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Geochemical characterisation of the Late Quaternary widespread Japanese tephrostratigraphic markers and correlations to the Lake Suigetsu sedimentary archive (SG06 core)

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Key words:

Japanese tephrostratigraphic markers; Lake Suigetsu (SG06 core); Tephrostratigraphy; Volcanic glass chemistry; LA-ICP-MS; Trace elements

Highlights:

- Near-source characterisation of Late Quaternary widespread Japanese tephrostratigraphic markers;
- Electron microprobe (EMP) and Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) grain-specific volcanic glass analyses;
- Chemical discrimination of Japanese volcanic source regions for the purposes of Tephrochronology
- Unlocking the Lake Suigetsu (SG06 core) visible tephra layers for reliable archive synchronisation;
- SG06 age estimates for widespread Japanese tephrostratigraphic markers;
- Proximal $^{40}\text{Ar}/^{39}\text{Ar}$ age of 86.4 ± 1.1 ka (2σ) for the Magnitude 7.7 caldera forming Aso-4 eruption.

Abstract

Large Magnitude (6-8) Late Quaternary Japanese volcanic eruptions are responsible for widespread ash (tephra) dispersals providing key isochrons suitable for the synchronisation and dating of palaeoclimate archives across East Asia, the NW Pacific and beyond. The transfer of geochronological information using these eruption deposits demands robust tephra correlations underpinned by detailed and precise volcanic glass geochemical data. Presented here is a major (electron microprobe; EMP) and trace element (Laser ablation inductively coupled plasma mass spectrometry; LA-ICP-MS) characterisation of near-source deposits from a series of large magnitude Japanese eruptions spanning approximately the last 150 ka. These data offer new insights into diagnostic compositional variations of the investigated volcanic sources spanning the Japanese islands. Whilst in the case of the highly productive Aso caldera (Kyushu), we are able to explore compositional variations through successive large magnitude eruptions (50-135 ka). These near-source volcanic glass data are used to validate and refine the visible tephrostratigraphy of the intensely dated Lake Suigetsu sedimentary record (SG06 core), Honshu Island, whilst also illustrating key tephrostratigraphic tie points to other East Asian palaeoclimate records (e.g. Lake Biwa). The identification of widespread Japanese tephrostratigraphic markers in the SG06 sediment record enables us to place chronological constraints on these ash dispersals, and consequently explosive volcanism at source volcanoes situated along the Kyushu Arc, including Kikai, Ata and Aso calderas. The proximal Aso-4 Ignimbrite (Magnitude 7.7) deposit is dated here by $^{40}\text{Ar}/^{39}\text{Ar}$ at 86.4 ± 1.1 ka (2σ), and provides a chronological anchor (SG06-4963) for the older sediments of the Lake Suigetsu record. Finally, trace element glass data verify visible ash fall layers derived from other compositionally distinct source regions of Japanese volcanism, including activity along the northern Izu-Bonin arc and North East Japan Arcs. These findings underline the Lake Suigetsu record as central node in the Japanese tephrostratigraphic framework.

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37 **1. Introduction**

38 Volcanic ash (< 2 mm) or tephra widely dispersed during explosive volcanic eruptions is near
39 instantaneously deposited and preserved as layers within long sedimentary records (e.g.,
40 lacustrine and marine) routinely utilised for paleoclimate reconstructions. Consequently,
41 tephra layers provide important time-parallel stratigraphic markers suitable for the
42 synchronisation of disparate climate archives, and the assessment of spatio-temporal
43 variations in past climate variability (e.g., Lowe et al., 2012; Lane et al., 2013). Furthermore,
44 where the age of a tephra layer is established they can provide crucial chronological
45 constraints to the host sediments. Distal tephra layers are often dated through precise
46 correlations to directly dated near-source eruption units (e.g., $^{40}\text{Ar}/^{39}\text{Ar}$; ^{14}C). Conversely,
47 eruptions are increasingly being indirectly dated using the varve (annual layering) or
48 radiocarbon chronologies of precisely dated sedimentary records (e.g., Wulf et al., 2004;
49 2012; Albert et al., 2013; Smith et al., 2013; Tomlinson et al., 2014; Plunkett et al., 2015). As
50 such long sedimentary archives preserving ash fall are also proving increasingly important
51 for constructing comprehensive and temporally constrained inventories of past explosive
52 activity in volcanic regions. These tephra repositories offer important insights into the ash
53 dispersal of individual pre-historic eruptions and can help provide useful constraints on the
54 magnitude or volume of past activity (e.g., Kutterolf et al., 2008; Costa et al., 2012).

55 The reliable exchange of Tephrochronological information requires robust tephra
56 correlations, whilst these depend upon strong stratigraphic and chronological lines of
57 evidence, they must be underpinned by detailed volcanic glass chemistry. Unfortunately,
58 many volcanoes, particularly those in related tectonic settings, erupt deposits with similar
59 major element glass compositions (e.g., Albert et al., 2012; 2017), furthermore, individual
60 centres can produce deposits with indistinguishable major element compositions over
61 extended time-scales (e.g., Allan et al., 2008; Smith et al., 2011; Tomlinson et al., 2012;
62 2014). To circumvent this, trace element characterisation of volcanic glasses is becoming
63 routinely used to help discriminate tephra deposits, and verify tephra correlations based on
64 major element glass data (e.g., Allan et al., 2008; Albert et al., 2012; 2015; 2017; Westgate
65 et al., 2013; Pearce et al., 2014; Kimura et al., 2015; Tomlinson et al., 2015; Maruyama et
66 al., 2016). The increasing number of cryptotephra (non-visible) studies far from volcanic
67 source are greatly extending the known ash dispersals from individual eruptions, and
68 consequently their application as tephrochronological markers (e.g., Pyne-O'Donnell et al.,
69 2012; Jensen et al., 2014; Davies et al., 2015; Bourne et al., 2016; McLean et al., 2018).
70 This geographical expansion of tephrochronological research, owing to the capability to
71 identify the finest ash component (typically < 40 μm) preserved ultra-distally, means that
72 multiple volcanic source regions must be considered when provenancing cryptotephra

73 horizons. Consequently, this exerts a greater need for detailed volcanic glass source
74 characterisation, which can ultimately facilitate more rigorous tephra correlations (e.g.,
75 Tomlinson et al., 2015).

76 In order to assist tephra correlations centred on Late Quaternary Japanese
77 tephrostratigraphic markers, we present new grain-specific major (Electron microprobe;
78 EMP) and trace element (Laser ablation inductively coupled plasma mass spectrometry; LA-
79 ICP-MS) volcanic glass chemistry from proximal and distal tephra deposits. These data are
80 used to assess compositional variability of the deposits from volcanoes along the Japanese
81 arcs to facilitate provenancing of tephra in the region. The near-source geochemical glass
82 data are used to refine the tephrostratigraphy of the Lake Suigetsu sedimentary archive
83 (SG06 core), Honshu Island, Japan. The iconic annually laminated (varved) and intensely
84 ^{14}C dated sediments of the SG06 core present an unrivalled chronology in the long record of
85 East Asian palaeoclimate (e.g., Nakagawa et al., 2003; 2012; Bronk Ramsey et al., 2012).
86 Importantly, the visible ash layers in the Lake Suigetsu sedimentary sequence present a
87 detailed tephrostratigraphy for the region spanning approximately the last 150 ka (Smith et
88 al., 2013). Major element chemistry of the visible tephra layers is presented in Smith et al.
89 (2013). However, the similar glass chemistry of many of these tephra layers, and paucity
90 comparable near-source volcanic glass datasets, meant that only a few of the layers could
91 be reliably correlated to their source volcanoes and particular eruptions. We present new
92 glass chemistry, including detailed trace element datasets, of the SG06 tephra layers and
93 eruption deposits sampled near volcanoes. These data provide crucial information on the
94 sources of the tephra layers and provides the geochemical fingerprints of the layers. In
95 addition to the geochemical data of widespread Late Quaternary Japanese tephra, we
96 present a $^{40}\text{Ar}/^{39}\text{Ar}$ age for the proximal Aso-4 ignimbrite deposit. This precise age constrains
97 the chronology of the deeper sections of the Lake Suigetsu record, and since the Aso-4
98 tephra is also found many other sedimentary records across the region it can also be used to
99 constrain their age models.

100 **1.1 Japanese volcanic arcs and sources of Late Quaternary widespread tephra**

101 Volcanoes along the islands of Japan are formed as the result of subduction along the
102 Ryukyu-Kyushu Arc, the SW Japan Arc (SWJA), the NE Japan Arc (NEJA) and the Kurile
103 Arc (**Fig. 1**). The Philippine Sea Plate is moving northwest and descends along the Ryukyu-
104 Kyushu Arc and SWJA (Zhao et al., 2012; Kimura et al., 2015). The subduction of the
105 Philippine Sea plate beneath Kyushu Island can be spatially subdivided with the occurrence
106 of both back-arc and forearc volcanism (Mahony et al., 2011). Calderas dominate along the
107 volcanic front of Kyushu Island, whilst the back-arc is dominated by stratovolcanoes and

108 monogenetic centres (Yoshida et al., 2013). Mahony et al., (2011) further divide the
109 volcanism along the Kyushu volcanic front into a southern and central volcanic region on the
110 basis of shared tectonic evolution, and are separated by a non-volcanic area (**Fig. 1**). The
111 Kyushu Southern Volcanic Region (SVR) includes Late Quaternary calderas (Kikai, Ata,
112 Ikeda, Aira), and extends as far north as Kirishima volcanic complex (**Fig. 1**). The Kyushu
113 Central Volcanic Region (CVR) is comprised of Aso Caldera, and the Hoho Volcanic Zone
114 (HVZ) that includes the Kuju volcanic complex, Yufu and Tsurumi volcanoes (**Fig. 1**). The
115 Kyushu CVR represents an area of higher potassium volcanism relative to that of the SVR,
116 owing to a combination of extensional tectonics and the subduction of the fluid-rich Kyushu-
117 Palau ridge (Mahony et al., 2011). Further north-east subduction of the Philippines plate
118 beneath SW Honshu results in rear-arc volcanism, and owing to lower rates of magma
119 production calderas are absent, with Late Quaternary explosive activity concentrated at
120 stratovolcanoes, specifically Daisen and Sambe (Kimura et al., 2015). Volcanism at Hakone
121 caldera in central Honshu is attributed to collision along the intra-oceanic Izu-Bonin arc
122 where the Pacific plate meets the Philippine Sea plate. North-west of Hakone is the iconic
123 Mount Fuji, which sits in a complex tectonic setting at the junction between the Izu-Bonin
124 collision and the NEJA and may also be influenced by subduction of the Philippines slab
125 (Wantabe et al., 2006; Tani et al., 2011).

126 Along the NEJA beneath northern Honshu and SW Hokkaido the Pacific plate is subducting
127 in a north-westward direction. During the Late Miocene and Pliocene the NEJA was
128 dominated by large caldera volcanism, during the Quaternary there is a shift to a prevalence
129 of stratovolcanoes, however a small number of Quaternary calderas are situated in the
130 forearc region of the NEJA (Kimura and Yoshida, 2006; Acocella et al., 2008; Kimura et al.,
131 2015). Higher eruption rates are recognised at NE Japan forearc volcanoes as appose to
132 those in the rear-arc (Kimura, 1996). Late Quaternary calderas situated along the NEJA
133 include Towada (Northern Honshu), Shikotsu and Toya (Hokkaido). Calderas on NE
134 Hokkaido (e.g., Kutcharo, Mashu) are related to the Kurile Arc and the subduction of the
135 Pacific plate beneath the Okhotsk plate (Kimura, 1986; Razzhigaeva et al., 2016). Overall
136 the complex interaction of tectonic plates causes intense volcanic activity in and around the
137 Japanese Islands; there are more than 110 active forearc and rear-arc volcanoes (Zhao et
138 al., 2012).

139 Numerous large caldera forming eruptions have occurred from volcanoes on Kyushu, NE
140 Honshu and Hokkaido during the Late Quaternary. Magnitude (M) estimates for these events
141 are classified following the method of Pyle (2000), and place them between M6.0-7.9
142 (Machida and Arai, 2003; Hayakawa 2010; Crosweller et al., 2012 [LaMEVE database];
143 **Table 1**). These eruptions are responsible for widespread ash dispersals mapped across the

144 Japanese islands, the Sea of Japan, and across the Pacific Ocean (Machida and Arai, 2003;
145 **Fig. 1**). In the Kyushu SVR Kikai caldera south of Kyushu island is the product of two large
146 magnitude eruptions the last ca.100 ka, the Kikai Akahoya (K-Ah) is one of the largest
147 Holocene eruptions globally (M7.3), and is dated at between 7,165-7,303 cal yrs BP in SG06
148 (Smith et al., 2013; This study), while the older M6.0 eruption Kikai Tozurahara (K-Tz) is
149 loosely constrained in age at between ca. 90-95 ka (Machida 1999, Machida and Arai, 2003;
150 Hayakawa 2017) and has a zircon fission track age of of 98 ± 26 ka (Danahara, 1995).
151 Further to the north-east is Ata caldera, which was at least partly generated during the M7.5
152 eruption at ca.105 ka (Machida and Arai, 2003). The smaller Ikeda caldera resides in the
153 western sector of the Ata caldera and is the product of the Ikeda M 5.4 eruption (**Table 1**).
154 Aira caldera was produced during the enormous M7.9 Aira Tanzawa (AT) eruption which
155 ejected approximately 463 km^3 of bulk tephra, and is most precisely dated at $30,009 \pm 189$
156 cal yrs BP SG06 (Smith et al., 2013; This study). Prior to the AT tephra, the Iwato eruption
157 from somewhere within the Aira caldera produced large ignimbrite units, it has an offshore
158 age, generated using the age-depth model of MD0124222, of at ca. 58 ka, and is positioned
159 close to the Marine Isotope Stage (MIS) 4/5 transition (Ikehara et al., 2006). The highly
160 active Sakurajima stratovolcano has more recently developed in the southern portion of the
161 Aira caldera.

162 Further north-east in the Kyushu CVR, Aso has been a highly productive centre during the
163 Late Quaternary with numerous Plinian eruptions of M4 or greater. These Plinian activities
164 have been punctuated by four caldera forming M6.0 to M7.7 eruptions, Aso-1 to Aso-4
165 (Machida and Arai, 2003; LaMEVE database). The Aso caldera today is the product of the
166 M7.7 Aso-4 eruption dated at between 86.8-87.3 ka, based on its stratigraphic position in the
167 MIS5b sediments of the northwest Pacific (Aoki, 2008). Chrono-stratigraphically between
168 Aso-4 and the penultimate caldera forming eruption Aso-3 (123-135 ka), at least 8 Plinian fall
169 deposits are identified outside the caldera (Ono et al., 1977). A series of post-caldera Plinian
170 eruptions of the Aso central cones are reported after the Aso-4 eruption and have estimated
171 ages of 60-51 ka (Miyabuchi, 2009). North-east of Aso caldera is the Hoho Volcanic Zone
172 (HVZ), the most productive centre Kuju has producing the thickest and most widely dispersed
173 Late Quaternary eruption deposits (Machida and Aira, 2003). The Kuju Handa (Kj-Hd)
174 Ignimbrite and associated Kuju-Pumice 1 (Kj-P1) fall, which is classified as M5.3, and is
175 radiocarbon dated at ca. 53.5 ka (Okuno et al., 2017).

176 The majority of Late Quaternary explosive volcanism that has occurred along the SWJA is
177 concentrated at Daisen and Sambe stratovolcanoes and has been restricted to M5
178 eruptions. The most widespread tephra dispersals at these volcanoes are associated with
179 the M6.5 Daisen Kurayoshi Pumice (DKP; Machida and Arai, 2003) recently assigned an

180 age of 59.6 ka using the Lake Suigetsu age-depth model (Albert et al., 2018) and the Samba
181 Kisuki (SK; ca.100 ka; Machida and Arai, 2003; Kimura et al., 1999). The stratovolcanoes of
182 the Norikura volcanic zone (e.g., Ontake and Tateyama) at the southern end of the NEJA
183 have experienced some large explosive eruptions but again these are restricted to $M \leq 6$
184 events, the largest eruption in the region being the Ontake Daiichi (On-Pm1; **Table 1**) which
185 occurred at ca. 95 ka based on its position within the marine isotope stratigraphy (Aoki et al.,
186 2008). Southeast of Ontake, at the northern limit of the Izu-Bonin arc, lies Hakone caldera,
187 that produced a succession of large magnitude eruptions between ~250-100 ka, with these
188 age constraints based on their stratigraphic positions in marine successions (Machida,
189 2008).

190 Further north along the NEJA, Towada volcano is responsible for many widespread ash
191 dispersals, with the largest relating to the most recent caldera forming M6.7 eruption,
192 Towada Hachinohe (To-H) (Hayakawa, 1985; Ikehara et al., 2017). Bourne et al. (2016)
193 report ash from the To-H eruption in the Greenland ice cores which offers the most precise
194 age estimate (Table 1). On SW Hokkaido the largest eruptions of the last 150 ka are
195 associated with caldera forming activities at Shikotsu-1 (Spfa-1) and Toya respectively
196 (Machida and Arai, 2003). Whilst in NE Hokkaido, at the southern-most extent of the Kurile
197 Island Arc, large explosive eruptions (M6-7) are related to the formation of Kutcharo caldera
198 and include the Kutcharo-Shorro (Kc-Sr [or Kc-1]), Kutcharo-2/3 and Kutcharo-Hb (Kc-Hb [or
199 Kc-4]) from youngest to eldest (Machida and Arai, 2003). Explosive activity during the early
200 Holocene saw the formation of the Mashu caldera (Mashu-f) located on the eastern side of
201 Kutcharo caldera, the age of this eruption has been determined using ^{14}C dating of charcoal
202 recovered from the ignimbrite deposits (Table 1; Kishimoto et al., 2009).

203 **1.2 Lake Suigetsu (SG06)**

204 Lake Suigetsu, Honshu Island (35°35'0"N, 135°53'0"E) is located in a small tectonic basin
205 situated on the western side of the Mikata fault line, adjacent to Wakasa Bay. It forms the
206 largest of the 'Mikata Five Lakes'. The catchment of the lake is small and is vegetated by
207 warm mixed-forest and is bound by a ring of Palaeozoic hills (maximum elevation 400 m)
208 (Yasuda, 1982; Kitagawa et al., 1995; Nakagawa et al., 2005). The main tributary feeding
209 the five Mikata lakes is the River Hasu, which enters on the south-east side of Lake Mikata.
210 Water feeds from Lake Mikata into Lake Suigetsu via the Seto channel, this shallow channel
211 creates a natural coarse sediment filter meaning that only fine grained autochthonous and
212 authigenic material enters Lake Suigetsu (Schlölaut et al., 2012). The sedimentary
213 environment is particularly stable and allows for continuous fine-grained deposition.

214 The Suigetsu lake sediments have been studied for over two decades, with the ‘SG93’
215 coring campaign leading to increased interest in the sediment record (Kitagawa and van der
216 Plicht, 1998). The SG93 coring revealed that a significant portion of the sequence contained
217 varves (‘nenko’) i.e. seasonal laminations, with alternations of diatom-rich (darker coloured)
218 and mineral-rich (lighter coloured) layers (Fukusawa, 1995; Kitagawa et al., 1995; Kitagawa
219 and Van der Plicht, 1998). In the summer of 2006 the Lake was re-cored as part of the ‘Lake
220 Suigetsu Varved Sediment Project’ with the aim to obtain a complete overlapping ‘master’
221 sediment sequence by recovering cores from four parallel boreholes (A, B, C and D, situated
222 ~20 m apart) (see Nakagawa et al., 2012). This coring campaign successfully obtained a
223 73.19 m-long composite core (‘SG06’), providing a continuous record of sedimentation
224 spanning the last ~ 150 ka (Nakagawa et al., 2012). The sequence is varved between ~ 10
225 and 70 ka and has been extensively radiocarbon (^{14}C) dated and the varves have been
226 counted to generate a high-resolution chronology (Staff et al. 2011, Bronk Ramsey et al.,
227 2012; Marshall et al., 2012; Schlolaut et al., 2012) for this high-resolution
228 palaeoenvironmental record.

229 The majority of the visible tephra layers preserved in the SG06 core are calc-alkaline (CA) to
230 high-K calc-alkaline layers of Japanese arc origin (Smith et al., 2013). These tephra layers
231 range in composition from basaltic through to rhyolitic ash units, which dominate and many
232 have overlapping major element glass chemistries. There are visible tephra layers derived
233 from explosive eruptions of Ulleungdo Island, South Korea (Smith et al., 2011; 2013;
234 McLean et al., 2018), and Changbaishan on the North Korea/China border (McLean et al.,
235 2016). The proximity Daisen and Sambe volcanoes to Lake Suigetsu and the prevailing
236 westerlies mean many of their $M\leq 5$ eruptions are preserved in the lake sediments. Major and
237 trace element volcanic glass chemistries of the SG06 visible tephra, and volcanic source
238 characterisation revealed that nine layers are from explosive activity of Daisen volcano, and
239 five layers are from Sambe (Albert et al., 2018). This facilitated the construction of a detailed
240 eruption event stratigraphy for these two stratovolcanoes located along the South-west
241 Japan Arc (SWJA).

242 **2. Samples and Methods**

243 **2.1 Proximal-medial reference glass samples**

244 Proximal (<20 km) and medial (<100 km) pumice/ash samples from large magnitude
245 eruptions were collected to generate a detailed glass reference dataset for Japanese
246 explosive volcanism, with a view to define the diagnostic geochemical signatures capable of
247 aiding tephra correlations across the Asian-Pacific region and beyond. All tephra deposits
248 analysed were erupted during the last 150 ka (**Table 1**), consistent with the estimated basal

249 age of the Lake Suigetsu (SG06) sediment record based on low-resolution pollen analysis.
250 Owing to the prevailing westerlies a greater emphasis was placed on volcanism south-west
251 of Lake Suigetsu. However a smaller number of large magnitude, widespread eruptive units
252 from stratovolcanoes and calderas in central-northern Honshu and Hokkaido are also
253 characterised.

254 In the Kyushu SVR two medial ash (fall) deposits of the Kikai Tozurahara (K-Tz) were
255 collected from Tanegashima and Yakushima Islands. Ash deposits of the Holocene caldera
256 forming Kikai Akahoya (K-Ah) eruption were collected from along the Takatoge pass, 90 km
257 north of Kikai caldera and from north-east of Aso caldera, at Doimakino. The Ata Ignimbrite
258 was collected at two localities, one east of the caldera and south of Sakurajima volcano,
259 whilst another at Fumuto along the coast. Co-ignimbrite ash fall attributed to the same
260 eruption was also sampled from beneath the Aso-ABCD eruption sequence and above Aso-
261 3 collected near Noga (Machida, 1996, Ono et al., 1977). The Ikeda pumice associated with
262 caldera forming event in the west of Ata caldera was collected east of Fumuto. Further north
263 at Aira caldera, the Aira-Iwato Ignimbrite (A-Iw) was sampled just north of Kirishima volcano,
264 whilst Aira Tanzawa (AT) fall and flow deposits were sampled at Fumuto. Glass data is also
265 presented for the Late-glacial eruption of Sakurajima, Sz-S from along the Takatoge Pass,
266 this the largest magnitude event of this presently active cone located in Aira caldera.

267 In the Kyushu CVR at Aso caldera the following prominent tephra fall and flow units (oldest
268 to youngest spanning ~45-135 ka) were sampled (**Table 1**), which include ignimbrite
269 deposits associated with the last two caldera-forming eruptions and a series of sub-Plinian to
270 Plinian fall out deposits. Samples characterised include Aso-3W (fall), Aso-3A (flow), Aso-3
271 (main-flow), Aso-N (fall), Aso-M (Fall) Aso-D, Aso-C, Aso-B, Aso-A (fall), Aso-Y (fall), Aso-4
272 (flow), Aso central cone pumice (ACP) 6 to 3 (fall; oldest to youngest). The ACP samples
273 follow the nomenclature and stratigraphy of Miyabuchi (2009), whilst the remaining samples
274 were collected from east of the caldera near Noga (Ono et al., 1977; Machida, 1996; **Fig. 1**).
275 Also analysed is a distal ash candidate of the Aso-4 eruption sample over 1500 km north-
276 east of source at Lake Mokoto, Abashiri, Northern Hokkaido. Further north-east, in the Hoho
277 Volcanic Zone, at Kuju volcano, the Kuju-D (fall), Kuju-Handa (Ignimbrite) and Kj-P1 (Fall)
278 deposits were all sampled (**Table 1**).

