

1 Tephrochronology in Aotearoa New Zealand

2
3
4 Jenni L. Hopkins*¹, David J. Lowe², Joanna L. Horrocks³

5 *Corresponding author: jenni.hopkins@vuw.ac.nz

6
7
8 ¹School of Geography Environment and Earth Science, Victoria University of Wellington, P.O. Box 600,
9 Wellington, New Zealand 6140

10 ² School of Science/Te Aka Mātuatua, University of Waikato, Private Bag 3105, Hamilton 3240, New
11 Zealand 3240

12 ³Earthquake Commission, P.O. Box 790, Wellington, New Zealand 6140

13
14
15
16
17
18 Revised text 1 April 2021 (proofs stage). See final journal article for definitive version.

19 IAVCEI special issue on NZ volcanism (North Island), *NZ Journal of Geology & Geophysics* vol. 64 (2)

20 Accepted for publication 22 March 2021

21
22
23 *Citation:* Hopkins, J.L., Lowe, D.J., Horrocks, J.L. 2021. Tephrochronology in Aotearoa New Zealand.

24 *New Zealand Journal of Geology and Geophysics* 64 (2), p. x-y.

25 <https://doi.org/10.1080/00288306.2021.1908368>

29 **Abstract**

30 Tephra deposits in Aotearoa New Zealand (ANZ) have been studied for >180 years. The now-global
31 discipline of tephrochronology, which has some developmental roots in ANZ, forms the basis of a
32 powerful chronostratigraphic correlational tool and age-equivalent dating method for geological,
33 volcanological, palaeoenvironmental, and archaeological research in ANZ. Its utility is founded on
34 the key principle that tephra or cryptotephra provide widespread isochrons in many different
35 environments. In the first part of this article, we summarise the history of tephra studies in ANZ and
36 then describe how tephra have been mapped, characterised, and correlated using field and laboratory-
37 based methods. We document advances in geochemical fingerprinting of glass; tephra/cryptotephra
38 detection and correlation by sediment-core scanning methods (e.g. X-radiography, CT imaging, XRF
39 elemental analysis, magnetic susceptibility); statistical correlation methods; and dating of
40 tephra/cryptotephra. We discuss the advent of ANZ cryptotephra studies (from mid-1970s) and their
41 more-recent growth. The second part comprises examples of applications of tephrochronology in
42 ANZ: climate-event stratigraphy (NZ-INTIMATE project); eruptive-event stratigraphy in the
43 Auckland Volcanic Field; developments in the marine tephra record; advances in identifying,
44 correlating, and dating old (pre-50 ka) tephra and weathered-tephra deposits; forming soils/paleosols
45 on tephra; tephra and archaeology; Kopouatai bog tephrostratigraphy and palaeoenvironments; and
46 volcanic-hazard assessments.

47

48

49

50 **Keywords**

51 Tephra, volcanic ash, tephrochronology, cryptotephra, stratigraphy, glass shards, fingerprinting,
52 EPMA, LA-ICP-MS, tephra mapping and analysis, statistical correlation, geochronology, age
53 modelling, radiocarbon, radiometric dating, archaeology, upbuilding pedogenesis, weathered tephra,
54 volcanic hazards, TVZ, CVZ, Rotoehu Ash, Kawakawa/Oruanui tephra, Taupō tephra, history of
55 science, New Zealand

56

57

58

59 Introduction

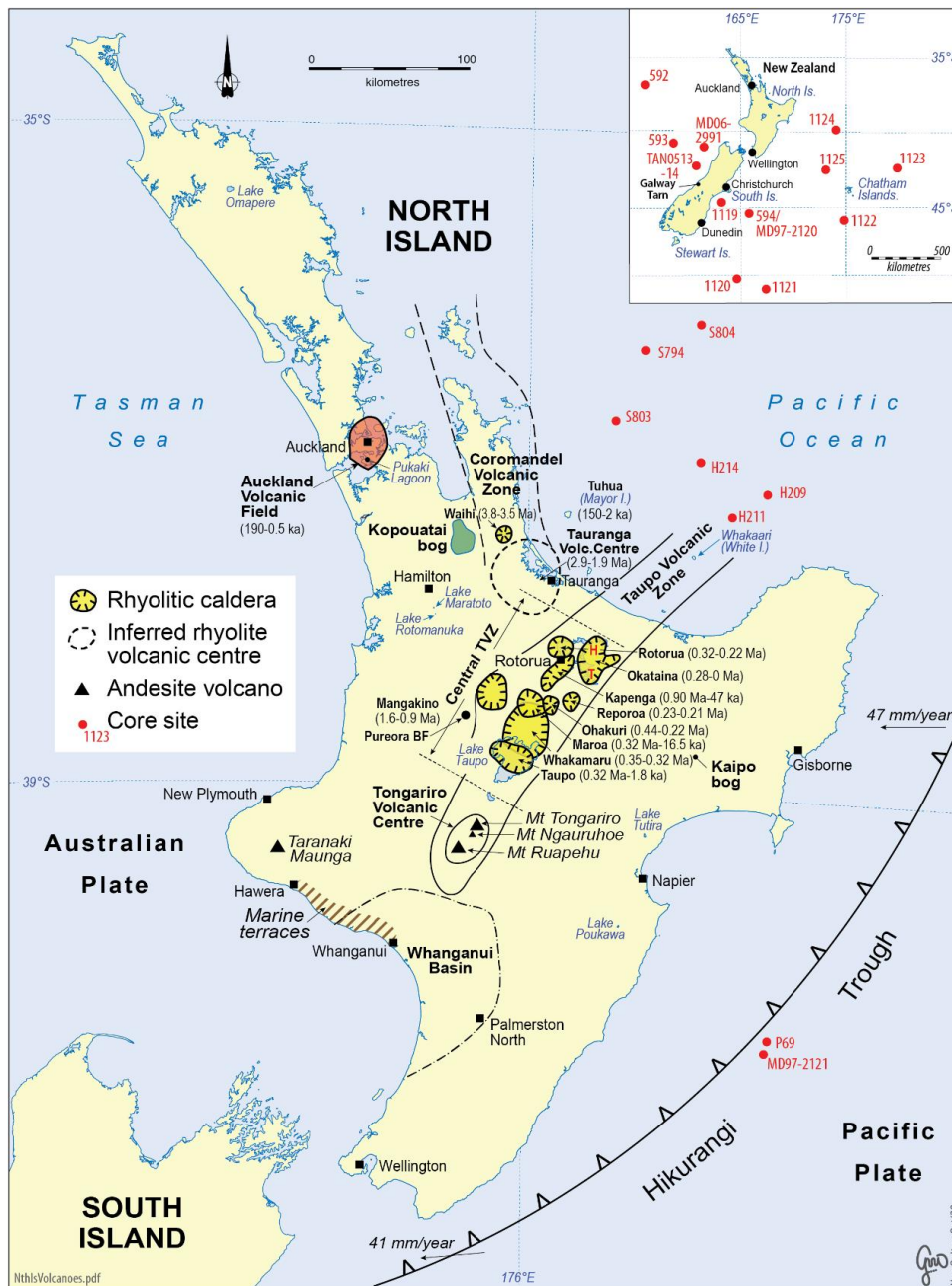
60 The term ‘tephra’ (from the Greek word τέφρα meaning ‘ash’ or ‘ashes’) includes all the explosively-
61 erupted, unconsolidated, fragmental (pyroclastic) products of a volcanic eruption. ‘Cryptotephra’ are
62 sparse, ash-sized glass-shard and/or crystal concentrations preserved in sediments (including ice) or
63 soils but insufficiently numerous to be visible as a layer to the naked eye (Lowe 2011).

64 ‘Tephrochronology’ (*sensu stricto*) is a correlational and dating method that uses characterised tephra
65 or cryptotephra deposits as isochronous (time-parallel) beds to link or synchronise geological,
66 palaeoenvironmental, or archaeological sequences or events, and to transfer and apply relative or
67 numerical ages to them using the tephra/cryptotephra compositional ‘fingerprints’ in combination
68 with stratigraphic superpositioning. ‘Tephrochronology’ (*sensu lato*) is also used as a portmanteau
69 term for all aspects of tephra or cryptotephra studies, and their application including volcanology
70 (Lowe 2008, 2011), which is the usage adopted for the title of this paper.

71 Fingerprinting is commonly undertaken through either the tephra’s physical properties in the
72 field or by characterising it through laboratory analysis, including mineralogy or glass-shard or crystal
73 chemical composition, or a combination of these methods (Lowe et al. 2017). When accurately
74 identified, relative or numerical ages can then be transferred between sites to build chronologies
75 underpinned by the tephra or cryptotephra isochrons. Ages are most commonly obtained through
76 either indirect radiometric methods (e.g. radiocarbon, ^{14}C , of entrained or encapsulating organic
77 deposits), direct radiometric dating on crystals (e.g. Ar/Ar analysis), incremental methods (e.g.
78 layering in ice cores or tree rings), or age-equivalence methods (e.g. palaeomagnetism), together
79 increasingly with applications of modelling methods including Bayesian age-depth modelling and ^{14}C
80 wiggle-matching.

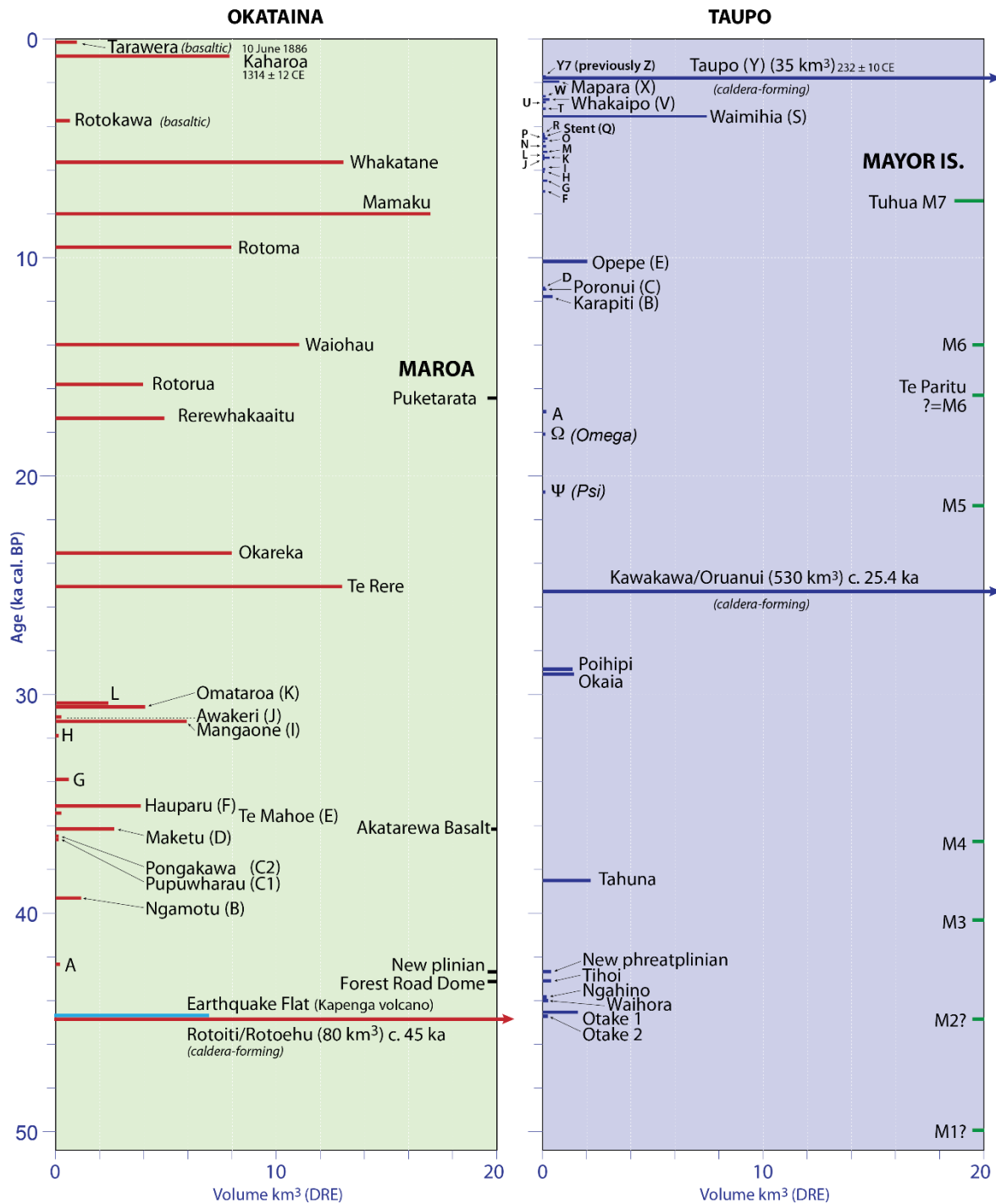
81 Aotearoa New Zealand (ANZ hereafter) has an extensive history of explosive volcanic
82 activity with relatively localised basaltic and more widely-dispersed andesitic events punctuated by
83 powerful rhyolitic events occurring from at least 24 Ma to the present in North Island (Houghton et al.
84 1995; Wilson et al. 1995, 2009; Briggs et al. 2005; Lowe et al. 2008a; Wilson and Rowland 2016;
85 Barker et al. 2021; Pittari et al. 2021). The most recent explosive activity since ~4 Ma has occurred at
86 centres in the southern Coromandel Volcanic Zone (CVZ) and Taupō Volcanic Zone (TVZ), with the
87 locus of activity since ~2 Ma in the TVZ and at Taranaki Maunga (previously known as Mt Taranaki
88 or Mt Egmont) and Mayor Island (Tuhua Volcanic Centre) (**Fig. 1**). (Other centres of active
89 volcanism in central North Island are described by Pittari et al. 2021; broad overviews of volcanism in
90 ANZ are provided by Hayward 2017; Shane 2017; and Mortimer and Scott 2020.) The eruptions have
91 been responsible for blanketing the landscape surrounding the volcanoes with both pyroclastic-flow
92 and widespread tephra-fall deposits, the distributions of which are governed by a number of factors
93 including eruption volume, mass eruption rate and temperature, eruption column height, particle sizes,

94 strength and direction of wind at the time of the eruption, and radius of the umbrella cloud (e.g.
 95 Alloway et al. 2013; Cashman and Rust 2016; Barker et al. 2019; Constantinescu et al. 2021).
 96



97
 98 **Figure 1.** Map of Te Ika-a-Māui/North Island showing the locations and ages of most of the main tephra-
 99 producing calderas, volcanic centres, fields, or stratovolcanoes (cones) active during the Quaternary or
 100 shortly before (mainly after Briggs et al. 2005; Wilson et al. 2009; Julian 2016; Hopkins et al. 2020a;
 101 Pittari et al. 2021). The calderas in central Taupō Volcanic Zone (TVZ) are overwhelmingly rhyolitic with
 102 Mangakino and Taupō being supervolcanoes; Taranaki Maunga and Tongariro Volcanic Centre are
 103 andesitic; Tuhua (Mayor Island) is peralkaline rhyolite; and the locally distributed tephras from Auckland
 104 Volcanic Field are basaltic. Other important volcanoes or volcanic fields of Quaternary age are reported by
 105 Pittari et al. (2021). The plate tectonic setting (Leonard et al. 2010) and various other features are also
 106 shown, including marine core locations in which tephra-fall deposits (including some cryptotephras) have
 107 been recorded (Pillans and Wright 1992; Carter et al. 1995, 2003, 2004; Alloway et al. 2005; Allan et al.
 108 2008; Hopkins et al. 2020b). BF, buried forest; H, Haroharo Volcanic Complex; T, Tarawera Volcanic
 109 Complex.

110 Rhyolitic (silica-rich) eruptions are generally the most voluminous and explosive and the
111 tephra deposits from these eruptions are the most pervasive in the New Zealand geologic record (**Fig.**
112 **2**). For example, the Kawakawa/Oruanui tephra was erupted from Taupō volcano c. 25,400 calendar
113 (cal) yr BP (Vandergoes et al. 2013) and it forms an extensive isochron linking terrestrial, lacustrine,
114 and marine sequences in New Zealand (e.g. Pillans et al. 1993; Carter et al. 1995; Newnham et al.
115 2007a, 2007b; Alloway et al. 2013; Van Eaton and Wilson 2013; Van Eaton et al. 2013; Harper et al.
116 2015; Hopkins et al. 2017), and beyond, including the Chatham Islands and Antarctica (Holt et al.
117 2010; Dunbar et al. 2017). The Kawakawa/Oruanui tephra is the only New Zealand-derived tephra to
118 be definitively identified via glass-shard composition thus far in a polar ice sheet. The presence of
119 Taupō tephra (of 232 ± 10 AD) in both Greenland and Antarctica ice sheets has been inferred from
120 sulphate spikes of appropriate age by Sigl et al. (2013) and Winstrup et al. (2019), but no glass shards
121 have yet been reported.
122



123
 124
 125
 126
 127
 128
 129
 130
 131
 132
 133

Figure 2. Stratigraphy, ages, and volumes (dense-rock equivalent, DRE) of eruptives derived from three rhyolitic centres in central TVZ (Okataina, Taupō, Maroa), and from Mayor Island (Tuhua), since ~50 cal ka. One eruptive (Earthquake Flat) from Kapenga Volcanic Centre is additionally depicted within the early eruptives of the Okataina sequence. Mainly after Shane et al. (2006) and Wilson et al. (2009) with updated information from Danišik et al. (2012, 2020), Barker et al. (2021), and Peti et al. (2021). See also supplementary materials (SM) **Table SM1**.

134 Although tephra studies in ANZ have been reviewed previously (see below), it is timely to
135 provide an update on recent advances, both methodological and scientific. The rest of this article is in
136 two parts. In PART 1 we examine tephra studies generally and identify recent advances. We initially
137 outline the history of tephra studies in ANZ, and then describe how tephtras have been mapped,
138 characterised, and correlated including at distal sites. We follow by discussing the advent and growth
139 of cryptotephra studies and finish with methods used to date tephtras and cryptotephtras. In PART 2 we
140 provide a selective series of applications and advances that highlight some of the most recent tephra-
141 related work undertaken in ANZ.

142 Although our review is focussed mainly on the rhyolitic tephra record, we document aspects
143 of the andesitic tephra record, and the basaltic tephtras of the Auckland Volcanic Field are also
144 examined briefly. For further coverage of recent studies on andesitic tephtras erupted from *Taranaki*
145 *volcano*, see Shane (2005), Platz et al. (2007a), Turner et al. (2009, 2011), Green et al. (2016),
146 Damaschke et al. (2017a, 2017b, 2018), Torres-Orozco et al. (2017a, 2017b), Lerner et al. (2019a,
147 2019b), and Cronin et al. (2021); for recent studies of tephtras from *Tongariro Volcanic Centre*, see
148 Moebis et al. (2011), Pardo et al. (2012), Heinrich et al. (2020), Pure et al. (2020), Voloschina et al.
149 (2020), and Leonard et al. (2021).

150 Previous reviews of tephrochronology (*sensu lato*) in ANZ, or global reviews that feature ANZ
151 examples, include those of McCraw (1975), Froggatt and Lowe (1990), Lowe (1990, 2008, 2011),
152 Shane (2000), Alloway et al. (2013), Lowe and Alloway (2015), Lowe et al. (2017), and Bonadonna et
153 al. (2020). A list of many of the key marker tephtras in ANZ erupted since ~3 Ma, their ages, and their
154 significance stratigraphically, volcanologically, or palaeoenvironmentally, is provided in Table SM1.

155 Numerous applications were not able to be covered, one example being the unique role of
156 tephrochronology in helping to disentangle complex geological deposits and events, such as
157 palaeoseismicity (including determining rates of fault movement, uplift, or subsidence, and
158 earthquake recurrence intervals), past geothermal activity, and landscape evolution in the tectonically
159 active, dynamic landscapes of the TVZ and elsewhere in North Island (e.g. Beanland et al. 1989;
160 Villamor et al. 2011; Hayward et al. 2015; Gómez-Vasconcelos et al. 2016; Persaud et al. 2016;
161 Loame et al. 2019). Tephtras have also been used very effectively in developing an understanding of
162 erosion and landsliding in hilly or coastal terrains (e.g. Cerovski-Darriau et al. 2014; Bilderback et al.
163 2015; Gomez and Rossiter 2017; Kluger et al. 2018). As well, both rhyolitic and andesitic tephra
164 deposits have helped facilitate the reconstruction of events pertaining to the development of
165 stratovolcanoes and associated ring plains, including debris avalanches, lahars, and soil formation
166 (pedogenesis) (e.g. McLeod et al. 2020; Proctor et al. 2020; Zemeny et al. 2021). Comprehensive
167 reviews of these and other emerging applications must await future syntheses.

168

169

170 **PART 1 – GENERAL ASPECTS AND ADVANCES**

171 **History of tephra studies in ANZ**

172 Tephra layers have been described and studied in ANZ since 1841. German naturalist and medical
173 doctor Ern(e)st Dieffenbach was the first to document a sequence of post-18 cal ka tephra and buried
174 soil horizons at Te Ngae near Lake Rotorua, which he visited from 4–14 June 1841 (Dieffenbach
175 1843). Of the sequence, he stated (p.392) “This is the general composition of the land around the lake,
176 and proves that the country was subject to successive volcanic eruptions”. Moreover, Dieffenbach
177 observed that the same tephra sequence was recognisable in different parts of Rotorua basin (Esler
178 2008). European geologists subsequently undertook reconnaissance and regional mapping, mainly of
179 hard rocks, but additionally noted that unconsolidated pyroclastic materials were widespread and they
180 commented on possible stratigraphic relationships and potential sources (Lowe 1990). In the Taupō
181 area, Hochstetter (1864, p.116) described some of the pyroclastic deposits as “volcanic fragmental
182 rocks” of rhyolitic composition. Later writers described the pumice deposits around Lake Taupō and
183 elsewhere in more detail. The historic eruption of Mt Tarawera on 10 June 1886, a basaltic
184 plinian fissure eruption of scoria followed by the eruption of fine, lithic-dominated ash and
185 phreatomagmatic ‘surge’ beds (Rotomahana Mud) (Nairn 1979; Walker et al. 1984; Rowe et al.
186 2021), resulted in publication of the first isopach map in ANZ (Thomas 1888), and made it clear that
187 other volcanoes must have erupted and spread “showers” of ash to distant parts of the North Island in
188 the recent past (e.g. Hill 1887).

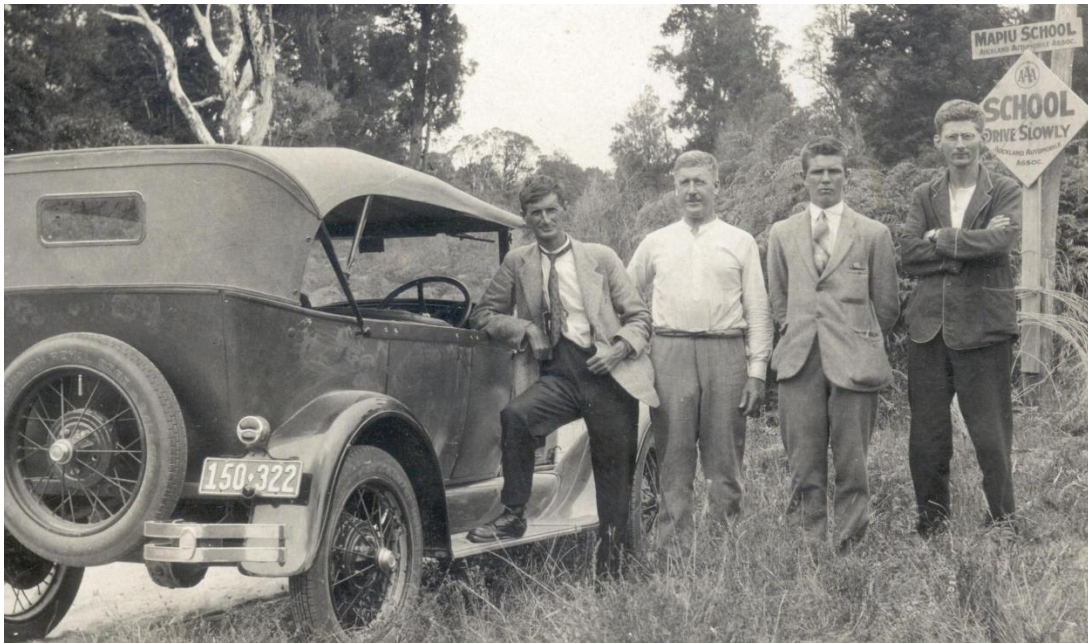
189 The first numerical age determined for a prehistoric tephra deposit was obtained in 1883 in
190 Taranaki by 19-year-old Arthur W.O. Burrell (reported in a presentation in 1917 to the Wanganui
191 Philosophical Society, and by Oliver 1931), who used dendrochronology to ascribe an eruption age of
192 ~1430 AD for the so-called Burrell tephra. This andesitic tephra was subsequently dated at ~1655 AD
193 by Druce (1966), who also dated eight other young Taranaki-derived tephra beds using ¹⁴C dating and
194 dendrochronology (Topping 1972; Lowe 1990).

195 The first application of tephrochronology as a dating tool was that of Oliver (1931) who used
196 the ~1430 AD tree-ring date for the Burrell tephra to provide a minimum age for a Māori oven (umu)
197 on Taranaki Maunga, and therefore the first minimum date for seafaring Polynesian arrival in ANZ
198 (Lowe et al. 2000).

199 Tephra mapping in central North Island began in the mid-1920s, close to the time (or slightly
200 before) studies of tephra layers as a tool for research began elsewhere (from ~1930) (Thorarinsson
201 1981; Alloway et al. 2013; Davies 2015). Leslie Issott Grange, who had served with the Corps of New
202 Zealand Engineers (Tunnelling Company) on the Western Front in World War I, started formal
203 mapping in TVZ in October 1926, motivated by two needs: (i) a volcanological survey to help define
204 likely volcanic hazards; and (ii) a survey of soil-forming tephra deposits, especially the widespread

205 rhyolitic pumice deposits of the Taupō (232 ± 10 AD) and Kaharoa (1314 ± 12 AD) eruptions, to try
206 to understand the so-called ‘bush sickness’ or ‘ill-thrift’ problem mainly in central North Island that
207 had resulted in numerous deaths of sheep and cattle (Grange 1929, 1931, 1937; Grange and Taylor
208 1932; Taylor 1933) (**Fig. 3**). The ill-thrift problem was subsequently identified (by Australian
209 researchers) in mid-1935 as a cobalt deficiency that was later found to cause a dearth of vitamin B12
210 (Hewitt et al. 2021). The ferromagnesian mineralogy of the deposits allowed four key volcanic source
211 areas to be recognised at the time: Taupō, Rotorua, Tongariro, and Taranaki (Lowe 1990).

212
213



214
215 **Figure 3.** Early tephra and soil mappers in the King Country in 1929 (from left): Leslie I. Grange,
216 Hartley T. Ferrar, J.A. Hurst, and Norman H. Taylor (photo courtesy of Manaaki Whenua-Landcare
217 Research).

218
219
220

221 One of the most prescient papers in these formative years was that of Berry (1928). James
222 Allan Berry (known as Allan) was a London-trained New Zealand surgeon who, after service on the
223 Western Front with the New Zealand Medical Corps in World War I, became medical superintendent
224 of Napier Hospital. As well as having an interest in fossil seal bones, Berry described the nature and
225 origin of accretionary lapilli (‘chalazoidites’) in the Scinde Island ash (recognised now as a fall unit of
226 the 25.4 cal ka Kawakawa/Oruanui tephra) preserved in loess on Bluff Hill, Napier (Berry 1928).
227 Remarkably, Berry was arguably the first person anywhere to enunciate that tephra layers could be
228 used to connect sequences from one place to the next by characterising the layers compositionally,
229 thereby providing stratigraphic isochrons (the foundation of tephrochronology) that would allow
230 palaeoenvironmental data associated with the layers to be compared spatially and temporally (Lowe

230 1990; see also Thorarinsson 1981). He presented his paper to the Hawke’s Bay Philosophical Society
231 on 20th August 1926. Specifically, Berry (1928, p.608) stated:

232 “...study of volcanic [ash] layers will acquire more importance as knowledge of them increases. In
233 an eruption, for example, in Miocene times, where volcanic material had covered a widespread
234 area of country, it seems extremely probable that much valuable information would be obtained as
235 to the contemporaneity of various deposits, and what effect influences such as climate, depth of
236 water, etc., have had in altering the fauna and flora, *if this particular volcanic deposit could be*
237 *identified by its continuity and its physical and chemical peculiarities.*” [italics added]
238

239 The first ¹⁴C date obtained in ANZ was on charcoal associated with the Taupō tephra (NZ-1,
240 1820 ± 150 ¹⁴C yr BP) (Fergusson and Rafter 1953), and was undertaken at the New Zealand (now
241 Rafter) Radiocarbon Laboratory. Further ¹⁴C-dating of tephra deposits followed, including early work
242 by Baumgart (1954) on Late-Holocene Taupō-volcano-derived eruptives. Numerous applications of
243 the ¹⁴C-method to tephra deposits, including via the Waikato Radiocarbon Laboratory that has
244 operated full-time since ~1980 (e.g. Hogg et al. 1987, 2019), continue to this day (see dating section
245 below).

246 The first late Quaternary tephrostratigraphic frameworks for central North Island and the
247 Taranaki region were developed increasingly systematically from the 1950s through to the 1970s (e.g.
248 Pullar 1959; Vucetich and Pullar 1964, 1969, 1973; Neall 1972; Pullar 1973; Topping 1973). The
249 studies were aided by the exposure of many new road cuttings made for access to the maturing exotic
250 forests that had been planted on the problematic Pumice Soils in the 1920s-1930s. Further details of
251 this remarkable tephrostratigraphic legacy are provided by Lowe (1990) and Lowe et al. (2008b).

252 The development of ‘fingerprinting’ methods for tephtras using laboratory-based analysis
253 began in the 1970s, typically in conjunction with stratigraphic and age data to help identify and
254 correlate medial and distal deposits (e.g. Cole 1970; Kohn 1970; Rankin 1973; Topping and Kohn
255 1973; Howorth and Rankin 1975). Prior to then, almost all mineralogical or geochemical analyses had
256 been undertaken on lavas, one notable exception being Ewart’s (1963) study. At the same time,
257 increasingly detailed studies relating to explosive volcanism and its products were developing
258 globally (e.g. Sparks et al. 1973; Walker 1973), and began burgeoning in ANZ from the late 1970s-
259 early 1980s with the catalytic arrival of global volcanologist George Walker, joined soon after by
260 Colin Wilson. Their work on Taupō volcano and its eruptives in particular (e.g. Walker 1980, 1981;
261 Wilson 1985, 1993, 2001; Wilson and Walker 1982, 1985; Houghton and Wilson 1986, 1989)
262 generated a plethora of globally-novel findings that are now regarded as archetypal for explosive
263 rhyolitic eruptions (Barker et al. 2021; Lowe and Pittari 2021).

264 The new studies involving laboratory work to facilitate tephra correlations relied initially on
265 ferromagnesian mineralogical assemblages (e.g. Cole 1970; Green and Lowe 1985; Froggatt and
266 Solloway 1986; Lowe 1988a; Froggatt and Lowe 1990) along with bulk analyses of Fe-Ti oxides (e.g.
267 Kohn 1970; Kohn and Neall 1973; Hogg and McCraw 1983; Lowe 1986b). Kohn’s seminal (1970)
268 paper was the first globally to show that trace elements in titanomagnetite in tephtras could be used as

269 a correlational tool. As well as revising or refining the proximal tephrostratigraphy associated with
270 particular volcanic centres (e.g. Kohn and Neall 1973; Howorth 1975; Vucetich and Howorth 1976;
271 Buck et al. 1981; Froggatt 1981), the analytical studies on distal tephra deposits in environments
272 favourable for preservation, such as lake sediments and peat bogs, enabled an integrated record of
273 interdigitating tephtras from multiple volcanic sources to be compiled (Lowe 1986a, 1988a, 1988b;
274 Froggatt and Rogers 1990) as well as allowing distal deposits to be characterised and identified (e.g.
275 Nelson et al. 1985; Mew et al. 1986; Hodder et al. 1991). Thus volcanologically-focussed applications
276 pertaining to tephra studies (as well as geological, palaeoenvironmental, and archaeological
277 employment) have long been important in ANZ (Baumgart and Healy 1956; Kohn and Vucetich
278 1974). The studies on thin distal tephtras morphed into the first cryptotephra-based research in ANZ
279 from the mid-1970s to early 1980s. These topics are covered in more detail below.

280 A key development has been the advent of single-particle methods including grain-by-grain
281 analyses of glass shards using refractive indices (Hodder and Wilson 1976; Hodder 1978). The
282 acquisition of an electron probe (JEOL JXA-733 Superprobe) in 1979 by Victoria University of
283 Wellington (VUW) enabled Paul Froggatt to develop the first protocols for undertaking major
284 elemental analysis of individual glass shards using electron-probe microanalysis (EPMA) (Froggatt
285 and Gosson 1982; Froggatt 1983, 1992). Such analyses effectively replaced the refractive indices
286 approach. The advantages of grain-discrete analyses compared with those of bulk separates are well
287 known (e.g. Hodder and Wilson 1976; Westgate and Gorton 1981; Froggatt 1992; Lowe 2011), and
288 EPMA is now the foundation technique for many tephra/cryptotephra studies in ANZ and elsewhere
289 (Shane 2000; Turney et al. 2004; Platz et al. 2007b; Kuehn et al. 2011; Pearce et al. 2014; Lowe et al.
290 2017). Froggatt's methods for glass analysis in ANZ, built on the pathfinding work of Smith and
291 Westgate (1969), allowed tephrochronology to be applied more effectively than before (such as when
292 field evidence alone was used) to many new disciplines (e.g. see Lowe 1990, 2008, 2014). Current
293 protocols for analysing glass using EPMA in ANZ, including beam width, standards, optimal numbers
294 of shards to be analysed, the need to normalise glass-derived major-element data, and so on, are
295 documented in Hopkins et al. (in press) with further details provided by Kuehn et al. (2011) and Lowe
296 et al. (2017).

297 Analyses of individual crystals (mineral grains) using EPMA were also undertaken for
298 correlational purposes, including of pyroxene (Froggatt and Solloway 1986; Lowe 1988b; Froggatt
299 and Rogers 1990), olivine (Donoghue et al. 1991), biotite (Shane et al. 2003a, 2003b), hornblende
300 (Froggatt and Rogers 1990; Cronin et al. 1996b; Donoghue and Neall 1996), and, especially, Fe-Ti
301 oxides (e.g. Froggatt and Solloway 1986; Lowe 1988b; Cronin et al. 1996a, 1996b; Donoghue and
302 Neall 1996; Shane 1998; Shane and Zawalna-Geer 2011; Damaschke et al. 2017b).

303 Trace elemental analyses (including rare-earth elements) of individual glass shards have been
304 much slower to develop than those involving major elements and have not been widely

305 employed (Shane 2000). The first papers using laser-ablation inductively coupled plasma mass-
306 spectrometry (LA-ICP-MS) of individual glass shards (not bulk glass) for tephra characterisation and
307 correlation in ANZ include those of Shane et al. (1998b), Nairn et al. (2004), Smith et al. (2004),
308 Allan et al. (2008) and Pearce et al. (2008). Such trace element applications are now accelerating (e.g.
309 Hopkins et al. 2015, 2017, 2020b), and Hopkins et al. (in press) have developed the first systematic
310 and comprehensive dataset for both major and trace elements in glass shards derived from a wide
311 range of prominent ANZ tephtras.

312

313 **Mapping, characterising, and correlating tephtras and cryptotephtras**

314 *Mapping tephtras and cryptotephtras*

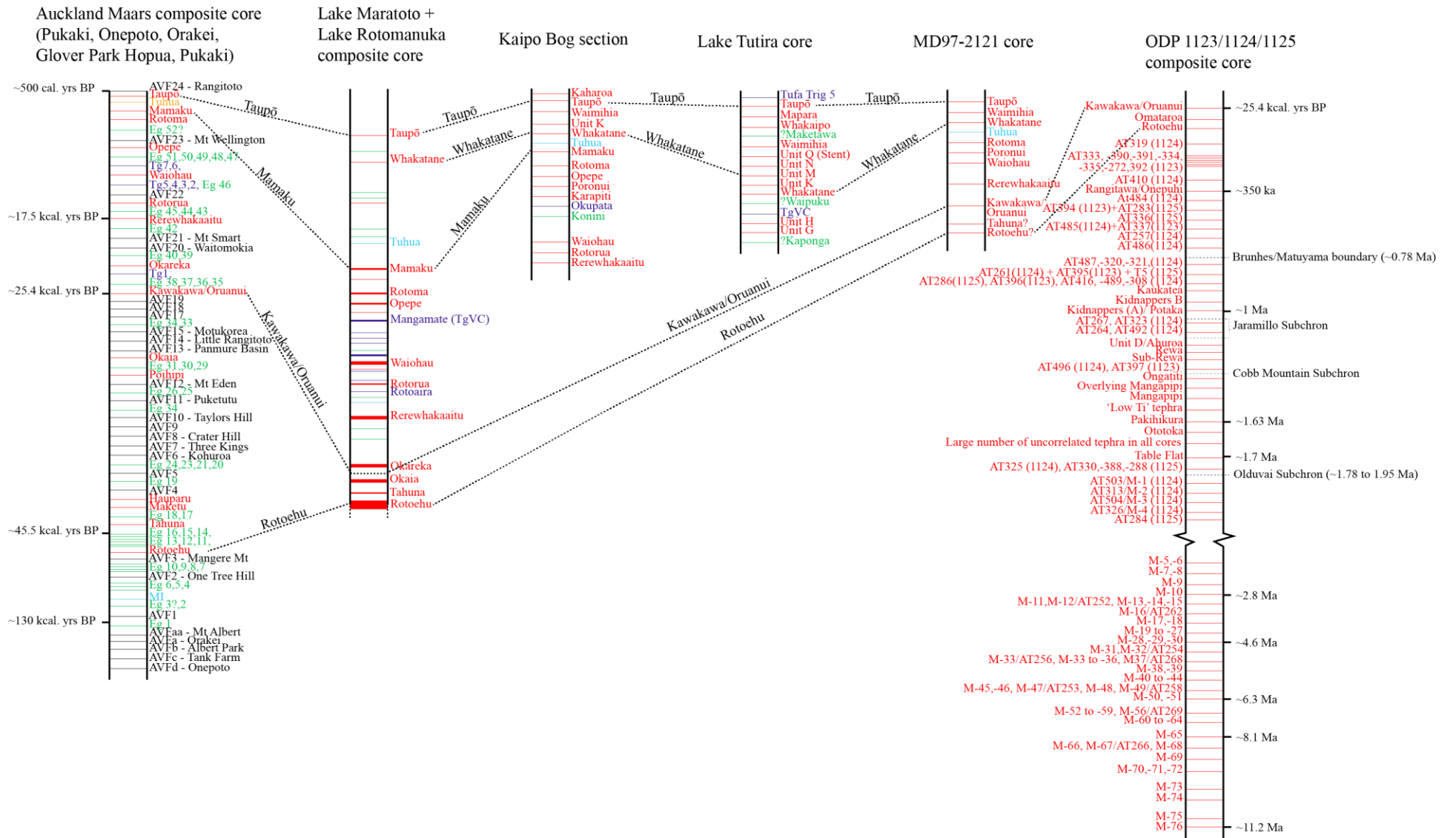
315 Tephtra mapping was dominated by stratigraphic field methods until the 1970s when (as noted above)
316 laboratory-based methods, including radiometric dating, began to inform and augment field-derived
317 data (Lowe 1990). In the field, the main approach was (and still is) the so-called ‘hand-over-hand’
318 method whereby relatively thick sequences of tephtras at metre-to-decimetre scale were traced
319 between successive road cuts or outcrops using stratigraphic relationships in conjunction with the
320 physical properties and morphologies of the tephtras including their overall colour, bedding
321 characteristics, pumice density and colour, and mineral componentry (such as the presence or not of
322 biotite, for example) (Froggatt and Lowe 1990). Associated loess deposits or buried soil horizons
323 were also used, together with distinct marker beds, to provide a basis to correlate units across
324 distances of tens of kilometres and up to about 150 km (e.g. Vucetich and Pullar 1969; Pullar and
325 Birrell 1973a). However, this method is limited by the degree of preservation of the tephtra layers and
326 their tendency to thin away from source exponentially with the attendant loss of identifying
327 characteristics (including a loss of mineralogic diagnostic features because of aerodynamic sorting of
328 minerals; e.g. Cashman and Rust 2016), and the masking effects of post-depositional erosion, mixing
329 (e.g. via bioturbation), and weathering in the near-surface soil-forming environment (Lowe 1986b,
330 1988a, 2011; Alloway et al. 1992, 1995; Donoghue et al. 1995). Vucetich and Pullar (1969)
331 commented that pedological features (such as buried soil horizons) associated with distal tephtras
332 could be somewhat variable and hence not necessarily diagnostic on their own.

