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REVIEW ARTICLE

Tephrochronology in Aotearoa New Zealand

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ABSTRACT

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

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

Introduction

The term ‘tephra’ (from the Greek word τέφρα meaning ‘ash’ or ‘ashes’) includes all the explosively-erupted, unconsolidated, fragmental (pyroclastic) products of a volcanic eruption. ‘Cryptotephras’ are sparse, ash-sized glass-shard and/or crystal concentrations preserved in sediments (including ice) or soils but insufficiently numerous to be visible as a layer to the naked eye (Lowe 2011). ‘Tephrochronology’ (*sensu stricto*) is a correlational and dating method that uses characterised tephra or cryptotephra deposits as isochronous (time-parallel) beds to link or synchronise geological, palaeoenvironmental, or archaeological sequences or events, and to transfer and apply relative or numerical ages to them using the tephra/cryptotephra compositional ‘fingerprints’ in combination with stratigraphic superpositioning. ‘Tephrochronology’ (*sensu lato*) is also used as a portmanteau term for all aspects of tephra or cryptotephra studies, and their application including volcanology (Lowe 2008, 2011), which is the usage adopted for the title of this paper.

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

Aotearoa New Zealand (ANZ hereafter) has an extensive history of explosive volcanic activity with relatively localised basaltic and more widely-dispersed andesitic events punctuated by powerful rhyolitic events occurring from at least 24 Ma to the present in North Island (Houghton et al. 1995; Wilson et al. 1995; Briggs et al. 2005; Lowe et al. 2008a; Wilson et al. 2009; Wilson and Rowland 2016; Barker et al. 2021; Pittari et al. 2021). The most recent explosive activity since ∼4 Ma has occurred at centres in the southern Coromandel Volcanic Zone (CVZ) and

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Taupō Volcanic Zone (TVZ), with the locus of activity since ~2 Ma in the TVZ and at Taranaki Maunga (previously known as Mt Taranaki or Mt Egmont) and Mayor Island (Tuhua Volcanic Centre) (Figure 1). (Other centres of active volcanism in central North Island are described by Pittari et al. 2021; broad overviews of volcanism in ANZ are provided by Hayward 2017; Shane 2017; Mortimer and Scott 2020.) The eruptions have been responsible for blanketing the landscape surrounding the volcanoes with both pyroclastic-flow and widespread tephra-fall deposits, the distributions of which are governed by a number of factors including eruption volume, mass eruption rate and temperature, eruption column height, particle sizes, strength and direction of wind at the time of the eruption, and radius of the umbrella cloud (e.g. Alloway et al. 2013; Cashman and Rust 2016; Barker et al. 2019; Constantinescu et al. 2021).

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

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

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

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

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

Part 1 — General aspects and advances

History of tephra studies in ANZ

Tephra layers have been described and studied in ANZ since 1841. German naturalist and medical doctor Ern(e)st Dieffenbach was the first to document a sequence of post-18 cal ka tephras and buried soil

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

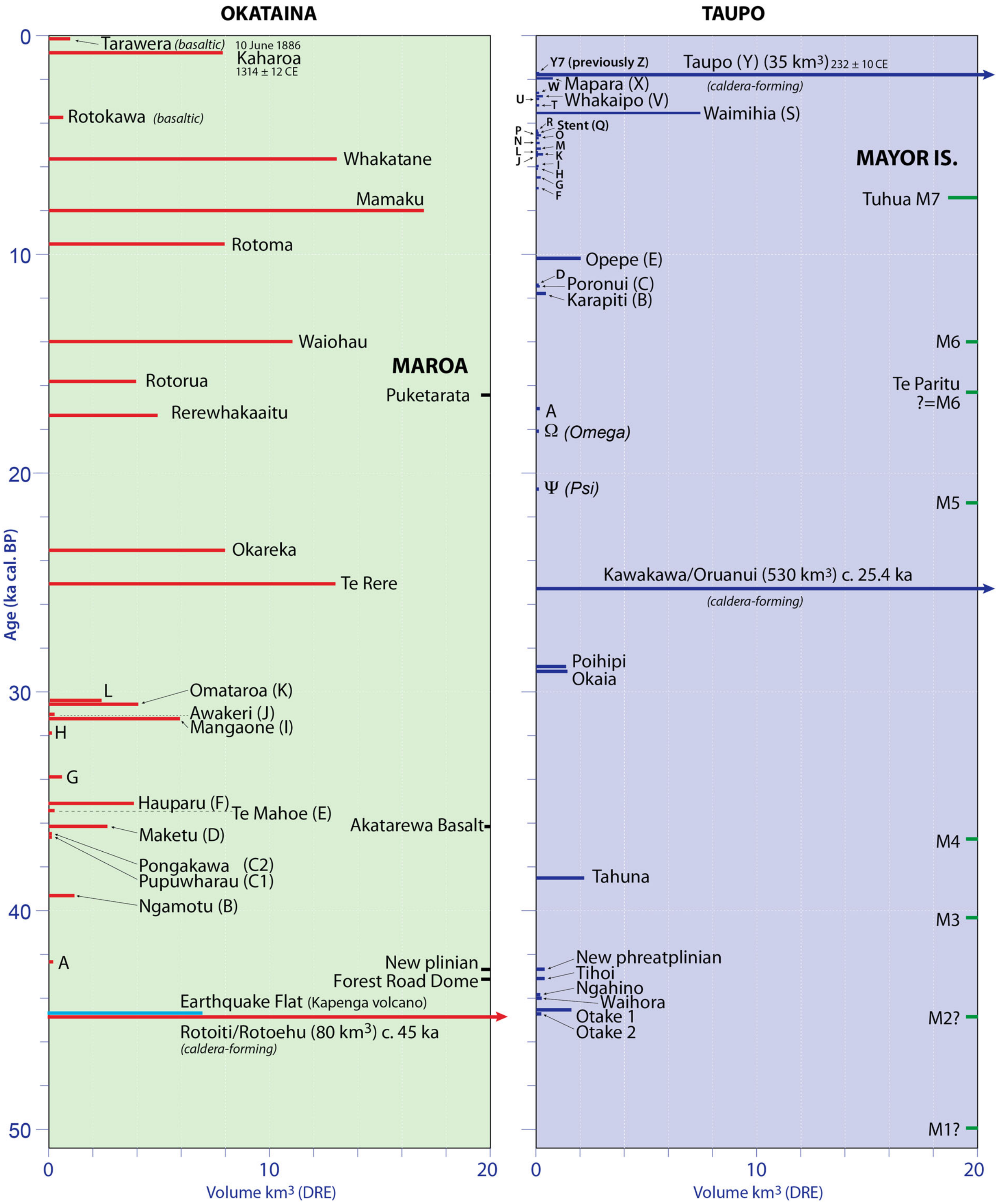

Figure 2. Stratigraphy, ages, and volumes (dense-rock equivalent, DRE) of eruptives derived from three rhyolitic centres in central TVZ (Okataina, Taupō, Maroa), and from Mayor Island (Tuhua), since ~50 cal ka. One eruptive (Earthquake Flat) from Kapenga Volcanic Centre is additionally depicted within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

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

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

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

Tephra mapping in central North Island began in the mid-1920s, close to the time (or slightly before) studies of tephra layers as a tool for research began elsewhere (from ~1930) (Thorarinsson 1981; Alloway et al. 2013; Davies 2015). Leslie Issott Grange, who had served with the Corps of New Zealand Engineers (Tunnelling Company) on the Western Front in World War I, started formal mapping in TVZ in October 1926, motivated by two needs: (i) a volcanological survey to help define likely volcanic hazards; and (ii) a survey of soil-forming tephra deposits, especially the widespread rhyolitic pumice deposits of the Taupō (232 ± 10 AD) and Kaharoa (1314 ± 12 AD) eruptions, to try to understand the so-called 'bush sickness' or 'ill-thrift' problem mainly in central North Island that had resulted in numerous deaths of sheep and cattle (Grange 1929, 1931, 1937; Grange and Taylor 1932; Taylor 1933) (Figure 3). The ill-thrift problem was subsequently identified (by Australian researchers) in mid-1935 as a cobalt deficiency that was later found to cause a dearth of vitamin B12 (Hewitt et al. 2021). The ferromagnesian mineralogy of the deposits allowed four key volcanic source areas to be recognised at the time: Taupō, Rotorua, Tongariro, and Taranaki (Lowe 1990).

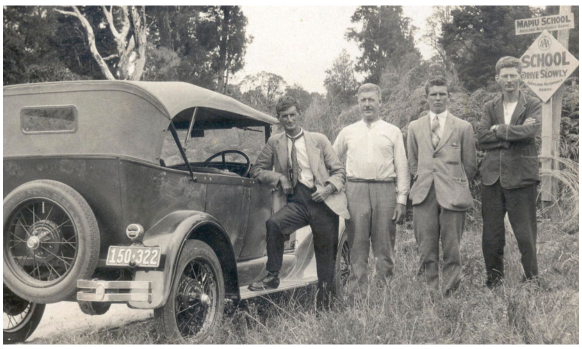

Figure 3. Early tephra and soil mappers in the King Country in 1929 (from left): Leslie I. Grange, Hartley T. Ferrar, J.A. Hurst, and Norman H. Taylor (photo courtesy of Manaaki Whenua-Landcare Research).

One of the most prescient papers in these formative years was that of Berry (1928). James Allan Berry (known as Allan) was a London-trained New Zealand surgeon who, after service on the Western Front with the New Zealand Medical Corps in World War I, became medical superintendent of Napier Hospital. As well as having an interest in fossil seal bones, Berry described the nature and origin of accretionary lapilli ('chalazoidites') in the Scinde Island ash (recognised now as a fall unit of the 25.4 cal ka Kawakawa/Oruanui tephra) preserved in loess on Bluff Hill, Napier (Berry 1928). Remarkably, Berry was arguably the first person anywhere to enunciate that tephra layers could be used to connect sequences from one place to the next by characterising the layers compositionally, thereby providing stratigraphic isochrons (the foundation of tephrochronology) that would allow palaeonvironmental data associated with the layers to be compared spatially and temporally (Lowe 1990; see also Thorarinsson 1981). He presented his paper to the Hawke's Bay Philosophical Society on 20th August 1926. Specifically, Berry (1928, p. 608) stated:

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

The first ^{14}C date obtained in ANZ was on charcoal associated with the Taupō tephra (NZ-1, 1820 ± 150 ^{14}C yr BP) (Fergusson and Rafter 1953), and was undertaken at the New Zealand (now Rafter) Radiocarbon Laboratory. Further ^{14}C-dating of tephra deposits followed, including early work by Baumgart

(1954) on Late-Holocene Taupō-volcano-derived eruptives. Numerous applications of the ^{14}C-method to tephra deposits, including via the Waikato Radiocarbon Laboratory that has operated full-time since ~1980 (e.g. Hogg et al. 1987; Hogg et al. 2019), continue to this day (see dating section below).

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

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

The new studies involving laboratory work to facilitate tephra correlations relied initially on ferromagnesian mineralogical assemblages (e.g. Cole 1970; Green and Lowe 1985; Froggatt and Solloway 1986; Lowe 1988a; Froggatt and Lowe 1990) along with bulk analyses of Fe-Ti oxides (e.g. Kohn 1970; Kohn and Neall 1973; Hogg and McCraw 1983; Lowe 1986b). Kohn's seminal (1970) paper was the first globally to show that trace elements in titanomagnetite in tephras could be used as a correlational tool. As well as revising or refining the proximal tephrostratigraphy associated with particular volcanic centres (e.g. Kohn and Neall 1973; Howorth 1975; Vucetich and Howorth 1976; Buck et al. 1981; Froggatt 1981), the analytical studies on distal tephra deposits in environments favourable for preservation, such as lake sediments and peat bogs, enabled an integrated record of interdigitating tephras from multiple volcanic sources to be compiled (Lowe 1986a, 1988a, 1988b; Froggatt and Rogers 1990) as well as allowing distal deposits to be characterised and identified (e.g. Nelson et al. 1985; Mew et al. 1986; Hodder et al. 1991). Thus volcanologically-focussed applications pertaining to tephra studies (as well as geological, palaeoeoenvironmental, and archaeological employment) have long been important in ANZ (Baumgart and Healy 1956; Kohn and Vucetich 1974). The studies on thin distal tephras morphed into the first cryptotephra-based research in ANZ from the mid-1970s to early 1980s. These topics are covered in more detail below.

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

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

Trace elemental analyses (including rare-earth elements) of individual glass shards have been much slower to develop than those involving major elements and have not been been widely employed (Shane 2000). The first papers using laser-ablation inductively coupled plasma mass-spectrometry (LA-ICP-MS) of individual glass shards (not bulk glass) for tephra characterisation and correlation in ANZ include those of Shane et al. (1998b), Nairn et al. (2004), Smith et al. (2004), Allan et al. (2008), and Pearce et al. (2008). Such trace element applications are now accelerating (e.g. Hopkins et al. 2015; Hopkins et al. 2017; Hopkins et al. 2020b), and Hopkins et al. (in press) have developed the first systematic and comprehensive dataset for both major and trace elements in glass shards derived from a wide range of prominent ANZ tephras.

