Quaternary Science Reviews 164 (2017) 230–235

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Ultra-distal Kamchatkan ash on Arctic Svalbard: Towards hemispheric cryptotephra correlation

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ARTICLE INFO

Article history:
Received 21 December 2016
Received in revised form
22 March 2017
Accepted 5 April 2017
Available online 14 April 2017

Keywords:
Holocene
Cryptotephra
Arctic
Pacific
Svalbard

ABSTRACT

Rapidly deposited and geochemically distinct volcanic ash (tephra) markers represent a powerful chronological tool that enables precise dating and correlation of geological archives. Recent analytical advances now allow fingerprinting of non-visible ash (cryptotephra) over thousands of kilometers. This has opened up tantalizing possibilities for the intercontinental synchronization of records. We present geochemical evidence to demonstrate that ash from a Svalbard lake sediment core correlates to the Kamchatkan KS_2 eruption. By expanding the known dispersal range of cryptotephra by thousands of kilometers and linking the Pacific and Atlantic Arctic, this study raises cryptotephra analysis to a new level. Also, the presented findings mark a step towards a hemispheric tephrochronological framework. Finally, this study highlights the importance of looking beyond proximal volcanic sources to find a correlation.

1. Introduction

Volcanic ashes (tephra) represent time-parallel markers (isochrons) that provide a unique means of precisely dating and correlating geological archives (Lowe, 2011). This powerful geochronological tool enables synchronization of paleoclimate records over millennia across distances of thousands of kilometers (Blockley et al., 2014). Apart from anchoring events in time, tephrochronology is invaluable to constrain phase relationship between components of the climate system (e.g. Lane et al., 2013a).

In recent years, key analytical advances have enabled robust geochemical fingerprinting of non-visible glass shards (cryptotephra) (Blockley et al., 2005; Hayward, 2011; Turney, 1998b). As a result, ash markers are detected at increasingly large distances from their respective volcanic source, expanding existing tephrochronological frameworks (Davies, 2015). Indeed, several recent studies correlate tephra markers between continents (Bourne et al., 2016; De Silva and Zielinski, 1998; Jensen et al., 2014; Lane et al., 2012, 2013b; Mackay et al., 2016; McLean et al., 2016; Pearce et al., 2014; Song et al., 2000; Sun et al., 2014; Tomlinson et al., 2012; references therein; Zdanowicz et al., 1999).

Yet, despite recent advances, the potential of this technique remains underutilized across large geographical areas (Machida, 2002). These include the High Arctic, where tephrochronology could contribute significantly as a scarcity of organic material often precludes radiocarbon dating. Moreover, tephra-based synchronization of regional paleoclimate records may help understand the causes of the amplified response of Arctic climate to change (Serreze and Barry, 2011).

We report detection of a Kamchatkan-sourced discrete ash layer in a lake sediment sequence from the High Arctic Svalbard archipelago (79°N). Geochemical analysis of shards using an electron microprobe enabled us to correlate this horizon to the KS_2 eruption ~7000 cal yr BP. This ultra-distal find raises cryptotephra analysis to a new level by linking the Pacific and Atlantic Arctic over up to ~14,000 km.

2. Setting

Our study site, Lake Hajeren, is a small (0.23 km^2) basin located on the Svalbard archipelago (79.26°N, 11.52°E, 35 m a.s.l) in the Arctic-Atlantic (Fig. 1a–b). The surrounding catchment covers 2.96 km^2, hosts two cirque glaciers and mostly comprises gently

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http://dx.doi.org/10.1016/j.quascirev.2017.04.007
0277-3791/

