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1 Towards characterising rhyolitic tephra layers from New Zealand with rapid, non-destructive μ -XRF
2 core scanning

3

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10

11 Abstract

12 Tephra layers are of importance for the construction of reliable age control in late Quaternary
13 paleoenvironmental and volcanic hazard studies, especially in volcanically-active settings such as the
14 North Island of New Zealand. However, their identification involves time-consuming and destructive
15 processing steps, making the application of non-destructive μ -XRF core scanners potentially
16 advantageous for tephra identification. Here, we investigate the potential of the Itrax μ -XRF core
17 scanner to differentiate between rhyolitic tephra layers sourced from various northern New Zealand
18 rhyolitic volcanic centres deposited in maar lakes of the Auckland Volcanic Field. In their
19 macroscopic form these tephra layers are usually visibly distinct when surrounded by a dark,
20 organic-rich sediment matrix, although their attribution to source volcanic centre and eruption
21 typically requires examination of their mineral assemblages, combined with chemical fingerprinting
22 of the rhyolite glass shards. We demonstrate that μ -XRF core scanning of rhyolitic tephra layers from
23 the Taupo Volcanic Zone and Tuhua Volcanic Centre can also allow identification, and sometimes
24 differentiation, of the tephra using μ -XRF-derived elemental counts, especially high Si, K, Ca and very
25 low Br and Ti. Different rhyolite tephra layers vary in their relative abundances of major, minor and
26 trace elements as is evident from electron microprobe and LA-ICP-MS analyses of their glass shards.
27 Mo-tube based μ -XRF cannot detect Na nor Mg and is of lower reliability for the lighter elements
28 (Ca, Al) which play an important role in traditional tephra fingerprinting. Nevertheless, we are able
29 to demonstrate that μ -XRF core scanning data can distinguish between previously identified tephra
30 layers using multivariate statistics. Furthermore, the study emphasises the need for a standard
31 protocol for μ -XRF core scanning of tephra layers for this approach to be more widely applicable,

32 especially to aid or be a substitute for conventional geochemical approaches used for tephra
33 fingerprinting.

34 Keywords: Itrax; Tephra; Multivariate Statistics; Principal Component Analysis; Discriminant Factor
35 Analysis; Auckland Volcanic Field, New Zealand

36

37 1 Introduction

38 Lake sediment-based reconstructions of late-Quaternary environmental change are only useful if
39 based on reliable chronologies. Nevertheless, many of the changes in climatic and environmental
40 conditions of interest occurred more than 50,000 years ago and/or cannot be dated by the
41 radiocarbon technique. Fortunately, volcanic eruptions produce tephra that are deposited as layers
42 both proximal and distal to volcanic centres and serve as time markers that aid the development of
43 reliable chronologies (Shane, 2000; Lowe, 2011; Lane et al., 2017). This is the science of
44 tephrochronology which is an important method for dating late Quaternary lake sediment
45 sequences in northern New Zealand (Molloy et al., 2009).

46 Tephrochronology involves the unambiguous identification of tephra that are sometimes spread
47 over large areas distal from the eruption site. Eruptions are effectively instantaneous events where
48 they are preserved in the geological record so that the resulting tephra layers are isochrons. If the
49 eruption has been dated by some means, the same age can be attributed to the widely-distributed
50 tephra layers produced thereby underlining the importance of tephra to dating sediment-based
51 records of past environmental change, as well as in volcanic hazard analysis (Shane, 2000; Lowe et
52 al., 2008; Lowe, 2011).

53 To be able to establish reliable correlations between tephra layers encountered at different
54 locations distal to the source and to proximal eruptive deposits, geochemical characterisation of the
55 tephra is necessary and termed “fingerprinting”. Traditionally, tephra layers are fingerprinted
56 geochemically and petrographically based on electron probe microanalysis (EPMA; for major
57 element oxide composition), LA-ICP-MS (Laser ablation inductively coupled plasma mass
58 spectrometry; for minor and trace elements) of volcanic glass and microscopic investigation of the
59 diagnostic mineral assemblage (e.g., Shane, 2000; 2005; Shane and Smith, 2000; Lowe et al., 2008;
60 2013; Dugmore and Newton, 2012; Lane et al., 2017). However, this process is destructive and time
61 consuming, thereby complicating the use of tephra as known-age isochrons in lake sediment
62 sequences.

63 In contrast, μ -XRF scanning of sediment cores is fast, non-destructive and needs virtually no sample
64 preparation (e.g., Croudace et al., 2006; Thomson et al., 2006; Croudace and Rothwell, 2010).
65 Sediment-based records of past environmental change often routinely undergo μ -XRF scanning to
66 obtain continuous time-series of geochemical data for elements with an atomic number $Z \geq 13$ (Al to
67 U). The geochemical data required for tephra recognition and identification/fingerprinting are
68 collected automatically in the μ -XRF process. Hence, the potential advantages of being able to
69 rapidly and reliably identify tephra using μ -XRF core scanners are clear.

70 Prior research into the potential of using μ -XRF core scanners as a tephrochronological aid has
71 focused on the ability to locate cryptotephra invisible to the un-aided eye (e.g., Balascio et al.,
72 2015), or to identify tephra in lake sediment cores (Kylander et al., 2012). The latter authors do not
73 recommend the use of μ -XRF core scanning data as a tool for tephra identification based on basaltic
74 and low-concentration rhyolitic tephra layers in sediment cores from the Faroe Islands. However,
75 improvements in the Itrax detector system and the abundance of macroscopic (visible) tephra layers
76 with distinctive chemistries in New Zealand (Lowe et al., 2008) require a more thorough
77 investigation of the potential of μ -XRF core scanning techniques for reliable tephra identification.

78 This study focuses on tephra in lake sediment cores retrieved from maars in the Auckland Volcanic
79 Field (AVF; northern New Zealand) which unites outstanding high-resolution and finely-laminated
80 records of late-Quaternary environmental change with well-preserved tephra deposits from a wide
81 variety of volcanic systems (andesitic, basaltic, and rhyolitic).

82

83 2 The AVF

84 The AVF consists of about 53 basaltic volcanoes (Lindsay et al., 2011). Thirteen of these are explosion
85 craters, called maars, formed by phreatomagmatic eruptions (Cas and Wright, 1988; Smith, 1989).
86 All maar craters referred to in this study (Fig. 1) have hosted a lake for varying durations over the
87 past ca. 250 ka (Molloy et al., 2009). Lake Pupuke is the only maar in the AVF which has not been in-
88 filled and/or breached and contains an extant lake (Augustinus et al., 2006; 2008; Stephens et al.,
89 2012; Newnham et al., 2018). The extant and in-filled maar lakes mostly have steep crater rims
90 combined with deep lacustrine basins with small width to depth ratios resulting in excellent
91 preservation potential of sediment and tephra derived from both tephra fall and reworking from the
92 steep subaqueous crater rim slopes (Molloy et al., 2009; Zawalna-Geer et al., 2016).

93 The AVF maar lake sediment sequences often show pronounced fine laminations recording changes
94 in regional climate and environmental conditions, possibly even at annual to decadal resolution

95 (Pepper et al., 2004; Augustinus et al., 2006; Striewski et al., 2013). For the past ca. 46 ka, good age
96 control was largely established based on identification of geochemically-distinct, well-dated and
97 well-preserved tephra (volcanic ash) isochrons (Shane, 2000; Molloy et al., 2009; Augustinus et al.,
98 2011). This dependence on tephra layers for AVF maar lake sediment sequence chronology
99 development highlights the need for fast and reliable identification of tephra in lake sediment cores
100 proximal or distal to tephra-producing volcanic zones.

101 *Figure 1 about here, over one column*

102 2.1 Tephra records from the AVF maar crater lakes

103 The North Island volcanic centres (VC) that contribute rhyolitic and andesitic tephtras to the Auckland
104 maar lakes are located south of Auckland: the Okataina (OVC), Taupo (TVC), Egmont volcano (Eg;
105 Taranaki) and Tongariro (TgVC) volcanic centres, as well as the smaller Tuhua VC (Mayor Island) to
106 the SE. In addition, the c. 53 volcanoes in the AVF produced basaltic tephra which are dispersed
107 locally (Fig. 1). Rhyolitic, basaltic and andesitic tephra from these centres have frequently reached
108 the AVF maar lakes (Molloy et al., 2009; Zawalna-Geer et al., 2016), highlighting their value as
109 known-age isochronous marker layers for both chronology development and correlation of the
110 sediment sequences between maars. Furthermore, volcanic hazard assessment for the AVF basaltic
111 volcanoes rely on identification of basaltic tephra layers contained in the maar lake sequences
112 although their timing has largely been constrained by the bracketing known age rhyolitic tephra
113 (Molloy et al., 2009; Hopkins et al., 2015). However, new approaches using $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the
114 basaltic lava flows from the source AVF volcanoes correlated to basaltic tephra deposits (Hopkins et
115 al., 2017; Leonard et al., 2017), zircon double-dating (Danišić et al., 2012), and meteoric ^{10}Be and
116 magnetic paleointensity studies of the maar lake sediments (Nilsson et al., 2011) have the ability to
117 dramatically improve the chronology of the sequences beyond the ^{14}C -dating- method limit of c. 60
118 cal ka under favourable conditions.