279 In central Honshu, at the northern extend of the Izu-Bonin arc, Hakone caldera, Hk-TAu8
280 pumice fall deposits (Machida, 2008) were sampled to provide an indication of glass
281 compositions erupted in this volcanic region. Volcanic glass data is provided from large
282 magnitude Late Quaternary eruptions along the NEJA (including the Norikura Volcanic
283 Zone); these include the Ontake-Daiichi (On-Pm1) and further north the Towada-Hachinohe

284 (To-H). On Hokkaido glass data is presented for the caldera forming eruptions Shikotsu-1
285 (Spfa) and Toya. Kurile Arc tephra deposits from Kutcharo caldera forming eruptions, Shoro
286 (Kc-Sr/1) and Kc-Hb eruptive units are analysed, along with the intervening Plinian Kc-2/3
287 activities (**Table 1**). Younger Holocene activities of Mashu caldera (Ma-f), situated in the
288 eastern sector of Kutcharo are also characterised here. Full details of all sample
289 geochemically investigated and sample localities can be found in **Table 1 and**
290 **Supplementary Material 1**.

291 **2.2 Lake Suigetsu (SG06 core) distal tephra layers**

292 In this contribution we present and discuss new trace element volcanic glasses data for
293 eleven visible SG06 tephra layers SG06-0967, SG06-2650, SG06-3485, SG06-3912, SG06-
294 4963, SG06-5181, SG06-5287, SG06-5353, SG06-6344, SG06-6413 and SG06-6634, many
295 of which are considered equivalent to large magnitude (>M6) eruptions and form widespread
296 Japanese tephrostratigraphic markers (**Table 2**). Here these data are integrated with the
297 trace element glass data of SWJA (Daisen and Sambe) derived SG06 layers (Albert et al.,
298 2018).

299 **2.3 Electron microprobe (EMP)**

300 Major and minor element volcanic glass chemistry of individual juvenile clasts from proximal
301 and medial deposits were determined using a wavelength-dispersive JEOL 8600 electron
302 microprobe in the Research Laboratory for Archaeology and the History of Art, University of
303 Oxford. A beam accelerating voltage of 15kV was used with a 6nA current and a beam
304 diameter of 10 μm . The instrument was calibrated with a suite of appropriate mineral
305 standards; peak count times were 30 s for all elements except Mn (40s), Na (12s), Cl (50s),
306 P (60s). Reference glasses from the Max Plank institute (MPI-DING suite; Jochum et al.,
307 2006) bracketing the possible chemistries were also analysed alongside the unknown
308 tephtras. These included felsic [ATHO-G (rhyolite)], through intermediate [StHs6/80-G
309 (andesite)] to mafic [GOR132-G and GOR128 (komatiites)] glasses. All glass data has been
310 normalised to 100 % for comparative purposes. This is of paramount importance for tephtras
311 in marine and lacustrine cores, as glass shards may absorb water from their surroundings,
312 which often results in low totals. Analytical totals < 93 wt.% were discarded, with the
313 exception of samples ITJ240-241 where all analyses were consistently below. Errors are
314 typically < $\pm 0.7\%$ RSD for Si; $\sim \pm 3\%$ for most other major elements, except for the low
315 abundance elements: Ti ($\sim \pm 7\%$), Mn ($\sim \pm 30\%$). Error bars on plots represent
316 reproducibility, calculated as a 2 x standard deviation of replicate analysis of MPI-DING
317 StHs6/80-G. Glass standard data are reported in **Supplementary Material 2**.

318 **2.4 Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)**

319 The volcanic glass analyses of proximal, medial and distal (SG06) tephra deposits were
320 performed using a Thermo Scientific iCAP Qc ICP-MS coupled to a Teledyne Photon
321 Machines Analyte G2 193 nm excimer laser ablation system with a HelEx II two-volume
322 ablation cell at the Department of Geology, Trinity College, Dublin. Spot sizes of 36, 30, 24
323 and 18 μm were used owing to varying size of the ash particles and glassy areas available
324 for analysis. The repetition rate was 5 Hz and the count time was 40 s on the sample and 40
325 s on the gas blank (background). The ablated sample was transported in He gas flow (0.65 L
326 min^{-1}) with additional N_2 (5 ml min^{-1}) via an in house signal smoothing device (PoshDOGII).
327 Concentrations were calibrated using NIST612 with ^{29}Si as the internal standard and using a
328 Ca correction factor as advocated in Tomlinson et al. (2010). Data reduction was performed
329 using Lolite 2.5 and portions of the signal compromised by the ablation of microcrysts and
330 resin-filled voids were excluded. A small subset of samples were analysed using an Agilent
331 8900 triple quadrupole ICP-MS (ICP-QQQ) coupled to a Resonetics 193nm ArF excimer
332 laser-ablation in the Department of Earth Sciences, Royal Holloway, University of London,
333 using the analytical procedures and data reduction (Microsoft Excel) methods outlined in
334 Tomlinson et al. (2010). Spot sizes used on this instrument were 34, 25 and 20 μm . MPI-
335 DING secondary standards were run alongside all tephra samples using the same spot size
336 on both instruments. Accuracies of ATHO-G and StHs6/80-G MPI-DING glass analyses
337 across the entire data set are typically $\leq 5\%$ for Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Pr, Nd, Sm, Eu,
338 Gd, Dy, Er, Yb, Hf, Ta, Th, U. Analyses of MPI-DING secondary standards run alongside
339 individual tephra samples on the respective instruments are provided in the **Supplementary**
340 **Material 2**, along with the full volcanic glass data sets.

341 **2.5 $^{40}\text{Ar}/^{39}\text{Ar}$ chronology**

342 A detailed sample preparation routine is discussed in Mark et al. (2010) but briefly: single
343 crystals of hornblende were separated from 1 kg of Aso-4 proximal sample (ITJ42), after
344 disaggregating, washing and sieving followed by magnetic and density separations and
345 finally ultrasonic cleaning in nitric acid for 5 minutes. Hornblendes were handpicked under
346 binocular microscope for analysis. Samples were irradiated in the CLICIT facility of the
347 Oregon State University TRIGA reactor using the Alder Creek sanidine (Nomade et al.,
348 2005) as a neutron fluence monitor.

349 $^{40}\text{Ar}/^{39}\text{Ar}$ analyses were conducted at the NERC Argon Isotope Facility, Scottish Universities
350 Environmental Research Centre (SUERC) and the Berkeley Geochronology Center (BGC).
351 Samples analyzed at BGC were run and reported blindly, without knowledge of the SUERC
352 results (and vice versa). Details of irradiation durations, J measurements, discrimination

353 corrections are provided in **Supplementary Material 3**. Irradiation correction parameters are
354 also listed in the same file.

355 For J determinations three bracketing standard positions surrounding the unknown were
356 used to monitor the neutron fluence. Ten measurements were made for each bracketing
357 standard position. The weighted average $^{40}\text{Ar}^*/^{39}\text{ArK}$ was calculated for each well, and the
358 arithmetic mean and standard deviation of these three values was used to characterize the
359 neutron fluence for the unknown. This approach was deemed sufficient, as due to the
360 relatively short irradiation durations there was no significant variation between the three
361 positions in a single level of the irradiation holder. This also facilitated high-precision
362 measurement of the J-parameter. Note that for all J-measurements no data were rejected.

363 Backgrounds and mass discrimination measurements (via automated analysis of multiple air
364 pipettes) specific to each batch are summarized in **Supplementary Material 3**. Air pipettes
365 were run after every 2 analyses. Backgrounds were run after every analysis and subtracted
366 from ion beam measurements (arithmetic averages and standard deviations). Mass
367 discrimination was computed based on a power law relationship (Renne et al., 2009) using
368 the isotopic composition of atmospheric Ar reported (Lee et al., 2006) that has been
369 independently confirmed (Mark et al., 2011). Corrections for radioactive decay of ^{39}Ar and
370 ^{37}Ar were made using the decay constants reported by Stoener et al. (1965) and Renne &
371 Norman (2001), respectively. Ingrowth of ^{36}Ar from decay of ^{36}Cl was corrected using the
372 $^{36}\text{Cl}/^{38}\text{Cl}$ production ratio and methods of Renne et al. (2008) and was determined to be
373 negligible.

374 Samples were analyzed by total fusion with a CO_2 laser and measurements made using a
375 MAP 215-50 (MAP2) noble gas mass spectrometer. The mass spectrometer is equipped
376 with a Nier-type ion source and analogue electron multiplier detector. Mass spectrometry
377 utilized peak-hopping by magnetic field switching on a single detector in 10 cycles (further
378 details in Mark et al., 2017).

379 Ages were computed from the blank-, discrimination- and decay-corrected Ar isotope data
380 after correction for interfering isotopes based on the following production ratios, determined
381 from fluorite and Fe-doped KAlSiO_4 glass. Ages and their uncertainties are based on the
382 methods of Renne et al. (2010) and the calibration of Renne et al. (2011) for decay constant,
383 adopting the Alder Creek Sanidine (ACs) age of 1.1891 ± 0.0008 Ma (Niespolo et al., 2017)

384 Where not otherwise distinguished, $^{40}\text{Ar}/^{39}\text{Ar}$ age uncertainties are stated as $X \pm Y/Z$, where
385 Y is the analytical uncertainty as defined above, and Z is the full external precision
386 considering both analytical and systematic sources of uncertainty (e.g., decay constant). Age

387 computation used the weighted (by inverse variance) mean of $^{40}\text{Ar}^*/^{39}\text{ArK}$ values for the
388 sample and standard. Outliers were tested for in both single-crystal samples and standards
389 using a 3-sigma filter applied iteratively until all samples counted are within 3 standard
390 deviations of the weighted mean \pm one standard error. There are no outliers in the dataset.
391 The data are reported at the 1-sigm confidence interval. All raw data and plots are reported
392 in **Supplementary Material 3**.

393 **2.6 The chronology of the SG06 sedimentary record**

394 The SG06 sedimentary record is underpinned by the chronology presented in Bronk Ramsey
395 et al. (2012), which provides an integral component of the International ^{14}C Calibration
396 (IntCal) dataset (Reimer et al., 2013). The independent chronology of the Lake Suigetsu
397 SG06 sedimentary sequence has subsequently been modelled on to the IntCal13 timescale
398 implementing three successive cross-referenced Poisson-process ('*P_Sequence*')
399 depositional models using OxCal (ver. 4.3; Bronk Ramsey 2008; 2017). These include 775
400 AMS ^{14}C dates obtained from terrestrial plant macrofossils from the upper 38 m (SG06-CD)
401 of the SG93 and SG06 sediment cores (Kitagawa and van der Plicht, 1998a, 1998b, 2000;
402 Staff et al., 2011, 2013a, 2013b) and varve counting between 12.88 and 31.67m SG06 CD
403 (Marshall et al. 2012; Scholaut et al. 2012). Beyond the annually laminated and ^{14}C dated
404 portion of the sequence the age-depth model of SG06 is based on a linear interpolation
405 which is anchored by deeper chronological tie points, which now includes the $^{40}\text{Ar}/^{39}\text{Ar}$ age
406 of the Aso-4 eruption presented here.

407 **3. Volcanic glass chemistry**

408 **3.1 Geochemical variations at Japanese arc volcanoes**

409 In this section we outline the geochemical variation observed in the matrix glasses erupted
410 during predominantly $\geq\text{M5}$ eruptions at productive calderas and stratovolcanoes extending
411 the length of the Japanese Islands, with an emphasis on the identification of diagnostic
412 features useful in determining the source regions of distal tephra layers. Average major and
413 trace element glass data of proximal-medial eruptive units analysed here are presented in
414 **Table 3**, and the full geochemical datasets are provided in **Supplementary Material 2**.

415 Vitreous tephra erupted at centres extending across the islands of Japan show low-K
416 (tholeiitic) through to high-K calc-alkaline (HKCA)/shoshonitic affinities (**Fig. 2A**). The K_2O
417 content offers a first order major element discriminator of Japanese eruptive source regions
418 (**Fig. 3A**). The highest K_2O contents observed in Japanese glasses analysed here were
419 associated with the volcanism in the Kyushu CVR (**Fig. 1**), specifically the HKCA rhyolitic

420 products of Aso Caldera, and the Kuju volcanic complex (HVZ; **Fig. 2A Fig. 3**). The HKCA
421 eruptive products of Aso caldera are some of the most compositionally distinctive in Japan,
422 with $K_2O > 3$ wt.% at ~ 66 wt.% SiO_2 , and the most evolved glasses analysed extending to 6
423 wt.% in K_2O (Aso-N; **Fig. 2**). Consequently the Aso caldera glasses reside on very distinct
424 evolutionary trends using either CaO content plotted against SiO_2 making attribution of
425 tephra to volcanic source straightforward (**Fig. 2A**). The HKCA eruptive products of Kuju
426 volcano extend to higher K_2O contents than glasses erupted further south in the Kyushu
427 SVR. However, there is some compositional overlap with the most K_2O -rich glasses erupted
428 at Aira (A-lw), thus making major element distinctions between Aira and Kuju tephra
429 challenging (**Fig. 2**). Fortunately, as outlined below, Kuju deposits can be distinguished from
430 those erupted in the Kyushu SVR based on their trace element signature (**Fig. 4**)

431 The volcanic glasses of explosive products erupted at forearc calderas in the Kyushu SVR
432 (Kikai, Ata, Aira; **Fig. 1**) reside on a transitional CA to HKCA trend, and show large degrees
433 of major element compositional overlap (**Fig. 2**). Further north-east the tephra deposits
434 erupted along the SWJA beneath Honshu, at Daisen and Sambe stratovolcanoes, show
435 dacite to rhyolite glasses that extend from CA through to HKCA compositions (Albert et al.,
436 2018) and partially overlap at a major element level with those erupted at volcanic centres in
437 the Kyushu SVR, the CVR (Kuju) and the Norikura volcanic chain (Ontake) (**Fig. 2**).

438 The dacite-rhyolitic eruptive products of calderas situated in forearc positions along the
439 NEJA show lower K_2O content than those at calderas on Kyushu (**Fig. 2**). Shikotsu (Spfa-1;
440 2.5-2.7 wt.% K_2O) and Toya (Toya; 2.5-3.0 wt.% K_2O) calderas along the NEJA (SW
441 Hokkaido) erupted glasses with CA affinities that are lower in K_2O content than those
442 erupted in the Kyushu SVR. The NEJA centres of Shikotsu and Toya centres (SW Hokkaido)
443 also erupt glasses with higher K_2O content than those CA glasses erupted at the southern
444 tip of the Kurile Island Arc at Kutcharo caldera (1.7-2.3 wt.% K_2O). Those calderas located
445 closest to the trench in the forearc produced distinctive arc tholeiitic (Low-K) glass
446 compositions (**Fig. 2**). Late Quaternary-Holocene silicic tholeiitic (low-K) large magnitude
447 eruptions are recognised at Hakone (Izu-Bonin arc), Towada (NEJA) and Mashu (Kurile arc)
448 calderas. Mashu has erupted low-K rhyolitic glasses (0.61-0.82 wt.% K_2O) which are
449 distinctive, whilst K_2O content in the Hakone (1.03-1.56 wt.% K_2O) and Towada (1.03-1.27
450 wt.% K_2O) dacite to rhyolite glasses is slightly more elevated (**Fig. 2**).

451 Discriminating the volcanic glasses of the forearc calderas in the Kyushu SVR from those in
452 the rear-arc along the SWJA (Daisen and Sambe) and in the Norikura volcanic zone
453 (Ontake) can be partially achieved using SiO_2 vs. FeOt content of the glasses (**Fig. 2C**).
454 Kyushu SVR forearc caldera glasses reside on a trend of higher FeOt content at overlapping

455 SiO₂ content. Glasses erupted from the Kuju volcanic complex (Kyushu CVR), appear to be
456 more akin to those erupted from the SWJA volcanoes (Daisen and Sambe), however there is
457 a degree of convergence at this high SiO₂ content with glass compositions erupted along the
458 Kyushu SVR (**Fig. 2C**). A SiO₂ vs CaO Harker diagram provides a useful means to
459 distinguish the Daisen and Sambe SWJA products (Albert et al., 2018), however again the
460 Kuju glasses reside a point of convergence between the two suites (**Fig. 2B**). The Kuju
461 glasses do typically extend to higher SiO₂ content than the eruptive products erupted from
462 Daisen. Whilst compared to Sambe rhyolitic glasses with similar K₂O content, the Kuju
463 glasses extend to higher SiO₂ content (**Fig. 2A**).

464 SiO₂ vs CaO is also useful for separating the eruptive products of the Kyushu SVR calderas
465 (Aira, Ata, Kikai) from those volcanoes along the NEJA (Towada, Shikotsu) and southern
466 Kurile Island Arc (Kutcharo, Mashu), where the glasses of the former reside on a trend of
467 lower CaO at a given SiO₂ content (**Fig. 2B**). The main exception to this being the rhyolitic
468 Toya deposits which are characterised by glasses with exceptionally low CaO content (0.33-
469 0.43 wt.%; **Fig. 2B**). Whilst a SiO₂ vs FeO Harker diagram largely separates the eruptive
470 products of Daisen from those of Kyushu SVR and NEJA calderas, overlap still exist with the
471 products of Ontake volcano (Norikura volcanic zone) (**Fig. 2C**).

472 Consistent with their subduction genesis, all glasses erupted at volcanic sources extending
473 the Japanese Islands display enrichment in fluid mobile Large Ion Lithophile elements (LILE
474 e.g., Rb, Ba, K) relative to insoluble high field strength elements (HFSE), specifically Nb and
475 Ta and the Rare Earth Elements (REE; La to Yb) (**Fig. 4**). Many of the Kyushu SVZ and
476 NEJA calderas have erupted silicic tephra with overlapping levels of incompatible trace
477 element enrichment and subsequently similar mantle normalised profiles (**Fig. 4**). Fluid
478 mobile elements are highly variable between felsic deposits of the different Japanese
479 volcanic sources, and as such are coupled to the K₂O content of the volcanic glasses.
480 Rubidium is a particularly useful discriminator of Japanese volcanic sources (**Fig. 3-4**). Low-
481 K (tholeiitic) glasses erupted at forearc calderas, Towada (NEJA), Hakone (Izu-Bonin) and
482 Mashu (Kurile arc), show the lowest levels of Rb enrichment (**Fig. 3-5**). With increased K₂O
483 content at CA sources of the Southern Kurile Arc (Kutcharo) and the NEJA (Toya/Shikotsu)
484 Rb content also increases. The higher K₂O content of the silicic magmas erupted at centres
485 in both the SVR (Kikai, Ata, Ikeda, Aira) and CVR of Kyushu, see the greatest levels of Rb
486 enrichment (**Fig. 3-4**). Similarly, Th content also displays a similar relationship to K₂O,
487 meaning Th content is variable at the different source regions of Japan and offers a key
488 means to compositionally decipher eruption deposits (**Fig. 5**) The lowest Th content glasses
489 are observed in the low-K tholeiitic dacite to rhyolite glasses of Mashu, Hakone and Towada
490 (**Fig. 3-5**). Silicic tephra deposits erupted from forearc calderas on Hokkaido

491 (NEJA/Southern Kurile Arc) show lower Th contents than those glasses erupted in both the
492 Kyushu SVR and the CVR (**Fig. 3-5**). Enrichment of the LREE is typical in the genesis of
493 fluid rich magmas, as such variations in the contents of La and Ce again broadly follow K_2O
494 content (**Fig. 4**). Tholeiitic (low-K) sources show restricted LREE enrichment relative to the
495 HREE, for instance at Mashu (Kurile Arc) and Hakone (Izu-Bonin Arc) calderas this is
496 manifested as a flat REE profile and low La/Yb ratios (**Fig. 4; Table 3**). Of the Japanese
497 sources investigated the HKCA glasses erupted at Aso, Kuju, Aira, and Ontake, are some of
498 the most enriched in fluid mobile trace elements (**Fig. 3-4**). The rhyolitic glasses of
499 Kutcharo/Mashu (Kurile Arc) and Hakone (Izu-Bonin Arc) display particularly low Nb and Ta
500 contents relative to the silicic glasses erupted on Kyushu Island (SVR and CVR), the NEJA
501 and the SWJA (**Fig. 4**).

502 The glasses erupted along the SWJA show strong depletions in the Middle and Heavy REE
503 (**Fig. 4**), including low-Y contents (**Fig. 5A**), a feature that was previously recognised in the
504 glasses erupted at Daisen and Sambe volcanoes (Kimura et al., 2015; Albert et al., 2018).
505 New trace element glass data presented here confirms that this feature is also observed in
506 the Kuju volcanic products of the HVZ, which some consider the southern extent of the
507 SWJA (Shibata et al., 2014; **Fig. 4**). This Middle and Heavy REE depletion provides a useful
508 diagnostic feature of these volcanoes. This feature, coupled with overall arc variations in Th
509 and REE content of Japanese volcanic glasses, make a Y vs. Th bi-plot particularly robust
510 tool for compositionally spreading the volcanic sources of Japan (**Fig. 5A-B**).

511 3.1.1 Kyushu SVR geochemical variations

512 In this section we explore the geochemical variations between the eruptive products of large
513 magnitude eruptions of the calderas of the Kyushu SVR (Kikai, Ata, Aira) for the purpose of
514 tephra correlations. These sources have tapped both low (~ 74 wt.%) and high (> 77 wt.%)
515 SiO_2 transitional CA to HKCA rhyolitic magmas with largely overlapping major element glass
516 chemistries (**Fig. 2**), making specific source attribution of tephra deposits from this region
517 more challenging. Overall, moving north to south between calderas in the SVR, there
518 appears a trend of decreasing K_2O content (**Fig. 3**) of the rhyolitic glasses erupted despite
519 overlapping SiO_2 content, with the lowest K_2O rhyolites erupted at Kikai caldera and the
520 highest at Aira (**Fig. 3**). The high- SiO_2 rhyolites erupted at Kikai caldera (K-Tz) can be
521 distinguished from those erupted at Aira caldera based on lower Al_2O_3 content at
522 overlapping SiO_2 (**Fig. 2D**). Distinguishing Kikai (K-Ah) and Ata low- SiO_2 rhyolites relies on
523 the Ata glasses extending to subtly lower CaO and FeO_t contents than those of Kikai caldera
524 (**Fig. 2C**).

525 Trace element concentrations offer useful means to distinguish the eruptive products of the
526 Kyushu SVR calderas. Irrespective of relating to high- or low-SiO₂ rhyolites, the Kikai caldera
527 volcanic glasses have lower Nb and Ta contents than the volcanic glasses with similar SiO₂
528 contents erupted at either Ata or Aira calderas (**Fig. 3-4**). Aira (AT, A-lw) and Ata (Ikeda)
529 high-SiO₂ rhyolitic glasses share very similar mantle normalised trace element profiles (**Fig.**
530 **4**). Indeed, they share significantly steeper REE profiles than those of Kikai caldera (**Fig. 4**),
531 reflected in more elevated La/Yb ratios (**Table 3**). High-SiO₂ rhyolites erupted at Aira are
532 most easily distinguished from those of Ata based on their higher concentrations of Rb, Th
533 and U content (**Fig. 3-4**). Zirconium content appears to vary between eruptive units at the
534 respective Kyushu SVR calderas. The high-SiO₂ rhyolites of Kikai and Ata show significantly
535 lower Zr content relative to the lower-SiO₂ rhyolites erupted at the same source (**Fig. 5D**).

536 **3.1.2 Kyushu CVR compositional variations**

537 In this section we explore the compositional variation in the deposits sampled from the CVR
538 and the challenges of distinguishing the products of successive eruptions from the same
539 volcanic centre. Here we have concentrated on two volcanic centres in the Kyushu CVR
540 which are responsible for a series of large magnitude eruptions during the Late Quaternary,
541 Kuju volcano and Aso caldera. As highlighted above the HKCA eruptive products of Aso
542 caldera plot on a distinctive evolutionary trend, consequently they are easily distinguished
543 from those erupted further north-east in the HVZ at Kuju volcano (**Fig. 2**).

544 Focusing specifically on eruption units at Kuju volcano, and the activity at ~53-55 ka (**Table**
545 **2**), moving up through the complex eruptive succession of Kj-D (fall), Kj-Hd (Hanada
546 Ignimbrite) and Kj-P1, all tephra units show volcanic glasses with overlapping major element
547 glass chemistries (**Fig. 2**). The precise temporal relationship between these chemically
548 overlapping eruptive units is unclear, only the Kj-Hd ignimbrite deposit is dated (**Table 1**), yet
549 somewhat peculiarly the overlying Kj-P1 (Plinian fall) deposit is considered time-equivalent,
550 rather than the underlying Plinian deposit Kj-D (Okuno et al., 2017; Tsuji et al., 2017a). A
551 subtle feature of possible distinction is that the glasses of the uppermost fall deposit (Kj-P1)
552 extend to higher SiO₂ and lower FeO_t compared to the units stratigraphically below (**Fig.**
553 **2C**). Distinguishing the three units on the basis of trace element glass chemistry has not
554 been achieved here owing to the absence of sufficiently large enough and crystal free matrix
555 glass for LA-ICP-MS analysis. Kuju-D was not successfully analysed at a trace element
556 level, whilst only a single analysis was obtained for the Kj-P1 and Kj-Hd deposits.
557 Importantly these analyses, combined with that of the older Kj-Mg tephra, all verify that Kuju
558 HKCA rhyolites display a SWJA-type chemistry with depletions in the Middle and Heavy
559 REE (**Fig. 4**), reflected by their high La/Yb ratios (**Table 3**).

