1 **Tephrostratigraphy and eruptive history of post-caldera stage of Toya**
2 **Volcano, Hokkaido, northern Japan**

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22

23 **Abstract**

24 A detailed tephrostratigraphy of Toya Volcano in Hokkaido, northern Japan has
25 been constructed to evaluate the post-caldera eruptive history of the volcano. The
26 tephrostratigraphic sequence preserved above the Toya ignimbrite reaches a total
27 thickness of 8 m southeast of the caldera. After the caldera formation (115-112 ka),
28 there was a long quiescent period of more than 60 ka yr. The first post-caldera activity
29 started with Nakajima Osarugawa pumice-fall deposit (Nj-Os) inside the caldera at 48
30 ka. Eruptive activity at Nakajima Volcano resumed at 30 ka with Nakajima Sekinai
31 pumice-fall deposit (Nj-Sk), and was followed by continuous emission of fine ash
32 including abundant accretionary lapilli. Soon after the Nakajima pyroclastic eruption
33 Usu Volcano began its activity with discharges of basaltic ash and scoria (forming the
34 Usu prehistoric tephra) and extrusion of homogeneous lavas namely Usu somma lava,
35 resulting in the formation of the initial volcanic edifice. Subsequently, A large sector
36 collapse occurred between 30 and 20 ka that emplaced the Zenkoji debris avalanche
37 with little break after the formation of the initial Usu volcanic edifice. After the sector
38 collapse, the volcano remained dormant for about 20-30 ka yr. Eruptive activity at
39 Usu Volcano resumed in 1663 AD with the most explosive plinian eruption in the
40 post-caldera stage of Toya Volcano. Since then, seven eruptions have been recorded in

41 1769, 1822, 1853, 1910, 1943-1945, 1977-1978 and 2000 at multi-decadal interval.
42 Total tephra volume during the post-caldera stage is estimated at about 0.9 km^3 (dense
43 rock equivalent: DRE), whereas total lava volume is calculated at about 2.3 km^3 .
44 Therefore, the average magma discharge rate during the post-caldera stage of Toya
45 Volcano is estimated at about $0.03 \text{ km}^3/\text{ky}$, which is one or two order smaller than those
46 of other Quaternary volcanoes in Japan.
47 *Keywords:* Toya Volcano; post-caldera activity; tephrostratigraphy; eruptive history;
48 magma discharge rate

49 **1. Introduction**

50 Caldera-forming volcanism is one of the most catastrophic volcanic phenomena
51 that affects not only its surrounding area but also worldwide. Most caldera volcanoes
52 experience multiple caldera-forming eruptions (e.g., Ono et al., 1977; Wilson et al.,
53 1984, 1995; Nagaoka, 1988; Druitt et al., 1999; Lanphere et al., 2002; Hasegawa et al.,
54 2012), and continue explosive and/or effusive eruptive activity after cataclysmic events.
55 These volcanic activities can be regarded as a premonitory process towards future
56 caldera-forming eruption. It is therefore very important to understand post-caldera
57 eruptive history and temporal variations in magma discharge in order to predict future
58 caldera-forming eruptions. Detailed tephrostratigraphic analyses have been done and
59 utilized in reconstructing post-caldera activity (e.g., Hasegawa et al., 2009; Miyabuchi,
60 2009, 2011).

61 Toya Volcano is one of the largest caldera volcanoes in Hokkaido, northern Japan
62 (Fig. 1). Toya caldera was formed by a series of large pyroclastic eruptions at ca.
63 115-112 ka (Machida and Arai, 2003). After the caldera formation, Nakajima and Usu
64 volcanoes formed at the center and the southern edge of the caldera, respectively (e.g.,
65 Yokoyama et al., 1973). Usu Volcano is one of the most active and hazardous
66 volcanoes in Japan, and has violently erupted multiple times since AD 1663 (Soya et al.,
67 2007). Previous studies on Toya Volcano have been focused on the caldera-forming
68 eruption and the related deposits (Suzuki et al., 1970; Ikeda and Katsui, 1986) and the

69 historical evolution of the magmatic system at Usu Volcano (Oba et al., 1983; Tomiya
70 and Takahashi, 1995, 2005; Matsumoto et al., 2005; Matsumoto and Nakagawa, 2010).
71 In contrast, the post-caldera tephra stratigraphy and eruptive history before AD 1663
72 Usu eruption remain poorly studied. Yamagata (1996) presented a tephrostratigraphic
73 framework of post-caldera stage of Toya Volcano. Recently, Goto et al. (2013)
74 described the characteristics of an andesitic tephra that was inferred to be erupted during
75 the initial stage of Usu Volcano. However, our interpretation including the source and
76 age of the tephra is different from their results.

77 This paper presents an integrated stratigraphy and detailed description of
78 post-caldera tephra deposits around the Toya caldera. Based on the resulting
79 tephrostratigraphy, this paper discusses the post-caldera eruptive history and temporal
80 variation in magma discharge of Toya Volcano mainly before the 1663 explosive Usu
81 eruption.

82

83 **2. Geological setting**

84 Toya caldera, which is approximately 12 km in diameter, is located at the
85 southwestern part of Hokkaido, northern Japan (Fig. 1). Neogene altered andesite and
86 pyroxene andesite rocks are distributed around the caldera. Early Pleistocene
87 ignimbrites including dominantly non-welded rhyolitic Sobetsu pyroclastic flow deposit
88 and mostly welded andesitic Takinoue pyroclastic flow deposit are exposed near the

89 southeastern rim of the caldera (Ota, 1956; Kondo, 1963). The Kaminagawa
90 Formation of middle Pleistocene age, which is composed of gravel, sand, silt and clay
91 (mainly fluvial and lahar deposits), occurs along the Osaru River, south of the caldera
92 (Suzuki et al., 1970). This formation and the underlying Takinoue and Sobetsu
93 pyroclastic flow deposits are believed to extend widely beneath Toya caldera because
94 they have been cut at borehole cores and are exposed in uplifted blocks (Katsui et al.,
95 1981).

96 The Toya caldera was formed by a series of large pyroclastic eruptions at ca.
97 115-112 ka (MIS stage 5d; Machida and Arai, 2003). The eruptions produced dacitic
98 pyroclastic flows of more than 20 km³ (bulk volume; Machida et al., 1987), and formed
99 a vast pyroclastic-flow plateau (ca. 20 km in diameter) around the Toya caldera (Suzuki
100 et al., 1970; Ikeda and Katsui, 1986). The co-ignimbrite ash-fall deposit (Toya tephra)
101 associated with the caldera-forming eruption is distributed in the Hokkaido and Tohoku
102 districts, northern Japan with a bulk volume of more than 150 km³ (Machida et al.,
103 1987). After the formation of Toya caldera, Nakajima Volcano, which is composed of
104 nine andesitic lava domes, occurred at the center of the caldera (Ota, 1956).

105 Usu Volcano was formed at the southern rim of Toya caldera (Fig. 2). It
106 comprises a stratovolcano with a 2-km-across summit crater, a parasitic scoria cone
107 (Donkoroyama), three lava domes, and more than 10 cryptodomes or volcanic mounds
108 not only within the summit crater but also on the flanks and at the foot of the edifice

109 (Oba, 1966; Yokoyama et al., 1973; Katsui et al., 1981; Soya et al., 2007; Yokoyama
110 and Seino, 2000; Tanaka and Yokoyama, 2013). The main stratovolcano was formed
111 by repeated eruptions producing lava flows (Usu Somma Lava) and scoria of basalt and
112 basaltic andesitic compositions (Oba et al., 1983). A large sector collapse is thought to
113 have occurred at about 8-7 ka (Yokoyama et al., 1973) forming the Zenkoji debris
114 avalanche deposit, which was first called Zenkoji mudflow deposit (Kondo, 1963), at
115 the southern foot of the volcano. After the edifice collapse, Usu Volcano remained
116 dormant for thousands of years until the historical period of activity (Yokoyama et al.,
117 1973).

118 Eruptive activity resumed in AD 1663 with the most explosive rhyolitic plinian
119 eruption (Soya et al., 2007). Since then, seven eruptions have been recorded in 1769,
120 1822, 1853, 1910, 1943-1945, 1977-1978 and 2000 at multi-decadal interval
121 (Yokoyama et al., 1973; Soya et al., 2007). A recent tephrostratigraphic study
122 recognized an eruption deposit between the 1663 and 1769 activity (Nakagawa et al.,
123 2005). The historical eruptions were sometimes accompanied with pyroclastic falls,
124 pyroclastic flows, base surge and lahars. These eruptions formed two lava domes
125 (Ko-Usu and O-Usu) in the summit crater, a dome (Showa Shinzan) at the eastern foot
126 of the volcano (Figs. 1 and 2), two cryptodomes (Ogariyama, Usu Shinzan) on the
127 summit and several cryptodomes or volcanic mounds (e.g., Nishiyama, Kompirayama,
128 Nishimaruyama, Meiji Shinzan, Higashimaruyama, and the area of upheaval during the

2000 activity) on the flank and at the foot of volcano (Soya et al., 2007; Yokoyama and Seino, 2000; Tanaka and Yokoyama, 2013). The SiO₂ contents of the historical products have decreased with time (Oba, 1966; Oba et al., 1983; Nakagawa et al., 2002, 2005). The change in chemical composition is explained by two models: a mafic magma injection during each eruption and a compositional and thermal gradient of the shallow magma chamber formed after 1663 (Tomiya and Takahashi, 1995, 2005).

