Towards a dendrochronologically refined date of the Laacher See Eruption

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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 12,900 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 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, and outline how the proposed, interdisciplinary dating approach can be applied to other large, yet undated, volcanic eruptions.

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 (Schmincke 2014, 2007; van den Boogard 1995), roughly 200 years before the end of the Late Glacial Allerød interstadial and the subsequent onset of the Younger Dryas cold spell (Lane et al. 2015; Baales et al. 2002). 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 2017), 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 magma 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 by more than 1 m of pumice and ash (Schmincke et al. 1999; Fig.1). Close to the vent, volcanic deposits accumulated up to 60 m or more in vertical thickness. Pyroclastic flows filled the nearby valleys with ignimbrites (Freundt and Schmincke 1986), which dammed the Rhine river and created a large ephemeral lake (Park and Schmincke 2019a, b; Baales et al. 2002; Park and Schmincke 1997). Ashes associated with the LSE are found widespread across Europe; the fallout deposits therefore represent an important time marker for the precise synchronization of terrestrial and lacustrine paleoenvironmental records at the transition from the Late Glacial period to the early Holocene (Riede et al. 2011; van den Bogaard and Schmincke 1985). 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 (Gunther et al. 2019; Engels et al. 2015; Baales et al. 2002), others argue for substantial cultural shifts amongst extant human populations caused by the eruption (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 (Baales et al. 2002; Waldmann 1996; Schweitzer 1958), its precise 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. Radiocarbon dates from these materials 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. 2002; 1998; 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 (IntCal; Reimer et al. 2013). An annually-laminated lake sediment record from the Meerfelder Maar (MFM; Lane et al. 2015; Brauer et al. 1999, 2008), anchored at 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 (van Raden et al et al. 2013; Blockley et al. 2008; Finsinger at al. 2008). Moreover, studies that combine information from lake sediments, tree rings and ice cores, produced age estimates between 12,880 and 12,980 (cal.) BP (Bronk Ramsey et al. 2015; Baales et al. 2002). Dating uncertainty in 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 limiting our understanding of the putative climatic, environmental and societal impacts of the LSE.

Here, we argue that dendrochronological dating of tree logs killed by the LSE at near-vent localities will help to establish a close to absolute date for the LSE. In addition to previously excavated subfossil tree-ring material within and immediately below the LST, the ongoing recovery of subfossil wood, buried *in situ* in LST gives hope to find more material. Given the more refined analytical methods in ^{14}C dating (Sookdeo et al. 2019) and if suitable samples are forthcoming, we are convinced that an absolute dendrochronological date of the LSE is within reach. A geochronological tie point would be particularly important for the improved calendric synchronization of those paleoclimate archives that contain LST, such as lacustrine varve sequences and other terrestrial records all over Europe.

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. in review).

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 circa 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 most ideal type of 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 1995, 1986) 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 Glacial period. A new high-resolution record of atmospheric ^{14}C level changes from Switzerland that spans almost 1,000 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).

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 would not be able to match the dendrochronological precision, a refined date of the LST would offer an important step towards enhanced proxy synchronization.

Age differences and dating uncertainty in Late Glacial archives challenge a secure alignment beyond a single tephrostratigraphic tie point as long as an independent chronological framework is unavailable (Lane et al. 2011). The Younger Dryas Vedde Ash, presented in both Greenland ice cores and European terrestrial sites (Lane et al. 2013, 2015), enables relative alignment. This placement, however, indicates a temporal paleoenvironmental offset between the proxy records in respect to the YD onset and duration, as well as the onset of the Holocene (Fig. 3). Robust comparison of paleoclimatic and paleoenvironmental North Atlantic responses in context of the YD remain vague due to the underlying dating uncertainty. Introducing a more precise and independent date of the LST would improve the absolute age modelling of high-resolution European varved records synchronised through LST and Vedde Ash. These revised well dated tephra markers, bracketing the transition into the YD, would not only facilitate the reassessment of the YD duration within and between individual European records, but would in addition align the Greenland ice core chronology age-model (GICC05, Rasmussen et al. 2006) with high temporal precision. Consequently, a dendrochronological LSE date would pave the way for secure North Atlantic climatic analysis, as well as improved insight into of the YD timing and transitions periods.