333 An associated problem relates to the development of soil horizons on tephtras, which have
334 then been buried by subsequent deposits, and what the pedogenic modification might mean
335 stratigraphically. Vucetich and Pullar (1964) measured tephtra thickness from the base of one unit to
336 the base of the next – i.e. including any pedogenically altered soil material at the top of each unit.
337 Wilson (1993) and others recognised that sometimes this practice (especially in the earlier studies)
338 resulted in tephtric loess, reworked materials, andesitic tephtras and even previously unrecognized
339 tephtras being included in tephtra thicknesses then used in constructing isopach maps (e.g. Vucetich
340 and Pullar 1964, 1969; Pullar and Birrell 1973b; Birrell 1974). Consequently, Wilson (1993) took a

341 different approach in his revision of the stratigraphy of post-Kawakawa/Oruanui Taupō-derived
342 tephtras and specifically excluded the weathered or soil material at the top of each unit that he could
343 not be certain was (a modified) part of the eruptive. This approach poses difficulties for geoscientists
344 working in medial to distal regions where many deposits may be weathered to some degree because of
345 their modification via upbuilding pedogenesis (discussed in the section below on soil formation on
346 tephtras). Note that buried soil horizons, even when only very weakly weathered, mark soil formation
347 that took place when the tephtra was at the land surface and represent a disconformity; the boundary
348 between the top of a buried soil and the succeeding tephtra deposit is a paraconformity that marks a
349 period of non-deposition (Neall 1972; Howorth 1975). Wilson (1993) used pedological features in the
350 post-25.4-cal-ka Taupō sequence very carefully to help develop a more comprehensive eruptive
351 history of volcanism than had been attained previously. The nature of the contacts and unconformities
352 between tephtra deposits and associated paleosols, and other stratigraphic features such as bedding and
353 grain size, help provide, inter alia, a picture of eruption history, landscape stability, and erosion (e.g.
354 Lowe 2011; Bilderbach et al. 2015; Dugmore et al. 2020).

355 In recent decades, mainly since ~1980, studies have increasingly identified the benefits of
356 using sediments as an archive for the preservation of tephtra layers and for their separation
357 stratigraphically, especially at the centimetre-to-millimetre scale over distances extending ~100–300
358 km from source and occasionally well beyond those distances. Such archives include sediments in
359 lakes (e.g. Lowe et al. 1980; Green and Lowe 1985; Lowe 1988b; Molloy et al. 2009; Hopkins et al.
360 2015, 2017; Zawalna-Geer et al. 2016; Peti et al. 2020a), bogs and fens (Howorth et al. 1980; Hogg
361 and McCraw 1983; Hodder et al. 1991; Lowe et al. 1999, 2013; Damaschke et al. 2017a), and oceans
362 (e.g. Pillans and Wright 1992; Carter et al. 1995, 2003, 2004; Alloway et al. 2005; Carter and
363 Manighetti 2006; Allan et al. 2008; Hopkins et al. 2020b). The chief advantages arising from studying
364 tephtras in lakes and bogs include the stratigraphic and chronological control and the high degree of
365 resolution potentially attainable, and the generally excellent preservation of the tephtras (because of
366 the reducing conditions and generally ‘quiet’ depositional environments provided by these archives)
367 that facilitates their reliable compositional investigation (see also Watson et al. 2016a). In addition,
368 and perhaps most importantly, the sediment cores provide a continuous record of interdigitating
369 tephtras from multiple volcanoes that therefore enables temporally closely-spaced tephtras from
370 different sources to be placed in unequivocal stratigraphic order (Lowe 1988b; Hopkins et al. 2015)
371 **(Fig. 4).**

372



374 **Figure 4.** Schematic composite stratigraphies of some key North Island tephra-bearing sediment sequences depicted here approximately from west to east
375 (locations shown on Fig. 1). Tephra correlated to known events or sources are named as follows: rhyolitic tephra are shown in red (OVC – from Okataina
376 Volcanic Centre; TVC – from Taupō VC); basaltic tephra in black; andesitic tephra in green (Eg – from Egmont, i.e. Taranaki Maunga) or blue (Tg – from
377 Tongariro VC); trachydacite tephra in orange; and peralkaline rhyolite tephra in teal (MI – from Tuhua VC/Mayor Island). Auckland maar core records
378 (note: also includes Pupuke) from Molloy (2008), Hopkins et al. (2015), Peti et al. (2020a). Auckland Volcanic Field-derived basaltic tephra “AVF#” are
379 given their centre names where the correlation is classified as “Confidence Level 1 or 2” in Hopkins et al. (2017). Lakes Rotomanuka and Maratoto
380 (composite core) after Green and Lowe (1985) and Lowe (1988a, 2019); Kaipo bog from Lowe et al. (1999, 2013); Lake Tutira from Eden et al. (1993) and
381 Orpin et al. (2010); MD97-2121 marine core from Carter et al. (2002) and Taiapa (2016), “?” indicates a suggested correlation; ODP 181 sites 1123, 1124,
382 and 1125 combined from Alloway et al. (2005), Allan et al. (2008), and Stevens (2010). Core source for each tephra is noted. Where tephra are correlated
383 across core, a “+” symbol is shown; where multiple distinct tephra horizons are identified in a shallow section of core, they are listed with “,” between them;
384 where tephra are the same in the same core but have been given different names by different studies, a “/” indicates this match. Key palaeomagnetic
385 subchrons or subchron boundaries are represented with dashed lines. Ages of core above the core break are given by their tephra correlatives, below the core
386 break by the paleomagnetic boundaries and sedimentation-rate-derived estimates. Tephra from below the core break are all from core ODP Site 1124-C
387 (Stevens 2010).

388 In general, cores taken from locations proximal or medial to source (e.g. Auckland maars,
389 lakes/bogs in the Hawke’s Bay or Waikato regions) produce a detailed (potentially with multiple beds
390 forming a single tephra unit) but relatively short (≤ 100 ka) record. In comparison, the records from
391 marine sediments are temporally longer (e.g. ≤ 12 Ma for core 1124 from International Ocean
392 Discovery Program, IODP; Stevens 2010), but because of their more distal locations, are less detailed
393 stratigraphically (Fig. 4). However, when these sequences are combined, a record of explosive
394 volcanism is obtained that is often much more comprehensive than that obtained close to volcanic
395 centres because of burial of proximal units by subsequent eruptions, or because of erosion, or both
396 (Lowe 1988b, 2011; Hopkins et al. 2015; Damaschke et al. 2017b).

397 One problem with using tephra in sediment cores for constructing isopachs (thicknesses) is
398 that of possible compaction of the layers within the accumulating sediment column under the mass of
399 a body of lake water. Another is the dissemination (scattering) of sparse glass shards within the
400 sediment so that upper and lower boundaries of the deposit are very diffuse and amorphous (Lowe
401 1988a). Consequently, tephra thicknesses in cores are often underestimated. As well as using X-
402 radiography to measure thickness, Lowe (1988a) mainly used bulk density estimates to generate a
403 thickness correction factor for lacustrine tephra distribution (following Borchardt et al. 1973).
404 Conversely, Cronin et al. (1998) calculated tephra thicknesses, and thus generated isopach maps, by
405 mapping deposits on surfaces of known area (e.g. car roofs). Such a fundamental parameter as tephra
406 thickness can therefore be difficult to measure accurately in sediment cores and subaerially (Lowe
407 2011; Cashman and Rust 2016).

408 Mapping cryptotephra deposits encompasses the millimetre-to-submillimetre scale and hence
409 such maps so far (in countries other than ANZ) have tended to report thicknesses in several ways: as
410 “occurrences > 0 mm”, as shard concentrations (e.g. Pyne-O’Donnell 2011), or as isomass maps
411 whereby thicknesses are replaced by mass per unit area (e.g. g/cm^2 or kg/m^2) (Lowe 2011; Cashman
412 and Rust 2016). By including bulk density measurements, thicknesses (albeit very thin and
413 approximate) can be calculated. Cashman and Rust (2020) suggested that 10–20% of an erupted mass
414 is typically deposited outside the mappable limits of visible tephra, and that ash-fall observed at
415 distances beyond mapped deposits can form cryptotephra deposits with relatively high shard counts
416 ($> \sim 1000$ shards/ cm^3).

417

418 *Characterising tephra and cryptotephra*

419 In order to combine proximal to distal records, tephra characterisation (‘fingerprinting’) and accurate
420 correlation are necessary. Fingerprinting in ANZ uses a range of analytical methods (**Table 1**).

421 Once tephra are physically, mineralogically, and/or geochemically characterised they can be
422 correlated. For eruptives < 50 cal ka in ANZ, generally orthopyroxene predominates in Taupō
423 Volcanic Centre (TVC)-derived tephra whereas biotite, hornblende, cummingtonite, or

424 orthopyroxene (along with felsic minerals and Fe-Ti oxides) predominate in Okataina Volcanic
 425 Centre (OVC)-derived tephtras (Froggatt and Lowe 1990; Smith et al. 2002, 2005, 2006; Lowe et al.
 426 2008a; Zawalna-Geer et al. 2016; Loame et al. 2019). Occasionally a mineral assemblage (together
 427 with stratigraphic constraints) is sufficiently distinctive for an individual tephtra (e.g. Rotoehu Ash or
 428 Tuhua tephtra) to be readily identified by a dominant or notably distinctive mineral (see below).
 429 However, the absence of diagnostic minerals does not necessarily negate an identification because
 430 minerals such as olivine are readily depleted by weathering in subaerial pedogenic environments, and
 431 biotite and orthopyroxene may be rapidly dissolved in some acid peat bogs (Hodder et al. 1991) or
 432 removed through winnowing of the deposit. For example, not all samples of Rerewhakaaitu tephtra
 433 contain biotite in distal sections (Alan Palmer pers. comm. 2021). This means there is a possibility of
 434 misidentifying Rerewhakaaitu as Waiohau tephtra, which contains negligible biotite but has
 435 overlapping major-element glass compositions (Eden et al. 2001; Lowe et al. 2008a; Hopkins et al. in
 436 press). Ferromagnesian minerals also tend to be sparse or absent at distal localities, having dropped
 437 out from proximal ash-clouds earlier because of their high density. In addition, studies of the OVC-
 438 derived tephtras (<50 cal ka) have shown that most comprise multiple magma types (Shane et al.
 439 2008), thus adding complexity to the use of ferromagnesian minerals for correlation purposes.
 440 Andesitic eruptives are usually distinguishable from rhyolitic tephtras because of their high pyroxene,
 441 or hornblende plus clinopyroxene, contents (Lowe 1988b; Shane 2005; further compositional details
 442 are reported by Lowe et al. 2008a and Hopkins et al. 2021).

443
 444 **Table 1.** Summary of the main analytical methods (excluding geochronology) used in New Zealand
 445 to characterize and correlate tephtras (after Lowe 2011).

Tephtra component/properties	Methods of analysis
<i>Ferromagnesian minerals</i>	
Assemblages	Petrographic microscope
Pyroxenes, amphiboles, olivine, biotite crystals	Electron microprobe
Crystal morphology (e.g. olivine)	Optical microscope, SEM
<i>Fe-Ti oxides</i>	
Major and minor elements in crystals	Electron microprobe
Eruption temperatures and oxygen fugacities	Electron microprobe
Titanomagnetite crystal textures	Reflected light microscopy
<i>Glass shards, selvages, or melt inclusions</i>	
Major and minor elements	Electron microprobe
Rare-earth and trace elements	LA- or SN-ICPMS, INAA, SIMS ^a
Shard morphology	Optical microscope, SEM
<i>Feldspars</i>	

465 Anorthite (An) content of
466 plagioclase crystals Electron microprobe
467

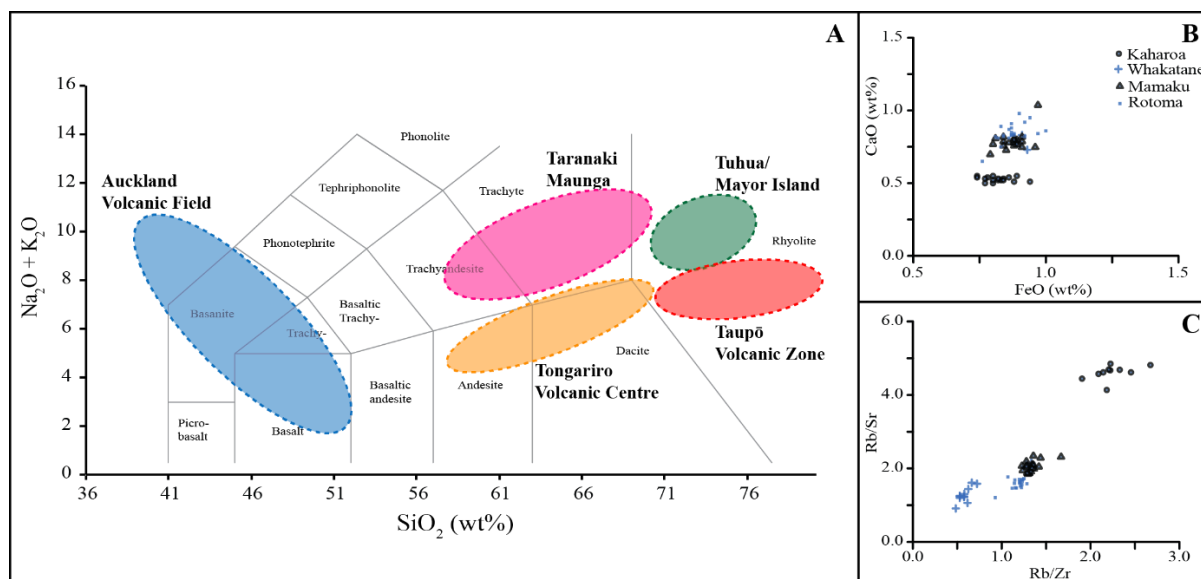
468 ^aLA- or SN-ICPMS, laser ablation or solution nebulisation inductively coupled plasma mass spectrometry;
469 INAA, instrumental neutron activation analysis; SIMS, secondary ionisation mass spectrometry (ion
470 microprobe); SEM, scanning electron microscope. See also Lowe et al. (2008a, 2017) for further details and
471 additional methods that are used in countries other than ANZ.

472

473 Thus, although the ferromagnesian mineral assemblages are typically adequate to identify the
474 source volcano (where chronological and stratigraphic information are available), they are often not
475 sufficiently distinctive to determine a specific eruptive associated with the volcanic centre. However,
476 the chemical composition of constituent glass shards enables almost all eruptives to be uniquely
477 identified. Indeed, recent studies (Allan et al. 2008; Hopkins et al. 2017, in press) have shown that
478 even if major elements are indistinguishable between glass shards of different events, the trace
479 elements and trace-element ratios can be used to distinguish between them (**Fig. 5**). Where the
480 recognition of more than one magma type in OVC-derived tephra has increased complexity and
481 potentially ambiguity, and glass compositions of some eruptives overlap those for other tephra
482 (Shane et al. 2008), adequate sampling from a range of dispersal sectors (azimuths), along with
483 chronostratigraphic data, should enable correlation to be successful.

484 In addition to mineral assemblages and glass-shard geochemistry, glass-shard morphology
485 can occasionally be used as an additional identifying characteristic. Vesicle size, shape, and density,
486 and bubble wall thickness, can be imaged and used to help predict tephra source (e.g. see references in
487 Lowe et al. 2017, p.5). However, glass morphology as a correlational tool has not been systematically
488 documented for ANZ-derived tephra apart from a handful of studies (Nelson et al. 1985; Gosson
489 1986; Smith and Houghton 1995; Dunbar et al. 2017). Partly this is because shard morphometry can
490 be diverse, reflecting eruption style, scale, and complexity, showing differences spatially and
491 temporally, and because shard composition attained via EPMA has become the pre-eminent analytical
492 correlational tool. A few studies have used crystal geometry and texture to help correlate distal
493 andesitic tephra (Donoghue et al. 1991; Turner et al. 2008).

494 Quirkily, widely dispersed deposits from the Kawakawa/Oruanui eruption often contain
495 North-Island-endemic diatoms including *Cyclostephanos novaezeelandiae* and so these, once
496 identified taxonomically, conveniently signal that the tephra must be “from New Zealand” (Van Eaton
497 et al. 2013).



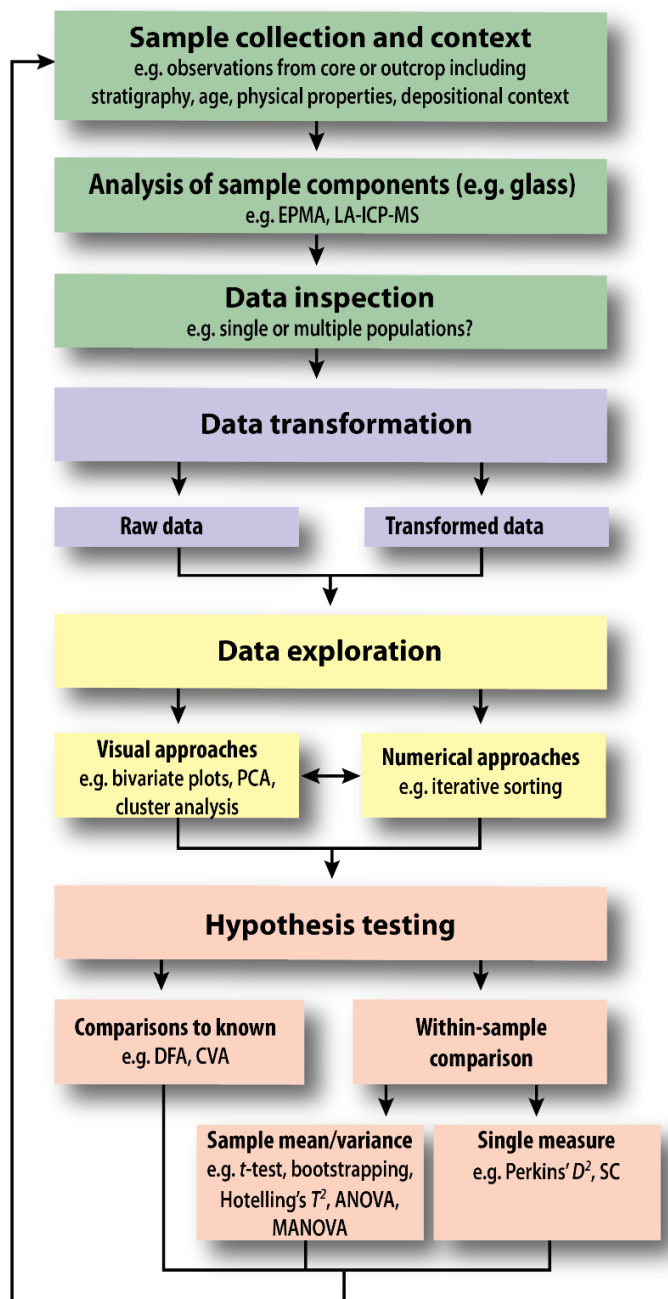
498
499

500 **Figure 5.** (A) Total alkali vs. SiO₂ plot (based on Le Maitre et al. 2002) showing EPMA-derived
501 glass-shard compositions (normalised data) of tephras erupted from five recently active volcanic
502 centres in ANZ. (B) Major element bivariate plot for glass shards from the most recent four eruptives
503 from Okataina VC (Fig. 1) showing that some tephras can be identified through major elements alone,
504 but others cannot. (C) Trace-element ratio bivariate plot for the same glass samples as in (B) showing
505 how such ratios can be used to further distinguish between the different eruptives not distinguishable
506 using major elements. Data from Hopkins et al. (in press).
507

508 *Correlating tephras and cryptotephras using numerical and statistical methods*

509 Statistical assessments of large data sets can be used to enhance and quickly identify
510 distinguishable elemental compositions. Lowe et al. (2017) provided a detailed review of statistical
511 correlation methods (including data reduction) and their applications (summarised in **Fig. 6**). They
512 divided the methods into visual (graphical, such as via bivariate plots of oxides), numerical (e.g. use
513 of similarity coefficients, SCs, or various statistical distance measures), and statistical and machine
514 learning including unsupervised (e.g. cluster analysis) and supervised (e.g. discriminant function
515 analysis, DFA), and other statistical methods such as principal components analysis (PCA). In ANZ,
516 the most commonly used methods have been SCs along with DFA (e.g. Stokes and Lowe 1988; Shane
517 and Froggatt 1991, 1994; Froggatt 1992; Stokes et al. 1992; Cronin et al. 1996a, 1997; Turner et al.
518 2011). Only rarely has PCA of glass or other compositional data for tephra correlation been
519 undertaken in ANZ (Horrocks 2000; Hopkins et al. in press). Once identified, fingerprinted, and
520 accurately correlated, the thickness and location of individual eruption units can be used to create
521 isopach or isomass maps. These maps can show eruption extent, and may support inferences of
522 eruption scale, and the dominant wind direction(s) during eruption (e.g. Barker et al. 2019), noting
523 that winds can blow in different directions in the atmospheric column at different times of the year
524 and at different latitudes (Buck 1985). For example, Nelson et al. (1985) showed from tephra-bearing
525 marine cores both west and east of ANZ that tephra deposits could be (counter-intuitively) thicker

526 'upwind' of source: ash ascending above 20 km altitude was able to be carried directly westward
 527 towards the Tasman Sea by easterly stratospheric winds, while coeval lower-level ash was blown
 528 eastward ('downwind') of ANZ into the southern Pacific Ocean.
 529



530
 531 **Figure 6.** General step-by-step guide for the correlation of tephra deposits (from Lowe et al. 2017,
 532 p.28). It is emphasised that there is potential for miscorrelation at any step (Lowe 2011), the most
 533 critical being the first in that sampling with respect to the stratigraphy must be carefully and
 534 accurately undertaken and documented, otherwise all subsequent steps (including database entries)
 535 will be wrong. Most abbreviations are defined in the text or see Lowe et al. (2017). CVA, canonical
 536 variates analysis.

537 **Cryptotephra studies**

538 Cryptotephra (from Greek *kryptein*, ‘to hide’) refers to tephra deposits that are not visible as a layer to
539 the naked eye and usually comprise glass shards in fine to very fine ash-size fractions ($< \sim 125 \mu\text{m}$) in
540 very small concentrations (typically tens to hundreds of shards per gram or unit volume). Although
541 Wastegård and Boyle (2012) and Davies (2015) correctly credited Swede, Christer Persson, with the
542 first Icelandic-derived cryptotephra discoveries in Scandinavian peat deposits in the 1960s (e.g.
543 Persson 1966, 1971), it is acknowledged that *systematic* cryptotephra studies of the modern era
544 effectively began with Andrew Dugmore’s seminal paper (Dugmore 1989), and that new and
545 increasingly efficacious techniques for cryptotephra detection, extraction, and identification were
546 subsequently developed primarily in northern and western Europe, then North America and elsewhere
547 (e.g. see references in Lowe 2008; Pyne-O’Donnell et al. 2012; Lane et al. 2014, 2017; Davies 2015;
548 Ponomareva et al. 2015; Abbott et al. 2020; Matsu’ura et al. 2021). Nevertheless, work in ANZ from
549 the middle to late 1970s and early 1980s has documented the occurrence of glass shards or crystals in
550 concentrations not visible as layers in sedimentary deposits or soils or paleosols, and so pioneering
551 cryptotephra studies in ANZ effectively date from around that time, second only to Persson’s world-
552 leading research. Note that the word ‘cryptotephra’ was not coined until 2001 (Lowe and Hunt 2001).

553

554 ***Pioneering cryptotephra research in ANZ***

555 Hodder and Wilson (1976) and Hodder (1978) developed a hot-stage microscope to measure
556 refractive index (RI) values for individual glass shards in composite, weakly- to moderately-
557 weathered late Quaternary tephra-derived soils (formed via developmental upbuilding pedogenesis
558 during slow, incremental accumulation of thin distal tephra or cryptotephra) in the Waikato region.
559 From the RIs, they were able to distinguish different component tephra, both rhyolitic and andesitic,
560 and, in conjunction with stratigraphic positioning, correlated several of them despite indistinct or no
561 layering being evident in the soil profiles examined. Using precise density measurements of different
562 size fractions of glass shards, Hodder (1977) was able to characterise five late Pleistocene tephra in a
563 stratigraphic sequence. He also showed that Okareka tephra ($\sim 23.5 \text{ cal ka}$) comprised glasses of two
564 different density populations.

565

566 Lowe et al. (1981) used X-radiography to detect non-visible glass-shard concentrations in peat and
567 lake sediments and developed a rudimentary bulk X-ray fluorescence (XRF) technique to help
568 characterise them. Robertson and Mew (1982) were the first to use counts of glass shards to detect a
569 cryptotephra in loessic soils on South Island, writing:

570

571 “Although no distinct ash layers were observed in the ... soil profiles, it is probable that, as the
572 amounts of glass present are low, such a layer would be difficult to detect in the field” (p.506).

573

574 These (hidden) glass shards of Robertson and Mew (1982) were later identified as correlatives of the
575 25.4-cal-ka Kawakawa/Oruanui tephra, and distal occurrences of this eruptive as a cryptotephra in
576 loess elsewhere, and occurrences of other Holocene tephras in lake sediments, have also been
577 identified through glass-shard counts and EPMA (Mew et al. 1986, 1988; Eden and Froggatt 1988,
578 1996; Eden et al. 1992, 1993, 2001; Almond 1996; Neall et al. 2001; Almond et al. 2007, 2020;
579 Vandergoes et al. 2013). In the Waikato region, de Lange and Lowe (1990) noted that non-visible
580 (crypto)tephras could be detected in peat by a gritty texture, and Lowe (1988a) recorded that
581 submillimetre deposits in organic lake sediment were “virtually microscopic layers best seen by X-
582 radiography” (p.132).

583 In the marine realm, Nelson et al. (1985) reported that silicic glass shards were a ubiquitous
584 but minor background component in DSDP-derived sediment cores around ANZ, and pale-green
585 laminae <2 mm thick were identified as altered, very thin tephra or cryptotephra deposits comprising
586 dissolved glass that had been replaced by neofomed secondary clays (Gardner et al. 1985). Aside
587 from the work of Sjøholm et al. (1991), the earliest cryptotephra study globally involving analysis of
588 glass concentrations in marine sediments is that of Pillans and Wright (1992). Working on cores
589 S794, S803, and S804 from offshore Bay of Plenty (Fig. 1), they quantified glass content
590 stratigraphically and showed that ~30% of the tephras identified occurred as “dispersed, non-
591 megascopic [vitric] ash” (i.e. as cryptotephras), and that high resolution stratigraphic analysis was
592 essential for their detection and identification amidst ‘megascopic’ (i.e. visible) layers.

593 Hogg and McCraw (1983) used the sparse occurrence of distinct aegirine crystals (mineral
594 grains) in upbuilding tephra-derived soils and paleosols in North Island to map the distribution of the
595 7.6-cal-ka Tuhua tephra at least 80 km beyond its visible limits in the field (**Fig. 7**). Of Holocene
596 volcanic eruptives in ANZ, aegirine is unique to Tuhua tephra and so just a few grains can indicate
597 the diminutive presence of the tephra and thus its associated isochron.

598

621 cryptotephra archives, as well as sediments, in recognition of the earliest soil-focussed cryptotephra
622 work undertaken in ANZ since 1976. Another crystal-based cryptotephra in ANZ is that denoting the
623 presence of ~45 cal ka Rotoehu Ash (in otherwise ‘homogenous’ tephra-derived soil) by the
624 occurrence of non-visible crystals of cummingtonite that predominate in the eruptive (e.g. Lowe 1981,
625 1986b, 2019).

626 Few if any cryptotephra studies in western Europe or Scandinavia, distant from source
627 volcanoes, have utilised crystal- rather than glass-shard concentrations as a basis for mapping, but
628 examples have been recorded from Japan where glass has all been lost by weathering (via dissolution
629 mainly by carbonic acid), leaving only crystals to ‘carry’ a cryptotephra’s identity (e.g. Matsu’ura et
630 al. 2011, 2012, 2014).

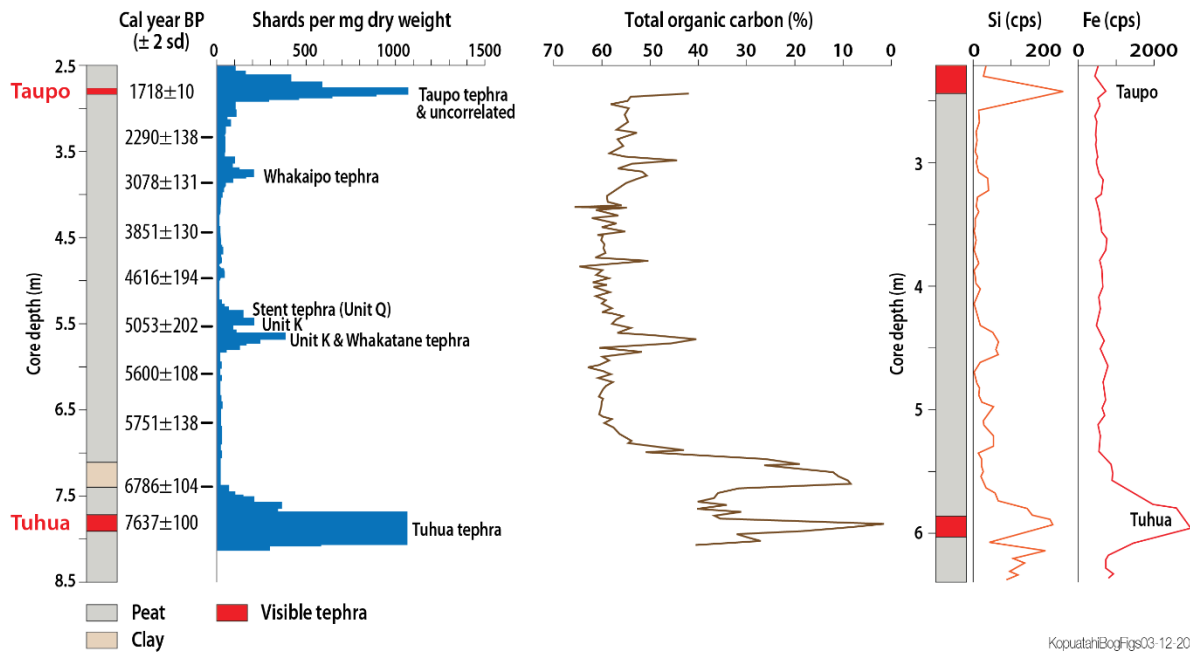
631

632 *Modern era of cryptotephra studies in ANZ*

633 In the modern era (since mid-2000s), cryptotephra studies in ANZ have been limited in comparison
634 with those elsewhere and mainly developed from records in lakes and bogs. Gehrels et al. (2006) led
635 the way by developing a systematic sampling strategy to locate peaks in glass-shard concentrations
636 and to determine loci of individual geochemical populations, and adapted a palynological method
637 involving spiking samples with *Lycopodium* spores to facilitate accurate counts of glass-shard
638 concentrations. Other recent cryptotephra studies include those of Gehrels et al. (2008), Shane et al.
639 (2013), Hopkins et al. (2015), Zawalna-Geer et al. (2016), and Newnham et al. (2019). In some
640 research, cryptotephra have been used primarily tephrochronologically (*sensu stricto*) rather than as a
641 focus of fundamental research (Eden et al. 2001; Cerovski-Darriau et al. 2014; Bilderback et al. 2015;
642 Newnham et al. 2018, 2019; Almond et al. 2020; Ratcliffe et al. 2020). Although marine sediments
643 contain background counts of glass shards (noted earlier), they seem to be fewer in number than in
644 terrestrial depocentres, likely due to a greater distance from source coupled with a less consistent
645 input from terrestrial reworking (e.g. through fluvial or aeolian transportation). Therefore the marine
646 systems have the potential to be more accurate in their preservation of primary cryptotephra
647 (Hopkins et al. 2020b; see section on marine tephra below)

648 To date, cryptotephra studies in ANZ have used the laborious and destructive method of
649 contiguous subsampling, commonly between known visible tephra layers or in cores with good
650 radiometric chronologies (e.g. Gehrels et al. 2006; Zawalna-Geer et al. 2016). Of note is the high
651 potential for contamination between subsamples when processing them for analysis, and thus
652 scrupulous attention to cleanliness during the separation of shards (and crystals) is essential. Once
653 separated, glass shards are then isolated using a range of methods (Gehrels et al. 2008; Abbott et al.
654 2018a) and, where the glass shard concentrations are above background, cryptotephra deposits are
655 identified and fingerprinted using their glass-shard major-element compositions (**Fig. 8**).

656



KopouataiBogFigs03-12-20

657

658

659 **Figure 8.** At left is a cryptotephra record derived from counts of glass shards in a peat core from
 660 Kopouatai bog (Fig. 1) that contains two bounding visible (macroscopic) tephra layers (Taupo and
 661 Tuhua) (after Gehrels et al. 2006, p.177). The peaks in glass concentration match those of the total
 662 organic carbon curve shown in the middle of the diagram (note reversed scale). At right, the core
 663 depicted, collected from Kopouatai bog 25 years earlier, shows analyses of Si and Fe that were
 664 obtained by XRF analysis (cps = elemental count rates per second) of contiguous 4-cm sections of
 665 dried bulk peat (Lowe et al. 1981). The Si peaks reflect glass content in the peat (i.e. cryptotephra
 666 occurrences) and show essentially the same trend stratigraphically as in the core at left. The Fe
 667 analyses (far right) enable Tuhua tephra to be picked out because, as a peralkaline rhyolite, its glass is
 668 notably enriched in Fe (total iron as FeO in glass shards of Tuhua tephra is ~5.9 wt% on average:
 669 Lowe et al. 2008a) (see also much more recent ITRAX-based paper by Peti et al., 2019, which shows
 670 a similar level of enrichment of Fe in Tuhua tephra).

671

672

673 It is important to appreciate that many studies have highlighted the high number of
 674 ‘background’ glass shards found in sediments in ANZ records (e.g. Lowe 1988a; Froggatt and Rogers
 675 1990; Gehrels et al. 2006; Zawalna-Geer et al. 2016). Although this is perhaps unsurprising because
 676 of North Island’s pervasive volcanic activity, it could potentially lead to difficulties in developing
 677 definitive isochrons using cryptotephra (Gehrels et al. 2006). Tapaia (2016) investigated the
 678 identification of cryptotephra in marine sediment cores through core-scanning techniques (following
 679 Croudance et al. 2006; Balascio et al. 2015; Croudance and Rothwell 2015), and emphasised the
 680 potential for reducing time, cost, and core destruction in finding cryptotephra in such cores using
 681 variations in specific elements in the sediments. Similarly, Loame et al. (2017, 2018) reported the
 682 trialling of non-invasive core scanning using X-ray computed tomography (CT; **Fig. 9b**) to detect
 683 cryptotephra preserved in lake sediments. This non-invasive (remote) detection of cryptotephra in

684 sediments is a research avenue being pursued currently by Hopkins and others at VUW, and by Lowe
 685 and others at Waikato, and associated researchers (see also Peti et al. 2020a).

686

687 *Detecting and identifying thin tephra or cryptotephra deposits in sediments*

688 Various techniques beyond simple visual observation have been employed in ANZ to detect (and
 689 potentially identify, i.e. correlate) very thin or indistinct tephra or cryptotephra deposits (**Table 2**).

690 Just three of the techniques are highlighted here: magnetic susceptibility, X-ray imaging, and XRF
 691 analysis.

692

693 **Table 2.** Techniques used to detect very thin or indistinct tephras, or cryptotephra, in sediment cores
 694 or sections, in ANZ (after Gehrels et al. 2008; Lowe et al. 2008a; Loame et al. 2017).

695

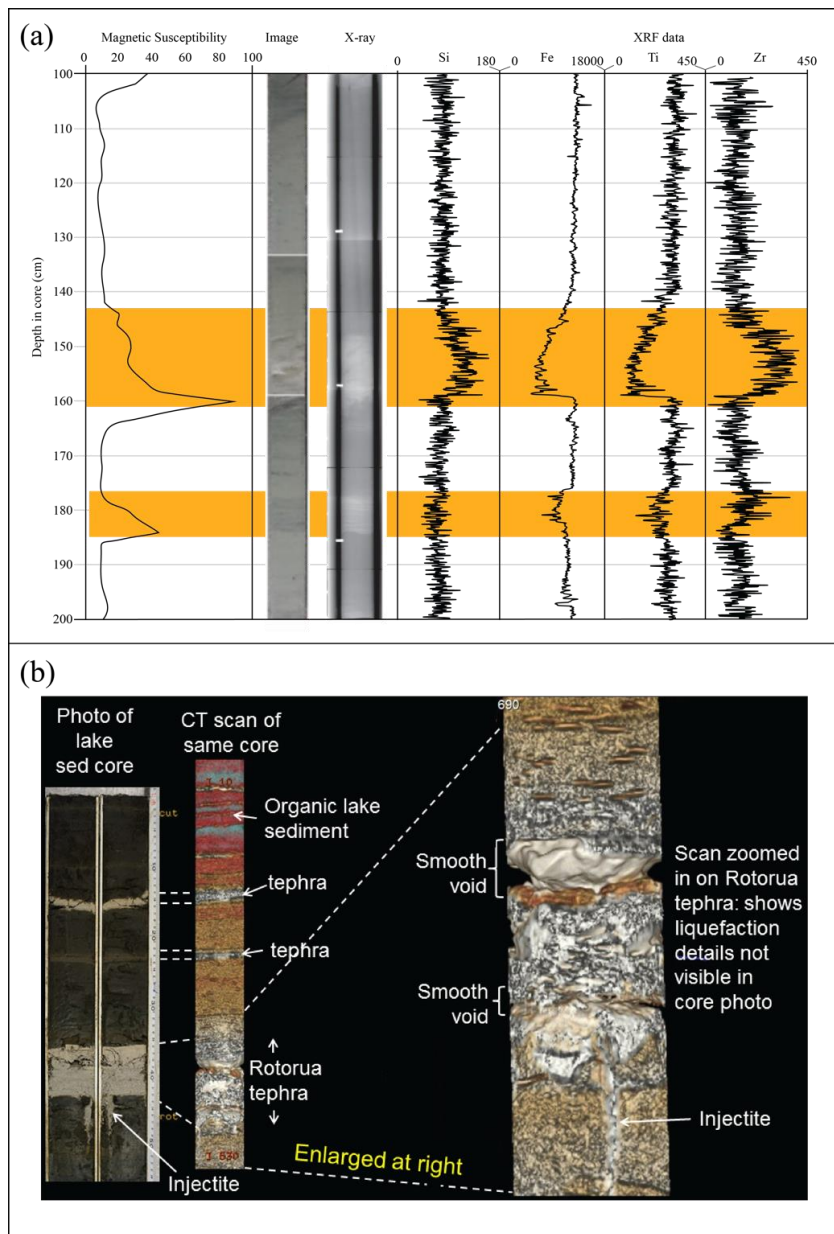
696 Application	Method
697 <i>Field</i>	Ground penetrating radar
698	Magnetic susceptibility
699 <i>Laboratory</i>	X-radiography
700	X-ray density scanning
701	Magnetic susceptibility
702	Dry bulk density
703	Rapid X-ray fluorescence
704	ITRAX core scanning (elements, magnetic susceptibility, X-radiography)
705	Spectrophotometry (reflectance and luminescence)
706	X-ray computed tomography (CT) imaging
707	Glass-shard counts, crystal counts (cryptotephra)
708	Total organic carbon, loss on ignition

709

710

711 Magnetic susceptibility (MS) is a non-destructive logging technique, most commonly applied
 712 continuously down the face of a split sediment core, usually at regular 0.5- to 2-cm intervals. The
 713 analysis relies on a difference in magnetic characteristics of the tephra and the host sediments.

714 Commonly the tephra will contain a higher concentration of (more) magnetic minerals than the host
 715 sediment, and therefore will show a peak in MS (measured in SI units) where tephra-derived deposits
 716 (often glass shards) are found (**Fig. 9a**).