3. Tephrostratigraphic sequence and description of eruptive products

A thick tephra sequence (average 5 m thick) that has erupted from Nakajima, Usu and other volcanoes is preserved above the Toya pyroclastic-flow plateau, especially east of Usu Volcano, because tephra dispersal is influenced by the prevailing west to southwest wind directions in Japan. The total thickness of fallout and reworked tephra deposits after the Toya caldera-forming eruption (115-112 ka; Machida and Arai, 2003) reaches about 8 m at the eastern side of the Osaru River (Figs. 3 and 4). Several key marker beds occur in the tephra sequence above the Toya ignimbrite. These are the Kuttara 2 tephra (Kt-2), Nakajima Osarugawa tephra (Nj-Os), Shikotsu pyroclastic-flow deposit (Spfl), Usu Kaminagawa tephra (Usu-Ka), Baitoushan Tomakomai tephra (B-Tm), Komagatake 1640 tephra (Ko-d), Usu 1663 and subsequent historical tephra in ascending order (Yamagata, 1996). In this study, we have defined Nakajima Sekinai tephra (Nj-Sk) instead of Usu Kaminagawa tephra. Field examination of tephra

149 stratigraphic sections located mainly southeast to south of Toya caldera was conducted.

150 The locations of all measured stratigraphic sections are shown in Fig. 1.

151 Bulk volumes of major tephra beds were calculated by using their isopach data
152 according to the Fierstein and Nathenson (1992) method. Mineral assemblages of
153 representative lapilli or ash beds of each tephra unit and pumice-fall deposits were
154 characterized by observation under a polarizing microscope.

155

156 3.1. Kuttara 2 tephra (*Kt-2*)

157 A thick pumice-fall deposit occurs about 1.4-2 m above the top of the Toya
158 ignimbrite (Fig. 5A) and reaches a maximum thickness of >270 cm in the study area.
159 The pumice-fall deposit was first described as Usu c tephra by Uragami et al. (1933)
160 because it was thought to originate from Usu Volcano. Thereafter, Kondo (1963)
161 presumed that the tephra was erupted from Nakaijima Volcano inside Lake Toya, and
162 Sasaki (1972) clarified that the thickness increased eastward of Lake Toya and renamed
163 as N, Us-c tephra. Iburi Collaborative Research Group (1990) identified the N, Us-c
164 tephra with Kt-c tephra erupted from Kuttara Volcano, which is located about 30 km
165 ENE of Toya caldera, and denoted that the Kt-c tephra is distributed more than 60 km
166 from the source with a NW-trending axis based on their detailed isopach. Finally,
167 Yamagata (1994) subdivided tephra layers from Kuttara and Shikotsu volcanoes by
168 volcanic ash soil layers (paleosols) indicating dormant periods, and renamed this tephra

169 as Kuttara 2 (Kt-2).

170 The Kt-2 tephra is composed of coarse (1-2 cm across) light gray (2.5Y8/2;
171 Munsell color) pumiceous lapilli and usually displays massive facies. Mineral
172 assemblage of pumice clasts is plagioclase, orthopyroxene, clinopyroxene and a small
173 amount of hornblende. Large (<1 cm) anorthite crystals are observed in the Kt-2
174 tephra at some sections. Although Yamagata (1996) reported that Aso-4 tephra from
175 Kyushu (southwestern Japan; 89 ka) and Nakajima Date tephra (Nj-Dt) were recognized
176 in the silty brown soil layer between the Toya ignimbrite and Kt-2 pumice-fall deposit,
177 we could not observe them.

178

179 3.2. *Nakajima Osarugawa tephra (Nj-Os)*

180 Nakajima Osarugawa tephra (Nj-Os) is a hornblende-rich pumice-fall deposit.
181 Kt-2 and Nj-Os tephras are usually separated by a 14-26 cm thick brown soil or
182 weathered ash (Fig. 6), but Nj-Os directly overlies the Kt-2 at site 46. The tephra was
183 first recognized as the upper part of N, Us-c tephra (Kt-2), and thereafter was separated
184 from N, Us-c and solely named as G-p tephra (Kasugai et al., 1990). Kasugai et al.
185 (1990) presented that G-p tephra is distributed with a SE-trending axis from Nakajima
186 Volcano and the vicinity inside the Toya caldera. Finally, Yamagata (1994) renamed it
187 as Nakajima Osarugawa tephra (Nj-Os) because it is fairly observed in the lower reach
188 of the Osaru River flowing near the southeastern rim of Toya caldera (Fig. 3). Nj-Os

189 consists mainly of sorted fine (2-4 mm) dull yellow orange (10YR6/4) to dull yellow
190 (2.5Y6/4) pumiceous lapilli in the study area. The pumice clasts are well vesiculated
191 and have andesitic composition ($\text{SiO}_2=61.7$ wt.%). The bulk density of pumiceous
192 clasts of Nj-Os, measured by the glass bead method (Sasaki and Katsui, 1981), is
193 $0.5\text{-}0.6\text{ g/cm}^3$ (average 0.6 g/cm^3). The maximum size of pumice (MP; average
194 long-axis diameter of the three largest pumice clasts at each locality) ranges from 1 to
195 4.3 cm and increases northward in the study area (Fig. 7A). The Nj-Os tephra is
196 always massive but divided into three parts by grain size and sorting at some sections.
197 It contains plagioclase, hornblende, orthopyroxene and minor quartz phenocrysts. The
198 bulk volume of Nj-Os was calculated as approximately 0.44 km^3 by Fierstein and
199 Nathenson (1992) method based on Kasugai et al. (1990) isopach data.

200

201 3.3. *Shikotsu tephra*

202 Shikotsu pyroclastic flow deposit (Spfl) and the underlying Shikotsu pumice-fall
203 deposit (Spfa1) are representative marker tephra beds in Hokkaido (Machida and Arai,
204 2003), and both tephra are related to the formation of Shikotsu caldera (about 40 km
205 ENE of Toya caldera; Katsui, 1958, 1959). Yamagata (1996) stated that Spfl is
206 recognized around the Toya caldera. We observed that the Shikotsu tephra occurs 19
207 cm above Nj-Os only at locality 32 (Figs. 3 and 6). Here, the Shikotsu tephra is
208 approximately 1.6 m thick and planner- to cross-stratified. The tephra contains

209 abundant dull yellow orange (10YR6/3) well-vesiculated pumiceous clasts set in a fine
210 to medium sand size non-cohesive vitric matrix. These occurrences suggest that the
211 Shikotsu tephra at the section is successive fluvially reworked deposits (lahar deposits)
212 rather than an original pyroclastic flow deposit. A black humic soil (1 cm thick)
213 including charcoal fragments underlies the reworked Shikotsu tephra deposits.

214

215 3.4. *Nakajima Sekinai tephra (Nj-Sk)*

216 Yamagata (1996) recognized a pumice-fall deposit and the overlying alternating
217 beds of ash and scoria above the Shikotsu tephra and named the tephra layers as Usu
218 Kaminagawa tephra (Usu-Ka) because it was presumed to be erupted from Usu Volcano.
219 Goto et al. (2013) described the distribution, lithology and age of Usu-Ka and
220 interpreted that the tephra was erupted during the initial stage of Usu Volcano.
221 However, our field examination demonstrated that the tephra layers are divided into two
222 parts: the lower andesitic part and the upper basaltic part, and that the lower part
223 originated from inside the Toya caldera (Nakajima Volcano) although the upper part was
224 ejected from Usu Volcano. Both the chemical composition and phenocryst assemblage
225 of the lower part are similar to those of Nakajima products (Nj-Os tephra and dome
226 lavas) rather than those of Usu Volcano. Therefore, we call Usu prehistoric tephra to
227 the upper part of the tephra layers whereas we rename the lower part as the Nakajima
228 Sekinai tephra.

