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25

26 Abstract

27

28 Frost rings can provide direct evidence of anomalously cold summertime conditions on hemispheric
29 scales. Here we report frost rings in subfossil pinewood from Finnish Lapland dated
30 dendrochronologically to AD 536 and 1627 BC. These exact calendar dates have been vividly
31 discussed in the literature in the respective contexts of a cold climate anomaly/dust veil/crop
32 failure/famine/Justinianic Plague and the Minoan eruption of Thera (Santorini). Coinciding anomalies
33 in growth and carbon isotope ratios ($\delta^{13}\text{C}$) indicate cold and overcast conditions in these years in
34 Finnish Lapland, typical to conditions induced by volcanic dust veils. This evidence reinforces the
35 view of multiple climatic drivers strongly effecting contemporary societies around AD 536 and
36 provides important new evidence regarding the 1627 BC event. We report a frost ring for this year,
37 and also consider evidence from Lapland for other Thera candidate eruptions in the 16th century BC.
38 The marker years 1560 BC and 1546 BC in bristlecone pine tree rings in North America are positioned
39 within negative departures in our $\delta^{13}\text{C}$ data. Most likely, the frosts occurred somewhere in July and
40 were driven by dust veils from Northern Hemisphere. Although not indicative of volcanic
41 provenance, frost rings and other dendroclimatic proxies dated to exact calendar years offer
42 important time markers for chronological frameworks which can synchronize archaeological,
43 historical and environmental data to further our understanding of environmental changes at scales
44 that matter to human societies.

45

46 Keywords: Holocene; Paleoclimatology; Scandinavia; Europe; North America; Tree-rings; Ice cores;
47 Minoan eruption; Late Antiquity

48

49

50 1. Introduction

51

52 Tree rings provide paleoclimatologists and archaeologists with long, continuous records and exact
53 dates of past events related to climatic, environmental and cultural changes. The longest tree-ring
54 chronologies span several millennia and can be used to infer the role that climatic changes and
55 anomalies have had on cultural transformation, collapse and florescence in Holocene human history.
56 Two examples of pivotal tree-ring derived dates occur in the 6th century AD and the second
57 millennium BC. The years AD 536 and 1627 BC have been discussed over a number of decades in
58 regards a potential correlation with major volcanic events and their human consequences (LaMarche
59 and Hirschboeck 1984; Baillie 2010). These dates are highlighted by rings damaged by frost in AD 536
60 from western North America (Salzer and Hughes 2007), from Mongolia (D'Arrigo et al. 2001), and
61 from the Altai mountains in central Asia (Churakova (Sidorova) et al. 2014). The frost rings identified
62 in bristlecone pine in 1627 BC (LaMarche and Hirschboeck 1984; Hughes 1988; Salzer and Hughes
63 2007) coincide with the conspicuous narrow ring formed in 1626 BC in north Siberian larches (Salzer
64 and Hughes 2007) and with narrow rings in Irish oaks (Baillie and Munro 1988). This cluster of
65 growth disruptions, indicating cold summer conditions, suggests a common forcing most likely of
66 volcanic origin, confirmed for the AD 536 event, by a strong correlation between high-resolution ice-
67 core records of volcanic sulfur (Larsen et al. 2008; Sigl. et al. 2015).

68

69 Recent campaigns to unearth and date subfossil pinewood materials from Finnish Lapland (Helama
70 et al. 2015, 2018a, 2018b) have produced tree-ring collections greatly extending the materials of
71 previous archives (Eronen et al. 1999, 2002) and, importantly, have resulted in new observations of
72 frost rings. In our material the only frequently observed frost rings pinpoint the AD 536 and 1627 BC
73 events, these observations forming the basis of this paper. Recent investigations have contributed
74 much discussion of the impact of the 'volcanic double event' beginning with an eruption apparently
75 in Northern Hemisphere (North America) in AD 536 and followed by a tropical eruption in AD 539 or

540 (Sigl et al. 2015) triggering a sustained climatic depression (Büntgen et al. 2016; Matskovsky and Helama 2016), with potential human impacts in the form of famine (McCormick et al. 2012), the Justinianic plague (Stathakopoulos 2000; Sarris 2002) and human migrations over the following century (Büntgen et al. 2016). The role of 1627 BC event as a candidate to tree-ring date the Minoan Thera (Santorini) eruption (LaMarche and Hirschboeck 1984) was previously supported by ^{14}C dates from samples taken directly from below the eruption deposits and calibrated to IntCal13 radiocarbon curve (e.g. Friedrich et al. 2006, 2014; Manning et al. 2006, 2014). Intriguingly, this connection is now questioned by the newly proposed revisions to the radiocarbon calibration curve that shift the calibrated ^{14}C dates towards the 16th century BC (Pearson et al. 2018). These results raise the possibility that the 1627 BC date relates to another volcanic cooling event, thus representing one more explosive eruption in the series of large volcanic events which must now be re-evaluated for Thera in a multi-proxy context.

