Connecting, synchronising, and dating with tephras: principles and applications of tephrochronology in Quaternary research

David J. Lowe

School of Science, Faculty of Science and Engineering, University of Waikato,
Hamilton, New Zealand 3240 (e-mail: d.lowe@waikato.ac.nz)

1. Introduction: what is tephrochronology?

Tephrochronology is a unique method for linking and dating geological, palaeoecological, palaeoclimatic, or archaeological sequences or events. The method relies firstly on stratigraphy and the law of superposition, which apply in any study that connects or correlates deposits from one place to another. Secondly, it relies on characterising and hence identifying or 'fingerprinting' tephra layers using either physical properties evident in the field or those obtained from laboratory analysis, including mineralogical examination by optical microscopy or geochemical analysis of glass shards or crystals (e.g., Fe-Ti oxides, ferromagnesian minerals) using the electron microprobe and other tools. Thirdly, the method is enhanced when a numerical age is obtained for a tephra layer by (1) radiometric methods such as radiocarbon, fission-track, U-series, (U-Th)/He, or Ar/Ar dating, (2) incremental dating methods including dendrochronology or varved sediments or layering in ice cores, or (3) age-equivalent methods such as palaeomagnetism or correlation with marine oxygen isotope stages or palynostratigraphy. Once known, that age can be transferred from one site to the next using stratigraphic methods and by matching compositional characteristics, i.e., comparing 'fingerprints' from each layer. Used this way, tephrochronology is an age-equivalent dating method.

Even if a tephra layer is undated, or if it is dated imprecisely, it nevertheless provides an isochron or time-plane (sometimes referred to as a 'time-parallel' marker bed) that allows the sequence in which it is found to be correlated with other sequences where it occurs. Herein lies the unique power of tephrochronology: deposits and their associated palaeoarchival evidence are thus able to be connected and synchronized − positioned precisely on a common time scale − using the tephra layer as a stratigraphically fixed tie-point, even where the tephra is poorly or undated. In this situation, the age scale is best envisaged as a length of elastic that can be stretched or contracted when numerical ages are obtained, or age precision is improved, whilst the tephra's stratigraphic juxtaposition with respect to the enclosing deposits and associated archival data remains fixed on the 'elastic'. When the tephra age is known, however, that age can be applied directly to the sequence where the tephra has been newly identified. This is because tephra layers are erupted over very short time periods (volcanic eruptions typically last for only hours or days to perhaps weeks or a few months or so at most), and thus each represent an instant in time, geologically speaking (Lowe, 2011).

A tephra layer from a powerful eruption can be spread widely over land, sea and ice, hence forming a thin blanket that has exactly the same age wherever it occurs (unless it has been reworked). For example, the Icelandic Fugloyarbanki tephra, identified in the NGRIP ice core from Greenland, has been dated at 26,740 ± 390 (1σ) calendar (cal.) years before AD 2000 on the basis of multi-parameter counting of annual layers in NGRIP (Davies et al., 2008). It forms a widespread marker horizon or isochron in marine deposits in the North Atlantic and on the distant Faroe Islands between Iceland and Scotland. Thus palaeoarchives at these widely separated localities are now able to be connected precisely. Moreover, the extent of the radiocarbon marine reservoir effect in this region at the time can be examined using the Fugloyarbanki tephra as an independent time-plane.

In the New Zealand region, the Kawakawa (or Oruanui) tephra, erupted from Taupo caldera c. 25,400 cal. yr BP (Vandergoes et al., 2013), similarly forms an extensive isochron linking numerous terrestrial and marine sequences to the same point in time (Pillans et al., 1993; Carter et al., 1995; Newnham et al., 2007a, 2007b; Holt et al., 2010; Alloway et al., 2013; Van Eaton and Wilson, 2013; Van Eaton et al., 2013) (Fig. 1).
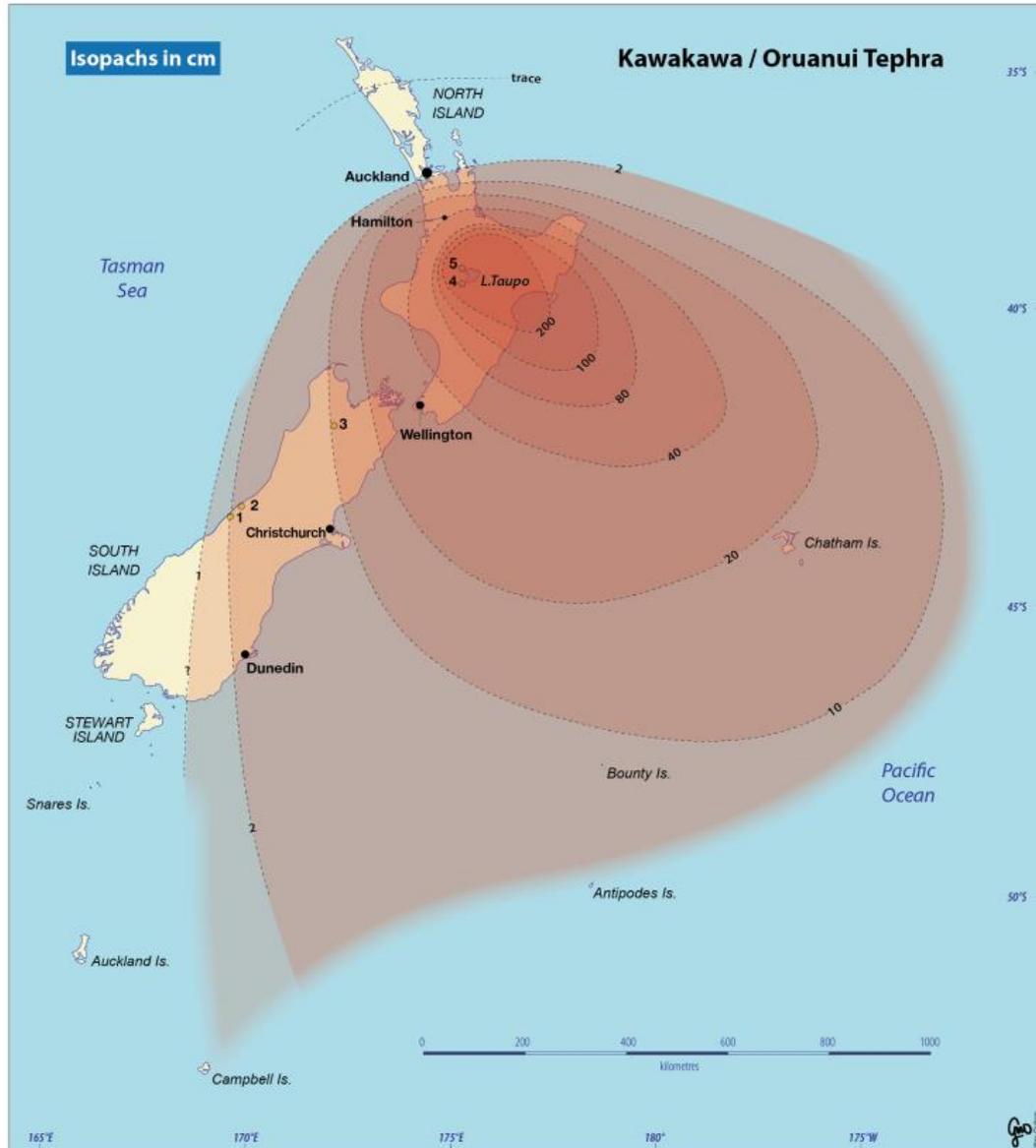

Fig. 1. Isopachs of Kawakawa/Oruanui tephra (in centimetres) showing the tephra's distribution extending >1000 km away from its source at Taupo caldera. Isopachs to the 10 cm mark are from Wilson (2001); beyond 10 cm, the thinner isopachs are based on relatively few sites and are indicative only (from Vandergoes et al., 2013). Trace occurrence in Northland is after Newnham et al. (2004).

Much of this article is based on Lowe (2011). A short article on tephrochronology is given by Lowe et al. (2015a), and Lowe et al. (2008a) partly updates Froggatt and Lowe (1990). Other reviews include those of Shane (2000), Alloway et al. (2013), Lowe and Alloway (2015), and Ponomareva et al. (2016). Numerous volcanological aspects of tephra studies are covered in detail by Sigurdsson (2015), and Smith et al. (2006) provided an introduction to New Zealand volcanology. Many historical aspects of tephra studies in New Zealand were described by Lowe (1990, 2014) and Lowe et al. (2008b). Special volumes containing tephra articles include those of Lowe et al. (2011a), Austin et al. (2014), and Saito et al. (2016). Articles that include, or focus on, archaeological applications beyond New Zealand include those of Riede and Thastrup (2012), Lane et al. (2014), Davies (2015), and Lowe and Alloway (2015).

2. More on nomenclature

Tephras (from the Greek *tephra* meaning 'ashes') are the explosively-erupted, unconsolidated pyroclastic (literally 'fiery fragmental') products of volcanic eruptions. They encompass all grain sizes: ash (grains <2 mm in diameter), lapillus or lapilli (64–2 mm), or blocks or bombs (>64 mm). Ash can be classed as coarse (2 mm–62.5 μm) and fine (<62.5 μm); lapilli can be divided into five classes from extremely fine to coarse (Cas et al., 2008). Further clast-size related information was reported by Fisher et al. (2006) and White and Houghton (2006). As noted above, tephrochronology in its original sense (*sensu stricto*) is the use of tephra layers as isochrons to connect, correlate, and synchronize sequences and to transfer relative or numerical ages to such sequences where the tephras have been dated (Fig. 2). It is not simply 'dating tephras'. Rather, tephrochronometry is the term used to describe the dating of tephra layers either directly or indirectly. In recent times, the term tephrochronology (*sensu lato*) has been used broadly to describe all aspects of tephra studies as used, for example, by Alloway et al. (2013) (Table 1).

The terms 'tephra' and 'tephrochronology' were coined by Icelandic geoscientist Sigurdur Thorarinsson in his doctoral thesis "Tephrochronological studies in Iceland (University of Stockholm) in 1944 (Thorarinsson, 1974, 1981; Lowe, 1990; Steinthorsson, 2012; Wastegård and Boygle, 2012; Davies, 2015). Often regarded as the 'father of tephrochronology', Thorarinsson was born a little over 100 years ago on 8 January 1912 and died 8 February 1983 (Lowe et al., 2011b). A special issue of the journal *Jökull* was published in 2012 to commemorate the centenary of his birth (Benediktsson et al., 2012).
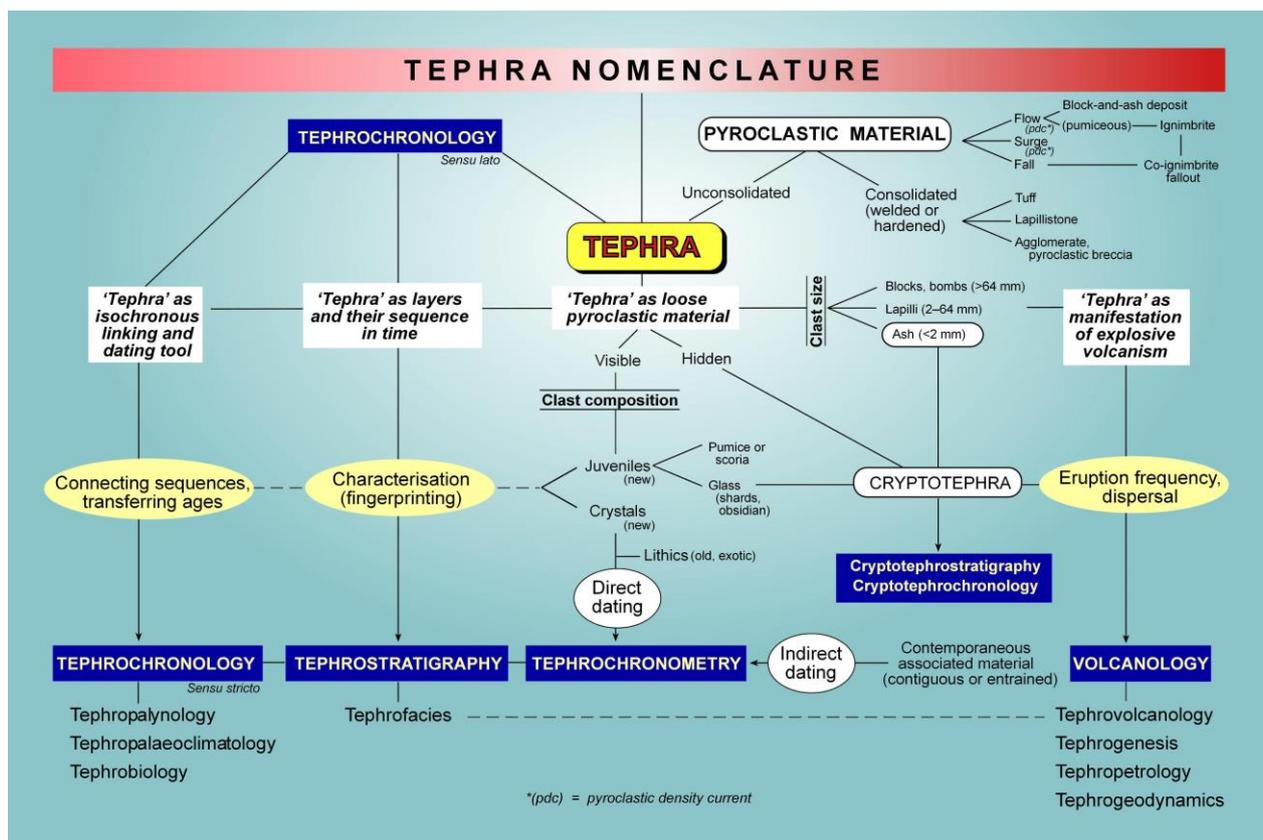
Fig. 2. Nomenclature of tephra and derivative terms and their relationships with one another and with other terms including the near-synonym pyroclastic material. 'Tephra', by definition unconsolidated or 'loose' pyroclastic material, is used in four different senses (white rectangles across centre). The terms listed beneath the blue rectangular boxes at the very bottom should be abandoned (from Lowe, 2008a). Cryptotephras may also comprise crystal concentrations (mineral grains) rather than, or in addition to, glass shard concentrations (Table 1; Lowe, 2011; Matsu'ura et al., 2011, 2012).

Undertaking tephrochronology always requires tephrostratigraphy to some degree (Lowe, 2011). Tephrostratigraphy is the study of sequences of tephras and associated deposits, their distribution and stratigraphic relationships (superpositions), and their relative and numerical ages. It involves defining, describing, characterizing, and dating tephra layers using their physical, mineralogical or geochemical properties from field or laboratory-based observations, or both. In the last two decades, there has been a revolutionary development focussed on detecting diminutive, distal tephras that are invisible in the field and referred to as cryptotephras (Davies, 2015). From the Greek word *kryptein*, meaning 'to hide', cryptotephras usually comprise fine-ash-sized (typically <~125 μm) glass shards or crystals, or both, preserved and 'hidden' in peats or in lake, marine or aeolian sediments or soils, or in ice cores (Table 1; Lowe and Hunt, 2001). Cryptotephrostratigraphy refers to the stratigraphic study of tephra-derived glass-shard, or crystal concentrations (e.g., Hogg and McCraw, 1983; Matsu'ura et al., 2011, 2012; Wastegård and Boygle, 2012; Lane et al., 2014), that are encompassed within sediments (including ice) or soils or paleosols but which are not visible in the field as layers. The term 'cryptotephra' has replaced the term 'microtephra' but the term 'microshard', defined as glass shards <32 μm in diameter, has been proposed by Lowe et al. (in revision).

Note that the letter 'o' rather than 'a' is the appropriate connecting letter in all these terms derived from tephra, and that the adjective 'volcanic' is redundant when referring to tephra. The term 'airfall' is no longer used (tephra-fall or tephra fallout, or ash-fall or ash fallout if appropriate, are used instead). Several other words in useage have *tephra* or *tephrós* ('ash coloured') at their root but none normally is relevant to tephrochronological studies. 'Tephrite' refers to a typically ash coloured alkalic basaltic volcanic rock erupted effusively as lava, not explosively. 'Tephroite' is a mineral, Mn_2SiO_4, in the olivine group that is commonly ash-grey to olive or bluish green in colour. And 'tephromancy' is divination by means of sacrificial (human) ashes, requiring supernatural insight!

Table 1. Tephra-related nomenclature in brief (from Lowe, 2011, 2015).

Term	Definition
Tephra	All the explosively-erupted, unconsolidated pyroclastic products of a volcanic eruption (Greek *tephra*, 'ashes') including volcanic ash (particles <2 mm in diameter), lapilli (2–64 mm), and blocks (angular) or bombs (rounded) (> 64 mm).
Cryptotephra	Tephra-derived glass-shard or crystal concentration, or both, preserved in sediments (including ice) or soils or paleosols but not visible as a layer to the naked eye (Greek *kryptein*, 'to hide').
Tephrostratigraphy	Study of sequences of tephra layers or cryptotephras and associated deposits, their lithologies, spatial distribution, and stratigraphic relationships, and relative and numerical ages. Tephrostratigraphy involves defining, describing, characterizing, and dating tephra layers or cryptotephra deposits in the field and laboratory to facilitate their correlation or explain their petrogenesis.
Tephrochronology (sensu stricto)	Use of primary tephra layers (or cryptotephra deposits) as isochrons* (time-parallel marker beds) to connect and synchronize depositional, or soils or paleosols, and to transfer relative or numerical ages to the sequences using lithostratigraphic, compositional, chronological, and other data relating to the tephras or cryptotephras, i.e. an age-equivalent dating and correlational tool. The use of primary cryptotephra deposits as stratigraphic isochrons is *cryptotephrochronology*.
Tephrochronology (sensu lato)	All aspects of tephra studies and their application.
Tephrochronometry	Obtaining a numerical age or calendrical date for a tephra layer or cryptotephra deposit.

