Mapping Henry: Dendrochronological Analysis of a Sixteenth-Century Panel Painting Based Upon Synchrotron-Sourced X-ray Fluorescence Mapping

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ABSTRACT

The study of materials that comprise artworks significantly contributes to understanding of age and provenance. While dendrochronology is a particularly valuable and well-established technique for panel paintings comprising oak timber, conventional practices of resurfacing end-grains to reveal tree rings is becoming less acceptable because it removes material, modifying the painting. Recently, application of non-destructive X-ray fluorescence (XRF) spectroscopy to a portrait of Henry VIII held by the Art Gallery of NSW (AGNSW) revealed tree-ring boundaries in the resulting high-resolution elastic scatter XRF map. In this study, we examine the dendrochronological potential of that mapping with the aim of contributing to resolving the relation of the AGNSW portrait to similar paintings elsewhere. Examination of the timber revealed affinities with *Quercus petraea* (Matt.). We measured tree-ring widths along multiple paths in the XRF scatter map and crossdated the resulting 81-year XRF ring-width ($XRF_{portrait}$)

series against master chronologies of English, western European, and Baltic origin. Rather than an arbitrarily defined threshold, we used a Bonferroni correction to determine a minimum significance level for crossdating. While the $\text{XRF}_{\textit{portrait}}$ series did not crossdate with the continental European chronologies, we identified a single significant ($\alpha = 3.4 \text{ x } 10^{-6}$) dating position with the English chronology (1400-1480 CE). Cross-matching with site-level chronologies revealed a cluster of high *t*-values in central-southern England. The earliest date of felling precedes the documented date of completion for the AGNSW and two similar Tudor portraits of Henry VIII held by the National Portrait Gallery (NPG), London and one at the Society of Antiquaries, London. While, the apparent British provenance of timber used in the AGNSW portrait contrasts to Baltic origin of timbers used for the two NPG portraits and the majority of English panel paintings, it is consistent with the provenance of the timber used for the Society of Antiquaries portrait.

KEYWORDS

Oak, Bonferroni, Henry VIII, XRF, crossdating, provenance, Tudor, portrait, panel painting

INTRODUCTION

Knowledge of the age and provenance of materials significantly contributes to the understanding of historical artworks, particularly where documentary information is sparse or absent. For pieces comprising timber, dendrochronology—the science of tree-ring dating—is a well-recognised source of both age and provenance data (Čufar 2007). Beyond enriching interpretation of a suite of wooden objects including panel paintings, statuary (Haneca et al. 2005a; Kim et al. 2013) and musical instruments (Topham and McCormick 2000; Burckle and Grissino-Mayer 2003), dendrochronological data from investigations of artworks have also shed light upon aspects of historical trade (Bonde et al. 1995; Wazny 2002) and human culture stretching to the Neolithic period (Becker and Kromer 1986; Hillam et al. 1990; Viellet 2002).

Dendrochronology relies upon the presence of identifiable annual rings as well as consistency in the response of trees to climate. Where the latter exists, sequences of tree-ring widths may be statistically cross-matched between trees. This quantitative process of *crossdating* facilitates age determination of timbers for which felling dates are unknown, and development of well-replicated and precisely dated master chronologies. The availability of preserved archaeological timbers means that master chronologies may extend well beyond the lifespan of individual trees, an outcome fundamental to dating wooden artefacts of unknown age.

The statistical strength of dendrochronological crossdating is shaped both by similarities in the growing conditions experienced by trees as well as their individual responses to those conditions. While species-level growth traits, micro-site differences, sociological ranking, and extrinsic disturbances can significantly affect crossdating between trees growing on the same site, spatial variability in climate means the relative proximity of the materials under examination can affect crossdating strength between sites. While this spatial dependence presents limitations, distance dependence in the similarity of tree-ring series also presents opportunities to identify a regional provenance for historical timbers.

The use of dendrochronology in revealing the age and provenance of artworks is well documented for panel paintings. Dendrochronological techniques were first applied in examinations of the supports used for panel paintings in the 1970s (Bauch and Eckstein 1970) and, since, have been applied to a host of studies of Dutch and English artworks (Fletcher 1976;

Bauch and Eckstein 1981; Fraiture 2009), contributing valuable objective data to subjective interpretations of authorship and authenticity.