718

719 **Figure 9.** (a) Marine sediment cores collected from a site 200 km offshore from the east coast of
 720 ANZ (TAN1613 cruise; Hopkins et al. 2020b) contain two visible or macroscopic rhyolitic tephra
 721 horizons highlighted by the orange shading. The tephras are also identified by high magnetic
 722 susceptibility, paler colour on the X-ray scan, peaks in Si and Zr, and troughs in Fe and Ti, which
 723 contrast with the host sediment compositions (blue-grey muds). (b) Example of CT scan of a
 724 lacustrine sediment core (from a lake just north of Hamilton) containing tephra layers. The distinctive
 725 upper white layer in the photograph at far left is Waiohau tephra (14.0 cal ka), and the lower thicker
 726 layer is Rotorua tephra (15.6 cal ka), which has been partly liquefied by seismic shaking (from Lowe
 727 et al. 2018). The CT imaging highlights the increased detail that can be observed through use of these
 728 developing methods (see also Griggs et al. 2015; van der Bilt et al. 2021).
 729

730

731

732

X-ray imaging is also non-destructive, and generally is undertaken on the face of a split
 sediment core (e.g. Hopkins et al. 2015; Zawalna-Geer et al. 2016). X-ray imagery can be used to
 examine many characteristics of the tephra deposits and sediments in the core including texture,

733 structure, disrupted bedding and liquefaction, bioturbation and subfossil content, and composition.
734 Different densities coupled with high concentrations of X-ray-absorbing elements in the cores are
735 used to reveal these characteristics, where commonly tephra or cryptotephra deposits (typically
736 mainly glass shards together with crystals and potentially with pumice fragments and lithics at
737 proximal sites) will appear paler in the core in comparison to the properties of the host sediments (Fig.
738 9a). Generally, this method is most appropriate for detecting basaltic (rather than rhyolitic) glasses
739 because they have higher X-ray-absorbing elements (e.g. higher FeO content) and a higher density in
740 comparison to that of the host sediments (Hopkins et al. 2015).

741 Using X-ray fluorescence (XRF) analysis on sediment to detect tephtras is not new (e.g.
742 Kylander et al. 2012; Cassidy et al. 2014) but has recently become a common tool for detecting and
743 also identifying tephtras and cryptotephtras, with the development of automated core-scanning
744 techniques (e.g. ITRAX scanners; Peti et al. 2019, 2020b). After scanning the core surface using a
745 laser to help ‘smooth out’ tiny high or low points so that the X-rays are directed on to an effectively
746 continuous ‘flat’ surface, cores are scanned using a Mo- and/or Cr-X-ray tube with a variety of
747 exposure times and step sizes. These variable parameters allow different elements to be analysed. For
748 example, the Cr-tubes have a lower detection limit for isotopically lighter elements, in contrast to
749 limits for the Mo-tubes, which are usually used for studies needing a broad range of elements
750 analysed (e.g. Croudance and Rothwell 2015; Peti et al. 2020b). XRF-based studies have shown that a
751 range of elements can be indicative of the presence of a cryptotephra deposit (e.g. Si, Al, Fe, Ti, Mn,
752 K, Zr, Rb, Sr, Sn, Ba) (Fig. 9a; Damaschke et al. 2013; Balascio et al. 2016). Commonly, element
753 ratios can be used to further enhance the distinction between tephra components and host sediment
754 (e.g. Si/K, Sr/Rb, K/Ti, Si/Ti, Zr/Ti, Ti/Ca, Mn/Ca, Si/Ca) (Balascio et al. 2016; Taiapa 2016). All
755 these methods rely on the concentrations of glass, minerals (crystals), pumice, and lithics that
756 potentially make up the tephra deposits being sufficiently high to elicit a signature that exceeds that of
757 the host sediments. The ITRAX and other methods may become increasingly challenging as glass (\pm
758 crystals, lithics) concentrations become sparser, such as for cryptotephra deposits.

759

760 **Dating tephtras and cryptotephtras**

761 The dating of tephra or cryptotephra deposits is an essential facet of the tephrochronological method.
762 Initial stratigraphic assessment can be made based on the law of superposition giving relative ages to
763 tephtras or cryptotephtras and associated deposits or landscapes or events. However, even more
764 valuable is the ability to numerically date tephra/cryptotephra deposits for two key reasons: (i)
765 obtaining an age often helps to identify a deposit (or at least narrow down the correlative options);
766 and (ii) a numerical age (note that ‘numerical’ is preferred over the misnomer ‘absolute’) allows the
767 transferral of ages and the use of tephtras as both stratigraphic and chronological marker horizons as
768 isochrons (Lowe et al. 2017).

769 Tephtras and cryptotephtras can be dated both directly and indirectly in various ways that can
 770 be broadly grouped into radiometric, incremental, age equivalence, age modelling, relative, and
 771 historic (**Table 3**).

772

773 **Table 3.** Methods used for dating* tephtras or cryptotephtras directly or indirectly in ANZ (after Lowe
 774 and Alloway 2015).

775
 776

777 Method	778 Applications
780 Radiometric	Radiocarbon dating (radiometric/beta counting, AMS) ^a
781	Fission-track dating of zircon or glass-ITPFT or glass-DCFT dating
782	Argon isotopes (K/Ar, ⁴⁰ Ar/ ³⁹ Ar including SCLF/P, LIH)
783	Luminescence dating (TL, OSL, IRSL, pIR-IRSL)
784	U-series including (U-Th)/He, U-Pb, and ²³⁸ U/ ²³⁰ Th zircon dating/double-
785	dating (SIMS/TIMS, SHRIMP, LA-ICPMS)
786	Electron spin resonance
787	²¹⁰ Pb, ¹⁰ Be
788 Incremental	Dendrochronology, varve chronology, layering in ice cores
789 Age equivalence	Magnetopolarity, palaeomagnetic secular variation, astronomical (orbital)
790	tuning, correlation with marine oxygen isotope stages, climatostratigraphy,
791	biostratigraphy, palynostratigraphy, palaeopedology
792 Age modelling	Various age-depth methods including Bayesian flexible depositional
793	modelling and wiggle matching
794 Relative	Obsidian hydration dating, amino acid racemisation
795 Historical	Eyewitness accounts or inferences from historical records (e.g. Thomas 1888;
796	Lorrey and Woolley 2018) or observations (e.g. via remote sensing)
797	

798 *An 'age' is a period of time before present, usually reported as (e.g.) cal yr BP or cal ka or b2k. (In the ¹⁴C time-
 799 scale, 'present' is 1950 AD/CE.) In contrast, a 'date' is a calendrical date (e.g. 1886 AD/CE).

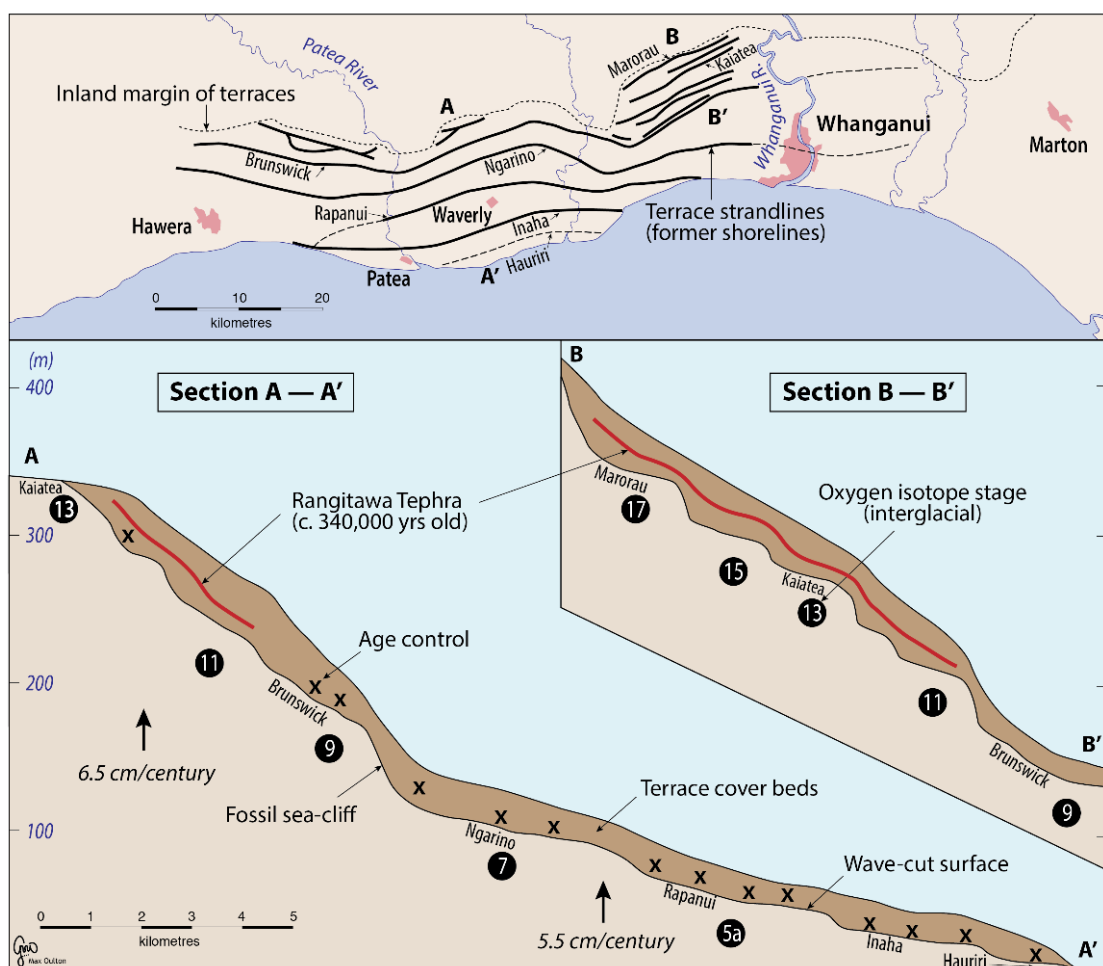
800 ^aAMS, accelerator mass spectrometry; ITPFT, isothermal-plateau fission track; DCFT, diameter-corrected fission
 801 track; SCLF/P, single-crystal laser fusion or probe; LIH, laser incremental heating; TL, thermoluminescence;
 802 OSL, optically stimulated luminescence; IRSL, infra-red stimulated luminescence; pIR-IRSL, post infrared-
 803 infrared stimulated luminescence; SIMS, secondary ionization mass spectrometry; TIMS, thermal ionization mass
 804 spectrometry; SHRIMP, sensitive high resolution ion microprobe; LA-ICPMS, laser ablation inductively coupled
 805 plasma mass spectrometry.

806

807 Tephrochronology (*sensu stricto*) is an age-equivalence dating method in itself. The term
 808 'tephrochronometry', in contrast, has been used to describe the dating of tephra layers either directly
 809 or indirectly (Lowe 2011). Recent articles that review tephrochronometry include Alloway et al.
 810 (2013), Westgate et al. (2013), Lowe and Alloway (2015), Danišik et al. (2017), Ito et al. (2017), and
 811 Hopkins and Seward (2019).

812 Direct and indirect dating of tephtras is becoming increasingly accurate through both method
 813 development and improving instrument precision. The main methods used in ANZ are described
 814 briefly below.

815 A transformational development in tephra studies has been that of the isothermal-plateau
 816 fission-track dating method (ITPFT) for glass shards, which is very well suited to dating distal
 817 rhyolitic tephra (Westgate 1989; Sandu et al. 1993; Sandhu and Westgate 1995; Westgate et al.
 818 2013). It has enabled ages to be obtained on many distal tephras that previously could not be dated
 819 because their main – usually only – component, glass, was unreliable because of annealing (Seward
 820 1979; Seward and Kohn 1997; Lowe and Alloway 2015). Examples of such applications include the
 821 dating of Quaternary glacioeustatic sedimentary cycles and uplifted terraces in the Whanganui Basin
 822 (Fig. 10), which is a globally unique archive that contains a shallow marine basal sequence, exposed
 823 on land, spanning the entire Quaternary (Alloway et al. 1993; Naish et al. 2005; Pillans et al. 2005;
 824 Pillans 2017; Rees et al. 2020). Another is providing dates for older terrestrial tephra deposits (e.g.
 825 Shane et al. 1996), or marine tephra sequences from ODP sites east of ANZ, thus testing chronologies
 826 based on alternative methods (Carter et al. 2004; Alloway et al. 2005; Allan et al. 2008; Hopkins et al.
 827 2020b).
 828



829
 830 **Figure 10.** Marine terraces (upper panel), up to 20 km inland from the coast and rising to over 300 m
 831 above present sea level, are preserved on the coastal plain between Hawera and Whanganui in
 832 southwestern North Island (Fig. 1), forming part of the comprehensive Quaternary stratigraphic
 833 sequence of the Whanganui Basin (Townsend et al. 2008; Pillans 2017; Rees et al. 2020). The uplifted

834 terraces become older and higher inland, their inner margins representing sea-level high-stands of
835 interglacials (Pillans 1983, 2017). The rhyolitic Rangitawa tephra (~340 ka) provides an important
836 well-dated datum (lower panel) and, along with fission-track and amino-acid racemisation ages,
837 helped in establishing rates of uplift of the terraces. Numerous other rhyolitic tephras provide
838 important chronostratigraphic markers for the entire basin record (Table SM1). Magnetostratigraphic
839 isochrons using palaeomagnetism have been pivotal in helping to construct tephrostratigraphic
840 frameworks in the sedimentary basins of southern North Island (e.g. Shane et al. 1996; Pillans et al.
841 2005; Alloway et al. 2013). In turn, such chronostratigraphies have been useful in large-scale regional
842 geological mapping (e.g. Briggs et al. 2006; Rees et al. 2018, 2020; McLeod et al. 2020) and for the
843 recently-completed national-extent 1:250,000 geological mapping of ANZ (the QMAP project) (e.g.
844 Leonard et al. 2010; Lee et al. 2011). Diagram after Pillans (1983), Bussell and Pillans (1997), and
845 Carter (2013).
846

847 Danišik et al. (2017, 2020) discussed recent methodological developments in zircon double-
848 dating, combining U-Th-Pb and (U-Th)/He analyses of zircon. Provided enough volcanogenic zircon
849 crystals can be extracted from a sample, this method can now be used to date tephra deposits as young
850 as 3 ka and up to 1 Ma with errors of $\leq 5\%$ (Danišik et al. 2020).

851 A related method also rapidly emerging is that of dating zircons from pyroclastic deposits
852 using U-Pb. Although used until now mainly in volcanic petrological studies in ANZ, and with data
853 acquired typically using secondary ion mass spectrometry (SIMS) techniques (e.g. Charlier et al.
854 2005; Wilson et al. 2008, 2010; Milicich et al. 2020), zircon U-Pb dating has been increasingly used
855 overseas to successfully date tephras by LA-ICP-MS analysis (e.g. Chang et al. 2006; Ito et al. 2017;
856 Österle et al. 2020). Horstwood et al. (2016) have developed standardised protocols for the technique.
857 In ANZ, LA-ICP-MS-based zircon U-Pb ages have been obtained on Miocene tuff/volcanic-ash beds
858 in northern Taranaki by Maier et al. (2016) and Sagar et al. (2020), and Pittari et al. (2021) similarly
859 reported new zircon U-Pb ages on 3- to 1-Myr-old eruptives in central and northern North Island.

860 The K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dating methods have mainly been applied to lavas or welded
861 ignimbrites in ANZ, but distal tephras do not lend themselves to the technique because the deposits
862 are typically too fine, crystal-poor, or too low in K-rich mineral phases. However, the method has
863 been critical in helping to determine the chronology and dynamics of caldera formation in the central
864 TVZ and CVZ (Briggs et al. 2005; Houghton et al. 1995; Wilson et al. 2009; Alloway et al. 2013;
865 Flude and Storey 2016) and, most recently, to determine the volcanological history of Tongariro
866 volcano (Pure et al. 2020). Consequently, because dated lavas or ignimbrites are often intercalated
867 with tephra-fall deposits, or have an equivalent (coeval) fallout component, then the lava/ignimbrite
868 ages are usually transferable (in conjunction with tephrostratigraphic, magnetostratigraphic, or other
869 data) to the associated tephra deposits (e.g. Briggs et al. 1989; Wilson et al. 2007; Hopkins et al. 2017,
870 2020a; Leonard et al. 2017). According to Leonard et al. (2017), improvements in $^{40}\text{Ar}/^{39}\text{Ar}$ analytical
871 techniques, together with the development of ultrasensitive rare-gas mass spectrometers, have
872 supplanted the K-Ar method. Primarily, use of single-crystal laser fusion has shown up contamination
873 and indicates that some crystals are relict, and also that some pumice blocks demonstrably contain

874 crystals with a range of ages (Alloway et al. 2013). Hence accurate ages on tephtras should be
875 determined by single-grain analysis using $^{40}\text{Ar}/^{39}\text{Ar}$.

876 Luminescence dating of tephtras (mainly applying thermoluminescence and optically
877 stimulated luminescence) (see also footnotes of Table 3) is a technique first developed in the 1980s
878 (e.g. Berger 1985, 1992). Not without challenges, it has been generally most successful for indirectly
879 dating tephtras via their host sediments, i.e. by dating fine-grained mineral fractions of loess or
880 paleosols encapsulating tephtra beds (e.g. Berger et al. 1992; Pillans et al. 1996; Lian and Shane 2000;
881 Peti et al. 2020a). The method shows promise in the search for long-term stable signals for direct
882 dating (Bösken and Schmidt 2020; Roberts et al. 2021; Scheidt et al. 2021).

883 The principles and application of ^{14}C methods used in ANZ to date tephtras have been
884 documented extensively (e.g. Alloway et al. 2013; Lowe and Alloway 2015). Ages on tephtras via ^{14}C
885 have been attained almost entirely by two methods: (1) radiometric (whereby benzene, C_6H_6 , is
886 synthesised and the decay of ^{14}C in it is counted in purpose-built scintillation spectrometers over
887 time); and (2) accelerator mass spectrometry (AMS). Both methods convey certain advantages. The
888 AMS method is useful where sample sizes are tiny or where separate components, such as pollen
889 grains within sediments, are dated to help acquire better age estimates for associated tephtra layers
890 (e.g. Newnham et al. 2007c).

891 Perhaps the most powerful area of advancement in developing age models for tephtras is the
892 advent of ^{14}C -based wiggle-match dating and Bayesian age-depth modelling, which are discussed
893 next. Bayesian age-depth modelling is now routine. Its pre-eminence also reflects in part the rise of
894 high-resolution palaeolimnological and palaeoenvironmental research in ANZ and elsewhere.

895

896 *Radiocarbon wiggle-match dating of Kaharoa and Taupō tephtras*

897 Calendar dates on two late Holocene tephtras in ANZ, Kaharoa and Taupō, have been obtained by
898 wiggle-matching log-derived tree-ring sequences dated by ^{14}C . The date obtained for Kaharoa ($1314 \pm$
899 12 AD) (95% probability) by Hogg et al. (2003) is supported by the Bayesian analysis of an
900 independent ^{14}C -age dataset (Buck et al. 2003). The main plinian phases of the Kaharoa eruption
901 likely took place during the austral winter (on the basis of tree-ring data).

902 Regarding the Taupō eruption date, Hogg et al. (2012, 2019) circumvented the uncertainty
903 arising from the inter-hemispheric offset in the ^{14}C -calibration curves by developing a high-precision
904 ANZ-derived ^{14}C -calibration curve using dendrochronology and samples of kauri (*Agathis australis*)
905 from northern ANZ. A tanekaha log (*Phyllocladus trichomanoides*) from the Pureora buried forest
906 northwest of Lake Taupō (Fig. 1) was then sampled dendrochronologically to generate 25 high-
907 precision ^{14}C dates from a sequence of 25 decadal samples, all pre-treated to form α -cellulose. The
908 contiguous dates were then statistically wiggle-matched against the kauri calibration curve to derive a
909 precise calendar date of $\text{AD } 232 \pm 10$ years (95% probability). This date contrasts with several other

910 calendar dates suggested for this eruption, including from Greenland ice cores and putative historical
911 records, which are no longer viable (Hogg et al. 2012). Tree-ring data and preserved plant
912 macrofossils have shown that the Taupō eruption occurred during the austral late-summer to early-
913 autumn period – i.e. probably late March–early April (Clarkson et al. 1988; Palmer et al. 1988). The
914 date of ~232 AD was supported by an independent estimate made using Bayesian age-modelling at
915 Kaipo bog (Fig. 1), where dates obtained for Taupō were AD 231 ± 12 (OxCal software) and AD 251
916 ± 51 (weighted-mean date AD 240) (Bacon software) (Lowe et al. 2013).

917 A date of AD 231/232 for the Taupō eruption event was inferred by Sigl et al. (2013) using
918 sulphate signals in annually-dated ice cores from both Greenland (core NEEM S1) and Antarctica
919 (core WDC06A). The annual minimum sulphur values exceeded the natural background in the ice for
920 up to seven consecutive years, indicating a moderate, long-lasting flux of volcanogenic sulphur,
921 which Sigl et al. (2013) attributed to Taupō's high plinian eruption column penetrating the tropopause
922 and hence injecting aerosols into the stratosphere to affect global dispersal (Wilson and Walker 1985;
923 Lowe and Pittari 2021). However, glass shards from the Taupō eruption have not yet been reported in
924 Greenland nor Antarctica, and so the definitive attribution of the ice-core sulphate signals at AD
925 231/232 to the Taupō eruption is not confirmed (Sigl et al. 2013).

926

927 *Bayesian age-depth modelling*

928 Bayesian age-modelling has added enhanced and more precise chronologies in tephrochronology (e.g.
929 Bronk Ramsey et al. 2015; Egan et al. 2015; Blaauw et al. 2018; McKay et al. 2021; Peti et al. 2021).
930 For example, 16 late Quaternary tephra comprising a sequence from Kaharoa to Rerewhakaaitu
931 tephra, preserved in peat at montane Kaipo bog (Fig. 1), were dated using Bayesian flexible
932 depositional age-modelling (Hajdas et al. 2006; Lowe et al. 2008a, 2013). The modelling was
933 undertaken using Bayesian programs Bpeat, Bacon, and OxCal, with Lowe et al. (2013) uniquely
934 applying two independent programs (Bacon; OxCal: *P_sequence* function) to the same stratigraphic-
935 age data.

936 Peti et al. (2020a, 2021) similarly used Bayesian age-modelling (Bacon software) on tephra-
937 bearing sediments in Ōrākei maar (Fig. 1) that integrated ^{14}C -dating, tephrochronology, luminescence
938 dating, and tuning of relative magnetic paleointensities to test and refine the reliability of existing
939 tephra ages and to improve their precision.

940 Regarding the very widespread Kawakawa/Oruanui tephra, its age was problematic until
941 recently. Modelling new dates (derived from optimal material) using OxCal's *Tau_Boundary*
942 function, Vandergoes et al. (2013) showed its age to be $25,358 \pm 162$ cal yr BP (95% probability).
943 After fingerprinting glass shards preserved in West Antarctic ice core WDC06, and matching them to
944 Kawakawa/Oruanui tephra geochemically using major-element analyses, Dunbar et al. (2017)
945 reported an (identical) ice-core-derived age of $25,580 \pm 258$ cal yr BP.

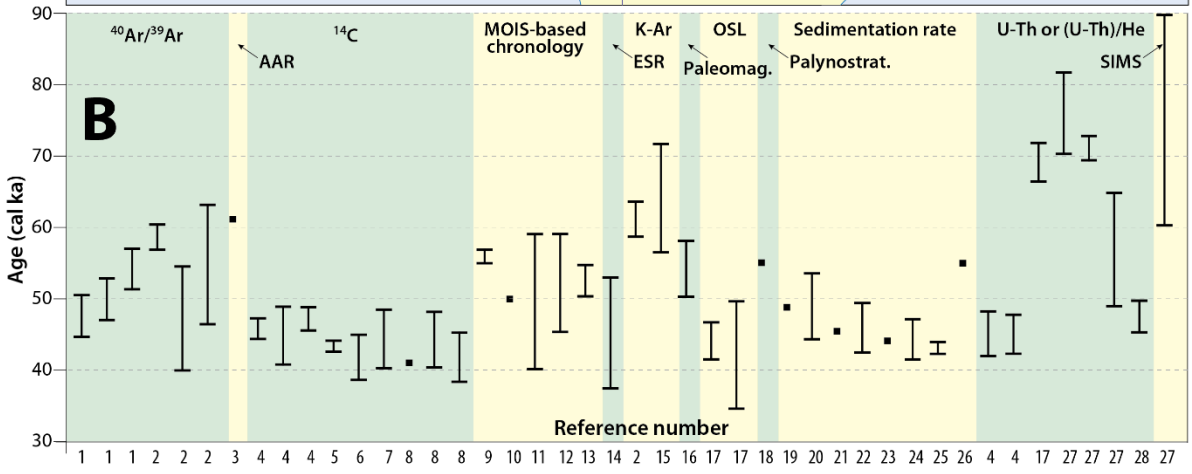
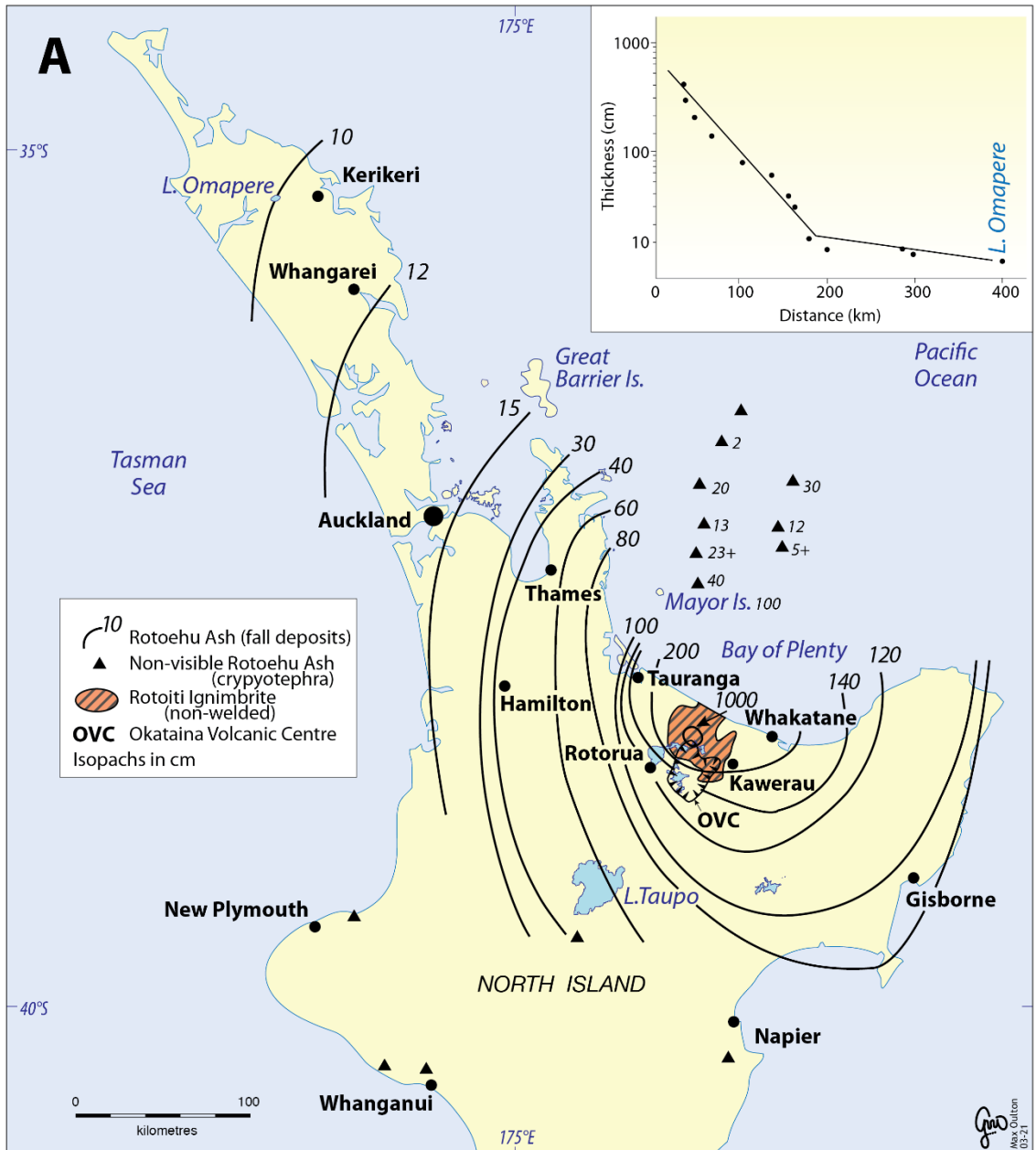
946 Most recently, Danišik et al. (2020) used Bayesian age modelling based on a ‘target event
947 date model’ incorporating zircon double-dates and ¹⁴C dates as well as stratigraphic information
948 (Lanos and Philippe 2017; Lanos and Defresne 2019). They constructed a set of ages for 13
949 rhyodacitic to rhyolitic tephtras of the Okataina-derived Mangaone Subgroup (and also for the
950 stratigraphically intercalated Taupō-derived Tahuna tephra), around half of which had not been
951 directly dated previously. Their findings suggest a sub-millennial eruptive recurrence interval for the
952 subgroup.

953

954 *Age of the Rotoiti Tephra Formation (including Rotoehu Ash)*

955 The Rotoiti Tephra Formation, erupted from Okataina Volcanic Centre (Fig. 1), comprises three
956 members: Matahi Scoria from basaltic fallout (a relatively minor component); the voluminous non-
957 welded Rotoiti Ignimbrite from rhyolitic pyroclastic flows or density currents; and the widely
958 dispersed Rotoehu Ash from rhyolitic fallout (Nairn 1972, 2002; Froggatt and Lowe 1990). The
959 Rotoehu Ash is an important marker bed in North Island and beyond (**Fig. 11A**). Because it forms a
960 basal deposit for the well-known late Quaternary rhyolitic tephra record (Fig. 2), a reliable age for the
961 Rotoehu Ash and its correlatives is an important benchmark in building age models for tephra
962 deposits both younger and older than 50 cal ka.

963



964
965

966 **Figure 11. A.** Isopach map of visible Rotoehu Ash fall deposits and onland cryptotephra (or very
 967 thin) deposits (marked by black triangles). Cryptotephra occurrences have also been recorded in deep-
 968 sea cores from ODP Site 1123 (Allan et al. 2008) and MD97-2121 (Taiapa 2016) (Fig. 1). Also shown
 969 is the distribution of coeval Rotoiti Ignimbrite (based on Nairn 1972). Inset shows log-normal plot of
 970 isopach thickness versus distance from source, showing thinning; the break in slope marks a change in
 971 dispersal mechanism during the plinian phase(s) of the eruption, or possibly fallout from co-
 972 ignimbrite ash (Newnham et al. 2004). Map after Pullar and Birrell (1973b) and Lowe (2011) with
 973 marine-core data from Shane et al. (2006). **B.** Assemblage of ages reported for samples from Rotoehu
 974 Ash or Rotoiti Ignimbrite deposits from a wide range of dating techniques as indicated. Full details
 975 can be found in **Table SM2** including the error, material analysed, and the stratigraphic relationship
 976 of the material to the fall or ignimbritic deposit. Sources: 1, Flude and Storey (2016); 2, Wilson et al.
 977 (2007); 3, Kimber et al. (1994); 4, Danišik et al. (2012); 5, Santos et al. (2001); 6, Nairn and Kohn
 978 (1973); 7, Grant-Taylor and Rafter (1971); 8, Pullar and Heine (1971); 9, Berryman et al. (2000); 10,
 979 Kennedy (1994); 11, Berryman (1993); 12, Berryman (1992); 13, Froggatt and Lowe (1990); 14,
 980 Buhay et al. (1992); 15, Wilson et al. (1992); 16, Newnham et al. (2004); 17, Lian and Shane (2000);
 981 18, Lowe and Hogg (1995); 19, Nilsson et al. (2011); 20, Molloy et al. (2009); 21, Allan et al. (2008);
 982 22, Shane et al. (2006); 23, Shane and Sandiford (2003); 24, Peti and Augustinus (2019); 25,
 983 Hayward and Hopkins (2019); 26, Pillans and Wright (1992); 27, Charlier et al. (2003); 28,
 984 Shulmeister et al. (2001). AAR, amino acid racemisation; ESR, electron spin resonance; OSL,
 985 optically stimulated luminescence; SIMS, secondary ion mass spectrometry.

988 The Rotoehu/Rotoiti eruption occurred during Marine Oxygen Isotope Stage (MOIS) 3
 989 (McGlone et al. 1984; Wright et al. 1995; Shane and Sandiford 2003; Newnham et al. 2004; Lorrey
 990 and Bostock 2017; Evans et al. 2021). However, its age until recently has been poorly constrained
 991 despite decades of study using many different methods. Published ages range between 35 and 71 cal
 992 ka although most are between ~40 and 60 cal ka (**Fig. 11B**). Following the successful glass-ITPFT
 993 dating of the Maninjau ignimbrite from west-central Sumatra (50 ± 3 ka; Alloway et al. 2004b),
 994 characterised by blocky glass with low vesicularity, Brent Alloway and John Westgate then attempted
 995 to date glass from the similarly-aged Rotoiti/Rotoehu eruptives. However, a combination of factors,
 996 including lack of glass surface area following HF etching (because of the relatively high vesicularity
 997 of constituent shards) in conjunction with the lower U content of Rotoehu glass (3.2 ± 0.7 ppm *cf.*
 998 Maninjau glass 4.4 ± 0.6 ppm), and corresponding lack of spontaneous tracks on account of its young
 999 age, precluded the attainment of either an ITPFT- or DCFT-age (Brent Alloway pers. comm. 2021).

1000 The most recently published ages on Rotoiti/Rotoehu eruptives include AMS-derived ^{14}C
 1001 ages between 44.8 ± 0.3 and 47.5 ± 2.1 cal ka (Danišik et al. 2012); an age of 45.2 ± 3.3 ka (2 s.d.)
 1002 from $^{238}\text{U}/^{230}\text{Th}$ disequilibrium and (U–Th)/He double-dating of zircon (Danišik et al. 2012); an age of
 1003 45.1 cal ka from orbitally-tuned sedimentation rates in ODP 1123 core (Allan et al. 2008); an age
 1004 range of 43.8–47.7 cal ka from sedimentation rates in marine cores from the Bay of Plenty (Fig. 11A)
 1005 (Shane et al. 2006); an age of 45.1 ± 1.65 cal ka from lacustrine sedimentation rates in the 2016 core
 1006 from Ōrākei Basin (Peti and Augustinus 2019), upgraded to 45.6–47.5 cal ka by Peti et al. (2021)
 1007 using Bayesian modelling, 42.2–43.5 cal ka for Pukaki, 43.0–43.5 cal ka for Onepoto, and 42.5–44.8
 1008 cal ka for Pupuke (Hayward and Hopkins 2019) (see Fig. 12 below for locations of these lakes); and a

1009 weighted mean age of 47.4 ± 1.5 ka by $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of co-magmatic K-feldspar and biotite
1010 crystals (Flude and Storey 2016).

1011 In view of the general concordance of these data, an age of around 45 to 47 cal ka for the
1012 Rotoehu/Rotoiti eruptives has been accepted by many in the tephra community (including Danišik et
1013 al. 2020, who used an age of 45.2 ± 3.3 cal ka (2σ) to underpin age models developed for tephras of
1014 the overlying Mangaone Subgroup). However, Barker et al. (2021) suggested that such a relatively
1015 young age was implausible from volcanological and pedological viewpoints, stating “multiple
1016 eruptive units and well-developed palaeosols” exist between the Rotoehu/Rotoiti deposits and the
1017 overlying, ^{14}C -dated, deposits. Barker et al.’s (2021) preferred age is the $^{40}\text{Ar}/^{39}\text{Ar}$ heating-stepped
1018 age of 54 ± 6 ka (2σ) of Flude and Storey (2016), which is indistinguishable from the marine terrace
1019 age of 54 ± 7 of Berryman (1992) and a number of other published ages (Fig. 11B). Although the
1020 exact age of the Rotoehu Ash and correlatives remains somewhat controversial, an age between ~45
1021 and ~55 cal ka is seemingly agreed.

1022

1023 **PART 2 – SOME APPLICATIONS AND NEW DEVELOPMENTS**

1024 **Climate-event stratigraphy and the NZ-INTIMATE project**

1025 A review of past climates of ANZ since 30 cal ka was developed by Alloway et al. (2007) and Barrell
1026 et al. (2013) for the NZ-INTIMATE project (INTEgration of Ice core, MARine, and TERrestrial
1027 records). To facilitate more detailed assessments of climate variability, a composite stratotype was
1028 proposed as an ANZ climate-event stratigraphy (NZce-11 through to NZce-1). It was based on
1029 terrestrial stratigraphic records with type sections selected on the basis of robust numerical age control
1030 and a clear proxy record based on pollen analysis. A major advantage of these records is that they are
1031 linked precisely by one or more tephra layers. More than 20 widespread tephras (from Taupō,
1032 Okataina, Tuhua, Tongariro, and Taranaki volcanoes/centres), each known to have been distributed
1033 \geq ~250 km from source, were selected as marker beds for the project, and their stratigraphic
1034 relationships, distributions, compositions, and ages were reported by Lowe et al. (2008a, 2013). Ages
1035 were developed via Bayesian age-modelling. The close stratigraphic and temporal relationships of
1036 various tephra layers to signals of climatic or environmental change (including landscape evolution,
1037 described broadly by, for instance, Pillans et al. 1992; Alloway et al. 2007, 2013; Willams 2017) since
1038 30 cal ka, and their stratigraphic relationships to specific climate events, were also documented by
1039 Lowe et al. (2008a, 2013), Barrell et al. (2013), and Peti et al. (2021). For example, the start of NZce-
1040 9 (Interstadial D of Otira Glaciation) is marked by the 25.4-cal-ka Kawakawa/Oruanui tephra;
1041 Termination 1 and the start of NZce-5 (beginning of the Last Glacial-Interglacial Transition, LGIT, at
1042 ~18 cal ka) is marked by the ~17.5-cal-ka Rerewhakaaitu tephra deposited a few centuries later
1043 (Newnham et al. 2003); the onset of NZce-3 (late-glacial cool episode) occurs about two centuries

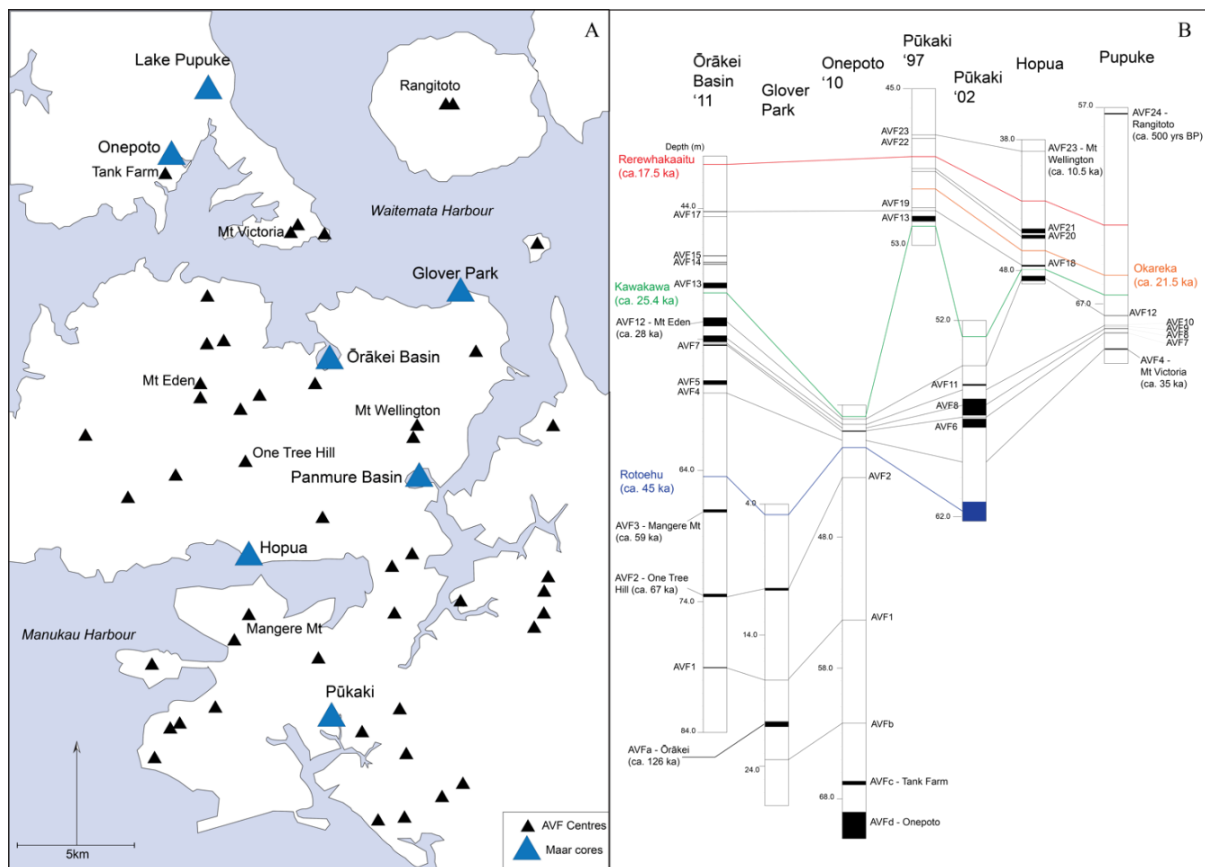
1044 after deposition of the ~14 cal ka Waiohau tephra (Newnham and Lowe 2000); and the start of NZce-
 1045 1, the Holocene, is marked by deposition of 11.7 cal ka Konini tephra (see also note about this tephra
 1046 in Table SM1).