Knowing the precise age of the LSE would also argue for a re-examination of Greenland ice cores at this period of time to continue searching for corresponding volcanic glasses (Büntgen et al. 2017). This task appears particularly relevant in the light of recent modelling efforts that demonstrate a much greater impact of extra-tropical eruptions 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 (Baldini et al. 2018; Kjær et al. 2018; Carlson 2010).

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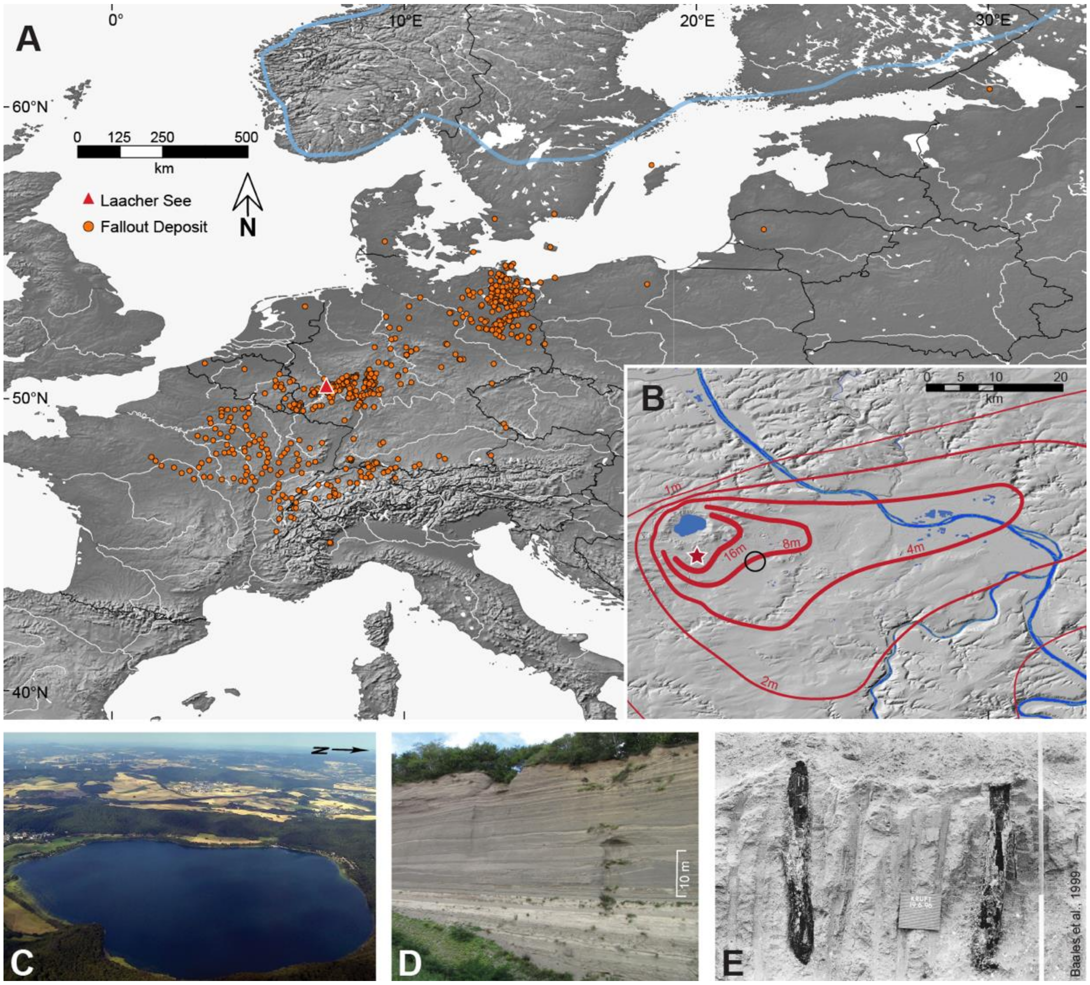

Figure 1. Characteristics of the LSE. (A) Orange dots show the spatial distribution of sites where LST has been identified, blue line indicates reconstructed Allerød Scandinavian ice sheet extent (modified from Riede 2017). **(B)** Red isopatchs show the spread of the LST fallout in the Neuwied Basin in m (after 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 **C**; Baales et al. 1998).