Here we present new data to contribute to debates surrounding these two events with new descriptions of frost rings, tree-ring width records and stable carbon isotopes ($\delta^{13}\text{C}$) from subfossil Scots pine (*Pinus sylvestris* L.) samples from Lapland (Fig. 1). In so doing, we present a new annually-resolved $\delta^{13}\text{C}$ record (1676-1533 BC), sensitive to reductions in incoming solar radiation potentially caused by emissions from explosive eruptions reaching the stratosphere (Robock 2000), the $\delta^{13}\text{C}$ record thus constitutes an additional proxy for past volcanic dust veils (Helama et al. 2018b). Combined, our annually dated tree-ring evidence adds to the ongoing discussion and illustrates exactly synchronous climate downturns at dates that reconcile the evidence gathered from the Northern Hemisphere sites, to seek answers to questions concerning the seasonal timing and provenance of the putative eruptions behind the anomalous summer climate conditions inferred from our tree-ring evidence.

2. Climate anomalies in the sixth century AD

2.1. Frost-damaged rings in AD 536

Symptoms of typical frost damage in subfossil Scots pine tree-ring materials (*sensu* Raitio 1992; Panayotov et al. 2013) were observed in thin sections stained with a safranin/alcian blue mixture generated from each sample using a cryo-microtome (Marjamaa et al. 2003). This damage is dated to the summer of AD 536 (Fig. 2a–c, Fig. 3a). These symptoms include a band of underlignified, deformed tracheids, illustrated with irregular cellular areas filled with wound parenchyma, as well as a band of disturbed tracheids/parenchyma formed with irregular structure and orientation. Their coinciding formation and presentation that follows the established formulation of frost rings (Glerum and Farrar 1966; Bräuning et al. 2016) suggests a common forcing i.e. frost event indicating a drop in minimum daily (most likely nocturnal) temperatures below the freezing point during the growing season/boreal summer (Hantemirov et al. 2000; Dy and Payette 2007; Gurskaya et al. 2016). As the wood formation in these trees starts in the last week of June and lasts until the first half of August (Schmitt et al. 2004), the frosts must have occurred somewhere in July. Apart from being frost-damaged, traits of less disturbed and even undisturbed growth were identified within the circumference of sample disks. So far, we have recorded the AD 536 frost ring at eight sites in Finnish Lapland. Overall, the sites represent conditions from the timberline to north boreal forests, altitudes from 75 to 399 meters above modern sea level and a wide latitudinal range (Fig. 1). Anatomical traits are not restricted to certain sites which suggests that the severity of the damage may result from microsite factors related to topography (Dy and Payette 2007) and/or slope exposure (Gurskaya et al. 2016). These results contribute to the literature that collectively indicates the existence of summertime frosts prevailing in western North America, Mongolia and the Altai mountains (LaMarche and Hirschboeck 1984; Baillie 2010; Salzer and Hughes 2007; D'Arrigo et al. 2001; Churakova (Sidorova) et al. 2014), demonstrating a climatic signal widely distributed over the Northern Hemisphere.

