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A mid to late Holocene cryptotephra framework from eastern North America

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ABSTRACT

Holocene cryptotephras of Alaskan and Pacific Northwestern origin have recently been detected *ca.* 7000 km away on the east coast of North America. This study extends the emerging North American tephrochronological framework by geochemically characterising seventeen cryptotephra layers from four newly explored peatlands. All detected tephras were deposited during the late Holocene, with no horizons present in the peat between *ca.* 3000–5000 years ago. The prevalence of the Alaskan White River Ash eastern lobe (AD 847 ± 1) is confirmed across the eastern seaboard from Newfoundland to Maine and a regional depositional pattern from Mount St Helens Set W (AD 1479–1482) is presented. The first occurrences of four additional cryptotephras in eastern North America are described, three of which may originate from source regions in Mexico, Kamchatka (Russia) and Hokkaido (Japan). The possibility of such tephras reaching eastern North America presents the opportunity to link palaeo-archives from the tropics and eastern Asia with those from the western Atlantic seaboard, aiding inter-regional comparisons of proxy-climatic records.

1. Introduction

Precise palaeoclimatic comparisons between sites and regions are essential for understanding past climate dynamics. However, inter-site correlation is often limited by poor chronological control. Tephrochronology provides an age-equivalent dating method by using volcanic ash layers with unique geochemical signatures as time-specific marker horizons (isochrons) to connect and synchronise archives (e.g. Alloway et al., 2013; Lowe, 2011). These isochrons are used to create high-resolution records of palaeoenvironmental or archaeological events, the relative timing of which can be compared across sites and regions (e.g. Hall et al., 1993; Lane et al., 2013a, b; Lowe et al., 2012; Plunkett and Swindles, 2008). An air-fall ash layer from a volcanic eruption can be regarded as having been deposited instantaneously in geological time and can thus adopt the eruption's age wherever it is found as a well-defined primary horizon. If the eruption history is unknown or poorly constrained then archives can still be correlated if the same tephra horizons are present and these fixed tie-points can be used to create a common timescale (Lowe, 2011).

Investigations of far-travelled microscopic volcanic glass shards (cryptotephra – with dimensions typically <~125 μm; *sensu* Lowe and Hunt, 2001) in sediments allow for the detection of previously unrecognised ash horizons and sometimes unknown eruptions. These cryptotephras provide the opportunity to obtain precise chronologies in areas that were thought to be outside the range of tephrochronology, thus greatly expanding the dating framework and increasing the number of regions that can be linked together. Cryptotephra studies originally focused on Icelandic tephras in Western Europe, but the potential for North American cryptotephra studies is rapidly emerging (Payne et al., 2008; Pyne-

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O'Donnell et al., 2012).

The first crypto-tephrostratigraphy for the eastern seaboard of North America in Newfoundland was recently developed from one peatland, Nordan's Pond Bog (Pyne-O'Donnell et al., 2012). Seven tephras in this *ca.* 9000-yr-long sequence were correlated to sources in Alaska and the Cascade Range, four of which occurred during the late Holocene: tephra from Mount St Helens (MSH) set W, AD 1479–1482 (Fiacco et al., 1993; Yamaguchi, 1985; Yamaguchi and Hoblitt, 1995); White River Ash, eastern lobe (WRAe), ~AD 847 ± 1 (Jensen et al., 2014a); Newberry Pumice *ca.* 1460 cal yr BP (Kuehn and Foit, 2006); and Aniakchak, Greenland Ice Core Chronology (GICC05) age 3590 ± 1 BP (Coulter et al., 2012). A fifth late Holocene tephra was tentatively correlated with Mount Augustine G, *ca.* 2100 cal yr BP (Tappen et al., 2009). However, subsequent geochemical comparisons with reference materials suggest that although this tephra shares characteristics with material sourced from Augustine, it is unlikely to be Augustine G (Kristi Wallace, pers. comm.). All correlated tephras in Nordan's Pond Bog were of North American origin but the detection of horizons from other source regions cannot be precluded. Ash from the 2010 eruption of Eyjafjallajökull, Iceland, approached Newfoundland (Davies et al., 2010) and tephra from Changbaishan, China, has been identified in Greenland ice cores (Sun et al., 2013); therefore, sources even further afield cannot be discounted.

This study builds on the existing eastern seaboard record by contributing four newly developed peatland tephrostratigraphies from the region. Undisturbed peatlands are excellent archives for preserving tephrostratigraphies since cryptotephra horizons are often present in discrete layers that have been subjected to minimal post-depositional movement (Dugmore and Newton, 1992; Dugmore et al., 1996; Payne et al., 2005). The primary air-fall tephra deposit may be reworked in some peatlands, particularly if the site has been disturbed (e.g. Swindles et al., 2013). However, the majority of deposited shards are usually confined within a narrow stratigraphic layer of no more than a few centimetres depth (Swindles and Plunkett, 2011). The findings from this study extend the known regional spatial distribution of previously identified tephras, add several newly characterised tephras, and demonstrate the increased potential of this technique in obtaining late Holocene high-precision chronologies. The major and minor element chemistry of several newly characterised tephras in this study suggests that there is potential for delivery of tephra from more distal, and previously unconsidered source regions, to eastern North America.

