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Tools and techniques for developing tephra stratigraphies in lake cores: A case study from the basaltic Auckland Volcanic Field, New Zealand

Jenni L. Hopkins [a, *], Marc-Alban Millet [b], Christian Timm [c], Colin J.N. Wilson [a], Graham S. Leonard [c], J. Michael Palin [d], Helen Neil [e]

[a] School of Geography, Environment and Earth Sciences, Victoria University, PO Box 600, Wellington 6140, New Zealand
[b] Department of Earth Sciences, Durham University, Durham DH1 3LE, England, UK
[c] GNS Science, PO Box 30368, Lower Hutt 5035, New Zealand
[d] Department of Geology, University of Otago, PO Box 56, Dunedin 9054, New Zealand
[e] National Institute of Water and Atmospheric Research, PO Box 14-911, Wellington 6021, New Zealand

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ABSTRACT

Probabilistic hazard forecasting for a volcanic region relies on understanding and reconstructing the eruptive record (derived potentially from proximal as well as distal volcanoes). Tephrostratigraphy is commonly used as a reconstructive tool by cross-correlating tephra deposits to create a stratigraphic framework that can be used to assess magnitude–frequency relationships for eruptive histories. When applied to widespread rhyolitic deposits, tephra identifications and correlations have been successful; however, the identification and correlation of basaltic tephras are more problematic. Here, using tephras in drill cores from six maars in the Auckland Volcanic Field (AVF), New Zealand, we show how X-ray density scanning coupled with magnetic susceptibility analysis can be used to accurately and reliably identify basaltic glass shard-bearing horizons in lacustrine sediments and which, when combined with the major and trace element signatures of the tephras, can be used to distinguish primary from reworked layers. After reliably identifying primary vs. reworked basaltic horizons within the cores, we detail an improved method for cross-core correlation based on stratigraphy and geochemical fingerprinting. We present major and trace element data for individual glass shards from 57 separate basaltic horizons identified within the cores. Our results suggest that in cases where major element compositions (SiO_2, CaO, Al_2O_3, FeO, MgO) do not provide unambiguous correlations, trace elements (e.g. La, Gd, Yb, Zr, Nb, Nd) and trace element ratios (e.g. $[La/Yb]_N$, $[Gd/Yb]_N$, $[Zr/Yb]_N$) are successful in improving the compositional distinction between the AVF basaltic tephra horizons, thereby allowing an improved eruptive history of the AVF to be reconstructed.

1. Introduction

Tephrostratigraphy is an important tool in many research disciplines because it has the ability to create chronostratigraphic horizons, by which other geological, palaeoenvironmental or archaeological events can be constrained (Lowe, 2011). When such chronostratigraphies are coupled with geochemical analysis of the tephra horizons, a detailed record of the evolution of a volcanic region can be established (e.g. Shane, 2005; Óladóttir et al., 2012; Kraus et al., 2013). A key aspect of tephrostratigraphy is the correlation of tephra deposits across localities (e.g. Shane, 2000; Alloway et al., 2004; Lowe et al., 2008; Lowe, 2011). Multiple problems can arise in cross correlation of tephra, most commonly where deposits are one or more of: (1) sparse or poorly preserved -for example where subsequent eruptions or urbanisation have occurred (e.g. Alloway et al., 1994; Dirksen et al., 2011; Engwell et al., 2014); (2) reworked (e.g. Payne and Gehrels, 2010; Bertrand et al., 2014; Sorrentino et al., 2014); or (3) where geochemical signatures are ambiguous, preventing unique characterisation of a deposit (e.g. Pearce et al., 2004; Brendryen et al., 2010; Bourne et al., 2013; Davies et al., 2014).

* Corresponding author.
E-mail address: jenni.hopkins@vuw.ac.nz (J.L. Hopkins).

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Preservation issues are often resolved by collecting samples in medial to distal environments rather than proximal locations (Lowe, 2011). Tephra deposits in sediment cores are preferable, for example from lacustrine (e.g. Shane and Hoverd, 2002), peat lands (Payne and Gehrels, 2010) or marine environments (e.g. Allan et al., 2008), because they represent stratigraphically constrained deposits (Lowe et al., 2008; Lowe, 2011). However, post-depositional reworking is sometimes observed in these environments (e.g. Payne and Gehrels, 2010), but a number of indicators can help identify areas where reworking has occurred. These include the geochemical signature of the shards (e.g. Allan et al., 2008), mineral assemblages within the deposits (e.g. de Klerk et al., 2008), palynostratigraphy (e.g. Newnham and Lowe, 1999), or the collection of multiple cores from a single area (e.g. Green and Lowe, 1985; Lowe, 1988a; Boygle, 1999). Where overlapping major element compositions preclude distinguishing between different eruptions (e.g. Icelandic tephra; Brendryen et al., 2010), trace element concentrations can be used to provide further fingerprinting because of their increased sensitivity to fractionation processes and mantle source heterogeneity (e.g. Westgate et al., 1994; Shane et al., 1998; Pearce et al., 2004; Alloway et al., 2004; Allan et al., 2008). Such techniques have permitted the distinction between tephra horizons that may otherwise be interpreted to be the same (e.g. Allan et al., 2008; Óladóttir et al., 2011).