1047

1048 **Eruptive event stratigraphy in Auckland Volcanic Field from tephra record**

1049 The Auckland Volcanic Field (AVF; Fig. 1) is a collection of 53 basaltic volcanic centres that have
 1050 erupted since ~190 ka (Fig. 12; Leonard et al. 2017; Hayward and Hopkins 2019; Hopkins and et al.
 1051 2020a). Each volcanic centre was formed from one eruptive event, but the events show a range of
 1052 eruptive styles (Kereszturi et al. 2014). Where the eruption styles were purely phreatomagmatic, small
 1053 maar craters were formed, providing depocentres for any subsequent tephra-fall events (either
 1054 proximal from eruptions within the AVF, or from distant volcanic centres). Sediment cores have been
 1055 retrieved from many of the maar craters (for example Ōrākei Basin, Pupuke, Pukaki, Onepoto; Fig.
 1056 12) and have been shown to have well preserved, extensive tephra records (Newnham et al. 1999;
 1057 Sandiford et al. 2001; Shane and Hoverd 2002; Hoverd et al. 2005; Molloy et al. 2009; Shane and
 1058 Zawalna-Geer 2011; Hopkins et al. 2015, 2017; Zawana-Geer et al. 2016).

1059



1060
 1061
 1062
 1063
 1064

1065 **Figure 12. A.** Map of volcanoes identified in the AVF. Highlighted are the main maar craters that
1066 have been cored for their lacustrine sediments, thus providing tephra records representing eruptions
1067 both proximal (from the AVF) and distal (from beyond the AVF; see Fig. 1). **B.** Tephra-correlated
1068 sediment cores (from Hopkins et al. 2017). The coloured text and layers show well-dated rhyolitic
1069 deposits used as chronological marker beds (ages from Lowe et al. 2013). Note that many more
1070 rhyolitic and andesitic tephtras are identified within these cores but are not shown here. Black text and
1071 layers show the basaltic AVF deposits (labelled “AVF”) with some of their likely correlative sources.
1072 Subsequent to this work, new records are being developed from fresh cores from Ōrākei and Onepoto,
1073 including a revised age of 23.5 cal ka for Ōkareka tephra (e.g. see Peti and Augustinus 2019; Peti et
1074 al. 2020a, 2021).

1075
1076
1077 The tephra records have been used in the AVF to provide a better understanding of the
1078 eruptive history of the individual centres (Hopkins et al. 2015, 2017, 2020a). Prior to 2011, the ages
1079 of most of the centres in the AVF were poorly constrained (Lindsay et al. 2011). Although a range of
1080 dating techniques had been employed (Lindsay and Leonard 2009), the uncertainties on the ages were
1081 often greater than eruption repose periods (Leonard et al. 2017). In addition, the eruption order of
1082 many centres was largely unknown. The order is important to enable patterns in the temporal or
1083 spatial evolution of the field to be determined, potentially allowing the characteristics of any future
1084 eruption to be predicted on the basis of eruption features through time (e.g. Connor et al. 1992).
1085 Rhyolitic tephtras within the maar cores (derived from distant sources) were geochemically correlated
1086 to known deposits, and used as chronological tie points, providing a basis for age-models and
1087 sedimentation-rate calculations (Molloy et al. 2009; Hopkins et al. 2017; Peti et al. 2020a). Basaltic
1088 tephtras were correlated between the cores and then to their source volcanoes using a multi-criteria
1089 approach that included obtaining major- and trace-element compositions of glass, ages, and
1090 thicknesses of the deposits, and their spatial locations and potential (nearby) sources (Hopkins et al.
1091 2017). This information was then combined with previously constructed chronologies to provide a
1092 temporal eruption history for 48 of the 53 centres, resolving questions about the field’s eruption
1093 patterns (Hopkins et al. 2020a). Findings included recognition of ‘flare-ups’ in eruptions, no pattern in
1094 the spatial evolution of the AVF overall, but a relationship between geochemical signatures and
1095 tephra volumes, and a positive relationship between short repose periods and closely located eruptions
1096 spatially.

1097

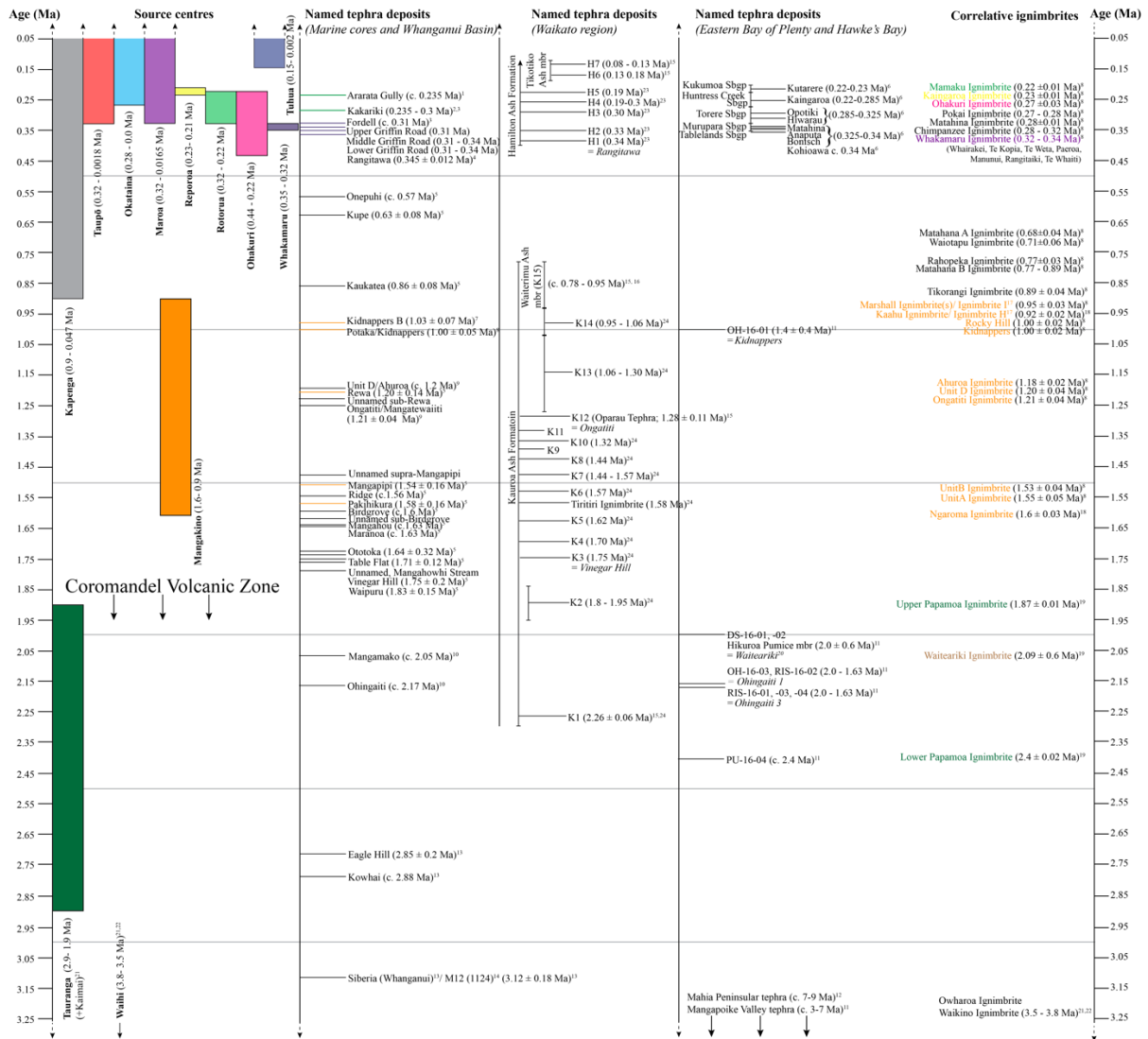
1098 **Developing an integrated record of older (pre-50 cal ka) tephra deposits**

1099 The tephrostratigraphy, and thus the eruptive history, since ~50 cal ka of TVZ rhyolitic volcanism is
1100 largely well known (Fig. 2). However, the older record is incomplete, and heavily biased towards the
1101 voluminous ignimbrite-forming eruptives that dominate much of the central North Island landscape.
1102 The tephra-fall record for events prior to 50 cal ka and since ~3.8 Ma is fragmentary and has been
1103 developed by research in three themes: (i) undertaking fundamental volcanological stratigraphy,
1104 dating, and mapping in proximal areas to recognise relationships between coeval pyroclastic-flow and

1105 fall units, such as those pertaining to (for instance) the Oruanui/Kawakawa tephra deposits (Vucetich
 1106 and Pullar 1969; Wilson 2001), the Rotoiti/Rotoehu tephra deposits (noted earlier), and the
 1107 Whakamaru/Rangitawa tephra deposits (Froggatt et al. 1986; Wilson et al. 1986; Kohn et al. 1992;
 1108 Matthews et al. 2012); (ii) by examining the stratigraphy, ages, and characteristics of distal tephra
 1109 deposits preserved in sedimentary and pyroclastic/volcanic sequences in the Auckland and Waikato
 1110 regions, eastern Bay of Plenty, Hawke's Bay, and Whanganui Basin (e.g. Erdman and Kelsey 1992;
 1111 Naish et al. 1996; Shane et al. 1998b; Lowe et al. 2001; Alloway et al. 2004a; Pillans et al. 2005; Lee
 1112 et al. 2011; Hopkins and Seward 2019; Rees et al. 2020); and (iii) by examining the marine record, an
 1113 archive that Kyle and Seward (1984) suggested would provide the best record of TVZ volcanism
 1114 (rather than terrestrial where the record can be difficult to interpret), as described in the next section.

1115 A compilation of all named tephra (fall) deposits found within the time frame 3.8 Ma to 0.05
 1116 Ma is given in **Fig. 13** (see also Table SM1).

1117



1118

1119

1120

1121 **Figure 13.** A collation of all named tephra-fall deposits found within the time frame of ~3.8 to 0.05
1122 Ma. Key sources in southern CVZ, TVZ, and Tuhua/Mayor Island (Fig. 1) are shown (colour co-
1123 ordinated) along with ages and known ignimbrite correlatives. All ages are shown with 1 s.d. errors
1124 (where reported). Sources: 1, Bussell and Pillans (1997); 2, Bussell (1984); 3, Pillans (1994); 4,
1125 Pillans et al. (1996); 5, Pillans et al. (2005); 6, Manning (1996); 7, Shane et al. (1996); 8, Houghton et
1126 al. (1995); 9, Alloway et al. (2005); 10, Naish et al. (1996); 11, Hopkins and Seward (2019); 12,
1127 Shane et al. (1998b); 13, Grant et al. (2018); 14, Stevens (2010); 15, Lowe et al. (2001); 16, Briggs et
1128 al. (1989); 17, Wilson (1986); 18, Briggs et al. (1993); 19, Briggs et al. (2005); 20, Prentice et al.
1129 (2020); 21, Pittari et al. (2021); 22, Julian (2016); 23, Lowe (2019); 24, Horrocks (2000); 25, Tanaka
1130 et al. (1996); 26, Wilson et al. (2010); Kate Mauriohoo pers. comm. 2021; and this study.

1131
1132
1133
1134

Many unnamed tephtras that occur in marine sediment cores (ODP 1123 and 1124) are not
1135 shown in Fig. 13 which, when coupled with on-land deposits at Mahia Peninsula (~9–7 Ma; Shane et
1136 al. 1998b) and Hawke’s Bay sites (~7–3 Ma; Hopkins and Seward 2019), point to enhanced periods of
1137 volcanism for the periods 11–8 Ma, 7.7–7.0 Ma, 6.63–6.0 Ma, and 5.2–4.5 Ma (Carter et al. 2003;
1138 Alloway et al. 2005; Allan et al. 2008; Stevens 2010). Very few correlations have been established
1139 either between sites or to proximal ignimbrites, leading to a piecemeal record. Many more eruptives
1140 have been identified offshore than onshore (e.g. Lowe et al. 2001; Stevens 2010). Additionally,
1141 because the tephtras deposited within this time period are often not linked to a known source eruption,
1142 their source zone (either TVZ or CVZ) remains unknown, meaning the exact location and timing of
1143 transition of activity from the CVZ to the TVZ remains ambiguous (e.g. Lowe et al. 2001; Carter et al.
1144 2003; Briggs et al. 2005; Prentice et al. 2020; Pittari et al. 2021). Hopkins and Seward (2019) also
1145 discussed the difficulty in accurately dating tephtras in the pre- and early-Quaternary time-frame,
1146 where the uncertainties associated with direct dating methods (e.g. U-Pb, $^{40}\text{Ar}/^{39}\text{Ar}$, U/Th(He), glass-
1147 ITPFT, or zircon fission-track dating) are often $\geq 5\%$, leading to a number of potential overlapping
1148 correlatives, and therefore an inability to unambiguously correlate such deposits for these older time
1149 periods using age alone.

1150 We make the point here that in sampling and analysing glass from welded ignimbrites to try
1151 to affect a correlation with a potential tephra-fall deposit, the constituent pumice clasts in the
1152 ignimbrite, not the matrix materials, should be sampled and analysed. In addition, the largest pumice
1153 clasts should be selected for glass compositional analysis (ideally >50 mm in diameter) to minimise
1154 the potential effects of variations in crystal proportions (Froggatt 1992). The size should be increased
1155 for coarsely crystalline samples.

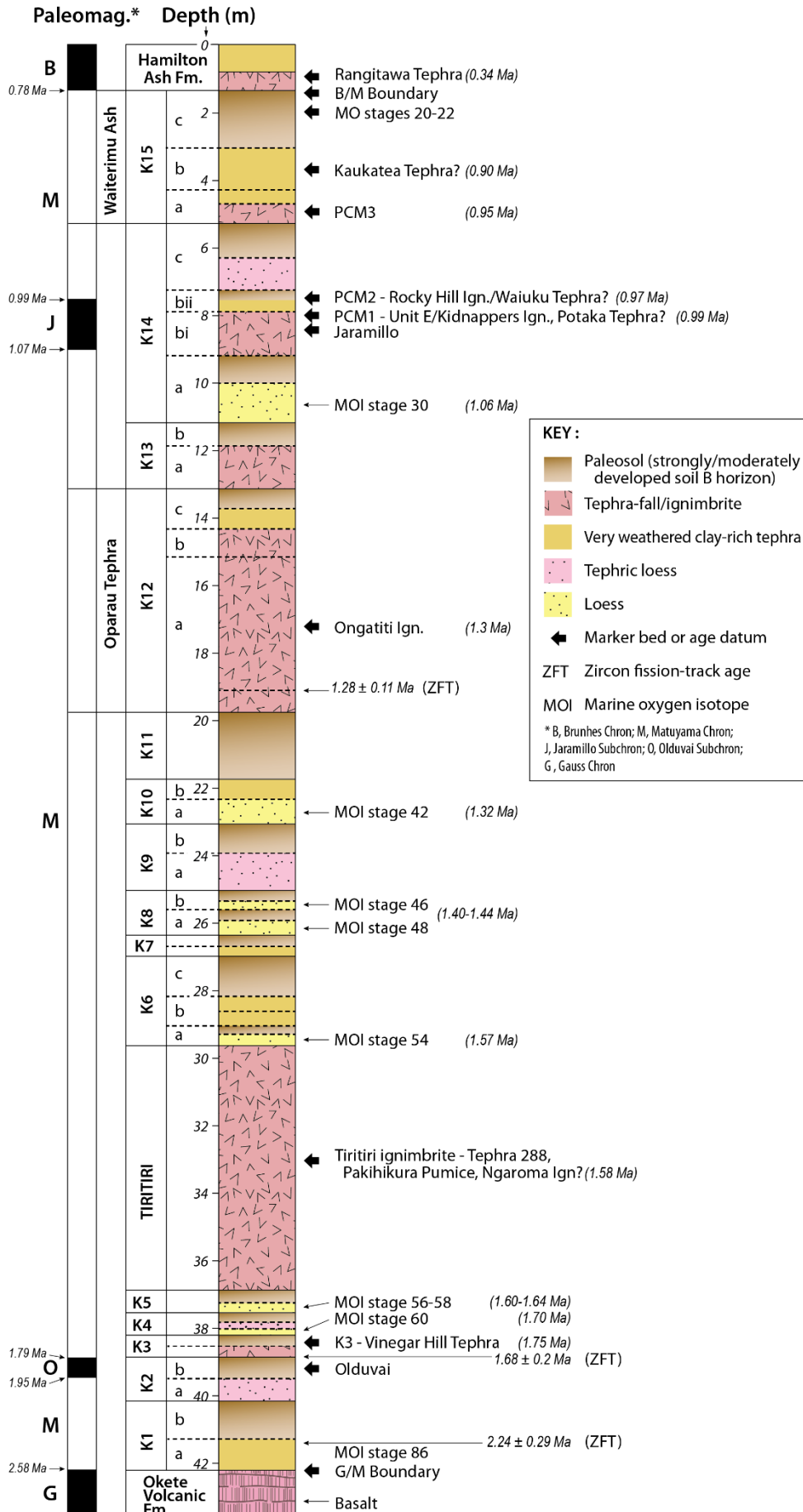
1156

1157 *Correlating strongly weathered old tephtras*

1158 Parts of central North Island are mantled with thick sequences of Quaternary or older tephtra deposits
1159 (including both tephtra fallout deposits and ignimbrites) and associated deposits, commonly loess, with
1160 no known source and little or no age control (Lowe et al. 2001). Many of these deposits are

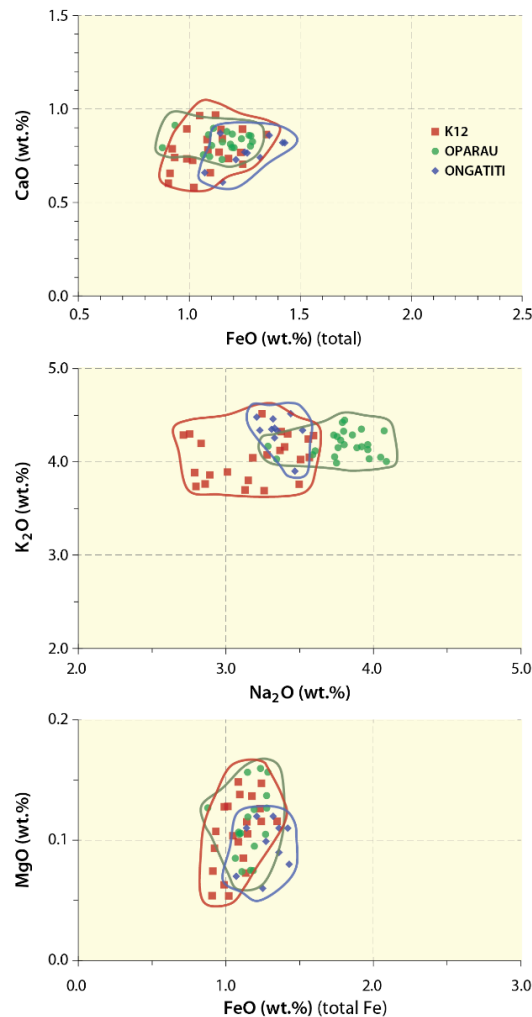
1161 weathered, sometimes very markedly with clay (<2 µm) content as high as 85%, and they also contain
1162 thick paleosols (soils, or soil horizons, of landscapes or environments of the past) (Lowe 2019). They
1163 have been broadly mapped as ‘undifferentiated brown tuffs’ or ‘brown ashes’ (e.g. Ward 1967; Pullar
1164 et al. 1973; Pain 1975; Lowe and Percival 1993; Lowe et al. 2001). Because these clay-rich beds,
1165 apart from a few less-weathered layers, contain few primary minerals and no glass (Lowe and
1166 Percival 1993; Churchman and Lowe 2012) then they have been difficult to correlate and date other
1167 than by stratigraphic relationships and morphological (palaeopedological) features (e.g. Briggs et al.
1168 1989, 1994).

1169 However, progress has been made in evaluating the origins and ages of the temporally-
1170 extensive Kauroa and Hamilton Ash sequences in the Waikato, Pukekohe, and Bay of Plenty regions
1171 (Lowe et al. 2001; Briggs et al. 1996, 2006; Lowe 2019). Horrocks (2000) was able to develop a
1172 chronology for the Kauroa Ash beds, which date between 2.25 Ma and 0.78 Ma, using three
1173 techniques: (i) measurements of palaeomagnetism enabled her to detect changes in magnetic polarity
1174 (an arresting result given the exceptionally clay-rich nature of the beds, discussed further below), and
1175 three chrons and two subchrons were identified (**Fig. 14**); (ii) some beds containing zircon were dated
1176 using the zircon fission-track method (Lowe et al. 2001); and (iii) the analysis by EPMA of melt
1177 inclusions (glass) preserved in scarce quartz grains in a number of the beds enabled major-element
1178 compositions to be obtained for them and hence these ‘fingerprints’ were then able to be compared
1179 with those of well-characterised glass shards in deposits elsewhere in North Island, including tephras
1180 in the well-dated Whanganui Basin sequences (Fig. 10; Table SM1). Other dating techniques,
1181 including combined U-Th-Pb and (U-Th)/He dating of zircon (zircon double-dating) and zircon U-Pb
1182 dating where circumstances are favourable, are also now being applied to such sequences (e.g. Pittari
1183 et al. 2021).



1185 **Figure 14.** Stratigraphy and chronology of the composite, weathered Kauroa Ash sequence in western
1186 Waikato. The sequence, originally divided by Salter (1979) into 15 units (K1–15), has been dated by
1187 Horrocks (2000) using palaeomagnetic measurements; tephrochronology (based on melt-inclusion
1188 glass compositions in quartz to determine possible correlatives as named; see also Table SM1); and
1189 zircon fission-track (ZFT) dating (Lowe et al. 2001). Tiritiri ignimbrite was first identified by
1190 Fergusson (1986). Units younger than Oparau Tephra (= Ongatiti Ignimbrite) at the type location
1191 (Pain 1975) are referred to informally as Papakura Creek members (PCM1–3).
1192

1193 The melt-inclusion EPMA-derived major-element data from bed K12 of the Kauroa Ash
1194 sequence and from the Oparau Tephra (Pain 1975) were identical to equivalent glass-shard-based
1195 analyses of the Ongatiti Ignimbrite (Wilson 1986), confirming their correlation (**Fig. 15**). Another
1196 possible correlative of Ongatiti Ignimbrite, probably a co-ignimbrite ash deposit (Cooper and Wilson
1197 2014), was reported from marine sediments by Allan et al. (2008).
1198



1199 **Figure 15.** EPMA-derived major elements in quartz-hosted melt inclusions from K12 and Oparau
1200 tephra deposits (normalised data from Horrocks 2000) and their close match with elements (as oxides)
1201 in glass shards from Ongatiti Ignimbrite (data for Ongatiti from Briggs et al. 1993; Black et al. 1996).
1202 The low Na₂O content in some inclusions in K12 reflects the difficulty of probing melt inclusions
1203 narrower in diameter (~10 µm) than the optimum beam diameter in the analysis using EPMA.
1204

1205 The fact that the clayey sequence has preserved reversed magnetic polarities dating back to
1206 the base of the Quaternary means that the remanence carrier has been unchanged by chemical
1207 weathering, consistent with the findings of Pillans (1997) who measured palaeomagnetism on
1208 weathered basaltic lava flows in semi-arid tropical northern Queensland as old as 5.6 Ma. The
1209 palaeomagnetic record obtained for the Kauroa sequence is supported by tephrochronology and the
1210 local ZFT dating. For example, the top of the Olduvai subchron is dated at ~1.79 Ma (Cohen and
1211 Gibbard 2019). It is overlain directly by Kauroa tephra K3, which by melt inclusion glass major-
1212 element composition (Horrocks 2000) is correlated with the Vinegar Hill tephra dated at ~1.75 Ma
1213 (Seward and Kohn 1997; Naish et al. 1998; Pillans et al. 2005; Table SM1). As well, these ages are
1214 consistent with the local (but somewhat imprecise) ZFT age of 1.68 ± 0.2 Ma obtained for K3 (Fig.
1215 14).

1216

1217 **Marine record of tephras**

1218 Tephra deposits were first identified in deep marine sediments around ANZ in the late 1960s-1970s
1219 (Ninkovich 1968; Lewis and Kohn 1973; Watkins and Huang 1977; Kohn and Glasby 1978). Further
1220 advances were made during the Deep Sea Drilling Project (DSDP, Leg 90) in the mid-1980s (Nelson
1221 et al. 1985; Froggatt et al. 1986; Lowe 2014), and the record subsequently has been developed mainly
1222 by research programmes of the Ocean Drilling Program (ODP, Leg 181) and IODP (*JOIDES*
1223 *Resolution*), the Scripps Institute of Oceanography, the French Polar Institute Paul-Emile Victor (e.g.
1224 core MD97-2121), the German Helmholtz Institute for Oceanographic Research (e.g. core SO247),
1225 and the NIWA research vessel (RV) *Tangaroa*. The marine sediments east of ANZ record numerous
1226 tephra deposits from eruptions (since 12 Ma) in both the CVZ and TVZ (Fig. 1) because of the
1227 dominantly westerly winds (e.g. Carter et al. 2004; Alloway et al. 2005; Allan et al. 2008). That very
1228 powerful eruptions have lofted ash above 20 km into the easterly stratospheric winds, depositing
1229 tephra westward into the Tasman Sea, however, was noted earlier. A rich record of tephra deposits
1230 has been identified in the Bay of Plenty region (e.g. Pillans and Wright 1992; Shane et al. 2006; Figs.
1231 1, 11).

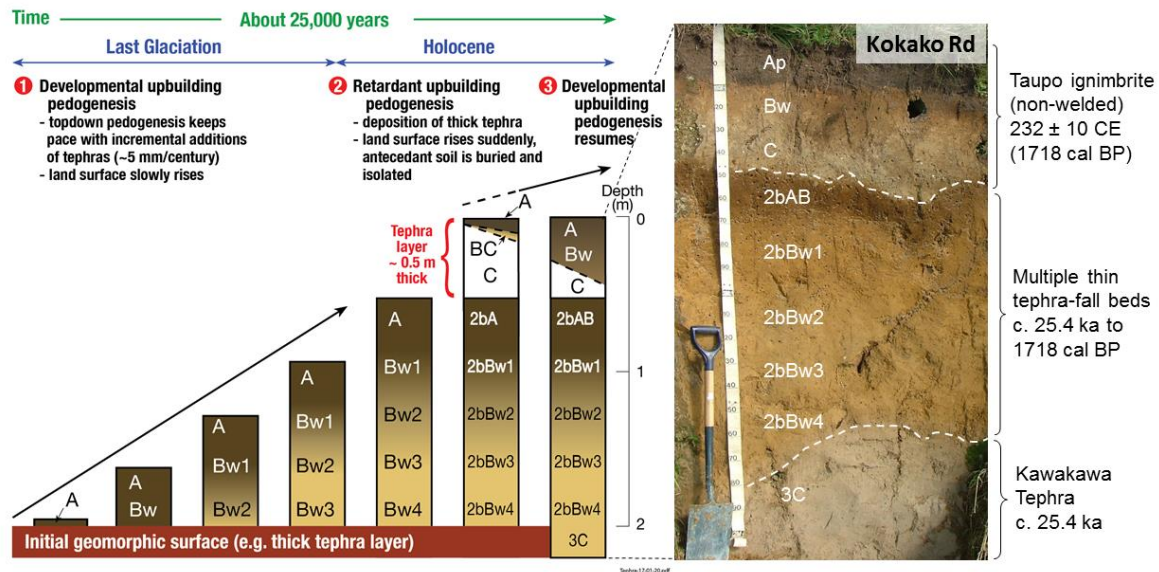
1232 These marine records have well constrained, orbitally-tuned chronologies, allowing the ages
1233 of some of the tephra deposits (when geochemically correlated) to be tested, confirmed, or applied to
1234 correlatives (Fig. 13; Carter 2005). Apart from Pillans and Wright's (1992) pioneering work, and the
1235 contributions of Allan et al. (2008) and Taiapa (2016), no cryptotephra research has been undertaken
1236 on the ANZ marine cores, as pointed out by Holt et al. (2011). This situation contrasts markedly with
1237 the highly advanced cryptotephra-based research being undertaken on cores from the North Atlantic
1238 (e.g. Austin et al. 2014; Abbott et al. 2015, 2018b) and Northwest Pacific (e.g. Matsu'ura et al. 2014,
1239 2021). Recent IODP research cruises (e.g. IODP 372/375, Saffer et al. 2019) to the east of ANZ
1240 provide a basis for rectifying this significant crypto-tephrostratigraphic gap in the near future.

1241 **Forming tephra-derived soils and paleosols in northern ANZ: geological versus**
1242 **pedological processes**

1243 Much of central North Island has been repeatedly overwhelmed or modified by the emplacement of
1244 ignimbrites and numerous mantling tephra-fall deposits. In proximal locations, relatively thick
1245 deposits buried and isolated antecedent soils whereas at medial and distal sites relatively thin tephra-
1246 fall deposits tended to generate ‘accumulating’ profiles (Neall 1977; Lowe and Palmer 2005). The
1247 resultant tephra-derived soils, comprising four distinct taxonomic classes in the New Zealand Soil
1248 Classification (Hewitt 2010) (Tephric Recent, Pumice, Allophanic, and Granular Soils) in a
1249 predictable spatial and temporal pattern, are important because they cover ~31% of North Island
1250 (~13.5% of NZ) (Hewitt et al. 2021). Their character relates mainly to their mode of formation –
1251 upbuilding pedogenesis – along with composition and age, as discussed below.

1252 Topdown pedogenesis is the ‘classical’ development of soil horizons by surface-driven soil-
1253 forming processes acting on a ‘fixed’, pre-existing parent material (i.e. with no or minimal additions
1254 at the land surface) in a downward-moving front. In such a scenario, the soil profile originates via a
1255 two-step process: step 1, accumulation (or exhumation) of a ‘new’ parent material at the land surface
1256 followed by step 2, the modification of the parent material by soil-forming processes and weathering
1257 (the latter mainly involving the dissolution of glass and crystals by hydrolysis and precipitation of the
1258 dissolution products as clays: Hodder et al. 1990; Churchman and Lowe 2012) to form soil horizons,
1259 thus generating a soil profile. However, in North Island landscapes where tephtras have been
1260 repeatedly deposited, many of the soils are formed by upbuilding pedogenesis. Upbuilding
1261 pedogenesis is the ongoing formation of soil via topdown processes whilst tephtras or loess (etc) are
1262 simultaneously added to the land surface (Johnson and Watson-Stegner 1987; Johnson et al. 1990;
1263 Lowe and Tonkin 2010; Lowe 2019). In this scenario, step 1 and step 2 occur together (not
1264 sequentially) so that the soil profile deepens as the land surface rises concomitantly over time. The
1265 profiles become multi-layered soils or paleosols that reflect this interplay of geological versus
1266 pedological processes (Cronin et al. 1996c; McDaniel et al. 2012; Palmer 2013; Alloway et al. 2018).

1267 The frequency and thickness of tephra accumulation, and other factors, determine how much
1268 impact topdown processes have on the ensuing soil-horizon development and profile character. Where
1269 a thick tephra layer is deposited (e.g. >0.5 m), or the rate of accumulation of multiple thin additions is
1270 exceptionally rapid, the pre-existing soil is suddenly buried and isolated at depth (becoming a buried
1271 paleosol), and soil formation begins again on the fresh materials at the new land surface. This process
1272 is *retardant* upbuilding pedogenesis (because the original soil’s development has been permanently
1273 retarded by rapid or ‘paroxysmal’ burial to use the term of Taylor 1933) (**Fig. 16**).
1274



1275

1276

1277

1278

1279

1280

1281

1282

1283

1284

1285

1286

1287

1288

1289

1290

1291

1292

1293

1294

1295

1296

1297

1298

1299

1300

1301

1302

1303

1304

Figure 16. Model of upbuilding pedogenesis, both developmental and retardant, in a multi-layered 25-ka tephra-derived soil profile on Kokako Road near Lichfield, south Waikato. In phase 1, thin, distal tephras/cryptotephras accumulated slowly whilst topdown processes imprinted (near-surface) weak soil horization features on them as the land surface gradually rose. In phase 2, the abrupt deposition of a ~0.5-m-thick tephra layer (non-welded Taupō Ignimbrite) from the powerful Taupō eruption buried the antecedent soil, isolating it from most surface processes so that topdown processes began anew on the freshly-deposited pumiceous tephra at the land surface. Each part of this profile (between the Kawakawa and Taupō tephras), now a buried soil or paleosol, has been an A horizon (topsoil) at some point, as recognised by Taylor (1933, p. 343), who wrote “each layer in a bed of intermittent origin has been, in its turn, the humus layer [topsoil] of the soil and has been subjected to the same series of [topdown soil-forming] conditions”. In phase 3, incremental tephra deposition on the new soil continued and slow developmental upbuilding resumed (after Lowe and Tonkin 2010, McDaniel et al. 2012, and Hewitt et al. 2021, p. 187). Soil horization is based on Clayden and Hewitt (1989). The prefix ‘b’ denotes an identifiable soil horizon with pedogenic features developed before its burial.

In other situations, typically at distal sites where individual tephra-fall beds are usually thin (a few millimetres or centimetres in thickness), the rate of accumulation is incremental and sufficiently slow to allow topdown pedogenesis to keep operating as the land slowly rises. This process is *developmental* upbuilding pedogenesis. The pivotal concept – concurrent deposition and pedogenesis – was originally proposed by Taylor (1933, p. 195), stating that “soil-forming processes are continuous” during the “slow addition of dust from eruptions of the intermittent type”. Thus, topdown pedogenesis continues as thin tephras and cryptotephras accumulate but its impacts are lessened because any one position in the sequence is not exposed to surface-dominated pedogenesis for long before it becomes buried too deeply for these processes to be effective. Thin tephra layers preserved in sediments of nearby lakes or bogs provide unequivocal evidence of persistent incremental tephra accretion to adjacent soil/land surfaces (Alloway et al. 1992; Selby and Lowe 1992; Damaschke et al. 2017a; Lowe 2019). This history thus leaves the profile with a weakly-weathered soil fabric inherited

1305 from when the tephra deposits were being modified at the surface as part of an A and/or upper subsoil
 1306 (AC, AB, or Bw) horizon (Fig. 16).

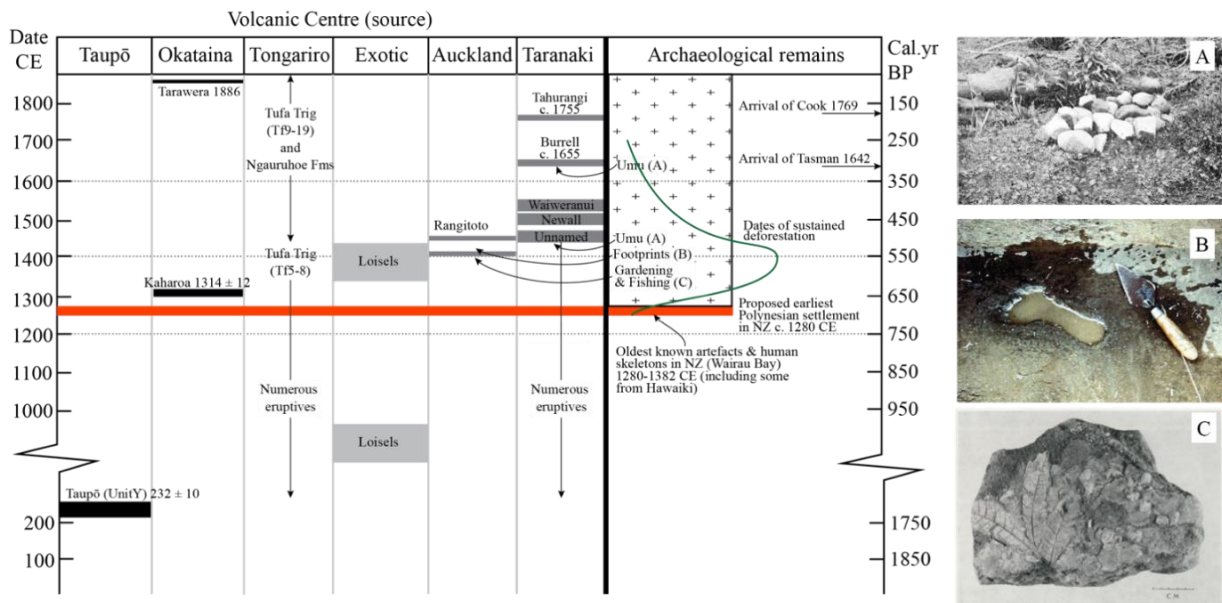
1307 Further information on ANZ's remarkable tephra-derived soils, including their origins,
 1308 distribution, unique allophanic or halloysitic properties, and special management requirements, is
 1309 given in Hewitt et al. (2021). The first successful extraction of palaeoenvironmental DNA from a
 1310 buried allophanic paleosol (on Rotoma tephra aged ~9.5 cal ka) was reported by Huang et al. (2016).

1311 **Tephra and archaeology in ANZ**

1312 Tephra deposits derived from five volcanic centres, together with exotic sea-rafted pumice (Loisels;
 1313 Shane et al. 1998a), provide isochronous constraints on the timing of earliest settlement and human
 1314 impacts in northern ANZ by Polynesian settlers (**Fig. 17**). The relevance of the tephra to archaeology
 1315 was reviewed by Lowe et al. (2000) and Lowe and Newnham (2004) and, in turn, the impacts of
 1316 volcanism on early Māori were reported by Lowe et al. (2002) and Cashman and Cronin (2008).

1317 The most important role of tephrochronology has been in helping to answer the question of
 1318 timing of the earliest Polynesian settlement of ANZ. This question has been difficult and controversial
 1319 because the settlement was very recent, barely 750 years ago (~1280 AD/CE), and so ¹⁴C-age data,
 1320 subject to question because of likely contamination of (e.g.) lake sediments by inwashing of old
 1321 carbon as a result of Polynesian deforestation activities, inbuilt age, or dietary effects, effectively
 1322 resulted in two contradictory models of settlement: 'early' settlement (or transient contact) about
 1323 1500–2000 years ago (Sutton 1987; Holdaway 1996) versus 'late' settlement about 700 years ago
 1324 (Anderson 1991; Higham and Hogg 1997; Higham et al. 1999, 2004; McGlone and Wilmshurst 1999;
 1325 Jacomb et al. 2014).