The utility of dendrochronology in examining panel paintings reflects key attributes of timbers comprising the panels. In particular, while a range of tree taxa were used for panel paintings, timber from two oak species—sessile (*Quercus petraea* (Matt.) Liebl.) and pedunculate (*Quercus robur* L.) oak—were particularly sought after by Dutch and English artists (Haneca et al. 2009). Both species are relatively long lived, widely distributed throughout continental Europe and the British Isles, form durable timber with easily identifiable tree rings, and exhibit similar responsiveness to climate variability. Their strength and durability mean both timbers were widely used for construction and shipping. Consequently, extensive repositories of preserved oak timber exist in modern architectural structures and, when combined with materials from extant oak populations, have supported development of a dense network of long oak tree-ring chronologies throughout Europe (Bonde et al. 1995; Bridge 2012) that are well suited to both dating and dendrochronological provenancing.

While it offers significant gains in knowledge, dendrochronological investigation of wooden relics also places them at risk. The end-grains of panel paintings, for example, must be resurfaced (*i.e.* sanded or laser ablated) to adequately reveal the anatomical features necessary for tree-ring identification. Although focussed on the non-facing side of a panel painting, the resurfacing process subtly modifies the artwork and risks inadvertent damage. The desire to minimise or entirely eliminate this modification of artworks and other timber relics is an ongoing stimulus for research into non-destructive dendrochronological techniques. Indeed, X-ray computed tomography (CT) has been the applied to dendrochronological studies of cultural objects for decades and recent advances in microscopic–CT imaging techniques (Van den Bulcke et al. 2014) have enabled rapid, non-destructive examination and dating of a range of timber statuary and musical instruments (*e.g.* Okochi 2016; Van den Bulcke et al. 2017). While the structural attributes of oak timber means it is well suited to examination using CT imaging (Van den Bulcke et al. 2014; Vannoppen et al. 2017), the technique offers little for interpretation of artistic aspects of painted artworks. Thus, while holding potential for dendrochronological investigations, CT imaging has limited application in conservation-focussed studies of panel paintings.

By detecting and resolving the distribution of metallic elements embedded within pigments, application of X-ray fluorescence (XRF) spectroscopy permits detailed interpretations of painted artworks. Although long detection times have previously limited the scale and resolution of the technique (*e.g.* Dik et al. 2008), recent advances in sensitivity and acquisition speed mean that XRF-based elemental mapping of large artworks is now possible at micron scales (Pushie et al. 2014; Howard et al. 2020). As a consequence, synchrotron-radiation sourced XRF can now yield fascinating and highly valuable insights at the scale of entire artworks (*e.g.* Alfeld et al. 2013) and is particularly useful in studying paintings that have previously proven difficult with conventional techniques (*e.g.* Howard et al. 2012; Thurrowgood et al. 2016). Critically, in addition to exposing the properties of the painted layers, XRF may also reveal properties of the supports underlying an artwork. Specifically, X-ray scattering is sensitive to lighter elements within organic materials and may permit quantitative analyses of variations in matrix properties of supporting materials. Howard et al. (2012), for example, reported that the canvas weave underlying a self-portrait of Sir Arthur Streeton was revealed by inelastic (Compton) scattering mapping with a monochromatic beam energy of 12.6 keV at a resolution sufficient for thread counting. More recently, Dredge et al. (2015) reported that elastic (Rayleigh) scatter maps from

XRF scans conducted at 18.5 keV revealed the wood grain of the underlying oak support of the AGNSW Henry VIII portrait. This observation supported reported associations between variation in intra-annual tree-ring structure and XRF-derived elemental concentrations (Scharnweber et al. 2016), and between XRF-imaged grain and anatomically defined tree-ring boundaries (Smith et al. 2014). These associations suggest high-resolution XRF imagery may be a source of non-invasive dendrochronological as well as artistic data.

In this study we examine the dendrochronological potential of tree-ring width data extracted from the elastic scatter mapping of the Henry VIII painting described by Dredge et al. (2015). The portrait is painted on oak panels and, while acquired in 1961, had remained in storage due to its poor condition. In response to deterioration and potential alteration in the 500 years since the original painting's completion, a conservation project was undertaken with three aims; to (a) identify, characterize, and record the surviving material, (b) distinguish and potentially remove any non-original alterations and additions, and (c) present the portrait more closely to its original conception.