229 The Nakajima Sekinai tephra (Nj-Sk) comprises poorly-vesiculated grayish yellow
230 (2.5Y7/2) pumiceous lapilli (Figs. 5B and 5D). The poorly-vesiculated pumice clasts
231 are andesite ($\text{SiO}_2=61.7\text{-}62.0$ wt.%) with small amounts of phenocrysts of plagioclase,
232 hornblende, orthopyroxene and minor clinopyroxene. The bulk density of pumiceous
233 clasts in Nj-Sk is $0.8\text{-}1.6$ g/cm³ (average 1.1 g/cm³). The MP of Nj-Sk ranges between
234 0.8 and 3.5 cm (Fig. 7B). Some coarse pumice clasts (<7 cm in diameter) show
235 radially arranged cooling joints. The Nj-Sk is massive or reversely graded at most
236 sections, but three to four fall units are recognized at some proximal sections. The
237 upper fall units are coarser grained than the lower fall units. The pumice-fall deposit
238 increases in thickness toward Lake Toya and is distributed with an SSE trending axis
239 (Fig. 8B). The bulk volume of the Nj-Sk is estimated at approximately 0.033 km³.
240 The pumice-fall deposit is underlain by a light gray (2.5Y7/1) vitric fine ash layer (Fig.
241 5C). The ash is characterized by an abundance of bubble-wall type glass shards. The
242 thickness of the vitric ash ranges between 1 and 10 cm in the study area but
243 unfortunately no distribution trend could be recognized for this tephra (Fig. 8A).

244 The Nj-Sk tephra is overlain by alternating beds of brown to gray fine ash-fall
245 deposits (Fig. 5E). Six to eight massive fine ash beds ($2\text{-}35$ cm thick) are recognized
246 at representative sections (localities 5 and 12), and some ash layers contain abundant
247 accretionary lapilli (<5 mm in diameter). The upper ash beds show a wavy
248 deformation and a deeply incised top (an erosional structure) at some sections (Fig. 5E).

249 The total thickness of the alternating beds of fine ash reaches 169 cm at the southeastern
250 foot of Usu Volcano (locality 12) (Fig. 8C). The dispersal axis of the fine ash-fall
251 deposits overlying Nj-Sk is thought to be toward the south to southeast, and the bulk
252 volume is calculated at 0.077 km³.

253

254 3.5. *Usu prehistoric tephra*

255 An alternating sequence of basaltic scoria and coarse to medium ash directly
256 overlies the erosional surface of brown to gray fine ash-fall deposits above Nj-Sk tephra
257 (Fig. 5F). The sequence is composed of at least eight scoriaceous lapilli beds and
258 fourteen coarse to medium ash beds. The scoria clasts are brownish black (2.5Y3/1) to
259 dull reddish brown (5YR4/3) colored and moderately vesiculated. Some coarse
260 scoriaceous lapilli have basaltic compositions (SiO₂=52.2-52.6 wt.%). The lower part
261 of the alternating sequence contains abundant pumiceous lapilli. Since the total
262 thickness of all fall units increases toward the Usu Volcano and reaches more than 3 m
263 at the southeastern summit of the volcano (Fig. 8D), the alternating sequence of scoria
264 and ash is inferred to originate from Usu Volcano. Therefore, we name the sequence
265 as Usu prehistoric tephra. The bulk volume of the Usu prehistoric tephra is estimated
266 approximately 0.055 km³.

267

268 3.6. *Usu somma lava*

269 At the southeastern foot of Usu Volcano (locality 12), coarse ash beds including
270 two scoria-fall deposits (total thickness 40 cm) are directly overlain by the Usu somma
271 lava (>10 m thick) (Fig. 9). The Usu somma lava is more than 20 m thick on the
272 southwestern slope of the volcano (locality 10). The lavas are overall gray (5Y4/1)
273 colored and poorly vesiculated, and have basaltic andesite composition ($\text{SiO}_2=53.8\text{-}54.8$
274 wt.%). The somma lavas are divided into seven groups by their occurrences and
275 petrographic features (Oba, 1964a, 1964b), but they are overall porphyritic and include
276 phenocrysts of plagioclase, orthopyroxene, olivine and minor clinopyroxene. The lava
277 is overlain by a 2-3 m thick basaltic ($\text{SiO}_2=52.2$ wt.%) scoria-fall deposit at the
278 southeastern summit of Usu Volcano (locality 9). We therefore believe that the somma
279 lavas are interbedded between the Usu prehistoric tephra. The volume of the Usu
280 somma lava is estimated at 0.35 km^3 (Oba, 1966). The Zenkoji debris avalanche
281 deposit as described below is composed mainly of blocks of Usu somma lava. The
282 volume of the debris avalanche deposit was calculated at 0.3 km^3 (Oba, 1966).
283 Assuming that half of the debris avalanche deposit consists of somma lava, the total
284 volume of Usu somma lava is estimated at about 0.5 km^3 .

285

286 3.7. *Zenkoji debris avalanche deposit*

287 Zenkoji debris avalanche deposit, which was previously called Zenkoji mud flow

288 deposit (Kondo, 1963), is distributed on the southern foot of Usu Volcano, mainly from
289 80 m asl to the coastline of Uchiura Bay (Soya et al., 2007). Numerous hummocky
290 hills can be recognized in the distributed area. The hummocky hills are divided into
291 two types of blocks: blocks of the Usu somma lava and pumiceous blocks including
292 Toya ignimbrite and Kaminagawa Formation. The pumiceous blocks appear from the
293 eastern to southern edges of the deposit, whereas lava blocks are uniformly recognized
294 all around the deposit area (Soya et al., 2007). The largest hummock is 700 m across
295 in long axis and 50 m high.

296 The debris avalanche blocks composed of Usu somma lava range in thickness
297 from 3 m to more than 7 m (Fig. 10A). These lavas are basaltic andesite in
298 composition ($\text{SiO}_2=53.7\text{-}54.7$ wt.%) and their occurrence is similar to the Usu somma
299 lava. Jigsaw cracks are distinctly observed in the lava blocks, indicating that lava
300 blocks are remarkably fractured (Fig. 10B). The Zenkoji debris avalanche deposit is
301 well exposed at a quarry located at the southeastern part of the deposit where it is at
302 least 15 m thick (locality 61; Fig. 10C). Two sets of fractured lava blocks divided the
303 upper (3-7 m thick) and lower parts (>7 m thick) of the deposit separated by a brown to
304 reddish brown tephra block of 1.5-4 m thick (Fig. 10D). Although this tephra block
305 consists mainly of fine ash, major pumice-fall deposits including Nj-Os and Nj-Sk are
306 recognized in the tephra block. The depositional structures of these fallout tephra
307 layers (alternating beds of pumice and ash) are well preserved though it is partially to

308 highly deformed (Fig. 10D). Moreover, the upper part of the fine tephra block is
309 notably reddish colored and contains abundant accretionary lapilli. At locality 13, the
310 reddish brown tephra block (10-20 cm thick) occurs at the base of Zenkoji
311 debris-avalanche deposit and directly overlies the Toya ignimbrite.

312

313 *3.8. Minor tephra layers below Usu 1663 tephra*

314 A black humic soil (<1 m thick) occurs about 60 cm above the Zenkoji
315 debris-avalanche deposit at locality 13. The black soil and the debris-avalanche
316 deposit is separated by reworked vitric sediments. At tephra sections where the
317 Zenkoji debris-avalanche deposit does not exist, the black soil occurs approximately
318 0.5-1.0 m above the Usu prehistoric tephra. Two vitric ash layers are intercalated in
319 the black humic soil at the locality 32. The thicknesses of the upper and the lower
320 vitric ash are 18 cm and 7 cm, respectively.

321 Komagatake 1640 tephra (Ko-d; Yamada, 1958) exists near the top of the black
322 soil (1 cm below the top) at most sections (Fig. 5G). Ko-d is a white fine vitric ash
323 and ranges in thickness between 0.7 and 1.3 cm in the study area. Baitoushan
324 Tomakomai tephra (B-Tm; Machida and Arai, 2003) is recognized 3 cm below the Ko-d
325 tephra at some sections (e.g., locality 20). B-Tm is also a white fine vitric ash of 1-2
326 cm thick. The age of B-Tm was determined at 923-939 AD by using wiggle-match
327 dating (Yin et al., 2012).

328

329 3.9. *Usu 1663 tephra*

330 Usu 1663 tephra, which is the most distinct tephra layer near the surface southeast
331 of Toya caldera, directly overlies the black humic soil including B-Tm and Ko-d tephras
332 (Fig. 5H). The 1663 eruption was divided into three stages in ascending order: stage I
333 (small plinian and phreatomagmatic eruptions), stage II (climatic plinian eruption) and
334 stage III (vigorous phreatomagmatic eruptions) (Matsumoto et al., 2005). The stage I
335 deposit, which corresponds to unit-A of Nakamura et al. (2005), is composed of the
336 lower well-stratified ash (ash-fall and surge) and the upper pumice fall.

337 The stage II deposit (unit-B; Nakamura et al., 2005) consists mainly of coarse light
338 gray (5Y8/1) well-vesiculated rhyolitic ($\text{SiO}_2 = 74.5\text{-}75.5$ wt.%) pumiceous lapilli with
339 small amount of gray lithic fragments. The bulk density of pumiceous clasts in the
340 stage II deposit is $0.4\text{-}0.5$ g/cm³ (average 0.4 g/cm³). The maximum thickness and
341 maximum size of pumice (MP) of stage II deposit are 175 cm and 8 cm at locality 22.
342 The stage II pumice-fall deposit shows a very narrow E-trending dispersal, but it
343 reaches the Tokachi Plain (ca. 250 km east of Usu Volcano), eastern Hokkaido. The
344 bulk volume of the stage II pumice was estimated at 2.2 km³ (Oba and Kondo, 1964).