560 Deposits explosively erupted at Aso caldera between 50-135 ka range from trachy-dacite
561 through to rhyolitic (63.4-75.0 wt.% SiO₂; 3.3-6.5 wt.% K₂O; **Fig. 2**). The most
562 heterogeneous eruptions deposits investigated at Aso are associated with the caldera
563 forming eruptions, Aso-3 and Aso-4 (**Fig. 6**). The Aso-3 glasses reside on a trend of higher
564 K₂O at a given SiO₂ content relative to the younger eruptive products Aso-4 and straddle the
565 HKCA/shoshonitic classification boundary (**Fig. 2A**). There is significant compositional
566 overlap between temporally distinct eruptive units of the volcano, with very few deposits
567 showing unique major element glass compositions (**Fig. 2; Fig. 6**). The most distinctive
568 glasses being those with the most elevated SiO₂ and K₂O content. These include the silicic
569 end-member of the Aso-3 caldera forming eruption deposits, and fall out from Plinian
570 eruptions Aso-N, Aso-Y and ACP3 (**Fig. 6**). Successive eruptive units from Aso caldera
571 show trace element glass compositions that overlap with one another (**Fig. 6D**).

572 The basal fall (Aso-3W) and the lower most ignimbrite unit (Aso-3A) are largely dominated
573 by the most silicic rhyolitic glass compositions produced during the caldera forming eruption
574 (~70 wt.% SiO₂; ~5 wt.% K₂O). Less evolved glasses (63-66 wt.% SiO₂) were found in the
575 upper and more voluminous portion of the ignimbrite (**Fig. 6**), which is broadly consistent
576 with the findings of Kaneko et al. (2015), who also report the appearance of the least
577 evolved magmas in the later phase of the eruption. However our data do not extend to the
578 most primitive compositions (53-62 wt.% SiO₂) reported by Kaneko et al. (2015), indicating
579 that perhaps our Aso-3 sampling is not completely representative. Significant variation is
580 observed in the levels of incompatible trace element enrichment of the Aso-3 glasses (235-
581 335 ppm Zr; 12.5-18.1 ppm Th). Strontium clearly behaves compatibly and therefore the
582 least evolved glasses are recognised by more elevated Sr content (~500 ppm), whilst the
583 most silicic rhyolitic glasses display lower Sr content (~240 ppm).

584 Plinian fall units between the Aso-3 and Aso-4 caldera forming eruptions at Noga Cave can
585 be broadly distinguished on chemo-stratigraphic grounds using their position relative to the
586 Ata tephra marker (99.3 ± 6.0 ka; Section 3.2.3) in the sequence. The four Plinian fall units
587 (Aso-N to Aso-I) that occur beneath the Ata tephra all reside on the trend of higher K₂O
588 content consistent with the older Aso-3 deposits, and including some geochemical overlap
589 with the Aso-3 upper Ignimbrite deposits. Excluding the distinctive high-K₂O (6.3 wt.%) Aso-
590 N Shoshonitic glasses (**Fig. 2A**), the remaining three units (Aso-M, Aso-K, Aso-I) all have
591 overlapping major element chemistries (**Fig. 6**), yet these tephra deposits compositionally
592 differ from the four Plinian fall deposits stratigraphically above the Ata tephra, Aso-ABCD
593 (**Fig. 6**). Aso-ABCD glasses show broadly overlapping chemistries, but can be distinguished
594 from the older Aso-M to Aso-I deposits owing to their higher SiO₂, and lower CaO and FeO_t

595 (Fig. 6C). Aso-D is seemingly distinguishable from Aso-ABC on the basis that the glasses
596 extend to subtly higher CaO content (Fig. 6C).

597 Eruption deposits Aso-M, Aso-K and Aso-I glasses are difficult to distinguish at a trace
598 element level, although one feature that is of note is that the Aso-M glasses contain subtly
599 more elevated Sr, relative to those of Aso-K and Aso-I (Fig. 6F). Aso-K and Aso-I volcanic
600 glasses are indistinguishable at a major and trace element level. Aso-ABCD glasses show
601 considerable variation in their incompatible trace element contents, importantly Aso-B and
602 Aso-C are restricted to lower levels of enrichment compared to those of Aso-A and Aso-D
603 (Fig. 6). Whilst Aso-B and Aso-C are indistinguishable from one another they also show
604 lower Sr content than the glasses of Aso-A and Aso-D (Fig. 6D). The Aso-A and Aso-D fall
605 deposits have glasses with overlapping trace element concentrations, yet Aso-D glasses
606 extend to higher levels of enrichment (e.g., Th; Zr; Fig. 6C-D).

607 The Aso-4 ignimbrite deposits are distinctive owing to their compositional heterogeneity (Fig.
608 6), proximal glasses from Noga Cave reveal three distinct glass populations, with two
609 rhyolitic populations dominating and being most easily distinguished using the CaO content
610 (Fig. 6C). Component 1 glasses show the lowest CaO content (1.0-1.2 wt.%) are associated
611 with higher SiO₂ (71.8-72.6 wt.%) content. Component 2 rhyolites show higher-CaO (1.4-1.6
612 wt.%) and are associated with the lower SiO₂ content glasses (70.4-71.9 wt.%). A third
613 component, observed in the Aso-4 ignimbrite deposit, is derived from dark scoriaeous
614 deposits, and have a less evolved trachy-dacite composition (ca. 65-66 wt.% SiO₂). These
615 primitive compositions are lower in K₂O content than the Aso-3 glasses with comparative
616 SiO₂ content (Fig. 2A; Fig. 6). The two rhyolitic components of the Aso-4 (1 and 2) tephra
617 are most easily distinguished at a trace element level using their Sr content. Component 1
618 glasses display lower Sr (131-184 ppm) at overlapping Th content relative to the component
619 2 (146-619 ppm Sr) rhyolites (Fig. 6F). The component 1 low-Sr rhyolitic glasses were
620 restricted to the lowermost Aso-4 ignimbrite deposits (ITJ40; Table 1). Aso-4 glasses display
621 a wide range in incompatible trace element contents (e.g., 165-311 ppm Zr; 9.1-17.7 ppm
622 Th) consistent with their significant major element variation. The Aso-4 range in incompatible
623 trace element concentrations encapsulates that of the combined Aso-ABCD succession.
624 Aso-4 high Th content component 1 glasses display lower Sr content than the Aso-D and
625 Aso-A glasses at equivalent Th (Fig. 6F). Furthermore these same Aso-4 glasses show
626 lower Y content than the Aso-A and Aso-D deposits (Fig. 6E).

627 Volcanic glasses of the successive ACP (6-3) Plinian fall deposits show trace element
628 concentrations that overlap with those of the older Aso activities (Fig. 6). The most silicic
629 ACP deposits, ACP3, are further distinguishable from the ACP6-4 as they show the lowest

630 Sr contents (**Fig. 6F**). Consistent with major element compositional overlap, ACP4 and
631 ACP5/6 glasses show trace element concentrations that broadly overlap with Aso-4
632 component 1 and 2 glasses (**Fig. 6**). Yttrium in the ACP4 glasses appear to be offset to
633 higher concentrations relative to the older Aso-4 deposits at overlapping Th content, more
634 consistent with the Aso-ABCD glasses (**Fig. 6E**), further reinforcing the importance of subtle
635 variations in the REE contents of the Aso glasses and in particular Y content.

636 **3.2 SG06 Tephra correlations, stratigraphic and geochronological constraints**

637 In the following section we utilise the new proximal-medial major and trace element volcanic
638 glass dataset to explore the provenance of the distal Lake Suigetsu (SG06) tephra layers.
639 Geochemical correlations are explored in figures **5-10**, whilst the fully integrated SG06
640 tephrostratigraphy developed and discussed below is presented in **Figure 11. Table 4**
641 contains the new trace element volcanic glass data for the SG06 layers, along with their
642 major element compositions. These tephra layers and correlations to source are grouped
643 based on similar volcanic source regions and in accordance with key diagnostic features
644 outlined above. All specific tephra correlations outlined below are summarised in **Table 2**.

645 **3.2.1 SWJA (*Daisen and Sambe*)**

646 Thirteen layers of the twenty-four visible SG06 tephra layers characterised at a trace
647 element level showed signatures consistent with those erupted along the SWJA. These
648 layers were deemed most likely to derive from Daisen and Sambe owing to their volcanic
649 glasses showing distinctively low-Y (**Fig. 5A**) and Middle/Heavy REE contents, a
650 characteristic of SWJA volcanism, a feature often referred to as adakitic (Kimura et al.,
651 2015). Subsequent, major element comparisons of the visible SG06 layers to chrono-
652 stratigraphically relevant proximal units at the two volcanoes facilitated the construction of an
653 integrated proximal-distal eruption event stratigraphy for the SWJA (Albert et al., 2018).
654 Major element similarities between two further visible SG06 tephra layers and known
655 eruption deposits from the two volcanoes, resulted in a total of nine layers being correlated
656 to eruptions at Daisen and five to Sambe volcano (Albert et al., 2018). The precise
657 correlations between the SG06 visible tephra layers and Daisen and Sambe eruptions unit
658 are listed in **Table 2**, along with SG06 age estimates. Arguably the most significant Daisen
659 eruptive unit discovered in the SG06 record relates to the Daisen Kurayoshi Pumice (DKP) -
660 SG06-4281 (59.6 ± 5.5 ka [2 σ]). Machida and Arai (2003) recognise this tephra as one of the
661 key Japanese tephrostratigraphic markers. This tephra is traced over 600 km NE of the
662 volcano, and provides a useful marker for constraining Late Quaternary sedimentary
663 sequences in Japan. Importantly the SG06 tephrostratigraphic record demonstrated that this
664 eruption deposit is temporally distinct from the widespread Sea of Japan SAN1 marine

665 tephra (= SG06-4141) preventing erroneous synchronisation of terrestrial and marine
666 archives around the MIS3/4 transition (e.g., Ikehara et al., 2004).

667 Albert et al. (2018) recognised that tephra SG06-4141 showed a trace element signature
668 consistent with the eruptive products of the SWJA. However, this layer correlated to the
669 widespread Sea of Japan SAN1 marine marker layer, had a major element composition that
670 subtly differed from those of Daisen and Sambe (higher-SiO₂ rhyolites). Whilst the trace
671 element glass data of SG06-4141 was most consistent with the Daisen eruptive products, no
672 obvious proximal candidate was recognised in the volcanic stratigraphy of either Daisen or
673 Sambe volcanoes. Consequently, this layer is discussed further in the context of explosive
674 volcanism in the Kyushu CVR (**Section 3.2.2.1**).

675 **3.2.2 Kyushu Central Volcanic Region (CVR)**

676 *3.2.2.1 Kuju volcano*

677 As outlined above tephra SG06-4141, dated at 54.4 ± 1.6 ka [2 σ], displays a SWJA-type
678 geochemical signature; yet no prominent chrono-stratigraphically relevant eruption units are
679 recognised at either Daisen or Sambe volcanoes. Instead the possibility is explored that this
680 tephra derived from an alternative source region, one that has produced magmas with a
681 similar low-Y/HREE affinity. Albert et al. (2018) acknowledged that SG06-4141/SAN1 had a
682 major element composition consistent with the eruptive products of Kuju volcano (Kj-Hd) in
683 the HVZ of central Kyushu (**Fig. 7**). Crucially the Kj-Hd Ignimbrite, and the associated Kuju-
684 P1 Plinian fall are dated at ~53.5 ka (Okuno et al., 2017) which is broadly consistent with the
685 age of the SG06-4141/SAN1. Trace element glass analyses presented here for Kuju
686 eruptive units (Kj-P1, Kj-Hd and Kj-Mg), verify that the volcano has also erupted magmas
687 displaying low-Y and middle and heavy REE contents, consistent with those erupted at
688 Daisen and Sambe (**Fig. 3; Fig. 5**). Therefore the new trace element glass data presented
689 here support the previous assignment of SG06-4141/SAN1 to explosive activity at Kuju
690 volcano (**Fig. 8D**). Linking SG06-4141 to a specific eruptive unit at Kuju is more challenging,
691 major element glass data from the Kj-P1 (Fall), the Kj-Hd (Ignimbrite) and Kj-D (Fall) are all
692 largely indistinguishable from one another (**Fig. 2**) and trace element glass data presented
693 here is not sufficient enough to discriminate the individual units.

694 Glass chemistry aside, the Kj-P1 fall has a strong eastward dispersal towards Shikoku Island
695 (Tsuji et al., 2017a), inconsistent with the SAN1 layers distribution further north-east in the
696 Sea of Japan. Instead we tentatively suggest that the distal tephra may relate to a co-
697 ignimbrite ash plume dispersed from the voluminous Kj-Hd Ignimbrite, indeed widespread
698 ash dispersals can often be the product of co-ignimbrite plumes (e.g., Smith et al., 2016).

699 Irrespective of specific at source attribution, the robust correlation of the widespread Sea of
700 Japan SAN1 marine layer (Ikehara et al., 2004) to SG06-4141 places important age
701 constraints on this event layer capable of synchronising marine and terrestrial palaeoclimate
702 archives in the region.

703 3.2.2.2 Aso Caldera

704 Comparisons with new proximal glass datasets from Aso caldera confirm that three visible
705 SG06 layers (SG06-3912; SG06-4963; SG06-5287) unequivocally show HKCA major and
706 trace element signatures consistent with the volcano (**Fig. 6-7**).

707 Previously, Smith et al. (2013) assigned both the geochemically indistinguishable SG06-
708 4963 and SG06-4979 tephra layers to the Aso-4 caldera forming eruption based on their
709 major element chemistry. However, the thinner tephra layer SG06-4979 is only identified in a
710 single borehole in the SG06 coring campaign, and has not been identified in any other core
711 sections that span the same depth interval, for this reason SG06-4979 is no longer
712 considered a primary tephra deposit (McLean et al., in prep). Smith et al. (2013) used major
713 element glass chemistry to relate SG06-5287 to the Aso-ABCD eruptive succession.

714 The SG06-3912 tephra was previously unassigned to a volcanic source, however the trace
715 element signature of these HKCA glasses, including enrichment of the LILE (Rb) and HFSE
716 (Th, U, Zr) are all consistent with those erupted from Aso caldera (**Fig. 5; 6; 8**). Based on the
717 SG06 age-depth model SG06-3912 has an interpolated age of 50.0 ± 0.3 ka (2σ), this
718 broadly corresponds to a succession of pumice fall out deposits from the Aso central cone
719 (Miyabuchi, 2011). Geochemical comparisons to these Plinian fall deposits reveal that
720 SG06-3912 has a major and trace element composition consistent with the Aso central cone
721 pumice (ACP) 4 fall unit (**Fig. 6G-H**). ACP4 represents one of the largest post-caldera
722 eruptions, with a total thickness reaching 159 cm at 3.5 km outside of the caldera rim with a
723 volume of 0.43 km³ (Miyabuchi, 2011). Its identification as a visible layer in the SG06 record
724 dramatically expands the known distribution of ash fall from this eruption, and may provoke a
725 future reassessment of the eruptive volume and magnitude estimates (M4.6; **Table 1**). It also
726 seems likely that this eruption deposits may be traced into other sedimentary records across
727 Japan. Importantly for the volcanic history of Aso caldera, Plinian deposits associated with
728 ACP4-6 are all identified above the Kuju Handa/P-1 tephra in the volcanic stratigraphy. With
729 the Kuju Handa/P-1 eruptive units correlated to SG06-4141 which has an age of 54.4 ± 1.6
730 ka (2σ) (Albert et al., in 2018), the SG06 record can place new chronological constraints on
731 this succession of Plinian eruptions at Aso caldera, illustrating a period of intense activity
732 spanning just 4-5 thousand years.

733 The major element glass chemistry of SG06-4963 is perfectly consistent with Aso-4 glass
734 data generated on the proximal succession from Noga Cave (**Fig. 6**) and verifies the
735 previous correlation of Smith et al. (2013). Trace element data reveals that the HKCA
736 rhyolitic tephra display identical levels of incompatible trace element enrichment compared
737 to the proximal Aso-4 ignimbrite deposits (**Fig. 8**). Importantly both diagnostic rhyolitic
738 components (1 and 2) of the eruption sequence are identified in the SG06-4963 layer (**Table**
739 **4**), and this is illustrated by the variations in Sr content of the glasses (**Fig. 6F**). SG06-4963
740 shows a sub-population of volcanic glasses with significantly lower levels of incompatible
741 trace element enrichment than are observed in the proximal sequence investigated here
742 (e.g., 4-5 ppm Th). The glass composition of the trachy-dacite glasses (component 3) found
743 in the proximal Aso-4 ignimbrite deposits are not observed in the distal SG06 tephra (**Fig. 6**).

744 The $^{40}\text{Ar}/^{39}\text{Ar}$ data from the proximal Aso-4 hornblende ($n = 25$) sampled define a single
745 population with an age of 86.4 ± 1.1 ka (2σ). When plotted on an isotope correlation plot the
746 data define an inverse isochron with an initial trapped component that is indistinguishable
747 from atmosphere $^{40}\text{Ar}/^{36}\text{Ar}$ (Lee et al., 2006; Mark et al., 2011) and an $^{40}\text{Ar}/^{39}\text{Ar}$ age that
748 overlaps with the weighted mean age (**Supplementary Material 3**). The data are statistically
749 robust defining a Mean Weight Square Deviates (MWSD) of 1 and a p-value of 0.4. We
750 interpret the $^{40}\text{Ar}/^{39}\text{Ar}$ weighted mean age of 86.4 ± 1.1 ka (2σ) to represent the age of
751 eruption for the Aso-4 event. This age is in strong agreement with the previous age
752 estimates derived based on the stratigraphic position of the Aso-4 tephra in orbitally-tuned
753 marine isotope records, where, Aoki (2008) assigned an age of 86.8-87.3 ka to the Aso-4
754 tephra, based on its stratigraphic position in the MIS5b (5.2) sediments of the northwest
755 Pacific.

756 The unequivocal (major and trace element) geochemical agreement between Aso-4 and
757 SG06-4963 mean that the $^{40}\text{Ar}/^{39}\text{Ar}$ age has been imported into the SG06 age-depth model
758 and provides a new chronological anchor for this deeper portion of the record. Importantly
759 the age of this tephra helps to impose more reliable age constraints on the linearly
760 interpolated age estimates of tephra deposits in the deeper portion of the Suigetsu record
761 and for instance this helps constrain the age of underlying K-Tz tephra (SG06-5181; **Section**
762 **3.2.3**).

763 New chemical data presented here from a distal Aso-4 tephra layer recovered from Lake
764 Mokoto (**Fig. 6**), northern Hokkaido, has both major and trace element concentrations
765 consistent with the proximal Aso-4 deposits and SG06-4963, therefore confirming visible ash
766 fall from this M7.7 eruption over 2000 km NE and is consistent with reported occurrences in
767 the Sea of Okhotsk (Aoki, 2008; Derkachev et al., 2016). The Aso-4 $^{40}\text{Ar}/^{39}\text{Ar}$ age presented

768 here offers an important independent age constraint on the MIS5b (5.2) sediments of the
769 western-Pacific region.

770 The HKCA rhyolitic tephra layer SG06-5287 was previously assigned to Aso-ABCD on the
771 basis of major element glass data (Smith et al., 2013), here we review this correlation in the
772 context of the comprehensive major and trace element data presented through the entire
773 eruptive succession sampled at Noga Cave beneath the Aso-4 ignimbrite (**Table 1; Fig. 6**).
774 SG06-5287 stratigraphic position above the Ata tephra (SG06-5353/**Section 3.2.3**) in the
775 SG06 record immediately rules out the pre-Ata Aso-NMKI Plinian units. Consistent with its
776 stratigraphic position above the Ata tephra, SG06-5287 instead has a major element
777 composition broadly consistent with all four Plinian fall out units (Aso-ABCD; **Fig. 6**).
778 However, major element data reveal that lower most fall unit Aso-D pumices are dominated
779 by glasses with more elevated CaO content than those of SG06-5287, with the distal tephra
780 instead consistent with the lower CaO content of Aso-ABC (**Fig. 6C**). Trace element data
781 reveals that there is very little geochemical overlap between the SG06-5287 tephra layer and
782 those of Aso-C and Aso-B fall units, which display restricted levels of incompatible trace
783 element enrichment (**Fig. 6**), this means we can exclude the two thinner fall units (C and B)
784 in the succession. SG06-5287 glasses show Y and Th contents consistent with the Aso-A
785 glasses. Whilst they do also overlap with Aso-D, glasses these proximal deposits largely
786 extend to higher levels of incompatible trace element enrichment, which are absent in the
787 distal SG06-5287 deposit (**Fig. 6D-F**). Major and trace element glass data indicate that the
788 distal tephra SG06-5287 can be most confidently assigned to the uppermost, and thickest
789 pre-Aso-4 eruption deposit, Aso-A (**Fig. 6A-F**). The SG06 age-depth model allows us to
790 provide an interpolated age estimate of 97.9 ± 6.0 ka (2σ) for the Aso-A eruption deposit.
791 Importantly, in terms of the tempo of explosive activity at Aso caldera, this correlation would
792 indicate that Aso-CBD, stratigraphically below Aso-A and above the Ata tephra (99.3 ± 6.0
793 ka; **Section 3.2.3**) were emplaced in a particularly short interval of time, perhaps as little as
794 ~ 1 ka, which would be consistent with the absence of any clear palaeosols between the
795 proximal eruptive units.

796 Age-models for many East Asian Late Quaternary marine and terrestrial sedimentary
797 archives are constrained by ages of Aso derived tephra layers preserved within their
798 sediments. Here we explore several of these tephra correlations in order to highlight the
799 importance of comparing proximal and distal glass chemistries when constructing
800 tephrochronological based age-depth models.

801 In the Pacific ICDP borehole U1436A (-2H-1-56-58cm) a 6 cm thick tephra unit is correlated
802 to the Aso-ABCD eruption deposits, whilst a thinner overlying layer of undefined thickness

803 (U1436A-2H-1-25-27 cm), is attributed to the Aso-4 caldera forming eruption (Schindlbeck et
804 al., 2018). The 6 cm thick tephra is inconsistent with the glasses erupted during the Aso-
805 ABCD succession, but are instead entirely consistent with the two dominant rhyolitic
806 components of the Aso-4 caldera forming eruption (**Fig. 6**). The overlying layer attributed to
807 Aso-4 is geochemically consistent with the underlying 6 cm thick ash layer, and again the
808 Aso-4 proximal glasses. Glass geochemistry and layer thickness indicate that the thicker
809 layer relates to the Aso-4 caldera forming eruption, not Aso-ABCD, and that the overlying
810 layer is probably re-worked volcanic glass from the same event. Consequently, it appears
811 erroneous age information has been transferred in to the age-models of this core.

812 In a second borehole, U1437B (-2H-6-78-80cm) Schindlebeck et al. (2018) identify a 2 cm
813 tephra deposit attributed to the Aso-3 caldera forming eruption. Comparisons to proximal
814 glass data sets here reveal that this tephra does not display the elevated and distinctive
815 levels of K_2O content seen in the proximal tephra at overlapping SiO_2 content (**Fig. 6**). Whilst
816 the distal tephra does unequivocally display a Aso-type glass chemistry, the correlation of
817 this marine tephra to the Aso-3 events is not supported by our proximal glass data,
818 particularly given the additional absence of less evolved glass compositions also diagnostic
819 of this eruption. Again this points to the erroneous transfer of age information into the marine
820 sedimentary record. Conversely, Sagawa et al. (2018) report Aso-3 tephra from the East
821 China Sea, their marine tephra glass data is entirely consistent with our proximal deposits
822 showing a wide range in composition from trachy-dacite to rhyolite (**Fig. 6**). Ultimately,
823 these discovery highlights the significant potential of this marker layer, also reported in
824 Lake Biwa (Nagahashi et al., 2007), to link palaeoclimate records over vast areas.