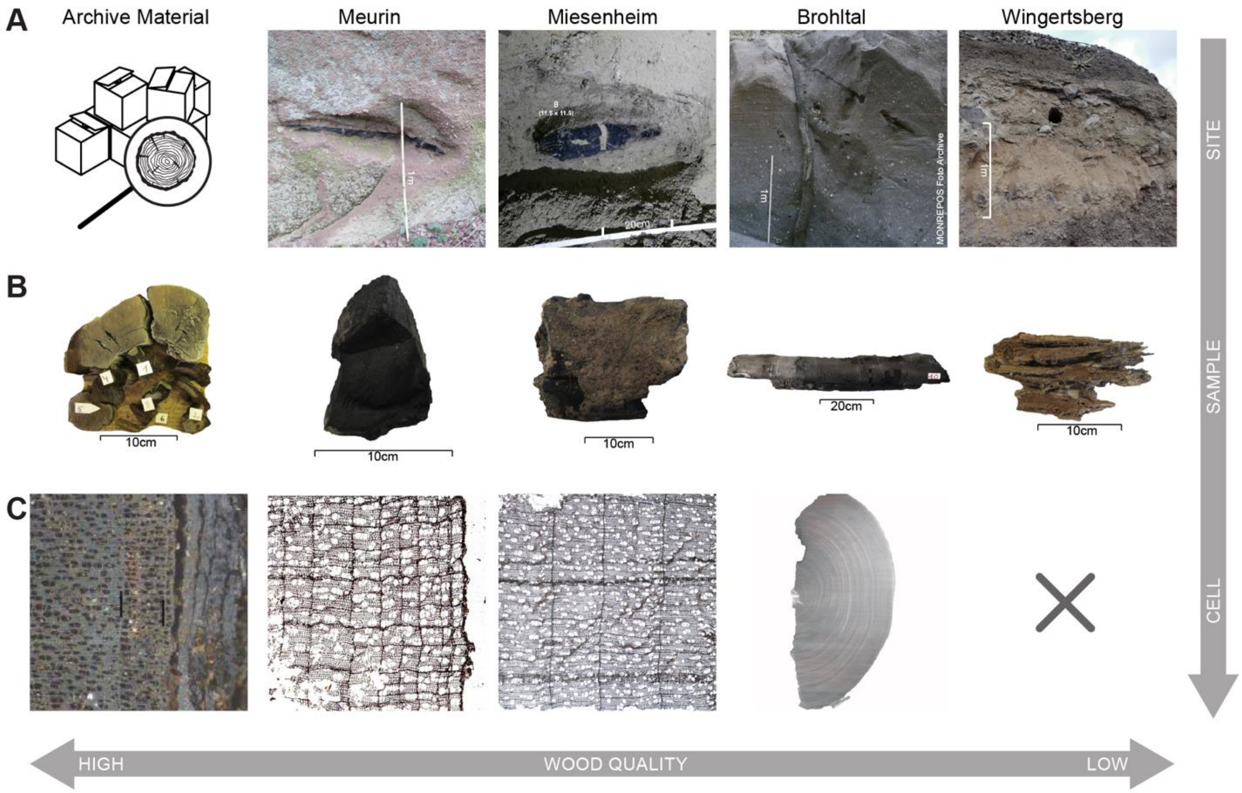

Figure 2. Wood samples from the LSE. (A) Sites where charcoal or wood remains were found and excavated (left to right): The origin and context of archived samples is not always clear; charcoal sample in a commercial tuff mine near Meurin; relocated charcoal sample in a mine shaft at the edge of the ignimbrite 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.