Mapping, characterising, and correlating tephras and cryptotephras

Mapping tephras and cryptotephras

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

An associated problem relates to the development of soil horizons on tephras, which have then been buried by subsequent deposits, and what the pedogenic modification might mean stratigraphically. Vucetich and Pullar (1964) measured tephra thickness from the base of one unit to the base of the next – i.e. including any pedogenically altered soil material at the top of each unit. Wilson (1993) and others recognised that sometimes this practice (especially in the earlier studies) resulted in tephric loess, reworked materials, andesitic tephras and even previously unrecognised tephras being included in tephra thicknesses then used in constructing isopach maps (e.g. Vucetich and Pullar 1964, 1969; Pullar and Birrell 1973b; Birrell 1974). Consequently, Wilson (1993) took a different approach in his revision of the stratigraphy of post-Kawakawa/Oruanui Taupō-derived tephras and specifically excluded the weathered or soil material at the top of each unit that he could not be certain was (a modified) part of the eruptive. This approach poses difficulties for geoscientists working in medial to distal regions where many deposits may be weathered to some degree because of their modification via upbuilding pedogenesis (discussed in the section below on soil formation on tephras). Note that buried soil horizons, even when only very weakly weathered, mark soil formation that took place when the tephra was at the land surface and represent a disconformity; the boundary between the top of a buried soil and the succeeding tephra deposit is a paraconformity that marks a period of non-deposition (Neall 1972; Howorth 1975). Wilson (1993) used pedological features in the post-25.4-cal-ka Taupō sequence very carefully to help develop a more comprehensive eruptive history of volcanism than had been attained previously. The nature of the contacts and unconformities between tephra deposits and associated paleosols, and other stratigraphic features such as bedding and grain size, help provide, inter alia, a picture of eruption history, landscape stability, and erosion (e.g. Lowe 2011; Bilderback et al. 2015; Dugmore et al. 2020).

In recent decades, mainly since ~1980, studies have increasingly identified the benefits of using sediments as an archive for the preservation of tephra layers and for their separation stratigraphically, especially at the centimetre-to-millimetre scale over distances extending ~100–300 km from source and occasionally well beyond those distances. Such archives include sediments in lakes (e.g. Lowe et al. 1980; Green and Lowe 1985; Lowe 1988b; Molloy et al. 2009; Hopkins et al. 2015; Hopkins et al. 2017; Zawalna-Geer et al. 2016; Peti et al. 2020a), bogs and fens (Howorth et al. 1980; Hogg and McCraw 1983; Hodder et al. 1991; Lowe et al. 1999; Lowe et al. 2013; Damaschke et al. 2017a), and oceans (e.g. Pillans and Wright 1992; Carter et al. 1995; Carter et al. 2003; Carter

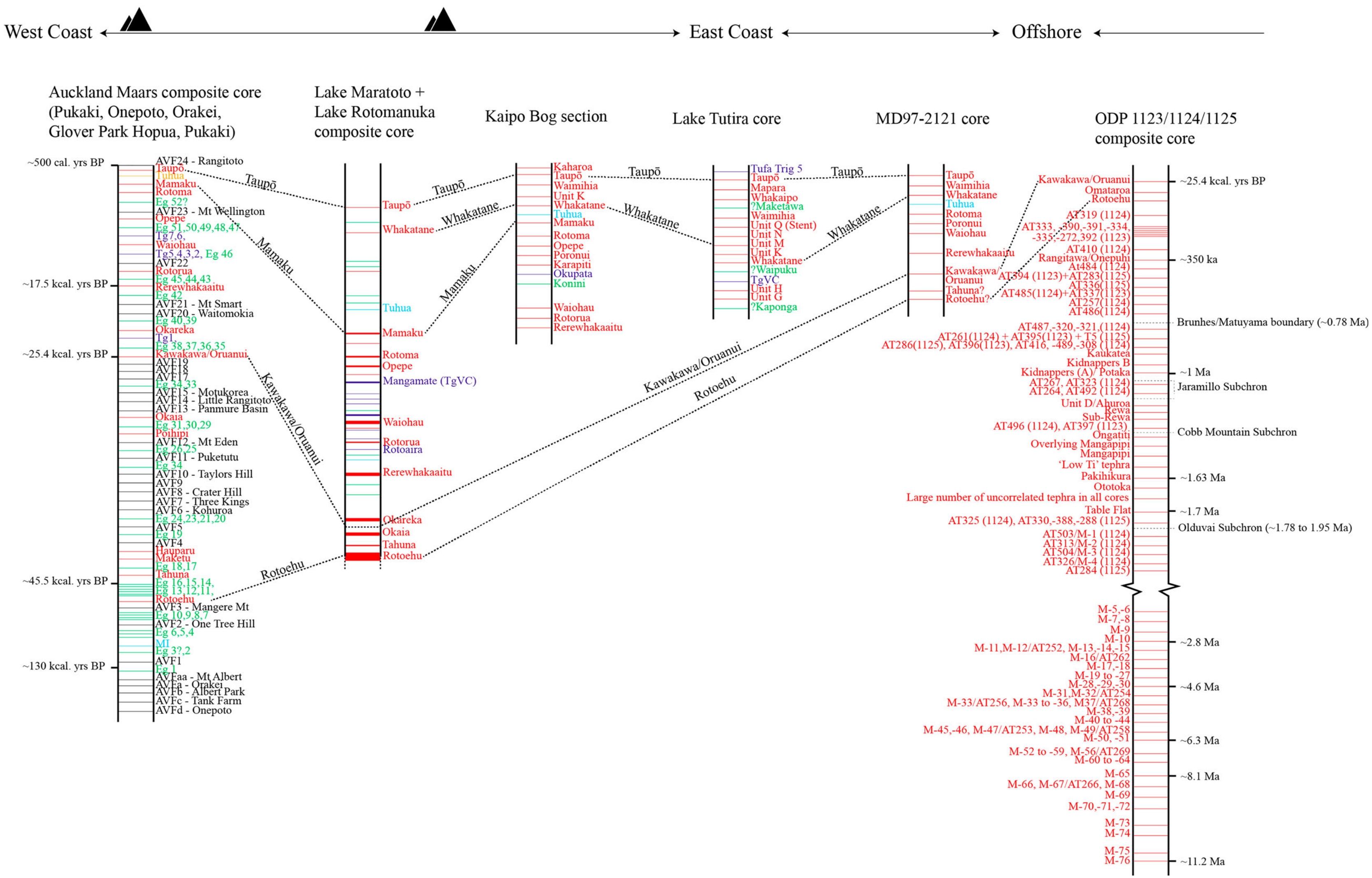

Figure 4. Schematic composite stratigraphies of some key North Island tephra-bearing sediment sequences depicted here approximately from west to east (locations shown on Figure 1). Tephras correlated to known events or sources are named as follows: rhyolitic tephras are shown in red (OVC – from Okataina Volcanic Centre; TVC – from Taupō VC); basaltic tephras in black; andesitic tephras in green (Eg – from Egmont, i.e. Taranaki Maunga) or blue (Tg – from Tongariro VC); trachydacite tephras in orange; and peralkaline rhyolite tephras in teal (MI – from Tuhua VC/Mayor Island). Auckland maar core records (note: also includes Pupuke) from Molloy (2008), Hopkins et al. (2015), Peti et al. (2020a). Auckland Volcanic Field-derived basaltic tephras 'AVF#' are given their centre names where the correlation is classified as 'Confidence Level 1 or 2' in Hopkins et al. (2017). Lakes Rotomanuka and Maratoto (composite core) after Green and Lowe (1985) and Lowe (1988a, 2019); Kaipo bog from Lowe et al. (1999; Lowe et al. 2013); Lake Tutira from Eden et al. (1993) and 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, and 1125 combined from Alloway et al. (2005), Allan et al. (2008), and Stevens (2010). Core source for each tephra is noted. Where tephras are correlated 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; where tephras are the same in the same core but have been given different names by different studies, a '/' indicates this match. Key palaeomagnetic 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 break by the palaeomagnetic boundaries and sedimentation-rate-derived estimates. Tephras from below the core break are all from core ODP Site 1124-C (Stevens 2010).

et al. 2004; Alloway et al. 2005; Carter and Manighetti 2006; Allan et al. 2008; Hopkins et al. 2020b). The chief advantages arising from studying tephras in lakes and bogs include the stratigraphic and chronological control and the high degree of resolution potentially attainable, and the generally excellent preservation of the tephras (because of the reducing conditions and generally 'quiet' depositional environments provided by these archives) that facilitates their reliable compositional investigation (see also Watson et al. 2016a). In addition, and perhaps most importantly, the sediment cores provide a continuous record of interdigitating tephras from multiple volcanoes that therefore enables temporally closely-spaced tephras from different sources to be placed in unequivocal stratigraphic order (Lowe 1988b; Hopkins et al. 2015) (Figure 4).

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

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

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

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

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

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

Characterising tephras and cryptotephras

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

Once tephras are physically, mineralogically, and/or geochemically characterised they can be correlated. For eruptives <50 cal ka in ANZ, generally orthopyroxene predominates in Taupō Volcanic Centre (TVC)-derived tephras whereas biotite, hornblende, cummingtonite, or orthopyroxene (along with felsic minerals and Fe-Ti oxides) predominate in Okataina Volcanic Centre (OVC)-derived tephras (Froggatt and Lowe 1990; Smith et al. 2002, 2005; Smith et al. 2006; Lowe et al. 2008a; Zawalna-Geer et al. 2016; Loame et al. 2019). Occasionally a mineral assemblage (together with stratigraphic constraints) is sufficiently distinctive for an individual tephra (e.g. Rotoehu Ash or Tuhua tephra) to be readily identified by a dominant or notably distinctive mineral (see below).

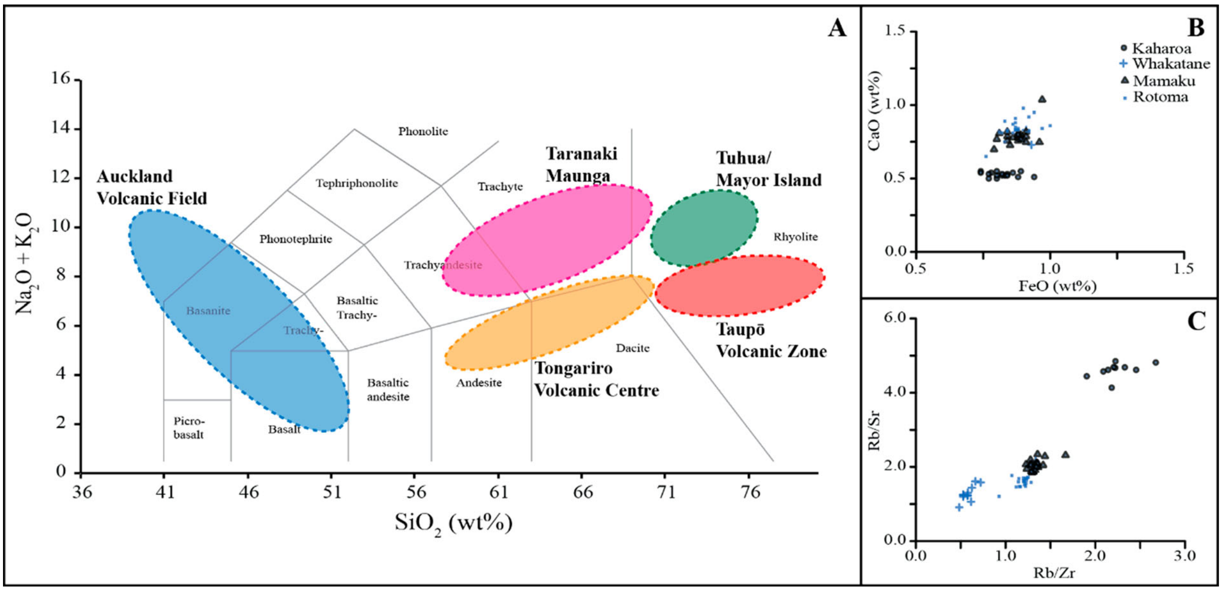

Figure 5. (A) Total alkali vs. SiO_2 plot (based on Le Maitre et al. 2002) showing EPMA-derived glass-shard compositions (normalised data) of tephras erupted from five recently active volcanic centres in ANZ. (B) Major element bivariate plot for glass shards from the most recent four eruptives from Okataina VC (Figure 1) showing that some tephras can be identified through major elements alone, but others cannot. (C) Trace-element ratio bivariate plot for the same glass samples as in (B) showing how such ratios can be used to further distinguish between the different eruptives not distinguishable using major elements. Data from Hopkins et al. (in press).

However, the absence of diagnostic minerals does not necessarily negate an identification because minerals such as olivine are readily depleted by weathering in subaerial pedogenic environments, and biotite and orthopyroxene may be rapidly dissolved in some acid peat bogs (Hodder et al. 1991) or removed through winnowing of the deposit. For example, not all samples of Rerewhakaaitu tephra contain biotite in distal sections (Alan Palmer pers. comm. 2021). This means there is a possibility of misidentifying Rerewhakaaitu as Waiohau tephra, which contains negligible biotite but has overlapping major-element glass compositions (Eden et al. 2001; Lowe et al. 2008a; Hopkins et al. in press). Ferromagnesian minerals also tend to be sparse or absent at distal localities, having dropped out from proximal ash-clouds earlier because of their high density. In addition, studies of the OVC-derived tephras (<50 cal ka) have shown that most comprise multiple magma types (Shane et al. 2008), thus adding complexity to the use of ferromagnesian minerals for correlation purposes. Andesitic eruptives are usually distinguishable from rhyolitic tephras because of their high pyroxene, or hornblende plus clinopyroxene, contents (Lowe 1988b; Shane 2005; further compositional details are reported by Lowe et al. 2008a and Hopkins et al. 2021).