345 The stage III deposit, which corresponds to Us-b₁ to -b₆ ash fall of Yokoyama et al.
346 (1973), is a well-stratified sequence of fine ash alternating with pumice falls, is
347 moreover divided into five units (units C to G) by Nakamura et al. (2005). The middle

348 part of the stage III deposits contains a cross-stratified fine to medium ash, indicating
349 that it is a surge deposit, whereas most of the stage III deposits are fallout tephras. The
350 upper ash-fall deposits include abundant accretionary lapilli. The total thickness of
351 stage III deposit reaches 147 cm at locality 46. The stage III deposits are distributed as
352 an oval around Usu Volcano (Yokoyama et al., 1973; Nakamura et al., 2005). The bulk
353 volume of the stage III deposits (Us-b₁ to -b₆ ash-fall and base surge deposits;
354 Yokoyama et al., 1973), was estimated at approximately 0.6 km³ (Katsui et al., 1981).

355

356 *3.10. Subsequent Usu historic tephra layers*

357 Some historical tephra layers are intercalated within black humic soil overlying the
358 Usu 1663 tephra. Four tephra units, which are separated by soil layers (4-18 cm thick),
359 are observed at the northwestern foot of Usu Volcano (locality 1). They comprise
360 alternating beds of pumice and ash except for the upper second unit (only 9-cm-thick
361 pumice-fall deposit). We believe that these tephra units are products of 1769, 1822,
362 1853 and 1977 eruptions in ascending order (Fig. 11). In contrast, three tephra units,
363 which are separated by soil layers (2-8 cm thick), can be recognized above the 1663
364 tephra at locality 18, about 5.5 km SSE of Usu Volcano. The lower unit consists of
365 alternating bed of ash and pumice (total 33 cm thick), whereas the middle (21 cm thick)
366 and upper (3 cm thick) units are single pumice-fall deposits. They may be 1769, 1822
367 and 1977 eruption deposits in ascending order. However, we could not find out the

368 pre-1769 eruption deposit (Nakagawa et al., 2005) during our fieldwork.

369

370 **4. Age determination**

371 Humic soils and charcoal fragments just below tephra layers were sampled at two
372 sections (localities 32 and 46) for radiocarbon dating. All samples were cleaned
373 chemically with acid-alkali-acid (AAA) treatment and combusted to CO₂. The CO₂
374 produced was cryogenically purified and then converted catalytically to graphite
375 (Kitagawa et al., 1993). Ages of four samples were measured by a
376 JAEA-AMS-TONO at the Tono Geoscience Center, JAEA (Xu et al., 2000). The three
377 carbon-isotopes in the samples and the NIST oxalic acid (HOxII) standard were
378 measured with the AMS systems. The ¹³C/¹²C ratios (δ¹³C_{PDB}) obtained by the AMS
379 were used to correct carbon isotopic fractionation when calculating conventional ¹⁴C
380 ages. To estimate the ¹⁴C background level, the ¹⁴C concentration of IAEA C1
381 (marble) was also measured in the same analytic sequence of sample and standard
382 measurements. The ¹⁴C age was calculated by subtracting the ¹⁴C concentration of the
383 background sample. An age of one sample was obtained at the Institute of Accelerator
384 Analysis Ltd., Japan.

385 Soil samples below upper and lower vitric ash in black soil from locality 32 were
386 dated at 5755±40 years BP and 8050±45 years BP, which correspond to 6656-6453 cal
387 years BP (2 σ; ca. 6.6 ka) and 9090-8727 cal years BP (2 σ; ca. 8.9 ka), respectively.

388 The charcoal sample from soil below vitric ash underlying Nj-Sk tephra at locality 46
389 was dated at $28,310 \pm 130$ years BP, corresponding to 33,153-31,966 cal years BP (2σ ;
390 ca. 33 ka). Since there is no soil layer indicating a long time interval between the
391 vitric ash and Nj-Sk tephra, both are believed to be erupted around 30 ka. Goto et al.
392 (2013) reported calibrated ^{14}C ages of 19-18 ka for the Nj-Sk tephra (they described as
393 Us-Ka tephra). However, these ages are stratigraphically inconsistent with the age of
394 Zenkoji debris avalanche deposit described below.

395 We obtained ^{14}C ages of $32,590 \pm 210$ years BP from humic soil below Shikotsu
396 tephra (reworked deposit), which corresponds to 37,917-36,552 cal years BP (2σ ; ca.
397 37 ka), and $42,350 \pm 450$ years BP ($46,379$ - $44,885$ cal years BP; ca. 46 ka) from charcoal
398 sample included in the humic soil underlying Shikotsu tephra. There is a difference of
399 about 9000 years in age between humic soil and charcoal samples. In respect to the
400 Shikotsu tephra (Spfa 1), Yanagida (1994) reported a ^{14}C date of $41,200 \pm 1180$ years BP,
401 which is close to our age (ca. 46 ka) obtained from charcoal sample. Since the
402 Shikotsu tephra at the sampling locality is reworked deposit, the age of tephra is thought
403 to range from 46 to 37 ka.

404 We could not obtain any radiometric ages for Nj-Os and Kt-2, which are below
405 Shikotsu tephra. A ^{14}C age of $45,500 \pm 2000$ years BP for Kuttara Takeura tephra
406 (Kt-Tk) was obtained at the Ishikari Lowland (Kato et al., 1995). Kt-Tk, which is
407 scoria-fall deposits alternating with ash, underlies Kt-2 tephra and the two tephra were

408 separated by not so thick soil layer (Yamagata, 1994). Therefore, the time gap
409 between Kt-Tk and Kt-2 is believed to be less than a few thousand years.

410 Based on ^{14}C ages from our study and previous tephrochronological studies, we
411 estimate the eruption ages of tephra layers distributed around Toya caldera as follows:
412 ca. 50 ka for Kt-2, 48 ka for Nj-Os, 46-37 ka for reworked Shikotsu tephra, and 30 ka
413 for Nj-Sk and the underlying vitric ash.

414

415 **5. Petrographic and chemical composition**

416 *5.1. Whole rock chemistry*

417 Major element compositions of post-caldera pumice and scoria clasts and lavas
418 obtained in and around Toya caldera were determined by X-ray fluorescence (XRF) on
419 flux-fused disks with a Rigaku ZSX100e at Division of Instrumental Analysis, Frontier
420 Science Research Center, Kagoshima University. Sample preparation techniques and
421 analytical procedures are based on those of Yokose and Nedachi (2011). To make
422 fused glass beads, lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$) was used as a flux (1:10 dilution).

423 The post-caldera eruptive products of Toya Volcano have a wide compositional
424 range from basalt to rhyolite (Table. 2, Fig. 12). The tephra fallout deposits (Nj-Os
425 and Nj-Sk) and dome lavas of Nakajima Volcano occupy a relatively narrow range with
426 andesitic to dacitic composition ($\text{SiO}_2=61.7\text{-}66.0$ wt.%). In contrast, tephtras and lavas
427 originating from Usu Volcano are characterized by bimodal composition. Usu

428 prehistoric tephra and somma lava including lava blocks in Zenkoji debris avalanche
429 deposit have mafic compositions ($\text{SiO}_2=51.9\text{-}54.8$ wt.%). Scoria clasts of
430 Donkoroyama, which is a parasitic scoria cone on the NE foot of Usu Volcano, have
431 similar chemical compositions ($\text{SiO}_2=54.2\text{-}54.3$ wt.%) to that of Usu somma lava. The
432 Usu 1663 pumice has extremely silicic composition ($\text{SiO}_2=74.5\text{-}75.5$ wt.%) and
433 subsequent historical tephra and dome lavas erupting between 1769 and 2000 show
434 dacitic to rhyolitic compositions (68.7-71.3 wt.%; Soya et al., 2007). It is reported that
435 SiO_2 contents of the historical products decreased with time (Oba, 1966; Oba et al.,
436 1983; Nakagawa et al., 2002, 2005). The chemical compositions of magma related to
437 post-caldera activity of Toya Volcano therefore vary between ages. On the K_2O versus
438 SiO_2 diagram Usu tephra and lavas have compositions corresponding to low-K basalt
439 to andesite. On the contrary, Nakajima tephra and dome lavas are plotted in the field
440 of medium-K andesite to dacite or near the boundary between the low- and medium-K
441 fields although only Nj-Sk pumice is plotted in the low-K field (Fig. 12).