825 **3.2.3 Kyushu Southern Volcanic Region (SVR)**

826 Six layers (SG06-0967, SG06-2650, SG06-3668b, SG06-5181, SG06-5353, and SG06-6413
827 **Table 2**) are assigned to explosive volcanism at calderas situated in the Kyushu SVR (Aira,
828 Ata and Kikai). All six tephra deposits show glasses with rhyolitic CA affinity, with the higher
829 SiO_2 tephra (SG06-2650 and SG06-5181) residing at the boundary with the HKCA
830 classification (**Fig. 7**). These tephra deposits all lie on a trend of lower CaO at a given SiO_2
831 content than the majority of CA deposits erupted at NEJA (excluding Toya glasses) and
832 Kurile Arc sources (**Fig. 7**). Whilst these tephra units appear to lie on a similar major element
833 trends (e.g., SiO_2 vs. CaO) to the eruption products of Daisen, they can be easily
834 distinguished based on their higher FeOt content at a given SiO_2 (**Fig. 2**) and relative
835 enrichment in the HREE compared to SWJA volcanism (**Fig. 8**).

836 **3.2.3.1 Kikai Caldera**

837 Two SG06 tephra layers have previously been assigned to explosive eruptions of Kikai
838 caldera during the last 100 ka. The Holocene tephra SG06-0967 was correlated by Smith et
839 al. (2013) to the Kikai-Akahoya (K-Ah) eruption based on major element data comparisons.
840 Whilst SG06-5181 was correlated to the Lake Biwa tephra layer (BT-25; Nagahashi et al.,
841 2007), which is considered the distal equivalent of the Kikai Tozurahara (K-Tz) in the
842 absence of proximal glass data (Smith et al., 2013).

843 New major and trace element glass data from K-Ah samples collected from along the
844 Takatoge Pass and further north at Doimakino (near Aso caldera) verify the correlation of
845 SG06-0967 to the K-Ah eruption (**Supplementary Fig. 1; Fig. 8-9**). Distal K-Ah ash fall
846 recorded in the SG06 record show significant trace element geochemical heterogeneity
847 mirrored by the near source deposits (**Fig. 8-9**). This heterogeneity offers a useful diagnostic
848 feature of this eruption, given that many widespread Japanese tephra are very
849 homogeneous. The major and trace element concentrations of the Lake Biwa K-Ah tephra
850 (BIW07-06-1.45m; Kigoshi et al., 2014) are consistent with those of SG06-0967. In turn
851 these data are also consistent with BT-3/K-Ah data from Kimura et al. (2015). The most
852 precise eruption age for the K-Ah is derived from the SG06 age-depth model (Smith et al.,
853 2013), which places the eruption at $7,253 \pm 46$ IntCal13 yrs BP. This tephra has a
854 widespread distribution over Kyushu, Shikoku and much of Honshu Island (**Fig.1**; Machida
855 and Arai, 2003). Consequently, it offers a key chronostratigraphic marker for Holocene
856 palaeoenvironmental and archaeological (Jōmon) sequences (see Moriwaki et al., 2016).

857 SG06-5181 has a major and trace element composition indistinguishable from the near
858 source deposits of K-Tz collected from Tanegashima and Yakushima south-east of Kikai
859 caldera (**Fig. 5; 7; Fig. 8-9**). Despite a slight major element discrepancy between SG06-
860 5181 and BT25 (**Supplementary Figure 1D**; Nagahashi, et al., 2007; Kimura et al., 2015),
861 possibly owing to different analytical conditions; the trace element data here verify their
862 geochemical agreement, and strengthening this tephra tie-point between the two important
863 palaeoclimate records (**Fig. 9A-D**). A diffuse layers of K-Tz is reported in a Uwa Basin core,
864 on Shikoku Island (UT 7.78; Tsuji et al., 2017b), however subtle differences exist between
865 the composition of this tephra and the glass data presented here for the K-Tz/SG06-5181
866 (**Fig. 9**). Given the major element similarity between the evolved (>77 wt.% SiO_2) products of
867 the volcanoes of the Kyushu SVR, this correlation would benefit from more detailed trace
868 element investigations.

869 K-Tz is not well dated, it is chrono-stratigraphic position between On-Pm1 (MIS 5.3) and
870 Aso-4 (MIS5.2) in the marine oxygen isotope stratigraphy, consequently it has been loosely
871 attributed an age of ca. 95 ka (Machida and Arai, 2003), whilst the tephra has a zircon

872 derived fission track age of 98 ± 26 ka (Danahara, 1995). The SG06 age-depth model
873 provides one of the most reliable age estimates for this eruption to date, with an interpolated
874 age of 94.5 ± 4.8 ka (2σ) which is constrained by the $^{40}\text{Ar}/^{39}\text{Ar}$ age of the overlying Aso-4
875 tephra (SG06-4963). Consequently, this age can be transferred to other
876 palaeoenvironmental records that preserve the same ash unit, for instance other lacustrine
877 sequences (e.g., Lake Biwa; Nagahashi et al., 2007; **Fig. 12**) and marine records (e.g., East
878 China Sea; Sagawa et al., 2018).

879 3.2.3.2 Ata Caldera

880 SG06-5353 has a major and trace element signature consistent with the proximal deposits of
881 the Ata Ignimbrite (**Fig. 8-9**). This tephra is also entirely consistent with the compositions of
882 the Ata co-ignimbrite ash sampled from beneath the Aso-ABCD succession at Noga Cave
883 (**Fig. 9**), and other distal occurrences of the Ata tephra (e.g., UT8.89; Tsuji et al., 2017b)
884 Combined proximal, medial and distal major and trace element glass data here confirm that
885 the caldera forming eruption tapped a particularly homogeneous rhyolitic magma (**Fig. 7-10**).
886 Currently, the age of the widely dispersed Ata tephra (**Fig. 1**) is poorly constrained. The
887 stratigraphic position of the Ata ash fall between MIS5.4 and MIS5.3 in the marine record
888 have been used to infer an age of ca. 105-110 ka (Oba, 1991). Furthermore. Zircon fission
889 track and K-Ar ages place the eruption age at 100 ± 27 ka (Danahara, 1995), and 108 ± 3 ka
890 (Matsumoto and Ui, 1997), respectively. Here, the SG06 age-depth model allows us to
891 provide an interpolated eruption age of 99.3 ± 6 ka (2σ).

892 3.2.3.3 Aira Caldera

893 SG06-2650 the thickest layer (>30 cm) in the SG06 record, is related to the rhyolitic caldera
894 forming eruption of Aira- (distally known as the AT (Smith et al., 2013) and is classified as an
895 M7.9 eruption. The new trace element data presented here verifies the correlation (**Fig. 8B**;
896 **9E-F**), and furthermore provides a strong geochemical match for the AT layer reported in
897 Lake Biwa reinforcing this stratigraphic tie-point between the two records (**Fig. 9E-F**; Kigoshi
898 et al., 2011; Kimura et al., 2015). The AT ash presents a key widespread tephrostratigraphic
899 marker for Japan being traced across much of Kyushu, Honshu and Hokkaido Islands, and
900 also across the Korean Peninsula (Machida and Arai, 2003; **Fig. 1**), and most recently it is
901 traced into N.E China (Mingram et al., 2018). Its stratigraphic position close to the MIS 3/2
902 transition enhances its potential as a key marker for assessing spatial variations in
903 palaeoenvironmental change. Furthermore it is also used to constrain archaeological
904 sequences, specifically the tephra provides a marker separating the Early Upper Palaeolithic
905 and the Late Upper Palaeolithic in Japan (Ono, 2002). The distribution of the tephra is likely
906 to be extended through future cryptotephra studies of Pacific marine cores.

907 3.2.3.4 Unresolved Kyushu SVR tephra layers

908 The remaining two layers attributed to explosive volcanism in the Kyushu SVR are more
909 difficult to attribute to a specific source eruption. The dominant glass population of SG06-
910 3668 was correlated to the Sambe Ikeda (SI) eruption (Albert et al., 2018). This tephra dated
911 by the SG06 age-depth model at $46,295 \pm 418$ IntCal13 years BP contained a small
912 secondary glass population (Component 2) which revealed volcanic glasses inconsistent
913 with Sambe volcanism based on their multi-element trace element profile (**Fig. 8B**). Thus,
914 this layer might record contemporaneous activity from another source. Glass chemistry
915 indicates a partial overlap with the eruptive products of the Kyushu SVR, and specifically
916 Aira caldera products (AT; **Supplementary Figure 1**). Trace element data from these
917 glasses show some similarity to the magmas erupted at Aira caldera (**Fig. 8**), however
918 variation in the trace element compositions of these secondary glasses also indicate multiple
919 eruption sources have contributed as fall to this unit (**Fig. 5**).

920 SG06-6412 is dated using in the SG06 record at ~ 125 ka and has a CA affinity which would
921 normally be considered more akin to volcanism on the NEJA, however the trace element
922 concentrations of this tephra are more comparable with a Kyushu SVR origin. Specifically,
923 these low-SiO₂ rhyolites display more elevated Th and Rb content than the most silicic CA
924 products analysed from NEJA sources (**Fig. 5**). While, considerable trace element overlap
925 exists with the products of Kikai caldera, the distal tephra displays far more enriched HREE
926 contents (**Fig. 8A**). Conflicting geochemical features mean the origin of this layer cannot yet
927 be resolved.

928 3.2.4 Izu-Bonin Arc (Hakone and Fuji)

929 Tholeiitic (low-K) tephra layers SG06-6344 (dacite-rhyolite) and SG06-3485 (basaltic-
930 andesite) display trace element signatures that are characterised by low levels of
931 incompatible trace element enrichment, in particular low contents of LILE (e.g., Rb) and
932 HFSE (e.g., Th, U), whilst also displaying flat REE profiles, reflected by low La/Yb ratios
933 (**Fig. 8C; Table 4**). Incompatible trace element ratios such as Zr/Y are consistent in the
934 volcanic glasses of SG06-3485 (2.92 ± 0.21 [1σ]) and SG06-6344 (3.12 ± 0.04 [1σ]) which is
935 likely to indicate a similar source region. The nearest and most likely source of low-K
936 volcanism to Lake Suigetsu is the northern sector of the Izu-Bonin Arc, and specifically
937 Hakone caldera, whilst more distally tholeiitic (silicic) volcanism is known to occur further
938 south along the Izu-Bonin Arc (Schindlbeck et al., 2018), and at Towada (NEJA) and Mashu
939 (Kurile Arc) calderas (**Fig. 7**).

940 3.2.4.1 Hakone Caldera

941 Comparing the major and trace element compositions of SG06-6344 and Hakone tephra
942 (Hk-TAu8) reveals significant similarity; the K_2O content of these Hakone caldera glasses
943 are more comparable than those of Mashu caldera (**Fig. 11A**). Whilst Towada glasses show
944 similar K_2O content, they are lower in FeO_t and CaO content relative to the SG06-6344
945 tephra (**Fig. 10B**). Both SG06-6344 and Hk-TAu8 share similar trace element profiles (**Fig.**
946 **8C**), and overlapping concentrations of incompatible trace elements (**Fig. 10E**). Towada
947 tholeiitic rhyolitic glasses display more elevated contents of Rb, Th, U and LREE compared
948 to SG06-6334 (**Fig. 8C**). Whilst trace element glass data from Mashu caldera enable us to
949 rule out an origin from volcanism along the southern portion of the Kurile arc, specifically the
950 Nb and Ta contents of the SG06-6344 glasses are far more elevated than those glasses
951 erupted at Mashu (**Fig. 8C**).

952 Glass data strongly support an origin of SG06-6344 from Hakone caldera, the volcano was
953 particularly active between ~100-250 ka based on the intercalation of multiple tephra units
954 within the marine successions (Machida, 2008). Hakone sample Hk-TAu8 was erupted
955 during this interval, yet this deposit is considered too old to be the proximal equivalent of
956 SG06-6344 which has an interpolated age of 123.3 ± 7.5 ka (2σ). Instead it is more probable
957 that the SG06-6344 relates to an eruption from within the Kissawa Lower Pumice series,
958 which represent the youngest activity of this period of intense activity at the volcano. Some
959 of the Kissawa Lower Pumice series deposits are distributed to the west of the volcano.
960 Near-source geochemical investigations are needed to further explore this correlation, and
961 could offer important geochronological constraints on the eruptive history of Hakone caldera.

962 3.2.4.2 Ko-Fuji

963 Given that the trace element profile and incompatible trace element ratios of the basaltic-
964 andesite tephra SG06-3485 (**Table 4**; Smith et al., 2013) are very similar to that of the
965 Hakone tephra/SG06-6344, albeit less evolved (**Fig. 8**), we must consider that the
966 provenance of this tephra relates to a nearby volcanic source. Marine records indicate that
967 basaltic-andesite deposits are typical of volcanism along the Izu-Bonin arc (Schindlbeck et
968 al., 2018), but the closest source of these compositions to Lake Suigetsu is Mount Fuji west
969 of Hakone caldera, positioned at the junction between the Izu-Bonin Arc and the NEJA
970 (Kaneko et al., 2010).

971 Marine tephra layers from the Izu-Bonin Arc (Schindlbeck et al., 2018) indicate that the
972 basaltic-andesite products are typically lower in both K_2O and Al_2O_3 at overlapping MgO
973 content when compared to the SG06-3485 tephra layer. The high- Al_2O_3 basaltic-andesite
974 tephra in SG06 appears more akin to the Fuji eruptive products (**Fig. 10C-E**). Whole-rock
975 and melt inclusion data from scoria sampled from both Ko- (100-20 ka) and Shin-Fuji (20 ka

976 to present) deposits display more elevated K_2O contents (Togahsi and Terashima, 1997;
977 Watanabe et al., 2006; Kaneko et al., 2010) compared to the basaltic-andesites reported
978 from further south along the Izu-Bonin Arc (**Fig. 10C**). From the sparse data available, the
979 younger Shin-Fuji deposits tend to be more enriched in K_2O contents relative to the older
980 Ko-Fuji deposits, which instead display a lower-K affinity. SG06-3485 displays K_2O contents
981 more consistent with Ko-Fuji activity (**Fig. 10**). The basaltic-andesite deposits of the Ko- and
982 Shin- Fuji can be also be distinguished from those erupted further south along the Izu-Bonin
983 Arc based on their more elevated Zr/Y ratios (**Fig. 10E**). Absolute concentrations of Y and Zr
984 in the eruptive products of Ko- and Shin-Fuji clearly distinguish the products of the two
985 eruptive periods of the volcano, and SG06-3485 glasses are entirely consistent with those of
986 the older Ko-Fuji activities (**Fig. 10E**), which is in agreement with the tephra deposits age in
987 the SG06 record, which at $43,713 \pm 300$ IntCal13 yrs BP pre-dates Shin-Fuji activity.

988 Clearly this distal tephra reflects a large magnitude eruption of Ko-Fuji, perhaps its
989 occurrence and thickness (0.5 cm) in Lake Suigetsu 250 km NW of source suggest the
990 eruption was similar in magnitude to the younger Shin-Fuji AD 1707 Plinian eruption (M5.2),
991 which was responsible for ash dispersed up to 250 km east of source (Miyaji, 1984,
992 Machida, 1964). The usefulness of this tephra as marker layer for linking sedimentary
993 archives is still to be explored, given the limited knowledge of the frequency and magnitude
994 of eruptions from Ko-Fuji (Kaneko et al., 2010), and also because these primitive melt
995 compositions are unlikely to yield diagnostic geochemical fingerprints suitable for
996 deciphering successive tephra units erupted from the volcano.

997 **3.2.5 Group 5: North East Japan Arc**

998 In the lower portion of the SG06 sequence tephra, SG06-6634 displays a CA affinity that is
999 broadly consistent with the eruption deposits of the NEJA, as such they are lower in K_2O at
1000 overlapping SiO_2 content with those from the Kyushu SVR or CVR (**Fig. 7**). SG06-6634 is
1001 dated at ~ 130 ka using the SG06 age-depth model, and was previously considered a
1002 possible correlative of the Kc-Hb tephra (Smith et al., 2013). Proximal glass data indicate
1003 that this tephra is inconsistent with Kutcharo (Kurile Arc) activity owing to their more elevated
1004 K_2O (**Fig. 10**) and Nb-Ta content (**Fig. 8D**). The SG06-6634 tephra displays some
1005 compositional overlap with the products of Akagi volcano (**Fig. 10A**), however Akagi glasses
1006 display lower FeO_t content at overlapping CaO (**Fig. 10B**). The most evolved glasses in the
1007 SG06-6344 overlap with the rhyolitic products of Shikotsu caldera, SW Hokkaido (Spfa-1;
1008 Fig. 10A-B). Chronologically the Suigetsu tephra cannot be related to this eruption (**Table 1**),
1009 yet compositional similarities extend a range of trace elements (**Fig. 8D**), most significantly
1010 the more restricted Rb and Th content of the SG06-6344 glasses, a feature of the NEJA

1011 tephra units analysed here (**Fig. 5, 8**). For now the precise origin of this tephra remains
1012 unresolved.

1013 **3.3 The Lake Suigetsu (SG06) tephrostratigraphy**

1014 **Table 2** and **Figure 11** summarise all the proximal-distal SG06 tephra correlations that have
1015 been established using new major and trace element glass data sets presented here and in
1016 Albert et al. (2018). The Lake Suigetsu (SG06) record preserves many of the key Japanese
1017 widespread tephra layers (**Fig. 11**) recognised by Machida and Arai (2003). The Lake
1018 Suigetsu sediment record is recognised as a central node in the tephrostratigraphic
1019 framework of Japan, owing to the range of different volcanic sources that have contributed
1020 ash fall to the lake (Smith et al., 2011; Smith et al., 2013; McLean et al., 2016; McLean et al.,
1021 2018; Albert et al., 2018; this study). The prevailing winds mean visible ash fall layers
1022 recorded are predominantly from volcanic source regions west of the lake (SWJA, the
1023 Kyushu CVR and SVR). Explosive volcanism at Daisen (nine layers) and Sambe (five layers)
1024 have been the dominant source of ash fall events (Albert et al., 2018), whilst visible ash
1025 layers are confirmed from a further seven volcanic sources; Aso (three), Kikai (two), Ata
1026 (one), Aira (one), Kuju (one). Trace element glass data here enables us to also verify visible
1027 ash fall layers from explosive volcanism elsewhere in Japan, including for the moment un-
1028 determined eruptions along the northern Izu-Bonin arc (Hakone, Fuji) and North East Japan
1029 Arcs.

1030

1031 The stratigraphy and chronology of the SG06 sequence is crucial for refining the Late
1032 Quaternary tephrochronology of Japan, particularly since it clearly resolves the relative-age
1033 ordering of closely spaced tephrostratigraphic markers. Tephra correlations reveal at least
1034 10 precise tephrostratigraphic tie points link the Lake Suigetsu (SG06 core) and Lake Biwa
1035 palaeoclimate archives during the last 100 ka (**Fig. 11**). The SG06 age-depth model
1036 provides some of the most reliable age estimates for many of the widespread tephra layers
1037 that cannot be reliably dated using routine methods (e.g., $^{40}\text{Ar}/^{39}\text{Ar}$). Thus, the detailed
1038 geochemical fingerprints presented here for the SG06 tephra layers is fundamental to
1039 robustly using this chronological information, and facilitating its transfer into other key
1040 palaeoclimate and archaeological archives across East Asia and beyond. Many of the large
1041 magnitude eruption deposits recorded in the Lake Suigetsu record are found in marine
1042 sequences beyond the Japanese Islands (e.g., AT, Aso-4, K-Tz) and as such, they present
1043 an important means to evaluate the synchronous or asynchronous response of terrestrial
1044 (e.g., Lake Suigetsu) and marine climate proxies to abrupt Late Quaternary climate
1045 variability in East Asia.

1046 **4. Conclusions**

1047 Numerous tephra layers preserved in the Lake Suigetsu (SG06 core) sediments are
1048 associated with large magnitude explosive eruptions and are widespread making them key
1049 to synchronising palaeoclimate archives across Japan, the NW Pacific and beyond.
1050 Crucially, the unrivalled chronology of the SG06 record provides critical age constraints for
1051 the SG06 tephra, and these can be transferred into other records (palaeoclimate,
1052 archaeological and volcanic) containing the same eruption deposits. This transfer of
1053 geochronological information demands high-precision tephra correlations, which is
1054 particularly pertinent in distal sedimentary records where multiple volcanic source regions
1055 can contribute fine-grained ash fall, often preserved as non-visible (cryptotephra) layers. To
1056 facilitate tephra correlations centred on the key Late Quaternary widespread Japanese
1057 tephrostratigraphic markers we integrate new grain-specific major EMP and trace element
1058 LA-ICP-MS glass analyses of proximal and medial deposits with the existing major element
1059 and new trace element glass data from their distal equivalents preserved in the SG06
1060 record.

1061 These data offer new insights into diagnostic compositional variations of the investigated
1062 volcanic sources spanning the Japanese Islands. Large Ion Lithophile elements, K and Rb,
1063 are very useful for discriminating the different Japanese volcanic source regions. The forearc
1064 calderas of Kyushu (SVR and CVR) have glasses with higher K_2O and Rb contents than
1065 deposits from those situated along the North East Japan and Kurile Arcs. Thorium behaves
1066 broadly similar to K_2O (and Rb), whereby higher K_2O rhyolites from the Kyushu SVR (Kikai,
1067 Ata, Aira) and CVR (Aso, Kuju) are more enriched in Th than those from the NEJA (Toya,
1068 Shikotsu) or Kurile Arc (Kutcharo). Contents of Nb and Ta also vary significantly between
1069 different Japanese volcanic sources, with lowest contents associated with lower-K volcanic
1070 sources, with the Kurile Arc (Kutcharo/Mashu) tephra deposits particularly depleted in Nb
1071 content. REE element contents can also be useful, and low-Y and HREE content (high-
1072 La/Yb ratios) in volcanic glasses is a feature of the SWJA volcanism (Daisen and Sambe),
1073 and is also recognised at Kuju volcano in the Hoho Volcanic Zone. Flat REE profiles are
1074 typically related to low-K tholeiitic sources, with those erupted along the Izu-Bonin arc
1075 (Hakone) and Kurile arc (Mashu) showing lower La/Yb ratios than those observed along the
1076 NEJA (Towada). Glass data presented here from individual volcanoes illustrate that glass
1077 compositions through eruptive successions are often similar, highlighting that proximal and
1078 distal stratigraphic control is also crucial for reliable tephra correlations.

1079 The geochemical data are used to validate and refine the tephrostratigraphy of the SG06
1080 record. Here we are able to offer new chronological constraints on the explosive volcanism

1081 at calderas situated along the Kyushu Arc, including Kikai, Ata and Aso. Correlations
1082 between the SG06 tephra layers and eruption units at Aso caldera allow the two-way
1083 transfer of geochronological information. Proximal Aso-4 (Magnitude 7.7) eruption deposits
1084 yielded an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 86.4 ± 1.1 ka (2σ), and provide a chronological anchor (SG06-
1085 4963) in the Lake Suigetsu age model beyond the radiocarbon timeframe. Distal ash fall
1086 from Plinian eruption of Aso are dated using the SG06 age-depth model, providing ages of
1087 97.9 ± 6.0 ka (2σ) for Aso-A (SG06-5287) and 50.0 ± 0.3 ka (2σ) for the Aso central cone
1088 pumice 4 (SG06-3912) eruption.. Proximal-distal correlations between the volcanic
1089 stratigraphy of Aso caldera and the SG06 record provide important new constraints on the
1090 tempo of explosive activity at this volcano. Whilst the prevailing winds mean visible ash fall
1091 layers recorded in Lake Suigetsu are predominantly from volcanic source regions west of the
1092 lake (SWJA, Kyushu CVR and SVR), trace element glass data here enables us to also verify
1093 visible ash fall layers from explosive volcanism elsewhere in Japan, including the Izu-Bonin
1094 and North East Japan Arcs.

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1490 **Table Captions**

1491 **Table 1:** Eruption deposits the focus of geochemical characterisation spanning the
 1492 Japanese Islands, including those recognised as widespread Japanese tephra markers
 1493 (bold; Machida and Arai, 2003). Dispersal, VEI (Volcanic Explosivity Index; following Newhall
 1494 and Self, 1982), Eruption Magnitudes (calculations following Pyle, 2000) and volumes
 1495 estimates are derived from Machida and Arai (2003), and the LaMEVE database (Crowweller
 1496 et al, 2012; references therein). Eruption age references are as follows: (1) Smith et al.
 1497 (2013); (2) This study [re-calibrated/IntCal13]; (3) Machida and Arai (2003); (4) Mirowaki et
 1498 al. (2016); (5) Hayakawa (2010); (6) Ikehara et al., 2006; (7) Miyabuchi et al. (2011); (8) Aoki
 1499 (2008); (9) Kaneko et al. (2015); (10) Albert et al. (2018); (11) Kimura et al. (1999); (12)
 1500 Machida (2008); (13) Aoki et al. (2008); (14) Bourne et al. (2016); (15) Uesawa et al. (2016);
 1501 (16) Ito et al. (2014); (17) Derkachev et al. (2017); (18) Hasegawa et al. (2016); (19)
 1502 Kishimoto et al. (2009). Corresponding sampling localities are listed in Supplementary Table
 1503 1. Pum = Pumice; Ign. = Ignimbrite; Ref. = Reference.