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

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

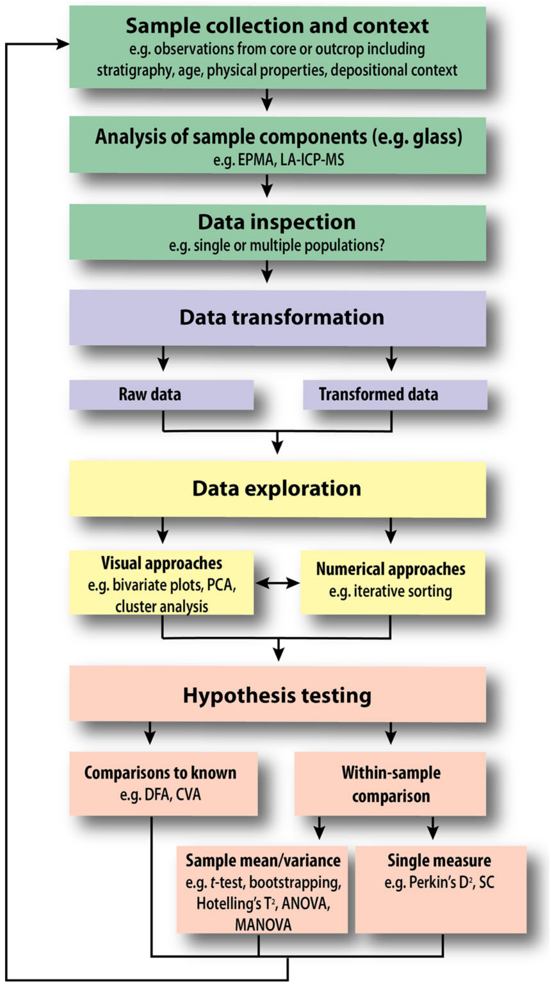

Figure 6. General step-by-step guide for the correlation of tephra deposits (from Lowe et al. 2017, p. 28). It is emphasised that there is potential for miscorrelation at any step (Lowe 2011), the most critical being the first in that sampling with respect to the stratigraphy must be carefully and accurately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

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

Correlating tephras and cryptotephras using numerical and statistical methods

Statistical assessments of large data sets can be used to enhance and quickly identify distinguishable elemental compositions. Lowe et al. (2017) provided a detailed review of statistical correlation methods (including data reduction) and their applications (summarised in Figure 6). They divided the methods into visual (graphical, such as via bivariate plots of oxides), numerical (e.g. use of similarity coefficients, SCs, or various statistical distance measures), and statistical and machine learning including unsupervised (e.g. cluster analysis) and supervised (e.g. discriminant function analysis, DFA), and other statistical methods such as principal components analysis (PCA). In ANZ, the most commonly used methods have been SCs along with DFA (e.g. Stokes and Lowe 1988; Shane and Froggatt 1991, 1994; Froggatt 1992; Stokes et al. 1992; Cronin et al. 1996a; Cronin et al. 1997; Turner et al. 2011). Only rarely has PCA of glass or other compositional data for tephra correlation been undertaken in ANZ (Horrocks 2000; Hopkins et al. in press). Once identified, fingerprinted, and accurately correlated, the thickness and location of individual eruption units can be used to create isopach or isomass maps. These maps can show eruption extent, and may support inferences of eruption scale, and the dominant wind direction(s) during eruption (e.g. Barker et al. 2019), noting that winds can blow in different directions in the atmospheric column at different times of the year and at different latitudes (Buck 1985). For example, Nelson et al. (1985) showed from tephra-bearing marine cores both west and east of ANZ that tephra deposits could be (counter-intuitively) thicker 'upwind' of source: ash ascending above 20 km altitude was able to be carried directly westward towards the Tasman Sea by easterly stratospheric winds, while coeval lower-level ash was blown eastward ('downwind') of ANZ into the southern Pacific Ocean.

Cryptotephra studies

Cryptotephra (from Greek *kryptein*, 'to hide') refers to tephra deposits that are not visible as a layer to the naked eye and usually comprise glass shards in fine to very fine ash-size fractions (< ~125 µm) in very small concentrations (typically tens to hundreds of shards per gram or unit volume). Although Wastegård and Boygle (2012) and Davies (2015) correctly credited Swede, Christer Persson, with the first Icelandic-derived cryptotephra discoveries in Scandinavian peat deposits in the 1960s (e.g. Persson 1966, 1971), it is acknowledged that *systematic* cryptotephra studies of the modern era effectively began with Andrew Dugmore's seminal paper (Dugmore 1989), and that new and increasingly efficacious techniques for cryptotephra detection, extraction, and identification were subsequently developed primarily in northern and western Europe, then North America and elsewhere (e.g. see references in Lowe 2008; Pyne-O'Donnell et al. 2012; Lane et al. 2014; Davies 2015; Ponomareva et al. 2015; Lane et al. 2017; Abbott et al. 2020; Matsu'ura et al. 2021). Nevertheless, work in ANZ from the middle to late 1970s and early 1980s has documented the occurrence of glass shards or crystals in concentrations not visible as layers in sedimentary deposits or soils or paleosols, and so pioneering cryptotephra studies in ANZ effectively date

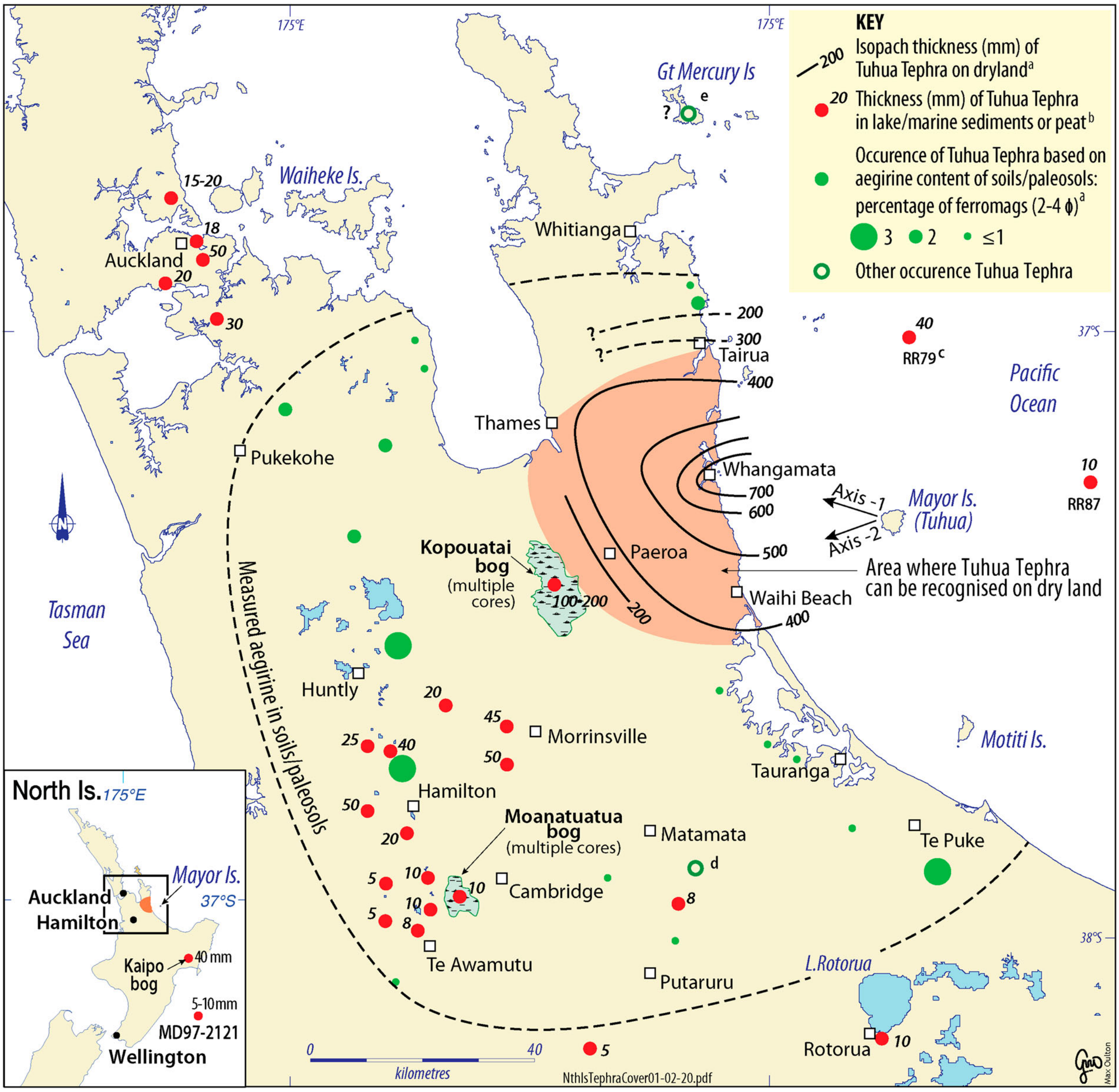

Figure 7. Map of the distribution of 7.6 cal ka Tuhua tephra based on both measured thicknesses of the tephra as a visible layer on dry land (orange area), in bogs and lakes and, uniquely, as a cryptotephra comprising sparse concentrations of aegirine crystals preserved but well-hidden in soils and paleosols. Sources: a, Hogg and McCraw (1983); b, Kennedy and Froggatt (1984), Lowe (1986b, 1988a), de Lange and Lowe (1990), Hodder et al. (1991), Newnham and Lowe (1991), Newnham et al. (1995), Lowe et al. (1999), Sandiford et al. (2001), Manighetti et al. (2003), Gehrels et al. (2006), Augustinus et al. (2008); c, Shane et al. (2006), Phil Shane pers. comm. (2016); d, Persaud et al. (2016); e, McCraw (1989). Ferromags, ferromagnesian minerals.

from around that time, second only to Persson's world-leading research. Note that the word 'cryptotephra' was not coined until 2001 (Lowe and Hunt 2001).

Pioneering cryptotephra research in ANZ

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

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

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

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

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

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

Beyond the isopachs denoting the distribution of visible tephra deposits in Figure 7, the zone of non-visible tephra (encompassed by the dashed line) depicts the distribution of Tuhua tephra entirely on the basis of non-visible aegirine crystals (concentrations of aegirine are marked by the different-sized green dots). The veracity of this cryptotephra map – the 1983 version being the first crystal-based cryptotephra map to be published in the world – was subsequently confirmed by the occurrences of visible deposits of Tuhua tephra preserved in lakes and bogs (Figure 7). Later studies on distal cryptotephras by Lowe (1986b) and Eden et al. (2001) included the use of crystal assemblages to help identify the diminutive deposits. Lowe (2011) therefore recognised that the hidden, sparse aegirine crystals underpinning the novel mapping by Hogg and McCraw (1983), and in other distal-tephra mapping projects subsequently, represented another type of cryptotephra additional to glass-shard concentrations. As a result, Lowe (2011) expanded the original definition (of Lowe and Hunt 2001) for cryptotephras to also include 'hidden' crystals. He also added soils or paleosols as potential cryptotephra archives as well as sediments in recognition of the earliest soil-focussed cryptotephra work undertaken in ANZ since 1976. Another crystal-based cryptotephra in ANZ is that denoting the presence of ~45 cal ka Rotoehu Ash (in otherwise 'homogenous' tephra-derived soil) by the occurrence of non-visible crystals of cummingtonite that predominate in the eruptive (e.g. Lowe 1981, 1986b, 2019).