128

129 2.2. Multiple tree-ring proxies for AD 536-570

130

131 Ring widths show sudden reduction in tree growth in AD 536 and even lower growth (undamaged by
132 frost) in AD 542 (Fig. 2d). Moreover, these events start a period of low growth until the AD 550s or
133 even until the AD 570s. Similar to frost ring evidence, these growth anomalies are indicative of
134 abrupt cooling of summer temperatures. Even more reliable estimates of mean summer
135 temperatures, derived from chronologies of maximum latewood density, show a similar pattern of
136 sudden cooling in AD 536 and over the next two decades as reconstructed for the study region (Fig.
137 2e). Highly similar insights are shown from composite records of high-resolution proxy data collected
138 around the Northern Hemisphere, indicating a cool climatic phase starting in AD 536 and lasting until
139 the AD 550s (Sigl et al. 2015) or even the AD 570s (Larsen et al. 2008; Helama et al. 2017) (Fig. 2g).
140 Moreover, the tree-ring $\delta^{13}\text{C}$ proxy demonstrates reductions in irradiance nearly three standard
141 deviation from the long-term mean as reconstructed for AD 536 and over the AD 541-544 period
142 (Helama et al. 2018b) (Fig. 2f). Coinciding reductions in Siberian and British tree-ring $\delta^{13}\text{C}$ archives
143 may provide an indication of extended spatial scale of this irradiance anomaly (Loader et al. 1998–
144 1999; Churakova (Sidorova) et al. 2014), similar to indications from the documentary sources
145 (Weisburd 1985; Woods 2010).

146

147 3. Climate anomalies in the 17th and 16th centuries BC

148

149 3.1. Frost-damaged rings in 1627 BC

150

151 Frost rings in 1627 BC are demonstrated at five sites across Finnish Lapland (Fig. 1). These sites
152 represent conditions from the polar timberline to north boreal forests north of the Arctic Circle, both
153 western and eastern sides of the study region and altitudes from 207 to 399 meters above modern

sea level. Symptoms akin to those observed for AD 536 are evident for the formation of this tree-ring feature (Fig. 4a–c, Fig. 3b), and are illustrated with a band of deformed, crumpled and underlignified tracheids belonging to typical formation of frost rings (Glerum and Farrar 1966; Bräuning et al. 2016). Similar to that event, severity of the symptoms observed in 1627 BC was found to vary within the circumference of sample disks. Moreover, the tree-ring records spanning the event show an abrupt drop in pine growth from 1628 to 1627 BC (Fig. 4d–e). Here, we also present new $\delta^{13}\text{C}$ data from subfossil pinewood sample K14 (Fig. 4b). This record shows vigorous $\delta^{13}\text{C}$ variations through the period indicating a drop in irradiance coeval to 1627 BC (Fig. 4f). These findings add independent evidence for abrupt, cool conditions, probably culminating in July, in agreement with the frost-damaged rings in exactly the same year as previously demonstrated (LaMarche and Hirschboeck 1984; Hughes 1988; Salzer and Hughes 2007) from different tree species (Scots pine versus bristlecone pine), ecosystems (riparian/subarctic versus semi-arid/subalpine) and widely separated continents (eastern versus western hemisphere), and reinforce the hypothesis of volcanic forcing being largely responsible for the temperature drop, a tentative link proposed previously by several dendrochronologists based on their reporting of frost rings in bristlecone pine (LaMarche and Hirschboeck 1984; Hughes 1988; Salzer and Hughes 2007) and the coinciding narrow rings in Irish oaks (Baillie, and Munro 1988; Baillie 1990, 1998, 2010).

3.2. Other events in the 17th and 16th century BC

The Thera eruption (Marinatos 1939) is of wide archaeological interest. The calibrated ^{14}C dates have placed the eruption in the late 17th century BC (Friedrich et al. 2006, 2014; Manning et al. 2006, 2014), albeit the problematic nature of the calibration curve in this period has been pointed out (e.g. Bronk Ramsey et al. 2004). In these scenarios the 1627 BC date would appear to fall within the modelled probability (2σ) distribution of the ^{14}C dates. Recent studies have, however, raised concerns about potential climatically derived regional ^{14}C off-sets (Manning et al. 2018) or

inaccuracies in how the current IntCal13 curve (Reimer et al. 2013) represents past radiocarbon levels (Pearson et al. 2018). Pearson et al. showed that deriving a calibration curve based on annual ^{14}C measurements (rather than decadal/sub-decadal blocks) can offer a heightened accuracy for the representation of past radiocarbon levels and therefore offers a potentially more accurate means by which to calibrate ^{14}C date. Using a new annually-resolved section of radiocarbon calibration curve (ICCP17; 1700-1500 BC), they demonstrate how the posterior distributions for calibrated ages in a number of previously published modeling scenarios (for materials from pre-eruption contexts), shift into the 16th century BC (Pearson et al. 2018) relative to this new dataset. While this new possible date range provides an opportunity to juxtapose the Thera ^{14}C -evidence with those of the New Kingdom in Egypt (Bronk Ramsey et al. 2010), and so generate an archaeological synchronism between the Egypt and the Aegean, and a connection to a text-based date for the eruption (Foster et al. 1996; Höflmayer 2012), the shift also places the 1627 BC date outside the 2σ range.

