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Towards a dendrochronologically refined date of the Laacher See eruption around 13,000 years ago

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ABSTRACT

The precise date of the Laacher See eruption (LSE), central Europe's largest Late Pleistocene volcanic event that occurred around 13,000 years ago, is still unknown. Here, we outline the potential of combined high-resolution dendrochronological, wood anatomical and radiocarbon (^{14}C) measurements, to refine the age of this major Plinian eruption. Based on excavated, subfossil trees that were killed during the explosive LSE and buried under its pyroclastic deposits, we describe how a firm date of the eruption might be achieved, and how the resulting temporal precision would further advance our understanding of the environmental and societal impacts of this event. Moreover, we discuss the relevance of an accurate LSE date for improving the synchronization of European terrestrial and lacustrine Late Glacial to Holocene archives.

1. Background and motivation

Located in the East Eifel region in Germany, around 40 km southeast of Bonn, the LSE occurred at approximately 12,900 BP (van den Bogaard, 1995; Schmincke, 2007, 2014), roughly 200 years before the end of the Late Glacial Allerød interstadial and the subsequent onset of the Younger Dryas cold spell (Baales et al., 2002; Lane et al., 2015). With a dense magma volume of around 6.3 km^3 and more than 20 km^3 of fall and flow deposits (collectively called Laacher See Tephra: LST; Schmincke, 2007), the LSE was central Europe's largest Late Pleistocene volcanic event, with a volcanic explosivity index of 6.0 and a magnitude of M = 6.2. The recent occurrence of earthquakes suggests a still active magmatic system near the southern rim of the crater lake (Hensch et al., 2019).

The LSE devastated the landscape in the immediate vicinity of its vent and covered an area of circa 1200 km^2 with more than 1 m thickness of pumice and ash (Schmincke et al., 1999, Fig. 1). Close to the vent, volcanic deposits accumulated up to 60 m or more in thickness. Pyroclastic flows filled the nearby valleys with

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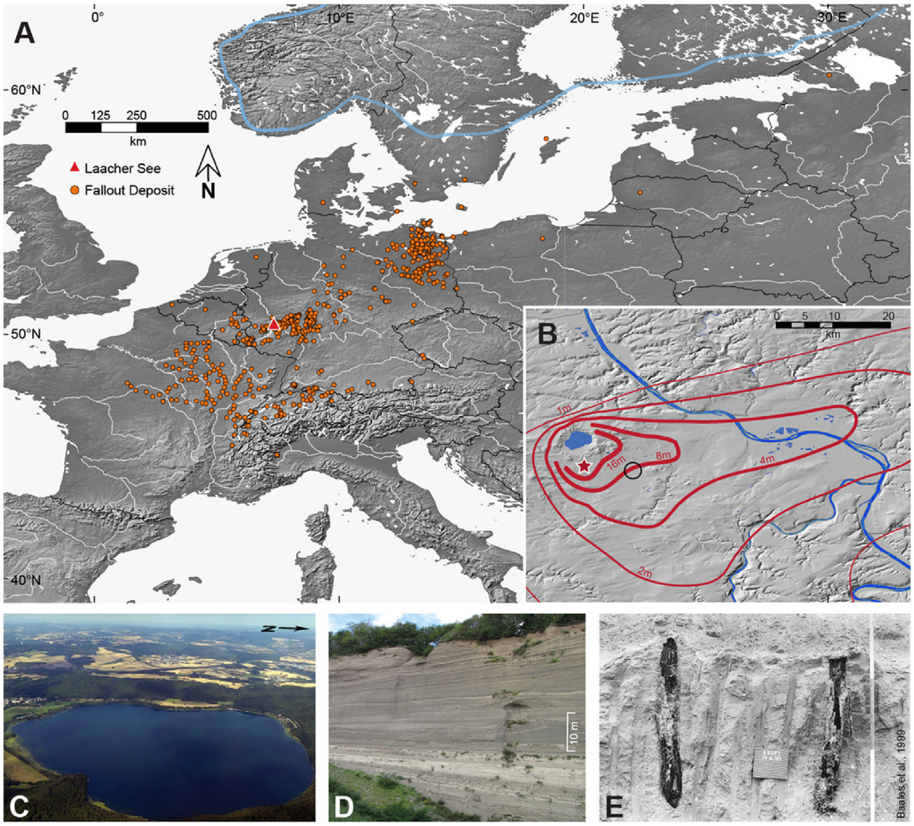