119 In this study, we investigate the scanning μ -XRF characteristics of rhyolite tephra layers in sediment
120 cores from five AVF maar paleolakes: Onepoto Domain, Orakei Basin, Panmure Basin, Hopua Crater,
121 and Pukaki Lagoon; plus one extant lake, Pupuke (Fig. 1). Only rhyolite tephra layers were used as
122 they are the most widely-dispersed and widely-used tephrochronological deposits in New Zealand.

123

124 3 Material and methods

125 3.1 Rhyolitic tephra layers

126 The tephra records documented in sediment cores from Hopua maar, Lake Pupuke and the Orakei
 127 Basin core collected in 2007, Pukaki and Onepoto maars are presented in Table 1. Figures 2 and 3 in
 128 Molloy et al. (2009) present the studied rhyolitic tephra layers in stratigraphic context of the
 129 Auckland Volcanic Field maar lake records. This study focusses only on macroscopic rhyolitic tephra
 130 layers which have previously been identified through EPMA glass chemical composition (Molloy et
 131 al., 2009 and unpublished data by Zawalna-Geer). Table 1 summarises the names, source volcanic
 132 centres and dominant mineralogy of the 13 rhyolitic tephra layers investigated in this study.

133

134 Table 1: Overview over investigated rhyolitic tephra layers in this study following Lowe et al. (2008)
 135 and Molloy et al. (2009).

Name	Ferromagnesian mineralogy ²	Centre ¹
Tuhua	aeg > cpx > opx ± aen ± rie ± hb ± olv(fa) ± tuh	TUVC
Mamaku	hb > opx >> ± cgt	OVC
Rotoma	cgt > hb	OVC
Opepe	opx >> cpx	TVC
Waiohau	opx > hb	OVC
Rotorua	bio > opx > hb	OVC
Okareka	bio	OVC
Kawakawa/Oruanui	opx > hb	TVC
Okaia	opx > hb	TVC
Hauparu	hb, opx	OVC
Maketu	hb > opx	OVC
Tahuna	opx > hb	TVC
Rotoehu	bio = hb = cgt	OVC

136 ¹TUVC: Tuhua Volcanic Centre (Mayor Island); OVC: Okataina Volcanic Centre; TVC: Taupo Volcanic
 137 Centre

138 ² aeg: aegirine; aen: aenigmatite; bio: biotite; cgt: cummingtonite; cpx: clinopyroxene; hb:
 139 hornblende; olv(fa): olivine (fayalite); opx: orthopyroxene; tuh: tuhualite. ± indicates may or may not
 140 be present.

141 3.2 Methods

142 3.2.1 μ -XRF Core Scanning

143 The sediment cores were scanned with three different Itrax μ -XRF Core Scanners (Cox Analytical
 144 Systems, Gothenburg, Sweden) at Aberystwyth University (AU, UK), the Australian Nuclear and
 145 Science Technology Organisation (ANSTO, Australia), and The University of Auckland (UOA, New
 146 Zealand) with settings specified in Table 2. Each scan resulted in an optical image, a radiograph and
 147 single dispersive energy spectra for each interval measured along the core profile. Integrated peak
 148 area integrals for each element are calculated from the spectra which are then output as X-ray
 149 fluorescence (XRF) count data (Croudace et al., 2006; Thomson et al., 2006; Croudace and Rothwell,
 150 2010).

151

152 Table 2: Overview of μ -XRF scanning locations and conditions used in this study

Site	Location of scan	Year of scan	X-ray tube	Voltage	Current	XRF exposure time	Step size
Pupuke	AU ¹	2008	Mo	30 kV	20 mA	10 s	200 μ m
Hopua	AU	2008	Mo	30 kV	45 mA	10 s	200 μ m
Panmure	AU	2010	Mo	30 kV	45 mA	10 s	200 μ m
Onepoto	ANSTO ²	2013	Mo	30 to 55 kV	50 to 55 mA	10 s	1000 μ m
Orakei	UOA ³	2017	Mo	30 kV	55 mA	10 s	1000 μ m
Hopua	UOA	2017	Mo	30 kV	55 mA	10 s	1000 μ m
Panmure	UOA	2017	Mo	30 kV	55 mA	10 s	1000 μ m
Onepoto	UOA	2017	Mo	30 kV	55 mA	10 s	1000 μ m

153 ¹: Aberystwyth University; ²: Australian Nuclear Science and Technology Organisation; ³: University of
 154 Auckland

155

156 3.2.2 Data Treatment

157 To correct for variability in sediment water, organic matter content and grain size, as well as X-ray
 158 tube ageing, all elemental peak intensities have been normalised to the sum of incoherent and
 159 coherent scattering (inc+coh; Löwemark et al., 2011; Kylander et al., 2012). Unless otherwise stated,
 160 element "X" refers to elemental peak areas normalised by inc+coh (Fig. 2).

161 *Figure 2 about here, landscape over full page*

162 As an initial step, we examined the kernel density estimation (KDE) of the distribution of elemental
163 counts of Al, Si, P, S, Cl, K, Ca, Ti, V, Mn, Fe, Ni, Zr, Br, Rb, Sr, Zr (all normalised to inc+coh) and
164 inc+coh (Fig. 3, 4). KDE estimates the probability density function of the variable in question and can
165 be understood as a smoothed version of a histogram.

166 Most elements follow approximately log-normal distributions. Some elements display bimodal
167 distributions within the general shape of a log-normal distribution (Fig. 3). The bimodality was
168 largely preserved after log-ratio transformation with many elements showing skewed distributions
169 to various degrees (Fig. 3, 4). A condition of the statistical tests described below is normal
170 distribution of the data (Zelterman, 2015). To obtain roughly normally distributed data the
171 normalised counts have been log-ratio transformed.

172 The bimodality and skewed distributions (Fig. 3) partly result from mixing μ -XRF scanning data from
173 different Itrax scanners using different detector generations (Fig. 4, Table 2). The maximum counts a
174 new detector (i.e., the Itrax at the University of Auckland) can record are several times higher than
175 those of the older detector (i.e., the Itrax at the Aberystwyth University in 2008). Despite
176 normalizing the data by inc+coh, substantial differences in the numerical counts remain (Fig. 4).
177 These differences between detectors have a stronger influence on the distribution shape than actual
178 differences in element "X" between the tephra layers, thereby causing a skewed or multimodal
179 shape. K_{norm} , Ca_{norm} and Sr_{norm} are presented in Fig. 4 as an example separated by tephra layer
180 (colour) and Itrax scanner (line pattern). Although differences between the tephra layers can
181 generally be observed, differences between the Itrax scanners become apparent too. For example,
182 the distribution of the Tahuna tephra reaches its respective peaks of K_{norm} (Fig. 4) in the lower end of
183 the entire distribution in the μ -XRF data from ANSTO and in the middle part in the data from UOA.
184 However, the Mamaku tephra is consistently recorded with overlapping highest density of the Ca_{norm}
185 and Sr_{norm} distribution in μ -XRF data from UOA and AU. Additionally, it becomes clear that different
186 tephra layers show distinct peaks in the density distribution of normalised μ -XRF counts, thus
187 pointing to the possibility of geochemical differentiation between tephra layers based on μ -XRF
188 counts.

189 For further analyses, the tephra layers have been split into pre-Kawakawa/Oruanui tephra (KOT,
190 inclusive) layers and post-KOT layers. The KOT is the product of a caldera-forming super eruption
191 $25,360 \pm 160$ cal yr BP (Pillans et al., 1993; Vandergoes et al., 2013) that produced widely-dispersed
192 tephra.

193

194 Data from three different Itrax μ -XRF core scanners

195 Mixing μ -XRF scanning data from different Itrax scanners used with different detector generations
196 and different scanning settings cause complications for numerical analyses which cannot be
197 corrected for easily. Hence, we split the dataset by core scanner location and only proceed with data
198 from the ANSTO Itrax (for pre-KOT) and the UOA Itrax (for post-KOT), separately for further
199 multivariate statistical analyses. The decision to exclude the data from the AU Itrax was motivated
200 by the smaller number of scanned tephra layers, the older detector¹ used with lower sensitivity for
201 lighter elements and different scanning settings from the ANSTO and UOA Itrax scans (see Table 1).

202 The logarithm of "0" is not defined. Hence, special care must be taken when applying log-
203 transformation to data including "0". Only elements which have been measured in all scanning
204 routines are kept for interpretation to avoid introducing artificial 0-values. Additionally,
205 measurements of some elements of low abundance and/or low detection limit in the μ -XRF
206 technique (e.g., Al) result in "0" in many measurements. Cuven et al. (2007) recommended
207 removing all elements that include more than 30% of 0-values. All measurements that still include
208 one or more 0-values after this step must also be removed, resulting in the possible removal of the
209 thinner tephra layers that are represented by fewer μ -XRF data points. Hence, we chose to remove
210 all elements that include more than 10% of 0-values and remove the few remaining measurements
211 including 0-values.

212 *Figure 3 about here, landscape over full page*

213 *Figure 4 about here, landscape over full page*

214

215 Data transformation

216 Elemental counts obtained from μ -XRF scanning are compositional data consisting of proportions
217 summing to a constant and are non-negative (Aitchison, 1986). Hence, the variation of one
218 component of the total (i.e., an element "X" whether it can be detected by the Itrax or not)
219 influences the amount of all other elements. This unit-sum constraint possibly results in incorrect
220 inference when improperly incorporated into the statistical analyses and is well known in the
221 geostatistical community (e.g., Lowe et al., 2017). Aitchison (1986) has developed a simple approach
222 to removing this constraint by applying log-ratio transformation where the natural logarithm of
223 ratios between two components of the sum are computed. Note, however, that all the data

¹ Note that the Aberystwyth University Itrax detector has been upgraded in 2008 and 2015 with improved sensitivity.