*Note the spelling of '**isochron**' (*not* 'isochrone'), derived from Greek *iso*, 'equal', and Greek *chronos*, 'time'.

3. Mapping tephras: from metre to sub-millimetre scale

Since the mid-late 1920s, tephras have been mapped using field and laboratory based methods in New Zealand. In the field, the most successful approaches have included the so-called 'hand-over-hand' method whereby relatively thick sequences of tephras (metre to decimetre scale) are traced from cutting to cutting (Fig. 3; Lowe, 1990) using their stratigraphy and salient physical properties including colour, bedding characteristics, or other features such as pumice density (e.g., hard vs soft) or colour, the presence of accretionary lapilli (e.g. Van Eaton and Wilson, 2013), or marker mineral grains (crystals) such as biotite visible via a hand lens. Distinctive marker beds provide a useful stratigraphic starting point in unravelling the complexities of a road cutting or other exposure (Fig. 4). The nature of buried soil horizons or loess associated with tephra layers may also provide helpful information in the field. Such methods are ultimately limited as the tephra layers thin away from source and lose diagnostic features in subaerial sequences, or where they become mixed together by soil-forming processes or by cryoturbation in periodically frozen landscapes.

But for several decades now, cores taken from lake sediments and peat bogs in Hawke's Bay, Waikato, Taranaki, and Auckland have revealed a rich record of visible tephra layers a few centimetres to millimetres in thickness preserved at sites distant from source volcanoes (e.g., Lowe, 1988; Molloy et al., 2009; Augustinus et al., 2011; Lindsay et al., 2011; Turner et al., 2011; Green et al., 2014) (Fig. 5). Most recently, sub-millimetre-scale cryptotephra studies on such sediments have been initiated in the Waikato and Auckland regions (Table 2). Marine cores have also revealed detailed tephra records – which, together with those from lakes and bogs, provide a record of explosive volcanism that can be more comprehensive than that obtainable near to source because of burial or erosion of eruptives near volcanic centres (Fig. 6; Lowe, 2014). New developments in North America and elsewhere have been dramatic (Davies, 2015) and 'ultra-distal' cryptotephras have been described by Pyne-O'Donnell et al. (2012) (eastern USA, Lane et al. (2013) (eastern Africa), and Blockley et al. (2015) (Greenland), and, amazingly, include the identification of the Alaskan White River ash (~AD 860) in western/northern Europe (Jensen et al., 2014). Streeter and Dugmore (2013) advocated the development of high-resolution tephrochronology from studies in Iceland where they used digital photography to obtain thousands of stratigraphic measurements of multiple tephra layers intercalated with sediments at a resolution of ± 1 mm (see also Dugmore and Newton, 2012).

Fig. 3. Metre-thick, proximal, coarse, partly bedded pumiceous late Holocene rhyolitic tephra beds (mainly blocks/bombs and lapilli) and associated darker buried soil horizons (marking volcanic quiescence) evenly draping an antecedent strongly-rolling landscape near Taupo (from Lowe, 2011).

Fig. 4. Example of a stratigraphic marker bed in a road cutting, Hamilton. The prominent white bed mid-section is Rangitawa tephra (c. 340 ka). Lying at the base of strongly-weathered tephra beds and associated buried soils (Hamilton Ash sequence), rhyolitic Rangitawa tephra contains characteristic coarse-ash-sized golden platy crystals (biotite-kaolinite intergrade) and coarse-ash-sized quartz crystals. This widespread tephra, erupted near the end of MOI stage 10 (Holt et al., 2010; Alloway et al., 2013), overlies unconformably a dark reddish-brown buried soil >c. 0.78 Ma, about 1 m of volcanogenic alluvium, and (at the base) either the Ongatiti Ignimbrite (c. 1.23 Ma) (Lowe et al., 2001) or the Kidnappers Ignimbrite (c. 1 Ma) (Wilson et al., 1995). Photo: D.J. Lowe.
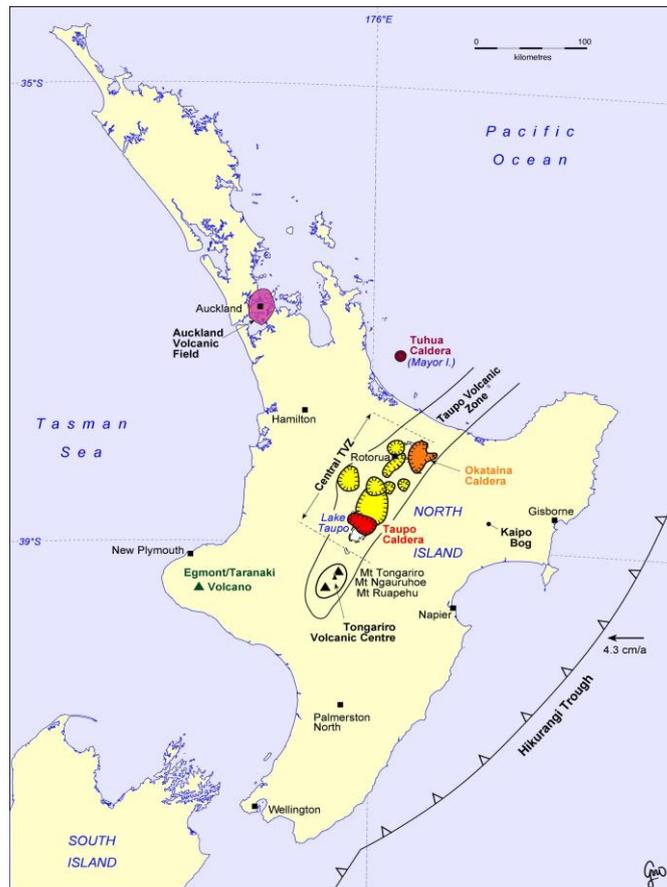
Fig. 5. Main tephra-producing Quaternary volcanic centres of North Island. The two most frequently active rhyolitic centres are Taupo and Okataina calderas (see Fig. 6). Egmont and Tongariro centres are andesitic, Tuhua (Mayor Island) is peralkaline, and the locally distributed tephras from Auckland Volcanic Field are basaltic. After Wilson and Leonard (2015).

OKATAINA

TAUPO

MAROA

MAYOR IS.

Age (ka cal. BP)

OKATAINA

Tarawera *(basaltic)* 10 June 1886
Kaharoa 1314 ± 12 AD
Rotokawa *(basaltic)*
Whakatane
Mamaku
Rotoma
Waiohau
Rotorua
Rerewhakaaitu
Okareka
Te Rere
L
Omataroa (K)
Awakeri (J)
Mangaone (I)
H
G
Hauparu (F)
Te Mahoe (E)
Maketu (D)
Pongakawa
C_2
Pupuwharau
C_1
Ngamotu (B)
A
Earthquake Flat (Kapenga volcano)
Rotoiti/Rotoehu (80 km³)*(caldera-forming)*

MAROA

Puketarata
Akatarewa
Un-named (Un)
Un
Forest Road Dome

TAUPO

Z
w Mapara (X)
Whakaipo (V)
U
T
Taupo (Y) (35 km³) 232 ± 10 AD
(caldera-forming)
Waimihia (S)
R
Stent (Q)
P
N
O
M
L
K
J
H
G
F
Opepe (E)
D
Poronui (C)
Karapiti (B)
A
Ω *(Omega)*
Ψ *(Psi)*
Kawakawa/Oruanui (530 km³)
(caldera-forming)
Poihipi
Okaia
Tahuna
Un-named (Un)
Ngangiho
Un
Un
Un
Un

MAYOR IS.

Tuhua M7
M6
Te Paritu
?=M6
M5
M4
M3
M2?
M1?

0
10
20
30
40
50

Volume km³ (DRE)
0   10   20

Volume km³ (DRE)
0   10   20

Fig. 6. Interfingering stratigraphic relationships, ages, and volumes (as non-vesiculated, void-free magma, i.e., dense-rock equivalent, DRE) of tephras erupted from Okataina, Maroa, Taupo, and Mayor Island (Tuhua) caldera volcanoes in North Island, , since ca. 55 ka cal. BP (from Lowe et al., 2015b, and based mainly on Jurado-Chichay and Walker, 2000; Shane et al., 2006; Wilson et al., 2009; Leonard et al., 2010; Danisik et al., 2012; Lowe et al., 2013; Vandergoes et al., 2013).

4. Fingerprinting

Tephra fingerprinting in New Zealand has been undertaken using a range of analytical methods, almost always in conjunction with stratigraphic and chronological criteria where available (Table 3). Accurate fingerprinting is an essential element (!) in developing any age models for tephras, and the level of probability that can be applied to their identification and correlation is an important consideration in quantitative tephrochronology. Ideally, multiple criteria (more than one thread of evidence) should be used to secure the correlation: for example, stratigraphic position together with mineralogical assemblage and glass major element composition. Numerical age data are also useful.

Table 2. Special techniques used to identify and map thin distal tephras, or detect cryptotephras in cores or sections, in New Zealand (after Lowe et al., 2008a) (see also Gehrels et al., 2008).

Application	Method
Field	Ground radar
	Magnetic susceptibility
Laboratory	X-radiography
	X-ray density scanning
	Magnetic susceptibility
	Dry bulk density
	Rapid X-ray fluorescence
	Spectrophotometry (reflectance and luminescence)
	Refractive indices of glass
	Glass counts (cryptotephras)
	Total organic carbon, loss on ignition

Table 3. Summary of main analytical methods (excluding geochronology) used in New Zealand to characterize and correlate tephras erupted since c. 30,000 cal. yr BP (after Lowe, 2011).

Tephra component/properties	Methods of analysis	Example
Ferromagnesian minerals		
Assemblages	Petrographic microscope	Table 4
Pyroxenes, amphiboles, olivine, biotite crystals	Electron microprobe	Fig. 9
Fe-Ti oxides		
Major and minor elements in crystals	Electron microprobe	Fig. 8
Eruption temperatures and oxygen fugacities	Electron microprobe	Table 4
Glass shards or selvedges		
Major elements	Electron microprobe	Figs. 10, 11
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.

Mineralogy

One of the most common methods has been to use optical microscopy (using a petrological or polarizing microscope) to identify ferromagnesian mineralogical assemblages where such minerals are abundant. These minerals can be extracted using magnetic separators (e.g., Frantz) together with non-toxic heavy liquids (e.g., sodium polytungstate). With stratigraphic constraints, the relative abundances of ferromagnesian minerals typically allow a source volcano to be identified. For eruptives <30,000 cal. yr BP, orthopyroxene is always dominant in Taupo Volcanic Centre (TP)-derived tephras whereas biotite, hornblende, cummingtonite, or orthopyroxene predominate in Okataina Volcanic Centre (OK)-derived tephras (Table 4; Lowe et al., 2008a). Sometimes a mineral assemblage is sufficiently distinctive for an individual tephra − for example, Tuhua Tephra (from Mayor Island), which contains sodic phases such as aegirine − to be readily identified by only a few grains. However, the absence of diagnostic minerals does not necessarily negate an identification because minerals such as olivine are readily depleted by weathering, and biotite and orthopyroxene may be rapidly dissolved in some acid peat bogs (e.g., Hodder et al., 1991). 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. Recent studies of the OK-derived tephras (erupted since 30,000 cal. yr BP) have shown that all but two comprise multiple magma types (Table 4), adding complexity to the use of ferromagnesian minerals for correlation purposes but increasing in some the potential for fingerprinting by chemical analysis of constituent minerals and glass (see below). Andesitic eruptives are usually distinguishable from rhyolitic tephras because of their high pyroxene, or hornblende plus clinopyroxene, contents.

Microprobe analysis

In undertaking electron microprobe analysis (EMPA), sample preparation (Fig. 7) and probe operating conditions are critically important in deriving accurate and robust data, especially for glass which normally requires a defocussed beam to minimise volatilisation of Na and K (Froggatt 1992; Hunt and Hill, 1996, 2001; Turney et al., 2004; Lowe, 2011). However, Hayward (2012) and Hall and Hayward (2014) have developed robust protocols that enable the routine use of narrow beam diameters of 5 μm, and as low as 3 μm, without loss of Na. Such a development is extremely important because it enables many fine-grained samples to be analysed from wider, more distal geographic locations than previously, it reduces or prevents bias in data collection because most or all shards in a sample can be analysed, it enables more shards that are vesicular or microlite-rich (microlites are tiny mineral inclusions and can occur frequently in andesitic or basaltic glasses, and also in rhyolitic glasses) to be analysed than previously possible, and EPMA data acquisition is more easily automated and hence potentially more cost-effective (Hayward, 2012; Hall and Hayward, 2014; see also Pearce et al., 2014).

Appropriate standards must be checked (analysed) frequently and there is now a general requirement for analyses of such standards to be published alongside new EMPA data (e.g., Westgate et al., 2008). A revised set of protocols for microprobing glass (and reporting such analyses) was published by Kuehn et al. (2011) following an intensive interlaboratory comparison exercise in 2010-2011. Glass EMPA analyses are usually normalized (summed to 100%, most of the deficit being attributable to water) to enable valid comparisons of analyses. Some consider that such normalization can 'cover up' poor data (low totals), and should therefore not be undertaken (e.g., Pollard et al., 2006).

Analyses of Fe-Ti oxides, titanomagnetites and ilmenites, by EMPA have been useful for tephra fingerprinting (Table 4). An example of the use of minor elements (Mn, Mg) to distinguish five TP-derived tephras is given in Fig. 8. Egmont (EG) or Tongariro Volcanic Centre (TG) sources are usually determinable. The eruption temperature and oxygen fugacity (oxidation state of magma) of rhyolitic tephras − estimated using single-grain EMPA of Fe-Ti oxide pairs of titanomagnetite and ilmenite − have provided a relatively new way to distinguish and match tephras and, in some cases, magma batches within an eruptive sequence (Table 4).

1. Block positioning

- Epoxy block (13 mm high max.)
  * max.diameter 1" (25mm)
- 7 holes drilled through
- Double-sided sticky tape
- Stick block to tape
- Flat glass plate

2. Add samples

- 1st - add sample into hole
  - drop onto sticky tape
- 2nd - add cold-mounting epoxy to holes
  - stir with a pin to remove bubbles
- 3rd - let epoxy set hard

- Block number
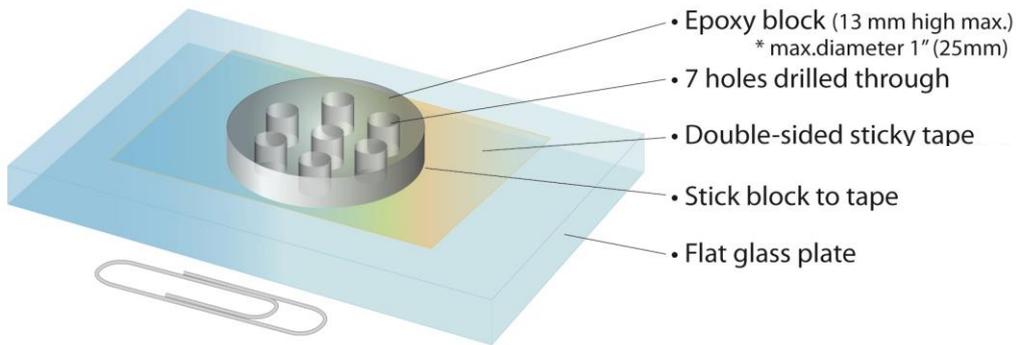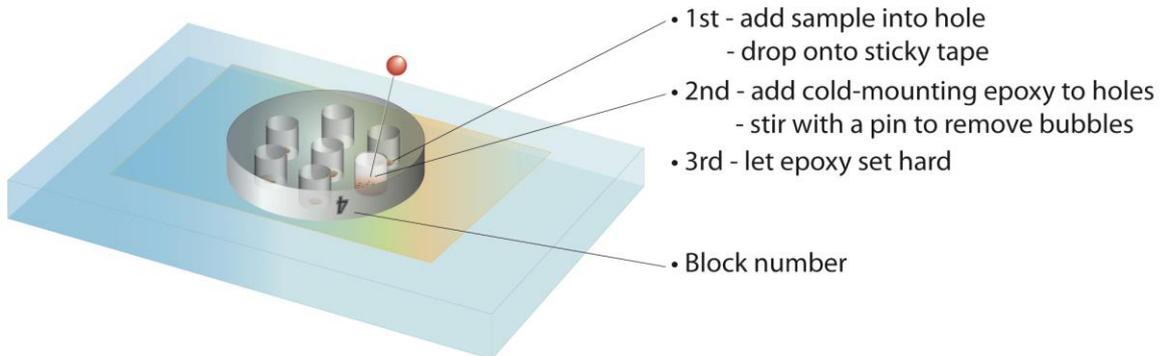
3. Invert block and remove tape from base

- Remove tape exposing glass shards in epoxy-filled holes as 'plugs'