1504 **Table 2:** The visible SG06 tephra layers which have been the focus of trace element
 1505 chemical fingerprinting. Also shown are the arc region, source and eruption specific
 1506 correlations based on the geochemical data presented. The tephra layer displayed in bold
 1507 are the focus of this contribution, whilst those marked with * were the focus of Albert et al.
 1508 (2018) and were linked to eruptions at Daisen and Sambe volcanoes along the SWJA. The
 1509 tephra samples used for trace element chemical analyses here were derived from the core
 1510 sections underlined.. Composite depth of the base of the tephra is taken from the SG06
 1511 correlation model. Ages in IntCal13 yrs BP are provided for all tephra layers within the ¹⁴C
 1512 timeframe (<50 ka), and beyond are presented in ka (uncertainties represent either 95.4%,
 1513 or 2σ). **The age of SG06-4963 is the ⁴⁰Ar/³⁹Ar age presented here for the Aso-4 ignimbrite
 1514 its proximal counterpart.

1515 **Table 3:** Major and trace element glass chemistry of proximal deposits investigated to
 1516 develop a reference glass dataset associated with large magnitude eruptions at Japanese
 1517 volcanic sources. Full geochemical datasets are available in Supplementary Material 2.

1518 **Table 4:** Major and trace element glass chemistry of SG06 tephra layers correlated to
 1519 source volcanic deposits in this contribution. *represents major element glass data as
 1520 presented in Smith et al. (2013); and C = Component. Full trace element volcanic glass
 1521 datasets for the SG06 tephra layers presented here are available in Supplementary Material
 1522 2.

1523 **Supplementary Table 1:** Eruption deposits the focus of geochemical characterisation
 1524 spanning the Japanese Islands. Sampling localities of tephra deposits analysed, along with
 1525 eruption details, dispersal, eruption magnitudes and volumes estimates follow Machida and
 1526 Arai (2003), and the LaMEVE database (Crowweller et al, 2012).

1527 **Figure 1:** A map of the Japanese islands, showing the volcanic centres that were active in
 1528 the Late Quaternary and the location of the Lake Suigetsu (SG06) record (black square).
 1529 Calderas are marked by circles with teeth, whilst the remaining stratovolcanoes are marked
 1530 by circles or black dots. Those volcanoes labelled in bold have been subjected to detailed
 1531 major and trace element characterisation for the purpose of geochemically characterising the
 1532 different volcanic region (**Table 1**). Labelled in red are the portions of the Japanese Island
 1533 arc which are referred to through the manuscript and the thick solid red lines represent the
 1534 plate boundaries.. Isopach maps are presented for the Late Quaternary key widespread

1535 Japanese tephrostratigraphic markers following Machida and Arai (2003), and for tephra
1536 labelling/abbreviations of the individual eruption deposits refer to **Table 1**. HVZ is the Hoho
1537 Volcanic Zone (HVZ) in central-northern Kyushu and is marked by a red dotted envelope.
1538 NAP is North American Plate.

1539 **Figure 2:** Major element geochemical variability of volcanic glasses analysed from large
1540 magnitude silicic eruption of Japanese volcanic centres spanning the last ca. 150 ka.
1541 Glasses at Japanese volcanic sources range from Low-K (tholeiitic) to High-K (calc-
1542 alkaline)/Shoshonitic affinities, with deposits of the large magnitude eruptions investigated
1543 dominated rhyolitic tephra units (>70 wt.% SiO₂). Compositional fields/envelopes for Daisen
1544 and Sambe glasses are following data presented in Albert et al. (2018). AT and Ata proximal
1545 glass data follow Smith et al. (2013). Classification fields follow Peccerillo and Taylor (1976).
1546 Error bars on plots represent reproducibility, calculated as a 2 x standard deviation of
1547 replicate analysis of MPI-DING StHs6/80-G

1548 **Figure 3:** Selected major and trace elements useful for recognising spatial variations in the
1549 chemistry of volcanic glasses erupted in the different Japanese volcanic regions.

1550 **Figure 4:** Average Primitive Mantle normalised volcanic glass compositions for
1551 representative near-source (proximal) large magnitude eruption deposits investigated here
1552 and considered representative of the various arc regions of Japan. Primitive mantle values
1553 used for normalisation follow Sun and McDonough (1989). Envelope for SWJA eruption
1554 deposits of Daisen and Sambe volcanoes follow Albert et al. (2018).

1555 **Figure 5:** Trace element bi-plots considered useful for depicting the compositional variation
1556 of the eruptive products investigated from the various Japanese sources. Data points
1557 represent grain-specific glass analyses. The envelopes for Daisen and Sambe volcanoes
1558 (SWJA) are based on data presented in Albert et al. (2018), interestingly Kuju volcano
1559 shares a similar low-Y feature. Error bars on plots represent reproducibility, calculated as a 2
1560 x standard deviation of replicate analysis of MPI-DING StHs6/80-G. (1) Tateyama-D glass
1561 data is from Kimura et al. (2015).

1562 **Figure 6:** Geochemical variability in the near-source volcanic glasses of Aso caldera
1563 eruption deposits spanning between ca. 50 and 135 ka. Shown are grain-specific glass data
1564 for SG06 tephra deposit related to large magnitude eruptions at Aso caldera (SG06-
1565 3912/ACP4; SG06-4963/Aso-4 and SG06-5287/Aso-A). Also presented are a selection of
1566 distal ash layers related to explosive volcanism at Aso caldera, and in some instances these
1567 have been used to construct age-depth models for their host sedimentary records
1568 (Schindlebeck et al. 2018; Sagawa et al., 2018), refer to text for full details. Error bars on
1569 plots represent reproducibility, calculated as a 2 x standard deviation of replicate analysis of
1570 MPI-DING StHs6/80-G

1571 **Figure 7:** SG06 tephra layers (grain-specific analyses after Smith et al., 2013) compared to
1572 the compositional fields generated from near-source (proximal) volcanic glass data sets
1573 presented and discussed here. Classification fields follow Peccerillo and Taylor (1976).
1574 Near-source compositional fields of Daisen and Sambe volcanic deposit follow Albert et al.
1575 (2018), whilst those of Aira and Ata combined data from this study with Smith et al. (2013).
1576 Error bars on plots represent reproducibility, calculated as a 2 x standard deviation of
1577 replicate analysis of MPI-DING StHs6/80-G.

1578 **Figure 8:** Average Primitive Mantle normalised volcanic glass compositions for
1579 representative SG06 visible tephra layers investigated and discussed here. Primitive mantle
1580 values used for normalisation follow Sun and McDonough (1989). Envelope for SWJA
1581 (Daisen and Sambe) volcanoes follow Albert et al. (2018), with the exception of the Izu Arc
1582 Basalts field generated using data presented in Schindlebeck et al., (2018), the remaining
1583 envelopes are based on near-source data presented in this study.

1584 **Figure 9:** Trace element volcanic glass data from large magnitude eruption deposits from
1585 the Kyushu SVR compared distal equivalents preserved in the Lake Suigetsu (SG06)
1586 sedimentary record. Tephra layers BIW07-06-1.45 m (K-Ah) and BIW07-06-9.87m (AT) were
1587 analysed from Lake Biwa core BIW07-06 (Kigoshi et al. 2014). References: (1) Kimura et al.,
1588 2015; (2) Maruyama et al., 2016. Error bars on plots represent reproducibility, calculated as
1589 a 2 x standard deviation of replicate analysis of MPI-DING StHs6/80-G.

1590 **Figure 10:** Major and trace element glasses analyses of Lake Suigetsu tephra deposits
1591 SG06-3485, SG06-6344, SG06-6413 and SG06-6634 compared to potential volcanic source
1592 data either included in this study or existing datasets (1) Hakone: Suzuki et al., unpublished;
1593 (2) Akagi: Suzuki et al., unpublished (3) Fuji: Kaneko et al., 2010; (4) Fuji: Togahsi and
1594 Terashima, 1997; (5) Izu-Bonin Arc: Schindlebeck et al., (2018).

1595 **Figure 11:** The integrated proximal-distal event stratigraphy of SG06 visible tephra layers,
1596 with correlations to other sedimentary records are also depicted including Lake Biwa (**Fig.**
1597 **1**). The SG06 tephra ages are shown as IntCal13 yrs BP in the radiocarbon timeframe (95.4
1598 %). Beyond the annually laminated and ^{14}C dated portion of the sequence, the age-depth
1599 model is based on a linear interpolation that is anchored to deeper chronological tie points,
1600 which now include the new $^{40}\text{Ar}/^{39}\text{Ar}$ age of the Aso-4 eruption deposit (SG06-4963). All
1601 ages reported that are outside the ^{14}C timeframe are provided in ka with 2σ errors
1602 (equivalent to 95.4% probability range). SG06 tephra layers correlated to eruptions at Daisen
1603 and Sambe volcanoes (SWJA) follow Albert et al. (2018) and are summarised in Table 2.
1604 The simplified tephrostratigraphy of Lake Biwa illustrates the tephra layers that can be used
1605 to correlate Lakes Suigetsu and Biwa, and is based on those layers identified and
1606 characterised from the Takashima-oki core (Nagahashi et al., 2004; 2007; Satoguchi et al.,
1607 2008; Kimura et al., 2015) and the BIW07-06 core (Takemura et al., 2010; Kigoshi et al.,
1608 2014; Albert et al., 2018). Sea of Japan core KT96-17 follows Domistu et al. (2004), whilst
1609 GH89-2-27 and GH89-2-25 are reported in Ikehara et al. (2004), both contain the SAN1
1610 marine tephra marker. The Takano formation follows Iriya et al. (2005), and Nagahashi et al.
1611 (2007), whilst the DKP identified in a borehole at Naka-iwata follows Suzuki et al. (2016).

1612 **Supplementary Figure 1:** Major element volcanic glass data from large magnitude eruption
1613 deposits from the Kyushu SVR compared distal equivalents preserved in the Lake Suigetsu
1614 (SG06) sedimentary record. Error bars on plots represent reproducibility, calculated as a 2 x
1615 standard deviation of replicate analysis of MPI-DING StHs6/80-G.

1616

1617

Volcano	Eruption *	Tephra	VE I	Magnitude (M)	Volume (km ³)	Dispersal	Eruption style	Sampled	Sample Ref.	Age cal yrs BP or Ka (95.4%)	Age Ref.
Kyushu Southern Volcanic Region (SVR)											
Kikai	Akahoya *	K-Ah	7	7.3	150	NE	Ign. (+Co)	ash	ITJ3 ITJ20	7,165-7,303	(1-2)
	Tozurahara*	K-Tz	7	7.2	150	NE (radial)	Ign. (+Co)	ash	ITJ241 ITJ240	~95	(3)
Ata (Ibusuki Volcanic field)	Ikeda	Ik	5	5.4	2.3	E	Plinian Fall	pumice	ITJ53 ITJ9	6,600	(4)
	Ata*	Ata	7	7.5	350	NE	Ign. (+Co)	pumice, ash	ITJ51 ITJ24	98-108	(1,5)
Aira/Sakurajima	Satsuma	Sz-S	6	6.0		S (radial)	Plinian Fall	pumice	ITJ2	12,800	(4)
	Tanzawa*	AT	≤ 8	7.9	463	NE (radial)	Plinian Fall Ign. (+Co)	pumice pumice, ash	ITJ5 ITJ8	30,009 ± 189	(1-2)
	Iwato	A-Iw	6	6.0	9.5	E	Plinian fall; Ign.	pumice, ash	ITJ54	~55	(6)
Kyushu Central Volcanic Region (CVR)											
Aso Caldera	ACP	ACP3		-	-	E	Plinian Fall	pumice	ITJ204	51	(7)
	ACP	ACP4	4	4.6	0.43	E (radial)	Plinian Fall	pumice	ITJ205	~51	(7)
	ACP	ACP5	4	4.2	0.15	NE	Plinian Fall	pumice	ITJ206	-	
	ACP	ACP6	4	4.6	0.21	E	Plinian Fall	pumice, ash	ITJ207	~60	(7)
	Aso-4*	Aso-4	7	7.7	600		Ign. (+Co)	pumice (Upper) pumice (middle) pumice (base)	ITJ42 ITJ41 ITJ40	~87-88 ka (MIS5b)	(8)
	Aso-Y	Aso-Y	4	4.0	0.1	E?	Sub-Plinian Fall	pumice	ITJ38		
	Aso-A	Aso-A	6	5.9		ENE	Plinian Fall	pumice	ITJ11, ITJ38		
	Aso-B	Aso-B	6	5.9	1.0	ENE	Sub-Plinian Fall	ash	ITJ34	~96	(5)
	Aso-C	Aso-C	6	5.9		ENE	Plinian Fall	pumice	ITJ29, ITJ32		
	Aso-D	Aso-D	6	5.9		ENE	Plinian Fall	pumice	ITJ10, ITJ25		
	Aso-I	Aso-I	5	5		ENE	Plinian Fall	pumice	ITJ242	> 100 < 123	

	Aso-K	Aso-K	5	5.0	1.0	ENE	Plinian Fall	pumice	ITJ243		
	Aso-M	Aso-M	5	5		ENE	Plinian Fall	pumice	ITJ244		
	Aso-N	Aso-N	5	5		ENE	Plinian Fall	pumice	ITJ245		
		Aso-3 Ig.					Ign. (+Co)	pumice, scoria, ash	ITJ254		
	Aso-3*	Aso-3-A	7	7.4	150	ENE	Ign. (+Co)	pumice, ash	ITJ44	~123-135	(3, 9)
		Aso-3-W					Plinian Fall	pumice	ITJ43		
Kuju (HVZ)	Pumice 1/Handa	Kj- P1/Hd	6	5.3	2.0	E	Plinian fall, Ign.	pumice	ITJ237, ITJ248- 250	54.4 ± 1.6	(10)
	Kuju-D	Kj-D	-	-			Plinian fall	pumice	ITJ246-247	-	
	Miyagi	Kj-Mg	-	-		S	Ign.	ash	ITJ18	>Aso-3	
South-West Japan Arc (SWJA)											
		Kurayoshi Pum.*									
Daisen		DKP	6	6.5	32	E	Plinian Fall		-	59.6 ± 5.5	(10)
Sambe		Kisuki*	6	6.3	20	NE	Plinian Fall		-	~100	(3, 11)
Izu-Bonin Arc											
Hakone	Hk-TAu8	Hk- TAu8	5	-	-		Plinian Fall	pumice	ITJ255	125-182 ka	(12)
North East Japan Arc (NEJA)											
Ontake	Daichi Pum.*	On-Pm1	6	6.7	50	E	Plinian Fall	pumice	ITJ80	95.7 ± 5.3	(13)
Towada	Hachinhoe	To-H	6	6.7	50	E	Plinian Fall + Ign.	pumice (Fall)	ITJ96, ITJ97	15706 ± 226 B2k	(14)
Shikotsu	Shikotsu-1*	Spfa-1	7	7.0	200	SE	Plinian Fall + Ign.	pumice (Fall)	ITJ132	45,105–46,560	(15)
Toya	Toya*	Toya	7	7.3	170	Radial	Ign.	pumice	ITJ81	112-115 (MIS 5d) / 108	(3, 16)
Southern Kurile Arc											
Kutcharo	Shoro (1)*	Kc-Sr	7	7.2	170	SE	Plinian Fall + Ign.	ash	ITJ95	39,265-45,070	(17)
	Kc-2/3	Kc-2/3	6	6.4	25	N-NNE	Ign.	ash, pumice	ITJ198, 199	~85	(1)
	Kc-Hb/4*	Kc-Hb	7	7.2	175	W	Plinian Fall +	pumice	ITJ104, ITJ238	120	(18)

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1618	Mashu	Mashu-f	Ma-f	6	6.3	18.6	ESE	Ign.	Ign.	pumice, ash	ITJ126	7,500-7,620	(19)
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1619 Table

Sample	Bore hole			Compos ite depth: Base (cm)	Thickne ss (cm)	Major element glass compositons			Trace element glass concentrations (ppm), Ratio (1σ)					SG06 Age		Source Arc	Volcano/proxima l unit	
	A	B	C			n	SiO ₂	K ₂ O	n	Rb	Y	Zr	Th	Y/Th	(IntCal13. yrs BP; 95.4%)			Interpolat ed (ka; 2σ)
(SG06-)																		
588	A-03-14	B-03-03a		587.8	0.2	2	74.33- 77.97	2.25- 3.99	1	58- 186	3.3-4.3	79- 108	9.1- 13.0	0.34 ± 0.04	4,036 ± 32		SWJA	Sambe/Th-pd*
967	A-06-01	B-05-04	C-07-γ	967.2	2.8	5	72.60- 74.60	2.77- 3.03	1	68-92	29.7- 39.3	160- 225	5.6-8.3	4.54 ± 0.50	7,253 ± 46		Kyushu SVZ	Kikai/K-Ah
1965	A-11-00	B-10-02	-	1964.4	0.7	2	76.19- 77.43	2.41- 3.96	1	64- 172	2.8-5.7	48-77	8.8- 13.3	0.33 ± 0.07	19,551 ± 80		SWJA	Sambe/Md-fl*
2504	A-13-07	B-12-150.8	-	2503.5	0.1	1	74.43- 77.74	3.08- 3.88	9	79- 179	3.8-8.7	82- 146	8.5- 10.4	0.54 ± 0.19	28,449 ± 78		SWJA	Daisen/DMS*
2534	A-13-08	B-13-02	-	2534.3	0.6	2	75.52- 76.77	3.04- 3.87	1	85- 106	3.5-6.5	72- 119	8.3- 10.4	0.54 ± 0.10	28,888 ± 72		SWJA	Daisen/HgP*
2601		B-13-06a	-	2600.5	0.2	2	72.67- 77.91	2.75- 4.68	1	64- 286	2.8-5.4	78- 124	6.8- 14.3	0.42 ± 0.06	29,830 ± 96		SWJA	Daisen/DSs (OdA)*
2602	-	B-13-06b	-	2601.4	0.4	2	74.14- 76.58	2.96- 4.16	2	70- 146	3.6-4.9	83- 128	6.3- 10.6	0.45 ± 0.06	29,837 ± 96		SWJA	Daisen/DSs (Sh)*
2650	A-14-01	B-13- Bottom	-	2650.2	35.1	3	77.02- 78.41	3.24- 3.55	1	130- 160	19.6- 22.4	106- 122	11.6- 13.3	1.67 ± 0.07	30,078 ± 96		Kyushu SVZ	Aira/AT Fuji-
3485		B-18-03	-	3485.3	0.5	1	51.11- 56.43	0.33- 0.67	7	7-24	14.6- 17.4	39-49	0.4-0.7	31 ± 14	43,713 ± 300		Izu-Bonin SWJA	Ko/Unknown
3668	A-19-04	B-19-03	-	3668.0	0.3	0	75.54- 78.54	2.63- 4.89	1	76- 198	3.8-9.2	45-65	5.9- 14.1	0.67 ± 0.07	46,295 ± 418		SWJA	Sambe/SI*
3912	-	B-20-α	-	3911.6	0.1	3	77.62- 78.09	3.11- 3.49	4	124- 477	20.8- 36.3	113- 131	8.9- 12.2	2.56 ± 0.96	46,295 ± 418		Kyushu SVR	Unknown
3974	-	B-20-07	-	3974.0	0.0	1	69.64- 73.63	4.46- 4.90	9	138- 194	29.0- 44.9	271- 353	12.9- 18.2	2.41 ± 0.20	50.0 ± 0.2		Kyushu CVR	Aso/ACP4
4124	-	B-21-03	C-17-06	4123.9	0.2	2	74.60- 78.29	2.70- 4.42	9	20- 128	1.2-5.5	24- 122	2.7- 12.5	0.47 ± 0.09	50.9 ± 0.4		SWJA	Daisen/Unknown*
4141	-	B-21-04	-	4141.1	1.3	1	76.33- 77.77	3.95- 4.59	1	89- 118	6.4-8.7	21-27	4.3-6.2	1.58 ± 0.11	53.8 ± 1.2		SWJA	Sambe/Sod*
4281	-	B-22-01	C-18-04	4281.0	0.3	4	76.87- 78.44	3.77- 4.24	1	99- 142	4.7-8.6	89- 121	9.4- 13.1	0.62 ± 0.10	54.4 ± 1.6		Kyushu CVR	Kuju/Kj-Hd/P-1 (SAN1)*
4318	A-23-01	B-22-03	-	4318.3	1.5	1	73.27- 76.69	2.67- 2.97	1	66-93	3.8-5.9	74- 132	4.2-8.5	0.61 ± 0.18	59.6 ± 5.5		SWJA	Daisen/DKP*
4963	A-28-01	B-28-01	C-19-03	4962.3	3.5	9	45.10- 52.18	0.33- 0.77	1	-	-	-	-	-	61.1 ± 5.9		SWJA	Daisen/DSP*
5181	A-29-01	B-29-04	-	5180.2	2.4	2	67.12- 72.55	1.99- 2.56	1	56-82	6.1-8.6	116- 146	5.2-7.3	1.04 ± 0.38	61.1 ± 5.9		SWJA	Daisen/DSP*
5287	-	-	C-21-01	5286.6	4.0	4	70.06- 72.38	4.17- 4.82	5	41- 199	9.3- 36.1	69- 321	3.9- 18.1	2.05 ± 0.12	**86.4 ± 1.1		Kyushu CVR	Aso/Aso-4
5353	A-30-02	B-30-02	-	5352.3	1.5	3	77.76- 78.50	3.14- 3.40	1	100- 130	28.5- 34.2	150- 179	8.3- 10.3	3.35 ± 0.07	94.5 ± 4.8		Kyushu SVR	Kikai/K-Tz
6344	A-37-01	B-37-02	-	6364.9	0.8	2	69.16- 70.31	4.43- 5.80	2	129- 167	25.7- 33.9	217- 305	11.3- 16.2	2.24 ± 0.17	97.9 ± 6.0		Kyushu CVR	Aso/Aso-A Ata/Ata
						2	72.44- 74.61	2.64- 2.98	1	88- 105	34.3- 41.2	190- 219	7.6-9.6	4.13 ± 0.13	99.3 ± 6.0		Kyushu SVR	Ignimbrite
						6	70.12- 73.77	0.96- 1.13	6	12-16	23.8- 31.7	74-98	0.7-0.9	33-38	123.3 ± 7.5		Izu-Bonin	Hakone

Table 2

6412	<u>A-37-07</u>	B-38-03	-	6433.6	0.4	3	69.93-	1.87-	1	50-	45.4-	201-	7.7-9.2	6.0 ±	124.5 ±	Kyushu	
	A-38-					0	73.27	2.55	1	107	55.6	245		0.6	7.7	SVR	Unknown
6457	α	<u>B-38-07</u>	-	6478.2	0.1	2	74.52-	2.84-	4	75-	4.9-6.2	70-	8.4-	0.59 ±	126.2 ±		
	A-40-					2	77.45	5.44		109		104	10.5	0.05	8.2	SWJA	DMP?*
6634	<u>02</u>	<u>B-40-04 a</u>	-	6655.2	0.1	3	72.77-	2.04-	1	43-88	21.3-	138-	3.7-7.1	5.77 ±	130.8 ±		
						4	77.55	2.67	1		40.6	267		0.12	9.2	NEJA	Unknown