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

Modern era of cryptotephra studies in ANZ

In the modern era (since mid-2000s), cryptotephra studies in ANZ have been limited in comparison with those elsewhere and mainly developed from records in lakes and bogs. Gehrels et al. (2006) led the way by developing a systematic sampling strategy to locate peaks in glass-shard concentrations and to determine loci of individual geochemical populations, and adapted a palynological method involving spiking samples with *Lycopodium* spores to facilitate accurate counts of glass-shard concentrations. Other recent cryptotephra studies include those of Gehrels et al. (2008), Shane et al. (2013), Hopkins et al. (2015), Zawalna-Geer et al. (2016), and Newnham et al. (2019). In some research, cryptotephras have been used primarily tephrochronologically *(sensu stricto)* rather than as a focus of fundamental research (Eden et al. 2001; Cerovski-Darriau et al. 2014; Bilderback et al. 2015; Newnham et al. 2018; Newnham et al. 2019; Almond et al. 2020; Ratcliffe et al. 2020). Although marine sediments contain background counts of glass shards (noted earlier), they seem to be fewer in number than in terrestrial depocentres,

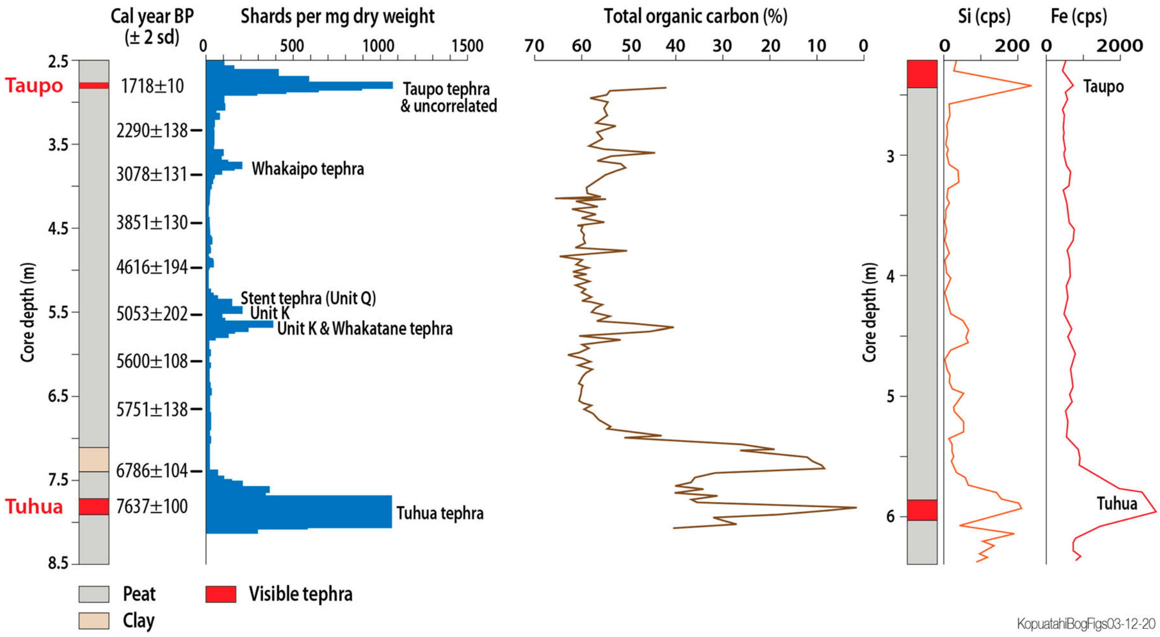

Figure 8. At left is a cryptotephra record derived from counts of glass shards in a peat core from Kopouatai bog (Figure 1) that contains two bounding visible (macroscopic) tephra layers (Taupō and Tuhua) (after Gehrels et al. 2006, p. 177). The peaks in glass concentration match those of the total organic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

likely due to a greater distance from source coupled with a less consistent input from terrestrial reworking (e.g. through fluvial or aeolian transportation). Therefore the marine systems have the potential to be more accurate in their preservation of primary cryptotephras (Hopkins et al. 2020b; see section on marine tephras below)

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

It is important to appreciate that many studies have highlighted the high number of 'background' glass shards found in sediments in ANZ records (e.g. Lowe 1988a; Froggatt and Rogers 1990; Gehrels et al. 2006; Zawalna-Geer et al. 2016). Although this is perhaps unsurprising because of North Island's pervasive volcanic activity, it could potentially lead to difficulties in developing definitive isochrons using cryptotephras (Gehrels et al. 2006). Taiapa (2016) investigated the identification of cryptotephras in marine sediment cores through core-scanning techniques (following Croudance et al. 2006; Balascio et al. 2015; Croudance and Rothwell 2015), and emphasised the potential for reducing time, cost, and core destruction in finding cryptotephras in such cores using variations in specific elements in the sediments. Similarly, Loame et al. (2017) and Loame et al. (2018) reported the trialling of non-invasive core scanning using X-ray computed tomography (CT; Figure 9b) to detect cryptotephras preserved in lake sediments. This non-invasive (remote) detection of cryptotephras in sediments is a research avenue being pursued currently by Hopkins and others at VUW, and by Lowe and others at Waikato, and associated researchers (see also Peti et al. 2020a).

Detecting and identifying thin tephra or cryptotephra deposits in sediments

Various techniques beyond simple visual observation have been employed in ANZ to detect (and potentially identify, i.e. correlate) very thin or indistinct tephra or cryptotephra deposits (Table 2). Just three of the techniques are highlighted here: magnetic susceptibility, X-ray imaging, and XRF analysis.

Magnetic susceptibility (MS) is a non-destructive logging technique, most commonly applied

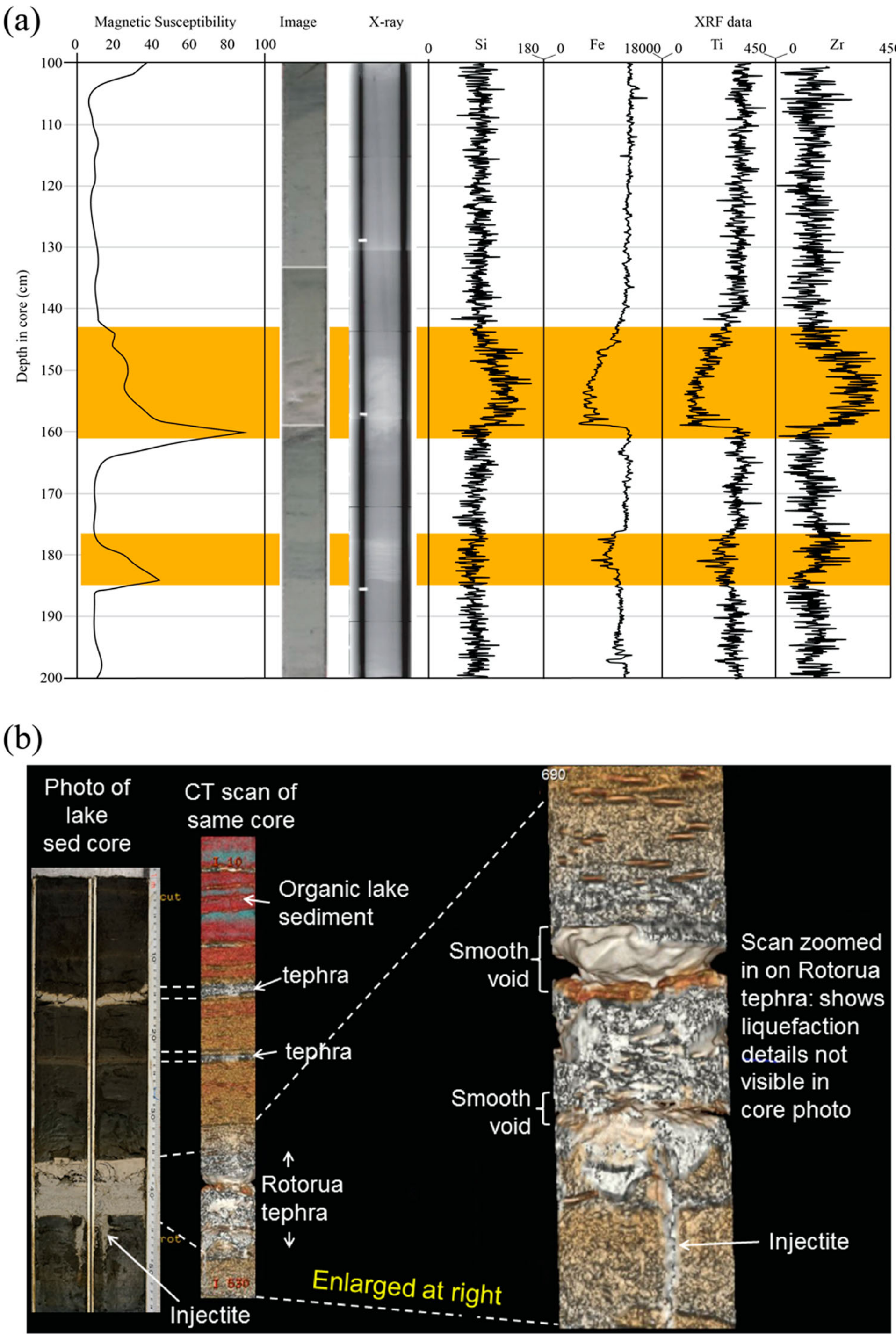

Figure 9. (a) Marine sediment cores collected from a site 200 km offshore from the east coast of ANZ (TAN1613 cruise; Hopkins et al. 2020b) contain two visible or macroscopic rhyolitic tephra horizons highlighted by the orange shading. The tephras are also identified by high magnetic susceptibility,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

continuously down the face of a split sediment core, usually at regular 0.5- to 2-cm intervals. The analysis relies on a difference in magnetic characteristics of the tephra and the host sediments. Commonly the tephra will contain a higher concentration of (more) magnetic minerals than the host sediment, and therefore will show a peak in MS (measured in SI units) where tephra-derived deposits (often glass shards) are found (Figure 9a).

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

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

Application	Method
Field	Ground penetrating radar
	Magnetic susceptibility
Laboratory	X-radiography
	X-ray density scanning
	Magnetic susceptibility
	Dry bulk density
	Rapid X-ray fluorescence
	ITRAX core scanning (elements, magnetic susceptibility, X-radiography)
	Spectrophotometry (reflectance and luminescence)
	X-ray computed tomography (CT) imaging
	Glass-shard counts, crystal counts (cryptotephras)
	Total organic carbon, loss on ignition

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

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

Table 3. Methods used for dating* tephras or cryptotephras directly or indirectly in ANZ (after Lowe and Alloway 2015).

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

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

[a]AMS, accelerator mass spectrometry; ITPFT, isothermal-plateau fission track; DCFT, diameter-corrected fission track; SCLF/*P*, single-crystal laser fusion or probe; LIH, laser incremental heating; TL, thermoluminescence; OSL, optically stimulated luminescence; IRSL, infra-red stimulated luminescence; pIR-IRSL, post infrared-infrared stimulated luminescence; SIMS, secondary ionisation mass spectrometry; TIMS, thermal ionisation mass spectrometry; SHRIMP, sensitive high resolution ion microprobe; LA-ICPMS, laser ablation inductively coupled plasma mass spectrometry.

Dating tephras and cryptotephras

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

Tephras and cryptotephras can be dated both directly and indirectly in various ways that can be broadly grouped into radiometric, incremental, age equivalence, age modelling, relative, and historic (Table 3).