- Bottom of block

4. Grind base

- Grind/polish the bottom of block with samples protruding
- Polisher/grinder
- Hand grind ➝ expose grains
- Check grinding surface to ensure 20+ grains are exposed
- Machine polish as usual

5. Polished surface

- ~ 1cm
- Max 1" (25mm)
- Label samples on surface
- Polished surface
- Sputter coat with carbon for emp
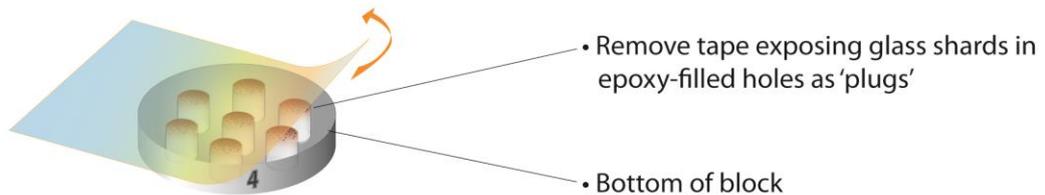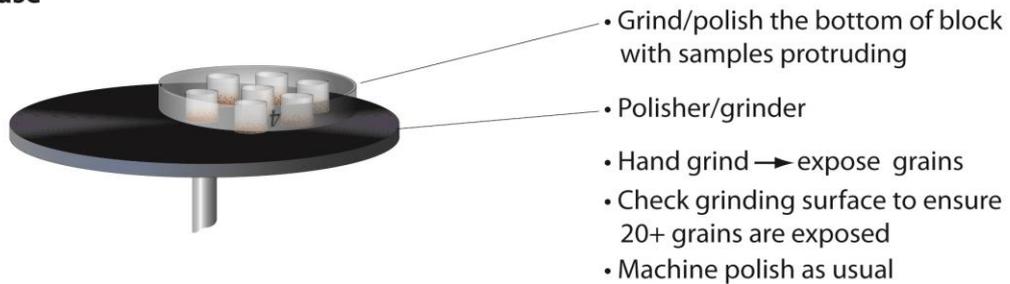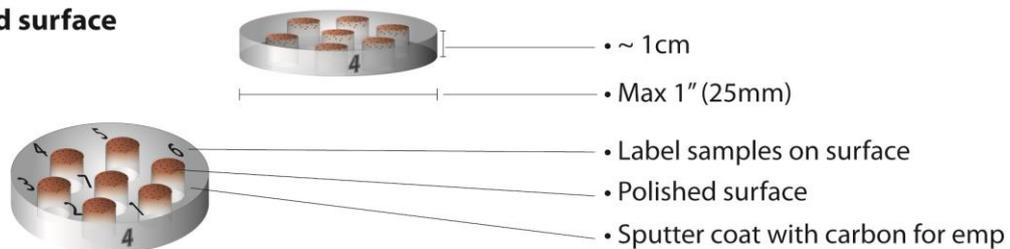
Fig. 7. Preparation of crystals or glass shards in 'blocks' for analysis by electron microprobe. Grains must be polished flat before analysis (from Lowe, 2011).
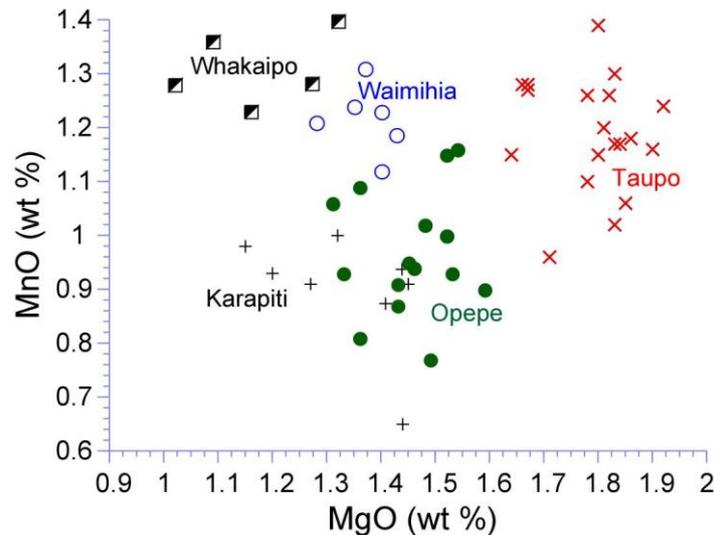
Fig. 8. Biplot of MnO vs MgO (wt%) analyses for ilmenites obtained using EMPA from five TP-derived tephras showing that Taupo (Unit Y), Whakaipo (V), and Waimihia (S) and are distinguishable from one another and from Karapiti (B) and Opepe (E) (from Lowe et al., 2008a).

The compositions of pyroxene, amphibole and olivine, obtained by EMPA, generally allow few individual tephra eruptive events to be identified but source volcanoes may be readily distinguished. For example, clinopyroxene and hornblende in EG-derived tephras are typically more calcic than those from TG, hornblende from these two andesitic sources is more pargasitic than that from the rhyolitic centres, and olivine in TG-derived tephras is forsteritic (Mg-rich) compared with that from Mayor Island which is fayalitic (Fe-rich). More recently, however, it has been demonstrated that the FeO and MgO contents of biotite derived from Kaharoa (two eruptive phases), Rotorua, Rerewhakaaitu, and Okareka tephras were different, thus enabling them to be distinguished from other OK-derived eruptives (Fig. 9).

The most commonly used tephra fingerprinting technique in New Zealand involves major-element analysis of volcanic glass shards using EMPA (Shane, 2000; Shane et al., 2006; Lowe et al., 2008a). Established initially in New Zealand in the early 1980s by Paul Froggatt (Froggatt and Gosson, 1982; Froggatt, 1983), EMPA of glass enabled volcanic sources to be readily identified for almost all eruptives <30,000 cal. yr BP in age. Although analyses of individual rhyolitic tephras of this age-range from Taupo or Okataina centres show many to be compositionally similar, some are distinguishable using bi-plots such as FeO or K_2O vs CaO content (Fig. 10), or using canonical discriminant function analysis (DFA) that incorporates eight or nine elements (oxides).

Detailed studies by EMPA, however, of thick sequences of proximal tephras erupted from Okataina have revealed much more compositional diversity and heterogeneity within individual lapilli-sized clasts and at different azimuths around the volcanic centre than previously recognised (Shane et al., 2008a). This heterogeneity is a consequence of the mingling of separate batches of magma that were tapped simultaneously or sequentially, accompanied by changes in wind direction, as eruptions proceeded. The recognition of more than one magma type in most of the OK-derived tephras has in some circumstances increased their potential for precise correlation in that some tephra beds might be identified uniquely, even where stratigraphic control is uncertain, because they were derived from two or three magma batches and so have multiple fingerprints or 'handprints' (Lowe et al., 2008a). For example, Kaharoa and Rotorua tephras are each the product of two magmas that can be distinguished on the basis of glass chemistry, one high (>4 wt%) and the other low (<4 wt%) in K_2O. Similarly, Rerewhakaaitu, Okareka, and Te Rere tephras are characterised by three magma types, the high K_2O-types (T2) containing distinctive biotite as well. However, it is also evident that the newly-recognised heterogeneity has increased complexity and potentially ambiguity, and glass compositions of some eruptive phases may overlap those for other tephras. An implication is that some tephras may have been misidentified (miscorrelated) in the past. The heterogeneity warns of the difficulty of characterising (thus fingerprinting) tephra beds using a limited set of distal samples from restricted dispersal sectors (Shane et al., 2008a).

Table 4. Ferromagnesian mineralogical assemblages and magma temperatures and oxygen fugacities of 22 marker tephras erupted since c. 30,000 cal. yr BP in New Zealand (from Lowe et al., 2008a)

Tephra name	Relative abundances of ferromagnesian minerals[a]	Eruption temperature[b] (° C)	Oxygen fugacity fO$_2$ (NNO)[c]

Taupo Volcanic Centre (rhyolitic) (see Fig. 5)

Taupo (Unit Y)	Opx >> Cpx	862 ± 17	-0.17 ± 0.11
Whakaipo (Unit V)	Opx	785 ± 10	-1.06 ± 0.12
Waimihia (Unit S)	Opx >> Hbe	816 ± 10	-0.72 ± 0.08
Unit K	Opx	822 ± 16	-0.59 ± 0.11
Opepe (Unit E)	Opx >> Cpx	812 ± 18	-0.54 ± 0.17
Poronui (Unit C)	Opx >> Cpx		
Karapiti (Unit B)	Opx >> Cpx + Hbe	788 ± 33	-0.75 ± 0.24
Kawakawa/Oruanui	Opx > Hbe	774 ± 12	-0.14 ± 0.10
Poihipi	Opx > Hbe > Bio	771 ± 6	0.07 ± 0.10
Okaia	Opx > Hbe	789 ± 17	0.21 ± 0.09

Okataina Volcanic Centre (rhyolitic)

Kaharoa T1[d]	Bio >> Hbe >> Cgt ± Opx	731 ± 10	0.09 ± 0.14
T2	Bio >> Cgt > Hbe ± Opx		
Whakatane T1	Hbe > Cgt > Opx	746 ± 13	0.33 ± 0.09
T2	Hbe > Cgt > Opx	737 ± 9	0.29 ± 0.11
T3	Opx > Hbe > Cgt	770 ± 5	0.52 ± 0.05
Mamaku	Hbe > Opx >> ± Cgt	735 ± 19	0.18 ± 0.13
Rotoma T1	Cgt > Hbe > Opx	752 ± 19	0.47 ± 0.12
T2	Hbe > Opx > Cgt	752 ± 19	0.47 ± 0.12
T3	Opx > Hbe > Cgt	752 ± 19	0.47 ± 0.12
Waiohau	Opx > Hbe	762 ± 23	0.36 ± 0.22
Rotorua T1	Opx > Hbe >> Cpx	871 ± 10	1.11 ± 0.13
T2	Bio > Hbe >> Opx	745 ± 30	0.17 ± 0.20
Rerewhakaaitu T1	Opx > Hbe	721	-0.31
T2	Hbe + Bio >> Opx	750 ± 18	0.43 ± 0.14
T3	Opx > Hbe		
Okareka T1	Opx + Hbe >> Cgt	759 ± 20	0.30 ± 0.20
T2	Hbe + Bio >> Opx	724 ± 14	0.05 ± 0.15
T3	Opx > Hbe	794 ± 12	0.82 ± 0.08
Te Rere T1	Opx + Hbe	801 ± 24	1.43 ± 0.16
T2	Opx + Hbe + Bio > Cpx	708 ± 3	-0.07 ± 0.01
T3	Opx + Hbe		

Tuhua Volcanic Centre (peralkaline rhyolitic)

Tuhua	Aeg > Cpx > Opx ± Aen ± Rie ± Hbe ± Olv(fa) ± Tuh		

Tongariro Volcanic Centre (andesitic)

Okupata	Opx > Cpx >> ± Olv(fo) ± Hbe	~900-1100	

Egmont Volcano (andesitic)

Konini	Hbe > Cpx >> ± Opx	~950	

(footnotes contd below)

Table 4 (contd)

[a]Opx, orthopyroxene (mainly hypersthene); Cpx, clinopyroxene (mainly augite); Hbe, hornblende; Cgt, cummingtonite; Bio, biotite; Aeg, aegirine; Aen, aenigmatite; Rie, riebekite; Olv, olivine (fa, fayalite; fo, forsterite); Tuh, tuhualite.

[b]Pre-eruption temperature data (mean ± 1 standard deviation).

[c]Oxygen fugacity data reported in NNO units relative to the NiNiO buffer.

[d]T1–T3 represent separate magma types (early to late eruptive phases, respectively) identified by Smith et al. (2005) for some Okataina eruptive episodes.
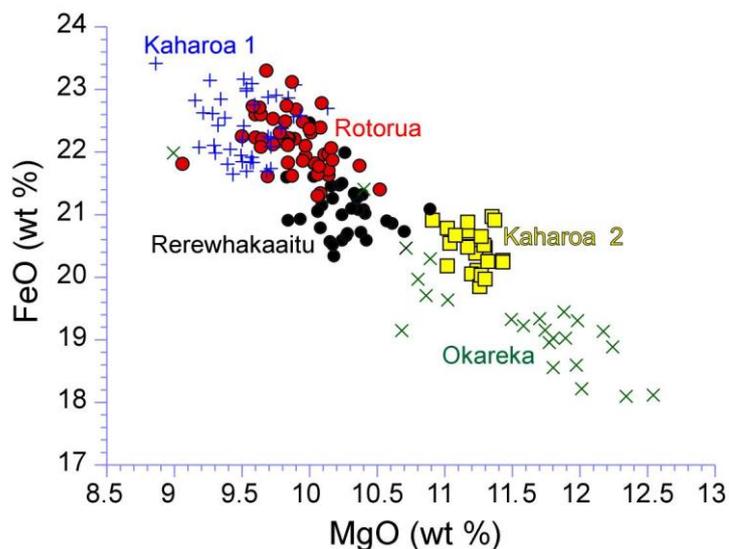
Fig. 9. Biplot of FeO vs MgO (wt%) analyses for biotite obtained using EMPA from four OK-derived tephras showing that Okareka (magma type T2), Rerewhakaaitu (magma type T2), and Rotorua (magma type T2) are distinguishable from one another, and that Kaharoa Tephra comprises two populations relating to early (Kaharoa 1, magma type T1) and late (Kaharoa 2, magma type T2) phases of the eruption that correspond to high K_2O and low K_2O glass compositions, respectively (from Lowe et al., 2008a).
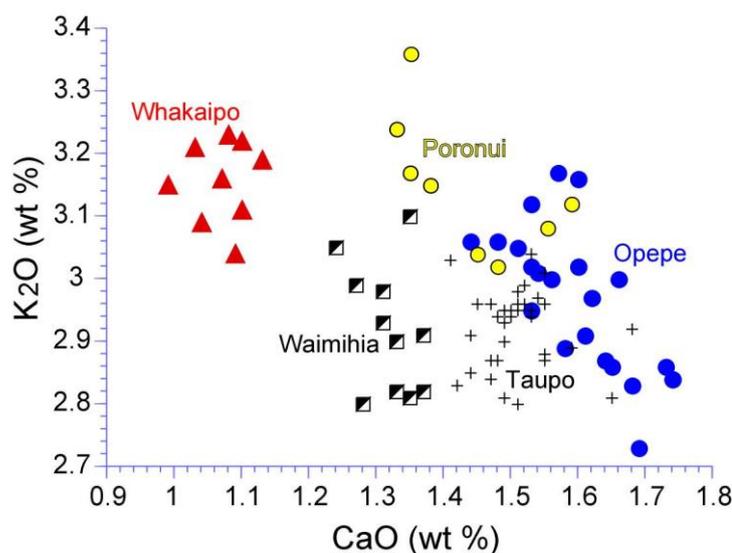
Fig. 10. Biplot of K_2O vs CaO (wt%) analyses for glass obtained using EMPA from five TP-derived tephras illustrating that Taupo (Unit Y), Whakaipo (V) and Waimihia (S) generally are able to be distinguished from one another but Poronui (C), Opepe (E), and Taupo (Y) partly overlap (from Lowe et al., 2008a).

Lowe: QT Short Course 2016

The correlation of andesitic tephras using glass chemistry generally has not been straightforward for various reasons including the multiplicity of units, the paucity of suitable glass for probing (few shards are free of microlite inclusions, and shards may be highly vesicular) and its vulnerability to weathering, and wide compositional ranges (SiO_2 = ~58–75 wt %) and heterogeneity arising from multiple magma-mixing events (e.g., Shane et al., 2008b; Turner et al., 2008, 2011). Moreover, there are limited databases for tephras from EG and TG and hence direct correlation is uncertain without precise radiometric age or stratigraphic control (Shane, 2000; Lowe, 2011). However, analyses of glass from >40 EG-derived tephras by Shane (2005) showed them to be enriched in K_2O (>4 wt %) and depleted in CaO, TiO_2 and FeO in comparison with andesitic tephras erupted from TG, and hence easily distinguished (see also Donoghue et al., 2007; Lowe et al., 2008a). Further, the compositional variation (heterogeneity) in glasses from some individual andesitic tephras allows their identification within short stratigraphic intervals of c. 5,000–10,000 cal. years (Shane, 2005). Platz et al. (2007) proposed an evaluation procedure using mixing calculations to reduce microprobe-determined glass heterogeneity arising from plagioclase microlites, and this method is proving useful in cryptotephra studies (e.g., Gehrels et al., 2010). Most recently, Moebis et al. (2011) demonstrated that tephras from the three main centres of the Tongariro Volcanic Centre (Ruapehu; Ngauruhoe; Red Crater, Tongariro) could be distinguished by major elements, specifically via K_2O and FeO (Fig. 11).