224 presented here are ratios because they have been normalized by inc+coh. Many authors favour log-
225 ratio transformation (e.g., Weltje and Tjallingii, 2008; Weltje et al., 2015; Martin-Puertas et al., 2017)
226 whereas others question its use (e.g., Pearce et al., 2008; Feng et al., 2014). Lowe et al. (2017) point
227 out that any statistical analyses should ideally be performed on transformed and un-transformed
228 data and if transformation alters the results obtained caution has to be taken with the use of the
229 dataset. Hence, all the following statistical approaches applied to the rhyolite tephra μ -XRF data
230 involve log-ratio transformed and raw (normalised) data to compare results. The results of both
231 approaches are very similar giving confidence to the presented μ -XRF-based geochemical
232 fingerprinting approach.

233

234 Principal component analysis

235 Principal component analysis (PCA) finds the direction of highest variance within the multivariate
236 data and fits the first principal component (PC) along this direction. Each subsequent component
237 describes a subsequently smaller amount of variance of the original dataset and is oriented
238 orthogonally to the prior component (e.g., Zelterman, 2015). In the resulting biplot, the proximity of
239 the data points to each other suggests a strong similarity between the measurements, while
240 proximity between the elemental loadings and data points emphasises the correlation between the
241 respective type of material (sediment or certain tephra layer) and the measured elements (e.g.,
242 Zelterman, 2015).

243 PCA has been applied to μ -XRF scanning results from the Onepoto core measured at ANSTO (Fig. 7A),
244 μ -scanning results from the Hopua core measured at the University of Auckland (Fig. 7B), pre-KOT
245 rhyolitic tephra layers in the Onepoto core (measured at ANSTO (Fig. 7A), and post-KOT rhyolitic
246 tephra layers in the Hopua and Panmure cores (measured at University of Auckland) (Fig. 7B).

247

248 Discriminant function analysis

249 Linear discriminant analysis (LDA) is a subclass among discriminant function analyses that
250 determines a linear combination of independent variables (here elemental intensities) leading to a
251 single transformed variable by which *a-priori* classified, mutually exclusive groups (here tephra
252 layers classified by EPMA data) may be discriminated (e.g., Zelterman, 2015). The first linear
253 discriminant function (LD) achieves the largest separation between the pre-classified groups similar
254 to the 1st PC. LDA has been successfully applied to EPMA data of tephra layers in New Zealand to
255 discriminate between previously classified tephra layers and test the applicability to identify

256 subsequently encountered tephra layers (Stokes and Lowe, 1988; Stokes et al., 1992; Shane and
257 Froggatt, 1994; Cronin et al., 1996).

258 4 Results and Discussion

259 4.1 Geochemical distinction between rhyolitic tephra layers and sediment matrix

260 Variability in elemental counts obtained by μ -XRF scanning clearly shows the rhyolitic tephra layers
261 in sediment cores (Fig. 4), which works well when the intervening sediment is organic matter-rich
262 resulting in marked geochemical contrast between lake sediment and tephra layers. Thinner tephra
263 layers are more difficult to locate by μ -XRF scanning than thicker tephra layers. Practically, there is
264 no clear minimum thickness for a tephra layer in order to be located and identified by this
265 technique. If a strong contrast in chemical composition to other tephra layers exists even $<200 \mu\text{m}$
266 tephra layers may be identified by this technique in the future. However, for statistical reliability a
267 minimum thickness of c. 1 mm is favourable for this technique.

268 PCA of normalised elemental counts highlights the power to differentiate between
269 lacustrine/marine sediment and rhyolitic tephra layers based on μ -XRF core scanning data (Fig. 5).

270 During μ -XRF scanning, Si, K and Ca are consistently elevated in the rhyolitic tephra with respect to
271 the sediment matrix. The high counts of the latter elements are consistent with the geochemistry of
272 the rhyolitic tephra (Winter, 2001; Lowe et al., 2008). Furthermore, most rhyolitic tephra layers are
273 positively correlated to Mn, Rb and Sr as identified by PCA (Fig. 5). In contrast, rhyolitic tephra layers
274 are always relatively depleted in Br which is consistent with Br being an indicator for organic rich
275 sediment (Davies et al., 2015; Rothwell and Croudace, 2015; note the correlation of Br with
276 lacustrine sediment in all PCA results in Fig. 5). It is striking that Zn, Rb, Sr and Zr vary in their
277 behaviour between discrete tephra layers of different ages, e.g., Zr is high in the Maketu, Hauparu
278 and Tuhua layers compared to the amounts in the encapsulating sediment whereas Sr is elevated in
279 most tephra layers but depleted in the Tuhua layer (Fig. 4).

280 The μ -XRF presented data shows that tephra layers sourced from the TVC are chemically distinct
281 from those sourced from the OVC and from those erupted by the TUV as has been observed in
282 conventional tephrochronological methods (e.g., Lowe et al., 2017). This finding provides confidence
283 that μ -XRF core scanners have the potential to fingerprint rhyolitic tephra layers to their source
284 volcanic centre.

285

286 *Figure 5 about here, landscape over full page*

287

288 4.2 Multivariate geochemical discrimination between the rhyolitic tephra layers

289 Most discrete rhyolitic tephra layers such as the Rotoehu, Tahuna, Maketu, Hauparu, Okaia,
290 Okareka, Waiohau, Rotoma and Tuhua tephra are strongly depleted in Ti whereas the
291 Kawakawa/Oruanui (KOT) and Rotorua tephra show no discernible difference in levels of Ti
292 compared with that of the sediment matrix. Only the Mamaku and Tuhua tephra are enriched in Fe
293 (Fig. 2B). Tahuna, Maketu, Hauparu and Tuhua tephra are enriched in Zn compared to the amounts
294 in the sediment matrix and the rhyolite tephra layers, except for Okareka and Mamaku tephra, are
295 enriched in Rb (Fig. 2). Tuhua is the only tephra clearly depleted in Sr while all other rhyolitic tephra
296 layers examined are enriched in Sr to various degrees. The Maketu, Hauparu, KOT, Rotorua,
297 Waiohau and Tuhua tephra layers are strongly enriched in Zr. All the other tephra layers show no or
298 very minor differences in Zr levels between the sediment and the tephra (Fig. 2).

299 Comparing only the tephra layers to one another indicates that the different layers form different
300 clusters in a biplot (Fig. 6) and linear discriminant analysis (Fig. 7). The thin tephra layers (Okaia,
301 Hauparu, Tahuna, Mamaku, Opepe and Waiohau) are not easily identifiable due to the limited
302 number of data points available due to their thickness. High-resolution (200 μm) $\mu\text{-XRF}$ scans over
303 multiple lateral positions of thin tephra layers may increase the possibility of identifying the thick
304 tephra layers.

305 Pre-KOT rhyolite tephra

306 PCA and LDA enabled identification of the largest difference between Rotoehu and the four other
307 pre-KOT rhyolitic tephra layers (Fig. 6A, 7A). Separation along PC1 and LD1 is mostly achieved with
308 Rotoehu tephra which is relatively enriched in Si, Sr, K and Rb, whilst displaying relative depletion in
309 Ca, Zn, Fe, Cl and Mn. PC2 and LD2 achieve a clear separation between the Maketu/Hauparu and
310 Tahuna/Okaia tephra, respectively, with the former being relatively enriched in Ca, Rb, Si, Ti and Fe
311 and the latter relatively enriched in Mn, Sr and K (Fig. 6A, 7A). Along LD2, the Maketu, Hauparu and
312 Rotoehu tephra form one cluster (Fig. 6A, 7A) corresponding to the OVC-source of these three
313 tephra layers (Table 1, Fig. 1). The other cluster along LD2 is formed by Okaia and Tahuna tephra and
314 corresponds to their TVC source (Fig. 1, 7A). Fig. 6A shows scattered outliers, especially in the lower
315 left corner where Tahuna and Okaia tephra chemistries mix (Fig. 7A). The observed wide scatter of
316 data points emphasizes the need for more elemental data points, especially for the thinner tephra
317 layers to better constrain the tephra-source defined clusters and remove outliers.

318 Post-KOT rhyolite tephra

319 PCA and LDA plots show clear elemental differentiation between the Tuhua and all other post-KOT
320 tephra (Fig. 2B, 5B) which is consistent with it being the only tephra from the Tuhua Volcanic Centre
321 examined in this study and its contrasting composition to the others as noted in earlier studies based
322 on glass shard EPMA data (e.g., Lowe et al., 2008). Tuhua tephra is relatively enriched in Fe, Zn, Zr, Y,
323 and Mn and depleted in Sr (Fig. 2B). Hence, PC1 and LD1 allow separation of the Mayor Island-
324 sourced tephra from the remaining post-KOT rhyolitic tephra layers. Rotoma, Rotorua and Opepe
325 tephra each have sufficient data points to produce well-defined clusters in the PCA bi-plot (Fig. 2B).
326 PC2 largely allows elemental discrimination between Rotorua (relatively enriched in Ca) and Opepe
327 tephra (Fig. 2B). The same trend is visible, but clearer, in the LDA where LD3 achieves separation
328 between TVC and OVC+TU sourced rhyolitic post-KOT tephra layers (Fig. 5B).