Fig. 1. Characteristics of the LSE. (A) Orange dots show the spatial distribution of sites where LST has been identified, blue line indicates reconstructed Allerød Scandinavian ice sheet extent (modified from Riede, 2017). (B) Red isopatchs show the spread of the LST fallout in the Neuwied Basin in m (after van den Bogaard and Schmincke, 1984). (C–E) Pictures of the Laacher See crater, its tephra deposits at Wingertsberg, 2 km south of the vent (red star in B), and the *in situ* excavated carbonized poplar trees near the village of Kruft (black circle in B; Baales et al., 1998). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

ignimbrites (Freundt and Schmincke, 1986), which dammed the Rhine river and created a large ephemeral lake (Park and Schmincke, 1997, 2020a, 2020b). Since ash fallout associated with the LSE is widespread across Europe, the LST represents an important time marker for precise synchronization of terrestrial and lacustrine paleoenvironmental records at the transition from the Late Glacial period to the early Holocene (van den Bogaard and Schmincke, 1985; Riede et al., 2011). The dimension and relevance of the environmental and socio-cultural impacts of the LSE are, however, still debated. While some authors consider the effects at the regional-scale to be minor (Baales et al., 2002; Engels et al., 2015; Gunther et al., 2019), others argue for substantial cultural shifts amongst contemporaneous human populations (Riede, 2008).

While the LST has been well-studied (Schmincke, 2007, 2014), and paleoenvironmental evidence suggests an onset of the eruption in late spring/early summer (Schweitzer, 1958; Waldmann, 1996; Baales et al., 2002), the precise eruption date remains unknown (Fig. 2). Direct radiometric ($^{40}Ar/^{39}Ar$) age estimates from Upper LST deposits at 12,900 ± 560 BP (van den Bogaard, 1995) are complemented by more precise ^{14}C measurements from organic materials that derive from within or below LST deposits. The latter dates cluster around a weighted mean of 11,066 ± 11 ^{14}C uncal. BP (Baales et al., 2002). Depending on the data and methods used to calibrate Late Glacial ^{14}C measurements, the resulting age estimates range between approximately 12,900 and 13,200 cal. BP (Baales et al., 1998, 2002; Friedrich et al., 1999).

More accurate ^{14}C dating is hindered by data paucity at this period in time, which reduces the precision of the ^{14}C calibration curve (IntCal13; Reimer et al., 2013). An annually-laminated lake sediment record from the Meerfelder Maar (MFM; Brauer et al., 1999, 2008; Lane et al., 2015), anchored temporally by the early Holocene Ulmener Maar tephra (Zolitschka et al., 1995), provides an age estimate for the LSE between 12,840 and 12,920 MFM varve years BP. Lower resolution lake records from Gerzensee, Lago Piccolo di Avigliana and Soppensee suggest more divergent calendar dates for the LSE between 12,700 and 13,200 local varve years BP (Blockley et al., 2008; Finsinger at al. 2008; Van Raden et al., 2013). Moreover, studies that combine information from lake sediments, tree rings and ice cores, produced age estimates between 12,880 and 12,980 (cal.) BP (Baales et al., 2002; Bronk Ramsey et al., 2015). Dating uncertainty of the order of several decades to centuries, as well as the fact that most of the available age models are not independent of each other (due to data overlap), continue to limit progress in understanding the climatic, environmental and societal impacts of the LSE.

Here, we argue that dendrochronological dating of subfossil tree logs buried by the LSE at near-vent localities will help to establish a close to absolute date for the LSE. In addition to previously excavated tree-ring material within and immediately below the LST, the ongoing recovery of subfossil wood, buried *in situ* in LST offers hope to find further material. A geochronological tie point would be particularly important for the improved calendric synchronization of those paleoclimatic archives that contain LST, such as lacustrine