Basaltic tephras in New Zealand, of restricted distribution, have been analysed by Shane and Smith (2000), Shane and Zawalna-Geer (2011), Needham et al. (2011), Shane et al. (2013), and Linnell et al. (2016) and others.
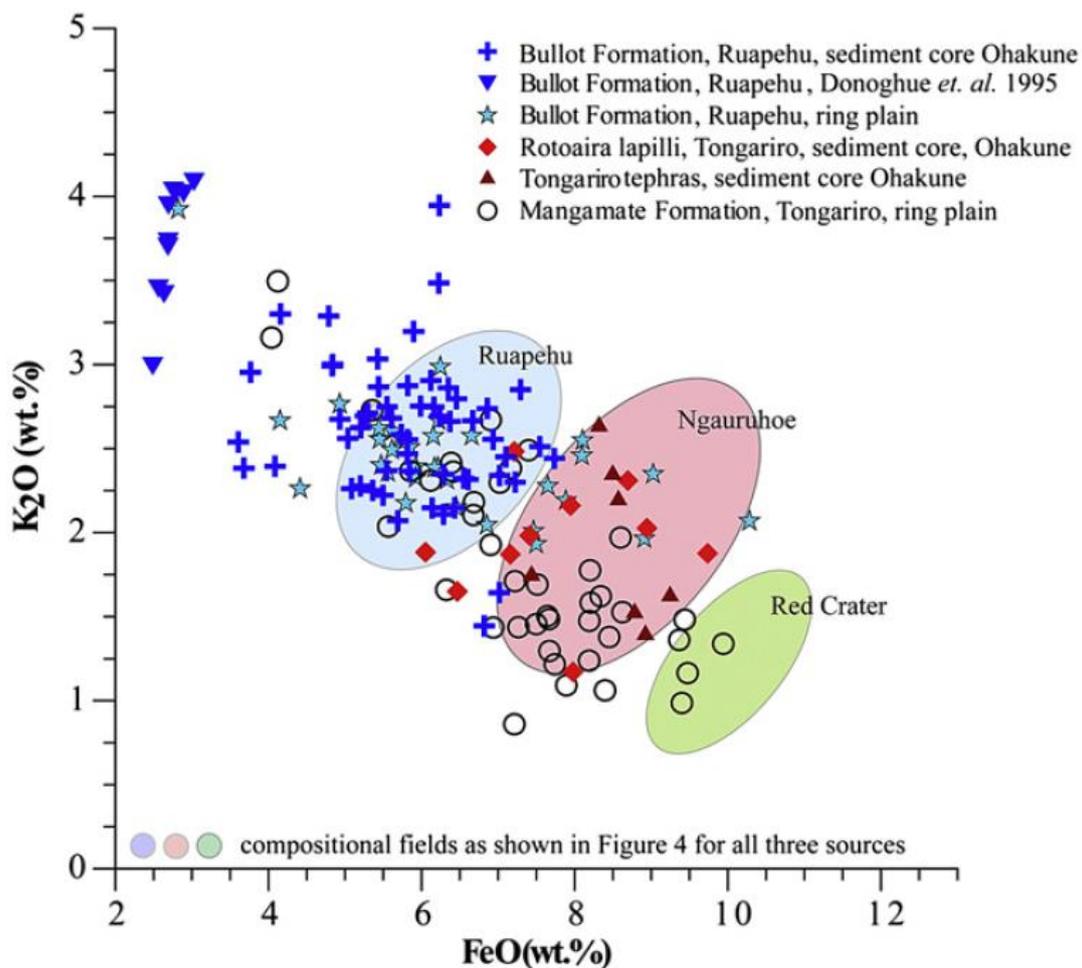

Fig. 11. Biplot of K_2O and FeO (total Fe expressed as FeO) derived by electron microprobe analyses of glass from tephras erupted from Ruapehu and Tongariro volcanoes younger than c. 12,000 cal. years, showing separation according to three sources (from Moebis et al., 2011, p. 359).

Trace- and rare-earth element (REE) data have not been widely employed in New Zealand tephrostratigraphy, although comprehensive studies have now been undertaken of Pleistocene tephras in the Auckland region (Pearce et al., 2008a) and in a core from ODP Site 1123 in the Pacific Ocean east of New Zealand (Allan et al., 2008). Earlier, various REEs and trace elements, based on analyses of small, bulk-glass samples, enabled some tephras from TP and OK within the <30,000 cal. yr BP time-frame to be distinguished. TP-derived tephras tend to show greater abundances of Sm, Eu, Tb, Lu, Hf, and Sc (Shane, 2000). Tuhua Tephra is distinguishable from both TP and OK-derived tephras because it has greater abundances of all REEs and other elements including U, Th, and Hf.

Because glasses from many OK-derived tephras are now known to be compositionally heterogeneous, the trace-element and REE analyses need to be re-examined and revised, probably using inductively coupled plasma mass spectrometry methods (LA-ICPMS). Advances in this method now enable it to obtain detailed major- and trace-element compositions from individual glass shards and for fingerprinting individual tephra beds or tephra successions of similar mineralogy or provenance, i.e., it is probably most useful to separate beds that are compositionally similar and not distinguishable using major element chemistry (Pearce et al., 1999, 2004, 2007, 2011, 2014; Allan et al., 2008; Westgate et al., 2008; Kuehn et al., 2009; Pearce, 2014; Tomlinson et al., 2015). The main advantage of a single-grain technique is that it allows mixed populations to be identified (such mixing arising from magmatic or volcanic eruption processes, or from post-depositional blending of thin tephras in soil-forming environments or the dissemination of glass shards in peat or in lake sediments, e.g., Gehrels et al., 2006).

Analyses by ion microprobe (secondary ionisation mass spectrometry, SIMS) of tephra components are also now being undertaken (e.g., Denton and Pearce, 2008) and look set to expand as the technique becomes more readily available (Lowe, 2011).

Somewhat unusually, diatom populations in the Kawakawa/Oruanui tephra and in the Okaia and Taupo tephras enable these deposits to be correlated. Morphometric analysis of *Aulacoseira* valve dimensions provides a helpful quantitative tool to distinguish environmental and eruptive processes within and between individual tephras (Van Eaton et al., 2013; Harper et al., 2015). The Kawakawa/Oruanui and Okaia diatom species and valve dimensions are highly consistent with a shared volcanic source, paleolake and eruption style (involving large-scale magma– water interaction). They are distinct from lacustrine sediments sourced elsewhere in the TVZ.

5. Statistical techniques to aid correlation

Statistical techniques in New Zealand have been limited mainly to DFA. Whilst not without potential flaws (see below), DFA has several advantages, the most important being that all or most elements in the analyses are taken into account non-subjectively, samples are able to be classified (matched) with known probability, and their degree of similarity is reflected in the Mahalanobis multidimensional distance statistic, D^2, which is preferable to the frequently used numerical 'similarity coefficients' measure. The efficacy of the technique can be tested using an iterative process to measure classification efficiency. DFA has been applied reasonably successfully to studies involving major-element analyses of glass (Fig. 12), Fe-Ti oxides or hornblende for both rhyolitic and andesitic tephras including composite (mixed) tephra deposits. In all these studies, many individual tephra layers or groups of tephras were able to be discriminated with a high-degree of probability (up to 100% classification efficiency) using either glass or titanomagnetite compositions, but some tephras, very similar compositionally, were less-well discriminated or unidentifiable using major elements alone.

The successful use of DFA is directly reliant upon the quality and comprehensiveness of the reference datasets against which unknowns are compared (e.g., Stokes et al., 1992; Cronin et al., 1996a, 1996b; Lowe, J.J. et al., 2007; Lowe, 2008a; Bourne et al., 2010). The generally poor analytical precision of some elements obtained by EMPA may limit the effectiveness of some DFA models, and the somewhat piecemeal glass compositional datasets for New Zealand tephras, acquired over several decades at a number of EMPA facilities, are of variable quality for several reasons, including changes in microprobe analytical procedures in the mid-1990s. Although further advances using DFA to identify and correlate rhyolitic tephras in New Zealand may now be feasible with the acquisition of the new glass major-element data (summarised in Smith et al., 2005; Lowe et al. 2008a), the approach must be

cautionary. Elsewhere, the statistical (or Euclidian) distance function (which is a variation of the similarity coefficient method), cluster analysis, or the Student's *t*-test have been used (e.g., Pollard et al., 2006; Pearce et al., 2008b; Preece et al., 2011). Pouget et al. (2014) used principal component analysis to correlate tephras in California. New approaches have been developed by Bebbington and Cronin (2011), Turner et al. (2011), and Green et al. (2014). Statistical correlation methods were reviewed by Lowe et al. (in review). Ultimately such statistical techniques will rely on the development of more comprehensive, regional tephrostatigraphic and geochemical databases of uniformly high quality (Lowe, 2011).
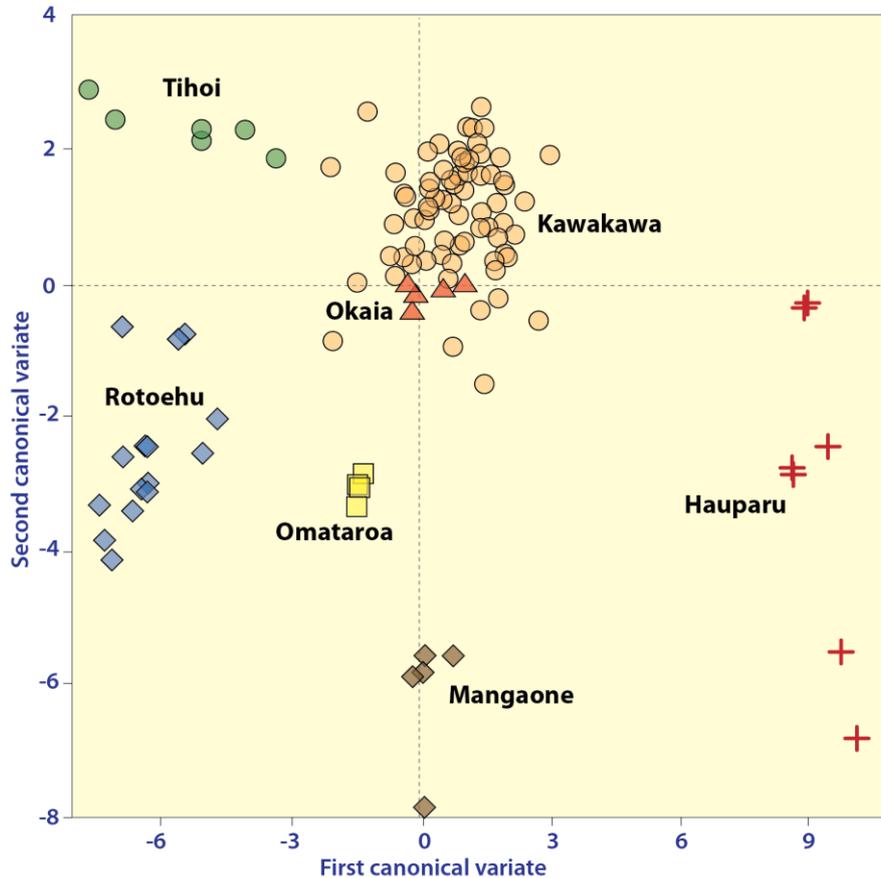

Fig. 12. Example of use of DFA to compare degree of similarity of seven late Quaternary rhyolitic tephras in central North Island, New Zealand. Glass compositions of each tephra were combined using DFA into the first two canonical variates. The Mahalanobis distance between groups (D_m^2) is a direct measure of their multivariate similarity/dissimilarity based on all seven major oxides analysed, not just two or three (from Lowe, 2011, after Cronin et al., 1997).

6. Developments in dating methods and age modelling

Dating methods relevant to tephra studies have described by Lowe (2011) and Lowe and Alloway (2015) (Table 5). A key advance has been the development of the isothermal-plateau fission-track dating method (ITPFT) for glass (Alloway et al., 2013). It has enabled ages to be obtained on many distal tephras that previously were unable to be dated because their main component, glass, was unreliable because of annealing (e.g., Westgate et al., 2013). Examples of such applications are the dating of initial loess deposition in Alaska at about 3 million years ago (Westgate et al., 1990), dating Quaternary glacioeustatic sedimentary cycles in the Wanganui Basin (Pillans et al., 2005), and dating marine tephra sequences from ODP sites east of New Zealand, thus testing chronologies based on alternative methods (Carter et al., 2004; Alloway et al., 2005; Allan et al., 2008). Another promising method for more proximal deposits, until recently used mainly for pre-Quaternary petrological or provenance studies, is the use of U-Pb analyses to date zircons using SIMS techniques (e.g., SHRIMP: Brown and Fletcher, 1999; Wilson et

al., 2008; ID-TIMS: Crowley et al., 2007) or LA-ICPMS (e.g., Chang et al., 2006) (see also Dickinson et al., 2010). A new method involving U-Th-disequilibrium/U-Pb and (U-Th)/He zircon 'double dating' is being applied to tephra studies (e.g. Schmitt et al., 2010; Danisik et al., 2012, in press; Howe et al., 2014). The application of varved sediments to help derive tephra ages includes research reported by Zillén et al. (2002), Lane et al. (2015), and Ott et al. (2016).

For tephras erupted within the past c. 50,000–60,000 cal. years, the radiocarbon (^{14}C) technique remains by far the most important method for developing age models (other methods are documented by Lowe et al., 2008a; Alloway et al., 2013; Westgate et al., 2013). Calendar dates on two late Holocene tephras, Kaharoa and Taupo, 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 Bayesian statistical analysis of an independent ^{14}C-age dataset (Buck et al., 2003). The main plinian phases of the Kaharoa eruption took place during the austral winter (on the basis of tree-ring data). The date for Taupo tephra is now established as 232 ± 10 AD (Hogg et al., 2012; 95% probability). This date contrasts with several other calendar dates suggested for this eruption and indicates that the Greenland ice-core date of 181 ± 2 AD, and the Roman and Chinese sunset date of c. 186 AD, are no longer viable. Tree-ring data and preserved plant macrofossils have shown that the Taupo eruption took place during the austral late summer−early autumn period, i.e. probably late March−early April.

Table 5. Methods used for dating tephras directly or indirectly (from Lowe and Alloway, 2015; after Lowe, 2011)

Main 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, Ar/Ar including SCLP/F, LIH)
	Luminescence dating (TL, OSL, IRSL, pIR-IRSL)
	U-series including (U-Th)/He, U-Pb, and ^{238}U/^{230}Th zircon dating (SIMS/TIMS, SHRIMP, LA-ICPMS)
	Electron spin resonance
	^{210}Pb, ^{137}Cs, ^{3}He and ^{21}Ne surface exposure dating
Incremental	Dendrochronology, varve chronology, layering in ice cores (ice sheets/ caps, glaciers)
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 modeling and wiggle matching, spline-fit modelling
Relative	Obsidian hydration dating, amino acid racemisation
Historical	Eyewitness accounts or observations (e.g., via remote sensing)

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

Bayesian age modelling
Together with wiggle-matching methods, Bayesian age modelling, derived ultimately from the theorem of 18th Century Englishman, Thomas Bayes, is adding another revolutionary aspect to the construction of enhanced and more precise chronologies in tephrochronology (e.g., Blockley et al., 2007b, 2008, 2012; Lowe, J.J. et al., 2007; Lowe, 2011; Bronk Ramsey et al., 2015a, 2015b). For example, 14 Holocene and late Pleistocene tephras comprising a sequence from Waimihia Tephra to Rerewhakaaitu Tephra,

preserved in peat at montane Kaipo bog in eastern North Island, were dated by using flexible depositional age-modelling (similar to wiggle-matching) their stratigraphic order and 51 associated ^{14}C-age points simultaneously against the IntCal04 calibration curve (Hajdas et al., 2006). The flexible depositional age-modelling of the Kaipo sequence was undertaken using the programme OxCal3, developed by Chris Bronk Ramsey, which utilises a Bayesian statistical framework (successor OxCal4: Bronk Ramsey, 2008, 2009). Subsequently, Lowe et al. (2008a) analysed the same age data independently using an alternative Bayesian age-depth modelling programme, Bpeat (Blaauw and Christen, 2005; Wolfarth et al., 2006; Blaauw et al., 2007).

