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 evolutionary history of the islands. The laser-scanner mapping survey covered the entirety of the Nakajima Islands, an area of $3 \times 3$ 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.

Keywords: laser-scanner mapping, geology, Nakajima Islands, Toya caldera, evolutionary 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 thinly 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 evolutionary 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 $10 \times 11$ 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.,...
1973) deposits around the caldera. The Toya caldera holds a freshwater lake (Lake Toya), which occupies the entire caldera floor \( (\text{i.e., } 10 \times 11 \text{ km}) \) 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 \( (2.5 \times 2.8 \text{ km}) \), Kannon-jima \( (380 \times 430 \text{ m}) \), Benten-jima \( (300 \times 450 \text{ m}) \), and Manju-jima \( (180 \times 230 \text{ m}) \); 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...
is able to measure distances of up to 1000 m with an accuracy of $\pm 10$ 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 thick).

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
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 Nishiyma 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...
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).

### Table 1. Specifications of the Develo LISA3 laser scanner.

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

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).
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, Kannonjima, 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
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
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.% SiO₂; Table 3). The matrix 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).
The 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...

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

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

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.

<table>
<thead>
<tr>
<th>Name</th>
<th>Higashiyama pyroclastic cone</th>
<th>Higashiyama pyroclastic cone</th>
<th>Higashiyama dome</th>
<th>Higashiyama dome</th>
<th>Nishiyama dome</th>
<th>Hokusei dome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample No.</td>
<td>NJ-03-L2A</td>
<td>NJ-03-L2B</td>
<td>NJ-01</td>
<td>NJ-02</td>
<td>NJ-34</td>
<td>NJ-32</td>
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<tr>
<td>SiO₂ (wt. %)</td>
<td>65.80</td>
<td>64.61</td>
<td>63.65</td>
<td>63.09</td>
<td>64.06</td>
<td>62.81</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.52</td>
<td>0.55</td>
<td>0.64</td>
<td>0.64</td>
<td>0.61</td>
<td>0.67</td>
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<tr>
<td>Al₂O₃</td>
<td>15.96</td>
<td>16.02</td>
<td>16.09</td>
<td>16.36</td>
<td>16.13</td>
<td>16.87</td>
</tr>
<tr>
<td>Fe₂O₃*</td>
<td>5.44</td>
<td>5.83</td>
<td>6.60</td>
<td>6.66</td>
<td>6.37</td>
<td>6.91</td>
</tr>
<tr>
<td>MnO</td>
<td>0.14</td>
<td>0.15</td>
<td>0.18</td>
<td>0.19</td>
<td>0.17</td>
<td>0.17</td>
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<tr>
<td>MgO</td>
<td>1.86</td>
<td>2.00</td>
<td>2.05</td>
<td>2.04</td>
<td>1.96</td>
<td>2.17</td>
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<tr>
<td>CaO</td>
<td>4.99</td>
<td>5.09</td>
<td>5.53</td>
<td>5.56</td>
<td>5.63</td>
<td>5.93</td>
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<tr>
<td>Na₂O</td>
<td>3.63</td>
<td>3.64</td>
<td>3.66</td>
<td>3.57</td>
<td>3.38</td>
<td>3.37</td>
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<tr>
<td>K₂O</td>
<td>1.34</td>
<td>1.36</td>
<td>1.00</td>
<td>0.99</td>
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<td>0.84</td>
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<tr>
<td>P₂O₅</td>
<td>0.11</td>
<td>0.11</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.15</td>
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<tr>
<td>Total</td>
<td>99.80</td>
<td>99.38</td>
<td>99.54</td>
<td>99.24</td>
<td>99.37</td>
<td>99.89</td>
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<tr>
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<td>1.25</td>
<td>-0.04</td>
<td>0.07</td>
<td>-0.06</td>
<td>0.15</td>
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<table>
<thead>
<tr>
<th>Name</th>
<th>Kitayama dome</th>
<th>Hokutou-misaki dome</th>
<th>Nansei dome</th>
<th>Kannon-jima dome</th>
<th>Benten-jima dome</th>
<th>Manju-jima dome</th>
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<tr>
<td>Sample No.</td>
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<td>NJ-37</td>
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<td>MJ-03</td>
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<td>65.90</td>
<td>60.23</td>
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<tr>
<td>TiO₂</td>
<td>0.62</td>
<td>0.59</td>
<td>0.51</td>
<td>0.69</td>
<td>0.55</td>
<td>0.68</td>
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<tr>
<td>Fe₂O₃*</td>
<td>6.56</td>
<td>6.36</td>
<td>5.56</td>
<td>8.34</td>
<td>6.22</td>
<td>7.34</td>
</tr>
<tr>
<td>MnO</td>
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<td>0.15</td>
<td>0.13</td>
<td>0.18</td>
<td>0.15</td>
<td>0.16</td>
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<tr>
<td>MgO</td>
<td>2.07</td>
<td>1.98</td>
<td>1.92</td>
<td>2.78</td>
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<tr>
<td>CaO</td>
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<td>5.46</td>
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<td>Na₂O</td>
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<td>3.32</td>
<td>3.23</td>
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<td>3.01</td>
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<tr>
<td>K₂O</td>
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<td>1.07</td>
<td>1.24</td>
<td>0.82</td>
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<td>1.00</td>
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<td>P₂O₅</td>
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<td>0.11</td>
<td>0.08</td>
<td>0.11</td>
<td>0.10</td>
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<tr>
<td>Total</td>
<td>100.24</td>
<td>99.48</td>
<td>99.87</td>
<td>99.49</td>
<td>99.39</td>
<td>100.04</td>
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<td>L.O.I.</td>
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<td>0.63</td>
<td>0.04</td>
<td>0.14</td>
<td>1.22</td>
<td></td>
</tr>
</tbody>
</table>

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.
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 900 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.% SiO₂; 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 differs from the Nishiyama dome in phenocryst assemblage (e.g., quartz is present; Table 2) and degree of viscosity, suggesting that they are independent domes that were emplaced during different stages of activity.

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 outcrops. The surface of the dome is covered with humus soil and a scattering of angular dacite lava blocks up to 1 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.% SiO₂; 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.% SiO₂; 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. 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.% SiO2; 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 southwest 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.% SiO2; 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.% SiO₂; Table 3).

The bathymetric map (Fig. 3) suggests that the Manju-
shima 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 andes-
ite magma. Judging from the degree of erosion, the Manju-
shima 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) esti-
mated that the Us-Ka tephra (Goto et al., 2013) was
erupted from the Nakajima Islands, the tephra is charac-
terized 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, sug-
gest ing the eruptions mostly occurred in a subaerial envi-
ronment. 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 sub-
spherical 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), com-
bined 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
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.

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.
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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