442

443 5.2. Petrography

444 With respect to tephra fallout deposits from Nakajima Volcano, the Nj-Os tephra
445 contains plagioclase, hornblende, orthopyroxene and quartz phenocrysts (Fig. 13).
446 Phenocrystic minerals in the Nj-Sk tephra are plagioclase, orthopyroxene, hornblende
447 and minor clinopyroxene. Dome lavas of Nakajima Volcano include plagioclase,

448 hornblende, orthopyroxene, and minor clinopyroxene and quartz phenocrysts and show
449 hyalopilitic to intersertal groundmass textures. In contrast, the Usu somma lavas
450 contain phenocrysts of plagioclase, orthopyroxene, olivine and minor clinopyroxene,
451 and exhibit intersertal or hyalopilitic groundmass textures. The Usu 1663 pumice is
452 nearly aphyric with small amounts of plagioclase, orthopyroxene phenocrysts and rare
453 hornblende and clinopyroxene phenocrysts. Although the major phenocrystic minerals
454 of subsequent historical (1769-2000) dome lavas and tephra are similar to the 1663
455 pumice, the 1769-1853 pumices include a small amount of quartz phenocrysts
456 (Matsumoto and Nakagawa, 2010). Thus, there is a difference in phenocrystic mineral
457 assemblage between Nakajima and Usu Volcanoes.

458

459 *5.3. Glass shard chemistry*

460 We analyzed the major chemical compositions of volcanic glass shards included in
461 major tephra around Toya caldera using an energy dispersive electron probe
462 microanalyzer (EDS-EPMA) to characterize these tephra layers. Tephra samples were
463 washed using an ultrasonic cleaner and wet-sieved using a 1/16-mm sieve. The
464 remaining particles were dried at <40 °C and embedded in mounts made of polyester
465 resin. Mount surfaces were polished with diamond paste (1 µm) until the internal
466 surfaces of the glass particles were exposed, and were then coated with carbon. We
467 analyzed the major oxide compositions of 9 major elements (Si, Ti, Al, Fe, Mn, Mg, Ca,

Na, and K) in the volcanic glass shards using a scanning electron microscope (SEM; JEOL JSM-7001F) equipped with an energy dispersive X-ray spectrometer (EDS; Oxford INCA X-Max) at the Faculty of Science, Kumamoto University, Japan. The EDS accelerating voltage was 15 kV, the specimen current was 1 nA, the live time was 50 s, and the beam scanning area was 10 μm wide for all samples. We used the ZAF correction method (Sweatman and Long, 1969) to calculate the oxide abundances. We measured 1 point on each volcanic glass shard and 10–20 points per sample. The accuracy and precision of this analysis were checked by an obsidian standard (ID3506, Mineralogical and Geological Museum at Harvard University). The AT ash (Aira caldera, SW Japan) was used as an in-house standard because it is very homogeneous with respect to the major elements (e.g., Machida and Arai 2003; Moriwaki et al. 2011).

The mean values and standard deviations of major chemical compositions of volcanic glass shards in each sample are shown in Table 3. On the CaO and K₂O versus SiO₂ diagrams (Fig. 14), glass shards included in the Toya ignimbrite are divided into two types: A type (potassium rich) and B type (calcium rich). On the CaO and Na₂O versus SiO₂ diagrams (Fig. 14), the plots of vitric ash overlying the Zenkoji debris avalanche deposit and vitric ash in black soil overlap with those of Toya ignimbrite (A type). Reworked Shikotsu tephra, the vitric ash underlying Nj-Sk and the 6.6 ka vitric ash occupy a similar area with proximal Shikotsu ignimbrite sampled at a site near Shikotsu caldera (45 km E of Toya caldera) on almost all diagrams although proximal

488 Shikotsu tephra can be distinguished from reworked Shikotsu tephra, the vitric ash
489 below Nj-Sk and the 6.6 ka vitric ash only on the Na₂O versus SiO₂ diagram. This
490 indicates a possibility that the Shikotsu pyroclastic flow deposit is composed of several
491 flow units which have different chemical compositions. The composition of the 8.9 ka
492 vitric ash is similar to that of Komagatake g tephra (Ko-g; M. Yoshimoto unpublished
493 data). The Nakajima Osarugawa tephra (Nj-Os) plots in a different field from other
494 tephtras. These facts suggest that vitric ash overlying the Zenkoji debris avalanche
495 deposit is a reworked tephra from Toya ignimbrite and that vitric ash underlying Nj-Sk
496 and the 6.6 ka vitric ash were formed by reworking of the Shikotsu tephra.

497

498 **6. Discussion**

499 *6.1. Age of initial activity of Usu Volcano*

500 It has been thought that Usu Volcano started its activity during early Holocene
501 (Kondo, 1963; Oba, 1966) or Late Pleistocene (14-9 ka: Ohshima, 1968; 20-10 ka?;
502 Soya et al., 2007). Furthermore, Goto et al. (2013) regarded Nj-Sk tephra as the initial
503 eruption deposit of Usu Volcano, and reported its age of 19-18 ka. However, we
504 demonstrated that the tephra originated not from Usu Volcano but from Nakajima
505 Volcano based on the petrographic and chemical characteristics. We assume that the
506 Usu prehistoric tephra, which is alternating sequence of scoria and ash, and somma lava
507 are products of the initial activity of Usu Volcano because we cannot recognize any

508 tephra and lava originating from the volcano below the Usu prehistoric tephra. As
509 mentioned above, the eruption age of Nj-Sk tephra from Nakajima Volcano inside the
510 Toya caldera is approximately 30 ka. The Nj-Sk pumice-fall deposit is overlain by
511 brown to gray fine ash-fall deposits containing abundant accretionary lapilli. Although
512 the top of the fine ash-fall deposits displays a wavy erosional surface, the overlying Usu
513 prehistoric tephra directly fills the erosional surface. There is no distinct soil layer
514 between the Nj-Sk and Usu prehistoric tephra. This indicates that three eruptive
515 phases, producing first the Nj-Sk and then the accretionary lapilli rich fine ash-fall
516 deposits, and thereafter the Usu prehistoric tephra, occurred with little break, although
517 the sources of the first two and the last are quite different. We therefore envisage that
518 Usu Volcano started its activity around 30 ka immediately after the Nakajima eruptions
519 produced the Nj-Sk pumice and the subsequent fine ash-fall deposits.

520

521 *6.2. Timing and generation mechanism of the Zenkoji debris avalanche*

522 Ohshima (1968) presumed that the Zenkoji debris avalanche occurred between 9
523 and 6 ka years BP based on the existence of archaeological remains and shell mounds
524 on top of the deposit. These remains are frequently found during the earlier and last
525 part of the Japanese Jomon period. The author also estimated the highest rise in the
526 sea level due to the Holocene glacial retreat, which is called the Jomon Transgression.
527 Our correlation of tephra layers around Toya caldera reveals that the Zenkoji debris

528 avalanche deposit underlies the black soil dated at 8.9 ka (calibrated ^{14}C age; Fig. 3).
529 Recently, the excavations of the Usu-6 site (locality 54), which is located above the
530 Zenkoji debris avalanche deposit, were conducted by Hokkaido University, yielded
531 another calibrated ^{14}C age of ca. 14 ka from charcoal fragments included in a soil layer
532 overlying the debris avalanche deposit (Kobayashi et al., 2006). This suggests that the
533 Zenkoji debris avalanche deposit is older than 14 ka. Furthermore, a drill hole
534 performed at a lowland between hummocks near the southern edge of the debris
535 avalanche deposit (near locality 14) yielded another calibrated ^{14}C date of ca. 20 ka near
536 the base of a muddy deposit, which is thought to be above the Zenkoji debris avalanche
537 deposit (Fujine et al., 2013). Thus, it is likely that the timing of occurrence of the
538 Zenkoji debris avalanche is much older than 9-6 ka years BP (Ohshima, 1968). We
539 envisage that Usu Volcano formed its edifice by discharges of tephra and lava around 30
540 ka and that the sector collapse, accompanying the Zenkoji debris avalanche deposit,
541 occurred with little break.

542 As mentioned above, a brown to reddish brown tephra block, which consists
543 mainly of fine ash, occurs inside the Zenkoji debris avalanche deposit, and the
544 depositional structure of fallout tephra layers (alternating beds of pumice and ash) is
545 well preserved although it is partially to highly deformed. We believe that the block
546 originated from tephra layers underlying the somma lava on the volcanic edifice. The
547 upper part of the fine tephra block in the debris avalanche deposit contains abundant

548 accretionary lapilli and is characterized by its reddish color. In contrast, the fine tephra
549 layers including Nj-Os and Nj-Sk pumices are brown to gray colored outside the
550 deposition area of the debris avalanche. We therefore presume that brown to reddish
551 colored fine tephra layers included in the Zenkoji debris avalanche deposit were altered
552 just below the Usu somma lava. There is a possibility that the altered and vulnerable
553 fine tephra layers caused an instability of the volcanic edifice (Frank, 1995; Day, 1996),
554 and that a large sector collapse resulting in the Zenkoji debris avalanche was triggered
555 probably by an intense earthquake (e.g., the 1792 Mayuyama debris avalanche at Unzen
556 Volcano, SW Japan; Katayama, 1974) because the associated eruption deposits cannot
557 be recognized around Usu Volcano.

