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Integrating the Holocene tephrostratigraphy for East Asia using a high-resolution cryptotephra study from Lake Suigetsu (SG14 core), central Japan

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A B S T R A C T

Tephra (volcanic ash) layers have the potential to synchronise disparate palaeoenvironmental archives on regional to hemispheric scales. Highly productive arc regions, like those in East Asia, offer a considerable number of widespread isochrons, but before records can be confidently correlated using these layers, a refined and integrated framework of these eruptive events is required. Here we present the first high-resolution Holocene cryptotephra study in East Asia, using the Lake Suigetsu sedimentary archive in central Japan. The Holocene tephrostratigraphy has been extended from four to twenty ash layers using cryptotephra extraction techniques, which integrates the deposits from explosive eruptions from North Korea/China, South Korea and along the Japanese arc. This Lake Suigetsu tephrostratigraphy is now the most comprehensive record of East Asian volcanism, and the linchpin site for correlating sequences across this region. Major element glass geochemical compositions are presented for the tephra layers in the sequence, which have been compared to proximal datasets to correlate them to their volcanic source and specific eruptions. This study has significantly extended the ash dispersal of many key Holocene marker layers, and has identified the first distal occurrence of isochrons from Ulleungdo and Changbaishan volcanoes. Utilising the high-precision Lake Suigetsu chronology, we are able to provide constrained eruption ages for the tephra layers, which can be transferred into other site-specific age models containing these markers. This new framework indicates that several isochrons stratigraphically bracket abrupt climate intervals in Japan, and could be used to precisely assess the regional and hemispheric synchronicity of these events.

1. Introduction

The importance of palaeoenvironmental archives for our understanding of abrupt climate change is well recognised, but it is essential that these records can be precisely integrated and dated to assess their ultimate drivers operating across large regional scales (e.g., the East Asian Monsoon; EAM). Widely dispersed volcanic ash (tephra) layers preserved in sedimentary sequences can provide ideal isochronous markers to facilitate high-precision correlations (tephrostratigraphy) and transfer absolute ages (tephrochronology) across palaeoclimate records (e.g., Albert et al., 2013; Lane et al., 2014; Abbott et al., 2016; Alloway et al., 2017). These markers can facilitate the assessment of the spatio-temporal variability of abrupt climate change, particularly when they bracket the onset or

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duration of these events (e.g., Lane et al., 2013). Deciphering the regional and global synchronicity of these changes is fundamental for our understanding of the forcing mechanisms and interplay between large-scale oceanic and atmospheric systems.

In order to integrate and compare palaeoenvironmental records, regional tephrostratigraphic frameworks are established, which connect sites using widespread, and well-characterised marker layers (e.g., Shane et al., 2006; Davies et al., 2014; Lowe et al., 2015). These regional frameworks are underpinned by key reference sites (often termed *tephrostratotypes*), which offer both detailed tephrostratigraphic sequences, and a precise chronology of eruptive events, usually from a range of volcanic sources (e.g., the Greenland ice cores; Abbott and Davies, 2012; Bourne et al., 2015). Both the number and geographical footprint of these visible ash layers can be significantly extended by examining sedimentary successions for the presence of non-visible (cryptotephra) ash layers (e.g., Wastegård, 2002; Lane et al., 2015; Albert et al., 2015; Mackay et al., 2016), which are essential to identify smaller magnitude and/or more distal occurrences of the largest eruptions.

Pioneering investigations by researchers such as Machida and Arai (1983) provide the foundation for Japanese tephrochronology, and have established a complex catalogue (via detailed mapping of visible ash deposits) of the succession and dispersal characteristics of the large explosive eruptions that occurred during the Quaternary (compiled in Machida and Arai, 2003). In other parts of the world, studies like those undertaken by the RESET ('Response of Humans to Abrupt Environmental Transitions') project, centred in continental Europe and across the Mediterranean Sea (see Lowe et al., 2015), have further refined tephrostratigraphic frameworks through detailed analysis of key eruption sequences and at distal sites. In the RESET project, all tephra deposits were sampled and geochemically fingerprinted from proximal eruptive units close to their source, and detailed cryptotephra studies were undertaken in distal sedimentary sequences. These analyses were able to: i) incorporate new and lower magnitude events into the master European tephrostratigraphic framework (e.g., Albert et al., 2013), ii) resolve the stratigraphic position of eruptions from different volcanic sources that were closely spaced in time (e.g., Karkanas et al., 2015), iii) establish which eruptions have a diagnostic geochemical signature for reliable tephra correlations (e.g., Smith et al., 2011a), (iv) identify erroneous tephra correlations (e.g., Albert et al., 2015), and v) extend the known geographical footprint of ash fallout from individual eruptions, and therefore widen the area over which the key isochrons could be used. This detailed work has revised and verified a comprehensive framework (Lowe et al., 2015) that can be used to robustly integrate key palaeoenvironmental and archaeological archives across the region surrounding the Mediterranean Sea, and test long-standing questions using the high-resolution chronology (e.g., Rohling et al., 2009; Grant et al., 2012; Lowe et al., 2012; Barton et al., 2015).