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Pr	5.4	0.7	5.4	0.	4.7	0.	5.0	0.	6.5	0.2	6.9	0.5	6.8	0.	5.1	0.2	5.2	0.3	5.2	0.2	-	-
Nd	22.	1	22.	2	17.8	2	19.8	0	27.	5	27.	0	29.	5	18.	8	18.	7	19.	0	19.	0
Sm	5.4	0.7	5.1	0.	4.1	0.	4.6	0.	6.6	0.4	6.9	0.5	6.6	0.	3.5	0.2	3.5	0.2	4.0	0.2	4.0	0.1
Eu	1.2	0.2	1.1	0.	0.6	0.	0.6	0.	1.4	0.1	1.5	0.3	1.6	0.	0.5	0.1	0.5	0.0	0.5	0.0	0.5	0.1
Gd	5.2	0.8	5.1	0.	4.1	0.	4.2	0.	6.4	0.3	6.6	0.2	6.3	0.	3.1	0.2	3.1	0.3	3.4	0.3	3.5	0.2
Dy	5.9	0.8	5.5	0.	4.8	0.	4.9	0.	7.3	0.4	7.4	0.5	7.6	0.	3.4	0.1	3.4	0.4	3.7	0.4	3.7	0.2
Er	3.9	0.5	3.6	0.	3.3	0.	3.6	0.	4.5	0.2	4.4	0.4	4.6	0.	2.5	0.1	2.2	0.1	2.4	0.1	2.3	0.2
Yb	4.1	0.6	3.8	0.	3.8	0.	4.2	0.	4.7	0.2	4.7	0.4	4.7	0.	2.9	0.1	2.4	0.1	2.7	0.1	2.5	0.2
Hf	5.8	0.8	5.7	0.	4.9	0.	5.4	0.	6.0	0.3	6.3	0.4	6.5	0.	3.6	0.2	3.2	0.2	3.8	0.2	3.6	0.3
Ta	0.5	0.1	0.4	0.	0.4	0.	0.5	0.	0.7	0.0	0.8	0.2	0.7	0.	0.6	0.0	0.7	0.1	0.8	0.1	0.8	0.1
Th	8.1	1.2	7.6	0.	9.2	0.	10.0	0.	9.2	0.2	9.6	0.6	9.6	0.	6	0.1	3	0.6	12.	0.6	5	0.6
U	2.1	0.3	2.2	0.	2.6	0.	2.8	0.	2.4	0.1	2.3	0.2	2.6	0.	2.8	0.1	3.1	0.2	3.1	0.2	3.1	0.2
La/Yb	4.6	0.6	5.1	0.	4.8	0.	4.5	0.	5.2	0.2	5.1	0.7	5.2	0.	7.6	0.4	11.	0.5	9.6	0.5	10.	0.7
Zr/Th	27.	1.2	26.	0.	18.1	0.	17.2	0.	23.	0.6	23.	1.0	22.	0.	10.	0.2	7.2	0.3	9.5	0.3	9.3	0.4
Nb/Th	2	0.1	6	0.	0.	0.	5	0.	5	0.0	5	0.0	7	0.	9.7	0.0	7.2	0.0	9.5	0.0	9.3	0.0
h	0.8	0.1	0.8	0.	0.6	0.05	0.6	0.02	1.0	0.7	1.0	0.6	0.9	0.	0.6	0.2	0.5	0.5	0.6	0.0	0.6	0.7
n	10		14		14		5		8		3		10		3		4		8		10	

Volcano	Aso Caldera												
Arc Eruption	Kyushu (Kyushu Central Volcanic Region)												
Local	Aso-3(W)	Aso-3(A)	Aso-3 Ign	Aso -N	Aso -M	Aso -K	Aso -I	Aso -D	Aso -C	Aso -B	Aso -A	As o-Y	
ity	Noga Cave	Noga Cave	Noga Cave	Noga Cave	Noga Cave	Noga Cave	Noga Cave	Noga Cave	Noga Cave	Noga Cave	Noga Cave	Noga Cave	
Sample	ITJ43	ITJ44	ITJ254	ITJ245	ITJ244	ITJ243	ITJ242	ITJ10, ITJ25	ITJ32	ITJ34	ITJ11, ITJ36	ITJ38	
wt. %	Avg. ± 1σ	Avg. ± 1σ	Avg. ± 1σ	Avg. ± 1σ	Avg. ± 1σ	Avg. ± 1σ	Avg. ± 1σ	Avg. ± 1σ	Avg. ± 1σ	Avg. ± 1σ	Avg. ± 1σ	Avg. ± 1σ	
SiO₂	69.92	70.	68.6	72.8	68.0	68.4	68.2	69.	70.	70.	69.	72.	
	22	10	9	1	6	1	3	0.	13	06	90	47	
	0.	0.6	0.	0.0	0.	0.	0.	0.	0.6	0.	0.6	0.3	
TiO₂	0.60	0	0.69	0.27	0.74	0.75	0.7	3	4	3	3	6	
	05	07	15	13.9	04	04	0	04	05	05	04	04	
	0.	0.	0.	0.1	0.	0.	0.	0.	0.	0.	0.	0.	
Al₂O₃	15.14	10	4	7	3	2	15.5	22	00	08	08	75	
	10	15	37	5	20	13	1	11	26	11	15	10	

FeO_t	2.40	0.12	2.30	0.22	2.98	99.00	1.83	0.08	3.04	16.00	2.97	10.00	2.9	0.02	2.4	0.15	2.3	0.09	2.2	0.13	2.3	0.11	1.3	0.14
MnO	0.10	0.05	0.02	0.04	0.12	0.04	0.06	0.02	0.12	0.04	0.11	0.04	0.1	0.00	0.04	0.01	0.05	0.02	0.04	0.01	0.04	0.01	0.03	0.01
MgO	0.56	0.03	0.06	0.09	0.78	0.39	0.16	0.02	0.83	0.06	0.79	0.04	0.8	0.00	0.04	0.06	0.06	0.01	0.03	0.06	0.03	0.03	0.09	0.05
CaO	1.67	0.08	0.04	0.19	2.15	0.85	0.82	0.04	2.20	0.07	2.24	0.10	2.3	0.01	0.11	0.03	0.09	0.04	0.06	0.07	0.07	0.07	0.08	0.08
Na₂O	4.33	0.08	0.01	0.13	4.19	0.19	3.66	0.07	4.46	0.20	4.10	0.48	4.5	0.02	0.11	0.18	0.14	0.14	0.14	0.14	0.17	0.17	0.12	0.12
K₂O	5.05	0.10	0.00	0.12	4.79	0.47	6.23	0.09	4.72	0.11	4.75	0.10	4.6	0.01	0.10	0.07	0.08	0.08	0.08	0.08	0.10	0.10	0.13	0.13
P₂O₅	0.10	0.02	0.01	0.04	0.18	0.13	0.04	0.03	0.18	0.04	0.16	0.03	0.2	0.00	0.02	0.02	-	-	-	-	0.02	0.02	0.01	0.01
Cl	0.13	0.02	0.03	0.03	0.11	0.03	0.14	0.01	0.10	0.01	0.10	0.02	0.1	0.00	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
n	30		26		27		29		8		21		23		26		9		13		38		12	

(ppm)

Rb	175.5	6.5	18.0	15.4	180.6	11.7	265.0	9.5	177.5	5.8	153.0	8.7	163.7	8.7	174.0	24.5	117.6	12.7	117.0	7.7	165.8	10.6	169.0	2.2
Sr	256.4	0.2	0.3	0.4	2.8	66.4	7.0	0.9	0.2	0.7	2.8	0.8	0.0	0.0	0.1	0.6	0.8	0.4	0.5	0.8	0.2	0.8	0.2	0.7
Y	32.2	9.5	5.7	33.9	6.6	36.5	0.8	34.3	8.8	32.2	9.3	32.0	9.9	32.0	6.0	7.2	23.7	1.2	23.8	6.6	34.6	3.4	33.0	0.4
Zr	292.1	5.0	3.0	2.2	6.5	0.2	1.1	0.1	1.4	0.6	5.4	1.5	0.4	0.5	0.8	0.3	0.6	0.3	0.6	0.6	0.9	0.5	0.5	0.0
Nb	17.0	5.13	9.7	17.1	4.4	21.0	0.8	17.8	6.6	16.0	0.9	16.7	1.2	16.7	2.2	2.8	8.3	0.3	3.1	2.6	8.6	6.3	6.3	3.3
Ba	840.9	0.4	0.6	0.8	7.7	4.0	0.3	0.5	0.7	0.9	0.5	0.9	0.5	0.8	0.2	0.2	0.2	0.1	0.8	0.9	0.5	0.4	0.8	0.8
La	35.8	8.1	5.3	36.7	9.3	44.1	0.9	39.4	3.4	33.8	0.8	35.6	3.3	35.6	1.9	1.5	23.5	2.2	25.1	1.4	33.1	1.6	34.1	1.1
Ce	78.0	9.0	1.3	80.7	0.0	94.3	3.7	86.0	9.0	77.2	3.3	77.1	2.0	77.1	1.7	1.8	8.3	0.5	0.5	0.5	5.5	7.4	7.4	4.4
Pr	9.0	2.1	9.2	5.3	9.3	3.3	10.3	0.3	9.8	5.3	8.7	5.3	8.9	5.3	9.3	2.2	6.1	5.5	6.5	5.5	8.4	6.8	8.8	3.3
Nd	36.1	0.6	36.2	2.1	38.1	7.0	40.6	1.0	40.7	6.6	36.7	1.3	37.2	4.0	38.0	4.5	25.2	1.4	25.4	1.8	35.1	3.0	35.1	1.2
Sm	7.6	3.0	7.6	4.4	8.0	5.8	8.3	0.4	8.2	7.7	8.1	3.7	7.7	7.7	7.9	2.2	5.1	3.3	5.4	7.7	7.2	8.7	7.4	2.2
Eu	1.5	1.0	1.5	2.0	1.6	1.1	0.8	0.1	1.7	1.0	1.5	1.1	1.5	2.2	1.7	2.2	1.1	1.1	1.1	1.1	1.5	1.3	1.3	1.1
Gd	6.0	3.0	6.2	4.4	6.7	3.3	6.7	0.3	6.9	6.6	6.1	4.4	6.2	6.6	6.9	0.0	4.2	3.3	4.5	4.4	6.5	7.5	5.8	2.2
Dy	5.7	2.0	5.8	3.0	6.1	3.3	6.3	0.3	6.7	5.5	5.6	5.5	6.0	4.4	6.5	0.0	3.9	3.3	4.4	4.4	6.1	6.7	5.7	2.2
Er	3.5	1.0	3.3	2.0	3.7	2.0	3.9	0.1	3.7	5.5	3.5	3.3	3.5	4.4	3.9	6.6	2.4	2.2	2.6	2.2	3.7	4.4	3.6	1.1
Yb	3.6	1.0	3.5	2.0	3.7	3.3	4.3	0.2	4.1	5.5	3.7	5.5	3.8	1.1	4.2	6.6	2.8	3.3	2.9	2.2	4.0	4.4	3.9	1.1
Hf	7.8	3.0	7.4	4.4	7.4	7.7	10.6	0.4	7.5	3.3	7.3	6.6	7.5	6.6	8.0	0.0	4.9	5.5	5.6	5.5	7.6	6.8	7.8	3.3
Ta	1.2	0.0	1.2	0.0	1.2	0.0	1.7	0.1	1.3	0.0	1.2	0.0	1.2	0.0	1.2	0.0	0.9	0.0	0.9	0.0	1.2	0.0	1.2	0.0

		0		0		1			1		1		1		2		1		1		1		0	
Th	16.1	0.5	15.0	0.9	15.9	0.5	27.1	0.7	16.8	0.2	15.6	0.9	15.5	0.6	16.2	0.1	10.7	0.4	11.4	0.9	15.1	0.8	15.9	0.7
U	4.8	0.2	4.8	0.1	4.8	0.4	8.0	0.3	5.5	0.9	4.4	0.1	4.9	0.2	5.0	0.6	3.5	0.5	3.3	0.2	4.6	0.4	4.8	0.2
La/Yb	9.9	0.2	10.5	0.4	9.9	0.7	10.2	0.4	5.3	0.9	5.7	0.1	5.5	0.2	8.6	0.7	8.6	0.0	8.7	0.8	8.5	0.8	8.9	0.3
Zr/Th	18.1	0.2	19.0	0.1	18.5	0.8	14.8	0.5	7.6	0.2	8.3	0.0	8.0	0.7	19.4	0.1	17.9	0.9	17.0	0.1	19.9	0.0	18.0	0.3
Nb/Th	1.05	0.01	1.14	0.09	1.08	0.09	0.77	0.4	0.41	0.52	0.43	0.31	0.42	0.09	1.18	0.14	1.10	0.04	0.99	0.07	1.14	0.11	0.98	0.03
n	6		6		16		10		4		7		6		11		8		12		16		6	

Volcano	Aso Central Pumice Cone (ACP)								Kuju (Hohi Volcanic Zone)															
Arc Region	Kyushu Central Volcanic Region																							
Erup-tion	Aso -4				AC P6		AC P5		AC P4		AC P3		Kj-Mg		Kj-D		Kj-Hd		Kj-P1					
Locality	Noga Cave		Noga Cave		Noga Cave		Noga Cave		Mizunomoto		Mizunomoto		Mizunomoto		Mizunomoto		NE Aso C. Rim		Tanbara		Yumiori			
Sample	ITJ40		ITJ142		ITJ142		ITJ142		ITJ207		ITJ206		ITJ205		ITJ204		ITJ18		ITJ246/7		ITJ37			
wt.%	Avg ± 1σ		Avg ± 1σ		Avg ± 1σ		Avg ± 1σ		Avg ± 1σ		Avg ± 1σ		Avg ± 1σ		Avg ± 1σ		Avg ± 1σ		Avg ± 1σ		Avg ± 1σ			
SiO ₂	72.17	0.39	72.32	0.26	71.18	0.35	67.16	0.48	70.10	0.64	70.16	0.27	71.70	0.21	74.03	0.43	77.40	0.62	77.56	0.30	78.02	0.35		
TiO ₂	0.41	0.05	0.43	0.03	0.45	0.03	0.61	0.06	0.62	0.06	0.59	0.08	0.47	0.04	0.33	0.05	0.18	0.04	0.21	0.05	0.20	0.03	0.18	0.04
Al ₂ O ₃	14.78	0.12	14.95	0.14	15.48	0.18	16.52	0.24	15.09	0.21	15.10	0.19	14.85	0.12	13.95	0.20	12.59	0.30	12.59	0.2	12.52	0.16	12.43	0.17
FeO _t	1.59	0.26	1.50	0.09	1.74	0.0	3.09	0.7	2.33	0.27	2.49	0.34	1.74	0.11	1.24	0.11	0.91	0.1	0.95	0.15	1.03	0.10	0.79	0.15
MnO	0.10	0.05	0.13	0.03	0.12	0.03	0.16	0.04	0.10	0.05	0.13	0.04	0.11	0.05	0.05	0.04	0.06	0.05	0.07	0.04	0.05	0.03	0.05	0.05
MgO	0.34	0.06	0.38	0.03	0.48	0.04	1.05	0.2	0.64	0.10	0.62	0.09	0.40	0.04	0.20	0.04	0.25	0.07	0.21	0.07	0.22	0.03	0.10	0.02
CaO	1.08	0.06	1.11	0.05	1.47	0.09	2.90	0.9	1.90	0.23	1.75	0.12	1.27	0.07	0.70	0.08	1.23	0.5	1.15	0.28	1.28	0.09	1.17	0.07
Na ₂ O	4.56	0.14	4.45	0.16	4.47	0.2	4.72	0.8	4.64	0.15	4.38	0.13	4.66	0.13	4.19	0.25	3.40	0.4	3.25	0.16	2.87	0.30	2.89	0.18
K ₂ O	4.78	0.1	4.55	0.03	4.39	0.08	3.47	0.8	4.34	0.18	4.55	0.12	4.62	0.08	5.19	0.11	3.78	0.9	3.98	0.13	4.05	0.17	4.05	0.09
P ₂ O ₅	0.07	0.03	0.08	0.03	0.09	0.02	0.23	0.04	0.10	0.03	0.10	0.04	0.00	0.02	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.04	0.02
Cl	0.13	0.02	0.14	0.01	0.14	0.02	0.10	0.2	0.10	0.01	0.10	0.03	0.10	0.02	0.10	0.02	0.09	0.03	0.15	0.05	0.17	0.02	0.07	0.03
n	11		5		21		14		16		7		25		25		15		6		26		15	

Volcano	Hakone		Ontake		Towada		Shikotsu		Toya		Kutcharo				Mashu			
Arc	Izu-Bonin		NEJA (Norikura)		NEJA		NEJA		NEJA		Southern Kurile Arc				Mashu-f			
Eruption	Hk-TAu8		On-Pm1		To-H		Spfa-1		Toya		Kc-Hb		Kc-2/3		Kc-Sr		Mashu-f	
Locality			Omachi		Mitateyama		MIsawa		Narugo		Raiun				Shoro		Naka-shunbetsu	
Sample	ITJ255		ITJ79		ITJ96		ITJ132		ITJ81		ITJ238		ITJ198		ITJ95		ITJ126	
wt.%	Avg.	± 1σ	Avg.	± 1σ	Avg.	± 1σ	Avg.	± 1σ	Avg.	± 1σ	Avg.	± 1σ	Avg.	± 1σ	Avg.	± 1σ	Avg.	± 1σ
SiO ₂	73.05	1.54	75.28	0.45	74.79	1.81	77.44	0.18	78.08	0.15	77.73	0.16	76.18	1.15	77.48	0.39	71.70	0.98
TiO ₂	0.67	0.14	0.08	0.03	0.42	0.11	0.16	0.03	0.04	0.03	0.35	0.04	0.38	0.08	0.30	0.03	0.67	0.05
Al ₂ O ₃	12.83	0.29	13.91	0.37	13.56	0.71	12.52	0.07	12.67	0.10	12.04	0.10	12.67	0.41	12.34	0.30	14.02	0.47
FeOt	3.63	0.64	1.13	0.15	2.18	0.40	1.51	0.08	0.95	0.06	1.58	0.08	1.88	0.35	1.43	0.09	3.47	0.34
MnO	0.11	0.04	0.16	0.04	0.10	0.07	0.07	0.05	0.09	0.03	0.10	0.06	0.11	0.05	0.08	0.04	0.18	0.04
MgO	0.81	0.20	0.24	0.02	0.59	0.19	0.16	0.02	0.04	0.02	0.29	0.02	0.39	0.11	0.29	0.03	0.94	0.28
CaO	3.10	0.55	1.54	0.11	2.68	0.49	1.47	0.05	0.37	0.03	1.39	0.05	1.81	0.29	1.65	0.11	3.76	0.35
Na ₂ O	4.36	0.15	3.91	0.16	4.33	0.69	3.91	0.13	4.86	0.10	4.34	0.15	4.49	0.15	3.97	0.16	4.25	0.15
K ₂ O	1.13	0.13	3.53	0.09	1.15	0.08	2.58	0.06	2.74	0.14	1.95	0.06	1.87	0.10	2.19	0.05	0.72	0.06
P ₂ O ₅	0.15	0.04	0.04	0.02	0.07	0.05	0.02	0.02	0.02	0.02	0.04	0.03	0.05	0.02	0.03	0.02	0.17	0.05
Cl	0.15	0.03	0.17	0.04	0.12	0.09	0.17	0.02	0.14	0.02	0.18	0.02	0.17	0.04	0.26	0.04	0.11	0.02
n	13		9		19		20		16		27		22		23		13	
(ppm)																		
Rb	18.1	3.9	102.8	62.8	27.5	3.6	69.6	1.85	61.0	2.0	42.6	0.6	41.4	2.0	51.3	3.7	11.6	0.7
Sr	247.6	97.3	121.8	98.4	201.6	41.9	126.7	5.63	22.8	3.0	123	9	167	33	124	15	213	23
Y	33.8	5.1	13.2	10.8	35.4	3.1	36.0	0.70	53.9	3.9	42.4	4.3	42.3	0.5	28.8	3.6	37.0	3.4
Zr	112.6	14.8	129.5	82.8	127.9	8.4	143.8	2.65	80.5	5.8	151.0	13.3	154.3	5.9	165.0	10.7	84.5	6.8
Nb	1.9	0.4	10.1	5.9	5.0	0.5	6.8	0.08	5.6	0.6	2.6	0.1	2.7	0.1	3.2	0.4	0.9	0.1
Ba	416.7	101.7	683	389	401.6	46.7	741	8	883	78	552	34	578	21	649	49	275	22
La	6.5	1.2	21.3	10.0	12.5	1.4	16.1	0.39	14.3	0.5	13.6	1.1	14.6	0.3	13.9	1.1	6.3	0.5
Ce	17.4	4.0	40.3	20.9	30.3	3.1	37.1	0.72	39.0	2.2	33.0	2.3	35.2	0.5	33.9	2.6	17.1	1.3
Pr	2.6	0.6	4.2	2.3	3.8	0.3	4.6	0.09	4.7	0.3	4.3	0.3	4.5	0.1	4.0	0.3	2.5	0.2
Nd	14.2	3.2	14.9	9.6	18.2	1.5	19.9	0.28	21.1	0.7	20.3	1.8	21.1	0.6	16.2	1.8	13.3	1.3
Sm	4.4	0.7	-	-	5.1	1.2	5.1	0.14	6.5	0.4	5.5	0.5	5.7	0.2	5.0	0.7	4.2	0.5
Eu	1.2	0.1	-	-	1.2	0.1	0.9	0.04	0.6	0.1	1.3	0.1	1.4	0.1	1.0	0.1	1.3	0.1
Gd	5.0	1.1	2.3	1.9	5.2	0.6	5.1	0.16	7.1	0.6	5.9	0.5	6.0	0.2	4.6	0.7	5.1	0.5
Dy	6.0	1.1	0.4	1.9	6.0	0.8	6.0	0.18	9.0	0.7	7.2	0.6	7.2	0.2	4.7	0.7	6.4	0.7
Er	3.8	0.6	0.2	1.2	3.9	0.6	3.9	0.10	5.7	0.6	4.8	0.5	4.7	0.1	3.4	0.5	4.1	0.4
Yb	4.0	0.6	1.7	1.4	4.2	0.2	4.2	0.14	6.1	0.7	5.2	0.4	5.1	0.2	3.8	0.4	4.4	0.4
Hf	3.5	0.4	3.8	2.1	3.8	0.0	4.4	0.16	3.5	0.2	4.4	0.4	4.6	0.2	4.7	0.3	2.7	0.2
Ta	0.2	0.0	0.9	0.4	0.3	0.0	0.5	0.01	0.4	0.0	0.2	0.0	0.2	0.0	0.3	0.1	0.1	0.0
Th	1.0	0.2	10.4	4.5	3.2	0.3	6.3	0.15	5.8	0.2	4.3	0.5	4.6	0.1	5.6	0.3	1.1	0.1
U	0.6	0.1	2.7	1.4	0.9	0.3	2.0	0.05	2.2	0.2	1.4	0.1	1.5	0.1	2.0	0.2	0.4	0.0
La/Yb	1.6	0.2	19.4	2.4	3.01	0.05	3.9	0.1	2.4	0.2	2.6	0.1	2.9	0.1	3.6	0.4	1.4	0.1

Zr/Th	121.3	19.4	12.7	0.6	40.06	2.92	22.9	0.3	14.0	0.9	35.0	1.1	33.5	0.7	29.7	1.9	76.1	2.6
Nb/Th	2.04	0.09	0.9	0.1	1.56	0.19	1.08	0.03	0.97	0.09	0.6	0.0	0.58	0.03	0.59	0.08	0.85	0.04
<i>n</i>	7		8		12		12		8		7		6		15		8	