The AGNSW portrait was historically catalogued as Anglo-Netherlandish (1535-40 CE) due to characteristic compositional conventions deployed in the painting. Specifically, the monarch sits in an apparently recessed space with hands resting on a cushioned ledge. Portraits similar to the AGNSW Henry VIII exist in prestigious English collections—two in the National Portrait Gallery (NPG 1376 and NPG 3638) and a third in the Society of Antiquaries in London (LDSAL 333). While costume details, the positioning of the fingers, and slight variations in the measurements differ between the portraits, their composition and execution are consistent with a single workshop producing likenesses of the King for display by members of the English elite. Little is known of the artists working in London prior to 1540—many were foreign immigrants working alongside native Londoners and thus the authorship of these paintings is often given as an unknown Anglo-Netherlandish workshop (Strong 1969; Cooper and Howard 2015).

If painted in the lifetime of Henry VIII, the AGNSW portrait is both an artwork and historical document—a rare survivor of a period from which few records remain. By analysing the material structure of the entire object, from wooden support to paint layers and mediums, study of the panel aimed to identify the materials and characteristic details of its manufacture and execution. These details could not only clarify the origin of the portrait, but also its relationship to similar portraits held by the NPG and Society of Antiquaries—shedding further light on the artists and workshops that were producing them as well as guiding the conservation of the artwork.

Specific knowledge of the panel's structure and details of its production would also allow comparison with similar portraits and provide precise and objective information as to the age of the artwork—corroborating or refuting subjective art-historical inferences. Thus, we investigated the potential to date and provenance the timber supports by crossdating tree-ring width data extracted from the scatter mapping against master chronologies from continental Europe and Great Britain. In addition to offering the opportunity to test the potential of XRF dating, our work aimed to aid in resolving the relation of the AGNSW portrait to the other similar paintings of Henry VIII, which have undergone previous dendrochronological study (Fletcher 1976).

MATERIALS AND METHOD

The AGNSW portrait

The support of the AGNSW Henry VIII portrait comprises three vertically aligned oak boards (Figure 1). Consistent with the dominant trend and traditional guild rules for panel manufacturing (Wadum 1998), the boards of the AGNSW portrait are radially sawn and the most recently formed (youngest) rings are centrally located in the two central boards. The sawing technique used in producing the panels as well as their arrangement means that tree rings within the boards are orientated perpendicular to the painted surface (Figure 1). The right-most board is an addition and not original to the painting. Photographic evidence indicates its addition during 1945–46, to replace a lost section of the painting along the right-hand edge. In light of its later addition, the right-most panel was not considered in this study.

The panel edges of the original boards are rough-sawn and coated with varnish and wax. These aspects of the edges, combined with growth distortions associated with the position of branches near the panel edge (Figure 1), restricted direct identification of tree rings on the raw panel edges to non-contiguous spans of 10-20 rings.

[INSERT FIGURE 1]

Species-level affinities

The two widely distributed oak species commonly used as supports for panel paintings—*Q. petraea* and *Q. robur*—may be distinguished from botanical traits (Kremer et al. 2002). Differentiation of the species based upon their timbers is more complex, requiring data on multiple wood anatomical traits. Species-level identification is further complicated by hybridisation and introgression between the species (Gardiner 1970). Nevertheless, tendency towards one of the two species may be indicated through bi-variate classification of the number of earlywood vessel rows and latewood percent (Feuillat et al. 1997).

We obtained quantitative vessel and latewood data from x7.5-power photomicrographs of the panel end grains. We captured photomicrographs using a Leica IC80 HD in-line camera mounted on a Leica microscope. We estimated latewood percent from radial measurements of both early-and latewood widths using WinDendro© (Guay 2012) in all measurable rings. Vessel rows were counted within the same rings. Consistent with key anatomical traits reported within the InsideWood online database (Wheeler 2011), we also recorded the appearance of latewood vessel groups as an additional diagnostic feature.

XRF elastic-scatter mapping

The scanning XRF used to generate the elastic scatter mapping used in this study was conducted at the X-ray fluorescence microscopy beamline at the Australian Synchrotron (Howard et al. 2020). Scanning of the AGNSW Henry VIII portrait is described in detail by Dredge et al. (2015). Briefly, scans were conducted of the entire panel at 12.6 and 18.5 keV. X-ray fluorescence data were collected using the Maia 384A detector at a 120 μm^2 resolution and deconvoluted into elemental and scatter maps using the GeoPIXE software suite (Ryan et al. 1990). As reported by Dredge et al. (2015), the underlying structure of the boards comprising the AGNSW Henry VIII portrait is evident within both 12.6 and 18.5 keV scatter mapping. While masked at both excitation energies, underlying structure of the panel was best revealed by the 18.5 keV elastic scatter map.