329

330 *Figure 6 about here, landscape over full page*

331 *Figure 7 about here, one and a half page width*

332

333 4.3 Bivariate scatterplots

334 Using multivariate statistics, a suite of bivariate scatterplots showing the clearest separation of
335 individual tephra layers can be produced and is supplemented by typical bivariate scatterplots for
336 rhyolitic tephra (e.g., SiO₂ vs. K₂O; Shane, 2000) identification based on traditional EPMA data in Fig.
337 8.

338

339 Pre-KOT rhyolite tephra

340 All pre-KOT elemental scatterplots (Fig. 8A) show the outliers of the Rotoehu, Maketu, Hauparu and
341 Okaia tephra layers at a significant distance from their respective clusters as was observed in the
342 PCA biplots (Fig. 6A). A standard bivariate plot used by the tephrochronological community for
343 differentiating and fingerprinting tephra layers to source, and possibly event of an
344 eruption, is SiO₂ vs. K₂O (e.g., Shane, 2000). However, the equivalent μ -XRF scanning of Si vs. K plot
345 of log-transformed μ -XRF core scanning data only achieves clear separation between Okaia+Tahuna
346 vs. Rotoehu+Maketu+Hauparu tephra (Fig. 8A). Bivariate plots of Ca vs. K, Fe vs. Ca, Si vs. Zn, Sr vs.
347 Ca and Rb vs. Sr (Fig. 8A) show a clear separation between the Maketu and Rotoehu tephra. The
348 lower number of μ -XRF data points for the Okaia and Tahuna tephra as well as the large variance in
349 μ -XRF elemental counts complicate the recognition of a clear cluster corresponding to their mean

350 count values of the latter elements. It is not possible to conclude whether the data points distal from
351 the centre of the cluster are outliers due to scanning or core condition (e.g., small amounts of
352 foreign material mixed with the tephra layer not visible at the core surface) or if these tephra layers
353 exhibit a large variance in the elements possibly due to pre-, syn- and/or post-eruptive processes.

354 Using this μ -XRF scanning approach has not enabled clear geochemical separation between the
355 Okaia and Tahuna tephra, nor separation of the Hauparu from the Maketu tephra (Fig. 8A). This
356 further highlights the need for more elemental data points from each of the tephra layers,
357 particularly the thinner layers (Fig. 2) to be able to better define mean count values of the elements,
358 their variance, and hence, delineate possible outliers. In addition to acquiring more elemental data
359 points during the scans, future work requires investigation of a greater range of elements, especially
360 minor and trace elements², which could achieve a clearer geochemical separation of the visually-
361 distinct tephra.

362 Post-KOT Rhyolite Tephra

363 Scatterplots of Si vs. K, Ca vs. K, Fe vs. Si, Mn vs. Si, Ti vs. Cl, and Y vs. Cr for post-KOT rhyolitic tephra
364 layers shown in Fig. 8B highlight the ease of differentiation of the Tuhua tephra from all others
365 examined here. The thicker Rotoma and Rotorua layers can also be separated clearly despite an
366 abundance of outliers, especially in the more common EPMA-based geochemical bivariate plots used
367 commonly in tephrochronology (e.g., SiO_2 vs. K_2O , CaO vs. K_2O , Fe_2O_3 vs. SiO_2 ; Shane, 2000). The
368 nature of these outliers is unclear but more precise Ca and Si μ -XRF elemental data and potentially
369 fewer outliers could be achieved on the Itrax μ -XRF core scanner using the Cr-tube as it has lower
370 detection limits for light elements. The minor elements contribute to separation of the post-KOT
371 tephra layers with fewer outliers evident in Mn vs. Si, Ti vs. Cl and Y vs. Cr bivariate plots (Fig. 8B).
372 The Opepe and Waiohau tephra do not plot as clearly defined clusters although the Opepe tephra
373 data points define a zone where most of its elemental data points lie.

374 *Figure 8 about here, landscape over full page*

375 5 Conclusions

376 This study demonstrates the potential of rapid and non-destructive μ -XRF core scanning for
377 separating rhyolitic tephra layers sourced from different volcanic centres, and sometimes different
378 eruptives from the same centre using elemental composition. The ability to use compositional

² Following definition by glass shard geochemistry: major elements expressed as oxides are usually defined as >1 wt %, minor element oxides as 0.1 to 1 wt %, and trace elements as <0.1 wt % or <1000 parts per million (ppm) of the element (Lowe et al., 2017).

379 analyses derived from μ -XRF core scanning as an aid to tephrochronology is abetted by the organic-
380 rich lacustrine sediment interbedded with the tephra infilling the Auckland maar lakes that allow
381 clear differentiation of the rhyolite tephra. This was able to be achieved despite the μ -XRF core
382 scanner measurements being generated using a Mo tube so that the light element data (Al, Ca) were
383 of lower precision than if a Cr tube was used. These elements are typically useful in conventional
384 tephra fingerprinting using major oxide data derived from electron microprobe analysis. Analyses of
385 minor and trace elements can be useful in tephra fingerprinting (e.g. Pearce et al., 2007; Davies et
386 al., 2012; Wastegård et al., 2013; Lowe et al., 2017), which are easily and quickly obtained by μ -XRF
387 core scanning during the same analysis as major elements are acquired. Consequently, future
388 studies should evaluate the full potential of the μ -XRF scanning technique for tephra fingerprinting
389 by varying the scanning settings and elements used. In particular, exposure time per measurement
390 interval and scanning settings need to be adjusted in order for the elemental counts to exceed "0"
391 where relevant, in order to avoid discarding many minor and trace elements that may be of
392 significance. Only then can the whole range of geochemical variability between tephra layers be
393 captured and utilised. Similarly, obtaining Al and Ca counts as high as possible might need to be the
394 focus when choosing the X-ray tube (favouring the Cr-tube for the light elements) and adjusting
395 scanning settings (kV, mA) and exposure time accordingly.

396 This study also shows that many factors, such as current (mA), voltage (kV) and exposure time
397 influence scanning results in a non-linear manner. Their influence has not yet been quantified and
398 we propose to avoid these complications by following a standard protocol for tephra
399 characterisation. Experimental scans of tephra layers to be undertaken in the future should
400 determine ideal current, voltage and exposure time to enable robust data comparison and
401 application of multivariate statistics.

402 An additional complication for robust tephra μ -XRF based fingerprinting arises from the difference
403 between different generation detector systems and related settings in the Itrax μ -XRF core scanners
404 used in this study. Despite normalisation of elemental count data, significant differences between
405 data sets from the same maar cores and tephra layers scanned by different core scanners remained.
406 To avoid this complication in the future, we propose to conduct all further tephra μ -XRF scans for
407 New Zealand tephra layers on the same Itrax core scanner following a standard protocol.

408 The results of the present study suggest that only one or two bivariate scatterplots (e.g., Ca vs. K, Rb
409 vs. Sr, Y vs. Cr; Fig. 8) of μ -XRF core scanning data may be enough to fingerprint one or more rhyolite
410 tephra layers. However, thin tephra layers, such as the Tahuna, Hauparu, Okaia, Okareka, Waiohau,

411 Opepe and Mamaku examined in the present study need to be investigated with repetitive μ -XRF
412 scans to obtain greater data density for the statistical approaches used.

413 Using these protocols, it is possible to establish a database of many μ -XRF scanning results from
414 tephra layers already identified using EPMA-based approaches which can be used as the input to
415 semi-automated machine learning algorithms to reliably identify rhyolitic tephra and thereby
416 decrease the time involved in tephra fingerprinting for tephrochronology in a non-destructive
417 manner. To be able to utilize this method of μ -XRF core scanning-based tephra fingerprinting to its
418 full potential, the approach will need to be extended to basaltic and andesitic tephra layers that are
419 commonly encountered in the AVF maar lakes sediment cores. Subsequently, tephrochronologists
420 working in other regions of the globe in which tephra layers of sufficient thickness are found in lake
421 sediments and peat may be able to use this approach. New Zealand is highly suitable to develop a μ -
422 XRF method for geochemically fingerprinting rhyolitic tephra layers due to the rhyolitic eruptions
423 from several volcanoes and volcanic centres being significantly different in their geochemical
424 composition. On the other hand, many volcanic systems in the world have erupted tephras of similar
425 composition throughout their history (e.g., southern America, Iceland, Anatolia). These tephra may
426 not be identifiable by μ -XRF scanning. As μ -XRF data from sediment cores are routinely acquired in a
427 rapid, semi-automated and non-destructive manner, the μ -XRF based geochemical composition of
428 these tephra layers can easily be studied and compared for differences. An increase in XRF exposure
429 time and modern detector technology may provide crucial trace elemental data, which may highlight
430 differences between these tephra layers. Detailed scans and comparison to the volcanic source are
431 necessary on a regional scale if implementation of this μ -XRF based approach is sought outside of
432 New Zealand. In addition, studies need to be undertaken in sediment cores from marine and
433 minerogenic terrestrial depositional environments to widen the possible applicability of this
434 promising approach.