This project aimed to refine and augment the Holocene tephrostratigraphic framework for the East Asian/Pacific region using a similar methodology to that employed by the RESET project (outlined above). Here, the sediments of Lake Suigetsu (SG14 core; Fig. 1) were targeted for detailed cryptotephra analysis, since it currently provides the most precisely dated Holocene sedimentary record from Japan (see Staff et al., 2011; Nakagawa et al., 2012). The objectives of this research were to: i) verify the successful application of cryptotephra analysis from a lake located along the highly productive volcanic arc, ii) chemically characterise and date identified tephra isochrons in order to correlate them to their volcanic source and, where possible, specific eruptions, and iii) use the Holocene tephrostratigraphic record from Lake Suigetsu to develop an integrated framework for the East Asian/Pacific region.

1.1. Tephra dispersal in and around Japan

Over 130 volcanic centres are distributed along the length of the Japanese arc (Fig. 1). These centres have been highly productive during the Late Quaternary, with numerous large caldera-forming eruptions (particularly on Hokkaido and the Kyushu Islands; Fig. 1) producing widespread tephra dispersal across the East Asian/Pacific region (Machida and Arai, 2003). Due to the prevailing westerly winds, ash from the explosive back-arc/intraplate volcanism in South Korea (Ulleungdo volcano) and North Korea/China (Changbaishan) has also blanketed Japan and the surrounding seas numerous times over the Quaternary (Machida and Arai, 2003; Lim et al., 2013, Fig. 1).

During the Holocene three key widespread marker beds are commonly identified in sedimentary sequences in and around Japan, and are named using their source volcano and distal tephra type-site, a common practice in Japanese tephrostratigraphy studies. These include the Baegdusan-Tomakomai (B-Tm), Kikai-Akahoya (K-Ah) and Ulleungdo-Oki (U-Oki) ash (Machida and Arai, 1983). The B-Tm is the tephra deposit from the 'Millennium' eruption of Changbaishan, and has been recently dated to AD 946 (Hakozaki et al., 2017; Oppenheimer et al., 2017). The K-Ah tephra was dispersed from the now largely sub-marine Kikai caldera, located 50 km south of Kyushu. The most precise date for this eruption (7303–7165 cal yrs BP) was obtained from the Lake Suigetsu SG06 sediment core (Smith et al., 2013). The U-Oki tephra is from Ulleungdo Island (South Korea), which is located in the Sea of Japan, and corresponds to the U-4 proximal eruptive unit (Smith et al., 2011b). Lake Suigetsu, situated in central Japan, is the only archive to currently record all three of these key Holocene marker beds (Fig. 1; Smith et al., 2011b, 2013; McLean et al., 2016).

In the past, the majority of tephra correlations in and around Japan are based on the physical characteristics of the deposit, i.e. refractive indices, layer thickness, grain-size and modal mineralogy. However, it is essential that tephra layers are geochemically characterised as accurately as possible to ensure unequivocal correlations across the proximal and distal settings. Volcanic glass compositions are routinely employed for robust tephra correlation around the world, including New Zealand (e.g., Froggatt, 1983; Shane and Smith, 2000), Europe (e.g., Tomlinson et al., 2015), North America (e.g., Smith and Westgate, 1968; Sarna-Wojcicki et al., 1987) and South America (e.g., Fontijn et al., 2016), but are only recently being utilised in Japan (e.g., Moriwaki et al., 2011; Okuno et al., 2011; Smith et al., 2013; Chen et al., 2016). Comprehensive glass datasets are yet to be obtained from many eruptive centres in this region, particularly those in central and southern Japan, which means that many distal correlations remain unconfirmed (e.g., Smith et al., 2013).

1.2. Constraining Holocene climate intervals using tephra layers

Palaeoenvironmental change during the Holocene can provide an improved perspective upon the causal mechanisms and drivers of climate change across the globe (Wanner et al., 2008). In the East Asian/Pacific region, the Holocene climate has been shown to vary considerably, with several abrupt (centennial-scale) warming and cooling phases, likely caused by fluctuations in the behaviour of the East Asian Monsoon (EAM; Wang et al., 2005; Sagawa et al., 2014; Tada and Murray, 2016). Despite the regional and global importance of this climate system, its causal relationship to both external (e.g., orbital, solar and volcanic) and internal forcing remains poorly understood (Morrill et al., 2003; Park, 2017). This is partly due to the inherent difficulties in precisely comparing the distant and diverse palaeoclimate archives across the monsoon region.

Tephra layers can be used to precisely integrate disparate