2. Methods

The study sites, Saco Heath (SCH10: 43°33′05″ N; 70°2′03″ W), Villagedale Bog (VDB12: 43°31′09″ N; 65°31′54″ W), Framboise Bog (FBB12: 45°43′14: N; 60°33′09″ W) and Jeffrey's Bog (JRB12: 48°12′46″ N; 58°49′06″ W) are ombrotrophic plateau bogs located along a south-west to north-east transect across Maine, Nova Scotia, and Newfoundland (Fig. 1). The cores were sampled from the centre of each bog using an 11-cm-diameter Russian pattern corer, following a full stratigraphic investigation based on the Troels-Smith (1955) system.

The stratigraphic position and shard concentration of the cryptotephra layers were established by the standard method of ashing the peat at 5 cm contiguous intervals (Pilcher and Hall, 1992). The ashed residues were mounted in glycerol and counted under a high power microscope. Guided by these counts, the stratigraphic depth of cryptotephra layers were refined to 1 cm resolution. Samples containing less than fifteen shards in the 5 cm resolution counts were not investigated further since they were unlikely to yield sufficient shard concentrations to be comprehensively geochemically characterised. If two consecutive samples contained similar elevated concentrations of cryptotephra shards then both were investigated at 1 cm resolution. Depths containing a further local rise in shard concentration within sections of successive elevated cryptotephra concentrations were also analysed at 1 cm resolution. Samples containing peak tephra concentrations were selected for geochemical analysis (Fig. 2; Appendix A, Supplementary Information), based on the assumption that they are representative of the primary air-fall deposition (cf. Payne and Gehrels, 2010).

Glass shards for electron probe microanalyses were extracted from the peat matrix using the heavy liquid flotation method (Blockley et al., 2005), modified with additional cleaning floats and gentle stirring to improve shard extraction yields. The flotation method was chosen to avoid any possible chemical alteration that may arise from the alternative acid digestion technique (Blockley et al., 2005). Whilst other peat studies have obtained consistent results using acid digestion (e.g. Roland et al., 2015), flotation was deemed an important precaution since the shards were small with a high surface to volume ratio, characteristics which may make shards prone to chemical alteration (Blockley et al., 2005; Dugmore et al., 1992). Extracted shards were mounted on epoxy resin discs and exposed at the surface by careful grinding and polishing.

Major and minor element compositions of single glass shards of unknown cryptotephra horizons were determined by electron probe microanalysis (EPMA) with wavelength dispersive spectrometry (WDS-EPMA) at the Tephra Analytical Unit, University of Edinburgh, using a 3 μm beam (Appendix B.1, Supplementary Information). This beam size was used because shard sizes were typically very small (25–102.5 μm) with many vesicles (Hayward, 2012). Ksudach 1 (KS1) proximal tephras were analysed at the University of Edinburgh using the same parameters and at Queen's University Belfast (analytical set up outlined in Appendix B.2, Supplementary Information). All Mount St. Helen's, Jala Pumice and White River Ash glass analyses were analysed at the University of Alberta on a JEOL 8900 using a 10 μm beam, 6 nA current, and 15 keV voltage. Analyses at all laboratories used a similar suite of minerals and glass for calibration, and a Lipari obsidian as a secondary standard to track the quality of calibration and assure repeatable analyses (e.g. Kuehn et al., 2011). The results of the standard analyses were consistent, predominantly remaining within the accepted analytical range (Appendix B, Supplementary Information). Therefore, the datasets are comparable among laboratories. All results are normalised to 100% on a water and volatile free basis (e.g. Froggatt, 1983; Lowe, 2011) to further assist comparisons. Correlations were identified by searching the University of Alberta tephra database (containing North American geochemical data with some Russian and Icelandic data), the Queen's University Belfast dataset (containing Icelandic and Russian geochemical data), Tephrabase (Newton et al., 1997; containing Icelandic/Europe and Mexican geochemical data) and published literature. Potential correlations to the unknown cryptotephra layers were visually examined using biplots of selected elements, with correlation strengths indicated by similarity coefficients (Borchardt et al., 1972; Appendix C, Supplementary Information).

Age-depth models were constructed using ^{14}C measurements on *Sphagnum* stems with the exception of the basal dates, which were obtained from bulk peat or brown mosses (Appendix D, Supplementary Information). ^{14}C measurements were converted to calendar age distributions using the IntCal13 calibration curve (Reimer et al., 2013) and the weighted averages of the date range distribution (2σ) are referred to throughout. Bayesian age-depth models were constructed using the R package "BACON" (Blaauw and Christen, 2011) assuming piece-wise linear accumulation (Fig. 2; Appendix D, Supplementary Information). The age-depth models were constructed using BACON's default prior settings