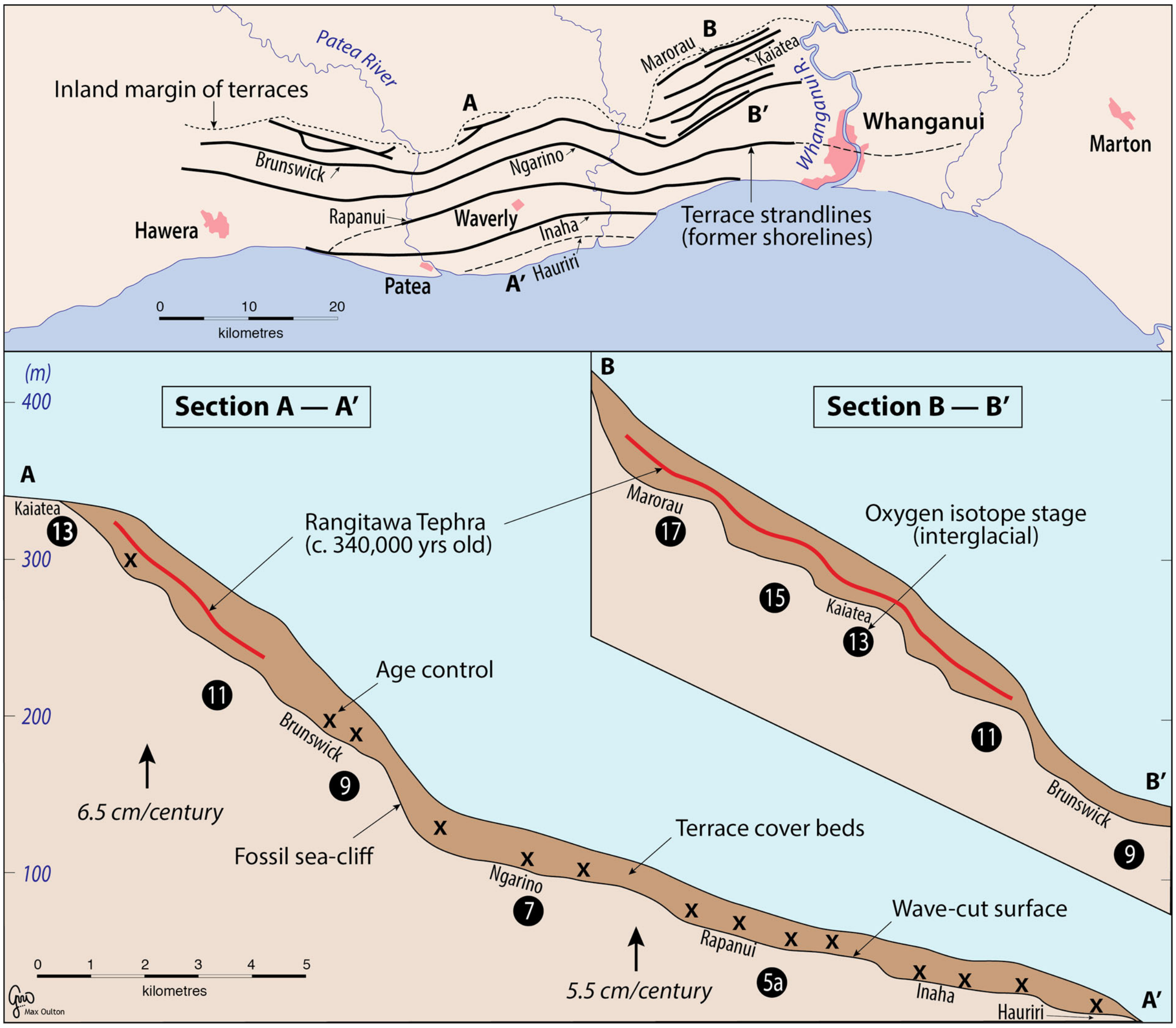

Figure 10. Marine terraces (upper panel), up to 20 km inland from the coast and rising to over 300 m above present sea level, are preserved on the coastal plain between Hawera and Whanganui in southwestern North Island (Figure 1), forming part of the comprehensive Quaternary stratigraphic sequence of the Whanganui Basin (Townsend et al. 2008; Pillans 2017; Rees et al. 2020). The uplifted terraces become older and higher inland, their inner margins representing sea-level high-stands of interglacials (Pillans 1983, 2017). The rhyolitic Rangitawa tephra (~340 ka) provides an important well-dated datum (lower panel) and, along with fission-track and amino-acid racemisation ages, helped in establishing rates of uplift of the terraces. Numerous other rhyolitic tephras provide important chronostratigraphic markers for the entire basin record (Table SM1). Magnetostratigraphic isochrons using palaeomagnetism have been pivotal in helping to construct tephrostratigraphic frameworks in the sedimentary basins of southern North Island (e.g. Shane et al. 1996; Pillans et al. 2005; Alloway et al. 2013). In turn, such chronostratigraphies have been useful in large-scale regional geological mapping (e.g. Rees et al. 2018, 2020; McLeod et al. 2020) and for the recently-completed national-extent 1:250,000 geological mapping of ANZ (the QMAP project) (e.g. Leonard et al. 2010; Lee et al. 2011). Diagram after Pillans (1983), Bussell and Pillans (1997), and Carter (2013).

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

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

A transformational development in tephra studies has been that of the isothermal-plateau fission-track dating method (ITPFT) for glass shards, which is very well suited to dating distal rhyolitic tephras (Westgate 1989; Sandhu et al. 1993; Sandhu and Westgate 1995; Westgate et al. 2013). It has enabled ages to be obtained on many distal tephras that previously could not be be dated because their main – usually only – component, glass, was unreliable because of annealing (Seward 1979; Seward and Kohn 1997; Lowe and Alloway 2015). Examples of such applications include the dating of Quaternary glacioeustatic sedimentary cycles and uplifted terraces in the Whanganui Basin (Figure 10), which is a globally unique archive that contains a shallow marine basinal sequence, exposed on land, spanning the entire

Quaternary (Alloway et al. 1993; Naish et al. 2005; Pillans et al. 2005; Pillans 2017; Rees et al. 2020). Another is providing dates for older terrestrial tephra deposits (e.g. Shane et al. 1996), or marine tephra sequences from ODP sites east of ANZ, thus testing chronologies based on alternative methods (Carter et al. 2004; Alloway et al. 2005; Allan et al. 2008; Hopkins et al. 2020b).

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

A related method also rapidly emerging is that of dating zircons from pyroclastic deposits using U-Pb. Although used until now mainly in volcanic petrological studies in ANZ, and with data acquired typically using secondary ion mass spectrometry (SIMS) techniques (e.g. Charlier et al. 2005; Wilson et al. 2008; Wilson et al. 2010; Milicich et al. 2020), zircon U-Pb dating has been increasingly used overseas to successfully date tephras by LA-ICP-MS analysis (e.g. Chang et al. 2006; Ito et al. 2017; Österle et al. 2020). Horstwood et al. (2016) have developed standardised protocols for the technique. In ANZ, LA-ICP-MS-based zircon U-Pb ages have been obtained on Miocene tuff/volcanic-ash beds in northern Taranaki by Maier et al. (2016) and Sagar et al. (2019), and Pittari et al. (2021) similarly reported new zircon U-Pb ages on 3- to 1-Myr-old eruptives in central and northern North Island.

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

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

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

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

Radiocarbon wiggle-match dating of Kaharoa and Taupō tephras

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

Regarding the Taupō eruption date, Hogg et al. (2012) and Hogg et al. (2019) circumvented the

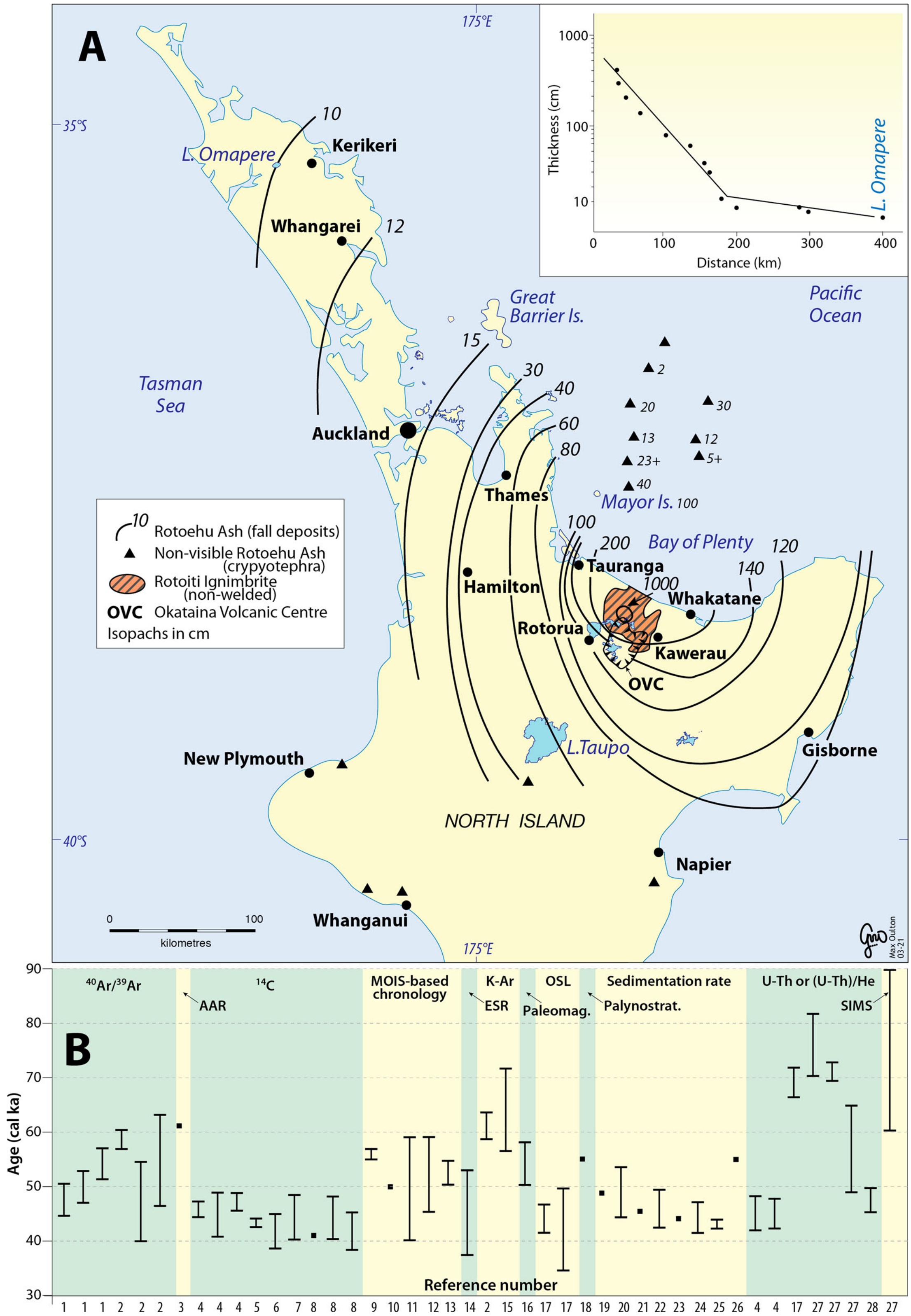

Figure 11. A. Isopach map of visible Rotoehu Ash fall deposits and onland cryptotephra (or very thin) deposits (marked by black triangles). Cryptotephra occurrences have also been recorded in deep-sea cores from ODP Site 1123 (Allan et al. 2008) and MD97-2121 (Taiapa 2016) (Figure 1). Also shown is the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

uncertainty arising from the inter-hemispheric offset in the ^{14}C-calibration curves by developing a high-precision ANZ-derived ^{14}C-calibration curve using dendrochronology and samples of kauri (*Agathis australis*) from northern ANZ. A tanekaha log (*Phyllocladus trichomanoides*) from the Pureora buried forest northwest of Lake Taupō (Figure 1) was then sampled dendrochronologically to generate 25 high-precision ^{14}C dates from a sequence of 25 decadal samples, all pre-treated to form α-cellulose. The contiguous dates were then statistically wiggle-matched against the kauri calibration curve to derive a precise calendar date of AD 232 ± 10 years (95% probability). This date contrasts with several other calendar dates suggested for this eruption, including from Greenland ice cores and putative historical records, which are no longer viable (Hogg et al. 2012). Tree-ring data and preserved plant macrofossils have shown that the Taupō eruption occurred during the austral late-summer to early-autumn period – i.e. probably late March –early April (Clarkson et al. 1988; Palmer et al. 1988). The date of ~232 AD is supported by an independent estimate made using Bayesian age-modelling at Kaipo bog (Figure 1), where dates obtained for Taupō were AD 231 ± 12 (OxCal software) and AD 251 ± 51 (weighted-mean date AD 240) (Bacon software) (Lowe et al. 2013).

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

Bayesian age-depth modelling

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

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

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

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

Age of the Rotoiti Tephra Formation (including Rotoehu Ash)

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

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

The most recently published ages on Rotoiti/Rotoehu eruptives include AMS-derived ^{14}C ages between 44.8 ± 0.3 and 47.5 ± 2.1 cal ka (Danišík et al. 2012); an age of 45.2 ± 3.3 ka (2 s.d.) from $^{238}U/^{230}Th$ disequilibrium and (U–Th)/He double-dating of zircon (Danišík et al. 2012); an age of 45.1 cal ka from orbitally-tuned sedimentation rates in ODP 1123 core (Allan et al. 2008); an age range of 43.8–47.7 cal ka from sedimentation rates in marine cores from the Bay of Plenty (Figure 11A) (Shane et al. 2006); an age of 45.1 ± 1.65 cal ka from lacustrine sedimentation rates in the 2016 core from Ōrākei Basin (Peti and Augustinus 2019), upgraded to 45.6–47.5 cal ka by Peti et al. (2021) using Bayesian modelling, 42.2–43.5 cal ka for Pukaki, 43.0–43.5 cal ka for Onepoto, and 42.5–44.8 cal ka for Pupuke (Hayward and Hopkins 2019) (see Figure 12 below for locations of these lakes); and a weighted mean age of 47.4 ± 1.5 ka by $^{40}Ar/^{39}Ar$ analysis of co-magmatic K-feldspar and biotite crystals (Flude and Storey 2016).

In view of the general concordance of these data, an age of around 45 to 47 cal ka for the Rotoehu/Rotoiti eruptives has been accepted by many in the tephra community (including Danišík et al. 2020, who used an age of 45.2 ± 3.3 cal ka (2σ) to underpin age models