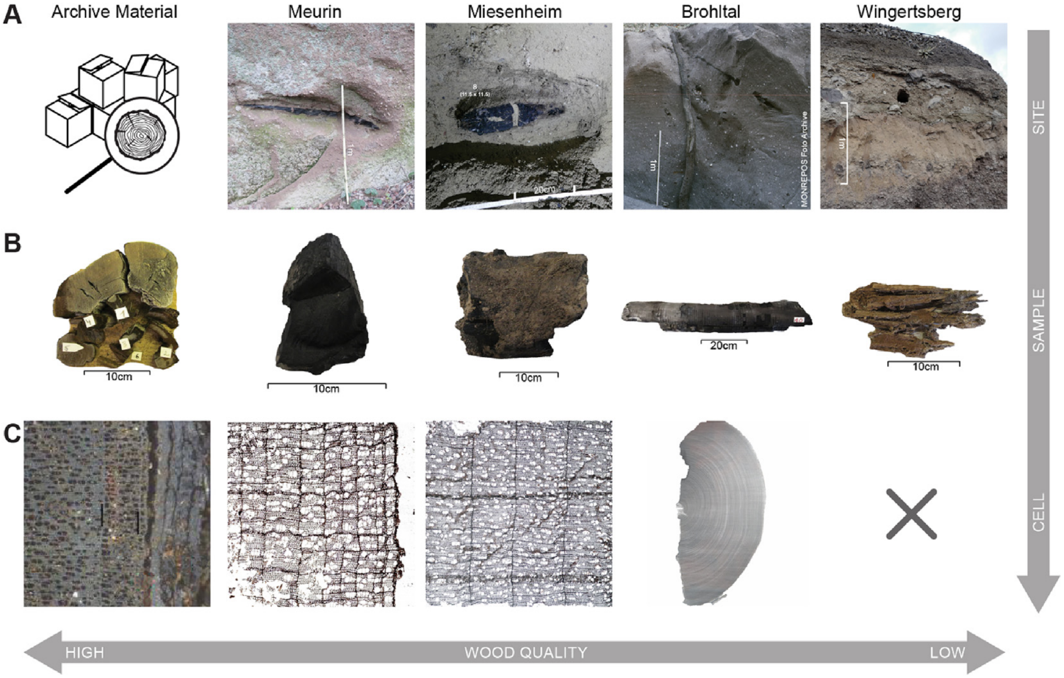

Fig. 2. Wood samples from the LSE. (A) Sites where charcoal or wood remains were found and excavated (left to right): The origin and context of archived samples is not always clear; charcoal sample in a commercial tuff mine near Meurin; relocated charcoal sample in a mine shaft at the edge of the ignimbrite flow near Miesenheim; lower part of an upright poplar stump buried *in situ* by fallout tephra during the initial eruption phase (Brohl Valley Exposure 1); mold of tree felled by initial blast of LSE in basal tuff at Wingertsberg. (B) Available wood samples (left to right): Stem disc with bark preserved frozen after recovery; charcoal fragment with outermost ring; charcoal fragment with adhering tephra remains indicate that the original outer part of the sample is intact; charcoal section with bark partly preserved; decayed wood remnant on which decomposition probably began after exposure to the atmosphere. (C) Transverse ring width patterns (left to right): Tree-ring boundaries and bark (courtesy of A. Land and S. Remmele); wood anatomical thin section of the outermost rings; rings on charcoal after cell stabilization; X-ray densitometry image of charcoal showing bark in the lower right corner, no image due to a lack of visible ring width boundaries in poor-quality subfossil wood.

varve sequences and other terrestrial records in Europe.

2. Dendrochronological dating

The combined analysis of high-precision tree-ring width measurements, wood anatomical traits and ^{14}C values from individual rings of trees that were killed during volcanic eruptions and buried by their deposits can provide eruption dates with annual and even sub-annual resolution (Büntgen et al., 2017; Oppenheimer et al., 2017). A dendrochronological re-assessment of the age of the LSE will further benefit from recent advancements in ^{14}C measurement techniques (Sookdeo et al., 2019), the development of new Late Glacial tree-ring width chronologies from Switzerland (Reinig et al., 2018a), and the subsequent improvement of the ^{14}C calibration curve during the time of interest (Reinig et al., 2020).

Numerous remains of charcoal and a smaller number of wood remnants were recovered between 1958 and 1996 at several localities in the LST ignimbrites up to about 15 km from the crater (Baales et al., 2002). Decadally-resolved ^{14}C measurements of three *in situ* excavated poplar and birch (*Populus* sp. and *Betula* sp.) stumps, standing upright in pumice and ignimbrite deposits near the village of Kruft (Fig. 1), place the LSE between 13,150 and 13,050 cal. BP (Baales et al., 1998). Low sampling resolution and low sample replication (i.e., utilization of decadal wood blocks without repeated ^{14}C measurements), however, affected the quality of this age estimate. A prolonged ^{14}C plateau from around 12,850–13,080 cal. BP (Reimer et al., 2013), which is now confirmed by new high-resolution ^{14}C data from Swiss subfossil pines (not shown), adds further uncertainty.