1326



1327

1328

1329 **Figure 17.** Summary of volcanic sources and the stratigraphic and age relationships of tephras
1330 relevant to Polynesian settlement (~1280 AD/CE) and archaeological (zone of small black crosses),
1331 palynological (green curve), and other evidence in northern ANZ (after Lowe et al. 2000, 2002; Lowe
1332 and Newnham 2004). Taupō tephra provides a widespread datum well before human arrival.
1333 Photographic panels show (A) umu stones from a pre-contact Māori oven from near Stratford
1334 mountain house, Taranaki Maunga (from Oliver 1931); (B) footprint in Rangitoto ash at the Sunde
1335 Site, Motutapu Island (from Nicol 1982), the ash being designated ‘Rangitoto 1’ and dated at 553 ± 7
1336 cal yr BP (Needham et al. 2011; Hopkins et al. 2017; Newnham et al. 2018); and (C) a leaf and fish
1337 scales preserved under Rangitoto ash at Sandy Cove, Motutapu Island (from Scott 1970).
1338
1339

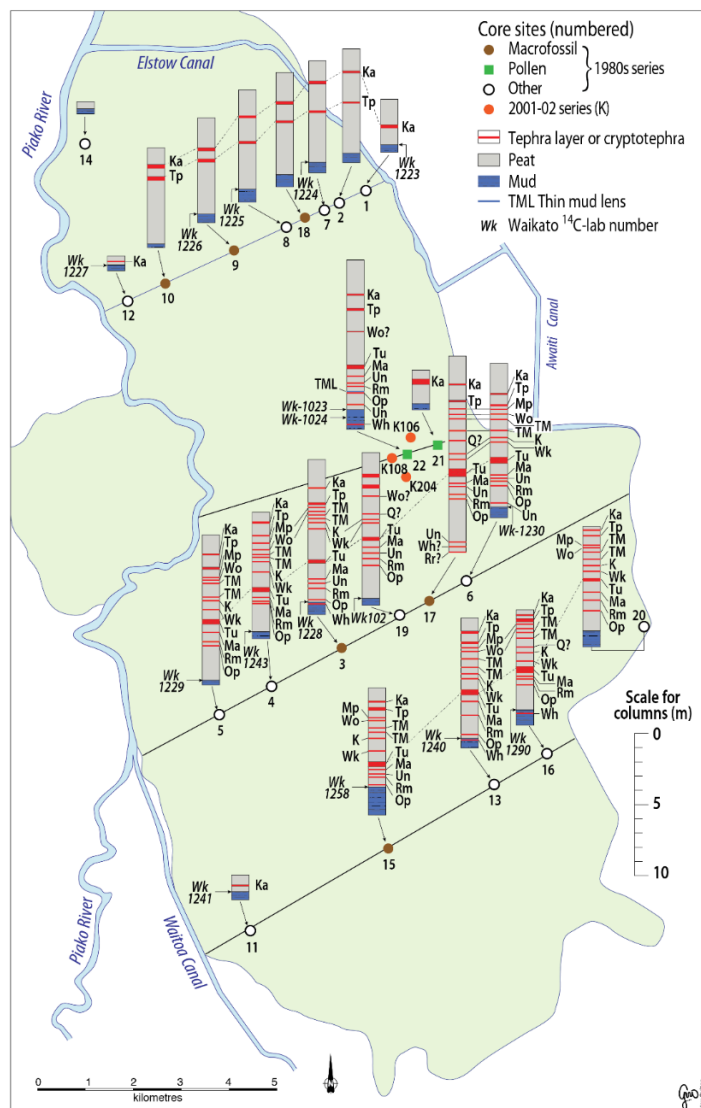
1340 The compositionally distinctive and easily recognisable rhyolitic Kaharoa tephra was erupted
1341 from Mt Tarawera in 1314 ± 12 AD, the most recent rhyolite eruption in ANZ (Lowe et al. 1998;
1342 Hogg et al. 2003; Lowe and Pittari 2014). The tephra was distributed over much of eastern and
1343 northern North Island and provides a critical ‘settlement datum’ that supports the late settlement
1344 model. The tephra provides an isochronous connection between (i) palynological evidence of initial
1345 human impact obtained from analyses of sediment in cores from bogs and lakes (i.e. indirect evidence
1346 of settlement), and (ii) archaeological and artefactual evidence (i.e. direct evidence of settlement)
1347 (Fig. 17). The pollen evidence indicates that deforestation (by burning) was initiated a few decades
1348 before the fall of the Kaharoa tephra (Newnham et al. 1998; see also Perry et al. 2012). Currently,
1349 only one artefact has been found beneath the Kaharoa tephra (out of innumerable archaeological sites
1350 investigated): a single, rat-nibbled seed gnawed by the exotic Pacific rat commensal, *Rattus exulans*,
1351 was found 5 cm beneath Kaharoa tephra in peat at Te Rerenga on the northeastern Coromandel
1352 Peninsula (Wilmshurst and Higham 2004). Thus almost all the Kaharoa-bearing archaeological sites
1353 date to ~1314 AD or younger. Nevertheless, the solitary pre-Kaharoa rat-gnawed seed implies that
1354 rats (and thus Polynesians) were in ANZ a short time before the Kaharoa eruption, a finding
1355 consistent with the palynological and other palaeoenvironmental evidence that indicates that
1356 deforestation began some decades before ~1314 AD, hence indicating that initial settlement was
1357 around 1280 AD or soon after (Brook 2000; Wilmshurst et al. 2008; Lowe 2011; Jacomb et al. 2014;
1358 Anderson 2015; Schmid et al. 2019).

1359

1360 **Kopouatai bog as a prospective Holocene type location for ANZ**

1361 Numerous Holocene tephrostratigraphic and palaeoenvironmental records in ANZ are based on
1362 analyses from terrestrial and marine sediments, with some generating important reference sequences
1363 such as those of Kaipo bog, lakes Pupuke, Maratoto, Tutira, and Poukawa, and marine core MD97-
1364 2121 (Figs. 1, 4, 12). Kopouatai bog in the Hauraki Rift or Depression, an active continental rift
1365 structure (Persaud et al. 2016), is another key site (Fig. 1). An international Ramsar Convention site
1366 and the largest unaltered raised, ombrotrophic peat bog in ANZ dominated by restiad vegetation
1367 (characterised by plant species of the Restionaceae family) (de Lange et al. 1999; Clarkson et al.

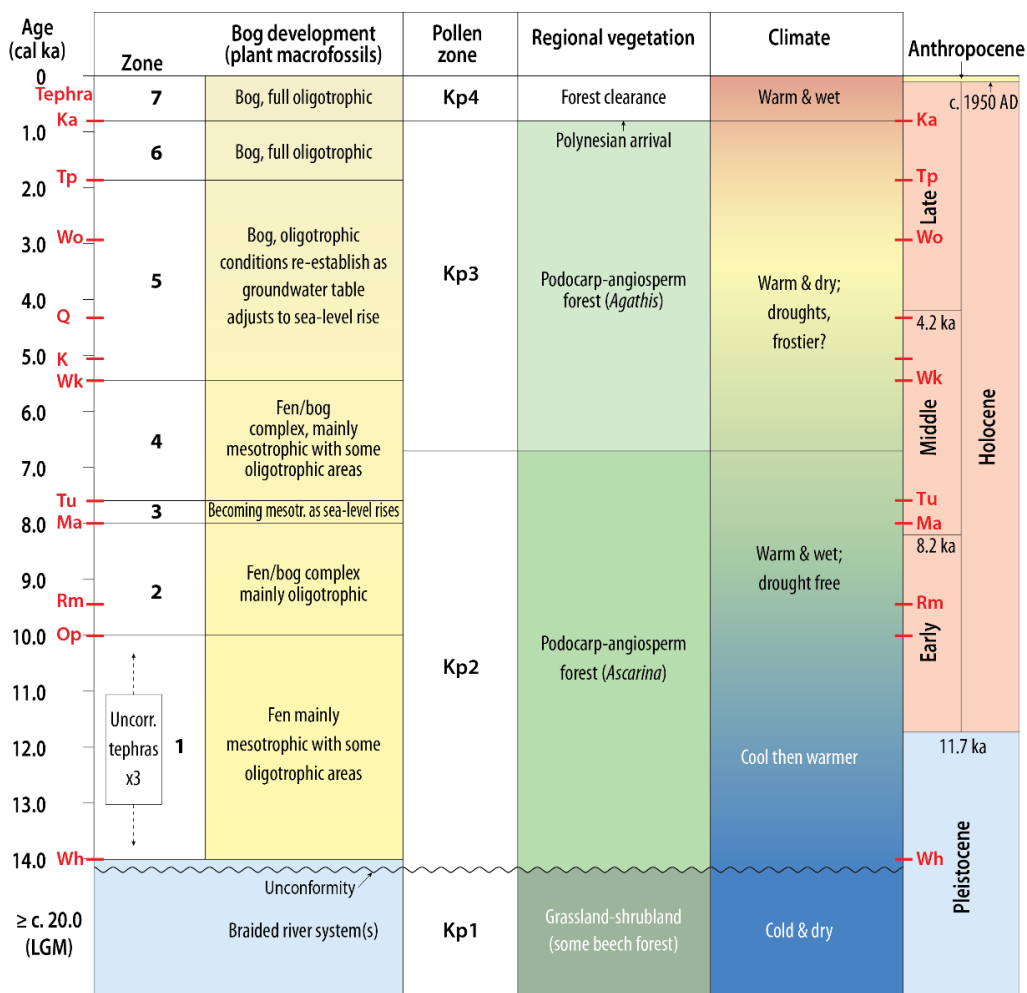
1368 2004; McGlone 2009), Kopouatai comprises thick peat (up to 14 m deep) dating back to the mid-
 1369 LGIT when development of the bog first began around 15 to 16 cal ka (based on the probable
 1370 presence of 15.6-cal-ka Rotorua tephra in core 17 and ¹⁴C dating: **Fig. 18**). More than 20 cores and
 1371 ~40 local ¹⁴C dates have been acquired for the bog, which contains at least 17 visible tephra and
 1372 cryptotephra deposits (Fig. 18). The tephras and cryptotephras (and attendant ages) allow cores to be
 1373 readily correlated stratigraphically from site to site in the bog, and to other tephra-bearing
 1374 palaeoenvironmental records in North Island and beyond (e.g. Newnham et al. 1989, 2019; Barrell et
 1375 al. 2013).



1376
 1377 **Figure 18.** Summary of the tephrostratigraphy (including cryptotephras identified thus far: see Fig. 8)
 1378 of Kopouatai bog based on records obtained from 22 cores (after Hogg and McCraw 1983; Hogg et al.
 1379 1987; de Lange 1989; de Lange and Lowe 1990; Hodder et al. 1991; Newnham et al. 1995, 2019;
 1380 Gehrels et al. 2006, 2008). The northern part of the bog is much younger than the central and southern
 1381 parts because it was inundated in the mid-Holocene, around 7.5 cal ka, by a relative sea-level high
 1382 stand (see Clement et al. 2016). Tephra abbreviations (see Lowe et al. 2013 for ages): Ka, Kaharoa
 1383 (from Okataina Volcanic Centre, OVC); Tp, Taupō (from Taupō Volcanic Centre, TVC); Mp, Mapara

1384 (Unit W, TVC); Whakaipo (Unit X, TVC); Unit Q (Stent, TVC); Unit K (TVC); Wk, Whakatane
 1385 (OVC); Tu, Tuhua (from Tuhua Volcanic Centre); Ma, Mamaku (OVC); Rm, Rotoma (OVC); Op,
 1386 Opepe (Unit E, TVC); Wh, Waiohau (OVC); Rr, Rotorua (OVC). TM, uncorrelated tephra from
 1387 Taranaki Maunga (Fig. 1); Un, uncorrelated tephra.
 1388

1389 By 15 to 14 cal ka, net precipitation at Kopouatai had increased sufficiently for regional water
 1390 tables to rise while temperatures were warming (Jara et al. 2017) so that conditions were favourable
 1391 for more peat to form, initially in scattered low-lying poorly-drained hollows on the fluvial surface
 1392 before coalescing into a series of fens (**Fig. 19**). These expanded rapidly by ~12–10 cal ka, merging to
 1393 form several bogs and eventually a large single bog (Newnham et al. 1995). A detailed but similar
 1394 ontogenetic pattern of tephrochronologically-dated development of peat-bound Lake Maratoto in the
 1395 Hamilton lowlands (Fig. 1), and adjacent raised Rukuhia bog (now largely drained), has been
 1396 described by Green and Lowe (1985).
 1397



1398
 1399 **Figure 19.** Past vegetation and climates reconstructed from Kopouatai bog (after Newnham et al.
 1400 1995). The main tephra marker beds are shown in red (abbreviations of names are explained in Fig.
 1401 18). The unconformity represents the late glacial period when conditions were too dry for extensive
 1402 peat to form and when local rivers were active. The base of the Holocene is that defined by Walker et
 1403 al. (2009); its tripartite subdivision is from Walker et al. (2019). Newnham et al. (1995) suggested that

1404 *Ascarina lucida* and *Agathis australis* may be used as regional pollen stratigraphic markers for the
1405 early and later parts of the Holocene, respectively. The start of the Anthropocene is yet to be formally
1406 defined; here we have arbitrarily suggested ~1950 AD (see Waters et al. 2018).

1407
1408 Kopouati bog thus provides a high-resolution, well-dated (both tephrochronologically and via
1409 local dates from the peat bog itself) palaeoenvironmental record for the entire Holocene based on both
1410 pollen and plant macrofossil analyses (Newnham et al. 1995a). Although Lake Maratoto is the
1411 Australasian parastratotype for the Pleistocene-Holocene boundary (Walker et al. 2009), a type
1412 section was not defined for the Holocene (NZce-1) in the New Zealand climate-event stratigraphy
1413 (Barrell et al. 2013). Because of Kopouatai bog's resolution, sound chronostratigraphy, and well-
1414 established palaeoecological and palaeoclimatic records, its deposits provide an ideal ANZ Holocene
1415 stratotype and NZce-1 type section (Fig. 19). Moreover, the bog contains the Mamaku (8.0 cal ka) and
1416 Stent/Unit Q (4.3 cal ka) tephras, which are close in age to the recently-established global Holocene
1417 subdivisions at 8.2 and 4.2 cal ka (Walker et al. 2019), respectively. Being relatively widespread in
1418 the North Island (e.g. Fig. 4; Alloway et al. 1994), Mamaku and Unit Q (Stent) tephras are therefore
1419 useful chronostratigraphic (isochronous) markers for the early-middle and middle-late Holocene
1420 boundaries, respectively.

1421 Past climates and bog development during the Holocene have been reconstructed in more
1422 detail from a range of studies on lake sediments (e.g. Newnham et al. 1989; Green and Lowe 1985)
1423 and both Kopouatai bog and a small remnant of the 'companion' restiad bog, Moanatuatua, that lies
1424 ~55 km inland (Haenfling et al. 2016; Jara et al. 2017; Newnham et al. 2019). Ratcliffe et al. (2020)
1425 showed how the deposition of tephras and cryptotephras, and associated aerosols, on Moanatuatua
1426 bog provided nutrient inputs that accelerated carbon accumulation rates through the addition of
1427 phosphorus, and by enhancing its release in situ by markedly accelerating the rate of hydrolysis of the
1428 tephra-derived, phosphorus-bearing glass shards and P-rich crystals of apatite in the peat.

1429

1430 **Volcanic hazard assessment**

1431 A range of impacts is associated with tephra-fall events including disruption to communities and
1432 commodities, contamination to food and water supplies, health hazards, and damage to buildings and
1433 infrastructure as well as agronomic activities (Cronin et al. 1998, 2003; Johnson et al. 2000; Hayes et
1434 al. 2017). In addition to their physical and societal impacts, tephra-fall events in ANZ have been used
1435 to produce a record of recurrence rates for volcanism, relevant for volcanic hazard analysis and risk
1436 management (e.g. Shane and Hoverd 2002; Shane 2005; Molloy et al. 2009). For example, in the
1437 Waikato region, Lowe (1988b) suggested that rhyolitic and andesitic tephras (erupted from distant
1438 volcanoes) were deposited at a mean rate of one event per 370 years since ~20 cal ka. Auckland
1439 (ANZ's biggest city, home to one-third of ANZ's population), however, is at risk from both proximal
1440 events (AVF-sourced) and distal events (TVZ- or Taranaki- or Tuhua- sourced). The detailed analysis

1441 of 106 macroscopic (>0.5 mm thick) tephra deposits has been used to show mean recurrence intervals
 1442 of tephra-fall events in Auckland over the last 80 kyrs (Molloy et al. 2009; **Table 4**). These authors
 1443 concluded that the minimum recurrence interval for a tephra fall event with ≥ 0.5 -mm-thick deposit
 1444 would be once every 1500 years, and that the highest probability event would be one with a <1-mm-
 1445 thick deposit.

1446

1447 **Table 4.** Average recurrence intervals of tephra-fall events in Auckland over the last 80 kyrs (after
 1448 Molloy et al. 2009).

Volcanic source	Number of events since 80 ka	Recurrence interval
Taranaki Maunga	52	1 event every 1.5 kyrs
Auckland Volcanic Field	24	1 event every 3.5 kyrs
Taupō Volcanic Zone	21	1 event every 3.8 kyrs
Tongariro Volcanic Centre	7	1 event every 11.4 kyrs
Tuhua Volcanic Centre	2	1 event every 40 kyrs

1449

1450

1451 The recurrence intervals calculated (Table 4) are, however, an oversimplification for two
 1452 main reasons. Firstly, they do not take into account the detail and variability in the eruptive patterns.
 1453 For example, it is known that periods of heightened activity occurred at all of the volcanic source
 1454 regions (e.g. Lowe 1988b; Leonard et al. 2017; Hopkins et al. 2017), which would inevitably produce
 1455 shorter repose periods than the mean period overall. Secondly, Molloy et al. (2009) noted that their
 1456 study was biased toward thicker tephra deposits (>0.5 mm), overlooking the impact from thinner
 1457 tephra-fall deposits including those of submillimetre thickness, namely cryptotephra. Together these
 1458 thin and submillimetre deposits provide a much more comprehensive record of volcanic events than
 1459 that revealed by visible tephra layers alone (e.g. Gehrels et al. 2006, 2010; Payne et al. 2008; Bourne
 1460 et al. 2016; Watson et al. 2016b, 2017; Loame et al. 2018). Hence the real frequency of fine ash
 1461 deposition could be orders of magnitude greater than present estimates. In addition, Newnham et al.
 1462 (1999) highlighted the impact of the eruptions of Ruapehu in 1995–1996, which, although these did
 1463 not leave any visible ash on the land surface at distal sites, nevertheless shut down aviation in
 1464 Auckland for several nights. Paradoxically, sparse, fine-grained glass-shard particles, essentially
 1465 invisible, may have had the deadliest effect: Newnham et al. (2010) suggested that such tiny shards
 1466 from Ruapehu may have caused dozens of respiratory-related deaths for people in Hamilton and
 1467 Auckland, which are 170 and 280 km, respectively, north of the volcano (see also Horwell and Baxter
 1468 2006; Baxter and Horwell 2015).

1469 As noted elsewhere, new cryptotephra-based studies are currently underway both on land
 1470 (e.g. Loame et al. 2016, 2017) and in the marine realm (Kutterolf and Hopkins 2019) and these will

1471 help to more accurately assess the number and thus impact of even the thinnest (submillimetre)
1472 tephra-fall events, allowing more accurate hazard and risk assessments to be made.

1473 Finally, we report that various probabilistic hazard models have also been developed in ANZ,
1474 including via the DEVORA project in Auckland, using available tephra records and other
1475 information, but we note that most of the models do not account for cryptotephra (e.g. Bonadonna et
1476 al. 2005; Magill and Blong 2005; Magill et al. 2006; Hurst and Smith 2010; Green et al. 2014, 2016;
1477 Deligne et al. 2017; Damaschke et al. 2018; Bebbington 2020; Cronin et al. 2021).

1478

1479 Acknowledgements

1480 We thank guest editor James Scott for inviting us to write this article for the IAVCEI (NZ) special
1481 issue. We are especially grateful to former students whose theses we have cited. Max Oulton is
1482 thanked for drawing many of the diagrams in the paper, Nic Ross (Hamilton Radiology) for scanning
1483 lake cores using CT imaging and for the images in Fig. 9b, and Simon Nathan for providing Fig. 3.
1484 John Stribling and Tehnuka Ilanko are thanked for information about A.W.O. Burrell, and Brent
1485 Alloway, Marlena Prentice, Paul Froggatt, and Kate Mauriohooho willingly provided very valuable
1486 comments on a number of topics in the paper. We especially thank reviewers Alan Palmer and James
1487 White for their insightful comments and suggestions that have markedly improved the paper. Helen
1488 Deayton of Taylor & Francis provided much-appreciated support during the article's production
1489 phase. Notable mention is due to Caitlin Buck, Irka Hajdas, and Maarten Blaauw who introduced us
1490 to the revelatory world of Bayesian age modelling. Hopkins acknowledges the NZ Marsden Fund Te
1491 Pūta Rangahau a Marsden for supporting her Marsden Fast Start project, "Cryptotephra: unearthing
1492 hidden eruptions from Taupō Volcanic Zone" (MFP-VUW1809). Lowe acknowledges the Earthquake
1493 Commission (EQC) for supporting the project, "Hidden hazards: revealing volcanic ashfall hazards in
1494 the Waikato region by detecting and analysing cryptotephra in sediments" (15/U713), the Marsden
1495 Fund for supporting two projects, "New Views from old soils: testing the reconstruction of
1496 environmental and climatic change using genetic signals preserved in buried paleosols" (UOW1006),
1497 and "Earth-shaking insight from liquefied volcanic-ash (tephra) layers in lakes: using geotechnical
1498 experiments, CT-scanned lake sediment cores, and tephrochronology to map and date prehistoric
1499 earthquakes" (UOW1902), and also the MBIE Endeavour Fund (Smart Ideas) for support for the
1500 project "Evaluating earthquake risk using liquefied volcanic-ash layers in lakes" (UOWX1903).
1501 Marsden-Fund projects are administered by the Royal Society of New Zealand (Royal Society Te
1502 Apārangi). The paper is also an output of the Commission on Tephrochronology (COT) of the
1503 International Association of Volcanism and Chemistry of the Earth's Interior (IAVCEI).

1504

1505 References

1506 Abbott, P.M., Bourne, A.J., Purcell, C.S., Davies, S.M., Scourse, J.D., Pearce,

1507 N.J.G., 2015. Last Glacial Period cryptotephra deposits in an eastern North Atlantic marine sequence:
1508 Exploring linkages to the Greenland ice-cores, *Quaternary Geochronology* 31, 62-76.
1509

1510 Abbott, P.M., Griggs, A.J., Bourne, A.J., Davies, S.M. 2018a. Tracing marine cryptotephra in the
1511 North Atlantic during the last glacial period: protocols for identification, characterisation and
1512 evaluating depositional controls. *Marine Geology* 401, 81-97.
1513

1514 Abbott, P.M., Griggs, A.J., Bourne, A., Chapman, M.R., Davies, S., 2018b. Tracing marine
1515 cryptotephra in the North Atlantic during the last glacial period: improving the North Atlantic marine
1516 tephra framework. *Quaternary Science Reviews* 189, 169-186.
1517

1518 Abbott, P.M., Jensen, B.J.L., Lowe, D.J., Suzuki, T., Veres, D. 2020. Crossing new frontiers:
1519 extending tephrochronology as a global geoscientific research tool. *Journal of Quaternary Science* 35,
1520 1-8.
1521

1522 Allan, A.S., Baker, J.A., Carter, L. and Wysoczanski, R.J., 2008. Reconstructing the Quaternary
1523 evolution of the world's most active silicic volcanic system: insights from an~ 1.65 Ma deep ocean
1524 tephra record sourced from Taupo Volcanic Zone, New Zealand. *Quaternary Science Reviews*, 27(25-
1525 26), pp.2341-2360.
1526

1527 Alloway, B.V., McGlone, M.S., Neall, V.E., Vucetich, C.G. 1992. The role of Egmont-sourced
1528 tephra in evaluating the paleoclimatic correspondence between the bio- and soil-stratigraphic
1529 records of central Taranaki, New Zealand. *Quaternary International* 13-14, 187-194.
1530

1531 Alloway, B.V., Pillans, B.J., Sandhu, A.S. and Westgate, J.A., 1993. Revision of the marine
1532 chronology in the Wanganui Basin, New Zealand, based on the isothermal plateau fission-track dating
1533 of tephra horizons. *Sedimentary geology*, 82(1-4), pp.299-310.
1534

1535 Alloway BV, Lowe DJ, Chan RPK, Eden DN, Froggatt PC, 1994. Stratigraphy and chronology of the
1536 Stent tephra, a c. 4000 year old distal silicic tephra from Taupo Volcanic Centre, New Zealand. *New
1537 Zealand Journal of Geology and Geophysics*, 37:37-47.
1538

1539 Alloway, B.V., Neall, V.E., Vucetich, C.G., 1995. Late Quaternary (post-28,000 year B.P.)
1540 tephrostratigraphy of northeast and central Taranaki, New Zealand. *Journal of the Royal Society of
1541 New Zealand* 25, 385–458.
1542

1543 Alloway, B., Westgate, J., Pillans, B., Pearce, N., Newnham, R., Byrami, M. and Aarburg, S., 2004a.
1544 Stratigraphy, age and correlation of middle Pleistocene silicic tephras in the Auckland region, New
1545 Zealand: a prolific distal record of Taupo Volcanic Zone volcanism. *New Zealand Journal of Geology
1546 and Geophysics*, 47(3), pp.447-479.
1547

1548 Alloway BV, Pribadi A, Westgate JA, Bird, M., Fifield, L.K., Hogg, A.G., Smith, I.E.M. et al. 2004b.
1549 Correspondence between glass-FT and ¹⁴C ages of silicic pyroclastic flow deposits sourced from
1550 Maninjau Caldera, West-Central Sumatra. *Earth and Planetary Science Letters* 227, 121–133.
1551

1552 Alloway, B.V., Pillans, B.J., Carter, L., Naish, T.R. and Westgate, J.A., 2005. Onshore–offshore
1553 correlation of Pleistocene rhyolitic eruptions from New Zealand: implications for TVZ eruptive
1554 history and paleoenvironmental construction. *Quaternary Science Reviews*, 24(14-15), pp.1601-1622.
1555

1556 Alloway, B.V., Lowe, D.J., Barrell, D.J.A., Newnham, R.M., Almond, P.C., Augustinus, P.C.,
1557 Bertler, N., Carter, L., Litchfield, N.J., McGlone, M.S., Shulmeister, J., Vandergoes, M.J., Williams,
1558 P.W., NZ-INTIMATE members, 2007. Towards a climate event stratigraphy for New Zealand over
1559 the past 30 000 years (NZ-INTIMATE project). *Journal of Quaternary Science* 22, 9–35.
1560

- 1561 Alloway, B.V., Lowe, D.J., Larsen, G., Shane, P.A.R., Westgate, J.A. 2013. Tephrochronology. In:
 1562 Elias, S.A., Mock, C.J. (editors), *Encyclopaedia of Quaternary science*, 2nd Edition, Vol. 4. Elsevier,
 1563 Amsterdam, pp. 277-304.
- 1564
 1565 Alloway, B.V., Almond, P.C., Moreno, P.I., Sagredo, E., Kaplan, M.R., Kubik, P.W., Tonkin, P.J.
 1566 2018. Mid-latitude trans-Pacific reconstructions and comparisons of coupled glacial/interglacial
 1567 climate cycles based on soil stratigraphy of cover-beds. *Quaternary Science Reviews* 189, 57-75.
- 1568
 1569 Almond, P.C., 1996. Loess, soil stratigraphy and Aokautere ash on late Pleistocene surfaces in south
 1570 Westland, New Zealand: interpretation and correlation with the glacial stratigraphy. *Quaternary*
 1571 *International*, 34, pp.163-176.
- 1572
 1573 Almond PJ, Shanun FL, Rieser U, Shulmeister J. 2007. An OSL, radiocarbon and tephra isochron-
 1574 based chronology for Birdlings Flat loess at Ahuriri Quarry, Banks Peninsula, Canterbury, New
 1575 Zealand. *Quaternary Geochronology* 2, 4-8.
- 1576
 1577 Almond, P. C., Gulyás, S., Sümegei, P., Sümegei, B. P., Covey-Crump, S., Jones, M., Shaw, J., Parker,
 1578 A. 2020. A palaeoenvironmental record of the Southern Hemisphere last glacial maximum from the
 1579 Mount Cass loess section, North Canterbury, Aotearoa/ New Zealand. *Quaternary Research* 1–15.
 1580 <https://doi.org/10.1017/qua.2020.95>
- 1581
 1582 Anderson, A. J. 1991. The chronology of colonization in New Zealand. *Antiquity* 65, 767-695.
- 1583
 1584 Anderson, A. 2015. Speaking of migration AD 1150-1450. In: Anderson, A., Harris, A., Williams, B.
 1585 (Eds.), *Tangata Whenua – An Illustrated History*. Bridget Williams Books, Auckland, pp. 42-69.
- 1586
 1587 Augustinus, P., Bleakley, N., Deng, Y., Shane, P., Cochrane, U., 2008. Rapid change in early
 1588 Holocene environments inferred from Lake Pupuke, Auckland City, New Zealand. *Journal of*
 1589 *Quaternary Science* 23, 435-447.
- 1590
 1591 Austin, W. E. N., Abbott, P. M., Davies, S. M., Pearce, N. J. G. & Wastegård, S. (eds) 2014.
 1592 *Marine Tephrochronology*. Geological Society, London, Special Publications 398.
- 1593
 1594 Balascio, N.L., Francus, P., Bradley, R.S., Schupack, B.B., Miller, G.H., Kvisvik, B.C., Bakke, J., and
 1595 Thordarson, T., 2015. Investigating the use of scanning X-Ray fluorescence to locate cryptotephra in
 1596 minerogenic lacustrine sediment: Experimental results. In Croudace, I.W., and Rothwell, R.G., (eds)
 1597 *Micro-XRF studies of sediment cores*, *Developments in Paleoenvironmental Research* 17.
- 1598
 1599 Barker, S.J., Van Eaton, A.R., Mastin, L.G., Wilson, C.J.N., Thompson, M.A., Wilson, T.M., Davis,
 1600 C. and Renwick, J.A., 2019. Modeling ash dispersal from future eruptions of Taupo
 1601 supervolcano. *Geochemistry, Geophysics, Geosystems*, 20(7), pp.3375-3401.
- 1602
 1603 Barker, S.J., Wilson, C.J., Illsley-Kemp, F., Leonard, G.S., Mestel, E.R., Mauriohooho, K. and
 1604 Charlier, B.L., 2021. Taupō: an overview of New Zealand’s youngest supervolcano. *New Zealand*
 1605 *Journal of Geology and Geophysics*, pp.1-27.
- 1606
 1607 Barrell, D.J.A., Almond, P.C., Vandergoes, M.J., Lowe, D.J., Newnham, R.M. 2013. A composite
 1608 pollen-based stratotype for inter-regional evaluation of climatic events in New Zealand over the past
 1609 30,000 years (NZ-INTIMATE project). *Quaternary Science Reviews* 74, 4-20.
- 1610
 1611 Baumgart, I.L., 1954. Some ash showers of the central North Island. *N.Z. Journal of Science and*
 1612 *Technology* B35: 456-467.
- 1613
 1614 Baumgart IL, Healy J. 1956. Recent volcanicity at Taupo, New Zealand. *Proceedings of the 8th*

- 1615 Pacific Science Congress (The Philippines, 1953). 2:113-125.
 1616
 1617 Baxter, P.J., Horwell, C.J. 2015. Impacts of eruptions on human health. In Sigurdsson, H. (ed), The
 1618 Encyclopaedia of Volcanoes, second edition. Elsevier, San Diego, p.1035-1047.
 1619
 1620 Beanland, A., Berryman, K.R., Blick, G.H. 1989. Geological investigations of the 1987 Edgecumbe
 1621 earthquake, New Zealand. *New Zealand Journal of Geology and Geophysics* **32**, 73-92.
 1622
 1623 Bebbington, M.S. 2020. Temporal-volume probabilistic hazard model for a supervolcano: Taupo,
 1624 New Zealand. *Earth and Planetary Science Letters* **536**, 116141.
 1625
 1626 Berger, G.W. 1985. Thermoluminescence dating of volcanic ash. *Journal of Volcanology and*
 1627 *Geothermal Research* **25**, 333-347.
 1628
 1629 Berger, G.W. 1992. Dating volcanic ash by use of thermoluminescence. *Geology* **20**, 11–14.
 1630
 1631 Berger, G.W., Pillans, B.J., Palmer, A.S. 1992. Dating loess up to 800 ka by thermoluminescence.
 1632 *Geology* **20**, 403–406.
 1633
 1634 Berry, J.A. 1928. The volcanic deposits of Scinde Island. With special reference to the pumice bodies
 1635 called chalazoidites. *Transactions of the N.Z. Institute* **59**, 571-608.
 1636
 1637 Berryman, K., 1992. A stratigraphic age of Rotoehu Ash and late Pleistocene climate interpretation
 1638 based on marine terrace chronology, Mahia Peninsula, North Island, New Zealand. *New Zealand*
 1639 *journal of geology and geophysics*, **35**(1), pp.1-7.
 1640
 1641 Berryman, K.R., 1993. Distribution, age, and deformation of late Pleistocene marine terraces at Mahia
 1642 Peninsula, Hikurangi subduction margin, New Zealand. *Tectonics*, **12**(6), pp.1365-1379.
 1643
 1644 Berryman, K., Marden, M., Eden, D., Mazengarb, C., Ota, Y. and Moriya, I., 2000. Tectonic and
 1645 paleoclimatic significance of Quaternary river terraces of the Waipaoa River, east coast, North Island,
 1646 New Zealand. *New Zealand Journal of Geology and Geophysics*, **43**(2), pp.229-245.
 1647
 1648 Bilderback, E.L., Pettinga, J.R., Litchfield, N.J., Quigley, M., Marden, M., Roering, J.J., Palmer, A.S.
 1649 2015. Hillslope response to climate-modulated river incision in the Waipaoa catchment, East Coast
 1650 North Island, New Zealand. *Bulletin of the Geological Society of America* **127**(1-2), 131-148.
 1651
 1652 Birrell, K.S. 1974. Tephric loess studies. In: Read NE, editor. *Soil Groups of New Zealand. Part 1:*
 1653 *Yellow-brown Pumice Soils.* Wellington: New Zealand Society of Soil Science; p. 56–61.
 1654
 1655 Blaauw, M., Christen, J.A., Bennett, K.D., Reimer, P.J. 2018: Double the dates and go for Bayes –
 1656 impacts of model choice, dating density and quality on chronologies. *Quaternary Science Reviews*
 1657 **188**, 58-66.
 1658
 1659 Black, T.M., Shane, P.A.R., Westgate, J.A., Froggatt, P.C., 1996. Chronological and palaeomagnetic
 1660 constraints on widespread welded ignimbrites of the Taupo volcanic zone, New Zealand. *Bulletin of*
 1661 *Volcanology* **58**, 226-238.
 1662
 1663 Bonadonna, C., Connor, C.B., Houghton, B.F., Connor, L., Byrne, M., Laing, A., Hincks, T., 2005.
 1664 Probabilistic modeling of tephra dispersion: hazard assessment of a multi-phase eruption at Tarawera,
 1665 New Zealand. *J. Geophys. Res. Solid Earth* **110** (B03203).
 1666
 1667 Bonadonna, C., Biass, S., Menon, S., Gregg, C.E. 2020. Assessment of risk associated

1668 with tephra-related hazards. In: Papale, P. (ed), Forecasting and Planning for Volcanic Hazards,
1669 Risks, and Disasters, pp. 329-378. Elsevier.
1670

1671 Borchardt, G. A.; Norgren, J. A.; Harward, M. E. 1973: Correlation of ash layers in peat bogs of
1672 eastern Oregon. Geological Society of America Bulletin 84, 3101-3108.
1673

1674 Bösken, J.J. and Schmidt, C., 2020. Direct and indirect luminescence dating of tephra: A
1675 review. Journal of Quaternary Science, 35(1-2), pp.39-53.
1676

1677 Bourne, A.J., Abbott, P.M., Albert, P.G., Cook, E., Pearce, N.J.G., Ponomareva, V., Svensson, A.,
1678 Davies, S.M., 2016. Risks of recurrent long-range ash dispersal from northern Pacific Arc volcanoes.
1679 Sci. Rep. 6 (29837), 1-8.
1680

1681 Briggs, R.M., Itaya, T., Lowe, D.J. and Keane, A.J., 1989. Ages of the Pliocene-Pleistocene
1682 Alexandra and Ngatutura Volcanics, western north Island, New Zealand, and some geological
1683 implications. New Zealand journal of geology and geophysics, 32(4), pp.417-427.
1684

1685 Briggs, R.M., Gifford, M.G., Moyle, A.R., Taylor, S.R., Norman, M.D., Houghton, B.F. and Wilson,
1686 C.J.N., 1993. Geochemical zoning and eruptive mixing in ignimbrites from Mangakino volcano,
1687 Taupo Volcanic Zone, New Zealand. Journal of volcanology and geothermal research, 56(3), pp.175-
1688 203.
1689

1690 Briggs, R.M.; Lowe, D.J.; Goles, G.G.; Shepherd, T.G. 1994. Intra-conference Tour Day 1:
1691 Hamilton–Raglan–Hamilton. In: Lowe, D.J. (ed) Conference Tour Guides. Proceedings International
1692 Inter-INQUA Field Conference and Workshop on Tephrochronology, Loess, and Paleopedology,
1693 University of Waikato, Hamilton, New Zealand, 24-44.
1694

1695 Briggs R, Hall G, Harmsworth G, Hollins A, Houghton B, Hughes G, Morgan M, and Whitbread-
1696 Edwards A (1996) Geology of the Tauranga area. Department of Earth Sciences, University of
1697 Waikato Occasional Report 22. 57 pp + map.
1698

1699 Briggs, R.M., Houghton, B.F., McWilliams, M. and Wilson, C.J.N., 2005. $^{40}\text{Ar}/^{39}\text{Ar}$ ages of silicic
1700 volcanic rocks in the Tauranga-Kaimai area, New Zealand: dating the transition between volcanism in
1701 the Coromandel Arc and the Taupo Volcanic Zone. New Zealand Journal of Geology and
1702 Geophysics, 48(3), pp.459-469.
1703

1704 Briggs, R.M.; Lowe, D.J.; Esler, W.R.; Smith, R.T.; Henry, M.A.C.; Wehrmann, H.; Manning, D.A.
1705 2006. Geology of the Maketu area, Bay of Plenty, North Island, New Zealand – Sheet V14 1:50 000.
1706 Department of Earth Sciences, University of Waikato, Occasional Report 26. 44 pp + map.
1707

1708 Bronk Ramsey, C., Albert, P.G., Blockley, S.P.E., Hardiman, M., Housley, R.A., Lane, C.S., Lee, S.,
1709 Matthews, I.P., Smith, V.C., Lowe, J.J. 2015. Improved age estimates for key Late Quaternary
1710 European tephra horizons in the RESET lattice. Quaternary Science Reviews 118, 18-32.
1711

1712 Brook, F.J. 2000. Prehistoric predation of the landsnail *Placostylus ambagiosus* Suter
1713 (Stylommatophora: Bulimulidae), and evidence for the timing of establishment of rats in
1714 northernmost New Zealand. Journal of the Royal Society of New Zealand 30, 227-241.
1715

1716 Buck, M.D. 1985. An assessment of volcanic risk on and from Mayor Island, New Zealand. New
1717 Zealand Journal of Geology and Geophysics 28, 283-298.
1718

1719 Buck, M.D., Briggs, R.M. and Nelson, C.S., 1981. Pyroclastic deposits and volcanic history of Mayor
1720 Island. New Zealand journal of geology and geophysics, 24(4), pp.449-467.
1721

- 1722 Buck, C.E., Higham, T.F.G., Lowe, D.J. 2003: Bayesian tools for tephrochronology. *The Holocene*
 1723 13, 639-647.
 1724
- 1725 Buhay, W.M., Clifford, P.M. and Schwarcz, H.P., 1992. ESR dating of the Rotoiti Breccia in the
 1726 Taupo volcanic zone, New Zealand. *Quaternary science reviews*, 11(1-2), pp.267-271.
 1727
- 1728 Bussell, M.R., 1984. Geology and paleobotany of the Rangitawa Stream area, southeast Wanganui
 1729 Basin. Unpublished B.Sc.(Hons) thesis. Victoria University of Wellington.
 1730
- 1731 Bussell, M.R. and Pillans, B., 1997. Vegetational and climatic history during oxygen isotope stage 7
 1732 and early stage 6, Taranaki, New Zealand. *Journal of the Royal Society of New Zealand*, 27(4),
 1733 pp.419-438.
 1734
- 1735 Carter, R.M. 2005. A New Zealand climate template back to c. 3.9 Ma: ODP Site 1119, Canterbury
 1736 Bight, south-west Pacific Ocean, and its relationship to onland successions. *Journal of the Royal*
 1737 *Society of New Zealand* 35, 9-42.
 1738
- 1739 Carter, R.M. 2013. Fleming's legacy. In Graham, I. (ed) *A Continent on the Move: New Zealand*
 1740 *Geoscience Revealed*, 2nd edition. Geoscience Society of New Zealand with GNS Science,
 1741 Wellington, GSNZ Misc Publ. 141, pp. 278-281.
 1742
- 1743 Carter, L. and Manighetti, B., 2006. Glacial/interglacial control of terrigenous and biogenic fluxes in
 1744 the deep ocean off a high input, collisional margin: a 139 kyr-record from New Zealand. *Marine*
 1745 *geology*, 226(3-4), pp.307-322.
 1746
- 1747 Carter, L., Nelson, C.S., Neil, H.L. and Froggatt, P.C., 1995. Correlation, dispersal, and preservation
 1748 of the Kawakawa Tephra and other late Quaternary tephra layers in the Southwest Pacific
 1749 Ocean. *New Zealand Journal of Geology and Geophysics*, 38(1), 29-46.
 1750
- 1751 Carter, L., Manighetti, B., Elliot, M., Trustrum, N., Gomez, B., 2002. Source, sea level and circulation
 1752 effects on the sediment flux to the deep ocean over the past 15 ka off eastern New Zealand. *Global*
 1753 *and Planetary Change* 33, 339-355.
 1754
- 1755 Carter, L., Shane, P., Alloway, B., Hall, I.R., Harris, S.E. and Westgate, J.A., 2003. Demise of one
 1756 volcanic zone and birth of another—a 12 my marine record of major rhyolitic eruptions from New
 1757 Zealand. *Geology*, 31(6), 493-496.
 1758
- 1759 Carter, L., Alloway, B., Shane, P. and Westgate, J., 2004. Deep-ocean record of major late Cenozoic
 1760 rhyolitic eruptions from New Zealand. *New Zealand Journal of Geology and Geophysics*, 47(3), 481-
 1761 500.
 1762
- 1763 Cashman, K., Cronin, S.J. 2008. Welcoming a monster to the world: Myths, oral tradition, and
 1764 modern societal response to volcanic disasters. *Journal of Volcanology and Geothermal Research* 176,
 1765 407–418
 1766
- 1767 Cashman, K., Rust, A. 2016. Volcanic ash: generation and spatial variations. In: *Volcanic ash*.
 1768 Elsevier, Amsterdam, pp. 5-22.
 1769
- 1770 Cashman, K., Rust, A. 2020. Far-travelled ash in past and future eruptions: combining
 1771 tephrochronology with volcanic studies. *Journal of Quaternary Science* 35, 11-22.
 1772
- 1773 Cassidy, M., Watt, S.F.L., Palmer, M.R., Trofimovs, J., Symons, W., Maclachlan, S.E., Stinton, A.J.,
 1774 2014. Construction of volcanic records from marine sediment cores: a review and case study
 1775 (Montserrat, West Indies). *Earth Sci. Rev.* 138, 137-155.