In this study we introduce a protocol to identify more accurately, and effectively correlate the basaltic tephra record in cores extracted from maar crater lakes in the Auckland Volcanic Field (AVF), New Zealand. We first use a combination of X-ray density and magnetic susceptibility scanning to reveal the detailed structure of tephra deposits and host sediments in order to provide new insights about reworking within the sediment cores. We then couple these results with in-situ major and trace element analysis of glass shards handpicked from tephra horizons, to test the ability of major and trace elements as well as trace element ratios to distinguish and fingerprint horizons, and thus aid cross-core correlations. Based on these correlations, the dispersal and frequency of the AVF eruptions can be developed to enable a more robust reconstruction of the eruptive history of the field.

2. The Auckland Volcanic Field

2.1. Geological setting

New Zealand's largest city, Auckland, has a population of ca. 1.4 million and is superimposed on a collection of 53 Quaternary monogenetic basaltic centres, the Auckland Volcanic Field (AVF; Fig. 1A). Individual centres typically show a range of eruption styles from explosive phreatomagmatic activity, caused by contact between upwelling magma and ground water, to magmatic activity, coupled with synchronous or subsequent effusive activity after exhaustion or disconnection from local water sources (Allen and Smith, 1994; Németh et al., 2012). The initial phreatomagmatic activity results in the formation of maars and associated tuff rings, whereas the magmatic stages build scoria cones. Pyroclastic material (tephra) is associated with all eruption styles but is more important in terms of its dispersal in the initial phreatomagmatic phases that produce both tephra fall and surge deposits (Agustin-Flores et al., 2014). The close proximity of the maar craters to other eruptive centres (e.g. Lake Pukaki and Orakei Basin; Fig. 1A) creates an environment that is favourable to preserve pyroclastic deposits from the other AVF eruptions.

Recent investigations of lacustrine tephra preservation elsewhere have discussed depositional complexities where deposits are affected by fluvial input from streams, run off, or lake currents, which lead to ambiguities in primary horizon identification (e.g. Bertrand et al., 2014; Shapley and Finney, 2015). The AVF maar craters are mostly closed systems; the surrounding tuff rings are outward dipping and composed of indurated, poorly sorted tuff, the surrounding topographic relief is very low, and the stream catchments that they intersect tend to be very small, resulting in minimal currents within the lakes (Striewski et al., 2013). During the Holocene sea-level maximum some of the maar craters were breached, but currently only Orakei Basin remains open to the marine environment. As a result the top ca. 25 m of the Orakei Basin core records marine muds rather than lacustrine sediments. The apparent pre-breach quiescence and consistency of the deposition in the maars is reflected in the finely laminated lacustrine sediments within core sequences (Hayward et al., 2008; Striewski et al., 2013). The maar lakes are therefore considered to provide a more accurate and complete tephra deposition history in comparison to open lacustrine systems, because they do not produce as many reworked or over-thickened deposits (Molloy et al., 2009).

The superimposition of Auckland city, with its large population and complex infrastructure, over the area of the AVF, with the likelihood of future eruptive activity poses a significant volcanic hazard. Tephrochronology facilitates the reconstruction of the eruptive history of the area, in order to aid accurate hazard and risk forecasting (e.g. Shane and Zawalna-Geer, 2011).

2.2. Previous tephrostratigraphic studies

To date, the highest resolution tephrostratigraphic study of the AVF maar lake cores have analysed shards from andesitic, rhyolitic (from distant sources) and basaltic (from the AVF) tephra horizons within multiple cores (Newnham et al., 1999; Molloy et al., 2009). The horizons were visually identified, which, although adequate for fine-grained, light-coloured silicic deposits, proved difficult for dark-coloured basaltic tephra deposits. This raises the possibility of errors in the identification of thin, very fine-grained basaltic tephra horizons or layers of a similar colour to the host lacustrine sediments. All glass shards in Molloy et al. (2009) were analysed for major element concentrations by electron microprobe analysis (EMPA), using energy dispersive X-ray spectroscopy (EDS) techniques, and sedimentation rates were estimated for each core based on reported ages of the rhyolitic tephras. These sedimentation rates were then used to estimate the age of the basaltic deposits, and thus constrain cross-core correlations.

In many cases where basaltic tephras were sparse and stratigraphically well constrained (by rhyolitic or andesitic marker horizons, and sedimentation rates), major element chemistries could uniquely fingerprint individual tephra horizons to allow correlations between cores (Molloy et al., 2009). However, when horizons were poorly constrained by stratigraphy, major element compositions for the basaltic tephras were not distinctive enough to distinguish and fingerprint individual horizons and cross-core correlations were ambiguous and unreliable. Some studies have identified the use of trace elements as a way to more uniquely fingerprint tephra horizons. For example, Alloway et al. (2004) measured Th, Nd and Y to distinguish tephras deposited in the Auckland region from rhyolitic and andesitic centres in the North Island, but these techniques have only been applied to local AVF basaltic tephras for Rangitoto by Needham et al. (2011). In addition, trace element ratios have the ability to outline smaller geochemical heterogeneities that provide additional fingerprinting criteria in correlations, however few studies have investigated the full use of these as a tool for correlation (Allan et al., 2008). Trace element ratios have the added advantage of being independent of the actual elemental concentrations and thus are also less affected by analytical issues (Pearce et al., 2007; Allan et al., 2008). They are