thickness on resurgent domes: insights from analogue models. *J. Volcanol. Geotherm. Res.*, **111**, 137–153.

Cas, R. F. and Wright, J. V. (1987) **Volcanic successions: modern and ancient**, Allen and Unwin, London, 528 p.

Chiba, T., Suzuki, Y. and Hiramatsu, T. (2007 a) Digital terrain representation methods and red relief map, a new visualization approach. *J. Japan Cartographic Association (Map)* , **45**, 27–36. (in Japanese with English abstract)

Chiba, T., Tomita, Y., Suzuki, Y., Arai, K., Fujii, N., Miyaji, N., Koizumi, S. and Nakashima, K. (2007b) Analysis of micro topography of the Aokigahara lava flows, Fuji volcano, by the light detection and ranging system. In *Fuji volcano* (Aramaki, S., Fujii, T., Nakada, S. and Miyaji, N. eds.), 349–363, Yamanashi Institute of Environmental Sciences, Yamanashi, Japan. (in Japanese)

Cole, J. W., Milner, D. M. and Spinks, K. D. (2005) Calderas and caldera structures: a review. *Earth-Science Review*, **69**, 1–26.

Ganzawa, Y., Usui, R., Tanaka, H. and Azuma, T. (2007) Red thermoluminescence dating of Toya pyroclastic flow using single-aliquot regenerative-dose (SAR). *Jour. Geol. Soc. Japan*, **113**, 470–478. (in Japanese with English abstract)

Goto, Y., Matsuzuka, S. and Kameyama, S. (2011) Three-dimensional digital mapping of Noboribetsu Geothermal Field, Kuttara Volcano, Hokkaido, Japan, using helicopter-borne high-resolution laser scanner. *Bull. Volcanol. Soc. Japan*, **56**, 127–135.

Goto, Y., Sekiguchi, Y., Takahashi, S., Ito, H. and Danhara, T. (2013) The 18–19 ka andesitic explosive eruption at Usu Volcano, Hokkaido, Japan. *Bull. Volcanol. Soc. Japan*, **58**, 529–541.

Hunter, G., Pinkerton, H., Airey, P. and Calvari, S. (2003) The application of a long-range laser scanner for monitoring volcanic activity on Mount Etna. *J. Volcanol. Geotherm. Res.*, **123**, 203–210.

Kasugai, A., Maeda, T. and Okamura, S. (1990) Tephrostoratigraphy and chronology of tephras erupted from Kuttara and Shikotsu volcanoes, southwestern Hokkaido, Japan. *Jour. Hokkaido Univ. Edu. (Section IIB)* , **40**, 31–46. (in Japanese with English abstract)

Katsui, Y. (1990) Toya caldera and Usu volcano. In *Regional Geology of Japan, Part 1, Hokkaido* (Kato, M., Katsui, Y., Kitagawa, Y. and Matsui, S. eds.) 162–165, Kyoritsu Shuppan, Tokyo. (in Japanese)

Katsui, Y., Komuro, H. and Uda, T. (1985) Development of faults and growth of Usu-Shinzan cryptodome in 1977–1982 at Usu volcano, north Japan. *J. Fac. Sci., Hokkaido Univ., Ser. 4*, **21**, 339–362.

Kimura, J. and Yamada, Y. (1996) Evaluation of major and trace element XRF analyses using a flux to sample ratio of two to one glass beads. *J. Mineral. Petrol. Econ. Geol.*, **91**, 62–72.

Lipman, P. W. (2000) Calderas. In *Encyclopedia of volcanoes* (Sigurdsson, H., Houghton, B., McNutt, S. R., Rymer, H. and Stix, J. eds.), 643–662, Academic Press, San Diego.

Machida, H. and Arai, F. (2003) **Atras of tephra in and**

around Japan. University of Tokyo Press, Tokyo, 360 p.

McPhie, J., Doyle, M. and Allen, R. (1993) **Volcanic textures**. Centre for Ore Deposit and Exploration Studies, Univ. Tasmania, Hobart, 196p.

Mimatsu, M. (1962) **Showa-Shinzan diary**. Mimatsu Masao Memorial Hall, Sobetsu, Hokkaido, 225 p. (in Japanese)

Minakami, T., Ishikawa, T. and Yagi, K. (1951) The 1944 eruption of Volcano Usu in Hokkaido, Japan. *Bull. Volcanol*., **11**, 45-160.

Miyabuchi, Y., Okuno, M., Torii, M., Yoshimoto, M. and Kobayashi, T. (2014) Tephrostratigraphy and eruptive history of post-caldera stage of Toya volcano, Hokkaido, northern Japan. *J. Volcanol. Geotherm. Res*., **281**, 34-52.