435 Established techniques such as EPMA and LA-ICP-MS acquire data from single grains/glass shards
436 whereas the μ -XRF scanner obtains data from the bulk of the tephra layer. In both techniques
437 measurements on 10 - 20 grains (EPMA, LA-ICP-MS) and over numerous downcore positions of the
438 tephra layer (μ -XRF) are obtained to capture subtle differences throughout a layer. Careful
439 comparison between EPMA-derived composition of glass shards and corresponding μ -XRF-based
440 composition of the bulk tephra layer are to be conducted in the future since we have now
441 demonstrated the general applicability of μ -XRF data to tephrochronology. Large compositional
442 heterogeneity in tephra layers due to pre- and syn-eruptive processes (Shane et al., 2008) rely on
443 EPMA or LA-ICP-MS measurements on separate grains or glass shards in EPMA or LA-ICP-MS. As a
444 result of the small step size of the μ -XRF core scanner, this technique may be employed to study

445 subtle differences in the chemical composition and grain size of tephra layers along the core axis,
446 i.e., during its eruptive and/or depositional history.

447 Classical EPMA- and LA-ICP-MS-based chemical fingerprinting of tephra are supported by their
448 stratigraphic order, physical properties such as thickness and colour, and independent ages to
449 enable them to be correlated (Lowe et al., 2017). The same indicators must not be ignored in μ -XRF
450 scanning based fingerprinting of tephra layers.

451 The speed of elemental scanning and wide range of elements detected in tephra layers makes the μ -
452 XRF scanning approach a possible future tool for refining tephra correlation work in which traditional
453 methods have failed to establish unambiguous correlations between given layers. This is partly the
454 case with strong inhomogeneity in the 30+ basaltic tephra layers encountered in the AVF (Hopkins et
455 al., 2015; 2017). Volcanic hazard assessment for Auckland city with >1.5 million inhabitants and
456 infrastructure of national importance largely depends on correct tephra correlation and age
457 estimates of tephra layers produced by eruptions from the AVF volcanoes.

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470 Conflict of Interest

471 The authors report no conflict of interest.

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Figure 1: Auckland Volcanic Field (left) with maar craters of this study highlighted in red and its position in New Zealand's North Island (right) in relation to the volcanic sources of the tephra layers found in the Auckland maars and wider New Zealand area: Tuhua (TUV, peralkaline rhyolitic), Taupo (TV, rhyolitic) and Okataina (OV, rhyolitic), Egmont (Eg volcano, andesitic), Tongariro (TgV, andesitic) and Auckland Volcanic Field (AVF, basaltic). VC: volcanic centre.

Figure 2: Variation of ten normalised elemental counts from μ -XRF core scanning across (A) six pre-KOT layers and (B) seven post-KOT layers alongside their optical core images. Note the contrast in μ -XRF data between enclosing sediment and rhyolite tephra layers.

Figure 3: Kernel density of normalised elemental counts of all 13 tephra layers analysed. Note how most elements approximate a log-normal distribution.

Figure 4: Kernel density of K_{norm} (up), Ca_{norm} (center), and Sr_{norm} (bottom) of all tephra μ -XRF core scanning data. Coloured lines differentiate between pre-identified tephra layers. Line pattern differentiates between Itrax lab locations of respective μ -XRF data. Note how, for example, the Tahuna tephra shows very different peaks depending on the scanning location whereas the Sr_{norm} peaks of the Rotoma tephra from UOA and UA almost overlap.

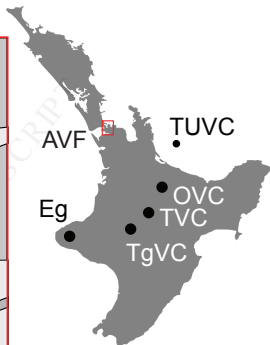
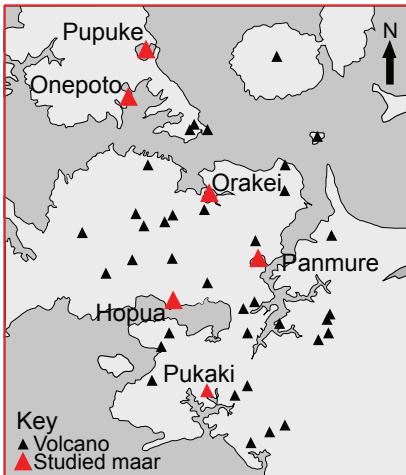
Figure 5: Principal component analysis of (A) log-ratio-transformed μ -XRF scanning results from the Onepoto core (pre-KOT) measured at ANSTO; (B) log-ratio-transformed μ -XRF scanning results from the Hopua core (post-KOT) measured at the University of Auckland; (C) and non-transformed μ -XRF scanning results as in B. Note how the log-transformed data plots in clusters with a larger spread of the datapoints than not transformed data. The log-transformed data also does not capture a cluster of the Tuhua tephra whereas not transformed data results in narrower clusters and captures clearly separated clusters for the Tuhua and Rotoma tephras.

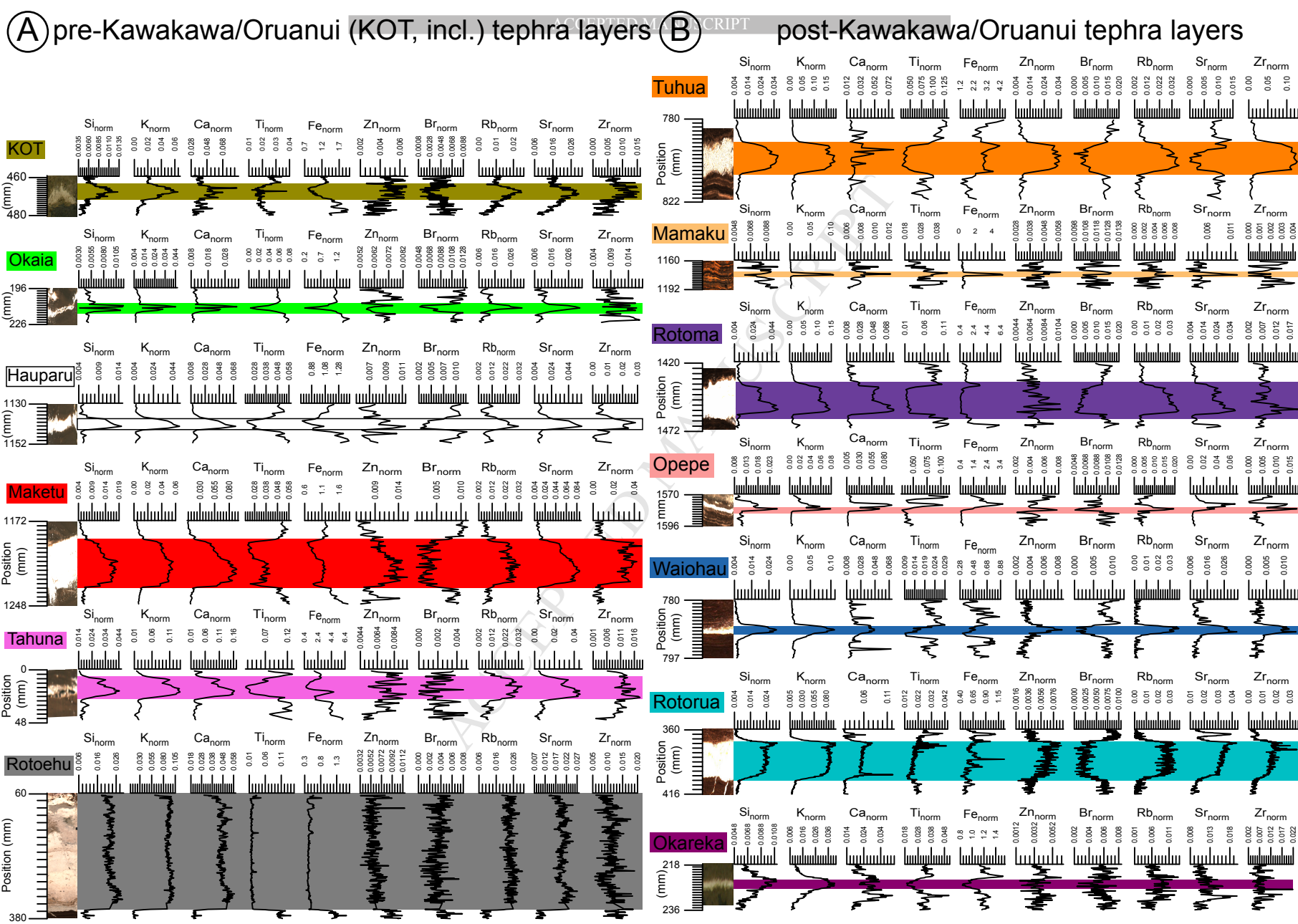
Figure 6: Principal component analysis of (A) log-ratio-transformed μ -XRF scanning results from the rhyolitic tephra layers in the Onepoto core (pre-KOT) measured at ANSTO; (B) log-ratio-transformed μ -XRF scanning results from the rhyolitic tephra layers in the Hopua and Panmure cores (post-KOT) measured at UOA. Note how all thicker tephra layers with >50 data points (Rotoehu, Maketu, Rotorua, Rotoma, Tuhua) form clear clusters.