In addition to the previously collected material, not all of which appears to have been archived properly, there is still a chance to find relict wood to support the dendrochronological dating of the LSE. However, there is an urgency to such endeavours since much of the LST close to the Laacher See has already been removed due to industrial exploitation. The ideal samples are upright trunks that were buried *in situ* by ignimbrites or fallout deposits (Fig. 2a). Although most of the excavated subfossil material has been carbonized in fine-grained and hot pyroclastic flow deposits (Chevrel et al., 2019), it is still possible to find intact wood cellulose in well-preserved samples that were not subject to intense thermal conditions. Wood remnants from the late Allerød forest of Miesenheim 2 (Street, 1986, Street, 1995), or the basal parts of tree trunks found in water-logged positions in the Brohl river valley (Street, 1995), were subject to rapid decay after exposure to the atmosphere (Fig. 2b). In contrast, carbonized samples are generally more stable under aerobic conditions. Accurate measurements of any such relict material are particularly challenging, because the annual ring width boundaries are often difficult to identify (Fig. 2c). The application of classical microscopy should therefore be supplemented by wood anatomical thin sectioning (Reinig et al., 2018b), as well as X-ray densitometry (Schweingruber, 1988). Samples for which the outermost ring and some bark have been preserved, and for which several tens of consecutive rings are intact, are thus of utmost importance for determining the exact calendar year of the LSE.

Consideration of all existing and newly collected subfossil wood samples from LST deposits will hopefully result in a well-replicated, decadal-to centennial-long tree-ring width chronology, with the last cells formed just prior to the eruption. New ^{14}C measurements of annual or even sub-annual resolution from such a chronology would allow precise wiggle-matching against a continuous dendrochronological record, suitable for ^{14}C calibration in the Late