The 2σ-age ranges for the tephras derived from both OxCal3 and Bpeat were listed in Lowe et al. (2008a), and are closely aligned. A revised age model for the Kaipo tephra sequence has been developed for the NZ-INTIMATE project using another Bayesian programme, *Bacon* (Blaauw and Christen, 2011), in conjunction with OxCal4 and the associated *P_Sequence* function (Bronk Ramsey, 2009) (Lowe et al., 2013). Older tephras (those erupted earlier than c. 18,000 cal. yr BP) were also re-dated using OxCal4 and the associated *Tau_Boundary* function (Lowe et al., 2013) (Fig. 13). The new age modelling has shown Waiohau tephra to have been erupted around 14,000 cal. yr BP (*cf.* c. 13,700 cal. yr BP in Lowe et al., 2008a). Regarding the very widespread Kawakawa/Oruanui tephra, its age has been problematic (Lowe et al. 2008a, 2010). Wilson et al. (1988) published a ^{14}C age of c. 22,590 ^{14}C yr BP, equivalent to about 27,000 cal. yr BP, but recent dating of optimal material using the *Tau_Boundary* function of OxCal4 showed this tephra is now dated firmly at 25,358 ± 162 cal yr BP (95% probability) (Vandergoes et al., 2013). In North America, Egan et al. (2015) refined the age of the eruption of Mazama tephra to 7682–7584 cal. yr BP (2σ range) using Bayesian modelling of a dataset comprising 81 ^{14}C ages, consistent with, but more precise than, an age of 7627 ± 150 ice-core yr BP derived from GISP2.
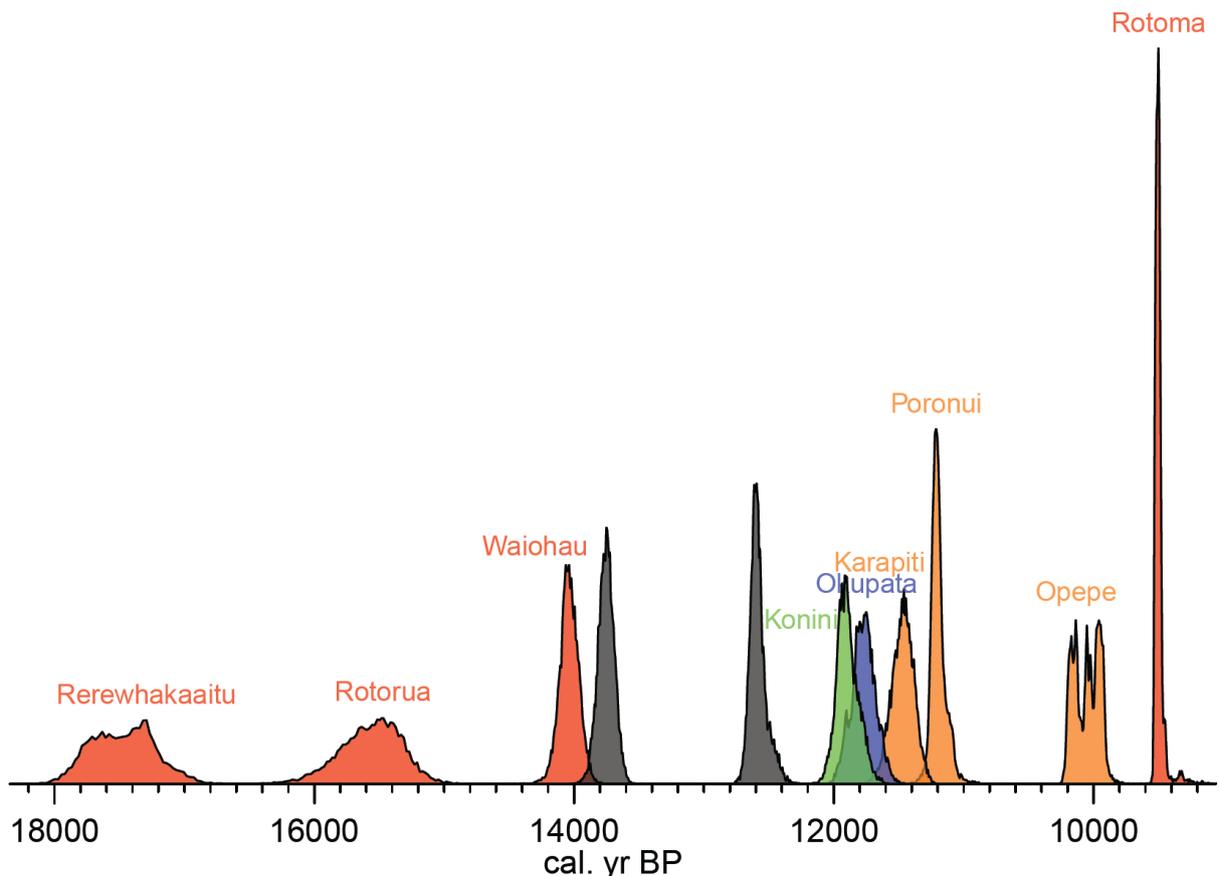

Fig. 13. Bayesian-derived age models for nine Lateglacial to Holocene tephras. Ages derived from modelling for part of a peat sequence at Kaipo bog in eastern North Island using Bacon (from Lowe et al., 2013). Probability plots (all are equal in area) are coloured according to tephra source volcanoes: red, Okataina; orange, Taupo; green, Egmont/Taranaki; blue, Tongariro. Grey plots show the Bacon-derived start and end ages of the Lateglacial cool episode (i.e., New Zealand climate event NZce-3 of Barrell et al., 2013) between the Waiohau and Konini tephras.

7. Tephrochronology as a high-precision synchronization or correlation tool

A critical recent development has been the enhanced use of tephrochronology to affect more precise correlations between marine, ice-core, and terrestrial records. This application holds the key to testing the reliability of high-precision correlations between sequences and current theories about the degree of synchroneity of climate change at regional to global scales – provided the tephra correlation is certain (e.g., see Denton and Pearce, 2008). Numerous studies have utilised this unique chronostratigraphic capability (e.g. Fig. 14; Lowe, 2008a; Zanchetta et al., 2011; Davies, 2015).

In Europe, Blockley et al. (2007a) for example showed that there is now potential to independently test climate synchroneity between Greenland and Europe as far south as the Alps via the Vedde ash. Similarly, Rasmussen et al. (2008) correlated the NGRIP, GRIP, and GISP2 ice core records across marine oxygen isotope stage 2 using mainly tephras as a means of applying the recent NGRIP-based Greenland ice-core chronology to the GRIP and GISP2 ice cores, thus facilitating the synchronizing of palaeoclimate profiles of the cores in detail. Remarkably, Lane et al. (2011, 2012) have now linked northern, central, and southern European climate records in part using cryptotephrochronology. The RESET project (RESponse of humans to abrupt Environmental Transitions) has also led to major advances in European tephra and cryptotephra studies including the development of a so-called 'tephra lattice' (Lowe et al., 2015c) whereby new tephrostratigraphical data generated by the project augment previously-established tephra frameworks for the region, and underpin a more evolved tephra 'lattice' that links palaeo-records between Greenland, the European mainland, sub-marine sequences in the Mediterranean, and North Africa. A tephra database has also been constructed (Bronk Ramsey et al., 2015).

The Australasian INTIMATE project, built along similar lines to the very successful INTIMATE project (integration of ice-core, marine and terrestrial records) of the North Atlantic and Greenland (Lowe, J.J. et al., 2008; Davies et al., 2012, 2014; Blockley et al., 2014; Bourne et al., 2015), has developed a climate event stratigraphy for the region for the past 30,000 years (Alloway et al., 2007; Barrell et al., 2013). The role of tephrochronology in linking all of the selected palaeoenvironmental records (apart from those based on speleothems) has been highlighted (Fig. 14; Lowe et al., 2008a, 2013). The advantage provided by key marker tephras in the NZ-INTIMATE project led to the development of new age models based on Bayesian probability methods noted above.

Tephras also provide the means to help quantify the marine reservoir effect for correcting the marine-based radiocarbon time-scale, as shown by studies in the Mediterranean Sea, the Adriatic Sea, the North Atlantic, and the South Pacific Ocean (e.g., Sikes et al., 2000; Lowe, J.J. et al., 2007; Carter et al., 2008; Lowe et al., 2013; Olsen et al., 2014). Further, they enable AMS-based radiocarbon dating of pollen concentrates or biological remains to be evaluated, and for demonstrating and hence correcting for the 'hard water' effect in dating lake sediments (Lowe, 2008a).

Tephrochronology, long used to provide ages on early hominins, is being increasingly applied to archaeology and studies of humans in antiquity (e.g., Tryon et al., 2008, 2009, 2010), including determining the timing and extent of initial human impacts on landscapes and ecosystems such as those of Great Britain, Ireland, Iceland, Scandinavia, and New Zealand (e.g., Dugmore et al., 2000, 2007; Lowe et al., 2000; Hogg et al., 2003; Wastegård et al., 2003; Edwards et al., 2004; Lowe and Newnham, 2004; Lowe, 2008b; Streeter et al., 2012; Riede and Thastrup, 2013). The potential key role of cryptotephrochronology in underpinning the study of the adaptation of humans to climatic change in Europe since about 20,000 years ago was highlighted by Blockley et al. (2006), and most recently further findings from the RESET project were published in a remarkable paper by Lowe et al. (2012). Noteworthy tephrochronological studies with a disease, medical, and forensic focus have also been undertaken recently (e.g., Newnham et al., 2010; D'Costa et al., 2011; Streeter et al., 2012; Lavigne et al., 2013). A new method developed at the universities of Waikato and Adelaide to extract DNA preserved in allophane-rich buried soils (paleosols) on Holocene tephras near Mt Tarawera was published by Huang et al. (2016).
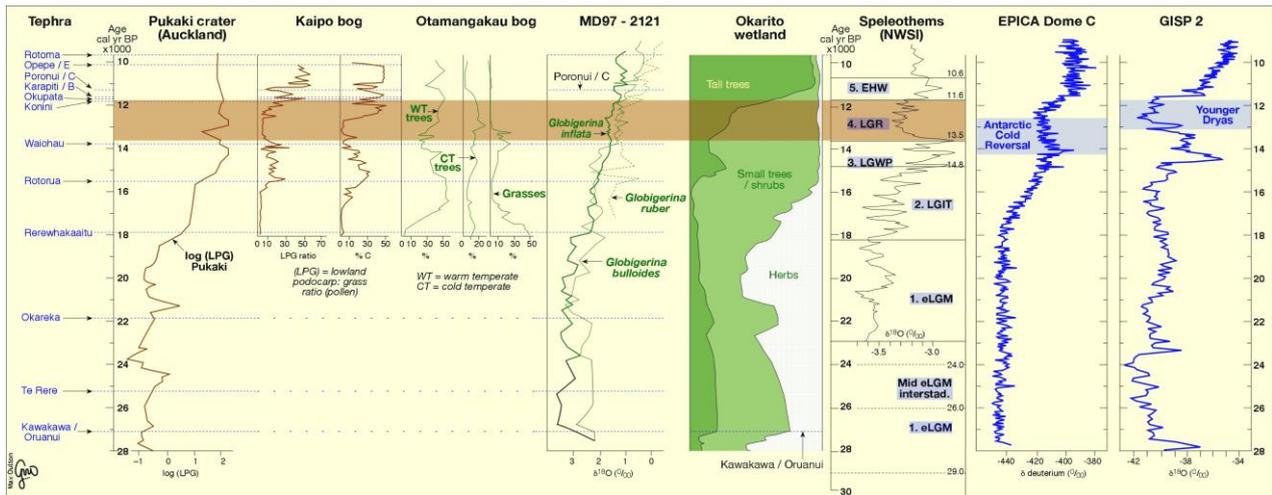
Fig. 14. Compilation of partial high-resolution palaeoenvironmental records spanning the interval c. 28,000 to 9500 cal. yr BP and showing how sites are linked by one or more tephra isochrons (NZ-INTIMATE project). Antarctic (EPICA Dome C) and Greenland (GISP2) records shown for comparison. The climatic events 1–5 are based on the speleothem record obtained from northwest South Island (NWSI) (Williams et al., 2005, 2010). (1) eLGM, 'extended' Last Glacial Maximum (Newnham et al., 2007a); (2) LGIT, last glacial–interglacial transition; (3) LGWP, late-glacial warm period; (4) LGR, late-glacial reversal; (5) EHW, early-Holocene warming. The boundary between events 1 and 2 is marked by Rerewhakaaitu Tephra (Newnham et al., 2003); the boundary between events 3 and 4 is marked approximately by Waiohau Tephra (Newnham and Lowe, 2000); the end of event 4 is marked by the closely spaced couplet of Konini and Okupata tephras, the former tephra essentially marking the start of the Holocene at c. 11,700 cal. yr BP in northern New Zealand (Walker et al., 2009). Evidence for event 4 (late-glacial reversal) (brown shading) is recorded at Kaipo, Otamangakau, MD97-2121 and to a lesser degree at Pukaki crater (see also Putnam et al., 2010, 2013; Newnham et al., 2012; Barrell et al., 2013; Sikes et al., 2013; Williams et al., 2015).

8. Summary and conclusions

Tephrochronology, the characterisation and use of volcanic-ash layers as a unique chronostratigraphic linking, synchronizing, and dating tool, has become a globally-practised discipline of immense practical value in a wide range of subjects including Quaternary stratigraphy, palaeoclimatology, palaeoecology, palaeolimnology, physical geography, geomorphology, volcanology, geochronology, archaeology, human evolution, anthropology, ancient DNA studies, and human disease and medicine. The advent of systematic studies of cryptotephras – the identification, correlation, and dating of sparse, fine-grained glass-shard concentrations 'hidden' within sediments or soils – over the past ~20 years has been revolutionary (Table 6). New cryptotephra techniques developed in northwestern Europe and Scandinavia in particular – and in North America most recently – adapted or improved to help solve problems as they arose, have now been applied to sedimentary sequences (including ice) on all the continents. The result has been the extension of tephra isochrons over wide areas hundreds to several thousands of kilometres from source volcanoes. Taphonomic and other issues, such as quantifying uncertainties in correlation, provide scope for future work (Lowe, 2011; Davies, 2015).

Developments in dating and analytical methods have led to important advances in the application of tephrochronology in recent times. In particular:

(i) the ITPFT (glass fission-track) method has enabled landscapes and sequences to be dated where previously no dates were obtainable or where dating was problematic;

(ii) new EMPA protocols enabling narrow-beam analyses (<5 μm) of glass shards, or small melt inclusions, have been developed, meaning that small (typically distal) glass shards or melt inclusions <~10 μm in diameter can now be analysed more efficaciously than previously (and with reduced risk of accidentally including microlites in the analysis as could occur with wide-beam analyses);

(iii)   U-Th-disequilibrium/U-Pb and (U–Th)/He zircon dating permits dating of tephras as young as 2.5 ka and in the range beyond that for routine ^{14}C dating and below the range for routine Ar/Ar dating (Danisik et al., in press);

(iv) LA-ICPMS method for trace element analysis of individual shards <~10 μm in diameter is generating more detailed 'fingerprints' for enhancing tephra-correlation efficacy (Pearce et al., 2011, 2014; Pearce, 2014; Tomlinson et al., 2015); and

(v) the revolutionary rise of Bayesian probability age modelling has helped to improve age frameworks for tephras of the late-glacial to Holocene period especially.

Developments in the understanding of magmatic heterogeneity at some volcanoes have shown that multiple fingerprints may arise according to tephra-dispersal direction during a 'single' eruption episode, adding complexity and the need for a careful approach in making long-range correlations. New debates on how various statistical methods should be used to aid correlation have emerged recently. The applications of tephrochronology and cryptotephrochronology are now seen as key correlation or 'synchronization' tools in high-resolution palaeoclimatic projects such as INTIMATE (Integration of ice-core, marine and terrestrial records since 30,000 years ago) and in dating, integrating and interpreting human-environmental interactions in antiquity. New INQUA-based projects SHAPE (Southern Hemisphere assessment of palaeoenvironments) and CELL50K (Calibrating environmental leads and lags over the last 50 ka) will utilise tephrochronology and cryptotephrochronology as well as other dating methods to meet their objectives.

INTAV, the leading INQUA-based global group of >120 tephrochronologists (Table 6), remarkably, now contains many geoscientists working in non-volcanic countries. These 'neo-tephrochronologists' have added new enthusiasm and skills to those of the geoscientists working on the typically thick, complex, multi-sourced tephrostratigraphic sequences in 'traditional' volcanic regions – Japan, New Zealand and western USA, for example – in an excellent example of intra-disciplinary mutualism (Froese et al., 2008; Lowe, 2008a; Lowe et al., 2015a).

An INTAV-led project INTREPID (Enhancing tephrochronology as a global research tool through improved fingerprinting and correlation techniques and uncertainty modelling) was initiated in 2009 and will continue from 2013 to 2015 as INTREPID-II. Papers from the INTAV conference "Active Tephra" held in Kirishima, southern Japan, in 2010 were published by *Quaternary International* (Lowe et al., 2011a). An INTREPID-led Bayesian age-modelling course was held in San Miguel de Allende, Mexico, in August 2010. In May, 2011, a workshop on the Eyjafjallajökull eruptions of 2010, and their implications for tephrochronology, volcanology, and Quaternary studies, was held in Edinburgh, U.K., by the 'Tephra in Quaternary Science' (TIQS) group (e.g., see Stevenson et al., 2012). This meeting was also sponsored in part by the INTREPID project. A one-day tephra meeting on marine tephrochronology, held in October, 2011, London, has led to the publication of a volume entitled "Marine tephrochronology" (Austin et al., 2014). In August 2014, a meeting, "Tephra 2014: 'Maximizing the potential of tephra for multidisciplinary science', was held in Portland, Oregon, USA, under the INTAV banner. Two symposia comprising more than 50 papers on tephra/cryptotephra studies and tephrochronological applications in palaeoenvironmental reconstructions, and in archaeology and studies of natural hazards, were held at the full INQUA Congress being in Nagoya, Japan, in late July-early August 2015. A number of the papers are being written up for a special issue of *Quaternary Geochronology* "Advancing tephrochronology as a global dating tool: applications in volcanology, archaeology, palaeoclimate and geohazard research" due out later this year.

In April 2016, a new overarching project, EXTRAS, "EXTending TephRAS as a global geoscientific research tool stratigraphically, spatially, analytical, and temporally within the Quaternary", was initiated by INTAV.