Figure 7: Linear discriminant analysis of (A) log-ratio-transformed μ -XRF scanning results from the rhyolitic tephra layers in the Onepoto core (pre-KOT) measured at ANSTO; (B) log-ratio-transformed μ -XRF scanning results from the rhyolitic tephra layers in the Hopua and Panmure cores (post-KOT) measured at the University of Auckland. Note that LD2 enables discrimination between the source

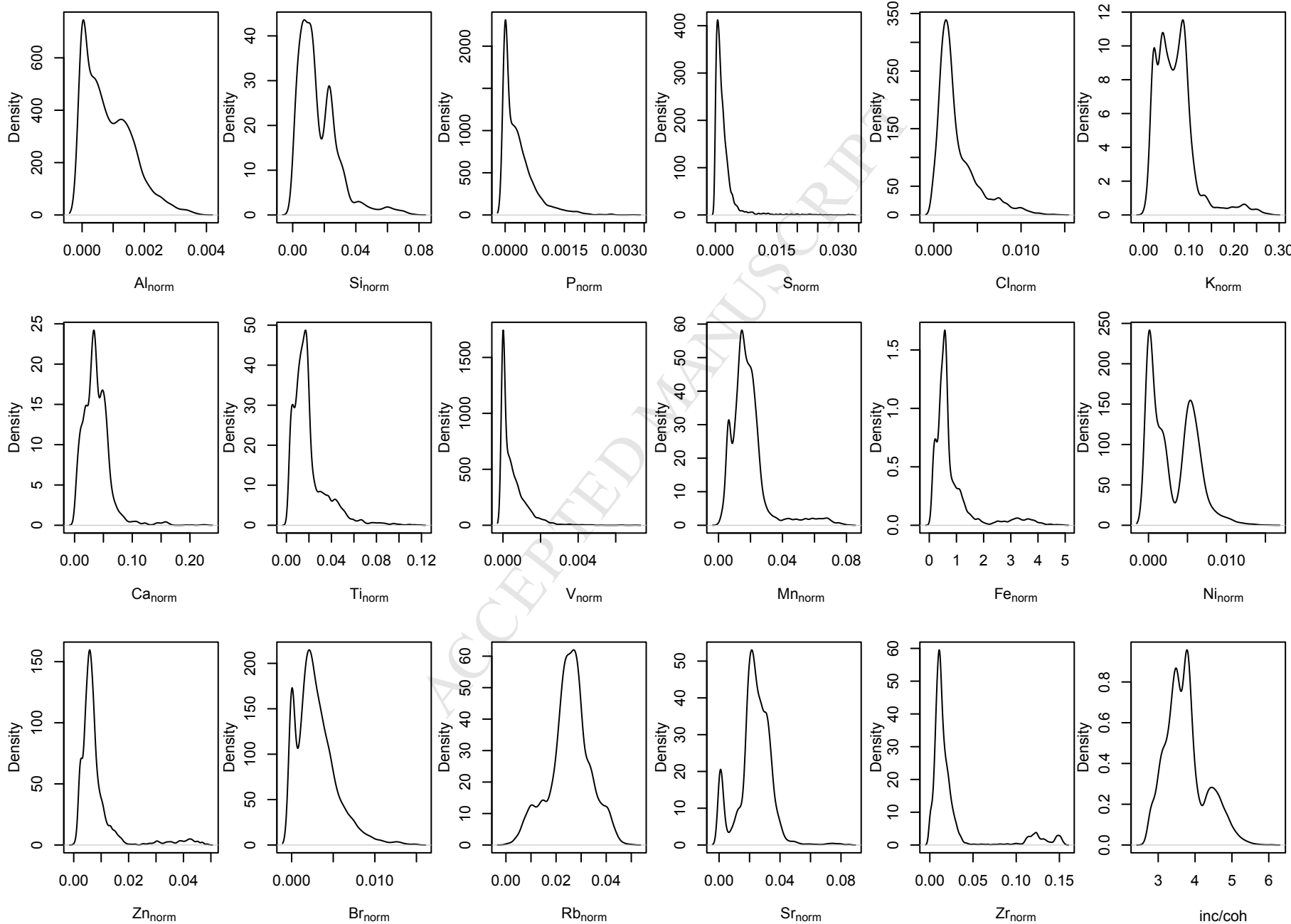
volcanic centres (TVC and OVC) in (A) and LD1 separates TU vs. TVC+OVC, whilst LD3 separates TVC vs. OVC+MI in (B). Black arrows mark the direction of relative enrichment of elements listed.

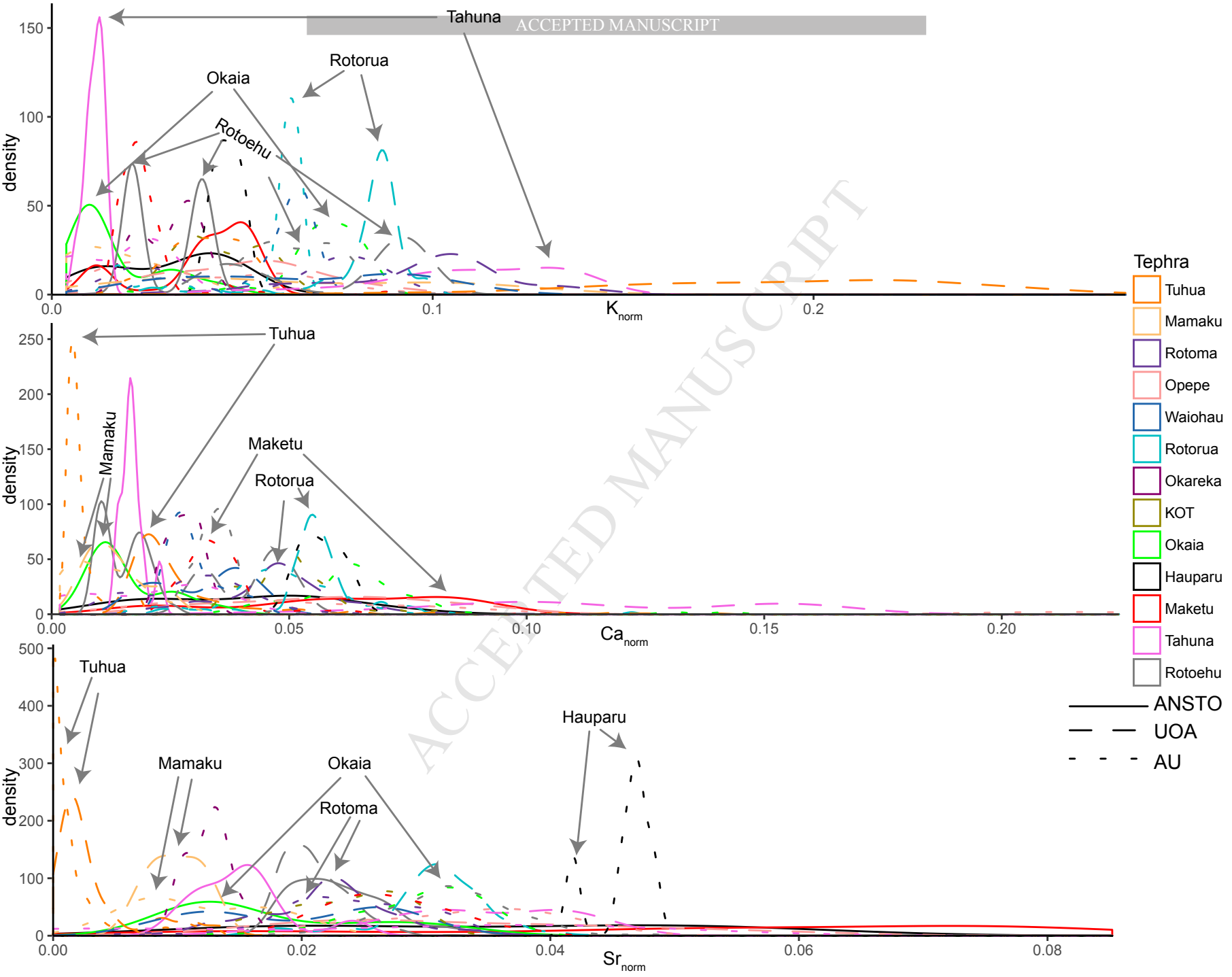
Figure 8: Bivariate scatter plots of six elemental ratios of (A) log-transformed μ -XRF scanning results from the rhyolitic tephra layers in the Onepoto core (pre-KOT) measured at ANSTO; (B) log-transformed μ -XRF scanning results from the rhyolitic tephra layers in the Hopua and Panmure cores (post-KOT) measured at the University of Auckland. Note how most plots allow for clear separation of the thicker tephra layers (Okaia, Maketu, Rotoehu in (A); Tuhua, Rotoma, Opepe and Rotorua tephra in (B)).