Tree-ring measurement

Objectively dating tree-ring width series of unknown age relies upon calculating goodness-of-fit statistics with an established master chronology. Pearson's correlation coefficient (*r*) is typically used as the measure of linear association and Student's *t* as an expression of the probability of achieving *r* by chance. Individual *r*-values are generated as the master and floating series are passed by each other *in silico*, generating distributions for *r* and *t*. An individual extreme-positive outlier at the upper end of the latter reflects the most likely, and theoretically correct, dating position (Baillie and Pilcher 1973; Fowler and Bridge 2017).

The length of an undated series presents a major limitation to crossdating. That is, to be suitable for crossdating, undated series must exceed a minimum length to adequately express the impact of climate on growth and reduce the probability of multiple and false dating positions (Wigley et al. 1987). Although this minimum span is affected by the climate responsiveness of the tree-ring series under examination (Haneca et al., 2009), a span of 50 years of continuous tree-ring width data is generally required for unambiguous crossdating of oak panels (Bauch and Eckstein 1970). The spans for which tree-ring widths could be reliably quantified from the end grains of the boards used in AGNSW portrait did not meet this criterion and were insufficient for dendrochronological dating.

Examination of panel end grains indicated that dark banding in the 18.5 keV elastic scatter map, apparent as wood granularity (Figure 1), corresponded with the position of earlywood vessels in the photomicrographs. Very high correlation between measured photomicrographic and XRF ring-width series (Figure 2) was consistent with this observation. Consistent with an earlier study of a canvas-based portrait (Howard et al. 2012), the clarity of features within the underlying support in the AGNSW portrait varied throughout the XRF imagery. Clarity was also impacted by damage to the left-central support attributed to wood boring insects. To overcome these limitations, we used WinDendro© to measure tree-ring widths along multiple overlapping paths in the two original—left and central—panels. Very strong correlation between the mean ring-width series from the left and right panels (Figure 2) indicated that the timbers were sourced from the same tree. Thus, we combined the respective series within a single portrait-level ($\mathrm{XRF}_{portrait}$) mean

[INSERT FIGURE 2]

Crossdating

We performed crossdating within the program COFECHA (Speer 2010). Briefly, COFECHA allows undated tree-ring series to be quantitatively compared to established master series. The program first allows tree-ring width trends that are assumed to be non-climate in origin as well as autocorrelation reflecting lagged biological effects within the source tree to be removed to produce a stationary indexed series. Linear cross-correlations are then calculated at all possible positions for which the length of overlap between the undated and master series are equal to or greater than a minimum user-defined span.

As a large portion of decadal-scale variation in oak ring widths is site or tree specific, highly flexible standardising functions may be used to strengthen correlation, and improve the likelihood of a correct match, between tree-ring series. Although underpinning much early crossdating of oak (Baillie and Pilcher 1973), the use of high-pass filtering using five-year moving averages induces phase shifts in the resulting series and can generate spurious dating outcomes (Fowler and Bridge 2017). Alternatively, cubic smoothing splines with a 50% frequency cut-off over eight years similarly reduce decadal-scale variability while avoiding the associated phase shifts (Fowler and Bridge 2015). Consistent with this latter approach, we indexed each of the panel- and portrait-level ring-width series using a smoothing spline with an eight-year frequency response. As highly flexible splines remove much of the decadal-scale variability in ring-width series, a high proportion of the retained variance reflects inter-annual climate variability. In these instances autoregressive modelling is not recommended within COFECHA and was not applied to the indexed XRF series.

The process of crossdating generates correlation estimates for individual chronology spans over multiple dating positions. This process greatly increases the risk of a Type I error above the probabilistic threshold conventionally accepted for hypothesis testing (*i.e.* $\alpha=0.05$). While arbitrary threshold values of r and Student's t may be applied to address this problem (Haneca et al. 2005b), we used the Bonferroni adjustment to derive appropriate significance levels and determine critical thresholds for r and t. Bonferroni-adjusted significance (α_B) may be defined as;

(Equation 1) $$\alpha_B = \frac{\alpha}{m}$$

where α is the null-hypothesis significance-testing threshold—typically 0.05—and m, the number of comparisons. In a tree-ring dating context m is calculated as the product of possible dating positions against the master chronology and spans of defined length tested from the undated series. A critical value for t (t_{crit}) is then derived from Student's t-distribution, defined by α_B and the user-defined span length in years (n), and r_{crit} calculated as;