1776
1777 Cerovski-Darriau, C., Roering, J.J., Marden, M., Palmer, A.S., Bilderback, E.L. 2014. Quantifying
1778 temporal variations in landslide-driven sediment production by reconstructing paleolandscapes using
1779 tephrochronology and lidar: Waipaoa River, New Zealand. *Geochemistry, Geophysics, Geosystems*
1780 15(11), 4117-4136.
1781
1782 Chang, Z., Vervoort, J.D., McClelland, W.C., Knaack, C. 2006. U-Pb dating of zircon by LA-ICP-
1783 MS. *Geochemistry, Geophysics, Geosystems* 7, Q05009, doi:10.1029/2005GC001100.
1784
1785 Charlier, B.L., Peate, D.W., Wilson, C.J., Lowenstern, J.B., Storey, M. and Brown, S.J., 2003.
1786 Crystallisation ages in coeval silicic magma bodies: ^{238}U - ^{230}Th disequilibrium evidence from the
1787 Rotoiti and Earthquake Flat eruption deposits, Taupo Volcanic Zone, New Zealand. *Earth and*
1788 *Planetary Science Letters*, 206(3-4), pp.441-457.
1789
1790 Charlier, B.L.A., Wilson, C.J.N., Lowenstern, J.B., Blake, S., van Calsteren, P.W., Davidson, J.P.,
1791 2005. Magma generation at a large, hyperactive silicic volcano (Taupo, New Zealand) revealed by U-
1792 Th and U-Pb systematics in zircons. *J. Petrol.* 46, 3-32.
1793
1794 Churchman, G.J., Lowe, D.J. 2012. Alteration, formation, and occurrence of minerals in soils. In:
1795 Huang, P.M.; Li, Y.; Sumner, M.E. (eds) "Handbook of Soil Sciences. 2nd edition. Vol. 1: Properties
1796 and Processes". CRC Press, Boca Raton, FL, pp.20.1-20.72
1797
1798 Clarkson, B.R., Patel, R.N. and Clarkson, B.D. (1988). Composition and structure of forest
1799 overwhelmed at Pureora, central North Island, New Zealand, during the Taupo eruption (c. A.D. 130).
1800 *Journal of the Royal Society of New Zealand* 18, 417-436.
1801
1802 Clarkson, B.R., Schipper, L.A. and Lehmann, A. 2004. Vegetation and peat characteristics in the
1803 development of lowland restiad peat bogs, North Island, New Zealand, since 13 000 ^{14}C years BP.
1804 *Wetlands* 24: 133-151.
1805
1806 Clayden, B., Hewitt, A.E. 1989. Horizon notation for New Zealand soils. Manaaki Whenua Press,
1807 Lincoln. 30pp.
1808
1809 Clement AJH, Whitehouse PL, Sloss CR. 2016. An examination of spatial variability in the timing
1810 and magnitude of Holocene relative sea-level changes in the New Zealand archipelago. *Quaternary*
1811 *Science Reviews* 131, 73-101.
1812
1813 Cohen, K.M., Gibbard, P.L. 2019. Global chronostratigraphical correlation table for the last 2.7
1814 million years, version 2019 QI-500. *Quaternary International* 500, 20-31.
1815
1816 Cole, J.W. 1970. Description and correlation of Holocene volcanic formations in the Tarawera-
1817 Rerewhakaaitu region. *Transactions of the Royal Society of N.Z. (Earth Sciences)* 8: 93-108.
1818
1819 Connor, C.B., Condit, C.D., Crumpler, L.S. and Aubele, J.C., 1992. Evidence of regional structural
1820 controls on vent distribution: Springerville Volcanic Field, Arizona. *Journal of Geophysical Research:*
1821 *Solid Earth*, 97(B9), pp.12349-12359.
1822
1823 Constantinescu, R., Hopulele-Gligor, A., Connor, C.B., Bonadonna, C., Connor, L.J., Lindsay, J.M.,
1824 Charbonneri, S., Volentik, A.C.M. 2021. The radius of the umbrella cloud helps characterize large
1825 explosive volcanic eruptions. *Communications Earth and Environment* 2: 3
1826 <https://doi.org/10.1038/s43247-020-00078-3>
1827
1828 Cooper, G.F., Wilson, C.J.N. 2014. Development, mobilisation and eruption of a large crystal-rich
1829 rhyolite: the Ongatiti ignimbrite, New Zealand. *Lithos* 198-199, 38-57.

1830
1831 Cronin, S.J., Neall, V.E., Stewart, R.B., Palmer, A.S., 1996a. A multiple-parameter approach to
1832 andesitic tephra correlation, Ruapehu volcano, New Zealand. *Journal of Volcanology and*
1833 *Geothermal Research* 72, 199-215.
1834
1835 Cronin, S.J., Wallace, R.C., Neall V.E., 1996b. Sourcing and identifying andesitic tephtras using
1836 major oxide titanomagnetite and hornblende chemistry, Egmont volcano and Tongariro Volcanic
1837 Centre, New Zealand. *Bulletin of Volcanology* 58, 33-40.
1838
1839 Cronin, D.J., Neall, V.E., Palmer, A.S. 1996c. Investigation of an aggrading paleosol developed into
1840 andesitic ring-plain deposits, Ruapehu volcano, New Zealand. *Geoderma* 69, 119-135
1841
1842 Cronin, S.J., Neall, V.E., Palmer, A.S. and Stewart, R.B. 1997. Methods of identifying late
1843 Quaternary rhyolitic tephtras on the ring plains of Ruapehu and Tongariro volcanoes, New
1844 Zealand. *New Zealand Journal of Geology and Geophysics* 40(2), 175-184.
1845
1846 Cronin, S.J., Hedley, M.J., Neall, V.E., Smith, R.G., 1998. Agronomic impact of tephra fallout from
1847 the 1995 and 1996 Ruapehu Volcano eruptions, New Zealand. *Environ. Geol.* 34 (1), 21–30.
1848
1849 Cronin, S.J., Neall, V.E., Lecointre, J.A., Hedley, M.J., Loganathan, P., 2003. Environmental hazards
1850 of fluoride in volcanic ash: a case study from Ruapehu volcano, New Zealand. *J. Volcanol.*
1851 *Geotherm. Res.* 121, 271–291.
1852
1853 Cronin, S.J., Zernak, A., Ukstins, I., Turner, M.B., Torres-Orozco, R., Stewart, R.B., Smith, I.E.M. et
1854 al. 2021. The geological history and hazards of a long-lived stratovolcano, Mt. Taranaki, New
1855 Zealand. *New Zealand Journal of Geology and Geophysics* (10.1080/00288306.2021.1895231)
1856
1857 Croudance, I.W. and Rothwell, R.G., 2015 Micro-XRF studies of sediment cores, *Developments in*
1858 *Paleoenvironmental Research* 17.
1859
1860 Croudance, I.W., Rindby, A., and Rothwell, R.G., 2006. ITRAX: description and evaluation of a new
1861 multi-function X-ray core scanner. In Rothwell, R.G., (eds) *New techniques in sediment core analysis*
1862 vol. 267. Geological Society Special Publication, London pp 51-564.
1863
1864 Damaschke, M., Sulpizio, R., Zanchetta, G., Wanger, B., Böhm, A., Nowaczyk, N., Rethemeyer, J.,
1865 Hilgers, A., 2013. Tephrostratigraphic studies on a sediment core from Lake Prespa in the Balkans.
1866 *Climate of the Past* 9: 267-287.
1867
1868 Damaschke, M., Cronin, S.J., Holt, K.A., Bebbington, M.S. and Hogg, A.G., 2017a. A 30,000 yr
1869 high-precision eruption history for the andesitic Mt. Taranaki, North Island, New Zealand. *Quaternary*
1870 *Research*, 87, 1-23.
1871
1872 Damaschke, M., Cronin, S.J., Torres-Orozco, R. and Wallace, R.C., 2017b. Unifying
1873 tephrostratigraphic approaches to redefine major Holocene marker tephtras, Mt. Taranaki, New
1874 Zealand. *Journal of Volcanology and Geothermal Research*, 337, pp.29-43.
1875
1876 Damaschke, M., Cronin, S.J. and Bebbington, M.S., 2018. A volcanic event forecasting model for
1877 multiple tephra records, demonstrated on Mt. Taranaki, New Zealand. *Bulletin of Volcanology*, 80(1),
1878 9.
1879
1880 Danišik, M., Shane, P., Schmitt, A.K., Hogg, A., Santos, G.M., Storm, S., Evans, N.J., Fifield, L.K.
1881 and Lindsay, J.M., 2012. Re-anchoring the late Pleistocene tephrochronology of New Zealand based
1882 on concordant radiocarbon ages and combined $^{238}\text{U}/^{230}\text{Th}$ disequilibrium and (U–Th)/He zircon
1883 ages. *Earth and Planetary Science Letters*, 349, pp.240-250.

1884
1885 Danišik, M., Schmitt, A.K., Lovera, O.M., Dunkl, I., Evans, N.J., 2017. Application of the combined
1886 U-Th-disequilibrium/U-Pb and (U-Th)/He zircon dating to tephrochronology. *Quaternary*
1887 *Geochronology* 40, 23-32.
1888
1889 Danišik, M., Lowe, D.J., Schmitt, A.K., Friedrichs, B., Hogg, A.G. and Evans, N.J., 2020. Sub-
1890 millennial eruptive recurrence in the silicic Mangaone Subgroup tephra sequence, New Zealand, from
1891 Bayesian modelling of zircon double-dating and radiocarbon ages. *Quaternary Science Reviews*, 246,
1892 article 106517.
1893
1894 Davies, S.M. 2015. Cryptotephra: the revolution in correlation and precision dating. *Journal of*
1895 *Quaternary Science* 30, 114-130.
1896
1897 de Lange, P.J. 1989: Late Quaternary development of the Kopouatai peat bog, Hauraki lowlands, and
1898 some palaeoenvironmental inferences. Unpublished MSc thesis, University of Waikato, Hamilton.
1899
1900 de Lange, P.J.; Lowe, D.J. 1990. History of vertical displacement of Kerepehi Fault at Kopouatai bog,
1901 Hauraki Lowlands, New Zealand, since c. 10 700 years ago. *New Zealand Journal of Geology and*
1902 *Geophysics* 33, 277-283.
1903
1904 de Lange, P.J., Heenan, P.B., Clarkson, B.D. and Clarkson, B.R. 1999. *Sporadanthus* in New Zealand.
1905 *New Zealand Journal of Botany* 37: 413–431.
1906
1907 Deligne, N.I., Horspool, N., Canessa, S., Matcham, I., Williams, G.T., Wilson, G., Wilson, T.M.,
1908 2017. Evaluating the impacts of volcanic eruptions using Risk Scape. *J. Appl. Volcanol.* 6, 1–21.
1909
1910 Dieffenbach J.K.E. 1843. *Travels in New Zealand*. Volume 1. John Murray, London.
1911
1912 Donoghue SL, Neall VE 1996. Tephrostratigraphic studies at Tongariro Volcanic Centre, New
1913 Zealand: an overview. *Quaternary International* 34-36, 13-20.
1914
1915 Donoghue, S.L., Stewart, R.B., Palmer, A.S., 1991. Morphology and chemistry of olivine phenocrysts
1916 of Mangamate Tephra, Tongariro Volcanic Centre, New Zealand. *J. R. Soc. N. Z.* 21, 225-236.
1917
1918 Donoghue SL, Neall VE, Palmer AS 1995. Stratigraphy and chronology of late Quaternary andesitic
1919 tephra deposits, Tongariro Volcanic Centre, New Zealand. *Journal of the Royal Society of New*
1920 *Zealand* 25, 115-206.
1921
1922 Druce, A.P. 1966. Tree-ring dating of recent volcanic ash and lapilli, Mt Egmont. *NZ. Journal of*
1923 *Botany* 4, 3-41.
1924
1925 Dugmore AJ. 1989. Icelandic volcanic ash in Scotland. *Scottish Geographical Magazine* 105, 168-
1926 172.
1927
1928 Dugmore, A.J., Thompson, P.I.J., Streeter, R.T., Cutler, N.A., Newton, A.J., Kirkbride, M.P. 2020.
1929 The interpretative value of transformed tephra sequences. *Journal of Quaternary Science* 35, 23-38.
1930
1931 Dunbar, N.W., Iverson, N.A., Van Eaton, A.R., Sigl, M., Alloway, B.V., Kurbatov, A.V., Mastin,
1932 L.G., McConnell, J.R., Wilson, C.J.N. 2017: New Zealand supereruption provides time marker for the
1933 Last Glacial Maximum in Antarctica. *Scientific Reports* 7, 12238 (8 pp.).
1934
1935 Eden, D.N., Froggatt, P.C., 1988. Identification and stratigraphic significance of distal Aokautere Ash
1936 in three cores from eastern South Island, New Zealand. In: Eden, D.N., Furkert, R.J. (Eds.), *Loess: Its*
1937 *Distribution, Geology and Soils*. A.A. Balkema, Rotterdam, pp. 47–58.

1938

1939 Eden, D.N. and Froggatt, P.C., 1996. A 6500-year-old history of tephra deposition recorded in the
1940 sediments of Lake Tutira, eastern North Island, New Zealand. *Quaternary international*, 34, pp.55-64.

1941

1942 Eden, D.N., Froggatt, P.C. and McIntosh, P.D., 1992. The distribution and composition of volcanic
1943 glass in late Quaternary loess deposits of southern South Island, New Zealand, and some possible
1944 correlations. *New Zealand Journal of Geology and Geophysics*, 35(1), 69-79.

1945

1946 Eden, D.N., Froggatt, P.C., Trustrum, N.A., Page, M.J., 1993. A multiple-source Holocene tephra
1947 sequence from Lake Tutira, Hawke's Bay, New Zealand. *New Zealand Journal of Geology and
1948 Geophysics* 36, 233–242.

1949

1950 Eden, D.N., Palmer, A.S., Cronin, S.J., Marden, M., Berryman, K.R., 2001. Dating the culmination of
1951 river aggradation at the end of the last glaciation using distal tephra compositions, eastern North
1952 Island, New Zealand. *Geomorphology* 38, 133–151.

1953

1954 Egan, J., Staff, A., Blackford, J., 2015. A revised age estimate of the Holocene Plinian eruption of
1955 Mount Mazama, Oregon using Bayesian statistical modelling. *The Holocene* 25, 1054-1067.

1956

1957 Erdman, C.F. and Kelsey, H.M., 1992. Pliocene and Pleistocene stratigraphy and tectonics, Ohara
1958 Depression and Wakarara Range, North Island, New Zealand. *New Zealand journal of geology and
1959 geophysics*, 35(2), pp.177-192.

1960

1961 Esler, W.R. 2008. An introduction to the Rotorua Basin: an iconoclastic view. In Lowe, D.J. (ed),
1962 Guidebook for Pre-conference North Island Field Trip A1, “Ashes to Issues” (28-30 November).
1963 Australian and New Zealand 4th Joint Soils Conference, Massey University, Palmerston North, p.100-
1964 106.

1965

1966 Evans, G., Augustinus, P., Gadd, P., Zawadzki, A., Ditchfield, A., Hopkins, J. 2021. A multi-proxy
1967 paleoenvironmental interpretation spanning the last glacial cycle (ca. 117–8.5 ka BP) from a lake
1968 sediment stratigraphy from Lake Kai Iwi, Northland, New Zealand. *J Paleolimnol* 65, 101–122.

1969

1970 Ewart, A., 1963. Petrology and petrogenesis of the Quaternary pumice ash in the Taupo area. *New
1971 Zealand. Journal of Petrology* 4: 392-431.

1972

1973 Fergusson, D.A., 1986. Geology of inland Kawhia: emphasis on Te Kuiti Group stratigraphy and
1974 sedimentation. Unpublished M.Sc. thesis, University of Waikato, Hamilton.

1975

1976 Fergusson, G.J., and Rafter, T.A., 1953. New Zealand ¹⁴C age measurements. *N.Z. Journal of Science
1977 and Technology* B35, 127-128.

1978

1979 Flude, S. and Storey, M., 2016. ⁴⁰Ar/³⁹Ar age of the Rotoiti Breccia and Rotoehu Ash, Okataina
1980 Volcanic Complex, New Zealand, and identification of heterogeneously distributed excess ⁴⁰Ar in
1981 supercooled crystals. *Quaternary Geochronology*, 33, pp.13-23.

1982

1983 Froggatt, P.C., 1981. Stratigraphy and nature of Taupo Pumice Formation. *N.Z. Journal of Geology
1984 and Geophysics* 24: 231-248.

1985

1986 Froggatt, P.C., 1983. Towards a comprehensive Upper Quaternary tephra and ignimbrite stratigraphy
1987 in New Zealand using electron microprobe analysis of glass shards. *Quaternary Research* 19:188-200.

1988

1989 Froggatt, P.C. 1992. Standardization of the chemical analysis of tephra deposits. Report of the ICCT
1990 working group. *Quaternary International* 13-14, 93-96.

1991

- 1992 Froggatt, P.C., Gosson, G.J. 1982. Techniques for the preparation of tephra samples for mineral or
1993 chemical analysis and radiometric dating. Geology Dept, Victoria University of Wellington Publication
1994 23, 1-12.
1995
1996 Froggatt, P.C. and Lowe, D.J., 1990. A review of late Quaternary silicic and some other tephra
1997 formations from New Zealand: their stratigraphy, nomenclature, distribution, volume, and age. New
1998 Zealand journal of geology and geophysics, 33(1), 89-109.
1999
2000 Froggatt, P.C., Rogers, G.M. 1990. Tephrostratigraphy of high-altitude peat bogs along the axial
2001 ranges, North Island, New Zealand. New Zealand Journal of Geology and Geophysics 33, 111-124.
2002
2003 Froggatt, P.C., Solloway, G.J., 1986. Correlation of Papanetu Tephra to Karapiti Tephra, central
2004 North Island, New Zealand. *NZ Journal of Geology and Geophysics* 29, 303-313.
2005
2006 Froggatt, P.C., Nelson, C.S., Carter, L., Griggs, G. and Black, K.P., 1986. An exceptionally large late
2007 Quaternary eruption from New Zealand. *Nature*, 319(6054), pp.578-582.
2008
2009 Gardner, J. V., Nelson, C. S. & Baker, P. A. 1985. Distribution and character of pale green laminae in
2010 sediment from Lord Howe Rise: a probable late Neogene and Quaternary tephrostratigraphic record.
2011 In: Kennett, J. P. & Von Der Borch, C. C. (eds) Proceedings of the Ocean Drilling Program, Initial
2012 Reports, 90. Ocean Drilling Program, Texas A & M University, College Station, TX, 1145–1159.
2013
2014 Gehrels, M.J., Lowe, D.J., Hazell, Z.J. and Newnham, R.M., 2006. A continuous 5300-yr Holocene
2015 cryptotephrostratigraphic record from northern New Zealand and implications for tephrochronology
2016 and volcanic hazard assessment. *The Holocene*, 16(2), pp.173-187.
2017
2018 Gehrels, M.J., Newnham, R.M., Lowe, D.J., Wynne, S., Hazell, Z.J. and Caseldine, C., 2008.
2019 Towards rapid assay of cryptotephra in peat cores: review and evaluation of various
2020 methods. *Quaternary International*, 178(1), 68-84.
2021
2022 Gehrels MJ, Lowe DJ, Newnham RM, Hogg AG 2010. Enhanced record of tephra fallout since ~232
2023 AD revealed by cryptotephra studies at Moanatuatua bog near Hamilton: implications for volcanic
2024 hazard analysis. *Geosciences Society of New Zealand Miscellaneous Publication 129A*, 103.
2025
2026 Gomez, B., Rosser, B.J. 2017. Slip slidin' away: a post-glacial environmental history of the Waipaoa
2027 River basin. *Geomorphology* 307, 65-76.
2028
2029 Gómez-Vasconcelos, M.G., Villamor, P., Cronin, S.J., Procter, J., Kereszturi, G., Palmer, A.S.,
2030 Townsend, D., Leonard, G., Berryman, K., Ashraf, S. 2016. Earthquake history at the eastern
2031 boundary of the South Taupo Volcanic Zone, New Zealand. *New Zealand journal of geology and*
2032 *geophysics* 59, 522-543.
2033
2034 Gosson, G.J. 1986. Miocene and Pliocene silicic tuffs in marine sediments of the East Coast Basin,
2035 New Zealand. Unpublished PhD thesis, Victoria University of Wellington, Wellington,
2036
2037 Grange, L I. 1929. A classification of soils of Rotorua county. *NZ. Journal of Science and*
2038 *Technology* 11, 219-228.
2039
2040 Grange, L.I. 1931. Volcanic ash showers. *N.Z. Journal of Science and Technology* 12, 228-240.
2041
2042 Grange, L.I. 1937. The geology of the Rotorua-Taupo subdivision, Rotorua and Kaimanawa divisions.
2043 *New Zealand Department of Scientific and Industrial Research Geological Survey Bulletin* 37. 138 p.
2044

2045 Grange, L.I., and Taylor, N.H. 1932. The distribution and field characteristics of bush-sick soils. N.Z.
2046 Department of Scientific and Industrial Research Bulletin 32, 21-35.
2047

2048 Grant, G.R., Sefton, J.P., Patterson, M.O., Naish, T.R., Dunbar, G.B., Hayward, B.W., Morgans,
2049 H.E.G., Alloway, B.V., Seward, D., Tapia, C.A. and Prebble, J.G., 2018. Mid-to late Pliocene (3.3–
2050 2.6 Ma) global sea-level fluctuations recorded on a continental shelf transect, Whanganui Basin, New
2051 Zealand. *Quaternary Science Reviews*, 201, pp.241-260.
2052

2053 Grant-Taylor, T.L. and Rafter, T.A., 1971. New Zealand radiocarbon age measurements—6. *New
2054 Zealand journal of geology and geophysics*, 14(2), pp.364-402.
2055

2056 Green, J.D.; Lowe, D.J. 1985. Stratigraphy and development of c. 17 000 year old Lake Maratoto,
2057 North Island, New Zealand, with some inferences about postglacial climatic change. *New Zealand
2058 Journal of Geology and Geophysics* 28, 675-699.
2059

2060 Green, R.M., Bebbington, M.S., Cronin, S.J., Jones, G., 2014. Automated statistical matching of
2061 multiple tephra records exemplified using five long maar sequences younger than 75 ka, Auckland,
2062 New Zealand. *Quat. Res.* 82, 405-419.
2063

2064 Green, R.M., Bebbington, M.S., Jones, G., Cronin, S.J., Turner, M.B. 2016. Estimation of tephra
2065 volumes from sparse and incompletely observed deposit thicknesses. *Bull Volcanol.* 78: 25.
2066

2067 Griggs, A.J., Davies, S.M., Abbott, P.M., Coleman, M., Palmer, A.P., Rasmussen, T.L., Johnston, R.
2068 2015. Visualising tephra deposits and sedimentary processes in the marine environment: the potential
2069 of X-ray microtomography. *Geochemistry, Geophysics, Geosystems* 16, 4329-4343.
2070

2071 Haenfling, C., Newnham, R., Rees, A., Jara, I., Homes, A., Clarkson, B., 2017. Holocene history of a
2072 raised bog, northern New Zealand, based on plant cuticles. *The Holocene* 27, 309-314.
2073

2074 Hajdas, I.; Lowe, D.J.; Newnham, R.M.; Bonani, G. 2006. Timing of the late-glacial climate reversal
2075 in the Southern Hemisphere using high-resolution radiocarbon chronology for Kaipo bog, New
2076 Zealand. *Quaternary Research* 65, 340-345.
2077

2078 Harper, M.A., Pledger, S.A., Smith, E.G.C., Van Eaton, A.R., Wilson, C.J.N. 2015. Eruptive and
2079 environmental processes recorded by diatoms in volcanically dispersed lake sediments from the
2080 Taupo Volcanic Zone, New Zealand. *Journal of Paleolimnology* 54, 263-277.
2081

2082 Hayward, B.W. 2017. *Out of the Ocean, Into the Fire*. Geoscience Society of New Zealand
2083 Miscellaneous Publication 146. 336 pp.
2084

2085 Hayward, B.W., Sabaa, A.T., Grenfell, H.R., Cochran, U.A., Clark, K.J., Litchfield, N.J., Wallace, L.,
2086 Marden, M., Palmer, A.S. 2015. Foraminiferal record of Holocene paleo-earthquakes on the subsiding
2087 south-western Poverty Bay coastline, New Zealand. *New Zealand Journal of Geology and Geophysics*
2088 58, 104-122.
2089

2090 Hayes, J., Wilson, T.M., Deligne, N.I., Cole, J. and Hughes, M., 2017. A model to assess tephra
2091 clean-up requirements in urban environments. *Journal of Applied Volcanology*, 6(1), p.1.
2092

2093 Hayward, B.W., and Hopkins, J.L., 2019. Basis for modified ages of Auckland volcanoes in
2094 “Volcanoes of Auckland: A Field Guide, 2019”. *Geocene* 21: 2-10.
2095

2096 Heinrich, M., Cronin, S.J., Pardo, N. 2020. Understanding multi-vent Plinian eruptions at Mt.
2097 Tongariro Volcanic Complex, New Zealand. *Bulletin of Volcanology*, 82, 30.
2098

- 2099 Hewitt, A.E., Balks, M.R., Lowe, D.J. 2021. *The Soils of Aotearoa New Zealand*. Springer, Cham,
 2100 332 pp.
 2101
- 2102 Higham, T.F.G., Hogg, A.G. 1997. Evidence for late Polynesian colonisation of New Zealand:
 2103 University of Waikato radiocarbon measurements. *Radiocarbon* 39, 149-192.
 2104
- 2105 Higham, T.F.G., Anderson, A.J., Jacomb, C. 1999. Dating the first New Zealanders: the chronology
 2106 of Wairau Bar. *Antiquity* 73, 420-427.
 2107
- 2108 Higham, T.F.G., Hedges, R.E.M., Anderson, A.J., Bronk Ramsey, C., Fankhauser, B., 2004. Problems
 2109 associated with the AMS dating of small bone samples: the question of the arrival of Polynesian rats
 2110 to New Zealand. *Radiocarbon* 46, 207-218.
 2111
- 2112 Hill, H. 1887. Traces of volcanic dust-showers at Napier, Petane, and generally throughout the East
 2113 Coast districts, north of Cape Kidnappers. *Transactions of the N.Z. Institute* 19, 385-387.
 2114
- 2115 Hochstetter, F. (von), 1864. *The Geology of New Zealand* (Translated by C.A. Fleming, 1959). N.Z.
 2116 Government Printer, Wellington.
 2117
- 2118 Hodder, A.P.W. 1977. Determination of densities of rhyolitic glass shards by a gradient method. *New
 2119 Zealand Journal of Geology and Geophysics* 20, 789-796.
 2120
- 2121 Hodder, A.P.W., 1978. Refractive index and hydration of rhyolitic glass from Holocene tephra,
 2122 North Island, New Zealand. *N.Z. Journal of Geology and Geophysics* 21: 155-166.
 2123
- 2124 Hodder, A.P.W., and Wilson, A.T., 1976. Identification and correlation of thinly bedded tephra: the
 2125 Tirau and Mairoa Ashes. *N.Z. Journal of Geology and Geophysics* 19: 663-682.
 2126
- 2127 Hodder, A.P.W., Green, B.E., Lowe, D.J. 1990. A two-stage model for the formation of clay minerals
 2128 from tephra-derived volcanic glass. *Clay Minerals* 25, 313-327.
 2129
- 2130 Hodder, A.P.W., de Lange, P.J. and Lowe, D.J., 1991. Dissolution and depletion of ferromagnesian
 2131 minerals from Holocene tephra layers in an acid bog, New Zealand, and implications for tephra
 2132 correlation. *Journal of Quaternary science*, 6(3), pp.195-208.
 2133
- 2134 Hogg, A.G., and McCraw, J.D., 1983. Late Quaternary tephra of Coromandel Peninsula, North
 2135 Island, New Zealand: a mixed peralkaline and calcalkaline tephra sequence. *N.Z. Journal of Geology
 2136 and Geophysics* 26: 263-301.
 2137
- 2138 Hogg, A.G., Lowe, D.J.; Hendy, C.H. 1987. University of Waikato radiocarbon dates I. *Radiocarbon*
 2139 29, 263-301.
 2140
- 2141 Hogg, A.G., Higham, T.F., Lowe, D.J., Palmer, J.G., Reimer, P.J. and Newnham, R.M., 2003. A
 2142 wiggle-match date for Polynesian settlement of New Zealand. *Antiquity* 77, 116-125.
 2143
- 2144 Hogg, A.G.; Lowe, D.J.; Palmer, J.G.; Boswijk, G.; Bronk Ramsey, C.J. 2012. Revised calendar date
 2145 for the Taupo eruption derived by ¹⁴C wiggle-matching using a New Zealand kauri ¹⁴C calibration
 2146 data set. *The Holocene* 22, 439-449.
 2147
- 2148 Hogg, A.G., Wilson, C.J.N., Lowe, D.J., Turney, C.S.M., White, P., Lorrey, A.M., Manning, S.W.,
 2149 Palmer, J.G., Bury, S., Brown, J., Southon, J., Petchey, F. 2019. Wiggle-match radiocarbon dating of
 2150 the Taupo eruption. *Nature Communications* 10:4669.
 2151
- 2152 Holdaway, R.N., 1996. Arrival of rats in New Zealand. *Nature* 384, 225-226.

2153
2154 Holt, K., Wallace, R.C., Neall, V.E., Kohn, B.P., Lowe, D.J. 2010: Quaternary tephra marker beds
2155 and their potential for palaeoenvironmental reconstruction on Chatham Islands east of New Zealand,
2156 southwest Pacific Ocean. *Journal of Quaternary Science* 25, 1169-1178.
2157
2158 Holt, K.A., Lowe, D.J., Hogg, A.G., Wallace, R.C. 2011. Distal occurrence of mid-Holocene
2159 Whakatane Tephra on the Chatham Islands, New Zealand, and potential for cryptotephra studies.
2160 *Quaternary International* 246, 344-351.
2161
2162 Hopkins, J.L. and Seward, D., 2019. Towards robust tephra correlations in early and pre-Quaternary
2163 sediments: A case study from North Island, New Zealand. *Quaternary Geochronology*, 50, pp.91-108.
2164
2165 Hopkins, J.L., Millet, M.-A., Timm, C., Wilson, C.J.N., Leonard, G.S., Palin, M.J., Neil, H. 2015.
2166 Tools and techniques for developing tephra stratigraphies in lake cores: a case study from the basaltic
2167 Auckland Volcanic Field, New Zealand. *Quaternary Science Reviews* 123, 58-75.
2168
2169 Hopkins, J.L., Wilson, C.J., Millet, M.A., Leonard, G.S., Timm, C., McGee, L.E., Smith, I.E. and
2170 Smith, E.G., 2017. Multi-criteria correlation of tephra deposits to source centres applied in the
2171 Auckland Volcanic Field, New Zealand. *Bulletin of Volcanology*, 79(7), p.55.
2172
2173 Hopkins, J.L., Smid, E.R., Eccles, J.D., Hayes, J.L., Hayward, B.W., McGee, L.E., van Wijk, K.,
2174 Wilson, T.M., Cronin, S.J., Leonard, G.S. and Lindsay, J.M. 2020a. Auckland Volcanic Field
2175 magmatism, volcanism, and hazard: a review. *New Zealand Journal of Geology and Geophysics*,
2176 pp.1-22.
2177
2178 Hopkins, J.L., Wysoczanski, R.J., Orpin, A.R., Howarth J., Strachan, L.J., Lunenburg, R., McKeown,
2179 M., Ganguly, A., Twort, E., Camp, S., 2020b. Deposition and preservation of tephra in marine
2180 sediments at the active Hikurangi subduction margin. *Quaternary Science Reviews* 247, article
2181 106500
2182
2183 Hopkins, J.L., Bidmead, J.E., Lowe, D.J., Wysoczanski, R.J., Pillans, B.J., Ashworth, L., Tuckett, F.
2184 in press. TephraNZ: a major and trace element reference database for glass-shard analyses from
2185 prominent Quaternary rhyolitic tephtras in New Zealand, and some implications for correlation.
2186 *Geochronology* (<https://doi.org/10.5194/gchron-2020-34>)
2187
2188 Horrocks, J.L. 2000. Stratigraphy, chronology, and correlation of the Plio-Pleistocene (c. 2.2- 0.8 Ma)
2189 Kauroa Ash sequence, western central North Island, New Zealand. Unpublished Ph.D. thesis,
2190 University of Waikato, Hamilton.
2191
2192 Horstwood, M.S.A., Košler, J., Gehrels, G., Jackson, E., McLean, N.M., Paton, C., Pearson, N.J.,
2193 Sircombe, K., Sylvester, P., Vermeesch, P., Bowring, J.F., Condon, D.J., Schoene, B. 2016.
2194 Community-derived standards for LA-ICP-MS U-(Th-)Pb geochronology – uncertainty propagation,
2195 age interpretation and data reporting. *Geostandards and Geoanalytical Research* 40, 311-332.
2196
2197 Horwell, C.J., Baxter, P.J., 2006. The respiratory health hazards of volcanic ash: a review for volcanic
2198 risk mitigation. *Bull. Volcanol.* 69, 1–24.
2199
2200 Houghton, B.F., Wilson, C.J.N. 1986. Explosive rhyolitic volcanism: the case studies of Mayor Island
2201 and Taupo volcanoes. *New Zealand Geological Survey Record*, 12, 33-100.
2202
2203 Houghton, B.F., Wilson C.J.N. 1989. A vesicularity index for pyroclastic deposits. *Bull Volcanol*, 51,
2204 451-462.
2205

- 2206 Houghton, B.F., Wilson, C.J.N., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M. and
 2207 Pringle, M.S., 1995. Chronology and dynamics of a large silicic magmatic system: Central Taupo
 2208 Volcanic Zone, New Zealand. *Geology*, 23(1), pp.13-16.
 2209
- 2210 Hoverd, J.L., Shane, P.A., Smith, I.E.M., Smith, V.C., Wilson, C.J.N., 2005. Towards an Improved
 2211 Understanding of Local and Distal Volcanic Stratigraphy in Auckland: Stratigraphy of a Long Core
 2212 from Glover Park (St Helier's Volcano) in Auckland. Institute of Geological & Nuclear Sciences
 2213 Science Report 2005/31. 45 p.
 2214
- 2215 Howorth, R., 1975. New formations of late Pleistocene tephra from the Okataina Volcanic Centre,
 2216 New Zealand. *N.Z. Journal of Geology and Geophysics* 18: 683-712.
 2217
- 2218 Howorth, R., and Rankin, P.C., 1975. Multi-element characterisation of glass shards from
 2219 stratigraphically correlated rhyolitic tephra units. *Chemical Geology* 15: 239-250.
 2220
- 2221 Howorth, R.; Froggatt, P. C.; Robertson, S. M. 1980. Late Quaternary volcanic ash stratigraphy of the
 2222 Poukawa area, central Hawke's Bay, New Zealand. *New Zealand journal of geology and*
 2223 *geophysics* 23, 487-491.
 2224
- 2225 Huang, Y-T., Lowe, D.J., Zhang, H., Cursons, R., Young, J.M., Churchman, G.J., Schipper, L.A.,
 2226 Rawlence, N.J., Wood, J.R., Cooper, A. 2016. A new method to extract and purify DNA from
 2227 allophanic soils and paleosols, and potential for paleoenvironmental reconstruction and other
 2228 applications. *Geoderma*. 247: 114-125.
 2229
- 2230 Hurst T, Smith W 2010. Volcanic ashfall in New Zealand – probabilistic hazard modelling for
 2231 multiple sources. *New Zealand Journal of Geology and Geophysics* 53, 1-14.
 2232
- 2233 Ito, H., Nanayama, F., Nakazato, H. 2017. Zircon U-Pb dating using LA-ICP-MS: Quaternary tephra
 2234 in Boso Peninsula, Japan. *Quaternary Geochronology* 40, 12-22.
 2235
- 2236 Jacomb, A., Holdaway, R.N., Allentoft, M.E., Bunce, M., Oskam, C.L., Walter, R., Brooks, E. 2014.
 2237 High-precision dating and ancient DNA profiling of moa (Aves: Dinornithiformes) eggshell
 2238 documents a complex feature at Wairau Bar and refines the chronology of New Zealand settlement by
 2239 Polynesians. *Journal of Archaeological Science* 50, 24-30.
 2240
- 2241 Jara, I.A., Newnham, R.M., Alloway, B.V., Wilmshurst, J.M., Rees, A.B.H. 2017. Pollen-based
 2242 temperature and precipitation records of the past 14,600 years in northern New Zealand (37°S) and
 2243 their linkages with the Southern Hemisphere atmospheric circulation. *The Holocene* 27, 1756-1768.
 2244
- 2245 Johnson, D.L., Watson-Stegner, D. 1987. Evolution model of pedogenesis. *Soil Science* 143, 349-366.
 2246
- 2247 Johnson, D.L., Keller, E.A., Rockwell, T.K. 1990. Dynamic pedogenesis: new views on some key soil
 2248 concepts, and a model for interpreting Quaternary soils. *Quaternary Research* 33, 306-319.
 2249
- 2250 Johnston, D.M., Houghton, B.F., Neall, V.E., Ronan, K.R. and Paton, D., 2000. Impacts of the 1945
 2251 and 1995–1996 Ruapehu eruptions, New Zealand: an example of increasing societal
 2252 vulnerability. *Geological Society of America Bulletin*, 112(5), pp.720-726.
 2253
- 2254 Julian, H.A., 2016. Volcanology of the Owharoa and Waikino ignimbrites, Waihi, Coromandel
 2255 Volcanic Zone. Unpublished MSc thesis, University of Waikato, Hamilton.
 2256
- 2257 Kennedy, N., 1994. New Zealand tephro-chronology as a tool in geomorphic history of the c. 140 ka
 2258 Mamaku Ignimbrite Plateau and in relating oxygen isotope stages. *Geomorphology*, 9(2), pp.97-115.
 2259