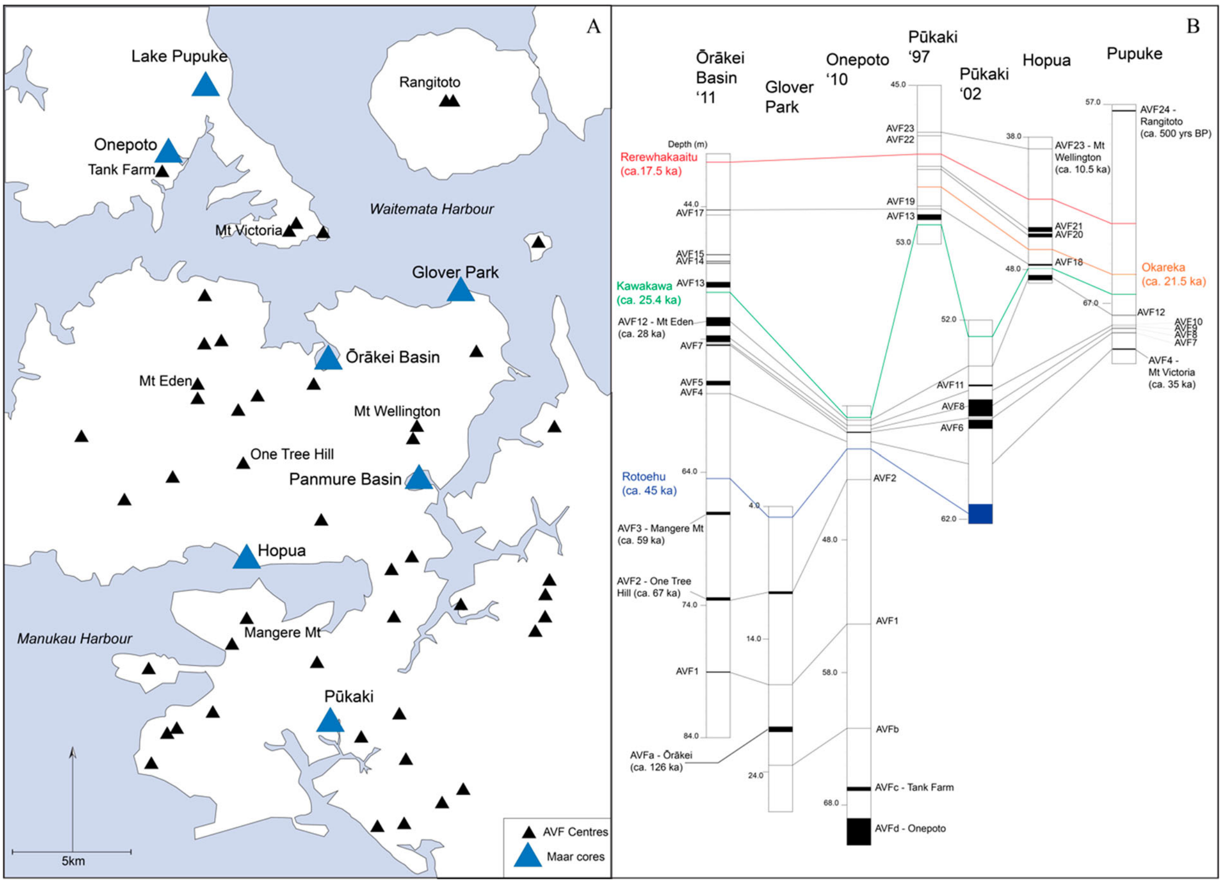

Figure 12. A. Map of volcanoes identified in the AVF. Highlighted are the main maar craters that have been cored for their lacustrine sediments, thus providing tephra records representing eruptions both proximal (from the AVF) and distal (from beyond the AVF; see Figure 1). **B.** Tephra-correlated sediment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

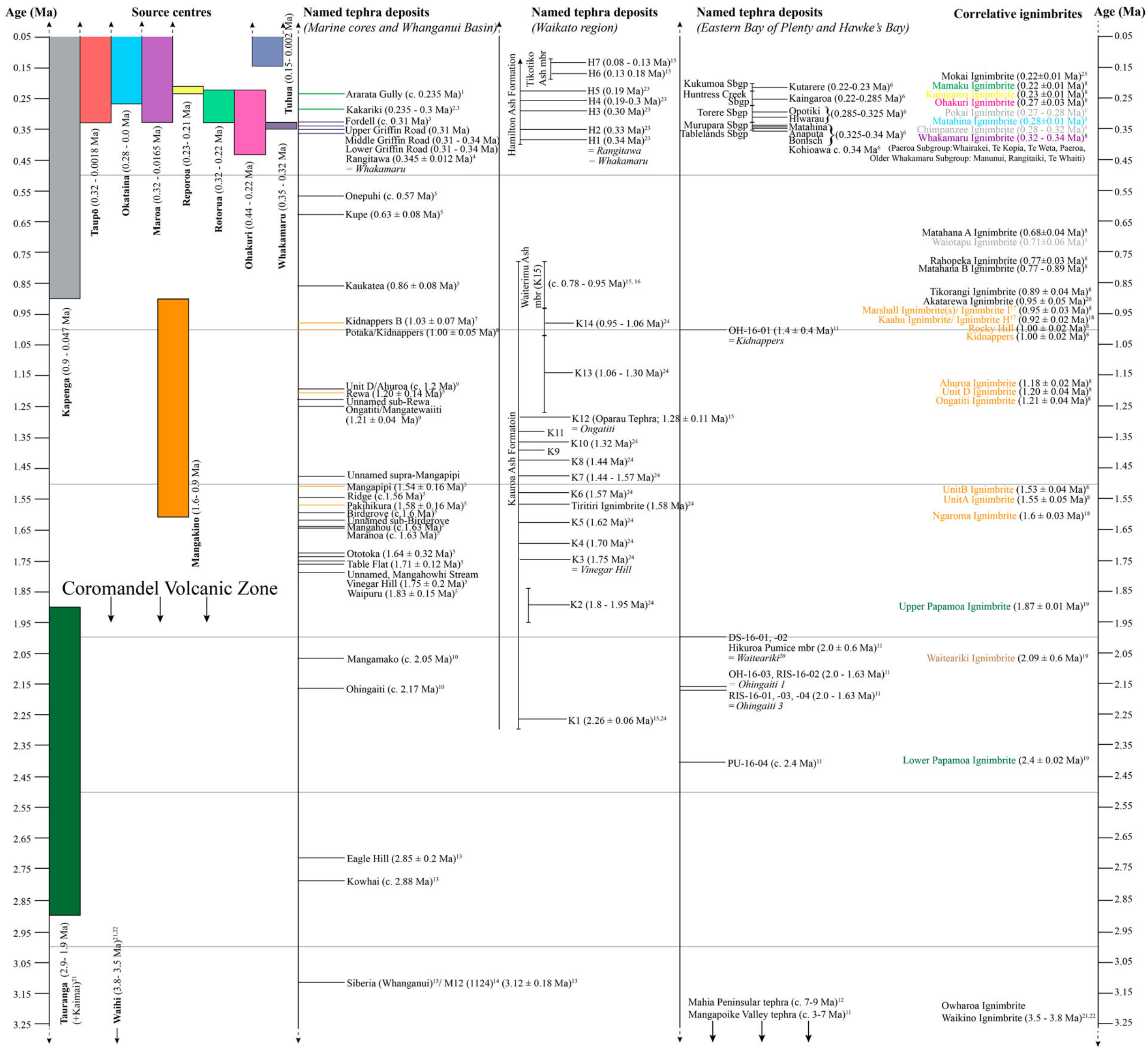

Figure 13. A collation of all named tephra-fall deposits found within the time frame of ~3.8–0.05 Ma. Key sources in southern CVZ, TVZ, and Tuhua/Mayor Island (Figure 1) are shown (colour co-ordinated) along with ages and known ignimbrite correlatives. All ages are shown with 1 s.d. errors (where reported).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

developed for tephras of the overlying Mangaone Subgroup). However, Barker et al. (2021) suggested that such a relatively young age was implausible from volcanological and pedological viewpoints, stating 'multiple eruptive units and well-developed palaeosols' exist between the Rotoehu/Rotoiti deposits and the overlying, ^{14}C-dated, deposits. Barker et al.'s (2021) preferred age is the $^{40}Ar/^{39}Ar$ heating-stepped age of 54 ± 6 ka (2σ) of Flude and Storey (2016), which is indistinguishable from the marine terrace age of 54 ± 7 of Berryman (1992) and a number of other published ages (Figure 11B). Athough the exact age of the Rotoehu Ash and correlatives remains somewhat controversial, an age between ~45 and ~55 cal ka is seemingly agreed.

Part 2 — Some applications and new developments

Climate-event stratigraphy and the NZ-INTIMATE project

A review of past climates of ANZ since 30 cal ka was developed by Alloway et al. (2007) and Barrell et al. (2013) for the NZ-INTIMATE project (INTegration of Ice core, MArine, and TErrestrial records). To facilitate more detailed assessments of climate variability, a composite stratotype was proposed as an ANZ climate-event stratigraphy (NZce-11 through to NZce-1). It was based on terrestrial stratigraphic records with type sections selected on the basis of robust numerical age control and a clear proxy record based on pollen analysis. A major advantage of these records is that they are linked precisely by one or more tephra layers. More than 20 widespread tephras (from Taupō, Okataina, Tuhua, Tongariro, and Taranaki volcanoes/centres), each known to have been distributed ≥∼250 km from source, were selected as marker beds for the project, and their stratigraphic relationships, distributions, compositions, and ages were reported by Lowe et al. (2008a) and Lowe et al. (2013). Ages were developed via Bayesian age-modelling. The close stratigraphic and temporal relationships of various tephra layers to signals of climatic or environmental change (including landscape evolution, described broadly by, for instance, Pillans et al. 1992; Alloway et al. 2007; Alloway et al. 2013; Williams 2017) since 30 cal ka, and their stratigraphic relationships to specific climate events, were also documented by Lowe et al. (2008a), Lowe et al. (2013), Barrell et al. (2013), and Peti et al. (2021). For example, the start of NZce-9 (Interstadial D of Otira Glaciation) is marked by the 25.4-cal-ka Kawakawa/Oruanui tephra; Termination 1 and the start of NZce-5 (beginning of the Last Glacial-Interglacial Transition, LGIT, at ∼18 cal ka) is marked by the ∼17.5-cal-ka Rerewhakaaitu tephra deposited a few centuries later (Newnham et al. 2003); the onset of NZce-3 (late-glacial cool episode) occurs about two centuries after deposition of the ∼14 cal ka Waiohau tephra (Newnham and Lowe 2000); and the start of NZce-1, the Holocene, is marked by deposition of 11.7 cal ka Konini tephra (see also note about this tephra in Table SM1).

Eruptive event stratigraphy in Auckland Volcanic Field from tephra record

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

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

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

The tephrostratigraphy, and thus the eruptive history, since ∼50 cal ka of TVZ rhyolitic volcanism is largely well known (Figure 2). However, the older record is incomplete, and heavily biased towards the voluminous ignimbrite-forming eruptives that dominate much of the central North Island landscape. The tephra-fall record for events prior to 50 cal ka and since ∼3.8 Ma is fragmentary and has been developed by research in three themes: (i) undertaking fundamental volcanological stratigraphy, dating, and mapping in proximal areas to recognise relationships between coeval pyroclastic-flow and fall units, such as those pertaining to (for instance) the Oruanui/Kawakawa tephra deposits (Vucetich and Pullar 1969; Wilson 2001), the Rotoiti/Rotoehu tephra deposits (noted earlier), and the Whakamaru/Rangitawa tephra deposits (Froggatt et al. 1986;

Wilson et al. 1986; Kohn et al. 1992; Matthews et al. 2012); (ii) by examining the stratigraphy, ages, and characteristics of distal tephra deposits preserved in sedimentary and pyroclastic/volcanic sequences in the Auckland and Waikato regions, eastern Bay of Plenty, Hawke's Bay, and Whanganui Basin (e.g. Erdman and Kelsey 1992; Naish et al. 1996; Shane et al. 1998b; Lowe et al. 2001; Alloway et al. 2004a; Pillans et al. 2005; Lee et al. 2011; Hopkins and Seward 2019; Rees et al. 2020); and (iii) by examining the marine record, an archive that Kyle and Seward (1984) suggested would provide the best record of TVZ volcanism (rather than terrestrial where the record can be difficult to interpret), as described in the next section.

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

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

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

Correlating strongly weathered old tephras

Parts of central North Island are mantled with thick sequences of Quaternary or older tephra deposits (including both tephra fallout deposits and ignimbrites) and associated deposits, commonly loess, with no known source and little or no age control (Lowe et al. 2001). Many of these deposits are weathered, sometimes very markedly with clay (<2 µm) content as high as 85%, and they also contain thick paleosols (soils, or soil horizons, of landscapes or environments of the past) (Lowe 2019). They have been broadly mapped as 'undifferentiated brown tuffs' or 'brown ashes' (e.g. Ward 1967; Pullar et al. 1973; Pain 1975; Lowe and Percival 1993; Lowe et al. 2001). Because these clay-rich beds, apart from a few less-weathered layers, contain few primary minerals and no glass (Lowe and Percival 1993; Churchman and Lowe 2012) then they have been difficult to correlate and date other than by stratigraphic relationships and morphological (palaeopedological) features (e.g. Briggs et al. 1989; Briggs et al. 1994).

