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The Late Quaternary tephrostratigraphy of annually laminated sediments from Meerfelder Maar, Germany

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A B S T R A C T

The record of Late Quaternary environmental change within the sediments of Meerfelder Maar in the Eifel region of Germany is renowned for its high precision chronology, which is annually laminated throughout the Last Glacial to Interglacial transition (LGIT) and most of the Holocene. Two visible tephra layers are prominent within the floating varve chronology of Meerfelder Maar. An Early Holocene tephra layer, the Ulmener Maar Tephra (~11,000 varve years BP), provides a tie-line of the Meerfelder Maar record to the varved Holocene record of nearby Lake Holzmaar. The Laacher See Tephra provides another prominent time marker for the late Allerød, ~200 varve years before the transition into the Younger Dryas at 12,680 varve years BP. Further investigation has now shown that there are also 15 cryptotephra layers within the Meerfelder Maar LGIT-Holocene stratigraphy and these layers hold the potential to make direct comparisons between the Meerfelder Maar record and other palaeoenvironmental archives from across Europe and the North Atlantic. Most notable is the presence of the Vedde Ash, the most widespread Icelandic eruption known from the Late Quaternary, which occurred midway through the Younger Dryas. The Vedde Ash has also been found in the Greenland ice cores and can be used as an isochron around which the GICC05 and Meerfelder Maar annual chronologies can be compared. Near the base of the annual laminations in Meerfelder Maar a cryptotephra is found that correlates to the Neapolitan Yellow Tuff, erupted from Campi Flegrei in southern Italy, 1200 km away. This is the furthest north that the Neapolitan Yellow Tuff has been found, highlighting its importance in the construction of a European-wide tephrostratigraphic framework. The co-location of cryptotephra layers from Italian, Icelandic and Eifel volcanic sources, within such a precise chronological record, makes Meerfelder Maar one of the most important tephrostratotype records for continental Europe during the Last Glacial to Interglacial transition.

1. Introduction

The detection of microscopic layers of volcanic ash (cryptotephra) within terrestrial, marine and ice core records is revolutionising the way widespread palaeoenvironmental archives are dated and compared. Tephra isochrons provide stratigraphic tie-lines between records, which permit precise inter-site correlation and comparison of the proxy record, whilst avoiding un-grounded assumptions of synchronicity. In addition, where tephra can be correlated to eruptions of known age, absolute age estimates can be achieved and transferred between records. Consequently, the last two decades have seen rapid growth in cryptotephra research, most notably within Late Quaternary palaeoenvironmental studies (e.g., Dugmore et al., 1995; Lowe, 2001; Wulf et al., 2004), but also within archaeological investigations (e.g., Plunkett, 2009; Housley et al.,

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2012; Lane et al., 2014). Across Europe in particular, there is now a wealth of tephrostratigraphic and chronological data that can be built into a regional tephrostratigraphic framework of interconnected sites, within which questions about the timing of environmental and climatic changes can be addressed (Blockley et al., 2012; Davies et al., 2012; Lane et al., 2012a; Wulf et al., 2013).

Key to the development of a regional tephrostratigraphic framework are two different sorts of distal sites: (i) *linking sites* that contain tephra records of multiple eruptions from different volcanic sources (e.g., Lane et al., 2011a) and (ii) *chronological reference sites* with annual to decadal precision, that can feedback dating information to sites around the network (e.g. the Greenland ice core records, Mortensen et al., 2005; Abbott and Davies, 2012). The rare sites that are able to fulfil both of these criteria are typically (partially, or wholly) varved records that sit within the fallout ranges of multiple volcanic centres. European examples include the Lateglacial to Early Holocene record in Soppensee, Switzerland (Hajdas, 1993; Lane et al., 2011b) and the 133 ka record in Lago Grande di Monticchio, Italy (Wulf et al., 2004, 2008, 2012).

A major strength of varve sequences lies in the opportunity to date the intervals between tephra isochrons, with annual to decadal precision. This *differential dating* approach provides important chronological constraints that can be built into a regional tephrostratigraphic framework and used to precisely compare periods of known equivalent duration wherever the same tephra layers are found co-registered. The combination of widespread tephra layers in varve palaeoenvironmental sequences therefore provides the rare, but exceptionally valuable, opportunity to study subtle variations in the timing and rate of environmental response to past abrupt climate changes (Lane et al., 2013).