(Equation 2) $$r_{\text{crit}} = \frac{t}{\sqrt{n-2+t^2}}$$

Spatial differences in climate and tree-ring width variability between continental Europe and the British Isles means that crossdating timber of unknown origin must be tested against chronologies representing each region. To test crossdating within continental Europe, we used the Hamburg (CE 1340-1967) (Eckstein 2002) and East Pomerania (CE 996-1986) (Wazny 1996) chronologies. These chronologies respectively represent tree-ring variability within western European and Baltic regions and were obtained via NOAA Palaeoclimatology Data Search (www.ncdc.noaa.gov/paleo-search). Crossdating within Great Britain was tested using a regional composite *Q. robur–petraea* chronology (663-2009 CE) for south-central England (SC

England) (Wilson et al. 2013). To assess the stability of dating positions, crossdating was tested for 50-year spans within the $XRF_{portrait}$ series lagged successively by one year (*i.e.* successive spans overlapped by 49 years). As the reference series already exist in an indexed form, no standardisation was applied to the Hamburg, East Pomerania or SC England master chronologies within COFECHA prior to crossdating.

Provenancing

Preliminary analysis indicated satisfactory crossdating for a single dating position with the SC England chronology for both panels. In response, we tested crossdating within *Dendro for Windows* (Tyers 1997) between $XRF_{portrait}$ series and a large (n > 2000) set of dated English and Welsh tree-ring chronologies, held collaboratively by the Oxford Dendrochronology Laboratory and University College London, with the aim of identifying the most likely possible geographic origin of the source timber. Comparisons were restricted to series for which a 50-year minimum overlap existed with our series. To identify a possible provenance, r-values were calculated for the total overlapping period between the standardised $XRF_{portrait}$ series and each site-level chronology standardised using a five-year moving average (Baillie and Pilcher 1973). While this standardisation method can generate phase shifts, affecting dating, its application within the site-level dating offered the opportunity to test the robustness of dating generated separately within COFECHA. The open-source mapping platform QGIS (www.qgis.org) was used to plot t-values associated with site-level correlations.

RESULTS

Species-level affinities

Measurements of latewood and vessel rows were restricted to 59 clearly identifiable rings on the lower edge of the two central panels. Mean latewood comprised 66.6 % (SD = 10.2; $n = 59$) of tree-ring width—within the range for both *Q. robur* and *Q. petraea* (Feuillat et al. 1997). Vessel rows were often singular with a mean of 1.28 (SD = 0.50; $n = 59$) vessel rows per ring. While within the range for *Q. petraea*, this mean is well below that reported for *Q. robur* (Feuillat et al. 1997). Latewood vessel bands also exhibited a narrow strap-like form with occasional bifurcations (Figure 3) that are more consistent with *Q. petraea* than *Q. robur*.

[INSERT FIGURE 3]

Measurement, crossdating, and provenancing

Identification of features consistent with tree-ring boundaries was conducted along 15 separate paths in the two central panels. In addition to poor clarity associated with overlying paint layers, narrow tree rings obscured tree-ring boundaries, restricting individual path lengths. The aggregated mean series represents approximately three-quarters of the central panels, including the innermost (most-recently formed) ring in the panel and spans 81 rings.

COFECHA failed to identify a cross-match between the $XRF_{portrait}$ series and either of the Hamburg or East Pomerania master chronologies (Table 1). However, a single dating position exceeded the Bonferroni-adjusted t_{crit} and r_{crit} thresholds within the SC England chronology. Specifically, highly significant ($\alpha = 3.4 \times 10^{-6}$) correlation is evident for the composite $XRF_{portrait}$ series for the period 1400-1480 CE. While correlation between the SC England chronology and the entire length of the $XRF_{portrait}$ series is moderate ($r = 0.50$) the 1400-1480 CE date is an extreme outlier within the distribution of t-values for all positively correlated overlaps with the SC England chronology (Figure 4a). This position, then, represents the only probable dating position. Correlation also exceeded the Bonferroni-adjusted significance threshold for all of the 32 50-year spans tested within COFECHA. The distribution of the associated *t*-values (Figure 4b) is relatively normally distributed, ranging between 3.10-5.42 with an almost identical mean and median.

[INSERT TABLE 1 AND FIGURE 4]

Crossdating with English and Welsh site-level chronologies generated *t*-values exceeding 3.0 for 218 unique sites (Figure 5). Only sites with $t > 3.5$ can be regarded as satisfying a conventional significance threshold ($\alpha < 0.05$). A small cluster of highly significant *t*-values is evident in the central-southern English counties. This cluster includes the ten highest correlations (Table 2) between the $\mathrm{XRF}_{portrait}$ series and site-level chronologies within the available dataset.