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

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

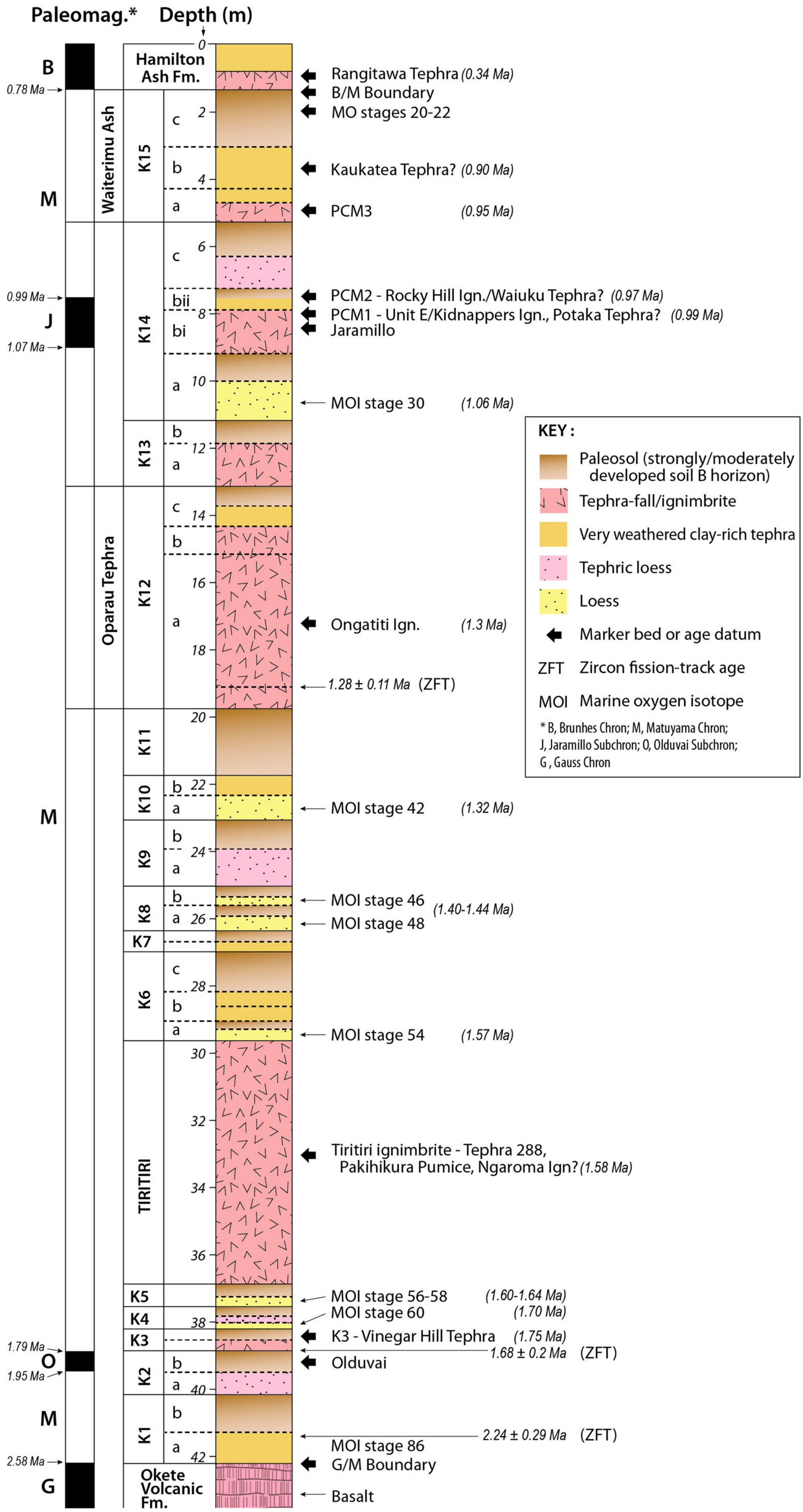

Figure 14. Stratigraphy and chronology of the composite, weathered Kauroa Ash sequence in western Waikato. The sequence, originally divided by Salter (1979) into 15 units (K1–15), has been dated by Horrocks (2000) using palaeomagnetic measurements; tephrochronology (based on melt-inclusion glass compositions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

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

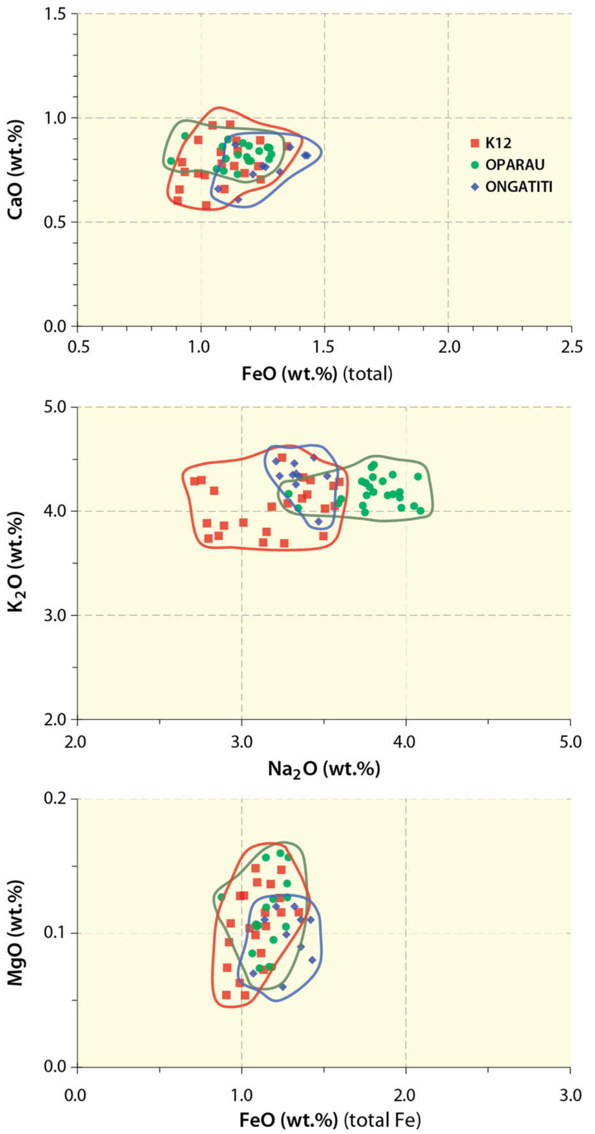

Figure 15. EPMA-derived major elements in quartz-hosted melt inclusions from K12 and Oparau tephra deposits (normalised data from Horrocks 2000) and their close match with elements (as oxides) in glass shards from Ongatiti Ignimbrite (data for Ongatiti from Briggs et al. 1993; Black et al. 1996). The low Na_2O content in some inclusions in K12 reflects the difficulty of probing melt inclusions narrower in diameter (~10 μm) than the optimum beam diameter in the analysis using EPMA.

Marine record of tephras

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

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

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

Much of central North Island has been repeatedly overwhelmed or modified by the emplacement of

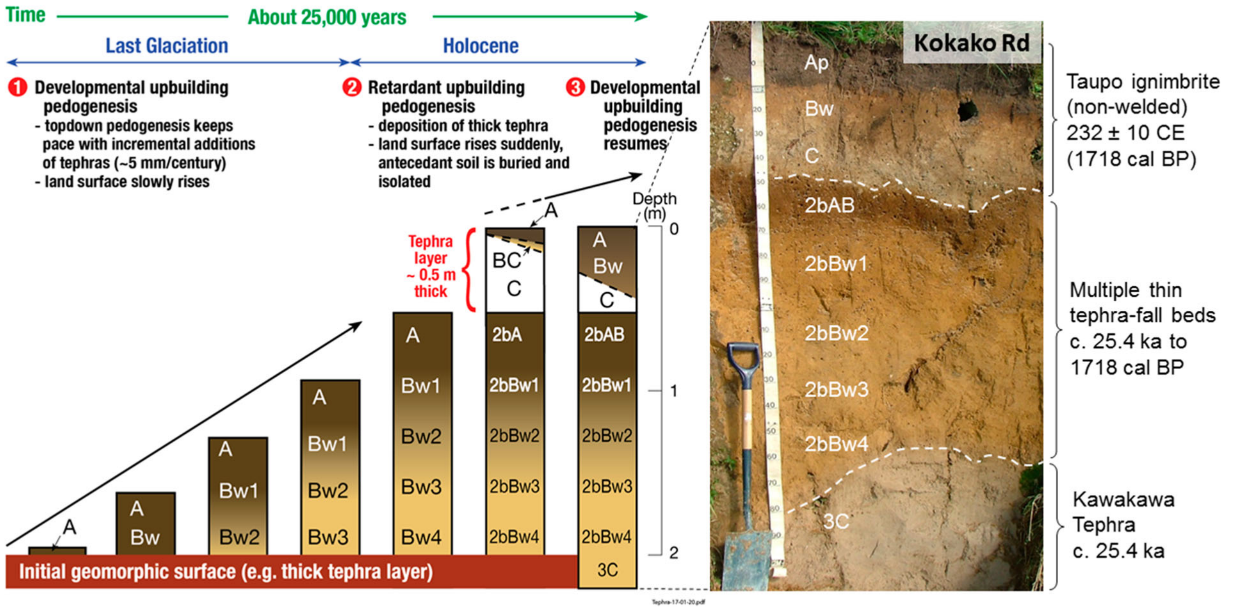

Figure 16. Model of upbuilding pedogenesis, both developmental and retardant, in a multi-layered 25-ka tephra-derived soil profile on Kokako Road near Lichfield, south Waikato. In phase 1, thin, distal tephras/cryptotephras accumulated slowly whilst topdown processes imprinted (near-surface) weak soil horizonation 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; Hewitt et al. 2021, p. 187). Soil horizonation is based on Clayden and Hewitt (1989). The prefix 'b' denotes an identifiable soil horizon with pedogenic features developed before its burial.

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

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

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

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

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

Tephras and archaeology in ANZ

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

The most important role of tephrochronology has been in helping to answer the question of timing of the earliest Polynesian settlement of ANZ. This question has been difficult and controversial because the settlement was very recent, barely 750 years ago (~1280 AD/CE), and so ^{14}C-age data, subject to question because of likely contamination of (e.g.) lake sediments by inwashing of old carbon as a result of Polynesian deforestation activities, inbuilt age, or dietary effects, effectively resulted in two contradictory

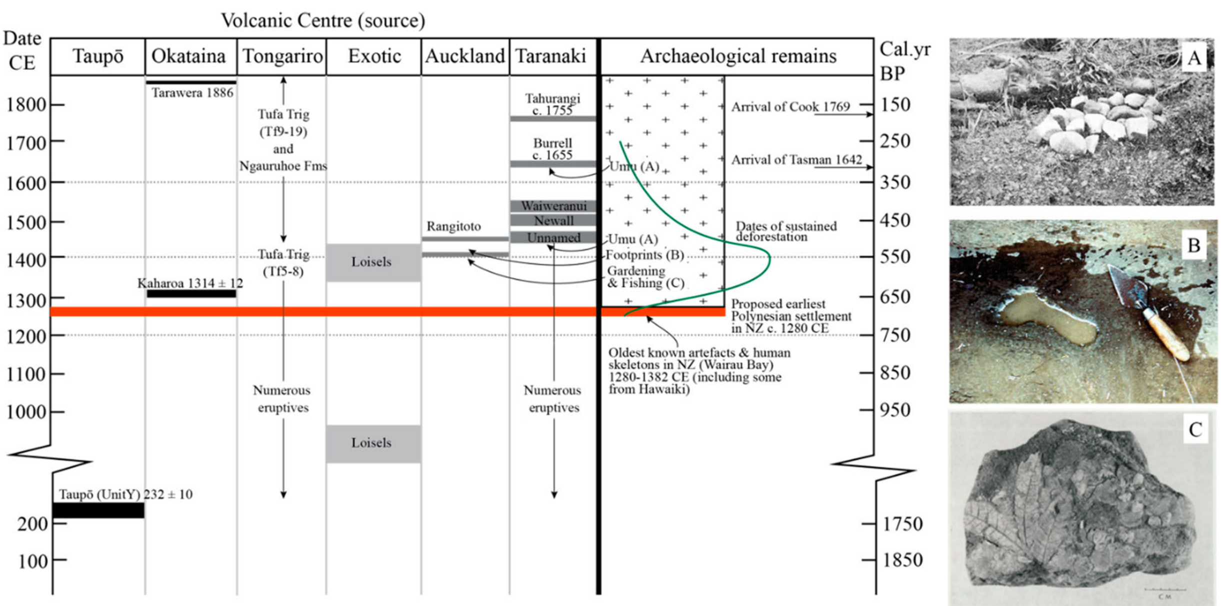

Figure 17. Summary of volcanic sources and the stratigraphic and age relationships of tephras relevant to Polynesian settlement (~1280 AD/CE) and archaeological (zone of small black crosses), palynological (green curve), and other evidence in northern ANZ (after Lowe et al. 2000; Lowe et al. 2002; Lowe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