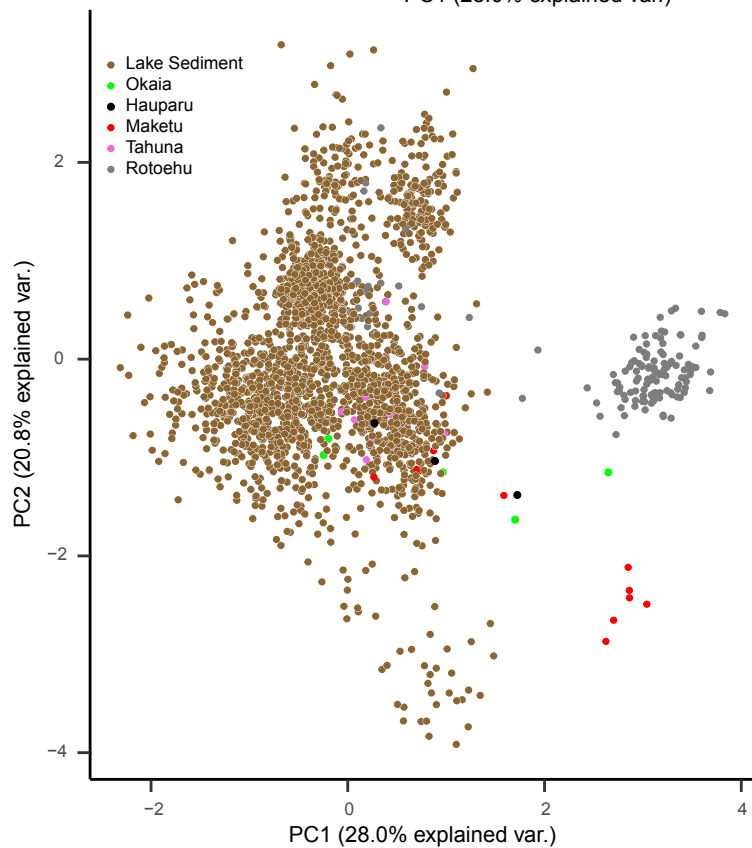
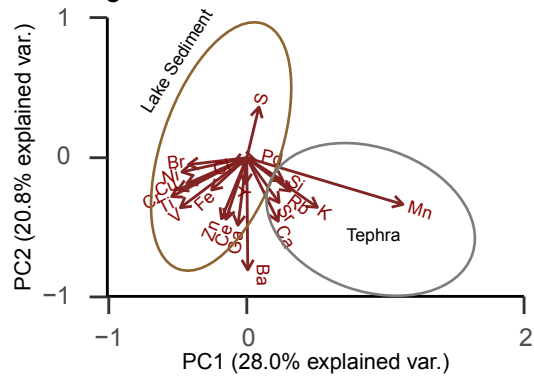
Kernel density plots of elements X_{norm} and inc/coh scattering ratio
(all 13 tephra layers, all measurements, not transformed)



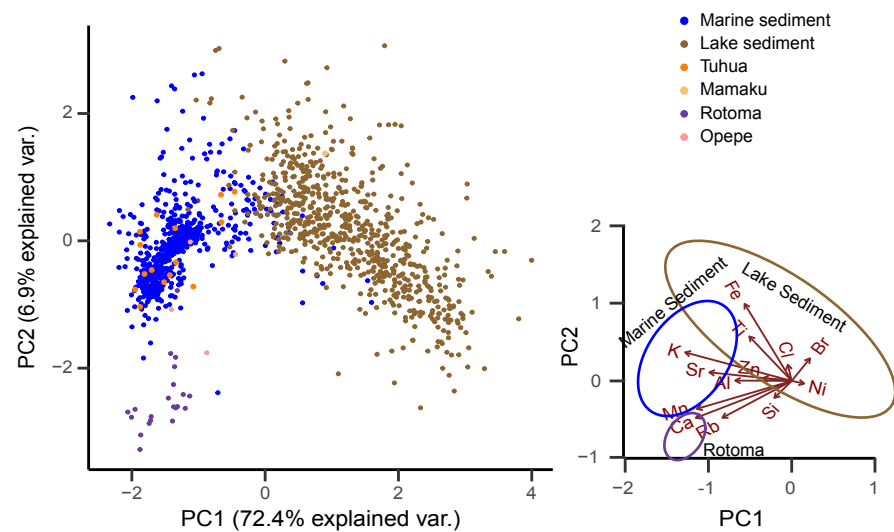


(A)

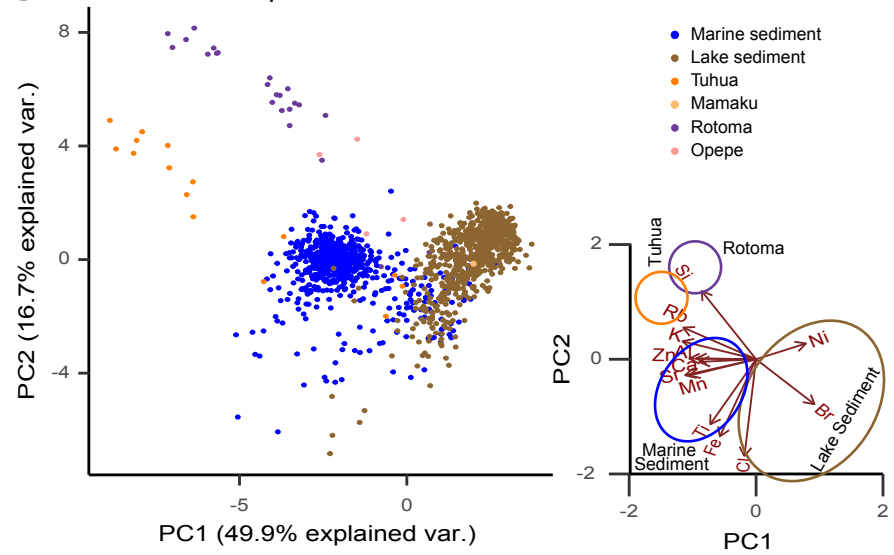
Onepoto (measured at ANSTO);
pre-KOT; log-ratio transformed

**(B)**

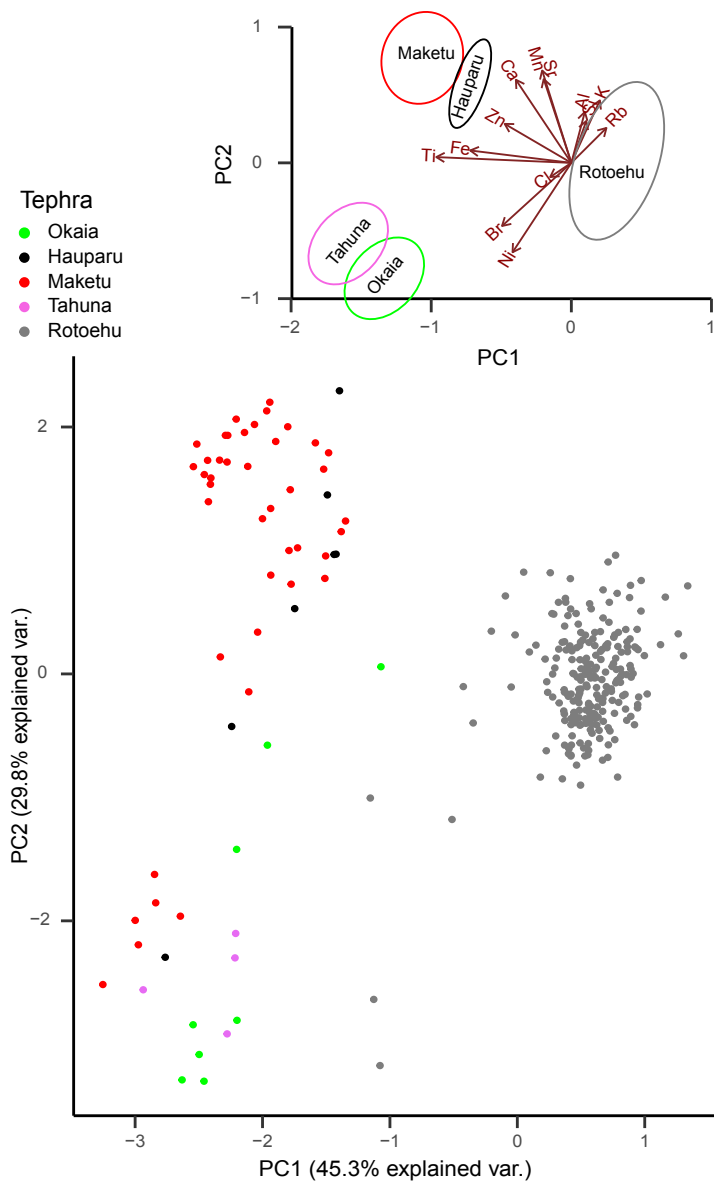
Hopua (measured at Auckland);
post-KOT; log-ratio transformed