558

559 *6.3. Post-caldera eruptive history of Toya Volcano based on reconstructed tephra* 560 *stratigraphy*

561 On the basis of the reconstructed tephrostratigraphy, the post-caldera eruptive
562 history of Toya Volcano is interpreted as follows (Fig. 15). A series of large
563 pyroclastic eruptions occurred at Toya Volcano ca. 115-112 ka (Machida and Arai,
564 2003), and the eruptions formed the Toya caldera, which is approximately 12 km in
565 diameter, and an extensive pyroclastic-flow plateau in the surrounding area. After the
566 caldera formation, there was a long quiescent period of more than 60 ka years at Toya
567 Volcano. In contrast, Kuttara Volcano, which is located about 30 km ENE of Toya

568 caldera, had repeated explosive pyroclastic eruptions after 90 ka (Yamagata, 1994).
569 One of the large pyroclastic eruptions gave rise to Kuttara 2 tephra (Kt-2), which is a
570 thick pumice-fall deposit and more than 2.7 m thick around Toya caldera, at ca. 50 ka.

571 The first distinct post-caldera eruptive activity occurred at Nakajima Volcano,
572 which is located near the center of Toya caldera, at ca. 48 ka. The eruption produced a
573 pumice-fall deposit named as Nakajima Osarugawa tephra (Nj-Os) with a bulk volume
574 of 0.44 km³. Yamagata (1996) recognized the Aso-4 tephra from Kyushu
575 (southwestern Japan; 89 ka) in the soil layer between the Toya ignimbrite and Kt-2
576 pumice-fall deposit, and furthermore Nakajima Date tephra (Nj-Dt) above the Aso-4
577 tephra, and regarded Nj-Dt as the first post-caldera eruption deposit. If his
578 presumption is right, the post-caldera activity started soon after 89 ka at Toya Volcano.
579 Because we could not discover any tephra layers correlated to Nj-Dt, we envisage that
580 the post-caldera activity initiated with Nj-Os at 48 ka.

581 At ca. 46 ka, a series of large caldera-forming eruptions occurred at Shikotsu
582 Volcano, which is located approximately 40 km ENE of Toya Volcano, and the related
583 large pyroclastic flows reached to Toya caldera and its surrounding area. Some parts
584 of the pyroclastic flow deposits were remobilized into lahars.

585 Thereafter, at ca. 30 ka a series of explosive eruptions occurred at Nakajima
586 Volcano inside the caldera. Just before the eruption wind erosion and reworking of
587 pyroclastic materials including the Shikotsu tephra formed a layer of vitric ash around

588 the Toya caldera. The 30 ka activity at Nakajima Volcano started with ejection of a
589 poorly-vesiculated andesitic pumice-fall deposit: Nakajima Sekinai tephra (Nj-Sk; 0.033
590 km³ in bulk volume). Subsequently, eruptions emitting fine ash occurred inside the
591 caldera. The existence of abundant accretionary lapilli in the fine ash-fall deposits
592 suggests that the eruptions were phreatomagmatic in an aquatic environment inside the
593 Toya caldera. A wavy deformation is observed in the upper part of fine-ash fall
594 deposits. The evidence suggests that intense earthquakes might have occurred and
595 deformed ash-fall deposits at the late stage of the Nakajima eruption.

596 Present Nakajima Volcano inside Lake Toya comprises about nine lava domes
597 (Yokoyama et al., 1973). The total volume of lava domes is estimated at about 1.8 km³,
598 assuming that the base of the lava domes is -160 m below the lake surface. Although
599 stratigraphic relationship between the dome lavas and other tephra layers is not clear,
600 we assume that lava domes were formed contemporaneously with pyroclastic eruptions
601 at Nakajima Volcano between 48 and 30 ka.

602 The 30 ka Nakajima pyroclastic eruptions were followed by eruptive activity of
603 Usu Volcano at the southern rim of Toya caldera. The initial activity at Usu Volcano is
604 characterized by discharges of basaltic ash and scoria, resulting in the Usu prehistoric
605 tephra east of the volcano. Moreover, homogeneous lavas namely Usu somma lavas
606 were extruded during the initial eruptive episode. The series of eruptions produced
607 lavas of about 0.5 km³ (Oba, 1966) and tephra of 0.055 km³, and formed an initial

608 volcanic edifice (Fig. 15). Donkoroyama cone on the northeastern foot of Usu Volcano
609 is thought to be formed during the initial stage of the volcano (Soya et al., 2007) based
610 on stratigraphic relationship that Donkoroyama scoria is overlain by the Usu 1663
611 pumice-fall deposit (locality 4).

612 A large sector collapse generated Zenkoji debris avalanche between 30 and 20 ka
613 with little break after the formation of the initial Usu volcanic edifice. The debris
614 avalanche cascaded down the southern slope of the volcano, involving pyroclastic
615 material including the Toya ignimbrite and the underlying Kaminagawa Formation
616 during its flow to the Uchiura Bay. The volume of the debris avalanche deposit was
617 estimated at 0.3 km³ (Oba, 1966). We presume that that the altered and vulnerable fine
618 tephra layers underlying the Usu somma lava caused an instability of the volcanic
619 edifice favoring the large sector collapse that produced the Zenkoji debris avalanche
620 likely triggered by an earthquake because no pyroclastic deposits have been recognized
621 around Usu Volcano.

622 After the sector collapse, there was a long dormant period of about 20-30 ka yr at
623 Toya Volcano. During the quiescent period, human activities are recognized on the
624 southern foot of Usu Volcano according to the existence of archaeological remains and
625 shell mounds in the earlier part (12-7 ka) to the last part (3.3-2.8 ka) of the Japanese
626 Jomon period above the debris avalanche deposit (Kobayashi et al., 2006). In
627 Holocene time, multiple vitric tephras were emplaced by explosive eruptions of other

628 volcanoes including Komagatake (ca. 60 km SSW) at southern Hokkaido and
629 Baitoushan at North Korea and China (ca. 1100 km west of Hokkaido).

630 A dormant period of about 20-30 ka yr was ended by a series of explosive
631 pyroclastic eruptions at Usu Volcano in 1663 AD. The eruptions began with relatively
632 small plinian and phreatomagmatic eruptions and shifted to a large plinian eruption
633 (Matsumoto et al., 2005; Nakamura et al., 2005). The plinian eruption produced 2.2
634 km³ pumice-fall deposit extending to the Tokachi Plain, eastern Hokkaido (Oba and
635 Kondo, 1964), and was followed by violent phreatomagmatic eruptions forming thick
636 alternating beds of ash-fall and pyroclastic surge deposits (total ca. 0.6 km³; Katsui et al.,
637 1981) around Usu Volcano (Nakamura et al., 2005). The 1663 eruption of Usu
638 Volcano is the largest pyroclastic eruption in the post-caldera stage of Toya Volcano.

639 Since 1663, seven historic eruptions have been recorded in 1769, 1822, 1853,
640 1910, 1943-1945, 1977-1978 and 2000 at multi-decadal interval (Yokoyama et al.,
641 1973; Soya et al., 2007). The 1769, 1822 and 1853 eruptions were explosive pumice
642 eruptions accompanying with pyroclastic flows, and formed lava domes (Ko-Usu in
643 1769 and O-Usu in 1853) or cryptodome (Ogariyama in 1822) on the summit (Soya et
644 al., 2007). The 1910 eruption expelled small amounts of ash-fall deposits (Us-IIa ash;
645 ca. 0.003 km³; Katsui et al., 1981) from numerous explosion craters and built the Meiji
646 Shinzan volcanogenetic mound on the northern foot (Yokoyama and Seino, 2000;
647 Tanaka and Yokoyama, 2013). The 1943-1945 eruption was characterized by the

648 formation of the Showa Shinzan lava dome on the eastern foot, preceded by a few tens
649 of explosions producing the Us-Ia ash (ca. 0.001 km³). The 1977-1978 eruption
650 produced subplinian pumice-fall deposit and ash-fall deposits and formed Usu Shizan
651 cryptodome on the summit (Katsui et al., 1981; Niida et al., 1982). In 2000, a
652 phreatomagmatic eruption discharging a small amount of juvenile materials occurred on
653 the northwestern foot of Usu Volcano (e.g., Ui et al., 2002; Nakagawa et al., 2002; Ohno
654 et al., 2002; Takarada et al., 2002). The 2000 eruption was characterized by
655 remarkable upheaval of grounds and the formation of fault swarms (Koarai et al., 2002;
656 Hirose and Tajika, 2002).

657

658 *6.4. Temporal variation in magma discharge*

659 On the basis of the bulk volumes and ages of tephra beds, the cumulative tephra
660 discharge volume of post-caldera activity of Toya Volcano was estimated (Fig. 16).
661 We assume that Nakajima lava domes were formed contemporaneously with pyroclastic
662 eruptions at Nakajima Volcano between 48 and 30 ka although the detailed dome
663 forming ages are unknown. The tephra volume is shown as the dense rock equivalent
664 (DRE; 2.5 g/cm³) calculated using a bulk density of 0.6 g/cm³ for Nj-Os pumice, 1.1
665 g/cm³ for Nj-Sk pumice and 0.4 g/cm³ for Usu 1663 and other historic pumice-fall
666 deposits. A bulk density of the Usu 2000 ash (1.0 g/cm³; Takarada et al., 2002) was
667 adopted for the ash-fall deposits around Toya caldera.