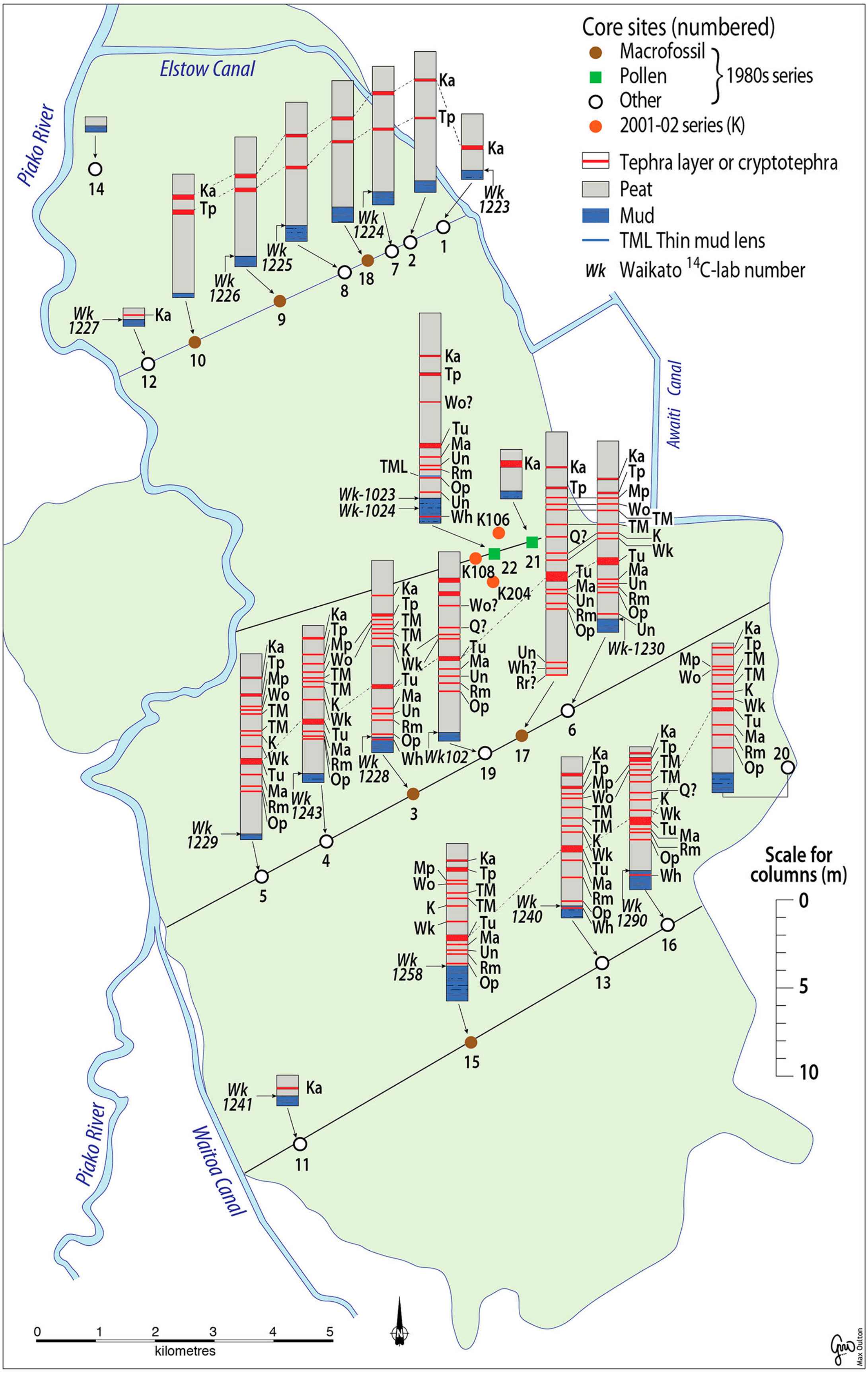

Figure 18. Summary of the tephrostratigraphy (including cryptotephras identified thus far: see Figure 8) of Kopouatai bog based on records obtained from 22 cores (after Hogg and McCraw 1983; Hogg et al. 1987; de Lange 1989; de Lange and Lowe 1990; Hodder et al. 1991; Newnham et al. 1995; Gehrels et al. 2006; Gehrels et al. 2008; Newnham et al. 2019). The northern part of the bog is much younger than the central and southern parts because it was inundated in the mid-Holocene, around 7.5 cal ka, by a relative sea-level high stand (see Clement et al. 2016). Tephra abbreviations (see Lowe et al. 2013 for ages): Ka, Kaharoa (from Okataina Volcanic Centre, OVC); Tp, Taupō (from Taupō Volcanic Centre, TVC); Mp, Mapara (Unit W, TVC); Whakaipo (Unit X, TVC); Unit Q (Stent, TVC); Unit K (TVC); Wk, Whakatane (OVC); Tu, Tuhua (from Tuhua Volcanic Centre); Ma, Mamaku (OVC); Rm, Rotoma (OVC); Op, Opepe (Unit E, TVC); Wh, Waiohau (OVC); Rr, Rotorua (OVC). TM, uncorrelated tephra from Taranaki Maunga (Figure 1); Un, uncorrelated tephra.

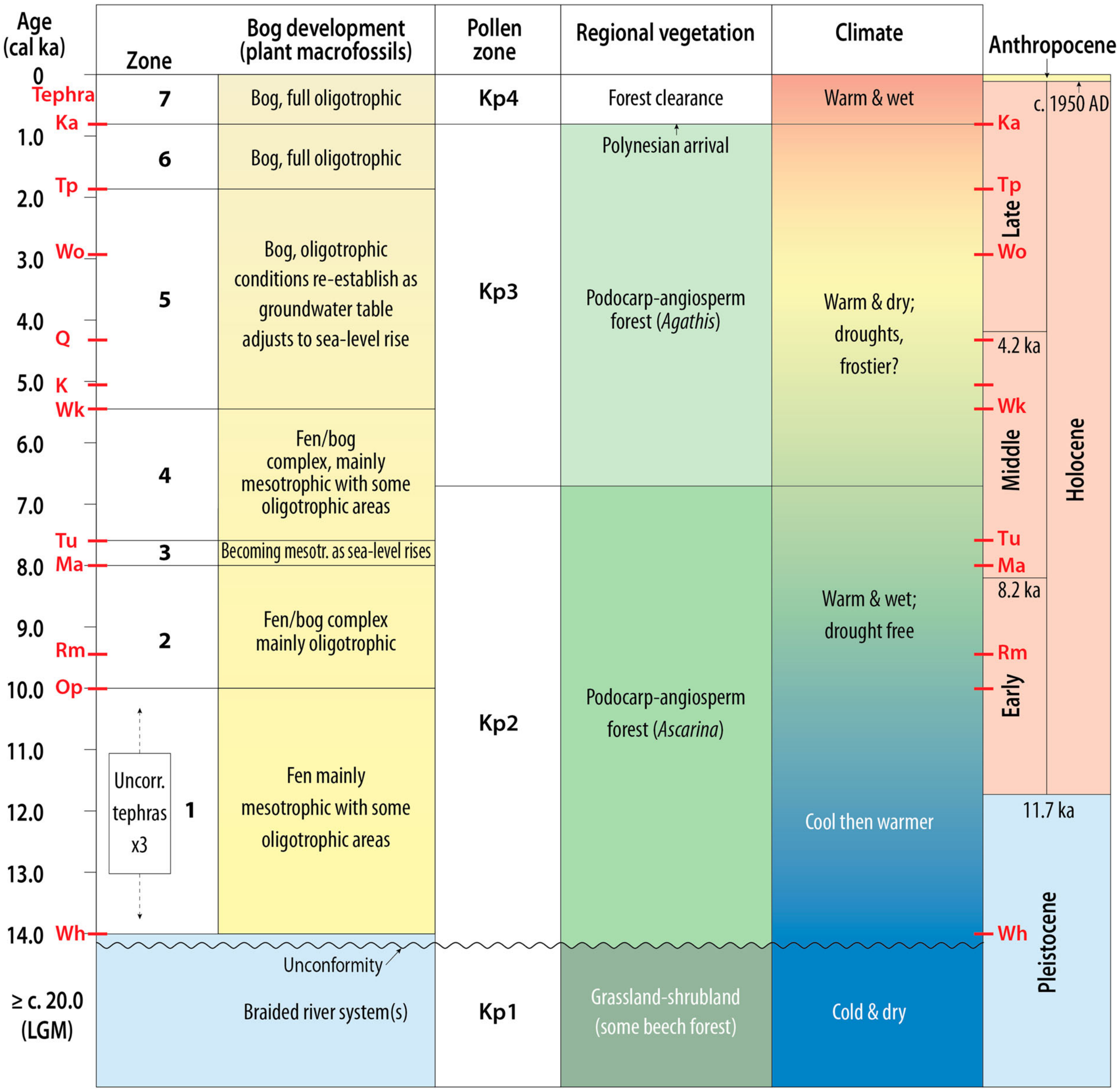

Figure 19. Past vegetation and climates reconstructed from Kopouatai bog (after Newnham et al. 1995). The main tephra marker beds are shown in red (abbreviations of names are explained in Figure 18). The unconformity represents the late glacial period when conditions were too dry for extensive peat to form and when local rivers were active. The base of the Holocene is that defined by Walker et al. (2009); its tripartite subdivison is from Walker et al. (2019). Newnham et al. (1995) suggested that *Ascarina lucida* and *Agathis australis* may be used as regional pollen stratigraphic markers for the early and later parts of the Holocene, respectively. The start of the Anthropocene is yet to be formally defined; here we have arbitrarily suggested ∼1950 AD (see Waters et al. 2018).

models of settlement: ‘early’ settlement (or transient contact) about 1500–2000 years ago (Sutton 1987; Holdaway 1996) versus ‘late’ settlement about 700 years ago (Anderson 1991; Higham and Hogg 1997; Higham et al. 1999; McGlone and Wilmshurst 1999; Higham et al. 2004; Jacomb et al. 2014).

The compositionally distinctive and easily recognisable rhyolitic Kaharoa tephra was erupted from Mt Tarawera in 1314 ± 12 AD, the most recent rhyolite eruption in ANZ (Lowe et al. 1998; Hogg et al. 2003; Lowe and Pittari 2014). The tephra was distributed over much of eastern and northern North Island and provides a critical ‘settlement datum’ that supports the late settlement model. The tephra provides an isochronous connection between (i) palynological evidence of initial human impact obtained from analyses of sediment in cores from bogs and lakes (i.e. indirect evidence of settlement), and (ii) archaeological and artefactual evidence (i.e. direct evidence of settlement) (Figure 17). The pollen evidence indicates that deforestation (by burning) was initiated a few decades before the fall of the Kaharoa tephra (Newnham et al. 1998; see also Perry et al. 2012). Currently, only one artefact has been found beneath the Kaharoa tephra (out of innumerable archaeological sites investigated): a single, rat-nibbled seed gnawed by the exotic Pacific rat commensal, *Rattus exulans*, was found 5 cm beneath Kaharoa tephra in peat at Te Rerenga on the northeastern Coromandel Peninsula (Wilmshurst and Higham 2004). Thus almost all the

Kaharoa-bearing archaeological sites date to ~1314 AD or younger. Nevertheless, the solitary pre-Kaharoa rat-gnawed seed implies that rats (and thus Polynesians) were in ANZ a short time before the Kaharoa eruption, a finding consistent with the palynological and other palaeoenvironmental evidence that indicates that deforestation began some decades before ~1314 AD, hence indicating that initial settlement was around 1280 AD or soon after (Brook 2000; Wilmshurst et al. 2008; Lowe 2011; Jacomb et al. 2014; Anderson 2015; Schmid et al. 2019).

Kopouatai bog as a prospective Holocene type location for ANZ

Numerous Holocene tephrostratigraphic and palaeoenvironmental records in ANZ are based on analyses from terrestrial and marine sediments, with some generating important reference sequences such as those of Kaipo bog, lakes Pupuke, Maratoto, Tutira, and Poukawa, and marine core MD97-2121 (Figures 1, 4, 12). Kopouatai bog in the Hauraki Rift or Depression, an active continental rift structure (Persaud et al. 2016), is another key site (Figure 1). An international Ramsar Convention site and the largest unaltered raised, ombrotrophic peat bog in ANZ dominated by restiad vegetation (characterised by plant species of the Restionaceae family) (de Lange et al. 1999; Clarkson et al. 2004; McGlone 2009), Kopouatai comprises thick peat (up to 14 m deep) dating back to the mid-LGIT when earliest development of the bog first began around 15 to 16 cal ka (based on the probable presence of 15.6 cal ka Rotorua tephra in core 17 and ^{14}C dating: Figure 18). More than 20 cores and ~40 local ^{14}C dates have been acquired for the bog, which contains at least 17 visible tephra and cryptotephra deposits (Figure 18). The tephras and cryptotephras (and attendant ages) allow cores to be readily correlated stratigraphically from site to site in the bog, and to other tephra-bearing palaeoenvironmental records in North Island and beyond (e.g. Newnham et al. 1989; Barrell et al. 2013; Newnham et al. 2019).

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

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

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

Table 4. Average recurrence intervals of tephra-fall events in Auckland over the last 80 kyrs (after 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

Volcanic hazard assessment

A range of impacts is associated with tephra-fall events including disruption to communities and commodities, contamination to food and water supplies, health hazards, and damage to buildings and infrastructure as well as agronomic activities (Cronin et al. 1998; Johnston et al. 2000; Cronin et al. 2003; Hayes et al. 2017). In addition to their physical and societal impacts, tephra-fall events in ANZ have been used to produce a record of recurrence rates for volcanism, relevant for volcanic hazard analysis and risk management (e.g. Shane and Hoverd 2002; Shane 2005; Molloy et al. 2009). For example, in the Waikato region, Lowe (1988b) suggested that rhyolitic and andesitic tephras (erupted from distant volcanoes) were deposited at a mean rate of one event per 370 years since ~20 cal ka. Auckland (ANZ's biggest city, home to one-third of ANZ's population), however, is at risk from both proximal events (AVF-sourced) and distal events (TVZ- or Taranaki- or Tuhua- sourced). The detailed analysis of 106 macroscopic (>0.5 mm thick) tephra deposits has been used to show mean recurrence intervals of tephra-fall events in Auckland over the last 80 kyrs (Molloy et al. 2009; Table 4). These authors concluded that the minimum recurrence interval for a tephra fall event with ≥0.5-mm-thick deposit would be once every 1500 years, and that the highest probability event would be one with a <1-mm-thick deposit.

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

As noted elsewhere, new cryptotephra-based studies are currently underway both on land (e.g. Loame et al. 2016; Loame et al. 2017) and in the marine realm (Kutterolf and Hopkins 2019) and these will help to more accurately assess the number and thus impact of even the thinnest (submillimetre) tephra-fall events, allowing more accurate hazard and risk assessments to be made.

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

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials. The data that support the findings of this study are also available from the corresponding author [JLH] upon reasonable request.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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