1624

1625 Table 3

ACCEPTED MANUSCRIPT

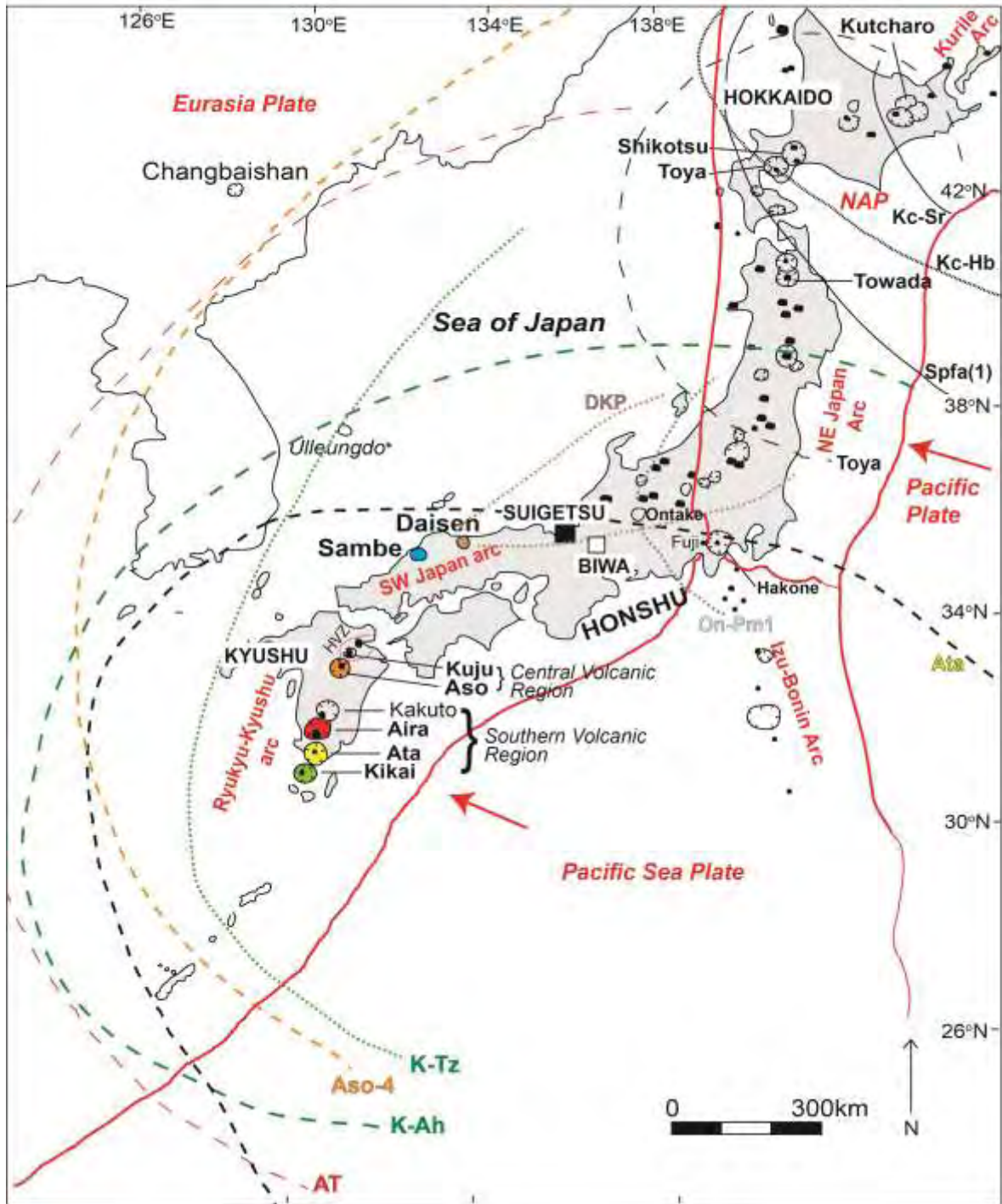
Tephra	SG06-0967*		SG06-2650*		SG06-3485*		SG06-3668 (C2)		SG06-3912*		SG06-4963 (C1)*		SG06-4963 (C2)*		SG06-5181*		SG06-5287*		SG06-5553*		SG06-6344*		SG06-6313		SG06-6634*	
Event Layer	A-06-01		B-13 Bottom		B-18-03		B-19-03		B-20-α																	
wt.%	Av	±1σ	Av	±1σ	Avg	±1σ	Avg	±1σ	Av	±1σ	Av	±1σ	Av	±1σ	Av	±1σ	Av	±1σ	Av	±1σ	Av	±1σ	Av	±1σ	Av	±1σ
SiO ₂	74.09	0.49	77.64	0.31	53.83	0.63	77.87	0.16	71.51	0.53	71.94	0.23	70.88	0.36	78.06	0.18	69.57	0.20	74.06	0.41	71.33	0.15	72.83	0.87	76.07	0.38
TiO ₂	0.54	0.03	0.14	0.03	1.32	0.11	0.13	0.03	0.49	0.05	0.42	0.03	0.48	0.03	0.25	0.03	0.11	0.03	0.50	0.03	0.75	0.11	0.43	0.13	0.39	0.09
Al ₂ O ₃	0.17	0.07	0.41	0.15	17.01	0.91	12.31	0.12	14.90	0.26	14.92	0.14	15.45	0.17	0.91	0.07	0.00	0.12	5.29	0.79	0.87	0.06	0.96	0.62	0.50	0.50
FeOT	2.51	0.16	1.27	0.09	10.13	0.66	1.28	0.08	1.88	0.20	1.54	0.14	1.79	0.09	1.08	0.07	2.37	0.13	2.17	0.10	3.75	0.57	3.45	0.30	1.87	0.36
MnO	0.09	0.04	0.06	0.04	0.17	0.07	0.03	0.02	0.08	0.05	0.10	0.05	0.13	0.06	0.04	0.03	0.11	0.04	0.10	0.03	0.14	0.04	0.10	0.04	0.05	0.04
MgO	0.48	0.05	0.13	0.02	4.73	0.76	0.14	0.01	0.41	0.08	0.35	0.03	0.49	0.04	0.20	0.02	0.62	0.03	0.45	0.02	0.77	0.18	0.49	0.10	0.40	0.12
CaO	1.99	0.11	1.12	0.04	9.37	0.50	1.13	0.06	1.32	0.13	1.08	0.04	1.43	0.09	1.08	0.04	1.81	0.06	1.92	0.18	3.40	0.58	2.65	0.24	1.87	0.39
Na ₂ O	4.02	0.17	3.68	0.27	2.69	0.44	3.70	0.21	4.62	0.26	4.82	0.15	4.75	0.17	3.93	0.13	4.73	0.16	4.47	0.20	4.67	0.20	4.47	0.22	4.09	0.17
K ₂ O	2.89	0.07	3.39	0.08	0.48	0.09	3.35	0.13	4.59	0.14	4.63	0.12	4.37	0.12	3.28	0.07	4.55	0.09	2.87	0.07	1.01	0.08	2.14	0.08	2.41	0.18
P ₂ O ₅	0.07	0.02	0.03	0.02	0.20	0.03	0.02	0.01	0.08	0.04	0.06	0.02	0.09	0.02	0.02	0.02	0.11	0.02	0.06	0.01	0.17	0.03	0.08	0.02	0.04	0.03
Cl	0.14	0.01	0.12	0.01	0.07	0.02	0.11	0.00	0.12	0.01	0.14	0.02	0.15	0.03	0.15	0.02	0.12	0.01	0.14	0.02	0.14	0.03	0.16	0.02	0.21	0.03
n	14		35		13		7		19		27		15		30		18		26		20		30		34	
(ppm)			14				15						10		15											
Rb	84.7	6.1	7.7	7.8	11.7	6.0	232.9	2.8	165.6	16.8	172.1	14.7	137.2	17.9	5.9	6.7	2.7	9.8	97.7	3.6	15.1	1.6	76.6	22.1	60.8	14.2
Sr	13.6	4.4	79.2	2.2	345.2	3.2	81.7	8.1	16.7	13.1	164.32	11.4	247.25	59.4	65.30	6.1	23.6	31.2	13.0	8.8	2.2	59.3	69.8	16.3	69.3	16.7
Y	34.1	2.7	20.5	0.6	15.6	1.4	27.4	7.0	37.1	4.4	32.3	2.1	25.9	3.2	30.9	1.8	30.7	5.5	38.3	1.9	28.8	0.9	39.1	8.0	30.1	7.1

Zr	20 8	17	11 3	4	45. 4	4. 1	120	7	29 6	25	288	16	228	27	16 5	9	26 0	25	20 5	9	90	9. 0	3	17 9.	38 1	19 3.	43 4	48 8	
Nb	6	6	8. 0	0	1.3	5	0	7	17. 5	2. 9	16. 0	1.2	12. 7	1.7	5. 9	0.	14. 3	1. 5	9. 5	0.	1. 7	0.	2	6. 8	1. 5	6. 6	2. 0	0	
Ba	44 2	29 18	56 6	18 0	162. 0	1. 0	790	8	34 8	82 85	859	56	741	7	50 9	29	78 3	86 8	45 27	37 6	9. 28	31 0	65 65	48 14	11 3.	6 3.	3 3.		
La	.8	2	.9	8	4.2	9	4	3	9	2	0	2.2	0	3.8	.2	9	.7	3	.0	3	7	4	.0	5	.1	1	.1	1	
Ce	44	2.	53	1.	11.	2.	48.	8.	76.	7.	77.	0	63.	8	41	2.	68	5.	58	3.	15	1.	42	7.	32	7.	2	2	
Pr	.1	7	.3	9	2	1	2	8	4	6	0	5.3	8	7.7	.2	7	.0	5	.0	9	.4	3	.5	7	.2	2	.2	2	
Sm	5.	0.	5.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	4.	0.	8.	0.	6.	0.	2.	0.	5.	1.	4.	0.	0.	0.	
Nd	1	4	2	2	1.7	2	5.0	7	8.6	7	8.9	0.6	7.4	0.9	7	2	0	7	3	4	3	2	2	0	1	8	1	8	
Er	21	1.	19	0.	19	0.	21.	2.	36.	3.	34.	0	29.	18	18	1.	32	3.	27	1.	12	0.	22	3.	17	4.	4.	4.	
Dy	.3	2	.0	9	8.5	2	8	5	1	9	7	2.3	4	4.2	.5	3	.5	7	.5	4	.3	9	.4	8	.5	0	.5	0	
Eu	5.	0.	3.	0.	0.	0.	0.	0.	1.	1.	0.	0.	4.	0.	4.	0.	6.	0.	6.	0.	3.	0.	5.	1.	5.	1.	5.	1.	1.
Gd	2	5	8	2	2.5	4	4.2	6	7.9	3	7.0	0.6	5.9	0.8	3	4	9	6	2	5	8	4	5	1	6	8	6	8	
Yb	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.	0.	1.	0.	1.	0.	1.	0.	0.	0.	0.	0.	0.
Y	4.	0.	3.	0.	0.	0.	0.9	1	1.	0.	1.3	0.1	1.2	0.2	6	1	3	1	3	1	1	1	3	2	9	3	9	3	
Hf	9	5	4	2	2.9	4	4.3	1	6.4	9	5.9	0.5	4.8	0.7	2	4	6	4	2	7	2	3	6	1	5	3	5	3	
Ta	5.	0.	3.	0.	0.	0.	1.	0.	0.	0.	0.	0.	4.	0.	4.	0.	5.	0.	6.	0.	5.	0.	6.	1.	5.	1.	5.	1.	
Er	8	5	5	2	2.9	3	4.7	3	6.3	7	5.6	0.5	4.6	0.7	7	3	3	4	7	5	1	5	6	4	2	1	2	1	
Er	3.	0.	2.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.	0.	3.	0.	3.	0.	4.	0.	3.	0.	4.	1.	3.	0.	3.	0.	0.
Yb	7	4	3	2	1.6	2	2.8	6	4.0	6	3.5	0.3	2.8	0.3	5	4	1	4	4	4	2	4	4	0	2	6	2	6	
Yb	3.	0.	2.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.	0.	3.	0.	3.	0.	4.	0.	3.	0.	4.	1.	3.	0.	3.	0.	0.
Hf	9	4	5	2	1.7	3	3.0	4	4.2	6	3.8	0.3	3.0	0.5	9	3	3	4	7	4	3	3	6	2	5	9	5	9	
Hf	5.	0.	3.	0.	0.	0.	0.	0.	1.	1.	0.	0.	4.	0.	4.	0.	6.	0.	5.	0.	2.	0.	5.	1.	5.	1.	5.	1.	1.
Ta	8	6	5	2	1.4	2	3.3	3	7.9	0	7.7	0.7	6.1	0.8	9	4	1	6	6	4	8	3	0	3	3	2	3	2	
Ta	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
Th	5	0	7	0	0.1	0	0.9	2	1.3	2	1.2	0.1	0.9	0.2	5	1	0	1	7	1	1	0	5	1	5	1	5	1	
Th	7.	0.	12	0.	0.	0.	11.	1.	14.	1.	16.	0	12.	0	9.	0.	13	1.	8.	0.	0.	0.	6.	1.	5.	1.	5.	1.	
Th	6	7	.3	5	0.6	2	1	4	7	1	1	1.1	7	1.6	2	6	.8	3	9	6	8	1	6	5	2	4	2	4	
U	2.	0.	3.	0.	0.	0.	2.	0.	0.	0.	0.	0.	2.	0.	2.	0.	4.	0.	2.	0.	0.	0.	1.	0.	1.	0.	1.	0.	
U	1	2	1	2	0.4	1	4.5	1	4.7	5	5.0	0.5	4.0	0.5	7	3	1	6	4	2	5	0	7	4	7	4	7	4	
La/Yb	4.	0.	10	0.	0.	0.	2.	0.	1.	0.	0.	0.	4.	0.	4.	0.	9.	0.	5.	0.	1.	0.	4.	0.	4.	0.	4.	0.	
La/Yb	9	4	.1	9	2.7	9	7.8	6	8.3	5	9.0	0.4	9.6	0.8	6	2	3	8	2	4	76	05	2	4	1	5	1	5	
Zr/Th	27	1.	9.	0.	78.	1.	11.	2.	20.	1.	17.	0	18.	0	17	1.	18	1.	23	0.	0.	4.	27	1.	37	2.	2.	2.	
Zr/Th	.6	6	2	3	9	0	0	0	4	0	9	0.6	0	0.8	.9	0	.9	2	.2	8	3	9	.4	2	.4	1	.4	1	
Nb/Th	0.	0.	0.	0.	1.7	3	1.0	0.	1.2	0.	1.0	0.0	1.0	0.0	0.	0.	1.	0.	1.	0.	2.	0.	1.	0.	1.	0.	1.	0.	
Nb/Th	87	09	66	05	9	0	4	54	2	13	0	6	0	7	64	05	05	12	08	10	08	03	04	08	28	23	23	23	
n	12		19		13		5		9		33		16		14		21		12		6		5		11				

1626

1627 Table

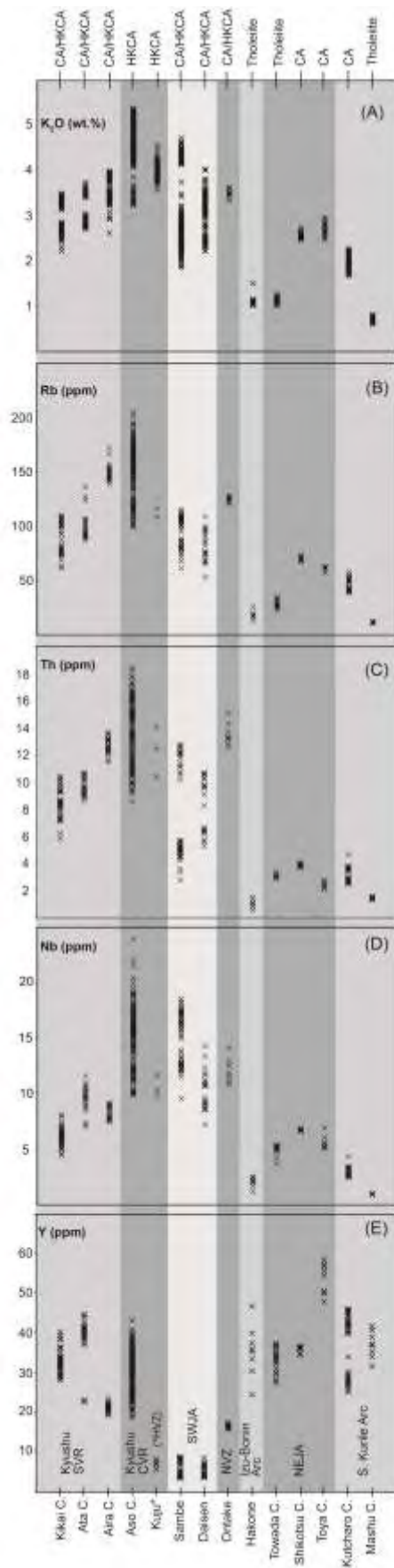
4



1628

1629 Figure

1

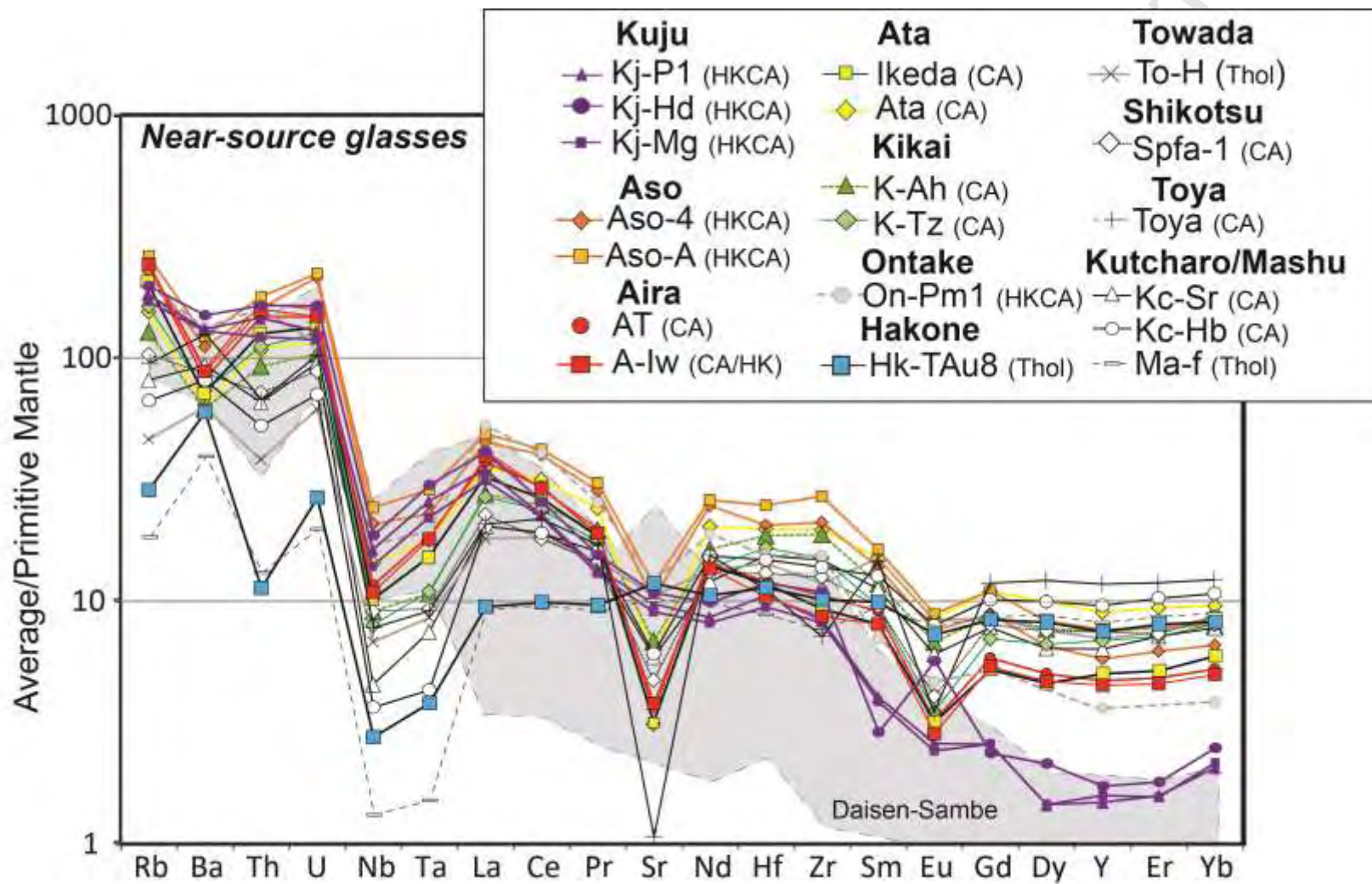


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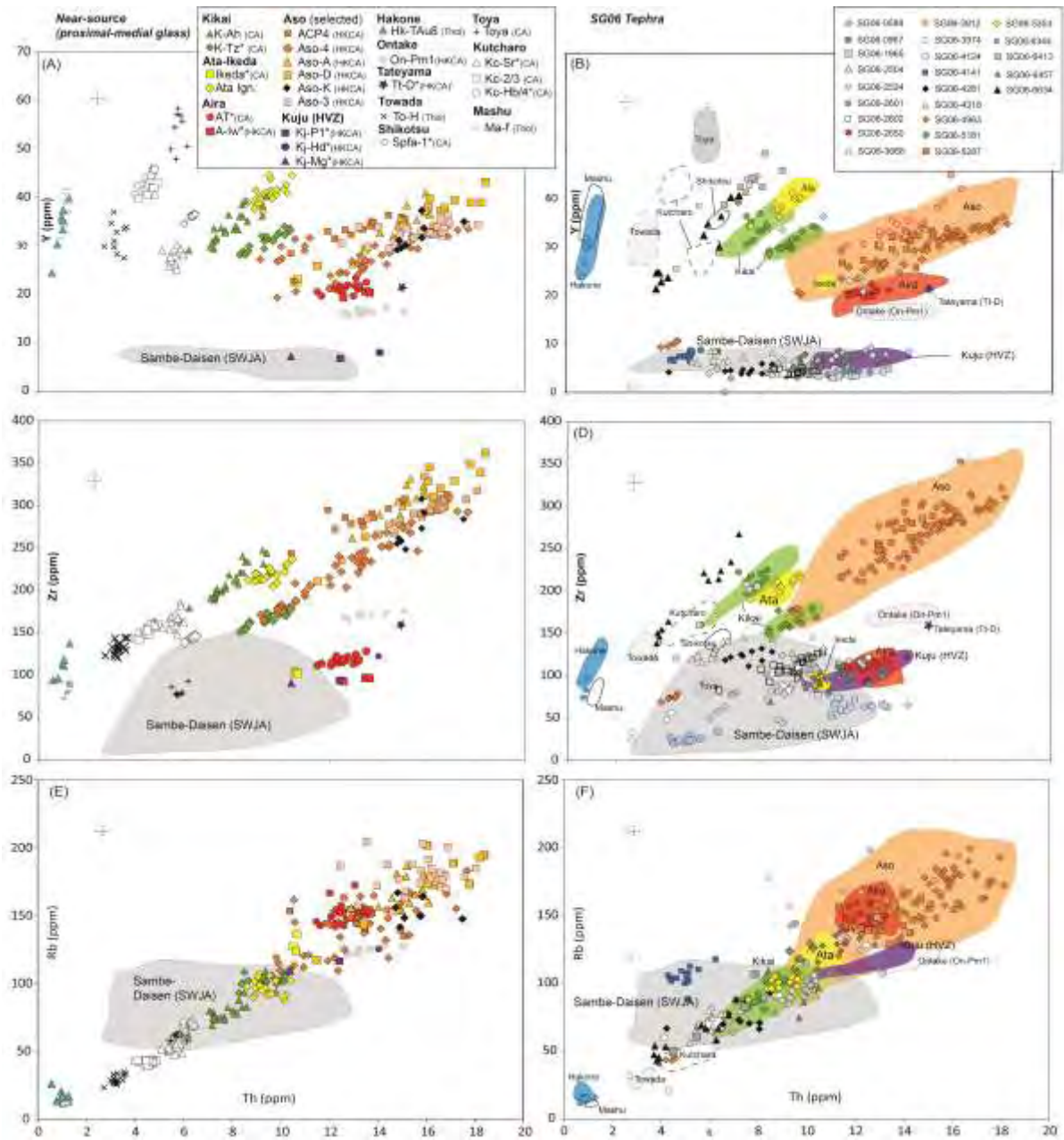
1633 Figure