- 2260 Kennedy, N. M.; Froggatt, P. 1984: Recognition of Tuhua Tephra (c. 6,200 BP) at Rotorua.
 2261 Geological Society of New Zealand Newsletter 66: 17-18.
 2262
- 2263 Kereszturi, G., Németh, K., Cronin, S.J., Procter, J. and Agustín-Flores, J., 2014. Influences on the
 2264 variability of eruption sequences and style transitions in the Auckland Volcanic Field, New
 2265 Zealand. *Journal of Volcanology and Geothermal Research*, 286, pp.101-115.
 2266
- 2267 Kimber, R.W.L., Kennedy, N.M. and Milnes, A.R., 1994. Amino acid racemization dating of a 140
 2268 000 year old tephra- loess- palaeosol sequence on the Mamaku Plateau near Rotorua, New
 2269 Zealand. *Australian journal of earth sciences*, 41(1), pp.19-26.
 2270
- 2271 Kluger, M.O., Moon, V.G., Kreiter, S., Lowe, D.J., Churchman, G.J., Hepp, D.A., Seibel, D., Jorat,
 2272 M.E., Mörz, T. 2017. A new attraction-detachment model for explaining flow sliding in clay-rich
 2273 tephras. *Geology* 45, 131-134.
 2274
- 2275 Kohn B.P., 1970. Identification of New Zealand tephra-layers by emission spectrographic analysis of
 2276 their titanomagnetites. *Lithos* 3: 361-368.
 2277
- 2278 Kohn, B. P., and Glasby, G. P., 1978. Tephra distribution and sedimentation rates in the Bay of
 2279 Plenty, New Zealand. *N.Z. Journal of Geology and Geophysics* 21: 49-70.
 2280
- 2281 Kohn, B.P., and Neall, V.E., 1973. Identification of late Quaternary tephras for dating Taranaki lahar
 2282 deposits. *N.z. Journal of Geology and Geophysics* 16, 781-792.
 2283
- 2284 Kohn, B.P., Vucetich, C.G. 1974. New Zealand. In: Westgate, J.A., Gold, C.M. (eds) *World*
 2285 *bibliography and index of Quaternary tephrochronology*. University of Alberta, Edmonton, Canada,
 2286 p.273-292.
 2287
- 2288 Kohn, B.P., Pillans, B. and McGlone, M.S., 1992. Zircon fission track age for middle Pleistocene
 2289 Rangitawa Tephra, New Zealand: stratigraphic and paleoclimatic significance. *Palaeogeography,*
 2290 *palaeoclimatology, palaeoecology*, 95(1-2), pp.73-94.
 2291
- 2292 Kuehn, S. C., Froese, D. G., Shane, P. A. R., INTAV intercomparison participants 2011. The INTAV
 2293 intercomparison of electron-beam microanalysis of glass by tephrochronology laboratories: results
 2294 and recommendations. *Quaternary International* 246, 19–47.
 2295
- 2296 Kutterolf, S., and Hopkins, J.L., 2019. Tephrochronostratigraphy in marine and terrestrial sediments of
 2297 New Zealand: Benchmark for Miocene to Quaternary explosive volcanism, German Research
 2298 Foundation (DFG), approved research proposal
 2299 42806458, <https://gepris.dfg.de/gepris/projekt/42806458?language=en>
 2300
- 2301 Kylander, M.A., Lind, E.M., Wastegård, S., Löwemark, L. 2012. Recommendations for using XRF
 2302 core scanning as a tool in tephrochronology. *The Holocene* 22, 371-375.
 2303
- 2304 Kyle, P.R., Seward, D. 1984. Dispersed rhyolitic tephra from New Zealand in deep-sea sediments of
 2305 the Southern Ocean. *Geology*, 12: 487-490.
 2306
- 2307 Lane, C.S., Cullen, V.L., White, D., Bramham-Law, C.W.F., Smith, V.C., 2014. Cryptotephra
 2308 as a dating and correlation tool in archaeology. *J. Archaeol. Sci.* 42, 42-50.
 2309
- 2310 Lane, C.S., Lowe, D.J., Blockley, S.P.E., Suzuki, T., Smith, V.C. 2017. Advancing tephrochronology
 2311 as a global dating tool: applications in volcanology, archaeology, and palaeoclimatic research
 2312 [Editorial]. *Quaternary Geochronology* 40, 1-7.
 2313

2314 Lanos, P., Philippe, A., 2017. Hierarchical Bayesian modeling for combining dates in archaeological
2315 context. *J. Soc. Fr. Stat.* 158, 72e88.
2316
2317 Lanos, P., Dufresne, P., 2019. ChronoModel Version 2.0: User Manual. Available from:
2318 <http://www.chronomodel.com>.
2319
2320 Lee, J.M., Bland, K.J., Townsend, D.B. and Kamp, P.J.J., 2011. Geology of the Hawke's Bay area.
2321 Institute of Geological and Nuclear Sciences 1:250,000 geological map 8. 1 sheet + 93p. GNS
2322 Sciences, Lower Hutt.
2323
2324 Le Maitre, R.W., Streckeisen, A., Zanettin, B., Le Bas, M.J., Bonin, B., Bateman, P., Bellieni, G.,
2325 Dudek, A., Efremova, S., Keller, J. and Lameyre, J., and others 2002. *Igneous rocks. A classification
2326 and Glossary of Terms*, 2nd ed. Cambridge Univ. Press, Cambridge.
2327
2328 Leonard, G.S., Begg, J.G., Wilson, C.J.N. (compilers) 2010. Geology of the Rotorua area: scale
2329 1:250,000. Institute of Geological and Nuclear Sciences 1: 250,000 geological map 5. 1 sheet and 99
2330 pp. Institute of Geological and Nuclear Sciences, Lower Hutt.
2331
2332 Leonard, G.S., Calvert, A.T., Hopkins, J.L., Wilson, C.J., Smid, E.R., Lindsay, J.M. and Champion,
2333 D.E., 2017. High-precision ⁴⁰Ar/³⁹Ar dating of Quaternary basalts from Auckland Volcanic Field,
2334 New Zealand, with implications for eruption rates and paleomagnetic correlations. *Journal of
2335 Volcanology and Geothermal Research*, 343, pp.60-74.
2336
2337 Leonard, GS, Cole, RP, Christenson, BW, Conway, CE, Cronin, SJ, Gamble, JA, Hurst, T, Kennedy,
2338 BM, Miller, CA, Procter, JN, Pure, LR, Townsend, DM, White, JDL, Wilson, CJN. 2021. Ruapehu
2339 and Tongariro stratovolcanoes: a review of current understanding. *New Zealand Journal of Geology
2340 and Geophysics*. 64 (2): (in press)
2341
2342 Lerner, G.A., Cronin, S.J., Turner, G.M., Rowe, M.C. 2019a. Paleomagnetic determination of the age
2343 and properties of the 1780–1800 AD dome effusion/collapse episode of Mt. Taranaki, New
2344 Zealand. *Bull Volcanol* 81, 15.
2345
2346 Lerner, G.A., Cronin, S.J., Bebbington, M.S., Platz, T. 2019b. The characteristics of a multi-episode
2347 volcanic regime: the post-AD 960 Maero Eruptive Period of Mt. Taranaki (New Zealand). *Bull
2348 Volcanol* 81, 61.
2349
2350 Lewis, K. B., and Kohn, B. P., 1973. Ashes, turbidites, and rates of sedimentation on the continental
2351 slope off Hawke's Bay. *N.Z. Journal of Geology and Geophysics* 16: 439-454.
2352
2353 Lian, O.B. and Shane, P.A., 2000. Optical dating of paleosols bracketing the widespread Rotoehu
2354 tephra, North Island, New Zealand. *Quaternary Science Reviews*, 19(16), pp.1649-1662.
2355
2356 Lindsay JM, Leonard GS. 2009. Age of the Auckland Volcanic Field. Auckland: Institute of Earth
2357 Science and Engineering Aotearoa (IESE) Report no.1-2009.02.
2358
2359 Lindsay JM, Leonard GS, Smid ER, Hayward B. 2011. Age of the Auckland Volcanic Field: A
2360 review of existing data. *New Zealand Journal of Geology and Geophysics* 54(4): 379-401.
2361
2362 Loame, R.C., Lowe, D.J., Davies, S.M., Moon, V.G., Magill, C.R., Johnston, R., Pearce, N.J.G.,
2363 Pittari, A., Fox, B.R.S. 2016. Hazard hunting: X-ray micro-CT reconnaissance analysis of c. 20,000
2364 year-old lake sediment cores for tephra seismites and cryptotephra deposits, Waikato region, New
2365 Zealand. Abstracts, Australasian Quaternary Association (AQUA) Biennial Conference, University of
2366 Auckland (5-9 December), p. 97.
2367

2368 Loame, R.C., Lowe, D.J., Pittari, A., Davies, S.M., Magill, C.R., Vandergoes, M.J., Rees, A.B.H.,
2369 Harpur, A., Ross, N. 2017. Reconnaissance and detection of cryptotephra in ~20,000-yr-old lake
2370 sediments, Waikato region, using CT scanning. In: Baker, J., Rowe, M. (eds). Abstracts, Geosciences
2371 2017, Auckland. Geoscience Society of New Zealand Miscellaneous Publication 147A, p. 63.
2372

2373 Loame, R.C., Lowe, D.J., Pittari, A., Davies, S.M., Magill, C.R., Vandergoes, M.J., Rees, A.B.H.,
2374 Ross, N. 2018. Using CT scanning for reconnaissance and detection of cryptotephra in ~22,000-yr-
2375 old lake sediments, central Waikato region, New Zealand. In: Hambach, U., Veres, D. (eds), Book of
2376 Abstracts, Crossing New Frontiers: INTAV International Field Conference on Tephrochronology,
2377 'Tephra Hunt in Transylvania', Moieciu de Sus, Romania (24 June-1 July), p. 41-42.
2378

2379 Loame, R.C., Villamor, P., Lowe, D.J., Milicich, S.D., Pittari, A., Barker, S.L.L., Rae, A., Gomez-
2380 Vasconcelos, M.G., Martinez-Martos, M., Ries, W.F. 2019. Using paleoseismology and
2381 tephrochronology to reconstruct fault rupturing and hydrothermal activity since c. 40 ka in Taupo
2382 Rift, New Zealand. *Quaternary International* 500, 52-70.
2383

2384 Lorrey, A.M., Bostock, H. 2017. The climate of New Zealand through the Quaternary. In:
2385 Shulmeister, J. (ed), *Landscape and Quaternary Environmental Change in New Zealand*, Atlantis
2386 *Advances in Quaternary Science* 3, 67-139.
2387

2388 Lorrey, A.M., Woolley, J-M. 2018. Locating relict sinter terrace sites at Lake Rotomahana, New
2389 Zealand, with Ferdinand von Hochstetter's legacy cartography, historic maps, and LIDAR. *Front.*
2390 *Earth Sci.* 6:205doi: 10.3389/feart.2018.00205
2391

2392 Lowe, D.J. 1981. Origin, composite nature, and pedology of late Quaternary airfall deposits, Hamilton
2393 Basin, New Zealand. Unpublished MSc thesis, University of Waikato, Hamilton.
2394

2395 Lowe, D.J., 1986a. Revision of the age and stratigraphic relationships of Hinemaiaia Tephra and
2396 Whakatane Ash, North Island, New Zealand, based on distal deposits in lake sediments and peats.
2397 *New Zealand Journal of Geology and Geophysics* 29, 61-73.
2398

2399 Lowe, D.J. 1986b. Controls on the rates of weathering and clay mineral genesis in airfall tephra: a
2400 review and New Zealand case study. In: Colman, S.M.; Dethier, D.P. (eds) *Rates of Chemical*
2401 *Weathering of Rocks and Minerals*. Orlando, Academic Press, pp. 265-330.
2402

2403 Lowe, D.J., 1988a. Stratigraphy, age, composition, and correlation of late Quaternary tephra
2404 interbedded with organic sediments in Waikato lakes. North Island, New Zealand. *N.Z. Journal of*
2405 *Geology and Geophysics* 31: 125-165.
2406

2407 Lowe, D.J., 1988b. Late Quaternary volcanism in New Zealand: towards an integrated record using
2408 distal airfall tephra in lakes and bogs. *Journal of Quaternary Science* 3, 111-120.
2409

2410 Lowe, D.J. 1990. Tephra studies in New Zealand: an historical review. *Journal of the Royal Society*
2411 *of New Zealand* 20, 119-150.
2412

2413 Lowe, D.J. 2008. Globalization of tephrochronology: new views from Australasia. *Progress in*
2414 *Physical Geography* 32, 311-335.
2415

2416 Lowe, D.J., 2011. Tephrochronology and its application: a review. *Quaternary Geochronology*, 6(2),
2417 pp.107-153.
2418

2419 Lowe, D.J., 2014. Marine tephrochronology: a personal perspective. *Geological Society, London,*
2420 *Special Publications* 398, 7-19.
2421

- 2422 Lowe, D.J. 2019. Using soil stratigraphy and tephrochronology to understand the origin, age, and
 2423 classification of a unique Late Quaternary tephra-derived Ultisol in Aotearoa New
 2424 Zealand. *Quaternary* 2(1), 34 pp, <https://doi.org/10.3390/quat2010009>.
 2425
- 2426 Lowe, D.J., Alloway, B.V. 2015: Tephrochronology. In: Rink, W.J., Thompson, J.W. (editors),
 2427 *Encyclopaedia of Scientific Dating Methods*. Springer, Dordrecht, pp. pp. 783-799.
 2428
- 2429 Lowe, D.J., Hogg, A.G., 1995. Age of the Rotoehu Ash. *Comment. N.Z. Journal of Geology and*
 2430 *Geophysics* 38, 399-402.
 2431
- 2432 Lowe, D.J., Hunt, J.B. 2001. A summary of terminology used in tephra-related studies. *Les Dossiers*
 2433 *de l'Archeo-Logis* 1, 17-22.
 2434
- 2435 Lowe, D.J., Newnham, R.M. 2004. Role of tephra in dating Polynesian settlement and impact, New
 2436 Zealand. *Past Global Changes* 12 (3), 5-7.
 2437
- 2438 Lowe, D.J., Palmer, D.J. 2005. Andisols of New Zealand and Australia. *Journal of Integrated Field*
 2439 *Science* 2, 39-65.
 2440
- 2441 Lowe, D.J., Percival, H.J., 1993. Clay mineralogy of tephtras and associated paleosols and soils, and
 2442 hydrothermal deposits, North Island. *Guide book for New Zealand Pre-Conference Field*
 2443 *Trip Fl, Tenth International Clay Conference, AIPEA, Adelaide*. 110 p.
 2444
- 2445 Lowe, D.J., Pittari, A. 2014. An ashy septingentarian: the Kaharoa tephra turns 700 (with notes on
 2446 its volcanological, archaeological, and historical importance). *Geoscience Society of New Zealand*
 2447 *Newsletter* 13, 35-46.
 2448
- 2449 Lowe, D.J., Pittari, A. 2021. The Taupō eruption sequence of AD 232 ± 10 in Aotearoa New
 2450 Zealand: a retrospection. *Journal of Geography (Chigaku Zasshi)* 130 (1), 117-141.
 2451
- 2452 Lowe, D.J., Tonkin, P.J. 2010. Unravelling upbuilding pedogenesis in tephra and loess sequences in
 2453 New Zealand using tephrochronology. *Proceedings of the 19th World Congress of Soil Science*
 2454 *(Brisbane), Symposium 1.3.2 Geochronological techniques and soil formation*, pp. 34-37. Published
 2455 on DVD and <https://iuss.org/19th%20WCSS/Symposium/pdf/0116.pdf>.
 2456
- 2457 Lowe, D.J., Hogg, A.G., Green, J.D., Boubée, J.A.T. 1980. Stratigraphy and chronology of late
 2458 Quaternary tephtras in Lake Maratoto, Hamilton, New Zealand. *New Zealand Journal of Geology and*
 2459 *Geophysics* 23, 481-485.
 2460
- 2461 Lowe, D.J., Hogg, A.G., Hendy, C.H., 1981. Detection of thin tephra deposits in peat and organic lake
 2462 sediments by rapid X-radiography and X-ray fluorescence techniques. *Geology Department, Victoria*
 2463 *University of Wellington Publication* 20, 74-77.
 2464
- 2465 Lowe, D.J., McFadgen, B.G., Higham, T.F., Hogg, A.G., Froggatt, P.C., Nairn, I.A. 1998.
 2466 Radiocarbon age of the Kaharoa Tephra, a key marker for late-Holocene stratigraphy and archaeology
 2467 in New Zealand. *The Holocene* 8, 487-495.
 2468
- 2469 Lowe, D.J., Newnham, R.M. and Ward, C.M., 1999. Stratigraphy and chronology of a 15 ka sequence
 2470 of multi-sourced silicic tephtras in a montane peat bog, eastern North Island, New Zealand. *New*
 2471 *Zealand Journal of Geology and Geophysics*, 42(4), pp.565-579.
 2472
- 2473 Lowe, D.J., Newnham, R.M., McFadgen, B.G. and Higham, T.F., 2000. Tephtras and New Zealand
 2474 archaeology. *Journal of Archaeological Science*, 27(10), pp.859-870.
 2475

- 2476 Lowe, D.J., Tippett, J.M., Kamp, P.J., Liddell, I.J., Briggs, R.M. and Horrocks, J.L., 2001. Ages on
 2477 weathered Plio-Pleistocene tephra sequences, western north Island, New Zealand. *Les Dossiers de*
 2478 *l'Archeo-Logis* 1, 45-60.
 2479
- 2480 Lowe, D.J., Newnham, R.M., McCraw, J.D. 2002. Volcanism and early Maori society in New
 2481 Zealand. In: Torrence, R., Grattan, J. (eds) *Natural Disasters and Cultural Change*. Routledge,
 2482 London, pp.126-161.
 2483
- 2484 Lowe, D.J., Shane, P.A., Alloway, B.V. and Newnham, R.M., 2008a. Fingerprints and age models for
 2485 widespread New Zealand tephra marker beds erupted since 30,000 years ago: a framework for NZ-
 2486 INTIMATE. *Quaternary Science Reviews*, 27(1-2), pp.95-126.
 2487
- 2488 Lowe, D.J., Tonkin, P.J., Neall, V.E., Palmer, A.S., Alloway, B.V., Froggatt, P.C. 2008b. Colin
 2489 George Vucetich (1918–2007) – pioneering New Zealand tephrochronologist. *Quaternary*
 2490 *International* 178, 11-15.
 2491
- 2492 Lowe, D.J., Blaauw, M., Hogg, A.G. and Newnham, R.M., 2013. Ages of 24 widespread tephtras
 2493 erupted since 30,000 years ago in New Zealand, with re-evaluation of the timing and palaeoclimatic
 2494 implications of the Lateglacial cool episode recorded at Kaipo bog. *Quaternary Science Reviews*, 74,
 2495 pp.170-194.
 2496
- 2497 Lowe, D.J., Pearce, N.J., Jorgensen, M.A., Kuehn, S.C., Tryon, C.A. and Hayward, C.L., 2017.
 2498 Correlating tephtras and cryptotephtras using glass compositional analyses and numerical and statistical
 2499 methods: Review and evaluation. *Quaternary Science Reviews*, 175, pp.1-44.
 2500
- 2501 Lowe, D.J., Loame, R.C., Moon, V.G., Johnston, R.E., Kluger, M.O., Villamor, P., Orense, R., de
 2502 Lange, W.P., Davies, S.M., Ross, N., Vandergoes, M.J., Rees, A.B.H. 2018. Earth-shaking insight
 2503 from liquefied tephtra layers in lakes in central Waikato region, New Zealand: a new tool to evaluate
 2504 and date palaeoseismicity? *In: Hambach, U., Veres, D. (eds), Book of Abstracts, Crossing New*
 2505 *Frontiers: INTAV International Field Conference on Tephrochronology, 'Tephtra Hunt in*
 2506 *Transylvania'*, Moieciu de Sus, Romania, 24 June-1 July, pp. 38-39.
 2507
- 2508 Magill CR, Blong RJ 2005. Volcanic risk ranking for Auckland, New Zealand. I. Methodology and
 2509 hazard investigation. *Bulletin of Volcanology* 67, 331-339.
 2510
- 2511 Magill CR, Hurst AW, Hunter LJ, Blong RJ 2006. Probabilistic tephtra fall simulation for the
 2512 Auckland Region, New Zealand. *Journal of Volcanology and Geothermal Research* 15, 370-386.
 2513
- 2514 Maier, K.L., Crundwell, M.P., Coble, M.A., King, PR, Graham, S.A. 2016. Refined depositional
 2515 history and dating of the Tongaporutuan reference section, north Taranaki, New Zealand: new
 2516 volcanic ash U–Pb zircon ages, biostratigraphy and sedimentation rates. *New Zealand Journal of*
 2517 *Geology and Geophysics*. 59(2):313–329.
 2518
- 2519 Manning, D.A., 1996. Middle-late Pleistocene tephrostratigraphy of the eastern Bay of Plenty, New
 2520 Zealand. *Quaternary International*, 34, pp.3-12.
 2521
- 2522 Manighetti, B., Palmer, A., Eden, D. and Elliot, M., 2003. An occurrence of Tuhua Tephtra in deep-
 2523 sea sediments from offshore eastern North Island, New Zealand. *New Zealand Journal of Geology*
 2524 *and Geophysics*, 46(4), 581-590.
 2525
- 2526 Matsu'ura, T., Miyagi, I., Furusawa, A. 2011. Late Quaternary cryptotephtra detection and correlation
 2527 in loess in northeastern Japan using cummingtonite geochemistry. *Quaternary Research* 75, 624-635.
 2528

- 2529 Matsu'ura, T., Furusawa, A. & Yanagida, M. 2012. Detection and correlation of widespread
 2530 cryptotephra in middle Pleistocene loess in NE Japan using cummingtonite
 2531 geochemistry. *Journal of Asian Earth Sciences*, 60, 49–67.
 2532
- 2533 Matsu'ura, T., Furusawa, A., Shimogama, K., Goto, N., Komatsubara, J. 2014. Late Quaternary
 2534 tephrostratigraphy and cryptotephrostratigraphy of deep-sea sequences (Chikyu C9001C cores) as
 2535 tools for marine terrace chronology in NE Japan. *Quaternary Geochronology* 23, 63-79.
 2536
- 2537 Matsu'ura, T., Ikehara, M., Ueno, T. 2021. Late Quaternary tephrostratigraphy and
 2538 cryptotephrostratigraphy of core MD012422: improving marine tephrostratigraphy of the NW Pacific.
 2539 *Quaternary Science Reviews* 257: 106808
 2540
- 2541 Matthews, N.E., Smith, V.C., Costa, A., Durant, A.J., Pyle, D.M., Pearce, N.J.G. 2012, Ultra-distal
 2542 tephra deposits from super-eruptions: examples from Toba, Indonesia and Taupo Volcanic Zone, New
 2543 Zealand. *Quat. Int.* 258, 54–79.
 2544
- 2545 McCraw, J.D. 1989. Tephra on Great Mercury Island. *Geological Society of New Zealand Newsletter*
 2546 83, 42-43.
 2547
- 2548 McCraw, J.D. 1975. Quaternary airfall deposits of New Zealand. *Royal Society of New Zealand*
 2549 *Bulletin* 13, 35-44.
 2550
- 2551 McDaniel, P.A., Lowe, D.J., Arnalds, O., Ping, C.-L. 2012. Andisols. In: Huang, P.M., Li, Y.,
 2552 Sumner, M.E. (eds) "Handbook of Soil Sciences. 2nd edition. Vol. 1: Properties and Processes". CRC
 2553 Press, Boca Raton, pp.33.29-33.48
 2554
- 2555 McGlone, M.S. 2009. Postglacial history of New Zealand wetlands and implications for their
 2556 conservation. *New Zealand Journal of Ecology* 33: 1–23.
 2557
- 2558 McGlone, M.S. Wilmshurst, J.M. 1999. Dating initial Maori environmental impact in New Zealand.
 2559 *Quaternary International* 59, 5-16.
 2560
- 2561 McGlone, M.S., Howorth, R., Pullar, W.A. 1984. Late Pleistocene stratigraphy, vegetation and
 2562 climate of the Bay of Plenty and Gisborne regions, New Zealand. *New Zealand journal of geology*
 2563 *and geophysics* 27: 327-350.
 2564
- 2565 McKay, N.P., Emile-Geay, J., Khider, D. 2021. geoChronR – an R package to model, analyze, and
 2566 visualize age-uncertain data. *Geochronology* 3, 149–169.
 2567
- 2568 McLeod, O.E., Pittari, A., Brenna, M., Briggs, R.M. 2020. Geology of the Pirongia Volcano,
 2569 Waikato: 1:30,000 Geological Map. Geoscience Society of New Zealand Miscellaneous Publication
 2570 156. 59 pp + map
 2571
- 2572 Mew, G., Hunt, J.L., Froggatt, P.C., Eden, D.N. and Jackson, R.J., 1986. An occurrence of Kawakawa
 2573 Tephra from the Grey River valley, South Island, New Zealand. *New Zealand journal of geology and*
 2574 *geophysics*, 29(3), pp.315-322.
 2575
- 2576 Mew, G., Thomas, R.F., Eden, D.N., 1988. Stratigraphy of loessic cover beds at The Lamplough,
 2577 West Coast, South Island, New Zealand. *Journal of the Royal Society of New Zealand* 18, 325–332.
 2578
- 2579 Milicich, S.F., Chambrfort, I., Wilson, C.J.N., Alcaraz, S., Ireland, T.R., Bardley, C., Dimpson, M.P.
 2580 2020. A zircon U-Pb geochronology for the Rotokawa geothermal system, New Zealand, with
 2581 implications for Taupō Volcanic Zone evolution. *Journal of Volcanology and Geothermal Research*
 2582 389, 106729.

2583
2584 Moebis, A., Cronin, S.J., Neall, V.E., Smith, I.E.M. 2011. Unravelling a complex volcanic history
2585 from fine-grained, intricate Holocene ash sequences at the Tongariro Volcanic Centre, New Zealand.
2586 Quaternary International 246, 352-363.
2587
2588 Molloy, C.M., 2008. Tephrostratigraphy of the Auckland Maar Craters (MSc thesis). University of
2589 Auckland, New Zealand
2590
2591 Molloy, C., Shane, P. and Augustinus, P., 2009. Eruption recurrence rates in a basaltic volcanic field
2592 based on tephra layers in maar sediments: implications for hazards in the Auckland volcanic
2593 field. Geological Society of America Bulletin, 121(11-12), pp.1666-1677.
2594
2595 Mortimer, N. and Scott, J.M., 2020. Volcanoes of Zealandia and the Southwest Pacific. New Zealand
2596 Journal of Geology and Geophysics, 64 (2), 371-377.
2597
2598 Nairn, I. A 1972. Rotoehu Ash and the Rotoiti Breccia Formation, Taupo Volcanic Zone, New
2599 Zealand. New Zealand journal of geology and geophysics 15, 251-261.
2600
2601 Nairn, I.A. 1979. Rotomahana-Waimangu eruption, 1886: base surge and basalt magma. New Zealand
2602 Journal of Geology and Geophysics 22, 363-378.
2603
2604 Nairn, I.A. 2002. Geology of the Okataina Volcanic Centre. Institute of Geological and Nuclear
2605 Sciences Geological Map 25, 156p + map.
2606
2607 Nairn, I.A. and Kohn, B.P., 1973. Relation of the Earthquake Flat Breccia to the Rotoiti Breccia,
2608 central North Island, New Zealand. New Zealand journal of geology and geophysics, 16(2), pp.269-
2609 279.
2610
2611 Nairn, I.A., Shane, P.A.R., Cole, J.W., Leonard, G.J., Self, S., Pearson, N., 2004. Rhyolite magma
2612 processes of the c. AD 1315 Kaharoa eruptive episode, Tarawera volcano, New Zealand. J. Volcanol.
2613 Geotherm. Res. 131, 265-294.
2614
2615 Naish, T., Kamp, P.J., Alloway, B.V., Pillans, B., Wilson, G.S. and Westgate, J.A., 1996. Integrated
2616 tephrochronology and magnetostratigraphy for cyclothem marine strata, Wanganui Basin:
2617 implications for the Pliocene-Pleistocene boundary in New Zealand. Quaternary International, 34,
2618 pp.29-48.
2619
2620 Naish, T.R., Abbott, S.T., Alloway, B.V., Beu, A.G., Carter, R.M., Edwards, A.R., Journeaux, T.D.,
2621 Kamp, P.J.J., Pillans, B.J., Saul, G. et al. 1998. Astronomical calibration of a southern hemisphere
2622 Plio-Pleistocene reference section, Wanganui Basin, New Zealand. Quaternary Science Reviews 17,
2623 695–710.
2624
2625 Naish, T.R., Field, B.D., Zhu, H., Melhuish, A., Carter, R.M., Abbott, S.T., Edwards, S., Alloway,
2626 B.V., Wilson, G.S., Niessen, F., Barker, A., Browne, G.H., Maslen, G. 2005. Integrated outcrop, drill
2627 core, borehole and seismic stratigraphic architecture of a cyclothem, shallow-marine depositional
2628 system, Wanganui basin, New Zealand. Journal of the Royal Society of New Zealand 35, 91-122.
2629
2630 Neall, V.E., 1972. Tephrochronology and tephrostratigraphy of western Taranaki (N108-N109), New
2631 Zealand. N.Z. Journal of Geology and Geophysics 15: 507-557.
2632
2633 Neall, V.E. 1977. Genesis and weathering of Andosols in Taranaki, New Zealand. Soil Science 123,
2634 400-408.
2635

- 2636 Neall, V.E., Stewart, R.B., Wallace, R.C., Williams, M.C., Mew, G. 2001. Mineralogy, stratigraphy,
2637 and provenance of soil coverbeds in the Kumara district, Westland. *New Zealand Journal of Geology*
2638 and *Geophysics* 44, 205-218.
- 2639
- 2640 Needham, A.J., Lindsay, J.M., Smith, I.E.M., Augustinus, P. and Shane, P.A., 2011. Sequential
2641 eruption of alkaline and sub-alkaline magmas from a small monogenetic volcano in the Auckland
2642 Volcanic Field, New Zealand. *Journal of Volcanology and Geothermal Research*, 201(1-4), pp.126-
2643 142.
- 2644
- 2645 Nelson, C.S., Froggatt, P.C., Gosson, G.J. 1985. Nature, chemistry, and origin of late Cenozoic
2646 megascopic tephra in Leg 90 cores from the southwest Pacific. In: Kennett, J. P. & Von Der Borch,
2647 C. C. (eds) *Proceedings of the Ocean Drilling Program, Initial Reports, 90*. Ocean Drilling Program,
2648 Texas A & M University, College Station, TX, 1160–1173.
- 2649
- 2650 Newnham, R.M.; Lowe, D.J. 1991. Holocene vegetation and volcanic activity, Auckland Isthmus,
2651 New Zealand. *Journal of Quaternary Science* 6, 177-193.
- 2652
- 2653 Newnham, R.M.; Lowe, D.J. 2000. Fine-resolution pollen record of late-glacial climate reversal from
2654 New Zealand. *Geology* 28, 759-762.
- 2655
- 2656 Newnham, R. M., Lowe, D. J., Green, J. D. 1989. Palynology, vegetation, and climate of the Waikato
2657 lowlands, North Island, New Zealand, since c. 18 000 years ago. *Journal of the Royal Society of New*
2658 *Zealand* 19, 127-150.
- 2659
- 2660 Newnham, R.M., de Lange, P.J., Lowe, D.J. 1995. Holocene vegetation, climate, and history of a
2661 raised bog complex, northern New Zealand, based on palynology, plant macrofossils and
2662 tephrochronology. *The Holocene* 5, 267-282. .
- 2663
- 2664 Newnham, R.M., Lowe, D.J., McGlone, M.S., Wilmshurst, J.M. and Higham, T.F.G., 1998. The
2665 Kaharoa Tephra as a critical datum for earliest human impact in northern New Zealand. *Journal of*
2666 *Archaeological Science*, 25(6), pp.533-544.
- 2667
- 2668 Newnham, R.M., Lowe, D.J. and Alloway, B.V., 1999. Volcanic hazards in Auckland, New Zealand:
2669 a preliminary assessment of the threat posed by central North Island silicic volcanism based on the
2670 Quaternary tephrostratigraphical record. *Geological Society, London, Special Publications*, 161,
2671 pp.27-45.
- 2672
- 2673 Newnham, R.M.; Eden, D.N.; Lowe, D.J.; Hendy, C.H. 2003. Rerewhakaaitu Tephra, a land-sea
2674 marker for the Last Termination in New Zealand, with implications for global climate change.
2675 *Quaternary Science Reviews* 22, 289-308.
- 2676
- 2677 Newnham, R.M., Lowe, D.J., Green, J.D., Turner, G.M., Harper, M.A., McGlone, M.S., Stout, S.L.,
2678 Horie, S. and Froggatt, P.C., 2004. A discontinuous ca. 80 ka record of Late Quaternary
2679 environmental change from Lake Omapere, Northland, New Zealand. *Palaeogeography,*
2680 *Palaeoclimatology, Palaeoecology*, 207(1-2), pp.165-198.
- 2681
- 2682 Newnham, R.M., Lowe, D.J., Giles, T., Alloway, B.V. 2007a: Vegetation and climate of Auckland,
2683 NZ, since ca 32 000 cal yr ago: support for an extended LGM. *Journal of Quaternary Science* 22, 517-
2684 534.
- 2685
- 2686 Newnham, R.M., Vandergoes, M.J., Hendy, C.H., Lowe, D.J., Preusser, F. 2007b: A terrestrial
2687 palynological record for the last two glacial cycles from southwestern NZ. *Quaternary Science*
2688 *Reviews* 26, 517-535.
- 2689

2690 Newnham RM, Vandergoes MJ, Garnett M, Lowe DJ, Prior C, and Almond PJ 2007c. Test of AMS
2691 ¹⁴C dating of pollen concentrates using tephrochronology. *Journal of Quaternary Science* 22, 37–51.
2692
2693 Newnham, R.M., Dirks, K.N. and Samaranayake, D., 2010. An investigation into long-distance health
2694 impacts of the 1996 eruption of Mt Ruapehu, New Zealand. *Atmospheric Environment*, 44(12),
2695 pp.1568-1578.
2696
2697 Newnham, R.M., Lowe, D.J., Gehrels, M.J., Augustinus, P. 2018. Two-step human–environmental
2698 impact history for northern New Zealand linked to late-Holocene climate change. *The Holocene* 28,
2699 1093-1106.
2700
2701 Newnham, R.M., Hazell, Z.J., Charman, D.J., Lowe, D.J., Rees, A.B.H., Amesbury, M.J., Roland,
2702 T.P., Gehrels, M.J., van den Bos, V., Jara, I.A. 2019. Peat humification records from Restionaceae
2703 bogs in northern New Zealand as potential indicators of Holocene precipitation, seasonality, and
2704 ENSO. *Quaternary Science Reviews* 218, 378-394.
2705
2706 Nicol, R., 1982. Fossilised human footprints in Rangitoto Ash on Motutapu Island. *Geological Society*
2707 *of New Zealand Newsletter* 51:11-13.
2708
2709 Nilsson, A., Muscheler, R., Snowball, I., Aldahan, A., Possnert, G., Augustinus, P., Atkin, D. and
2710 Stephens, T., 2011. Multi-proxy identification of the Laschamp geomagnetic field excursion in Lake
2711 Pupuke, New Zealand. *Earth and Planetary Science Letters*, 311(1-2), pp.155-164.
2712
2713 Ninkovich, D., 1968. Pleistocene volcanic eruptions in New Zealand recorded in deep-sea sediments.
2714 *Earth and Planetary Science Letters* 4: 89-102.
2715
2716 Oliver, W.R.B., 1931. An ancient Maori oven on Mount Egmont. *Journal of Polynesian Society* 40:
2717 73-80.
2718
2719 Orpin, A., Carter, L., Page, U., Trustrum, N., Gomez, B., Palmer, A., Mildenhall, D., Rogers, K.,
2720 Brackley, H., Northcote, L., 2010. Holocene sedimentary record from Lake Tutira: A template for
2721 upland watershed erosion proximal to the Waipaoa Sedimentary System, northeastern New Zealand.
2722 *Marine Geology* 270, 11-29.
2723
2724 Österle, J.E., Stockli, D.F., Seward, D., Little, T.A. 2020. Dating of young (<1 Ma) tephros: using U-
2725 Pb (zircon) and (U-Th[-Sm])/He (zircon, apatite, magnetite) chronometers to unravel the eruption age
2726 of a tephra in the Woodlark Rift of Papua New Guinea. *Terra Nova* 33, 345-354.
2727
2728 Pain, C. F, 1975. Some tephra deposits in the southwest Waikato area, North Island, New Zealand.
2729 *New Zealand Journal of Geology and Geophysics* 18, 541-550.
2730
2731 Palmer, A.S. 2013. Pedostratigraphy. In: Elias, S.A., Mock, C.J. (Eds) *The Encyclopaedia of*
2732 *Quaternary Science*, 2nd ed. Volume 4, pp. 250–259. Elsevier, Amsterdam.
2733
2734 Palmer, J.G., Ogden, J. and Patel, R.N. (1988): A 426-year floating tree-ring chronology from
2735 *Phyllocladus trichomanoides* buried by the Taupo eruption at Pureora, central North Island, New
2736 Zealand. *Journal of the Royal Society of New Zealand*, 18, 407-415.
2737
2738 Pardo, N., Cronin, S.J., Palmer, A.S., Nemeth, K. 2012. Reconstructing the largest explosive
2739 eruptions of Mt. Ruapehu, New Zealand: lithostratigraphic tools to understand subplinian–plinian
2740 eruptions at andesitic volcanoes. *Bull Volcanol.* 74, 617–640.
2741

2742 Payne R, Blackford J, van der Plicht J 2008. Using cryptotephra to extend regional
2743 tephrochronologies: an example from southeast Alaska and implications for hazard assessment.
2744 Quaternary Research 69, 24-55.
2745

2746 Pearce, N.J.G., Alloway, B.V., Westgate, J.A. 2008. Mid-Pleistocene silicic tephra beds in the
2747 Auckland region, New Zealand. Quaternary International 178, 16-43.
2748

2749 Pearce, N.J.G., Abbott, P.M., Martin-Jones, C. 2014. Microbeam methods for the analysis of glass in
2750 fine-grained tephra deposits: a SMART perspective on current and future trends. Geological Society,
2751 London, Special Publications 398, 29-46.
2752

2753 Perry, G.L.W., Wilmshurst, J.M., McGlone, M.S., McWethy, D.B., Whitlock, C. 2012. Explaining fire-
2754 driven landscape transformation during the Initial Burning Period of New Zealand's prehistory. Global
2755 Change Biology 18, 1609-1621.
2756

2757 Persaud, M., Villamor, P., Berryman, K.R., Ries, W., Cousins, W.J., Litchfield, N., Alloway, B.V.
2758 2016. The Kerepehi Fault, Hauraki Rift, North Island, New Zealand: active fault characterisation and
2759 hazard. New Zealand Journal of Geology and Geophysics 59, 117-135.
2760

2761 Persson, C. 1966. Försök till tefrokronologisk datering av några svenska torvmossar. Geologiska
2762 Föreningen i Stockholm Förhandlingar 88(3), 361-394 (DOI: 10.1080/11035896609448933).
2763

2764 Persson C. 1971. Tephrochronological investigation of peat deposits in Scandinavia and on the Faroe
2765 Islands. Geological Survey of Sweden C 656: 1-34.
2766

2767 Peti, L. and Augustinus, P.C., 2019. Stratigraphy and sedimentology of the Ōrākei maar lake sediment
2768 sequence (Auckland Volcanic Field, New Zealand). Scientific Drilling, 25, pp.47-56.
2769

2770 Peti, L., Augustinus, P.C., Gadd, P.S. and Davies, S.J., 2019. Towards characterising rhyolitic tephra
2771 layers from New Zealand with rapid, non-destructive μ -XRF core scanning. Quaternary
2772 International, 514, pp.161-172.
2773

2774 Peti, L., Fitzsimmons, K.E., Hopkins, J.L., Nilsson, A., Fujioka, T., Fink, D., Mifsud, C., Christl, M.,
2775 Muscheler, R. and Augustinus, P.C., 2020a. Development of a multi-method chronology spanning the
2776 Last Glacial interval from Ōrākei maar lake, Auckland, New Zealand. Geochronology 2, 367-410
2777 (doi: 10.5194/gchron-2020-23)
2778

2779 Peti, L., Gadd, P.S., Hopkins, J.L. and Augustinus, P.C., 2020b. Itrax μ -XRF core scanning for rapid
2780 tephrostratigraphic analysis: a case study from the Auckland Volcanic Field maar lakes. Journal of
2781 Quaternary Science, 35(1-2), pp.54-65.
2782

2783 Peti, L., Hopkins, J.L., Augustinus, P. 2021. Revised tephrochronology for key tephra in the 130-ka
2784 Ōrākei Basin maar core, Auckland Volcanic Field, New Zealand: implications for the timing of
2785 climatic changes, New Zealand. New Zealand Journal of Geology and Geophysics (in press)
2786 <https://doi.org/10.1080/00288306.2020.1867200>
2787

2788 Pillans, B.J. 1983. Upper Quaternary marine terrace chronology and deformation, South Taranaki,
2789 New Zealand. Geology 11, 292-297.
2790

2791 Pillans, B., 1994. Direct marine-terrestrial correlations, Wanganui Basin, New Zealand: the last 1
2792 million years. Quaternary science reviews, 13(3), pp.189-200.
2793

2794 Pillans, B.J. 1997. Soil development at snail's pace: evidence from a 6 Ma soil chronosequence on
2795 basalt in north Queensland, Australia. Geoderma 80, 117-128.