Table 6. Some recent advances in methodology and applications in global tephra studies (after Lowe, 2008a, 2011; see also Davies, 2015; Danisik et al., in press)

Advance/method	Application
1. Cryptotephra studies: identifying, correlating, and dating ash-sized glass-shard and/or crystal concentrations (not visible as layers) 'hidden' within sediments (including ice) or soil	Extending isochrons over wider areas, some >7000 km from volcano source including 'ultra-distal'(hence see 4), and improving records of volcano eruption history and thus developing better models of volcanic hazards and their mitigation
2. (a) Isothermal-plateau fission-track dating of glass (ITPFT) and (b) U-Th-disequilibrium/U-Pb and (U–Th)/He zircon dating	(a) Dating tephras (especially those comprising only glass shards), hence dating landscapes or palaeoenvironmental or geoarchaeological sequences not previously datable at distal locations; (b) permits dating as young as 2.5 ka and in the range beyond ^{14}C and below Ar/Ar
3. Laser-ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) and ion microprobe (SIMS) analysis of single grains	Correlation of tephras using trace elements and REEs of glass shards (especially of tephras with similar major-element compositions as determined by electron microprobe), with enhanced reliability obtained using single-grain analysis that can reveal magma mingling or contamination
4. Connecting and dating palaeoenvironnmental sequences and geoarchaeological deposits with high precision using tephras or cryptotephras as isochrons	Classical tephrochronology applied in high-resolution palaeoclimatic projects such as INTIMATE to test synchronization of various stratigraphic records, correcting for marine reservoir or hard-water effects, and dating, integrating and interpreting human-environmental interactions in antiquity
5. Bayesian probability analysis of age sequences involving tephras	Bayesian methods are providing enhanced and more precise chronologies for tephrostratigraphic sequences via OxCal, BCal, Bpeat, Bacon (etc)
6. Recognition of heterogeneity in the composition of some tephras, especially high *vs* low K_2O contents; mainly by analysis of glass components but also of minerals (e.g., biotite)	Petrological insight into magma processes such as mingling and volcano eruptive histories, including the finding that multiple fingerprints of some tephras differ according to direction of dispersal
7. Improving the reliability of electron microprobe-derived analyses of fine-grained glass and melt inclusions (<5 μm), and of microlite-rich andesitic glass through development of new narrow-beam protocols	New procedures to evaluate and correct for common microlite presence in andesitic glass shards, and the development of protocols for use of narrow beams in microprobe analysis, enable fine glass shards and melt inclusions (<5 μm) to be analysed more efficaciously than before
8. 'Neoformation' of International Focus group on Tephrochronology and Volcanism (INTAV) in 2007 (previously known as SCOTAV and COT: see Lowe et al., 2011b) through to 2019 and beyond	INQUA*-based global group of tephra specialists with interests in developing and improving analytical techniques of known reliability to characterize tephras, to map their distributions and improve volcano eruptive histories, to develop high-precision age models for tephras, and to apply tephrochronology to numerous disciplines as a precise correlation and dating tool

*International Union for Quaternary Research

9. References

Allan, A.S.R., Baker, J.A., Carter, L., Wysoczanks, R.J. 2008: Reconstructing the Quaternary evolution of the world's most active silicic volcanic system: insights from a ~1.65 Ma deep ocean tephra record sourced from the Taupo Volcanic Zone, New Zealand (NZ). *Quaternary Science Reviews* 27, 2341-2360.

Alloway, B., Pillans, B., Carter, L., Naish, T., Westgate, J. 2005: Onshore-offshore correlation of Pleistocene rhyolitic eruptions from New Zealand: Implications for TVZ eruptive history and paleoenvironmental construction. *Quaternary Science Reviews* 24, 1601-1622.

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

Alloway, B.V., Lowe, D.J., Larsen, G., Shane, P.A.R., Westgate, J.A. 2013: Tephrochronology. *In*: Elias, S.A., Mock, C.J. (editors), *Encyclopaedia of Quaternary science,* 2nd edition. Elsevier, Amsterdam, pp. 277-304

Augustinus, P., D'Costa, D., Deng, Y., Hagg, J., Shane, P. 2011: A multi-proxy record of changing environments from ca. 30 000 to 9000 cal. a BP: Onepoto maar palaeolake, Auckland, New Zealand. *Journal of Quaternary Science* 26, 389–401.

Austin, W.E.N., Abbott, P.M., Davies, S.M., Pearce, N.J.G., Wastegård, S. (editors) 2014: "Marine Tephrochronology". *Geological Society, London, Special Publications* 398, 1-213.

Barrell, D.J.A., Almond, P.C., Vandergoes, M.J., Lowe, D.J., Newnham, R.M., NZ-INTIMATE members 2013: A composite pollen-based stratotype for inter-regional evaluation of climatic events in New Zealand over the past 30,000 years (NZ-INTIMATE project). *Quaternary Science Reviews* 74, 4-20.

Bebbington, M.S., Cronin, S.J. 2011: Spatio-temporal hazard estimation in the Auckland Volcanic Field, New Zealand, with a new event-order model. *Bulletin of Volcanology* 73, 55-72.

Benediktsson, I.O., Björnsson, H., Larsen, G., Sigmarsson, O. (editors) 2012. Glaciology and volcanology on the centenary of Sigurdur Thorarinsson's birth: a special issue. *Jökull* 62, 1-184.

Blaauw, M., Christen, J.A. 2005: Radiocarbon peat chronologies and environmental change. *Journal of the Royal Statistical Society Series C (Applied Statistics)* 54, 805-816.

Blaauw, M., Christen, J.A. 2011: Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* 6, 457-474.

Blaauw, M., Bakker, R., Christen, J.A., Hall, V.A., van der Plicht, J. 2007: Bayesian framework for age-modelling of radiocarbon dated peat deposits: case studies from The Netherlands. *Radiocarbon* 49, 357-367.

Blockley, S.P.E., Blockley, S.M., Donahue, R.E., Lane, C.S., Lowe, J.J., Pollard, A.M. 2006: The chronology of abrupt climate change and Late Upper Palaeolithic human adaptation in Europe. *Journal of Quaternary Science* 21, 575-584.

Blockley, S.P.E., Lane, C.S., Lotter, A.F., Pollard, A.M. 2007a: Evidence for the presence of the Vedde Ash in central Europe. *Quaternary Science Reviews* 26, 3030-3036.

Blockley, S.P.E., Blaauw, M., Bronk Ramsey, C., van der Plicht, J. 2007b: Building and testing age models for radiocarbon dates in Lateglacial and Early Holocene sediments. *Quaternary Science Rev.* 26, 1915-1926.

Blockley, S.P.E., Bronk Ramsey, C., Lane, C.S., Lotter, A.F. 2008: Improved age modelling approaches as exemplified by the revised chronology for the central Europeaan varved lake Soppensee. *Quaternary Science Reviews* 27, 61-71.

Blockley, S.P.E., Lane C.., Hardiman M., Rsamussen S.O., Seierstad I.K., Steffensen J.P., and others 2012: Synchronisation of palaeoenvironmental records over the last 60,000 years, and an extended INTIMATE event stratigraphy to 48,000 b2k. *Quaternary Science Reviews* 36, 2-10.

Blockley, S.P.E., Bourne, A.J., Brauer, A., Davies, S.M., Harding, P.R., Lane, C.S., MacLeod, A., Matthews, I.P., Pyne-O-Donnell, S.D.F., Rasmussen, S.O., Wulf, S., Zanchetta, G., 2014: Tephrochronology and the extended intimate (integration of ice-core, marine and terrestrial records) event stratigraphy (8-128 ka b2k). *Quaternary Science Reviews* 106, 88-100.

Blockley, S.P.E., Edwards, K.J., Schofield, J.E., Pyne-O'Donnell, S.D.F., Jensen, B.J.L., Matthews, I.P., Cook, G.T., Wallace, K.L., Froese, D. 2015: First evidence of cryptotephra in palaeoenvironmental records associated with Norse occupation sites in Greenland. *Quaternary Geochronology* 27, 145-157.

Bourne, A.J., Lowe, J.J., Trincardi, F., Asioli, A., Blockley, S.P.E., Wulf, S., and others 2010: Distal tephra record of the last c. 105,000 years from core PRAD 1-2 in the central Adriatic Sea: implications for marine tephrostratigraphy. *Quaternary Science Reviews* 29, 3079-3094.

Bourne, A., Cook, E., Abbott, P., Seierstad, I., Steffensen, J., Svensson, A., Fischer, H., Schüpbach, S., Davies, S. 2015: A tephra lattice for Greenland and a reconstruction of volcanic events spanning 25–45 ka b2k. *Quaternary Science Reviews* 118, 122-141.

Bronk Ramsey, C. 2008: Depositional models for chronological research. *Quaternary Science Rev.* 27, 42-60.

Bronk Ramsey, C. 2009: Bayesian analysis of radiocarbon dates. *Radiocarbon* 51, 337-360.

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

Bronk Ramsey, C., Housley, R.A., Lane, C.S., Smith, V.C., and Pollard, A.M., 2015b: The RESET tephra database and associated analytical tools. *Quaternary Science Reviews* 118, 33-47.

Brown, S.J.A., Fletcher, I.R. 1999: SHRIMP U-Pb dating of the pre-eruption growth history of zircons from the 340 ka Whakamaru Ignimbrite, New Zealand: evidence for >250 k.y. magma residence times. *Geology* 27, 1035-1038.

Buck, C.E., Higham, T.F.G., Lowe, D.J. 2003: Bayesian tools for tephrochronology. *Holocene* 13, 639-647.

Carter, L., Nelson, C.S., Neil, H.L., Froggatt, P.C. 1995: Correlation, dispersal, and preservation of the Kawakawa Tephra and other late Quaternary tephra layers in the southwest Pacific Ocean. *New Zealand Journal of Geology and Geophysics* 38, 29–46

Carter, L., Alloway, B., Shane, P. and Westgate, J. 2004: Deep-ocean record of major late Cenozoic rhyolitic eruptions from New Zealand. *New Zealand Journal of Geology and Geophysics* 47, 481-500.

Carter, L., Manighetti, M., Ganssen, G., Northcote, L. 2008: Southwest Pacific modulation of abrupt climate change during the Antarctic Cold Reversal–Younger Dryas. *Palaeogeography, Palaeoclimatology, Palaeoecology* 260, 284-298.

Cas, R., Porritt, L., Pittari, A., Hayman, P. 2008: A new approach to kimberlite facies terminology using a revised general approach to the nomenclature of all volcanic rocks and deposits: descriptive to genetic. *Journal of Volcanology and Geothermal Research* 174, 226-240.

Chang, Z., Vervoort, J.D., McClelland, W.C., Knaack, C. 2006: U-Pb dating of zircon by LA-ICP-MS. *Geochemistry, Geophysics, Geosystems* 7, Q05009, doi:10.1029/2005GC001100.

Cronin, S.J., Neall, V.E., Stewart, R.B., Palmer, A.S. 1996a: A multiple-parameter approach to andesitic tephra correlation, Ruapehu volcano, NZ. *Journal of Volcanology and Geothermal Research* 72, 199-215.

Cronin, S.J., Wallace, R.C., Neall V.E. 1996b: Sourcing and identifying andesitic tephras using major oxide titanomagnetite and hornblende chemistry, Egmont volcano and Tongariro Volcanic Centre, New Zealand. *Bulletin of Volcanology* 58, 33-40.

Cronin, S.J., Neall, V.E., Palmer, A.S., Stewart, R.B. 1997: Methods of identifying late Quaternary tephras on the ring plains of Ruapehu and Tongariro volcanoes, New Zealand. *New Zealand Journal of Geology and Geophysics* 40, 175-184.

Crowley, J.L., Schoene, B., Bowring, S.A. 2007: U-Pb dating of zircon in the Bishop Tuff at the millennial scale. *Geology* 35, 1123-1126.

Danišík, M., Shane, P.A.R., Schmitt, A.K., Hogg, A.G., Santos, G.M., Storm, S., Evans, N.J., Fifield, L.K., Lindsay, J.M. 2012: Re-anchoring the late Pleistocene tephrochronology of New Zealand based concordant radiocarbon ages and combined $^{238}U/^{230}$Th disequilibrium and (U-Th)/He zircon ages. *Earth and on Planetary Science Letters* 349-350, 240-250.

Danišík, M., Schmitt, A.K., Lovera, O.M., Dunkl, I., Evans, N.J. in press: Application of the combined U-Th-disequilibrium/U-Pb and (U-Th)/He zircon dating to tephrochronology. *Quaternary Geochronology*.

Davies, S.M. 2015: Cryptotephras: the revolution in correlation and precision dating. *Journal of Quaternary Science* 30, 114-130.

Davies, S.M., Wastegård, S., Rasmussen, T.L., Svensson, A., Johnsen, S.J., J. P. Steffensen, J.P., Andersen, K.K. 2008: Identification of the Fugloyarbanki tephra in the NGRIP ice core: a key tie-point for marine and ice-core sequences during the last glacial period. *Journal of Quaternary Science* 23, 409-414.

Davies, S.M., Peter M. Abbott, P.M., Nicholas J.G. Pearce, N.J.G., Stefan Wastegård, S., Simon P.E. Blockley, S.P.E. 2012: Integrating the INTIMATE records using tephrochronology: rising to the challenge. *Quaternary Science Reviews* 36, 11-27.

Davies, S.M., Abbott, P.M., Meara, R.H., Pearce, N., Austin, W., Chapman, M., Svensson, A., Bigler, M., Rasmussen, T., Rasmussen, S., Farmer, E. 2014: A North Atlantic tephrostratigraphical framework for 130–60 ka b2k: new tephra discoveries, marine-based correlations, and future challenges. *Quaternary Science Reviews* 106, 101-121.

D'Costa, V.M., King, C.E., Kalan, L., Morar, M., Sung, W.W.L., Schwarz, C., and others 2011: Antibiotic resistance is ancient. *Nature* 477, 457-461.

Denton, J.S., Pearce, N.J.G. 2008: Comment on "A synchronized dating of three Greenland ice cores through the Holocene" by B.M. Vinther et al.: No Minoan tephra in the 1642 B.C. layer of the GRIP ice core. *Journal of Geophysical Research* 113, D04303, DOI: 10.1029/2007JD008970.

Dickinson, W.R., Stair, K.N., Gehrels, G.E., Peters, L., Kowallis, B.J., Blakey, R.C., Amar, J.R., and -Greenhalgh, B.W. 2010: U-Pb and ^{40}Ar/^{39}Ar ages for a tephra lens in the Mid-Jurassic Page Sandstone: first direct isotopic dating of a Mesozoic eolianite on the Colorado Plateau. *Journal of Geology* 118, 215-221.

Donoghue, S.L., Vallance, J., Smith, I.E.M., Stewart, R.B. 2007: Using geochemistry as a tool for correlating proximal andesitic tephras: case studies from Mt Rainier (USA) and Mt Ruapehu (New Zealand). *Journal of Quaternary Science* 22, 395-410.

Dugmore, A.J., Newton, A.J. 2012: Isochrons and beyond: maximising the use of tephrochronology in geomorphology. *Jökull* 62, 39-52.

Dugmore, A., Newton, A.J., Larsen, G., Cook, G.T. 2000: Tephrochronology, environmental change and the Norse settlement of Iceland. *Environmental Archaeology* 5, 21-34.

Dugmore, A.J., Church, M.J., Mairs, K.-A., McGovern, T.H., Perdikaris, S., Vésteinsson, O. 2007: Abandoned farms, volcanic impacts, and woodland management: revisiting Þjórsárdalur, the "Pompeii of Iceland". *Arctic Anthropology* 44, 1-11.

Edwards, K.J., Dugmore, A.J., Blackford, J.J. 2004: Vegetational response to tephra deposition and land use change in Iceland: a modern analogue and multiple working hypothesis approach to tephropalynology. *Polar Record* 40, 113-120.

Egan, J., Staff, A., Blackford, J., 2015: A revised age estimate of the Holocene Plinian eruption of Mount Mazama, Oregon using Bayesian statistical modelling. *The Holocene*, doi: 10.1177/0959683615576230

Fisher, R.V., Heiken, G., Mazzoni, M. 2006: Where do tuffs fit into the framework of volcanoes? *In*: Heiken, G., editor, "Tuffs – their properties, uses, hydrology, and resources". *Geological Society of America Special Paper* 408, 5-9.

Froese, D.G., Slate, J.L., Lowe, D.J., Knott, J.R. (editors) 2008: 'Global Tephra Studies: John Westgate and Andrei Sarna-Wojcicki Commemorative Volume'. *Quaternary International* 178, 1-320.

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

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

Froggatt, P.C., Gosson, G.J. 1982: Techniques for the preparation of tephra samples for mineral or chemical analysis and radiometric dating. *Geology Dept, Victoria University of Wellington Publication* 23, 1-12.

Froggatt, P.C., Lowe, D.J. 1990: A review of late Quaternary silicic and some other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution, volume, and age. *New Zealand Journal of Geology and Geophysic*s 33, 89-109.

Gehrels, M.J., Lowe, D.J., Hazell, Z.J., Newnham, R.M. 2006: A continuous 5300-year Holocene cryptotephrostratigraphic record from northern New Zealand and implications for tephrochronology and volcanic-hazard assessment. *The Holocene* 16, 173-187.

Gehrels, M.J., Newnham, R.M., Lowe, D.J., Wynne, S., Hazell, Z.J., Caseldine, C. 2008: Towards rapid assay of cryptotephra in peat cores: review and evaluation of various methods. *Quaternary Internatl.* 178, 68-84.

Gehrels, M.J., Lowe, D.J., Newnham, R.M., Hogg, A.G. 2010: Enhanced record of tephra fallout since ~232 AD revealed by cryptotephra studies at Moanatuatua bog near Hamilton: implications for volcanic hazard analysis. *Geosciences Society of New Zealand Miscellaneous Publication* 129A, 103.

Green, R.M., Bebbington, M.S., Cronin, D.J., Jones, G. 2014: Automated statistical matching of multiple tephra records exemplified using five long maar sequences younger than 75 ka, Auckland, New Zealand. *Quaternary Research* 82, 405-419.

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

Hall, M., Hayward, C. 2014: Preparation of micro- and crypto-tephras for quantitative microbeam analysis. *Geological Society, London, Special Publications* 398, 21-28.