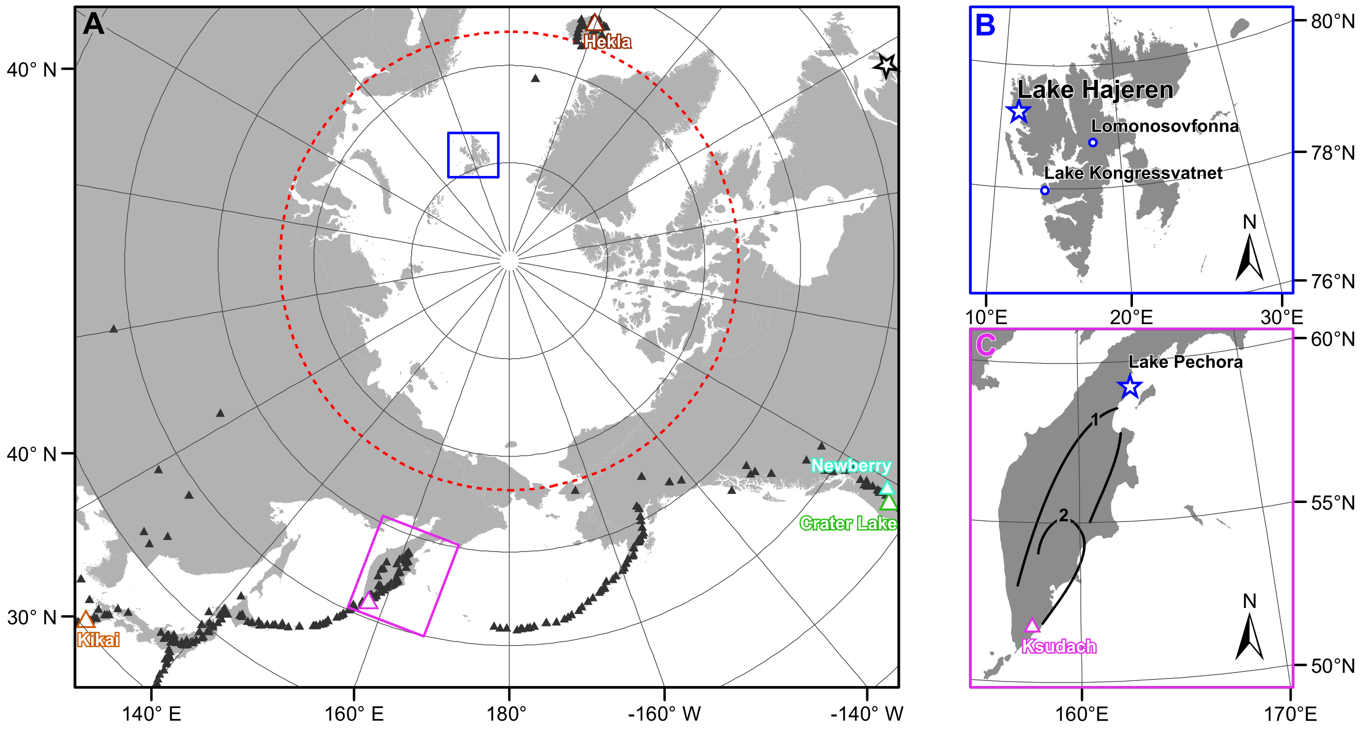

Fig. 1. **A:** Pan-arctic overview, showing volcanoes that have been active during the Holocene in black triangles after USGS (2005) as well as those discussed in this paper as color-coded triangles: Crater Lake (blue), Hekla (brown), Kikai (orange), Ksudach (pink) and Newberry (green). The dashed red line marks the Arctic Circle, while the pink and blue rectangles outline insets B and C, respectively. The open star highlights the only other extra-regional site where KS$_2$ ash has been found (S. Pyne-O'Donnell, pers. comm.). **B:** the Svalbard archipelago, indicating the location of Lake Hajeren with a star. Blue circles highlight the localities of previous tephra finds on Spitsbergen, Lake Kongressvatnet (D'Andrea et al., 2012) and Lomonosovfonna Ice Cap (Kekonen et al., 2005). **C:** close-up of the Kamchatka peninsula, highlighting the Ksudach volcano in pink and delineating 1 and 2 cm isopachs of the KS$_2$ tephra after Kyle et al. (2011). The blue star indicates the location of mentioned Lake Pechora. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sloping terrain that minimizes exposure to mass-wasting processes (van der Bilt et al., 2016b). With a recorded average temperature of −5 °C (Nordli, 2010), the lake is typically frozen for ~10 months a year. The sediment core sampled for this study (HAP0212) has been extracted from the basin's deep (~19 m) and flat center. This Holocene-length laminated sequence has been previously studied: details pertaining to core extraction and radiocarbon dating are described in van der Bilt et al. (2015) and van der Bilt et al. (2016a). Previous cryptotephra studies on Svalbard report Late Holocene (past 2 kyrs) horizons from the second closest volcanic source region, Iceland (D'Andrea et al., 2012; Kekonen et al., 2005), ~1800 km to the South (Fig. 1a).

3. Methods

Cryptotephra glass was separated from sediments using the flotation procedure of Turney (1998a) and Blockley et al. (2005) by sieving (>15 μm) and density extraction (1.95–2.55 g/cm^3). We scanned the entire core length (332.5 cm) for shards by applying a three-phase routine. First, contiguous 10 cm vertical intervals were analyzed to identify core sections with glass shards. For this purpose, samples were mounted in Canada balsam and examined under a light microscope (×200). Next, we zoomed in on intervals with tephra shards at a 1 cm resolution using the same approach. Finally, we re-investigated the horizon discussed in this paper, to pick individual shards for geochemical analysis. For this purpose, we used a gas chromatography syringe (cf. Lane et al., 2014).

To fingerprint shards geochemically, we measured major and minor element oxide concentrations using wavelength dispersive X-Ray spectrometer electron microprobe (WDS-EMP) analysis. Analyses were carried out at **1**) the Research Laboratory for Archaeology and the History of Art at the University of Oxford with a JEOL JXA-8600, using an accelerating voltage of 15 kV, a 6 nA beam current and a 10 μm beam size, and **2**) the Electron Probe Microanalysis Facility at the School of Geosciences of the University of Edinburgh with a Cameca SX100, using an accelerating voltage of 15 kV, beam currents of 0.5 nA (Na/Al), 2 nA (Mg/Si/K/Fe/Ca) and 60 nA (P/Ti/Mn) and a 6 μm beam size. As Chlorine (Cl) was not measured in Edinburgh, we removed it from our dataset prior to normalization for comparison purposes. Both instruments were calibrated using a suite of characterized mineral standards, while secondary glass standards were analyzed between and within runs to monitor analytical precision. (Un)normalized glass compositional data, including means and standard deviations, for sample and secondary standard measurements are provided in Tables S1–2.

To help identify the source eruption of the presented horizon, we complemented bivariate plots with Principal Component Analysis (PCA), an ordination technique often used to identify (dis) similarities between sample groups (Birks et al., 2012). PCA combines data on the variability of all measured oxides, providing more information to help distinguish between volcanic sources than bivariate plots. To permit PCA on closed compositional tephra oxide concentrations, we log-transformed data after Aitchison (1986). Following the recommendations of Pollard et al. (2006), we employed the centered log-ratio approach, dividing the natural log of element oxide values by that of the geometric sample mean after data normalization c.f. Pearce et al. (2008). PCA analysis was then carried out using the CANOCO 5 software (Ter Braak, 1988), scaling and centering sample scores in the ensuing ordination diagram to