2796
2797 Pillans, B.J. 2017: Quaternary stratigraphy of Whanganui Basin—a globally significant archive. In:
2798 Shulmeister, J. (ed), *Landscape and Quaternary Environmental Change in New Zealand*, Atlantis
2799 *Advances in Quaternary Science* 3, 141-170.
2800
2801 Pillans, B. and Wright, I., 1992. Late Quaternary tephrostratigraphy from the southern Havre Trough-
2802 Bay of Plenty, northeast New Zealand. *New Zealand journal of geology and geophysics*, 35(2),
2803 pp.129-143.
2804
2805 Pillans, B.J., Pullar, W.A., Selby, M.J., Soons, JM. 1992. The age and development of the New
2806 Zealand landscape. In: Soons, J.M., Selby, M.J. (eds) *Landforms of New Zealand: Second Edition*.
2807 Auckland, Longman Paul, 31-62.
2808
2809 Pillans, B., McGlone, M., Palmer, A., Mildenhall, D., Alloway, B. and Berger, G., 1993. The Last
2810 Glacial Maximum in central and southern North Island, New Zealand: a paleoenvironmental
2811 reconstruction using the Kawakawa Tephra Formation as a chronostratigraphic
2812 marker. *Palaeogeography, palaeoclimatology, palaeoecology*, 101(3-4), pp.283-304.
2813
2814 Pillans, B., Kohn, B.P., Berger, G., Froggatt, P., Duller, G., Alloway, B. and Hesse, P., 1996. Multi-
2815 method dating comparison for mid-Pleistocene Rangitawa tephra, New Zealand. *Quaternary Science*
2816 *Reviews*, 15(7), pp.641-653.
2817
2818 Pillans, B., Alloway, B., Naish, T., Westgate, J., Abbott, S. and Palmer, A., 2005. Silicic tephras in
2819 Pleistocene shallow-marine sediments of Wanganui Basin, New Zealand. *Journal of the Royal Society*
2820 *of New Zealand*, 35(1-2), pp.43-90.

2821 Pittari, A., Prentice, M.L., McLeod, O.E., Yousefzadeh, E., Kamp, P.J.J., Danišik, M., Vincent, K.A.,
2822 2021. Inception of the modern North Island (New Zealand) volcanic setting: spatio-temporal patterns
2823 of volcanism between 3.0 and 0.9 Ma. *New Zealand Journal of Geology and Geophysics* 64 (2)
2824 <https://doi.org/10.1080/00288306.2021.1915343>

2825 Ponomareva, V., Portnyagin, M., Davies, S. 2015. Tephra without borders: far-reaching clues into
2826 past explosive eruptions. *Frontiers in Earth Sciences* 3, article 83, [doi: org/10.3389/feart.2015.00083](https://doi.org/10.3389/feart.2015.00083)
2827
2828 Platz, T., Cronin, S.J., Cashman, K.V., Stewart, R.B., Smith, I.E.M. 2007a. Transition from effusive
2829 to explosive phases in andesite eruptions – a case-study from the AD1655 eruption of Mt. Taranaki,
2830 New Zealand. *Journal of Volcanology and Geothermal Research* 161, 15-34.
2831
2832 Platz, T., Cronin, S.J., Smith, I.E.M., Turner, M.B., Stewart, R.B. 2007b. Improving the reliability of
2833 microprobe-based analyses of andesitic glasses for tephra correlation. *The Holocene* 17, 573-583.
2834
2835 Prentice M, Pittari A, Kamp PJJ, Lowe DJ, Kilgour G. 2020. The 2.1 Ma Waiteariki Ignimbrite:
2836 defining a new super-eruption at the onset of TVZ volcanism. In: Bassett K.N., Nichols A.R.L.,
2837 Fenton C.H. (eds). *Geosciences 2020: Abstract Volume*. Geoscience Society of New Zealand
2838 *Miscellaneous Publication 157A*, p.227.
2839
2840 Procter, J., Zernack, A., Mead, S., Morgan, M., Cronin, S. 2020. A review of lahars; past deposits,
2841 historic events and present-day simulations from Mt. Ruapehu and Mt. Taranaki, New Zealand. *New*
2842 *Zealand Journal of Geology and Geophysics*. DOI: 10.1080/00288306.2020.1824999
2843
2844 Pullar WA. 1959. The significance of volcanic ash beds in archaeology. *Journal of the Polynesian*
2845 *Society* 68, 8-11.
2846

- 2847 Pullar, W.A. 1973. Tephra marker beds in the soil and their application in related sciences. *Geoderma*
2848 10, 161-168.
- 2849
2850 Pullar, W.A., Birrell, K.S., 1973a. Parent materials of Tirau silt loam. *N.Z. Journal of Geology and*
2851 *Geophysics* 16: 677-686.
- 2852
2853 Pullar, W.A. Birrell, K.S., 1973b. Age and distribution of late Quaternary pyroclastic and associated
2854 cover deposits of the Rotorua and Taupo area, North Island, New Zealand. *N.Z. Soil Survey Report* 1.
2855
- 2856 Pullar, W.A., Heine, J.C., 1971. Ages, inferred from ¹⁴C dates, of some tephra and other deposits from
2857 Rotorua, Taupo, Bay of Plenty, Gisborne and Hawke's Bay districts. *Proceedings Radiocarbon Users'*
2858 *Conference, Lower Hutt*. Pp. 117-138.
- 2859
2860 Pullar, W.A., Selby, M.J. 1971. Coastal progradation of Rangitaiki Plains, New Zealand. *New*
2861 *Zealand Journal of Science* 14, 419-434.
- 2862
2863 Pullar, W. A., Birrell, K. S., and Heine, J.C., 1973. Named tephtras and tephra formations occurring in
2864 the central North Island, with notes on derived soils and buried paleosols. *NZ. Journal of Geology and*
2865 *Geophysics* 16: 497-518.
- 2866
2867 Pure, L.R., Leonard, G.S., Townsend, D.B., Wilson, C.J.N., Calvert, A.T., Cole, R.P., Conway, C.E.,
2868 Gamble, J.A., Smith, T. 'B'. 2020. A high resolution ⁴⁰Ar/³⁹Ar lava chronology and edifice
2869 construction history for Tongariro volcano, New Zealand, *Journal of Volcanology and Geothermal*
2870 *Research*, 403, article 106993.
- 2871
2872 Pyne-O'Donnell S.D.F. 2011. The taphonomy of Last Glacial-Interglacial Transition (LGIT) distal
2873 volcanic ash in small Scottish lakes. *Boreas* 40,131-145.
- 2874
2875 Pyne-O'Donnell, S.D.F., Hughes, P.D.M., Froese, D.G., Jensen, B.J.L., Kuehn, S.C., Mallon, G.,
2876 Amesbury, M.J., Charman, D.J., Daley, T.J., Loader, N.J., Mauquoy, D., Street-Perrott, F.A.,
2877 Woodman-Ralph, J., 2012. High-precision ultra-distal Holocene tephrochronology in North America.
2878 *Quat. Sci. Rev.* 52, 6-11.
- 2879
2880 Rankin, P.C., 1973. Correlation of volcanic glasses in tephtras and soils using micro-element
2881 composition. *N.Z. Journal of Geology and Geophysics* 20: 697-717.
- 2882
2883 Ratcliffe, J.L., Lowe, D.J., Schipper, L.A., Gehrels, M.J., French, A., Campbell, D.I. 2020.
2884 Rapid carbon accumulation in a peatland following Late Holocene tephra deposition, New
2885 Zealand. *Quaternary Science Reviews* 246, article 106505
- 2886
2887 Rees, C., Palmer, J., Palmer, A. 2018. Plio-Pleistocene geology of the lower Pohangina valley, New
2888 Zealand. *New Zealand journal of geology and geophysics* 61, 44-63.
- 2889
2890 Rees, C., Palmer, J. and Palmer, A., 2020. Tephrostratigraphic constraints on sedimentation and
2891 tectonism in the Whanganui Basin, New Zealand. *New Zealand Journal of Geology and*
2892 *Geophysics*, 63(2), 262-280.
- 2893
2894 Roberts, S.J., Sanderson, D.C.W., Dugmore, A.J. 2021. Developing luminescence analysis of
2895 Icelandic volcanic glass: a case study using the Þórsmörk Ignimbrite. *PLoS One* (in press).
- 2896
2897 Robertson, S.M., Mew, G. 1982. The presence of volcanic glass in soils on the West Coast, South
2898 Island, New Zealand. *New Zealand Journal of Geology and Geophysics* 25, 503-507.
- 2899

2900 Rowe, M.C., Carey, R.J., White, J.D.L., Kilgour, G., Hughes, E., Ellis, B. Rosseel, J.-B., Segovia, A.
2901 2021. Tarawera 1886: an integrated review of volcanological and geochemical characteristics of a
2902 complex basaltic eruption. *New Zealand Journal of Geology and Geophysics* 64 (2), DOI:
2903 10.1080/00288306.2021.1914118
2904
2905 Saffer, D.M., Wallace, L.M., Barnes, P.M., Pecher, I.A., Petronotis, K.E., LeVay, L.J., Bell, R.E.,
2906 Crundwell, M.P., Engelmann de Oliveira, C.H., Fagereng, A., Fulton, P.M., Greve, A., Harris, R.N.,
2907 Hashimoto, Y., Hüpers, A., Ikari, M.J., Ito, Y., Kitajima, H., Kutterolf, S., Lee, H., Li, X., Luo, M.,
2908 Malie, P.R., Meneghini, F., Morgan, J.K., Noda, A., Rabinowitz, H.S., Savage, H.M., Shepherd, C.L.,
2909 Shreedharan, S., Solomon, E.A., Underwood, M.B., Wang, M., Woodhouse, A.D., Bourlange, S.M.,
2910 Brunet, M.M.Y., Cardona, S., Clennell, M.B., Cook, A.E., Dugan, B., Elger, J., Gamboa, D.,
2911 Georgiopoulou, A., Han, S., Heeschen, K.U., Hu, G., Kim, G.Y., Koge, H., Machado, K.S.,
2912 McNamara, D.D., Moore, G.F., Mountjoy, J.J., Nole, M.A., Owari, S., Paganoni, M., Rose, P.S.,
2913 Scream, E.J., Shankar, U., Torres, M.E., Wang, X., and Wu, H.-Y., 2019. Expedition 372B/375
2914 summary. *In*: Wallace, L.M., Saffer, D.M., Barnes, P.M., Pecher, I.A., Petronotis, K.E., LeVay, L.J.,
2915 and the Expedition 372/375 Scientists, “Hikurangi Subduction Margin Coring, Logging, and
2916 Observatories”. *Proceedings of the International Ocean Discovery Program, 372B/375: College*
2917 *Station, TX (International Ocean Discovery Program).*
2918 <https://doi.org/10.14379/iodp.proc.372B375.101.2019>
2919
2920 Sagar, M.W., Browne, G.H., Arnot, M.J., Seward, D., Strogon, D.P. 2019 New U–Pb zircon ages and
2921 a revised integrated age model for the late Miocene northern Taranaki coastal section, New Zealand,
2922 *New Zealand Journal of Geology and Geophysics* 62, 357-370.
2923
2924 Salter, R. T., 1979. A pedological study of the Kauroa Ash Formation at Woodstock. Unpublished
2925 M.Sc. thesis, University of Waikato, Hamilton.
2926
2927 Sandiford, A., Alloway, B. and Shane, P., 2001. A 28 000–6600 cal yr record of local and distal
2928 volcanism preserved in a paleolake, Auckland, New Zealand. *New Zealand Journal of Geology and*
2929 *Geophysics*, 44(2), pp.323-336.
2930
2931 Sandhu, A. S., Westgate, J. A. 1995. The correlation between reduction in fission-track diameter and
2932 areal track density in volcanic glass shards and its application in dating tephra beds. *Earth and*
2933 *Planetary Science Letters* 131, 289–299.
2934
2935 Sandhu, A.D., Westgate, J.A., Alloway. B.V. 1993. Optimizing the isothermal plateau fission track
2936 dating method for volcanic glass shards. *Nucl. Tracks* 21, 479– 488.
2937
2938 Santos, G.M., Bird, M.I., Pillans, B., Fifield, L.K., Alloway, B.V., Chappell, J., Hausladen, P.A. and
2939 Arneth, A., 2001. Radiocarbon dating of wood using different pretreatment procedures: application to
2940 the chronology of Rotoehu Ash, New Zealand. *Radiocarbon*, 43(2A), pp.239-248.
2941
2942 Scheidt S, Berg S, Hambach U, Klasen N, Pötter S, Stolz A, Veres D, Zeeden C, Brill D, Brückner H,
2943 Kusch S, Laag C, Lehmkuhl F, Melles M, Monnens F, Oppermann L, Rethemeyer J and Nett JJ. 2021.
2944 Chronological assessment of the Balta Alba Kurgan loess-paleosol section (Romania) – a comparative
2945 study on different dating methods for a robust and precise age model. *Front. Earth Sci.* 8:598448. doi:
2946 10.3389/feart.2020.598448
2947
2948 Schmid, M.M.E., Wood, R., Newton, A., Vésteinsson, O., Dugmore, A. 2019. Enhancing
2949 radiocarbon chronologies of colonization: chronometric hygiene revisited. *Radiocarbon* 61, 629–647.
2950
2951 Scott, S.D., 1970. Excavations at the “Sunde Site”, N38/24, Motutapu Island, New Zealand. *Records*
2952 *of the Auckland Institute and Museum* 7, 13-30.
2953

- 2954 Selby, M.J., Lowe, D.J. 1992. The middle Waikato Basin and hills. In: Soons, J.M., Selby, M.J. (eds)
 2955 "Landforms of New Zealand, 2nd edition". Longman Paul, Auckland, pp. 233-255.
 2956
- 2957 Seward, D. 1979. Comparison of zircon and glass fission track ages from tephra horizons. *Geology* 7,
 2958 479-482.
 2959
- 2960 Seward, D., Kohn, B.P. 1997. New zircon fission-track ages from New Zealand Quaternary tephra: an
 2961 interlaboratory experiment and recommendations for the determination of young ages. *Chemical*
 2962 *Geology* 141, 127-140.
 2963
- 2964 Shane, P., 1998. Correlation of rhyolitic pyroclastic eruptive units from the Taupo volcanic zone by
 2965 Fe-Ti oxide compositional data. *Bulletin of Volcanology* 60(3), 224-238.
 2966
- 2967 Shane, P.A.R. 2000. Tephrochronology: a New Zealand case study. *Earth-Science Reviews* 49, 223-
 2968 259.
 2969
- 2970 Shane, P., 2005. Towards a comprehensive distal andesitic tephrostratigraphic framework for New
 2971 Zealand based on eruptions from Egmont volcano. *Journal of Quaternary Science* 20, 45-57.
 2972
- 2973 Shane, P.A.R. 2017. The southern end of the Pacific Ring of Fire: Quaternary volcanism in New
 2974 Zealand. In: Shulmeister, J. (ed). *Landscape and Quaternary Environmental Change in New Zealand*.
 2975 Springer/Atlantis Press, pp. 35-66.
 2976
- 2977 Shane, P.A.R. and Froggatt, P.C., 1991. Glass chemistry, paleomagnetism, and correlation of middle
 2978 Pleistocene tuffs in southern North Island, New Zealand, and western Pacific. *New Zealand journal of*
 2979 *geology and geophysics*, 34(2), pp.203-211.
 2980
- 2981 Shane, P.A.R., Froggatt, P.C., 1994. Discriminant function analysis of glass chemistry of New
 2982 Zealand and North American tephra deposits. *Quat. Res.* 41, 70-81.
 2983
- 2984 Shane, P. and Hoverd, J., 2002. Distal record of multi-sourced tephra in Onepoto Basin, Auckland,
 2985 New Zealand: implications for volcanic chronology, frequency and hazards. *Bulletin of*
 2986 *Volcanology*, 64(7), pp.441-454.
 2987
- 2988 Shane, P. and Sandiford, A., 2003. Paleovegetation of marine isotope stages 4 and 3 in northern New
 2989 Zealand and the age of the widespread Rotoehu tephra. *Quaternary Research*, 59(3), pp.420-429.
 2990
- 2991 Shane, P. and Zawalna-Geer, A., 2011. Correlation of basaltic tephra from Mt Wellington volcano:
 2992 implications for the penultimate eruption from the Auckland Volcanic Field. *Quaternary*
 2993 *International*, 246(1-2), pp.374-381.
 2994
- 2995 Shane, P.A., Black, T.M., Alloway, B.V. and Westgate, J.A., 1996. Early to middle Pleistocene
 2996 tephrochronology of North Island, New Zealand: Implications for volcanism, tectonism, and
 2997 paleoenvironments. *Geological Society of America Bulletin*, 108(8), pp.915-925.
 2998
- 2999 Shane, P., Froggatt, P., Smith, I. and Gregory, M., 1998a. Multiple sources for sea-rafted Loiseles
 3000 pumice, New Zealand. *Quaternary Research*, 49(3), pp.271-279.
 3001
- 3002 Shane, P., Black, T., Eggins, S. and Westgate, J., 1998b. Late Miocene marine tephra beds: recorders
 3003 of rhyolitic volcanism in North Island, New Zealand. *New Zealand Journal of Geology and*
 3004 *Geophysics*, 41(2), pp.165-178.
 3005
- 3006 Shane, P., Smith, V. and Nairn, I., 2003a. Biotite composition as a tool for the identification of
 3007 Quaternary tephra beds. *Quaternary Research*, 59(2), pp.262-270.

3008
3009 Shane, P.A.R., Smith, V.C., Lowe, D.J., Nairn, I.A. 2003b. Re-identification of c. 15 700 cal yr BP
3010 tephra bed at Kaipo bog, eastern North Island: implications for dispersal of Rotorua and Puketarata
3011 tephra beds. *New Zealand Journal of Geology and Geophysics* 46, 591-596.
3012
3013 Shane, P., Sikes, E.L. and Guilderson, T.P., 2006. Tephra beds in deep-sea cores off northern New
3014 Zealand: implications for the history of Taupo Volcanic Zone, Mayor Island and White Island
3015 volcanoes. *Journal of Volcanology and Geothermal Research*, 154(3-4), pp.276-290.
3016
3017 Shane, P.A.R., Nairn, I.A., Martin, S.B., Smith, V.C. 2008. Compositional heterogeneity in tephra
3018 deposits resulting from the eruption of multiple magma bodies: implications for tephrochronology.
3019 *Quaternary Intern* 178, 44-53.
3020
3021 Shane, P., Gehrels, M., Zawalna-Geer, A., Augustinus, P., Lindsay, J., Chaillou, I. 2013. Longevity of
3022 a small shield volcano revealed by crypto-tephra studies (Rangitoto volcano, New Zealand): change in
3023 eruptive behavior of a basaltic field. *Journal of Volcanology and Geothermal Research* 257, 174-183.
3024
3025 Shulmeister, J., Shane, P., Lian, O.B., Okuda, M., Carter, J.A., Harper, M., Dickinson, W.,
3026 Augustinus, P. and Heijnis, H., 2001. A long late-Quaternary record from Lake Poukawa, Hawke's
3027 Bay, New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology* 176(1-4), 81-107.
3028
3029 Sigl, M., McConnell, J.R., Layman, L., Maselli, O., McGwire, K., Pasteris, D., Dahl-Jensen, D.,
3030 Steffensen, J.P., Vinther, B., Edwards, R., Mulvaney, R., Kipfstuhl, S. 2013. A new bipolar ice core
3031 record of volcanism from WAIS Divide and NEEM and implications for climate forcing of the last
3032 2000 years. *Journal of Geophysical Research: Atmospheres* 118, 1151-1169.
3033
3034 Sjøholm, J., Sejrup, H.P., Furnes, H. 1991. Quaternary volcanic ash zones on the Iceland Plateau,
3035 southern Norwegian Sea. *Journal of Quaternary Science* 6, 159-73.
3036
3037 Smith, R.T., Houghton, B.F., 1995. Vent migration and changing dynamics during the 1800a Taupo
3038 eruption: new evidence from the Hatepe and Rotongaio ashes. *Bull. Volcanol.* 57, 432-439.
3039
3040 Smith, D.G.W., Westgate, J.A. 1969. Electron probe technique for characterizing pyroclastic deposits.
3041 *Earth and Planetary Science Letters*, 5, 313-319.
3042
3043 Smith, V. C., Shane, P., Smith, I. E. M. 2002. Tephrostratigraphy and geochemical fingerprinting of
3044 the Mangaone Subgroup tephra beds, Okataina Volcanic Centre, New Zealand. *New Zealand Journal*
3045 *of Geology and Geophysics* 45, 207-219.
3046
3047 Smith, V.C., Shane, P.A.R., Nairn, I.A. 2004. Rotorua eruptive episode: implications for magma
3048 storage in the Okataina Volcanic Centre, New Zealand. *J. Geol. Soc.* 161, 757-772.
3049
3050 Smith, V.C., Shane, P.A.R., Nairn, I.A. 2005. Trends in rhyolite geochemistry, mineralogy, and
3051 magma storage during the last 50 kyr at Okataina and Taupo volcanic centres, Taupo Volcanic Zone,
3052 New Zealand. *J. Volcanol. Geotherm. Res.* 148, 372-406.
3053
3054 Smith, V.C., Shane, P.A.R., Nairn, I.A., Williams, C.M. 2006. Geochemistry and magmatic properties
3055 of eruption episodes from Haroharo linear vent zone, Okataina Volcanic Centre, New Zealand during
3056 the last 10 kyr. *Bull. Volcanol.* 69, 57-88.
3057
3058 Sparks, R.S.J., Self, S., Walker G.P.L. 1973. Products of ignimbrite eruptions. *Geology* 1, 115-118.
3059

3060 Stevens, M.T., 2010. Miocene and Pliocene silicic Coromandel Volcanic Zone tephra from ODP Site
3061 1124-C: petrogenetic applications and temporal evolution. Unpublished MSc Thesis, Victoria
3062 University of Wellington, Wellington, New Zealand.
3063
3064 Stokes, S., Lowe, D.J., 1988. Discriminant function analysis of late Quaternary tephra from five
3065 volcanoes in New Zealand using glass shard major element chemistry.
3066 *Quat. Res.* 30, 270-283.
3067
3068 Stokes, S., Lowe, D.J., Froggatt, P.C., 1992. Discriminant function analysis and correlation of late
3069 Quaternary rhyolitic tephra deposits from Taupo and Okataina volcanoes, New Zealand, using glass
3070 shard major element composition. *Quat. Int.* 13-14, 103-117.
3071
3072 Sutton, D.G. 1987. A paradigmatic shift in Polynesian prehistory: implications for New Zealand. *New
3073 Zealand Journal of Archaeology* 9, 135-155.
3074
3075 Taiapa, B. 2016. Millennial scale events from marine sediment cores in the SW Pacific during Marine
3076 Isotope Stage 3. Unpublished MSc thesis, Victoria University of Wellington, Wellington.
3077
3078 Taylor, N.H., 1933. Soil processes in volcanic ash-beds (parts I and II). *N.Z. Journal of Science and
3079 Technology* 14: 193-202, 338-352.
3080
3081 Thomas, A.P.W., 1888. Report on the eruption of Tarawera and Rotomahana. N.Z. Government
3082 Printer, Wellington.
3083
3084 Thorarinsson, S., 1981. Tephra studies and tephrochronology: a historical review with special
3085 reference to Iceland. In: Self, S., Sparks, R.S.J. (eds), *Tephra Studies*. D. Reidel, Dordrecht, p.1-12.
3086
3087 Topping, W.W. 1972. Burrell Lapilli eruptives, Mount Egmont, New Zealand. *New Zealand Journal
3088 of Geology and Geophysics* 15, 476-490.
3089
3090 Topping WW. 1973. Tephrostratigraphy and chronology of late Quaternary eruptives from the
3091 Tongariro Volcanic Centre, New Zealand. *New Zealand Journal of Geology and Geophysics* 16, 397-
3092 423.
3093
3094 Topping, W. W., Kohn, B. P. 1973. Rhyolitic tephra marker beds in the Tongariro area, North Island,
3095 New Zealand. *New Zealand journal of geology and geophysics* 16, 375-395.
3096
3097 Torres-Orozco, R., Cronin, S.J., Pardo, N. and Palmer, A.S., 2017a. New insights into Holocene
3098 eruption episodes from proximal deposit sequences at Mt. Taranaki (Egmont), New Zealand. *Bulletin
3099 of Volcanology*, 79, 3.
3100
3101 Torres-Orozco, R., Cronin, S.J., Damaschke, M., Pardo, N. 2017b. Diverse dynamics of Holocene
3102 mafic-intermediate Plinian eruptions at Mt. Taranaki (Egmont), New Zealand. *Bulletin of
3103 Volcanology*, 79, 76.
3104
3105 Townsend, D., Vonk, A., Kamp, P.J.J. (compilers) 2008. *Geology of the Taranaki area: scale
3106 1:250,000. Lower Hutt: GNS Science. Institute of Geological & Nuclear Sciences 1:250,000
3107 geological map 7. 77 p. + 1 map*
3108
3109 Turner, M.B., Cronin, S.J., Stewart, R.B., Bebbington, M., Smith, I.E.M. 2008. Using titanomagnetite
3110 textures to elucidate volcanic eruption histories. *Geology* 36, 31-34.
3111

3112 Turner, M.B., Bebbington, M.S., Cronin, S.J. and Stewart, R.B., 2009. Merging eruption datasets:
3113 building an integrated Holocene eruptive record for Mt Taranaki, New Zealand. *Bulletin of*
3114 *volcanology*, 71(8), pp.903-918.
3115

3116 Turner, M.B., Cronin, S.J., Bebbington, M.S., Smith, I.E. and Stewart, R.B., 2011. Integrating records
3117 of explosive and effusive activity from proximal and distal sequences: Mt. Taranaki, New
3118 Zealand. *Quaternary International*, 246(1-2), pp.364-373.
3119

3120 Turney, C.S.M., Lowe, J.J., Davies, S.M., Hall, V.A., Lowe, D.J., Wastegård, S., Hoek, W.Z.,
3121 Alloway, B.V. 2004. Tephrochronology of Last Termination sequences in Europe: a protocol for
3122 improved analytical precision and robust correlation procedures (a joint SCOTAV-INTIMATE
3123 proposal). *J. Quat. Sci.* 19, 111-120.
3124

3125 van der Bilt, W.G.M., Cederstrøm, J.M., Støren, E.W.N., Berben, S.M.P., Rutledal, S. 2021. Rapid
3126 tephra identification in geological archives with computed tomography (CT): experimental results and
3127 natural applications. *Frontiers in Earth Science (Volcanology)*. 8:622386 (doi:
3128 10.3389/feart.2020.622386)
3129

3130 Vandergoes, M.J., Hogg, A.G., Lowe, D.J., Newnham, R.M., Denton, G.H., Southon, J., Barrell, D.J.,
3131 Wilson, C.J., McGlone, M.S., Allan, A.S. and Almond, P.C., 2013. A revised age for the
3132 Kawakawa/Oruanui tephra, a key marker for the Last Glacial Maximum in New Zealand. *Quaternary*
3133 *Science Reviews*, 74, pp.195-201.
3134

3135 Van Eaton, A.R., Wilson, C.J.N. 2013. The nature, origins and distribution of ash aggregates in a
3136 large-scale wet eruption deposit: Oruanui, New Zealand. *Journal of Volcanology and Geothermal*
3137 *Research* 250,129-154.
3138

3139 Van Eaton, A.R., Harper, M.A., Wilson, C.J.N. 2013. High-flying diatoms: widespread dispersal of
3140 microorganisms in an explosive volcanic eruption. *Geology* 41, 1187-1190.
3141

3142 Villamor, P., Berryman, K.R., Nairn, I.A., Wilson, K., Litchfield, N., Ries, W., 2011. Associations
3143 between volcanic eruptions from Okataina volcanic center and surface rupture of nearby active faults,
3144 Taupo rift, New Zealand: insights into the nature of volcano-tectonic interactions. *Geol. Soc. Am.*
3145 *Bull.* 123, 1383–1405.
3146

3147 Voloschina M, Lube, G., Procter, J., Meobis, A., Timm, C. 2020. Lithosedimentological and
3148 tephrostratigraphical characterisation of small-volume, low-intensity eruptions: the 1800 years Tufa
3149 Trig Formation, Mt. Ruapehu (New Zealand). *Journal of Volcanology and Geothermal Research* 402,
3150 article 106987.
3151

3152 Vucetich, C.G., Howorth, R., 1976. Late Pleistocene tephrostratigraphy in the Taupo district, New
3153 Zealand. *N.Z. Journal of Geology and Geophysics* 19: 51-69.
3154

3155 Vucetich, C.G., Pullar, W.A., 1964. Stratigraphy of Holocene ash in the Rotorua and Gisborne
3156 districts. *New Zealand Geological Survey Bulletin*, 73, pp.43-88.
3157

3158 Vucetich, C.G., Pullar, W.A., 1969. Stratigraphy and chronology of late Pleistocene volcanic ash beds
3159 in central North Island, New Zealand. *New Zealand journal of geology and geophysics*, 12(4),
3160 pp.784-837.
3161

3162 Vucetich, C.G. and Pullar, W.A., 1973. Holocene tephra formations erupted in the Taupo area, and
3163 interbedded tephtras from other volcanic sources. *New Zealand journal of geology and*
3164 *geophysics*, 16(3), pp.745-780.
3165

3166 Walker, G.P.L. 1973. Explosive volcanic eruptions — a new classification scheme. *Geologische*
3167 *Rundschau* 62, 431–446.
3168
3169 Walker, G.P.L. 1980. The Taupo plinian pumice: product of the most powerful known (ultraplinian)
3170 eruption? *Journal of Volcanology and Geothermal Research*, 8, 69-94.
3171
3172 Walker, G.P.L. 1981. New Zealand case histories of pyroclastic studies. In Self, S., Sparks, R.S.J.
3173 (eds), *Tephra Studies*. Reidel, Dordrecht, p. 317-330.
3174
3175 Walker, G.P.L., Self, S., Wilson, L. 1984. Tarawera 1886, New Zealand – a basaltic plinian fissure
3176 eruption. *Journal of Volcanology and Geothermal Research* 21, 61-78.
3177
3178 Walker, M.; Johnsen, S.; Rasmussen, S.O.; Popp, T.; Steffensen, J.-P.; Gibbard, P.; Hoek, W.; Lowe,
3179 J.J.; Andrews, J.; Björck, S.; Cwynar, L.; Hughen, K.; Kershaw, P.; Kromer, B.; Litt, T.; Lowe, D.J.;
3180 Nakagawa, T.; Newnham, R.M.; Schwander, J. 2009. Formal definition and dating of the GSSP
3181 (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice
3182 core, and selected auxiliary records. *Journal of Quaternary Science* 24, 3-17.
3183
3184 Walker, M.J.C., Head, M.J., Lowe, J.J., Berkelhammer, M., Björck, S., Cheng, H., Cwynar, L.C.,
3185 Fisher, D.A., et al. 2019. Subdividing the Holocene Series/Epoch: formalization of stages/ages and
3186 subseries/subepochs, and designation of GSSPs and auxiliary stratotypes. *Journal of Quaternary*
3187 *Science* 34, 173–186.
3188
3189 Ward, W.T, 1967. Volcanic ash beds of the lower Waikato Basin, North Island, New Zealand. *New*
3190 *Zealand Journal of Geology and Geophysics*, 10: 1109-1135.
3191
3192 Wastegård, S., Boyle, J. 2012. Distal tephrochronology of NW Europe – the view from Sweden.
3193 *Jökull* 62, 73-80.
3194
3195 Waters, C.N., Jan Zalasiewicz, J., Summerhayes, C. and 21 others 2018. Global Boundary Stratotype
3196 Section and Point (GSSP) for the Anthropocene Series: where and how to look for potential
3197 candidates. *Earth-Science Reviews* 178, 379–429.
3198
3199 Watkins, N. D. and Huang, T. C., 1977. Tephtras in abyssal sediments east of North Island. *New*
3200 *Zealand: chronology, paleowind velocity, and paleoexplosivity*. *N.Z.J. Geol. Geophys.* 20, 179-198.
3201
3202 Watson, E.J., Swindles, G.T., Lawson, I.T., Savov, I.P. 2016a. Do peatlands or lakes provide the most
3203 comprehensive distal tephra records? *Quaternary Science Reviews* 139, 110-128.
3204
3205 Watson, E.J., Swindles, G.T., Stevenson, J.A., Savov, I., Lawson, I.T. 2016b. The transport of
3206 Icelandic volcanic ash: insights from northern European cryptotephra records. *Journal of Geophysical*
3207 *Res: Solid Earth* 121, 7177-7192. (<https://doi.org/10.1002/2016JB013350>)
3208
3209 Watson, E.J., Swindles, G.T., Savov, I.P., Lawson, I.T., Connor, C.B., Wilson, J.A. 2017. Estimating
3210 the frequency of volcanic ash clouds over northern Europe. *Earth and Planetary Science Letters* 460,
3211 41–49.
3212
3213 Westgate, J.A., 1989. Isothermal plateau fission-track ages of hydrated glass shards from silicic tephra
3214 beds. *Earth and planetary science letters*, 95(3-4), pp.226-234.
3215
3216 Westgate, J.A., Gorton, M.P. 1981. Correlational techniques in tephra studies. In: Self, S. & Sparks,
3217 R.S.J. (eds), *Tephra Studies*. Reidel, Dordrecht, 73–94.
3218

- 3219 Westgate, J.A., Naeser, N.D., Alloway, B.V. 2013. Fission-track dating. In: Elias, S.A., Mock, C.J.
3220 (editors), *The Encyclopaedia of Quaternary Science*, 2nd edition. Elsevier, Amsterdam, pp. 643-662.
3221
- 3222 Williams PW 2017. *New Zealand landscape - behind the scene*. Elsevier, Amsterdam. 470 pp.
3223
- 3224 Wilmshurst, J.M., Higham T.F.G. 2004. Using rat-gnawed seeds to independently date the arrival of
3225 Pacific rats and humans to New Zealand. *The Holocene* 14, 801-806.
3226
- 3227 Wilmshurst, J.M., Anderson, A.J., Higham, T.F.G., Worthy, T.H., 2008. Dating the late prehistoric
3228 dispersal of Polynesians to New Zealand using the commensal Pacific rat. *Proceedings of the National
3229 Academy of Sciences of the United States of America* 105, 7676-7680.
3230
- 3231 Wilson, C.J.N. 1985. The Taupo eruption, New Zealand II. The Taupo ignimbrite. *Philosophical
3232 Transactions of the Royal Society, London*, A314, 229-310.
3233
- 3234 Wilson, C.J.N., 1986. Reconnaissance stratigraphy and volcanology of ignimbrites from Mangakino
3235 volcano. *Late Cenozoic volcanism in New Zealand. Royal Society of New Zealand Bulletin*, 23,
3236 pp.179-193.
3237
- 3238 Wilson, C. J. N. 1993. Stratigraphy, chronology, styles and dynamics of Late Quaternary eruptions
3239 from Taupo volcano, New Zealand. *Philosophical Transactions of the Royal Society of London Series
3240 A*, 343, 205–306.
3241
- 3242 Wilson, C.J.N. 2001: The 26.5 ka Oruanui eruption, New Zealand: an introduction and overview.
3243 *Journal of Volcanology and Geothermal Research* 112, 133-174.
3244
- 3245 Wilson, C.J.N., Rowland, J.V. 2016. The volcanic, magmatic and tectonic setting of the Taupo
3246 Volcanic Zone, New Zealand, reviewed from a geothermal perspective. *Geothermics*, 59, 168-187.
3247
- 3248 Wilson, C.J.N., Walker, G.P.L. 1982. Ignimbrite depositional facies: the anatomy of a pyroclastic
3249 flow. *Journal of the Geological Society, London*, 139, 581-592.
3250
- 3251 Wilson, C.J.N., Walker, G.P.L. 1985. The Taupo eruption, New Zealand. I. General aspects.
3252 *Philosophical Transactions of the Royal Society, London*, A314, 199-228.
3253
- 3254 Wilson, C. J. N., Houghton, B. F. and Lloyd, E. F., 1986. Volcanic history and evolution of the
3255 Maroa-Taupo area, central North Island. *R. Soc. N.Z., Bull.*, 23: 194-223.
3256
- 3257 Wilson, C.J.N., Houghton, B.F., Lanphere, M.A. and Weaver, S.D., 1992. A new radiometric age
3258 estimate for the Rotoehu Ash from Mayor Island volcano, New Zealand. *New Zealand
3259 Journal of Geology and Geophysics* 35, 371-374.
3260
- 3261 Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D. and Briggs, R.M.,
3262 1995. Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. *Journal of
3263 volcanology and geothermal research*, 68(1-3), pp.1-28.
3264
- 3265 Wilson, C.J.N., Rhoades, D.A., Lanphere, M.A., Calvert, A.T., Houghton, B.F., Weaver, S.D. and
3266 Cole, J.W., 2007. A multiple-approach radiometric age estimate for the Rotoiti and Earthquake Flat
3267 eruptions, New Zealand, with implications for the MIS 4/3 boundary. *Quaternary Science
3268 Reviews*, 26(13-14), pp.1861-1870.
3269
- 3270 Wilson, C.J.N., Charlier, B.L.A., Fagan, C.J., Spinks, K.D., Gravley, D.M., Simmons, S.F., Browne,
3271 P.R.L., 2008. U–Pb dating of zircon in hydrothermally altered rocks as a correlation tool: application
3272 to the Mangakino geothermal field, New Zealand. *J. Volcanol. Geotherm. Res.* 176, 191–198.

3273
3274 Wilson, C.J.N., Gravley, D.M., Leonard, G.S., Rowland, J.V. 2009. Volcanism in the central Taupo
3275 Volcanic Zone, New Zealand: tempo, styles and controls. In: Thordarson, T., Self, S., Larsen, G.,
3276 Rowland, S.K., Hoskuldsson, A. (eds), 'Studies in volcanology: the legacy of George Walker'.
3277 Special Publications of IAVCEI (Geological Society, London), 2, 225-247.
3278
3279 Wilson, C.J.N., Charlier, B.L.A., Rowland, J.V., Browne, P.R.L., 2010. U–Pb dating of zircon in
3280 subsurface, hydrothermally altered pyroclastic deposits and implications for subsidence in a
3281 magmatically active rift: Taupo Volcanic Zone, New Zealand. *J. Volcanol. Geotherm. Res.* 191, 69–
3282 78.
3283
3284 Winstrup, M., Vallenga, P., Kjær, H.A, Fudge, T.J., Lee, J.E., Riis, M.H., Edwards, R., Bertler.,
3285 N.A.N., Blunier, T., Brook, E.J., Buizert, C., Ciobanu, G., Conway, H., Dahl-Jensen, D., Ellis, A.,
3286 Emanuelsson, B.D., Hindmarsh, R.C.A., Keller, E.D., Kurbatov, A.V., Mayewski, P.A., Neff, P.D.,
3287 Pyne, R.L., Simonsen, M.F, Svensson, A., Tuohy, A., Waddington, E.D., Wheatley, S. (2019): A
3288 2700-year annual timescale and accumulation history for an ice core from Roosevelt Island, West
3289 Antarctica. *Climate of the Past*, 15, 751-779.
3290
3291 Wright, I. C., McGlone, M. S., Nelson, C. S., Pillans, B. J., 1995. An integrated latest Quaternary
3292 (Stage 3 to present) paleoclimatic and paleoceanographic record from offshore northern New Zealand.
3293 *Quaternary Research*, 44, 283-293.
3294
3295 Zawalna-Geer, A., Lindsay, J.M., Davies, S., Augustinus, P. and Davies, S., 2016. Extracting a
3296 primary Holocene cryptoptephra record from Pupuke maar sediments, Auckland, New Zealand. *Journal*
3297 *of Quaternary Science*, 31(5), pp.442-457.
3298
3299 Zemeny, A., Procter, J., Nemeth, K., Zellmer, G.F., Zernack, A.V., Cronin, S.J. 2021. Elucidating
3300 stratovolcano construction from volcanoclastic mass-flow deposits: the medial ring-plain of Taranaki
3301 Volcano, New Zealand. *Sedimentology*. <https://doi.org/10.1111/sed.12857>
3302

3303 **Supplementary material**

3304

3305 **Table SM1:** Some key marker tephtras in New Zealand erupted since ~3 Ma, their approximate ages,
3306 and their stratigraphic, volcanological, or palaeoenvironmental significance.

3307

3308 **Table SM2:** Summary of published ages obtained for the coeval Rotoiti Ignimbrite and Rotoehu Ash
3309 deposit.