Pearson et al. (2018) suggest four anomalies present in parts of the bristlecone pine tree-ring record could be used as a starting point for investigation of other proxy sequences as potential candidates for Thera: a narrow ring in 1597 BC (Salzer and Hughes 2007), a frost-damaged ring in 1560 BC, and two more narrow rings, in 1546 and 1544 BC, could also fit within the radiocarbon range on the plateau. There are, however, several issues central to the multi-proxy interpretation. The 1597/1560/1546/1544 BC dates may not currently be regarded as such large-scale anomalies: the 1560 and 1546 BC dates are positioned within negative departures in our $\delta^{13}\text{C}$ data albeit these excursions do not, similar to 1627 BC departure, represent excessively large $\delta^{13}\text{C}$ variation and may have initiated a year or more earlier (Fig. 4f; see also Fig. S1). Moreover, none of them are listed as notable growth anomalies in the Yamal or Swedish/Finnish Lapland chronologies (Salzer and Hughes 2007; Helama et al. 2013; Jones et al. 2013). Instead, a growth reduction in 1584 BC was previously discussed in connection to the Thera eruption (Helama et al. 2013). A high-resolution speleothem chronology shows peaks in bromine, molybdenum and sulfur at 1621 ± 25 BC, 1613 ± 25 BC and

1589±25 BC (Fig. 4g), respectively, suggesting a phasing apparently related to differences in retention rates in the soil (Badertscher et al. 2014). Accepting bromine as the primary volcanic tracer in this Turkish stalagmite (Badertscher et al. 2014), this evidence would agree with 1627 BC and 1597 BC dates for the eruption. Moreover, tablets inscribed by Babylonian astronomers suggest aerosol loading for 1627 and 1626 BC, with a probable eruption date between October 13th 1628 BC and May 1st 1627 BC (de Jong and Foertmeyer 2010) helping cement the relationship between volcanism (from Thera or other sources) and tree-ring growth anomalies observed for c. 1627 BC.

4. Discussion

Frost-damaged rings in AD 536 and 1627 BC reinforce the view of wide-spread summer temperature anomalies. Together with ice-core data, tree rings indicate climatic hardships in and after AD 536 including reductions in temperature and irradiance sufficient causing widespread crop failures and subsequent famine (McCormick et al. 2012; Toohey et al. 2016), and even creating circumstances preferential for the Justinianic Plague to rage in Constantinople, capital of the eastern Roman Empire, between AD 541 and 544 (Stathakopoulos 2000; Sarris 2002). An extra-Mediterranean context is relevant as the plague later spread widely not only to the entire Mediterranean but central Europe and, putatively, as far north as Finland over the coming decades and centuries (Seeger 1982). Although links between the volcanic signals in the Greenland ice-cores and tree-ring dates potentially related to Thera eruption have been reported (Hammer et al. 1987, 2003; Hughes 1988; Salzer and Hughes 2007; Vinther et al. 2008), thus far no evidence to support such connections appear conclusive (Abbott and Davies 2012). Analogues between the frosts suggest they are indeed connected with volcanic eruptions, in agreement with proxy and documentary evidence (Sigl et al. 2015; de Jong and Foertmeyer 2010). Sigl et al. (2015) propose eruption date late in previous or early in concurrent (AD 536) year, as did de Jong and Foertmeyer (2010) for 1626/1627 BC.