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

Hayward, C. 2012: High spatial resolution electron probe microanalysis of tephras and melt inclusions without beam-induced chemical modification. *The Holocene* 22, 119-125.

Hodder, A.P.W., de Lange, P.J., Lowe, D.J. 1991: Dissolution and depletion of ferromagnesian minerals from Holocene tephras in an acid bog, New Zealand, and implications for tephra correlation. *Journal of Quaternary Science* 6, 195-208.

Hogg, A.G., McCraw, J.D. 1983: Late Quaternary tephras of Coromandel Peninsula, North Island, New Zealand: a mixed peralkaline and calkalkaline tephra sequence. *New Zealand Journal of Geology and Geophysics* 26, 163-187.

Hogg, A.G., Higham, T.F.G., Lowe, D.J., Palmer, J., Reimer, P., Newnham, R.M. 2003: A wiggle-match date for Polynesian settlement of New Zealand. *Antiquity* 77, 116-125.

Hogg, A.G., Lowe, D.J., Palmer, J.G., Boswijk, G., Bronk Ramsey, C.J. 2011: Revised calendar date for the Taupo eruption derived by ^{14}C wiggle-matching using a New Zealand kauri ^{14}C calibration data set. *The Holocene* 22, 439-449.

Holt, K., Wallace, R.C., Neall, V.E., Kohn, B.P., Lowe, D.J. 2010: Quaternary tephra marker beds and their potential for palaeoenvironmental reconstruction on Chatham Islands east of New Zealand, southwest Pacific Ocean. *Journal of Quaternary Science* 25, 1169-1178.

Howe, T. M., Lindsay, J.M., SHANE, P., SCHMITT, A.K., STOCKLI, D.F. 2014: Re-evaluation of the Roseau Tuff eruptive sequence and other ignimbrites in Dominica, Lesser Antilles. *Journal of Quaternary Science* 29 531-546.

Howe, T.M., Schmitt, A.K., Lindsay, J.M., Shane, P., Stockli, D.F. 2015: Time scales of intra-oceanic arc magmatism from combined U-Th and (U-Th)/He zircon geochronology of Dominica, Lesser Antilles. *Geochemistry, Geophysics, Geosystems* 16, 347-365.

Huang, Y-T., Lowe, D.J., Zhang, H., Cursons, R., Young, J.M., Churchman, G.J., Schipper, L.A., Rawlence, N.J., Wood, J.R., Cooper, A. 2016: A new method to extract and purify DNA from allophanic soils and paleosols, and potential for paleoenvironmental reconstruction and other applications. *Geoderma* 247, 114-125.

Hughen, K.A., Southon, J., Lehman, S., Bertrand, C., Turnbull, J. 2006: Marine-derived ^{14}C calibration and activity record for the past 50,000 years updated from the Cariaco Basin. *Quaternary Science Reviews* 25, 3216-3227.

Hunt, J.B., Hill, P.G. 1996: An inter-laboratory comparison of the electron probe microanalysis of glass geochemistry. *Quaternary International* 34-36, 229-241.

Hunt, J.B., Hill, P.G. 2001: Tephrological implications of beam size – sample-size effects in electron microprobe analysis of glass shards. *Journal of Quaternary Science* 16, 105-117.

Jensen, B. J. L., Pyne-O'Donnell, S., Plunkett, G., Froese, D. G., Hughes, P. D. M., Sigl, M., McConnell, J. R., Amesbury, M. J., Blackwell, P. G., van den Bogaard, C., Buck, C. E., Charman, D. J., Clague, J. J., Hall, V. A., Koch, J., Mackay, H., Mallon, G., McColl, L., Plicher, J. R. 2014: Transatlantic distribution of the Alaskan White River Ash. *Geology* 42, 875-878.

Jurado-Chichay, Z., Walker, G.P.L. 2000: Stratigraphy and dispersal of the Mangaone Subgroup pyroclastic deposits, Okataina Volcanic Centre, New Zealand. *Journal of Volcanology and Geothermal Research* 104, 319-383.

Kuehn, S.C., Froese, D.G., Carrara, P.E., Foit, F.F., Jr., Pearce, N.J.G., Rotheisler, P. 2009: Major- and trace-element characterisation, expanded distribution, and a new chronology for the latest Pleistocene Glacier Peak tephras in western North America. *Quaternary Research* 71, 201-216.

Kuehn, S.C., Froese, D.G., Shane, P.A.R., INTAV intercomparison participants 2011: The INTAV intercomparison of electron-beam microanalysis of glass by tephrochronology laboratories: results and recommendations. *Quaternary International* 246, 19-47.

Lane, C.S., Andri, M., Victoria L. Cullen, V.L., Blockley, S.P.E. 2011: The occurrence of distal Icelandic and Italian tephra in the Lateglacial of Lake Bled, Slovenia. *Quaternary Science Reviews* 30, 1013-1018.

Lane, C.S., Blockley, S.P.E., Lotter, A.F., Finsinger, W., Filippi, M.L., Matthews, I.P. 2012: A regional tephrostratigraphic framework for central and southern European climate archives during the Last Glacial to Interglacial transition: comparisons north and south of the Alps. *Quaternary Science Reviews* 36, 50-58.

Lane, C.S., Chorn, B.T., Johnson, T.C. 2013: Ash from the Toba supereruption in Lake Malawi shows no volcanic winter in East Africa at 75 ka. *Proceedings of the National Academy of Sciences of the United States of America* 110, 8025-8029.

Lane, C.S., Cullen, V.L., White, D., Bramham-Law, C.W.F., Smith, V.C. 2014: Cryptotephra as a dating and correlation tool in archaeology. *Journal of Archaeological Science* 42, 42-50.

Lane, C.S., Brauer, A., Martín-Puertas, C., Blockely, C.P.E., Smith, V.C., Tomlinson, E.L. 2015: The Late Quaternary tephrostratigraphy of annually laminated sediments from Meerfelder Maar, Germany. *Quaternary Science Reviews* 122, 192-206.

Lavigne, F., Degeai, J.-P., Komorowski, J.-C. and others 2013: Source of the great A.D. 1257 mystery eruption unveiled, Samalas volcano, Rinjani Volcanic Complex, Indonesia. *Proceedings of the National Academy of Sciences of the USA* 110, 16742-16747.

Leonard G.S., Begg J.G., Wilson, C.J.N. 2010: Geology of the Rotorua area: scale 1: 250,000. *Institute of Geological and Nuclear Sciences 1: 250,000 geological map* **5**. Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand.

Lindsay, J.M., Leonard, G.S., Smid, E.R., Hayward, B.W. 2011: Age of the Auckland Volcanic Field: a review of existing data. *New Zealand Journal of Geology and Geophysics* 54, 379-401.

Linnell, T., Shane, P., Smith, I., Augustinus, P., Cronin, S., Lindsay, J., Maas, R. 2016: Long-lived shield volcanism within a monogenetic basaltic field: the conundrum of Rangitoto volcano, New Zealand. *Geological Society of America Bulletin* doi:10.1130/B31392.1

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

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

Lowe, D.J. 2008a: Globalisation of tephrochronology – new views from Australasia. *Progress in Physical Geography* 32, 311-335.

Lowe, D.J. 2008b: Polynesian settlement of New Zealand and the impacts of volcanism on early Maori society: an update. *In*: Lowe, D.J. 2008. Guidebook for Pre-conference North Island Field Trip A1 'Ashes and Issues'. Australian and New Zealand 4th Joint Soils Conference, Massey University, Palmerston North (1-5 Dec.). *New Zealand Society of Soil Science*. Pp.142-147.

Lowe, D.J. 2011: Tephrochronology and its application: a review. *Quaternary Geochronology* 6, 107-153.

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

Lowe, D.J., de Lange, W.P. 2000: Volcano-meteorological tsunamis, the c. AD 200 Taupo eruption (New Zealand) and the possibility of a global tsunami. *The Holocene* 10, 401-407.

Lowe, D.J., Hunt, J.B. 2001: A summary of terminology used in tephra-related studies. *Les Dossiers de l'Archeo-Logis* 1, 17-22.

Lowe, D.J., Newnham, R.M. 2004: Role of tephra in dating Polynesian settlement and impact, New Zealand. *PAGES (Past Global Changes) News* 12 (3), 5-7.

Lowe, D.J., Alloway, B.V. 2015: Tephrochronology. *In*: Rink, W.J., Thompson, J.W. (editors), *Encyclopaedia of Scientific Dating Methods*. Springer, Dordrecht, pp. pp. 783-799.

Lowe, D.J., Newnham, R.M., McFadgen, B.G., Higham, T.F.G. 2000: Tephras and New Zealand archaeology. *Journal of Archaeological Science* 27, 859-870.

Lowe, D.J., Tippett, J.M., Kamp, P.J.J., Liddell, I.J., Briggs, R.M., Horrocks, J.L. 2001: Ages on weathered Plio-Pleistocene tephra sequences, western North Island, NZ. *Les Dossiers de l'Archeo-Logis* 1, 45-60.

Lowe, J.J., Blockley, S., Trincardi, F., Asioli, A., Cattaneo, A., Matthews, I.P., Pollard, M., Wulf, S. 2007: Age modelling of late Quaternary marine sequences in the Adriatic: towards improved precision and accuracy using volcanic event stratigraphy. *Continental Shelf Research* 27, 560-582.

Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J.C., Yu, Z., INTIMATE group 2008: Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. *Quaternary Science Rev.* 27, 6-17.

Lowe, D.J., Shane, P.A.R., Alloway, B.V., Newnham, R.M. 2008a: Fingerprints and age models for widespread New Zealand tephra marker beds erupted since 30,000 years ago: a framework for NZ-INTIMATE. *Quaternary Science Reviews* 27, 95-126.

Lowe, D.J., Tonkin, P.J., Neall, V.E., Palmer, A.S., Alloway, B.V., Froggatt, P.C. 2008b: Colin George Vucetich (1918–2007) – pioneering New Zealand tephrochronologist. *Quaternary International* 178, 11-15.

Lowe, D.J., Wilson, C.J.N., Newnham, R.M., Hogg, A.G. 2010: Dating the Kawakawa/Oruanui eruption: comment on "Optical luminescence dating of a loess section containing a critical tephra marker horizon, SW North Island of New Zealand" by R. Grapes et al. *Quaternary Geochronology* 5, 493-496.

Lowe, D.J., Moriwaki, H., Davies, S.M., Suzuki, T., Pearce, N.J. (editors) 2011a: 'Enhancing tephrochronology and its application (INTREPID project): Hiroshi Machida commemorative volume.' *Quaternary International* 246, 1-396.

Lowe, D.J., Davies, S.M., Moriwaki, H., Pearce, N.J., Suzuki, T. 2011b: (Preface) Enhancing tephrochronology and its application (INTREPID project): Hiroshi Machida commemorative volume. *Quaternary Int* 246, 1-5.

Lowe, J.J. and 41 others 2012: Volcanic ash layers illuminate the resilience of Neanderthals and early modern humans to natural hazards. *Proceedings of the National Academy of Sciences of the United States of America* 109, 13532-13537.

Lowe, D.J., Blaauw, M., Hogg, A.G., Newnham, R.M. 2013: Ages of 24 widespread tephras erupted since 30,000 years ago in New Zealand, with re-evaluation of the timing and palaeoclimatic implications of the late-glacial cool episode recorded at Kaipo bog. *Quaternary Science Reviews* 74, 170-194.

Lowe, D.J., Alloway, B.V., Shane, P.A.R. 2015a: Far-flown markers. *In*: Graham, I.J. (editor) "A Continent on the Move: New Zealand Geoscience Revealed", 2nd edition. *Geoscience Society of New Zealand (Misc Publication 241) with GNS Science, Wellington*, pp. 172-175.

Lowe, D.J., Holt, K.A., Shane, P.A.R., Hogg, A.G., Lorrey, A.M., Vincent, K.A., Esler, W.R., Cronin, S.J., Newnham, R.M. 2015b: Developing a tephrostratigraphic framework for 60 to 30 cal ka for SHAPE in New Zealand. 19th INQUA Congress, Nagoya. Abstract T00616, 1 p.

Lowe, J.J., Bronk Ramsey, C., Housley, R.A., Lane, C.S., Tomlinson, E.L., RESET Team, RESET Associates 2015c: The RESET project: constructing a European tephra lattice for refined synchronisation of environmental and archaeological events during the last c. 100 ka. *Quaternary Science Reviews* 118, 1-17.

Lowe, D.J., Pearce, N.J.G., Jorgensen, M.A., Kuehn, S.C., Tryon, C.A., Hayward, C.L. in revision. Correlating tephras and cryptotephras using glass compositional analyses and statistical methods: a review. *Quaternary Science Reviews*

Matsu'ura, T., Miyagi, I., Furusawa, A. 2011: Late Quaternary cryptotephra detection and correlation in loess in northeastern Japan using cummingtonite geochemistry. *Quaternary Research* 75, 624-635.

Matsu'ura, T., Furusawa, A., Yanagida, M. 2012: Detection and correlation of widespread cryptotephras in middle Pleistocene loess in NE Japan using cummingtonite geochemistry. *Journal of Asian Earth Sciences* 60, 49-67.

Moebis, A., Cronin, S.J., Neall, V.E., Smith, I.E.M. 2011: Unravelling a complex volcanic history from fine-grained, intricate Holocene ash sequences at the Tongariro Volcanic Centre, New Zealand. *Quaternary International* 246, 352-363.

Molloy, C., Shane, P., Augustinus, P.C. 2009: Eruption recurrence rates in a basaltic volcanic field based on tephra layers in maar sediments: implications for hazards in the Auckland volcanic field. *Geological Society of America Bulletin* 121, 1666-1677.

Moriwaki, H., Suzuki, T., Murata, M., Ikehara, M., Machida, H., Oba, T., Lowe, D.J. 2011: Sakurajima-Satsuma (Sz-S) and Noike-Yumugi (N-Ym) tephras: new tephrochronological marker beds for the last deglaciation, southern Kyushu, Japan. *Quaternary International* 246, 203-212.

Needham, A.J., Lindsay, J.M., Smith, I.E.M., Augustinus, P., Shane, P.A. 2011: Sequential eruption of alkaline and sub-alkaline magmas from a small monogenetic volcano in the Auckland Volcanic Field, New Zealand. *Journal of Volcanology and Geothermal Research* 201, 126-142.

Newnham, R.M., Lowe, D.J. 2000: Fine-resolution pollen record of late-glacial climate reversal from New Zealand. *Geology* 28, 759-762.

Newnham, R.M., Eden, D.N., Lowe, D.J., Hendy, C.H. 2003: Rerewhakaaitu Tephra, a land-sea marker for the Last Termination in New Zealand, with implications for global climate change. *Quaternary Science Reviews* 22, 289-308.

Newnham, R.M., Lowe, D.J., Green, J.D., Turner, G.M., Harper, M.A., McGlone, M.S., Stout, S.L., Horie, S., Froggatt, P.C. 2004: A discontinuous ca. 80 ka record of Late Quaternary environmental change from Lake Omapere, Northland, New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology* 207, 165-198.

Newnham, R.M., Lowe, D.J., Giles, T., Alloway, B.V. 2007a: Vegetation and climate of Auckland, NZ, since ca 32 000 cal yr ago: support for an extended LGM. *Journal of Quaternary Science* 22, 517-534.

Newnham, R.M., Vandergoes, M.J., Hendy, C.H., Lowe, D.J., Preusser, F. 2007b: A terrrestrial palynological record for the last two glacial cycles from southwestern NZ. *Quaternary Science Reviews* 26, 517-535.

Newnham, R.M., Dirks, K.N., Samaranayake, D. 2010: An investigation into long-distance health impacts of the 1996 eruption of Mt Ruapehu, New Zealand. *Atmospheric Environment* 44, 1568-1578.

Newnham, R.M., Vandergoes, M., Sikes, E., Carter, L., Wilmshurst, J., Lowe, D.J., McGlone, M.S., Sandiford, A. 2012: Does the bipolar seesaw extend to the terrestrial southern mid-latitudes? *Quaternary Science Reviews* 36, 214-222.

Olsen, J., Rasmussen, T.L., Reimer, P.J. 2014: North Atlantic marine radiocarbon reservoir ages through Heinrich event H4: a new method for marine age model construction *Geological Society, London, Special Publications* 398, 95-112.

Ott, F., Wulf, S., Serb, J., Słowiński, M., Obremska, M., Tjallingii, R., Błaszkiewicz, M., Brauer, A. 2016: Constraining the time span between the Early Holocene Hässeldalen and Askja-S tephras through varve counting in the Lake Czechowskie sediment record, Poland. *Journal of Quaternary Science* DOI: 10.1002/jqs.2844

Pearce, N. J. G., 2014: Towards a protocol for the trace element analysis of glass from rhyolitic shards in tephra deposits by laser ablation ICP-MS. *Journal of Quaternary Science*, 29, 627-640.

Pearce, N.J.G., Westgate, J.A., Perkins, W.T., Eastwood, W.J., Shane, P.A.R. 1999: The application of laser ablation ICP-MS to the analysis of volcanic glass shards from tephra deposits: bulk glass and single shard analysis. *Global and Planetary Change* 21, 151-171.

Pearce, N.J.G., Westgate, J.A., Perkins, W.T., Preece, S.J. 2004: The application of IC-PMS methods to tephrochronological problems. *Applied Geochemistry* 19, 289-322.