668 The total tephra volume in the post-caldera stage of Toya Volcano is estimated at
669 about 0.9 km³ (DRE), corresponding to an average tephra discharge rate of 0.01 km³/ky.
670 The discharge rate is one order of magnitude smaller than those of Shikotsu Volcano at
671 SW Hokkaido (0.13 km³/ky in post-caldera stage; Furukawa and Nakagawa, 2010) and
672 Aso Volcano at Kyushu, SW Japan (0.2 km³/ky in post-caldera; Miyabuchi, 2009), and
673 it is two order smaller than Kutcharo Volcano at eastern Hokkaido (3 km³/ky in
674 post-caldera; Hasegawa et al., 2009). The tephra discharge at post-caldera Toya
675 Volcano concentrated in three periods: 48 ka, 30 ka and historic time (mainly 1663 AD),
676 was intercalated with long dormant periods of about 20-30 ka years. The 1663
677 eruption of Usu Volcano is the largest pyroclastic eruption in the post-caldera stage that
678 produced 0.59 km³ tephra (pumice and ash). About 70 % of the post-caldera tephra in
679 volume was discharged during the 1663 eruption.

680 In contrast, the total volume of lavas erupted in the post-caldera stage of Toya
681 Volcano is calculated at about 2.3 km³ (DRE), corresponding to an average lava
682 extrusion rate of 0.02 km³/ky. The discharge rate of lava is two times larger than that
683 of the tephra. The lava extrusion at post-caldera Toya Volcano occurred at two
684 periods: 48-30 ka and historic time (1769, 1853 and 1945 AD), intercalated with a long
685 dormant period of about 30 ka years. Most (99 %) of post-caldera lava was effused at
686 48-30 ka, whereas the total volume of historic dome lavas was very small (0.04 km³).
687 Nakajima Volcano is thought to form at least nine lava domes with a total volume of

688 about 1.8 km³ between 48 and 30 ka although detailed age of individual lava dome
689 cannot be determined in this study. The Nakajima dome-forming eruptions were
690 followed by extrusion of the Usu somma lava with volume of about 0.5 km³ (Oba,
691 1966).

692 Thus, post-caldera activity of Toya Volcano is characterized by long quiescent
693 periods (30-60 ky) and explosive or effusive eruptions between the dormant periods.
694 The lava extrusion volume was large at 48-30 ka, whereas the tephra discharge volume
695 was larger in historic time (mostly 1663 AD).

696 Most of historical activity since 1663 AD was characterized by subplinian or
697 plinian eruptions accompanied by pyroclastic flows and/or surges, with intervals of
698 several decades between these eruptions. The silica content of the historical products
699 of Usu Volcano tends to decrease with time from 74 wt.% (AD 1663) to 69 wt.% (AD
700 2000) (Oba et al., 1983; Nakagawa et al., 2002). Tomiya and Takahashi (2005)
701 suggested that the same magma-feeding system beneath Usu volcano has existed
702 continuously between the 1663 and the 2000 eruption. Thus, the characteristics of
703 erupted magma and eruption style in historic time were quite different from those before
704 30 ka. This suggests that a new magma plumbing system, which was quite different
705 from that before 30 ka, was formed after the long repose of about 30 ka years at Toya
706 Volcano.

707

708 **7. Conclusions**

709 Toya Volcano is one of the largest caldera volcanoes in Hokkaido, northern Japan.
710 The tephrostratigraphic sequence preserved above the Toya ignimbrite (caldera-forming
711 pyroclastic flow deposit) reveals the post-caldera eruptive history of Toya Volcano.
712 The total tephra volume in the post-caldera stage of Toya Volcano is estimated at about
713 0.9 km³ (DRE), corresponding to an average tephra discharge rate of 0.01 km³/ky. In
714 contrast, the total volume of lavas erupted in the post-caldera stage of Toya Volcano is
715 calculated at about 2.3 km³ (DRE), corresponding to an average lava extrusion rate of
716 0.02 km³/ky. The post-caldera activity of Toya Volcano is characterized by long
717 quiescent periods (30-60 ka years) and explosive or effusive eruptions between the
718 dormant periods. The lava extrusion volume was large at 48-30 ka, whereas the tephra
719 discharge volume was large in historic time (mostly 1663 AD). The characteristics of
720 erupted magma and eruption style vary between before 30 ka and after 1663 AD. We
721 consider that the magma plumbing system before 30 ka was different from that formed
722 after the long repose of about 30 ka years at Toya Volcano.

723 Although the average magma discharge rate in the post-caldera stage (115-112 ky)
724 of Toya Volcano (ca. 0.03 km³/ky) may be one or two orders of magnitude smaller than
725 those of other Quaternary volcanoes in Japan, both the frequency (multi-decadal
726 interval) and magma discharge rate (0.77 km³ for the last 350 years; corresponding to
727 2.2 km³/ky) since 1663 AD are very high. Therefore, Usu Volcano, which is one of

728 post-caldera volcanoes of Toya Volcano, can be inferred to be one of the most hazardous
729 active volcanoes in Japan.

730

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960 **Figure captions**

961 **Table 1.** Results of AMS ^{14}C age determinations for paleosols and charcoal around
962 Toya caldera.

963 **Table 2.** Whole-rock chemical compositions of tephra and lava units distributed in
964 and around Toya caldera.

965 **Table 3.** Major element compositions (wt.%; normalized to an anhydrous basis) of
966 glass shards of tephtras distributed around Toya caldera.

967

968 **Fig. 1.** Location map of stratigraphic sections measured in and around Toya caldera.

969 The relief map was produced by Kashmir 3D using the 50-m-mesh DEM data
970 published by the Geospatial Information Authority of Japan.

971 **Fig. 2.** Aerial photograph of Usu Volcano, Showa Shinzan dome and Toya caldera
972 including Nakajima Volcano. The photo was taken by Mitsuhiro Yoshimoto on
973 May 21, 2009.

974 **Fig. 3.** Stratigraphic relations of tephra layers above the Toya ignimbrite around Toya
975 caldera. See Fig. 1 for locations of the sites.

976 **Fig. 4.** Photographs of typical tephra sequences at locality 5 (A) and locality 18 (B).

977 **Fig. 5.** Photographs of major tephtras above the Toya ignimbrite. (A) Kuttara 2
978 tephra (Kt-2) occurring 2 m above the Toya ignimbrite at locality 5. (B) Nakajima
979 Osarugawa tephra (Nj-Os) and Nakajima Sekinai tephra (Nj-Sk) at locality 5. (C)

980 Vitric ash layer underlying Nj-Sk tephra at locality 32. Scale segments are 10 cm.
981 (D) Nakajima Sekinai pumice-fall deposit (Nj-Sk) at locality 5. (E) Alternating
982 beds of brown to gray fine ash overlying Nj-Sk at locality 5. An erosional structure
983 occurs the top of the alternating beds. (F) Usu prehistoric tephra layers (basaltic
984 scoria falls alternating with layers of coarse to medium ash) directly overlying the
985 erosional surface of brown to gray fine ash at locality 20. (G) Komagatake 1640
986 tephra (Ko-d) included in black soil layer underlying Usu 1663 tephra at locality 18.
987 Scale in centimeters. (H) Usu 1663 tephra divided into three units at locality 11.
988 Scale segments are 10 cm.

989 **Fig. 6.** Photograph of tephra sequence including Kt-2, Nj-Os and Shikotsu tephra at
990 locality 32.

991 **Fig. 7.** Isopleth maps of Nakajima Osarugara tephra (A) and Nakajima Sekinai tephra
992 (B).

993 **Fig. 8.** Isopach maps of major tephra deposits in the post-caldera stage of Toya
994 Volcano.

995 **Fig. 9.** Photograph of tephra sequence below Usu somma lava at locality 12.

996 **Fig. 10.** Photographs of Zenkoji debris avalanche deposit. (A) Lava-block-rich
997 Zenkoji debris avalanche deposit at locality 8. (B) Fractured lava block included in
998 the Zenkoji debris avalanche deposit at locality 61. (C) Zenkoji debris avalanche
999 deposit of more than 15 m thick at a quarry located at the southeastern part of the

1000 deposit (locality 61). Fractured lava blocks are divided into the upper part and
1001 lower part by a brown to reddish brown tephra block. (D) Deformed tephra block
1002 including vitric ash and Nj-Os in the Zenkoji debris avalanche deposit at locality 61.
1003 Scale segments are 10 cm.

1004 **Fig. 11.** Usu historic tephra layers above the 1663 eruption deposit at locality 1.
1005 Scale segments are 10 cm.