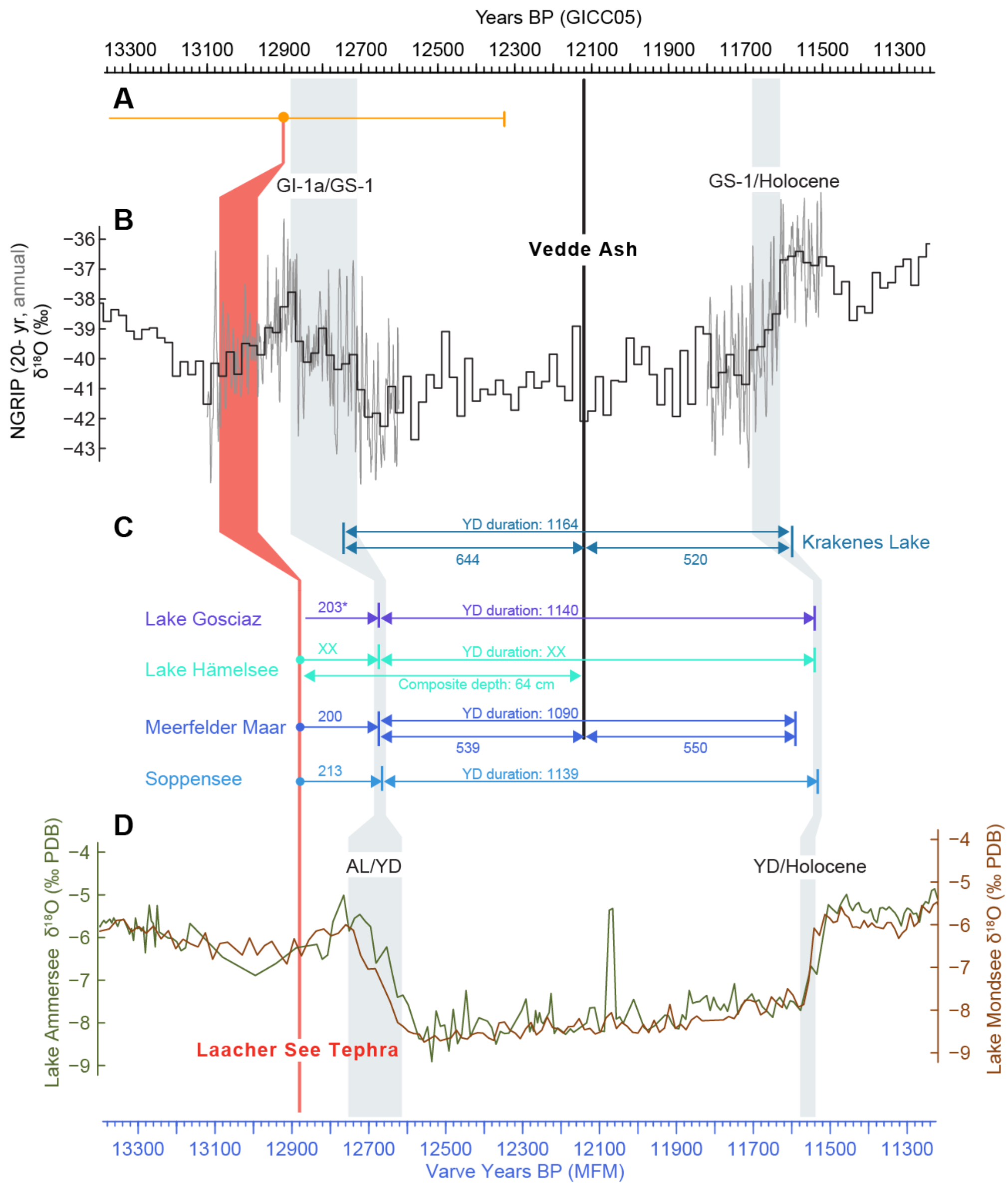

Figure 3. Comparison of relative LST and Vedde Ash dates. (A) Independent radiometric $^{40}Ar/^{39}Ar$ date of Upper LSE tephra (orange, van den Bogaard 1995); **(B)** Age modeled NGRIP oxygen isotopes (□^{18}O) containing Vedde Ash evidence in 20-year (Rasmussen et al. 2006) and annual (Steffensen et al. 2008) resolution during the YD transition. **(C)** European (partly) varved sediment records aligned relative to the Vedde Ash (black line) and/or LST (red line), outlining the individual records varve counting and resulting YD transitions dates from north to south: Kråkenes Lake, Norway (Lohne et al. 2013); Lake Gosciaz, Poland (Goslar et al. 1995); Lake Hämelsee,

Germany (Jones et al. 2018); Meerfelder Maar, Germany (Brauer et al. 1999); Soppensee, Switzerland (Hajdas et al., 1993). **(D)** Comparison of $\delta^{18}O$ values from Lake Mondsee (Lauterbach et al. 2011) and Lake Ammersee (von Grafenstein et al. 1999) plotted according to the MFM age model. While the Vedde Ash represents in this display a relative fix point, the transition into the YD (GI-1a/GS-1; AL/YD), as well as out of (GS-1/Holocene; YD/Holocene) indicate regional leads and legs (grey bands). The YD transitions in $\delta^{18}O$ records appear more gradual, whereas laminated records outline a more abrupt respond. The diverging age models from Greenland and Europe. Alignment of age models from Greenland and Europe according to their $\delta^{18}O$ sequences, outlines a revised range of possible LST occurrence in Greenland ice cores.