3



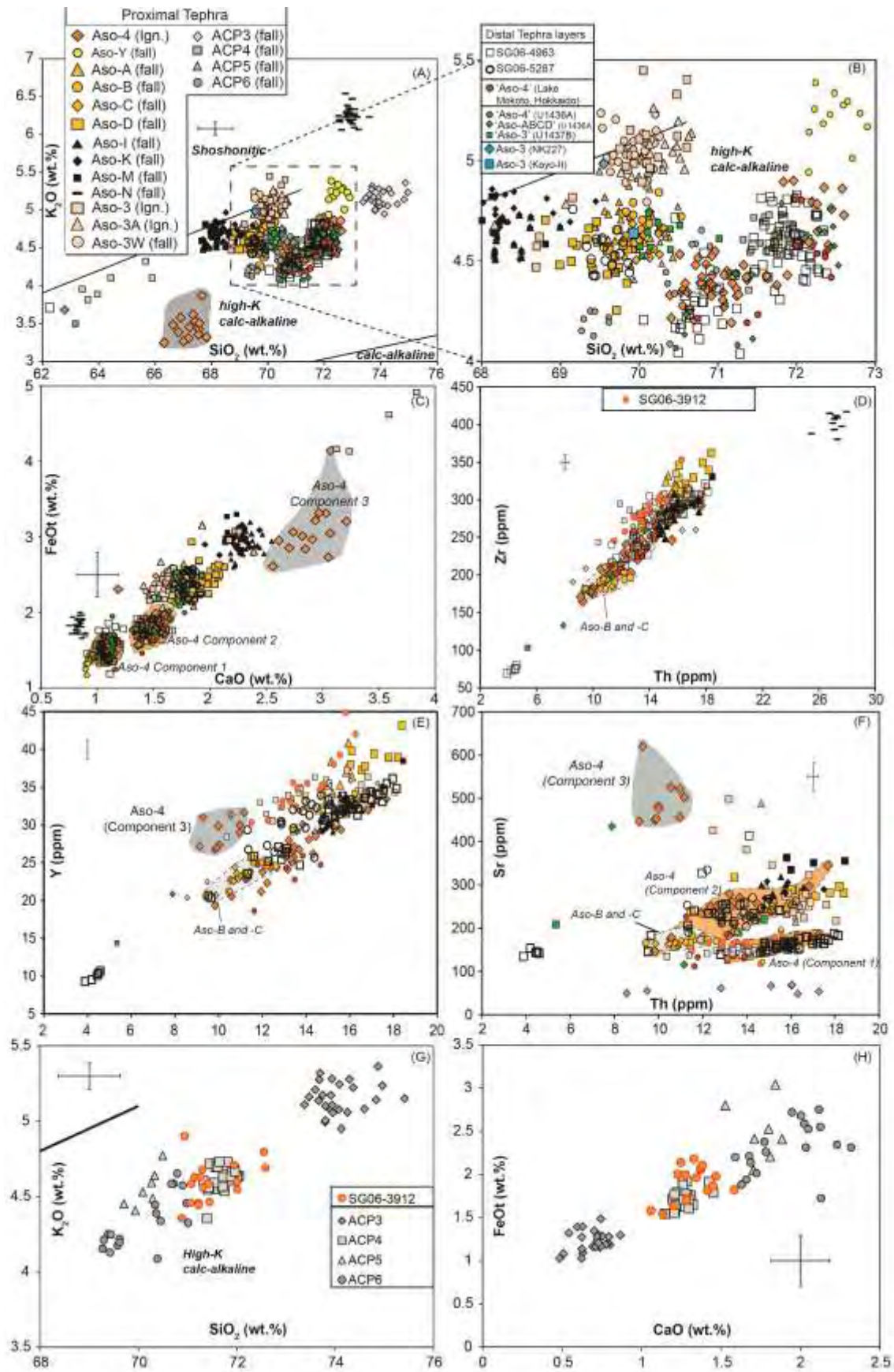
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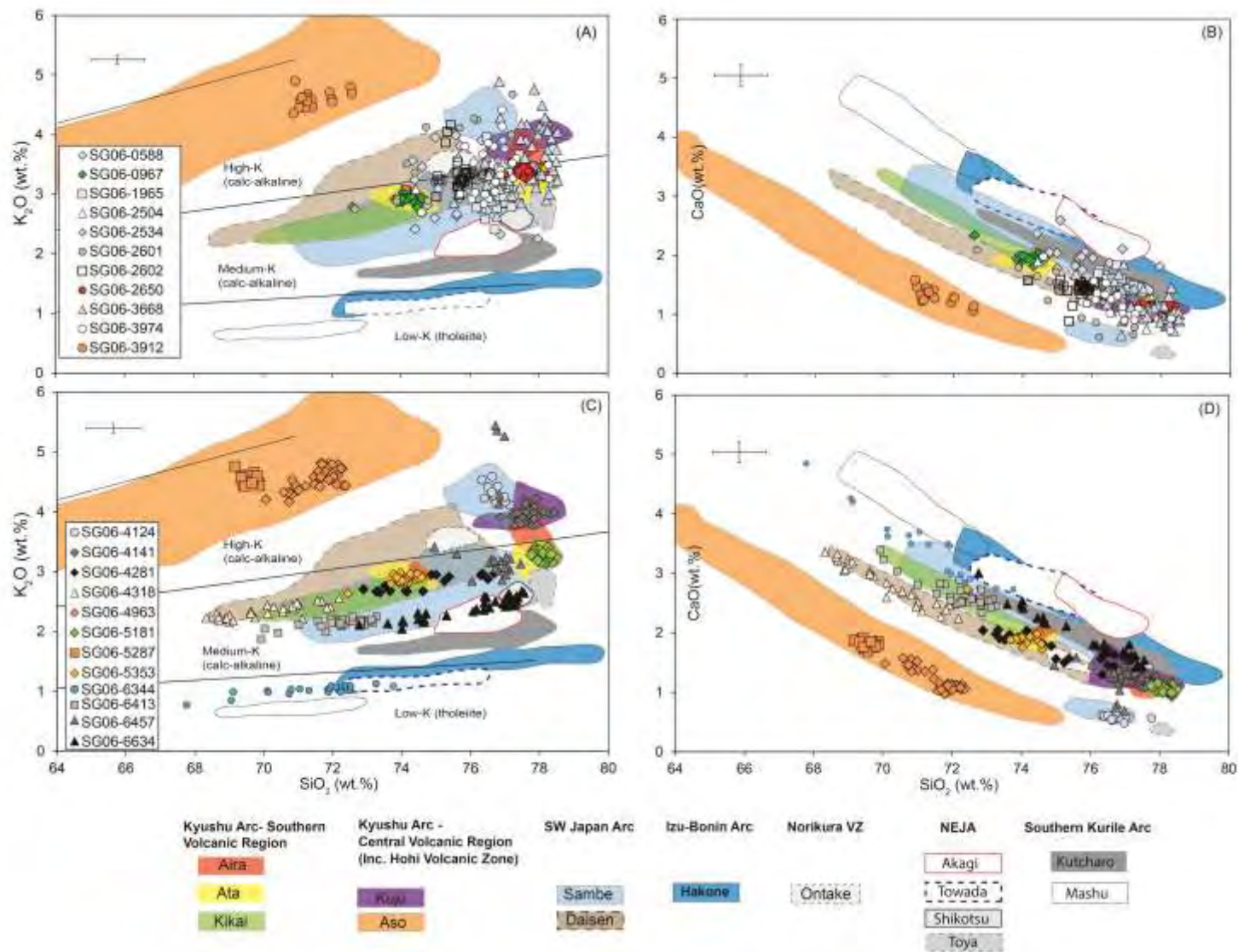
1635 Figure 4



1636

1637 Figure 5

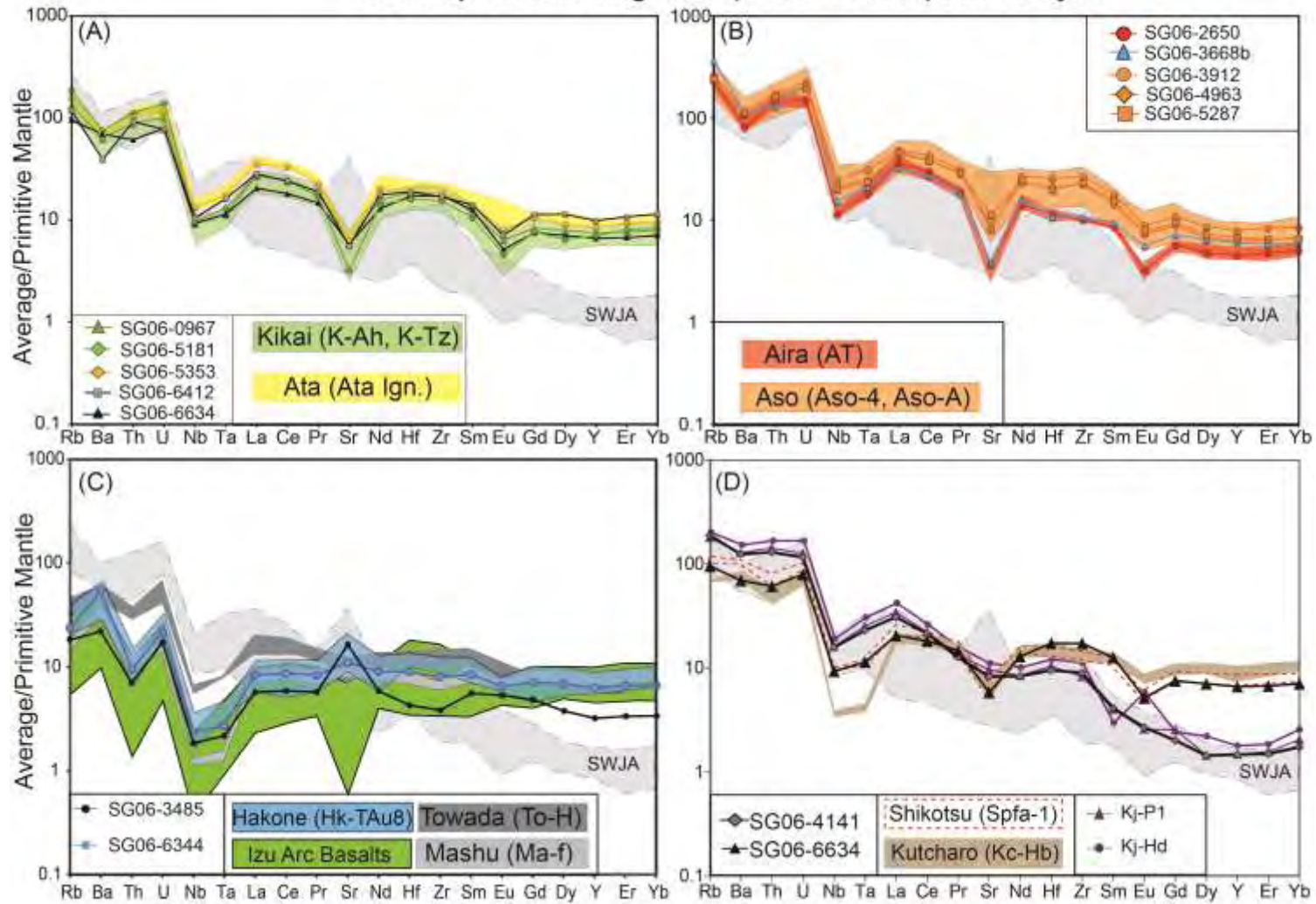




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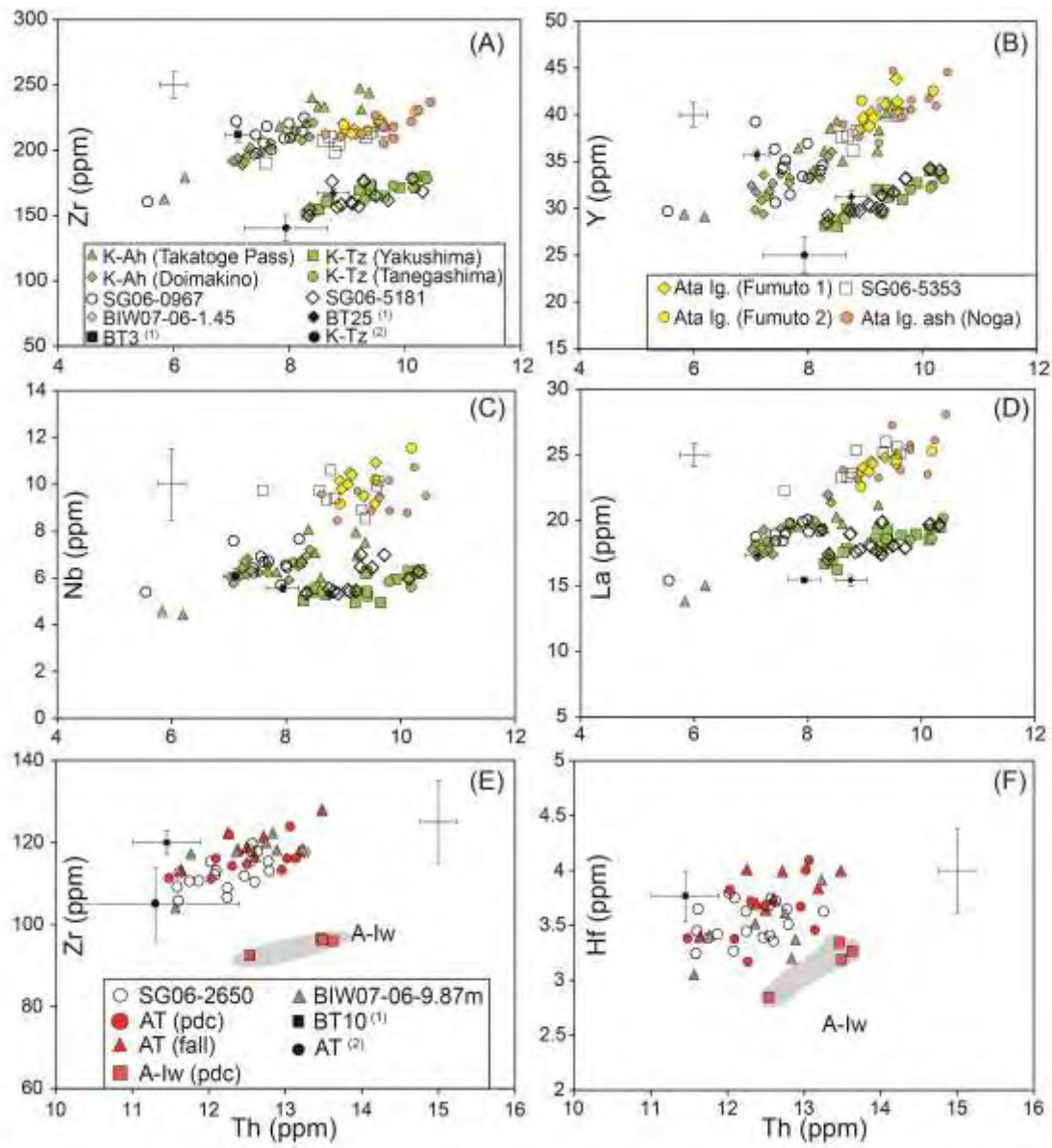
1640 Figure 7

SG06 tephra- Excluding SWJA (Daisen - Sambe) derived layers



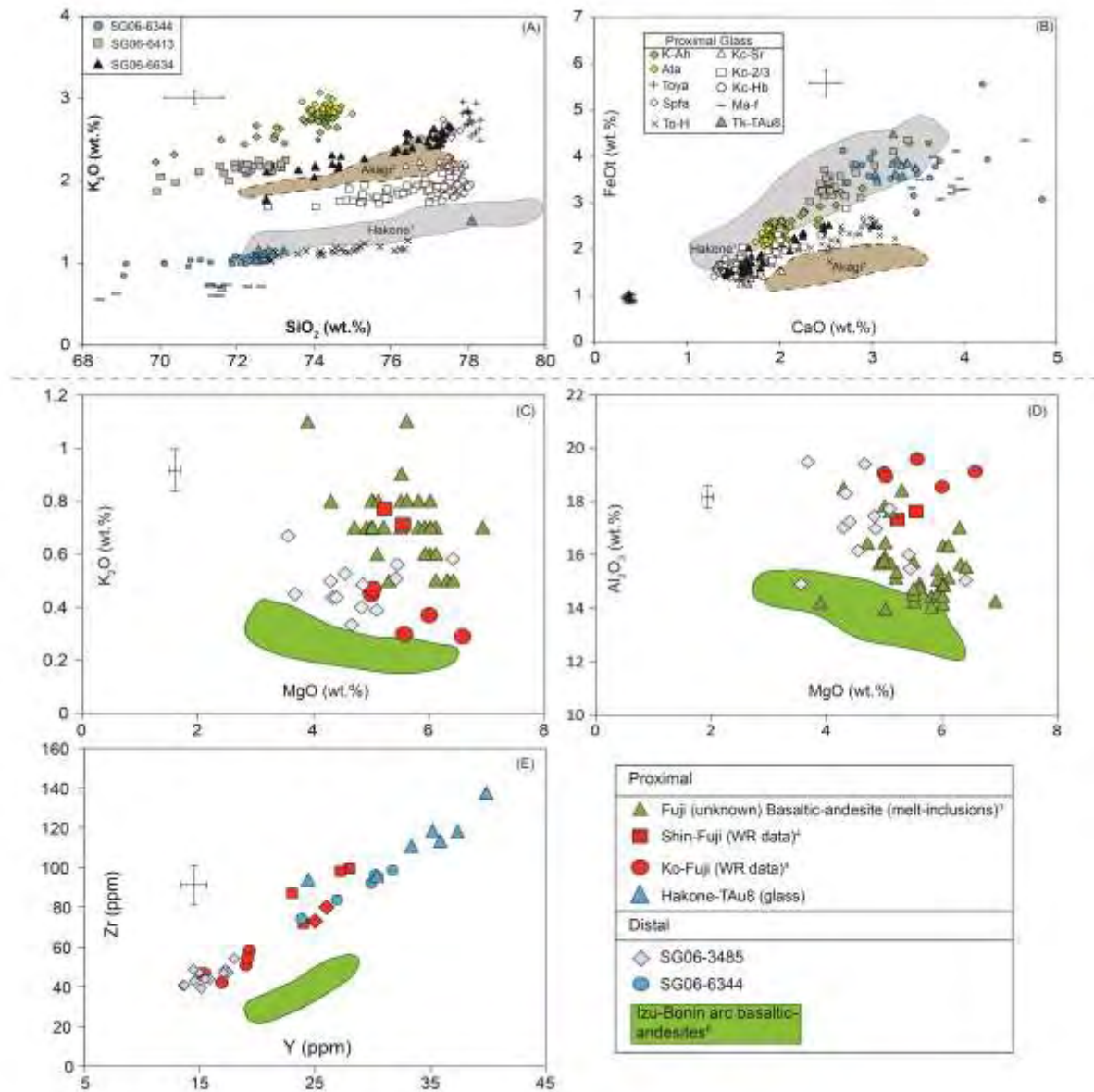
1641

1642 Figure



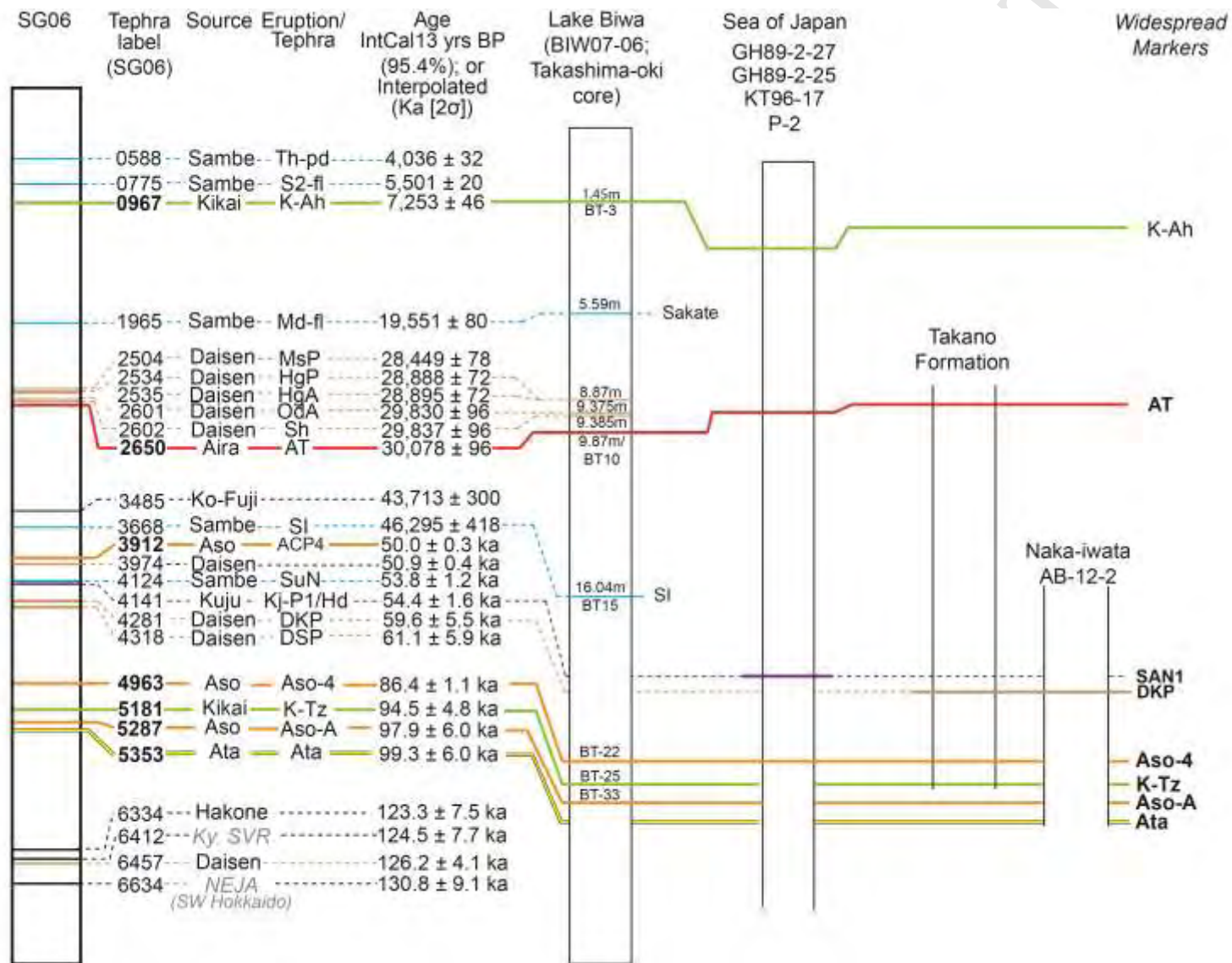
1643

1644 Figure 9



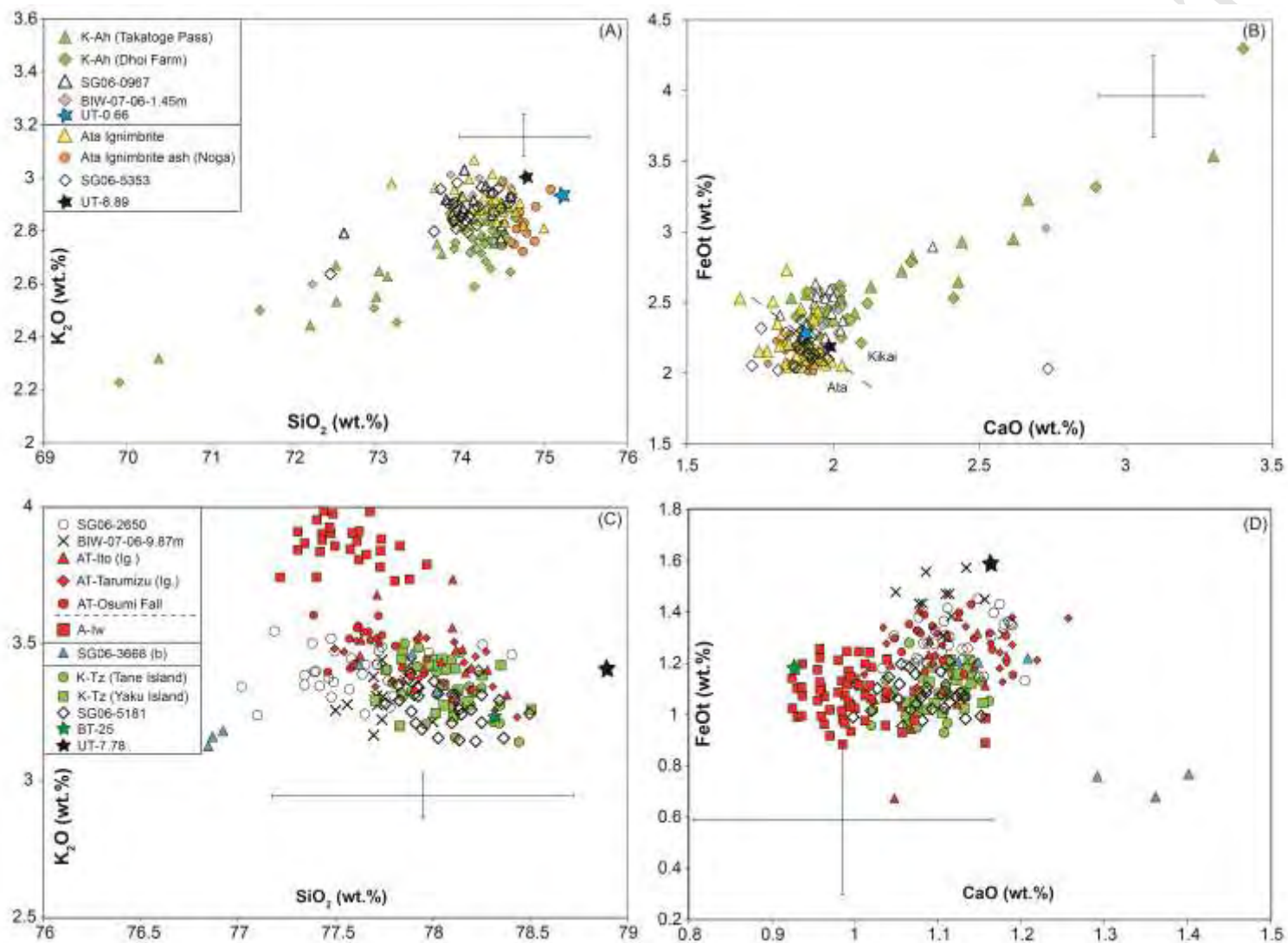
1645

1646 Figure 10



1647

1648 Figure 11



1649

1650 Supplementary Figure 1