1006 **Fig. 12.** SiO₂ variation diagrams for major elements of tephra and lavas in the
1007 post-caldera stage of Toya Volcano corresponding to whole-rock composition. Data
1008 for Usu 1769-2000 tephra and dome lava are from Soya et al. (2007). Lines in the
1009 K₂O versus SiO₂ diagram show the Low-K, Medium-K and High-K rock series
1010 boundaries summarized by Le Maitre et al. (1989).

1011 **Fig. 13.** Photomicrographs of tephra and lava units of post-caldera activity of Toya
1012 Volcano: (A) Nakajima Osarugawa pumice at locality 45; (B) Nakajima Sekinai
1013 pumice at locality 20; (C) Nakajima dome lava at locality 63; and (D) Usu somma
1014 lava at locality 10. Abbreviations: ho=hornblende; ol=olivine; opx=orthopyroxene;
1015 pl=plagioclase and qt=quartz.

1016 **Fig. 14.** Major element compositions in wt.% (normalized to an anhydrous basis) of
1017 glass shards included in tephra layers around Toya and Shikotsu calderas.
1018 Analytical value of Komagatake g tephra (Ko-g; M. Yoshimoto, unpublished data) is
1019 also plotted for comparison.

1020 **Fig. 15.** Schematic illustration showing post-caldera eruptive history of Toya Volcano.

1021 **Fig. 16.** Cumulative erupted volume versus time for tephra fallout and lava in the
1022 post-caldera stage of Toya Volcano. We assume that Nakajima lava domes were
1023 formed contemporaneously with pyroclastic eruptions at Nakajima Volcano between
1024 48 and 30 ka although the detailed dome forming ages are unknown.

Table 1Results of AMS ^{14}C age determinations for paleosols and charcoal around Toya caldera.

Stratigraphic position	Sample	Sampling site	$\delta^{13}\text{C}$ (‰)	Conventional ^{14}C age* (yrs BP)	Lab code	Calibrated result** (cal BP, 95.4%)
Soil below upper vitric ash	Humic soil	32	-24.9	5755 ± 40	JAT- 8291	6656 - 6453
Soil below lower vitric ash	Humic soil	32	-27.3	8050 ± 45	JAT- 8292	9090 - 8727
Soil below vitric ash underlying Nj-Sk pumice	Charcoal	46	-28.1	$28,310 \pm 130$	IAAA- 120535	33,153 - 31,966
Soil below Shikotsu tephra	Humic soil	32	-22.0	$32,590 \pm 210$	JAT- 8293	37,917 - 36,552
Soil below Shikotsu tephra	Charcoal	32	-27.8	$42,350 \pm 450$	JAT- 8287	46,379 - 44,885

* Conventional ^{14}C ages were calculated based on the Libby's ^{14}C half life of 5,568 years with $\delta^{13}\text{C}$ correction.

**Using the OxCal v4.1.7 program (Ramsey, 2009) based on the IntCal09 calibration database (Reimer et al., 2009).

Table 2

Whole-rock chemical compositions of tephra and lava units distributed in and around Toya caldera.

Sampling locality	Loc.45	Loc.20	Loc.63	Loc.20	Loc.10	Loc.61	Loc.4	Loc.11
Unit name	Nakajima Osarugawa	Nakajima Sekinai	Nakajima dome lava	Usu prehistoric	Usu somma lava	Zenkoji debris avalanche	Donkoro- yama	Usu 1663
Occurrence	pumice	pumice	lava	scoria	lava	lava block	scoria	pumice
Phenocryst assemblage	pl, ho, opx, qt, op	pl, ho, opx, cpx, op	pl, ho, opx, qt, op	pl, ol, opx, op	pl, opx, ol, cpx, op	pl, opx, op	pl, ol, opx, op	pl, opx, cpx, ho, op
SiO ₂ (wt.%)	61.70	61.68	65.74	52.64	53.76	54.00	54.35	74.48
TiO ₂	0.68	0.66	0.52	0.87	0.71	0.87	0.80	0.21
Al ₂ O ₃	18.56	17.69	16.14	19.07	17.71	19.28	17.93	14.07
FeO*	6.59	6.62	5.18	10.24	9.93	9.21	10.35	2.56
MnO	0.16	0.23	0.13	0.18	0.18	0.16	0.19	0.16
MgO	2.33	2.14	1.96	4.33	4.97	2.81	4.03	0.43
CaO	5.62	6.28	5.28	9.85	9.87	10.27	9.63	2.57
Na ₂ O	3.26	4.00	3.64	2.38	2.34	2.75	2.19	4.35
K ₂ O	0.93	0.54	1.30	0.34	0.44	0.50	0.44	1.14
P ₂ O ₅	0.16	0.17	0.11	0.11	0.09	0.16	0.10	0.04
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Values of whole rock chemical compositions are normalized on the anhydrous basis of total = 100 wt.%.

Abbreviations for phenocrystic minerals; cpx: clinopyroxene, ho: hornblende, ol: olivine, op: opaque mineral, opx: orthopyroxene, pl: plagioclase

Table 3

Major element compositions (wt.%; normalized to an anhydrous basis) of glass shards of tephra distributed around Toya caldera.

Sampling locality	Loc.32		Loc.32		Loc.32		Loc.32		Loc.12		Loc.13		Loc.13		Loc.32		Loc.32		45 km E of Toya caldera		----		----	
Tephra name	Toya pyroclastic flow deposit (a)		Toya pyroclastic flow deposit (b)		Nakajima Osarugawa		Shikotsu pyroclastic flow deposit (reworked)		Vitric ash underlying Nakajima Sekinai tephra		Vitric ash overlying Zenkoji debris avalanche deposit		Vitric ash in black soil		8.9 ka vitric ash		6.6 ka vitric ash		Shikotsu pyroclastic flow deposit		Obsidian standard (MGMH ID3506)		AT tephra (in-house standard)	
	AV (wt.%)	STD	AV (wt.%)	STD	AV (wt.%)	STD	AV (wt.%)	STD	AV (wt.%)	STD	AV (wt.%)	STD	AV (wt.%)	STD	AV (wt.%)	STD	AV (wt.%)	STD	AV (wt.%)	STD	AV (wt.%)	STD	AV (wt.%)	STD
SiO ₂	78.67	0.35	78.37	0.27	75.89	0.32	77.79	0.17	77.77	0.21	78.19	0.27	78.13	0.17	74.08	0.32	77.78	0.17	78.29	0.31	73.71	0.74	78.15	0.24
TiO ₂	0.11	0.07	0.16	0.07	0.48	0.07	0.16	0.07	0.19	0.09	0.12	0.09	0.09	0.06	0.55	0.08	0.21	0.06	0.18	0.07	0.06	0.07	0.14	0.08
Al ₂ O ₃	12.16	0.26	12.17	0.25	12.34	0.13	12.17	0.11	12.20	0.11	12.37	0.14	12.45	0.12	12.91	0.21	12.21	0.12	12.23	0.13	12.62	0.21	12.08	0.12
FeO*	0.91	0.12	1.13	0.15	2.34	0.15	1.57	0.12	1.47	0.08	0.96	0.13	0.91	0.12	2.97	0.16	1.50	0.16	1.20	0.35	1.50	0.11	1.18	0.13
MnO	0.08	0.06	0.10	0.08	0.08	0.11	0.08	0.08	0.08	0.10	0.09	0.07	0.11	0.07	0.12	0.09	0.05	0.08	0.09	0.06	0.06	0.09	0.06	0.09
MgO	0.06	0.04	0.16	0.04	0.55	0.06	0.16	0.05	0.17	0.05	0.04	0.04	0.06	0.05	0.67	0.05	0.17	0.05	0.17	0.06	0.04	0.06	0.12	0.07
CaO	0.35	0.07	1.21	0.10	2.49	0.10	1.49	0.09	1.50	0.08	0.40	0.06	0.41	0.04	2.93	0.10	1.47	0.09	1.52	0.05	0.77	0.06	1.07	0.15
Na ₂ O	4.81	0.18	4.53	0.11	3.94	0.08	4.01	0.10	4.13	0.09	4.88	0.10	4.89	0.17	4.05	0.10	4.05	0.10	3.67	0.10	3.89	0.14	3.70	0.08
K ₂ O	2.85	0.13	2.16	0.08	1.87	0.07	2.58	0.07	2.46	0.09	2.95	0.09	2.95	0.11	1.72	0.07	2.57	0.07	2.63	0.09	5.15	0.09	3.51	0.28
Cl																					0.32	0.03		
Total	95.11	0.81	95.89	0.64	96.11	1.39	96.93	0.57	96.49	1.33	94.68	0.60	97.68	1.05	97.79	1.24	97.91	0.83	95.10	0.91	98.13	1.04	93.30	0.91
N	19		7		23		19		25		22		20		12		17		25		39		15	

Analyses presented as a mean (AV) and standard deviation (STD). FeO*, total iron oxide as FeO; N, number of analyses.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16