A cryptotephra study of the Lateglacial to Holocene age sediments from Meerfelder Maar, in the Eifel region of Germany, was carried out with the aim of establishing a new European tephrostratotype sequence in a site that has high (seasonal to annual) chronological resolution as well as the potential to contain tephra from a number of European volcanic centres (the Eifel, Massif Central, Icelandic and Italian). This paper presents the full results of this study, with the following three objectives:

i. To report the Lateglacial and Holocene tephrostratigraphy of Meerfelder Maar.
ii. To provide improved varve-age estimates, with uncertainties, for a number of the tephra layers within Meerfelder Maar and to constrain the inter-eruption ages.
iii. To place the Meerfelder Maar record within a broader European tephrostratigraphic framework, which permits direct correlation of palaeoenvironmental archives from the North Atlantic, Europe and the Mediterranean.

2. Site & methods

2.1. The site

Lake Meerfelder Maar (50°06′ N, 6° 45′ E, 336.5 m a.s.l.) is located in the Eifel region, Germany (Fig. 1), within a volcanic crater formed a minimum of 30 ka BP according to previous radiocarbon dating (Büchel and Lorenz, 1984; Brauer et al., 1999) or even ca 80 ± 8 ka BP according to recent thermoluminescence dating (Zöller and Blanchard, 2009). The lake has a surface area of approximately 248 m^2 and a maximum depth of 18 m. The lake catchment is small, defined by the steep, vegetated, crater walls, which reach up to 520 m at their highest.

The Holocene varved sediments are composed of spring/summer diatomaceous organic sub-layers and winter sub-layers of allochthonous sediment (Brauer et al., 1999), whereas the lateglacial sediments exhibit a succession of different varves types including siderite varves (late Allerød) and clastic-dominated snow melt varves (second half of Younger Dryas), triggered by rapid climate changes and lake evolution (Brauer et al., 1999). The sediment formation in Lake Meerfelder Maar is sensitive to North Atlantic climate variability. Abrupt sedimentary and biological responses to Lateglacial and Holocene climatic shifts recorded at Meerfelder have provided new insights into the nature and mechanism of Late Quaternary climate dynamics (Brauer et al., 2008; Martin-Puertas et al., 2012a, 2012b; Lane et al., 2013).

2.2. Field work and varve counting

During a coring expedition in 2009 seven new and parallel core sequences were retrieved from the deepest part of the lake basin using a UWITEC piston corer. The maximum distance between individual coring sites was 20 m. These sediment profiles, labelled as cores MFM09-A to MFM09-G, were split, imaged, described and correlated. Each of this sediment profiles consists of a sequence of 5–6 up to 2 m long core segments, typically with gaps of a few cm between each individual core. Two sediment profiles (Fig. 1) were selected for thin sections analyses: core MFM09-A (11.50 m long) and core MFM09-D (10.58 m long). Core A was recovered from the water/sediment interface, whereas core D starts 70 cm below. A composite profile (MFM09; 11.71 m long) was constructed through detailed correlation based on macroscopic and microscopic marker layers. Martin-Puertas et al. (2012) used the same marker layers to correlate the new sediment profile with a previous profile MFM-6 (Brauer et al., 1999, 2000a). The new continuous sediment record (MFM09) so far has been investigated in particular for Holocene climate and environment changes (Martin-Puertas et al., 2012a).

Varve counting was carried out on a continuous series of thin sections (100 × 35 mm, with 2 cm overlaps) using a petrographic microscope under parallel and polarized light (Brauer et al., 1999; Martin-Puertas et al., 2012a). Varve counting involved thickness measurements for each varve at higher microscopic magnification (100×). In order to assess the individual error, varve counting was realised twice by the same counter.

2.3. Cryptotephra investigations

The entire core sequence MFM09-D was investigated for the presence of cryptotephra following the non-destructive density floatation method of Turney (1998) and Blockley et al. (2005). Tephra glass shards within the 1.95–2.55 g/cm^3 residue (and also >2.55 g/cm^3 for low resolution samples) were identified and absolute numbers counted under high powered polarised light microscopy, then quantified as shards per gram of dry sediment (s/g). Where tephra glass shards were discovered in initial low-resolution contiguous samples, these 10 cm lengths were re-investigated at 1 cm resolution to better define the location of the tephra layer. Where possible, thin section inspection of the cores was then used to locate the tephra layer to its exact varve position. All tephra layers are given sample codes based upon their first occurrence depth below lake floor (cm) and these are used throughout the manuscript.

2.4. Geochemical analysis

In order to concentrate glass shards for geochemical analysis, they were picked from samples under high-powered microscopy, using a gas chromatography syringe (Lane et al., 2014). The tephra shards were then mounted in epoxy resin, sectioned and polished for geochemical analysis. Major and minor element concentrations