**(C)**

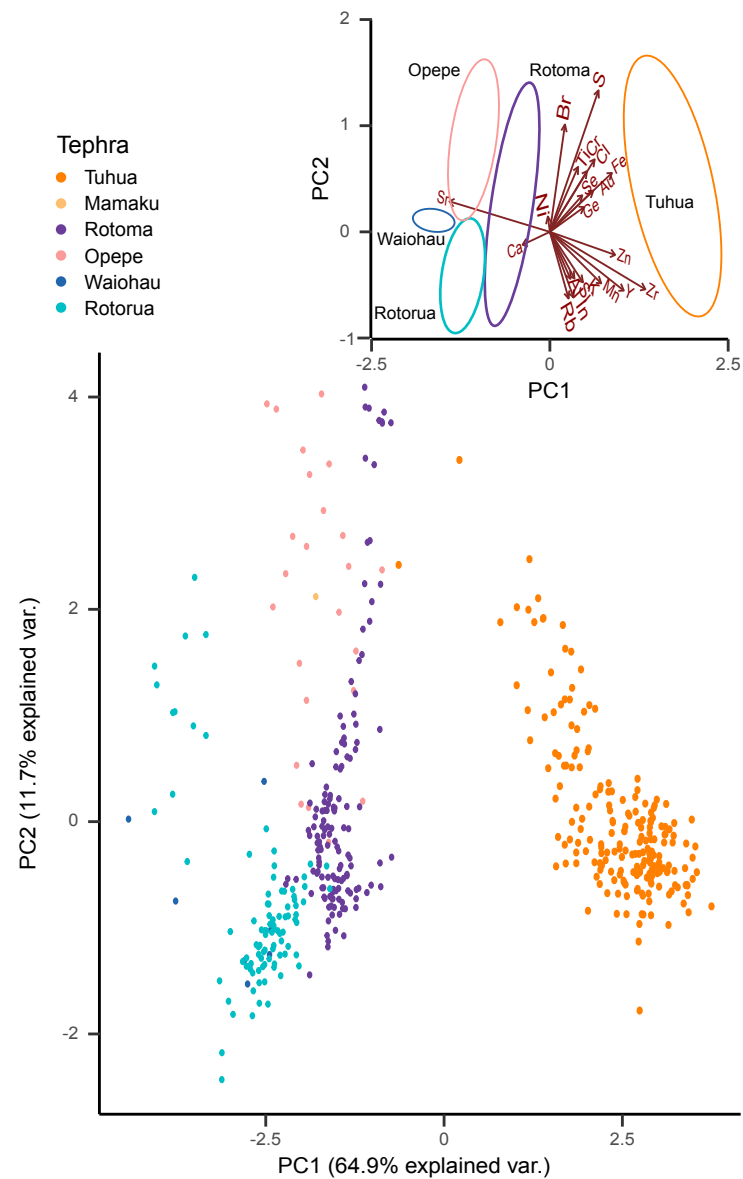
Hopua (measured at Auckland);
post-KOT; not transformed



(A) Rhyolitic tephras in Onepoto (measured at ANSTO); pre-KOT; log-ratio transformed

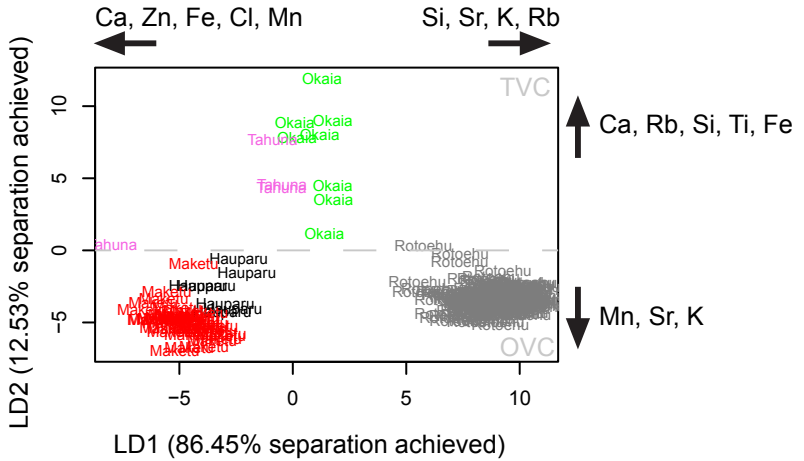


(B) Rhyolitic tephras in Hopua and Panmure (measured at Auckland); post-KOT; log-ratio transformed



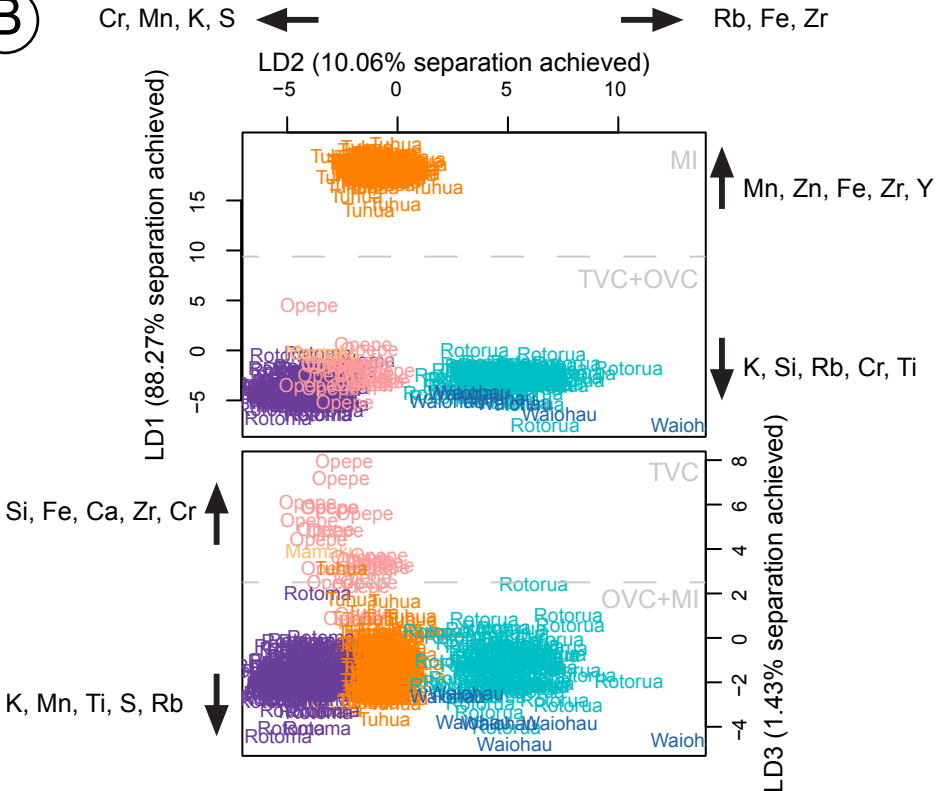
Rhyolitic tephros in Onepoto (measured at ANSTO);
pre-KOT; log-ratio transformed

(A)



Rhyolitic tephros in Hopua and Panmure (measured at Auckland);
post-KOT; log-ratio transformed

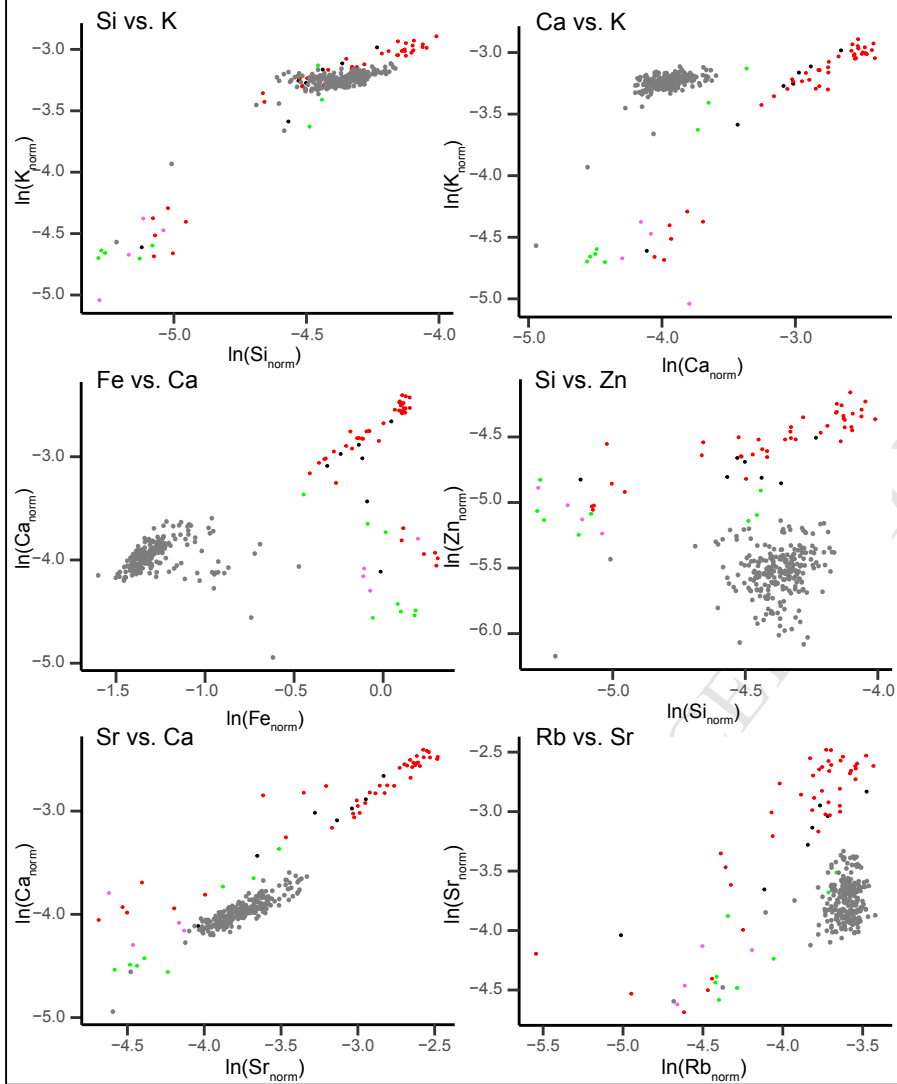
(B)



(A) Rhyolitic tephras in Onepoto (measured at ANSTO);
pre-KOT; log-ratio transformed

Tephra

● Okaia ● Hauparu ● Maketu ● Tahuna ● Rotoehu



(B) Rhyolitic tephras in Hopua and Panmure (measured at Auckland);
post-KOT; log-ratio transformed

Tephra

● Tuhua ● Mamaku ● Rotoma ● Opepe ● Waiohau ● Rotorua