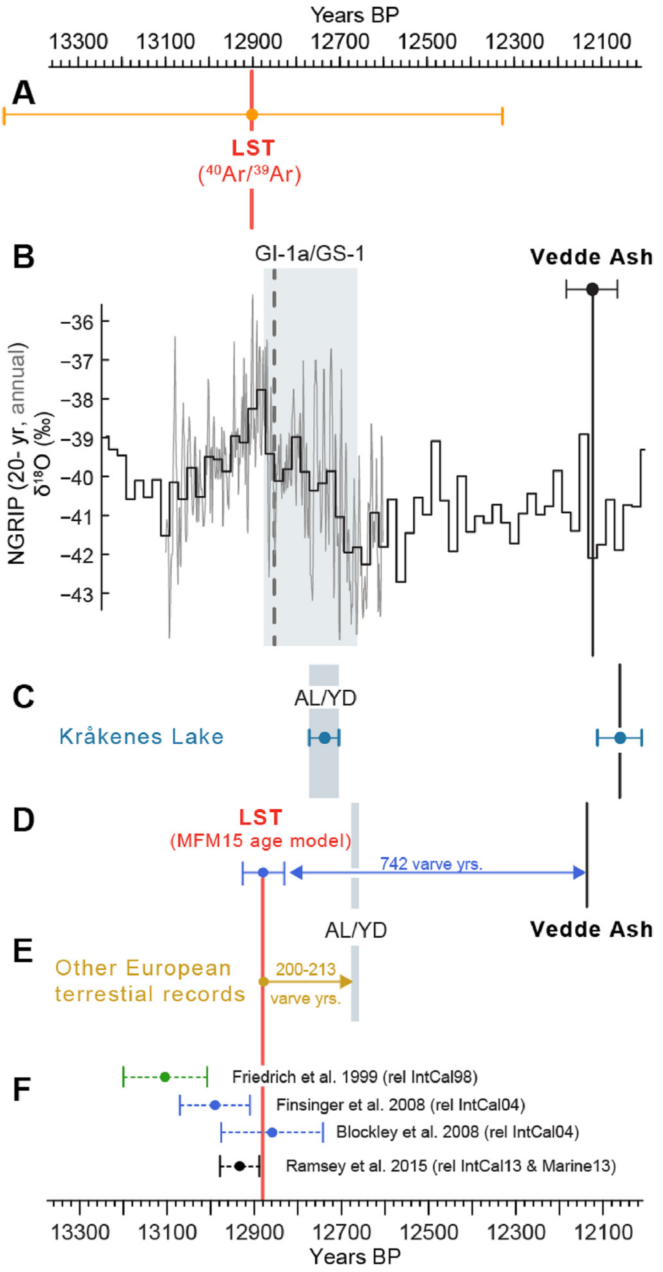

Fig. 3. Comparison of relative LST and Vedde Ash dates. (A) Independent radiometric ^{40}Ar/^{39}Ar date of Upper LSE tephra (orange, van den Bogaard, 1995); **(B)** Age-modeled NGRIP oxygen isotope time series (δ^{18}O) containing Vedde Ash evidence (black line) at 20-year (Rasmussen et al., 2006) and annual (Steffensen et al., 2008) resolution. Grey shading denotes the GI-1a/GS-1 transition in δ^{18}O**,** while the grey dashed line outlines the transition in deuterium excess (Steffensen et al., 2008). **(C)** Mean Allerød/YD boundary and Vedde Ash ages obtained from Kråkenes Lake (Norway, Lohne et al., 2014), calibrated against IntCal13. **(D)** Annually-laminated Meerfelder Maar record (MFM, Germany, Brauer et al., 1999; Lane et al., 2015) outlining 742 varve years between LST (red line) and Vedde Ash. **(E)** Summarized European varved terrestrial records (Soppensee, Switzerland, Hajdas et al., 1993; Rehwiese, Germany, Neugebauer et al., 2012; Trzechowskie, Poland, Wulf et al., 2013) aligned relative to the MFM LST date, indicating consistently approximately 200 years between the LST and the Allerød/YD boundary (grey shading). **(F)** Age estimates of the LSE obtained through $^{14-}$Cdated subfossil tree remains (Friedrich et al., 1999); sediment record of Lago Piccolo di Avigliana, Southern Alps, Italy (Finsinger et al., 2008); age modelling of Lake Soppensee, Swiss Plateau, Switzerland (Blockley et al., 2008); Bayesian model result including the tree-ring data of Friedrich et al. (1999) constrained by the LSE tephra in the Holzmaar, Soppensee and Rotsee (Bronk Ramsey et al., 2015). Colors refer to different proxy archives and dating methods (green = dendrochronology; blue = lake sediments; black = multi-proxy), and brackets show the different references used for calibration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Glacial period. A new high-resolution record of atmospheric ^{14}C level changes from Switzerland that spans almost 1000 years from around 13,200–12,320 cal. BP covering the time of the LSE, could serve as a standard record for wiggle-matching (Reinig et al., 2018a).

3. Relevance and outlook

In order to provide a refined date of the LSE, the herein proposed interdisciplinary approach should combine innovative techniques of dendrochronology, wood anatomy, paleoclimatology, paleoecology and volcanology (Büntgen, 2019). In addition to the valuable information that originates from the relative stratigraphy of the LST that is used as a major Late Pleistocene tephra isochron across Europe, determination of the exact year of the eruption would further improve the quality of any attempt at synchronizing such records. An absolute calendar date of the LSE would also enhance the accuracy of comparisons between proxy records with and without evidence of the eruption. Even though lower resolution proxy archives will not match the dendrochronological precision, a refined date of the LST would offer an important step towards enhanced proxy synchronization.

Age differences and dating uncertainties in Late Glacial proxy archives hamper their alignment beyond distinct tephra layers (Lane et al., 2011). During the Late Glacial/Holocene transition, the Vedde Ash in the second half of the Younger Dryas (YD), preserved in Greenland ice cores and European terrestrial archives (Lane et al., 2011, 2013), as well as the LST represent important relative temporal tie points. These relative dates, however, imply a temporal offset in the onset of the YD (Fig. 3). The current ice core dating of the transition from Greenland Interstadial 1a (GS-1a) to Greenland Stadial 1 (GS-1) predates the terrestrial Allerød/YD transitions in Scandinavia and central Europe, where approximately 200 varve years have been identified consistently between LST and the putative onset of the YD. Moreover, the abrupt cooling recognized in Greenland deuterium records (Steffensen et al., 2008), coincides with the LST date in the annually-laminated MFM sediments (Brauer et al., 1999). A robust comparison of paleoclimatic and paleoenvironmental North Atlantic and European responses in the context of the YD still remains vague due to the underlying dating uncertainty and resolution. A more precise and independent date of the LST would improve the absolute age modelling of high-resolution European varved records, for which the LST and Vedde Ash provide important synchronization. This would not only facilitate the reassessment of the YD duration within and between individual European proxy records but could also offer to improve the Greenland ice core chronology age-model (GICC05; Rasmussen et al., 2006).

Knowing the precise age of the LSE would also argue for a reexamination of Greenland ice cores for tephra fallout associated with the eruption (Büntgen et al., 2017). This task appears particularly relevant in the light of recent modelling efforts that demonstrate a disproportionate impact of extra-tropical eruptions on Northern Hemisphere climate than hitherto assumed (Toohey et al., 2019). The firm synchronization within and between different stratigraphic contexts would ultimately result in a refined reconstruction of both, regional and supra-regional climate and environmental changes at the Late Glacial to early Holocene transition, and potentially shed new light on the controversial question of the timing and duration, as well as the causes and consequences of the Younger Dryas (Carlson, 2010; Baldini et al., 2018; Kjær et al., 2018).

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