Pearce, N.J.G., Denton, J.S., Perkins, W.T., Westgate, J.A., Alloway, B.V. 2007: Correlation and characterisation of individual glass shards from tephra deposits using trace element laser ablation ICP-MS analyses: current status and future potential. *Journal of Quaternary Science* 22, 721-736.

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

Pearce, N.J.G., Bendall, C.A., Westgate, J.A. 2008b: Comment on "Some numerical considerations in the geochemical analysis of distal microtephra" by A.M. Pollard, S.P.E. Blockley and C.S. Lane, Applied Geochemistry, vol. 21, p.1692-1714. *Applied Geochemistry* 23, 1353-1364.

Pearce, N.J., Westgate, J.A., Perkins, W.T., Wade, S.C. 2011: Trace-element microanalysis by LA-ICP-MS: the quest for comprehensive chemical characterisation of single, sub-10-μm volcanic glass shards. *Quaternary International* 246, 57-81.

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

Pillans, B.J., McGlone, M.S., Palmer, A.S., Mildenhall, D.C., Alloway, B.V., Berger, G.W. 1993: The Last Glacial Maximum in central and southern North Island, New Zealand: a paleoenvironmental reconstruction using the Kawakawa Tephra Formation as a chronostratigraphic marker. *Palaeogeography, Palaeoclimatology, Palaeoecology* 101, 283-304.

Pillans, B., Alloway, B.V., Naish, T., Westgate, J.A., Abbot, S., Palmer, A.S. 2005: Silicic tephras in Pleistocene shallow marine sediments of Wanganui Basin, New Zealand. *Journal of the Royal Society of NZ* 35, 43-90.

Platz, T., Cronin, S.J., Smith, I.E.M., Turner, M.B., Stewart, R.B. 2007: Improving the reliability of microprobe-based analyses of andesitic glasses for tephra correlation. *The Holocene* 17, 573-583.

Pollard, A.M., Blockley, S.P.E., Lane, C.S. 2006: Some numerical considerations in the geochemical analysis of distal microtephra. *Applied Geochemistry* 21, 1692-1714.

Ponomareva, V., Portnyagin, M., Siwan Davies, S. 2016: Tephra without borders: far-reaching clues into past explosive eruptions. *Frontiers in Earth Sciences – Volcanology* 3: 83 (31 pp.)

Pouget, S., Bursik, M., Cortés, J. A., Hayward, C. 2014: Use of principal component analysis for identification of Rockland and Trego Hot Springs tephras in the Hat Creek Graben, northeastern California, USA. *Quaternary Research* 81, 125-137.

Preece S.J., Pearce N.J.G., Westgate J.A., Froese D.G., Jensen B.J.L., Perkins W.T. 2011: Old Crow tephra across eastern Beringia: a single cataclysmic eruption at the close of Marine Isotope Stage 6. *Quaternary Science Reviews* 30, 2069-2090.

Putnam, A.E., Denton, G.H., Schaefer, J.M., Barrell, D.J.A., Anderson, B.G., Finkel, R.C., Schwartz, R., Doughty, A.M., Kaplan, M.R., Schlüchter, C. 2010: Glacier retreat in New Zealand during the Younger Dryas stadial. *Nature* 467, 194-160.

Putnam, A.E., Schaefer, J.M., Denton, G.H., Barrell, D.J.A., Anderson, B.G., Koffman, T.N.B., Ro, A.V., Finkel, R.C., Rood, D.H., Schwartz, R., Vandergoes, M.J., Plummer, M.A., Brocklehurst, S.H., Kelley, S.E., Ladig, K.L. 2013: Warming and glacier recession in the Rakaia valley, Southern Alps of NewZealand, during Heinrich Stadial 1. *Earth and Planetary Science Letters* 382, 98-110.

Pyne-O'Donnell, S.D.F., Hughes, P.D.M., Froese, D.G., Jensen, B.J.L., Kuehn, S.C., Mallon, G., Amesbury, M.J., Charman, D.J., Daley, T.J., Loader, N.J., Mauquoy, D., Street-Perrott, F.A., Woodman-Ralph, J. 2012. High-precision ultra-distal Holocene tephrochronology in North America. *Quaternary Science Reviews* 52, 6-11.

Rasmussen, S.O., Seierstad, I.K., Anderson, K.K., Bigler, M., Dahl-Jensen, D., Johnsen, S.J. 2008: Synchronization of the NGRIP, GRIP, and GISP2 ice cores across MIS 2 and palaeoclimatic implications. *Quaternary Science Reviews* 27, 18-28.

Riede, F., Thastrup, M.D. 2013: Tephra, tephrochronology and archaeology – a (re-)view from northern Europe. *Heritage Science* 1 (15), 1-17.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S.,Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E. 2009: IntCal09 and Marine09 radiocarbon age calibration curves, 0-50,000 years cal BP. *Radiocarbon* 51, 1111-1150.

Reimer, P.J. and others 2013: IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55, 1869-1887.

Saito, Y., Okumura, K., Suzuki, T., Yokoyama, Y., Izuho, M. (eds) 2016: Japanese Quaternary studies. *Quaternary International* 397, 1-588.

Schmitt, A.K., Stockli, D.F., Niedermann, S., Lovera, O.M., Hausback, B.P. 2010: Eruption ages of Las Tres Vírgenes volcano (Baja California): a tale of two helium isotopes. *Quaternary Geochronology* 5, 503-111.

Shane, P.A.R. 2000: Tephrochronology: a New Zealand case study. *Earth-Science Reviews* 49, 223-259.

Shane, P.A.R. 2005: Towards a comprehensive distal andesitic tephrostratigraphic framework for New Zealand based on eruptions from Egmont volcano. *Journal of Quaternary Science* 20, 45-57.

Shane, P., Smith, I. 2000: Geochemical characterisation of basaltic tephra deposits in the Auckland Volcanic Field. *New Zealand Journal of Geology and Geophysics* 43, 569-577.

Shane, P., Zawalna-Geer, A. 2011: Correlation of basaltic tephra from Mt Wellington volcano: implications for the penultimate eruption from the Auckland Volcanic Field. *Quaternary International* 246, 374-381.

Shane, P.A.R., Sikes, E.L., Guilderson, T.P. 2006: Tephra beds in deep-sea cores off northern New Zealand: implications for the history of Taupo Volcanic Zone, Mayor Island and White Island volcanoes. *Journal of Volcanology and Geothermal Research* 154, 276-290.

Shane, P.A.R., Nairn, I.A., Martin, S.B., Smith, V.C. 2008a: Compositional heterogeneity in tephra deposits resulting from the eruption of multiple magma bodies: implications for tephrochronology. *Quaternary International* 178, 44-53.

Shane, P., Doyle, L.R., Nairn, I.A. 2008b: Heterogeneous andesite-dacite ejecta in 26-16.6 ka pyroclastic deposits of Tongariro volcano, New Zealand: the product of multiple magma-mixing events. *Bulletin of Volcanology* 70, 517-536.

Shane, P., Gehrels, M., Zawalna-Geer, A., Augustinus, P., Lindsay, J., Chaillou, I. 2013: Longevity of a small shield volcano revealed by crypto-tephra studies (Rangitoto volcano, New Zealand): change in eruptive behavior of a basaltic field. *Journal of Volcanology and Geothermal Research* 257, 174-183.

Sigurdsson, H. (ed-in-chief) 2015: *The Encyclopaedia of Volcanoes, 2nd ed*. Academic Press, San Diego, 1-1456.

Sikes, E.L., Samson, C.R., Guilderson, T.P., Howard, W.R. 2000: Old radiocarbon ages in the southwest Pacific Ocean during the last glacial period and deglaciation. *Nature* 405, 555-559.

Sikes, E.L., Medeiros, P.M., Augustinus, P., Wilmshurst, J.M., Freeman, K.R. 2013: Seasonal variations in aridity and temperature characterize changing climate during the last deglaciation in New Zealand. *Quaternary Science Reviews* 74, 245-256.

Smith, V.C., Shane, P., Nairn, I.A. 2005: Trends in rhyolite geochemistry, mineralogy, and magma storage during the last 50 kyr at Okataina and Taupo volcanic centres, Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research* 148, 372-406.

Smith, R.T., Lowe, D.J., Wright, I.C. 2006: Volcanoes. *Te Ara – The Encyclopedia of New Zealand*. NZ Ministry for Culture and Heritage, Wellington.
    URL: http://www.TeAra.govt.nz/EarthSeaAndSky/NaturalHazardsAndDisasters/Volcanoes/en

Steinthorsson, S. 2012: Sigurdur Thorarinsson (1912-1983). *Jökull* 62, 3-20.

Stevenson, J.A., Loughlin, S., Rae, C., Thordarson, T., Milodowski, A. E., Gilbert, J.S., Harangi, S., Lukács, R., Højgaard, B., Árting, U., Pyne-O'Donnell, S., MacLeod, A., Whitney, B., Cassidy, M., 2012: Distal deposition of tephra from the Eyjafjallajökull 2010 summit eruption. *Journal of Geophysical Research* 117, B00C10, doi: 10.1029/2011JB008904 (pp.1-10).

Stokes, S., Lowe, D.J., Froggatt, P.C. 1992: Discriminant function analysis and correlation of late Quaternary rhyolitic tephra deposits from Taupo and Okataina volcanoes, New Zealand, using glass shard major element composition. *Quaternary International* 13-14, 103-117.

Streeter, R., Dugmore, A.J., Vésteinsson, O. 2012: Plague and landscape resilience in premodern Iceland. *Proceedings of the National Academy of Sciences of the United States of America* 109, 3664-3669.

Streeter, R.T., Dugmore, A.J. 2013. Reconstructing late-Holocene environmental change in Iceland using high-resolution tephrochronology. *The Holocene* 23, 197-207.

Thorarinsson, S. 1974: The terms *tephra* and *tephrochronology. In*: Westgate, J. A., Gold, C. M. (editors) *World Bibliography and Index of Quaternary Tephrochronology*. University of Alberta, Edmonton, pp. xvii-xviii.

Thorarinsson, S. 1981: Tephra studies and tephrochronology: a historical review with special reference to Iceland. *In*: Self, S., Sparks, R. S. J. (editors), *Tephra Studies*. D. Reidel, Dordrecht, pp. 1-12.

Tomlinson, E.L., Smith, V.C., Albert, P.G., Aydar, E., Civetta, L., Cioni, R., Çubukçu, E., Gertisser, R., Isaia, R., Menzies, M.A., Orsi, G., Rosi, M., Zanchetta, G., 2015: The major and trace element glass compositions of the productive Mediterranean volcanic sources: tools for correlating distal tephra layers in and around Europe. *Quaternary Science Reviews* 118, 48-66.

Turner, M.B., Cronin, S.J., Smith, I.E., Stewart, R.B., Neall, V.E. 2008: Eruption episodes and magma recharge events in andesitic systems: Mt Taranaki, New Zealand. *Journal of Volcanology and Geothermal Research* 177, 1063-1076.

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

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

Tryon, C.A., Roach, N.T., Logan, M.A.V. 2008: The Middle Stone Age of the northern Kenya Rift: age and context of new archaeological sites from the Kepedo Tuffs. *Journal of Human Evolution* 55, 652-664.

Tryon, C.A., Logan, M.A.V., Mouralis, D., Kuehn, S., Slimak, L., Balkan-Atl1, N. 2009: Building a tephrostratigraphic framework for the Paleolithic of central Anatolia, Turkey. *Journal of Archaeological Science* 36, 637–652.

Tryon, C.A., Faith, J.T., Peppe, D.J., Fox, D.L., Jenkins, K., Dunsworth, H., Harcourt-Smith, W. 2010: The Pleistocene archaeology and environments of the Wasiriya Beds, Rusinga Island, Kenya. *Journal of Human Evolution* 59, 657-671.

Vandergoes, M.J., Hogg, A.G., Lowe, D.J., Newnham, R.M., Denton, G.H., Southon, J., Barrell, D.J.A., Wilson, C.J.N., McGlone, M.S., Allan, A.S.R., Almond, P.C., Petchey, F., Dalbell, K., Dieffenbacher-Krall, A.C., Blaauw, M. 2013: A

revised age for the Kawakawa/Oruanui tephra, a key marker for the Last Glacial Maximum in New Zealand. *Quaternary Science Reviews* 74, 195-201.

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

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

Walker, M., Johnsen, S., Rasmussen, S.O., Popp, T., Steffensen, J.-P., Gibbard, P., Hoek, W., Lowe, J.J., Andrews, J., Björck, S.; Cwynar, L., Hughen, K., Kershaw, P., Kromer, B., Litt, T., Lowe, D.J., Nakagawa, T., Newnham, R.M., Schwander, J. 2009: Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenand NGRIP ice core, and selected auxiliary records. *Journal of Quaternary Science* 24, 3-17.

Wastegård, S., Hall, V.A., Hannon, G.E., van den Bogaard, C., Pilcher, J.R., Sigurgeirsson, M.A., Hermanns-Auoardóttir, M. 2003: Rhyolitic tephra horizons in northwestern Europe and Iceland from the AD 700s–800s: a potential alternative for dating first human impact. *The Holocene* 13, 277-283.

Wastegård, S., Boygle, J. 2012: Distal tephrochronology of NW Europe: the view from Sweden. *Jökull* 62, 73-80.

Westgate, J.A., Stemper, B.A., Péwé, T.L. 1990: A 3 m.y. record of Pliocene–Pleistocene loess in interior Alaska. *Geology* 18, 858–861.

Westgate, J.A., Naeser, N.D., Alloway, B.V. 2013: Fission-track dating. *In*: Elias, S.A., Mock, C.J. (editors), *The Encyclopaedia of Quaternary Science*, 2nd edition. Elsevier, Amsterdam, pp. 643-662.

Westgate, J.A., Preece, S.J., Froese, D.G., Pearce, N.J.G., Roberts, R.G., Demuro, M., Hart W.K., Perkins, W. 2008: Changing ideas on the identity and stratigraphic significance of the Sheep Creek tephra beds in Alaska and the Yukon Territory, northwestern North America. *Quaternary International* 178, 183-209.

White, J.D.L., Houghton, B.F. 2006: Primary volcaniclastic rocks. *Geology* 34, 677-680.

Williams, P.W., King, D.N.T., Zhao, J.-X., Collerson, K.D. 2005: Late Pleistocene to Holocene composite speleothem ^{18}O and ^{13}C chronologies from South Island, New Zealand – did a global Younger Dryas really exist? *Earth and Planetary Science Letters* 230, 301-317.

Williams, P.W., Neil, H.L., Zhao, J.-X. 2010: Age frequency distribution and revised stable isotope curves for New Zealand speleothems: palaeoclimatic implications. *International Journal of Speleology* 39, 99-112.

Williams, P.W., McGlone, M.S., Neil, H.L., Zhao, J.-X. 2015: A review of New Zealand palaeoclimate from the Last Interglacial to the global Last Glacial Maximum. *Quaternary Science Reviews* 110, 92-106.

Wilson, C.J.N. 2001: The 26.5 ka Oruanui eruption, New Zealand: an introduction and overview. *Journal of Volcanology and Geothermal Research* 112, 133-174.

Wilson, C.J.N., Leonard, G. 2015: Slumbering giants. *In*: Graham, I. (editor), "A Continent on the Move: New Zealand Geoscience in the 21st Century", 2nd edition. *Geoscience Society of New Zealand (Misc Publication 241) with GNS Science, Wellington*, pp. 168-171.

Wilson, C.J.N., Switsur, R.V., Ward, A.P. 1988: A new ^{14}C age for the Oruanui (Wairakei) eruption, New Zealand. *Geological Magazine* 125, 297-300.

Wilson, C.J.N., Houghton, B.F., Kamp, P.J.J., McWilliams, M.O. 1995: An exceptionally widespread ignimbrite with implications for pyroclastic flow emplacement. *Nature* 378, 605-607.

Wilson, C.J.N., Rhoades, D.A., Lanphere, M.A., Calvert, A.T., Houghton, B.F., Weaver, S.D., Cole, J.W. 2007: A multiple-approach radiometric age estimate for the Rotoiti and Earthquake Flat eruptions, New Zealand, with implications for the MIS 4/3 boundary. *Quaternary Science Reviews* 26, 1861-1870.

Wilson, C.J.N., Charlier, B.L.A., Fagan, C.J., Spinks, K.D., Gravley, D.M., Simmons, S.F., Browne, P.R.L. 2008: U–Pb dating of zircon in hydrothermally altered rocks as a correlation tool: Application to the Mangakino geothermal field, NZ. *Journal of Volcanology and Geothermal Research* 176, 191-198.

Wilson, C.J.N., Gravley, D.M., Leonard, G.S., Rowland, J.V. 2009: Volcanism in the central Taupo Volcanic Zone, New Zealand: tempo, styles and controls. *In*: Thordarson, T., Self, S., Larsen, G., Rowland, S.K., Hoskuldsson, A. (eds), Studies in Volcanology: the Legacy of George Walker. *Special Publications of IAVCEI (Geological Society, London)* 2, 225-247.

Wohlfarth, B., Blaauw, M., Davies, S.M., Andersson, M., Wastegård, S., Hormes, A., Posnert, G. 2006: Constraining the age of Lateglacial and early Holocene pollen zones and tephra horizons in southern Sweden with Bayesian probability methods. *Journal of Quaternary Science* 21, 321-334.

Zillén, L.M., Wastegård, S., Snowball, I.F. 2002: Calendar year ages of three mid- Holocene tephra layers identified in varved lake sediments in west central Sweden. *Quaternary Science Reviews* 21, 1583-1591.