Okumura, K. and Sangawa, A. (1984) Distribution and age of Toya pyroclastic flow. *Bull. Volcanol. Soc. Japan*, **29**, 638. (in Japanese)

Ota, R. (1956) **Explanatory text of the geological map of Japan, scale 1 : 50,000, Abuta**. Geological Survey of Japan, 76p. (in Japanese with English abstract)

Pesci, A., Fabris, M., Conforti, D., Loddo, F., Baldi, P. and Anzidei, M. (2007) Integration of ground-based laser scanner and aerial digital photogrammetry for topographic modeling of Vesuvio volcano. *J. Volcanol. Geotherm. Res*., **162**, 123-138.

Smith, R. L. and Bailey, R. A. (1968) Resurgent cauldrons. *Mem. Geol. Soc. Am*., **116**, 613-662.

Soya, T., Katsui, Y., Niida, K., Sakai, K. and Tomiya, A. (2007) **Geological map of Usu volcano (2nd edition).** Geological survey of Japan, AIST, Tsukuba. (in Japanese)

Takashima, I., Yamazaki, T., Nakata, E. and Yukawa, K. (1992) TL age of the Quaternary volcanic rocks and pyroclastic flow deposits around the Lake Toya, Hokkaido, Japan. *J. Mineral. Petrol. Econ. Geol*., **87**, 197-206.

Tanakadate, S. (1918) Lava domes in Hokkaido. *Geological Society of Japan*, **25**, 287-304. (in Japanese)

Tomiya, A. and Goto, Y. (2014) Petrologic characteristics of Usu-Kaminagawa tephra : Toward a comprehensive understanding of the Toya-Nakajima magma system. *Abstracts of the Volcanological Society of Japan 2014 fall meeting*, **100** (B3-13).

Ui, T., Kawaminami, E., Tanaka, M., Ishihata, T. and Hirose, W. (2013) **Toya caldera and Usu volcano global geopark guide, No. 7, Toya caldera and surrounding area.** Toya-Usu Geopark Organization, Sobetsu, Hokkaido, 31p. (in Japanese)

Vespermann, D. and Schmincke, H.-U. (2000) Scoria cones and tuff rings. In *Encyclopedia of volcanoes* (Sigurdsson, H., Houghton, B., McNutt, S. R., Rymer, H. and Stix, J. eds.), 683-694, Academic Press, San Diego.

Yokoyama, I., Katsui, Y., Oba, Y. and Ehara, Y. (1973) **Usuzan, its volcanic geology, history of eruption, present state of activity and prevention of disasters**. Committee for Prevention and Disasters of Hokkaido, Sapporo, 254p. (in Japanese)

Zimmer, B. W., Riggs, N. R. and Carrasco-Nunez, G. C. (2010) Evolution of tuff ring-dome complex : the case study of Cerro Pinto, eastern Trans-Mexican Volcanic Belt. *Bull. Volcanol*., **72**, 1223-1240.

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北海道洞爺カルデラ中島火山の火山地質と形成史：空中レーザーマッピングと地表地質調査による推定

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我々は，北海道洞爺カルデラ中島火山の火山地質を明らかにするため，ヘリコプター搭載型の高分解能レーザースキャナを用いたレーザーマッピングと，地表地質調査を行った．レーザーマッピングは中島の全域を含む 3×3 km で行い，計測データから 3 次元のデジタル地形図を作成した．地表地質調査は 3 次元デジタル地形図を用いて中島の全域で行い，詳細な産状記載と岩石記載を行った．デジタル地形図と地表地質調査から，中島の詳細な火山地質と形成史が明らかになった．中島は，デイサイトおよび安山岩質マグマが噴出して形成した 8 個の溶岩ドーム（東山ドーム，西山ドーム，北西ドーム，北山ドーム，南西ドーム，観音島ドーム，弁天島ドーム，饅頭島ドーム），デイサイトマグマが湖底堆積物を押し上げて形成した潜在ドーム（北東岬ドーム），およびデイサイト質のマグマ水蒸気噴火により形成したタフコーン（東山火砕丘）からなる．中島の北東部と南西部には，泥岩と砂岩からなる湖底堆積物が分布しており，中島の火山活動がカルデラ底の隆起を伴ったことを示す．中島は，洞爺カルデラ中央部のリサージェントドームの形成と，それに伴うデイサイト～安山岩質マグマの噴出により形成されたと考えられる．高分解能レーザースキャナによる地形計測と 3 次元デジタル地形図を用いた地質調査は，火山地質の解明に極めて有効である．