The Thera eruption may have been the largest known Holocene eruption (Johnston et al. 2014), however, the actual size and impact of Thera has been much debated (e.g. Pyle 1997; McCoy and Heiken 2000; Eastwood et al. 2002) and the effects of Mediterranean volcanism on climate are not as well established as they are for other regions. Therefore, the fact that our $\delta^{13}\text{C}$ data indicate responses to volcanic aerosols c. 1560/1546 BC should also be considered. The probable Northern Hemispheric provenance (indicating multiple North American volcanoes as likely candidates; Sigl. et al. 2015) leading to AD 536 event could imply that a similar volcanic source was behind the mid-summer 1627 BC frost event as both show clearly in the record from Lapland. Assuming that our new evidence is indicative of multiple eruptions (in 1627 BC and c. 1560/1546 BC), the former could be conceivably linked with Aniakchak (Alaska) eruption (previously associated with ice core dating to c. 1645 BC in Pearce et al. 2004) that may be younger than previously thought (Blackford et al. 2014; Davies et al. 2016). Blackford et al. (2014) report a radiocarbon sample from immediately below the tephra as dating to 1636–1446 cal yr BC (2σ) relative to IntCal13. Yet, we note that both the dating of this eruption (Pearce et al. 2017) and the provenance of the ice core tephra (Abbott and Davies 2012) are under discussion. Even so, the difference between the AD 536 and 1627 BC events appears as the former was followed by an eruptive episode probably from tropical sources in AD 539/540, with even higher global aerosol loadings than in AD 536 (Sigl et al. 2015), this volcanic double event resulting in remarkably strong decadal-scale Northern Hemisphere radiative forcing episode (Toohey et al. 2016). The spacing of several decades, as suggested here for the 17th/16th century BC eruptions, should not have allowed aerosol forcing pattern similar to such a double event to create climate anomalies to persist several years or even decades after the eruptions.

Last, as noted by Pearson et al. (2018), the annually dated ICCP17 curve highlights the danger of ignoring the radiocarbon plateau effect in considering the Thera ^{14}C -evidence, whereas the curve itself may still require further replication to ascertain the requested dating revisions. As for the tree-ring data, adding the frost ring for 1627 BC may suggest a previously unknown annual increment in

the data published as a part of the Finnish Lapland tree-ring width chronology (Zetterberg et al. 1996a, 1996b) and, as a consequence, in the data constituting the full 7.6 ka chronology (Eronen et al. 2002; Helama et al. 2008), an indication (i.e. a missing ring) that necessitates more detailed analyses. The narrow ring identified now for 1627 BC contributes to chronological and climatic assessments critically needed to detail the late seventeenth century BC records. The number of high-resolution, well-dated proxy records predating the medieval period is still low (Helama et al. 2017) and the spatial extent of reconstructed changes becomes increasingly uncertain further back in time. Despite the volcanic forcing is well demonstrated over the 1-2 year post-eruption period (Robock 2000), much remains to be elucidated about this forcing on longer scales that matter to resilience and adaptation of past cultures. Collaboration between scholars from humanities and natural sciences is needed to analyze the spectrum of climatic, environmental and human consequences during the protracted periods for which the anomalies evident as frost damages in AD 536 and 1627 BC may have been only the beginning. To this end, we emphasize a need of quantitative methodology based on multiple datasets to fingerprint volcanic effects from of growth, isotopic and elemental proxy data.

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541 FIGURE CAPTIONS

542

543 Fig. 1. Map showing the study area with the sampling sites in Finnish Lapland. Shown are the sites
544 with frost ring samples representing the AD 5356 and 1627 BC events, the northern timberline and
545 the Arctic Circle. Some of the nearby sites are marked with one circle. Photos by Samuli Helama
546 (1–2, 3, 5), Mauri Timonen (4) and Hannu Herva (6–8).

547

548 Fig.2. Frost ring in AD 536 in three samples K8-99 (a), NK2-6 (b) and N3-1 (c), the tree-ring width
549 series from these samples (d), the reconstructed summer temperature (Matskovsky and Helama
550 2014) (e) and irradiance (Helama et al. 2018) with 95 % confidence intervals for the study region (f),
551 and the mean record of temperature variability from thirteen proxy sites around the Northern
552 Hemisphere (Helama et al. 2017) (g). Scale bar is 0.2 mm (a–c).

553

554 Fig. 3. Frost rings in AD 536 (a) and 1627 BC (b) exemplified for the samples NK2-6 and K14,
555 respectively. Scale bar is 0.4 mm.

556

557 Fig. 4. Frost ring in 1627 BC exemplified for three samples K98-43(a), K14 (b) and HAT040/HAT041
558 (c), the tree-ring width series from these samples (d), and the mean records of the nine ring-width
559 series from our Scots pine trees spanning the 1627 BC event with 95 % confidence intervals (e), the
560 $\delta^{13}\text{C}$ record of K14 sample (f), and the stalagmite records of bromine, molybdenum and sulfur from
561 Sofular Cave (Turkey) (Badertscher et al. 2014) (g). Scale bar is 0.2 mm (a–c).

562