[INSERT FIGURE 5 AND TABLE 2]

DISCUSSION

Measurement of XRF-derived ring widths

The direct observation of tree-ring boundaries on stem cross-sections was foundational during the establishment of dendrochronological sciences and remains so in the vast majority of the current literature. In addition to facilitating tree-ring measurement, direct observation permits examination of anatomical features that aid crossdating and add considerable depth to interpretation of the environmental history embedded within the rings themselves. Where necessary, direct observation of timber also permits identification of the species from which the timber was collected. However, as the science of dendrochronology has progressively expanded to consider geographic regions and species of the world in which tree-ring boundaries are indistinct, the role of indirect tree-ring identification via isotopic and X-ray techniques has increased in importance. The use of non-destructive techniques suited to dendrochronological dating of cultural relics has developed in parallel with these advances.

In this study, direct identification and measurement was only possible for several short (<10 years) discontinuous ring series on the panel end-grain of the AGNSW Henry VIII portrait. These measurements permitted wood anatomical investigation, revealing a closer affinity to *Q. petraea* than *Q. robur* within the panel timbers. However, directly measured series were of insufficient length for crossdating. Alternatively, an existing XRF dataset, generated as a product of conservation-based studies of the painted surface, presented an opportunity to explore the temporal and geographic origins of the timber. The use of XRF data is relatively rare in dendrochronology and has, to date, largely focused upon forensic investigation of environmental contamination (MacDonald et al. 2011; Rodriguez et al. 2018; Lehmann and Arruda 2019). Only very recent studies have considered its potential for climatological (Sánchez-Salguero et al. 2018) or geological (Hevia et al. 2018) reconstructions. Although it has been known for some time that heterogeneity within tree rings, such as the matrical differences between earlywood and latewood in *Quercus* spp, can affect XRF results (Smith et al. 2008), we are aware of no attempt, prior to this study, to date timber based upon XRF-derived ring-width data alone.

The very strong positive correlation between direct and XRF-derived data in this study confirmed an earlier suggestion by Dredge et al. (2015) that dark banding within XRF mapping of the Henry VIII portrait corresponds with the position of tree-ring boundaries. While this banding represents variation in elemental concentrations rather than density *per se* (Smith et al. 2014), the two variables—density and elemental concentration—are likely correlated within rings. That is, the earlywood in the panels examined in this study is likely to have both lower density and elemental concentration relative to latewood as a consequence of the large open lumens characteristic of ring-porous oak. The apparent association between these wood traits in this study is consistent with that evident in both *Pinus* and *Castanea* (Scharnweber et al. 2016).

Masking of the underlying wood structure by overlying paint meant that tree-ring boundaries were only sufficiently distinct to allow objective identification in a number of non-contiguous areas of the portrait. For example, areas overpainted with pigments comprising copper (surrounding the sitter's head and shoulders) and mercury (face and beard) were heavily masked and tree-ring boundaries largely indistinguishable. In contrast, tree-ring boundaries were relatively clear in portions of the portrait comprising dark pigmented paint (sitter's hat and vest) or gold-leaf. Thus, while variability in masking presented a limitation to measurement, the availability of the entire surface of the portrait allowed a derivation of composite ring-width series for both of the central panels.

Consistent with the construction of many panel-painting supports, tree rings were largely orientated perpendicular to the painted surface in the panel under investigation. While a small number of rings intersected the outer edge of the centre-left panel at an oblique angle, this angle did not appear to attenuate the scatter intensity associated with tree-ring boundaries. That is, the boundaries remained narrowly defined and relatively distinct. Nevertheless, since width of the interval between two boundaries is directly proportionate to the angle of intersection, measurement of obliquely angled rings may have led to consistent over-estimation of the associated tree-ring widths. While a potential problem for derivation of tree growth rates, this over-estimation is unlikely to have affected our crossdating given the highly flexible spline used in this study.

It is important to note that in regions of narrow ring widths the resolution of the X-ray scatter signal was insufficient to identify tree-ring boundaries and ultimately restricted the length of the resultant ring-width series. This limitation may present a significant impediment for application of XRF-based measurement for panels comprising slow-grown oak timbers, such as those of Baltic origin (Haneca et al. 2005b)

Crossdating and provenancing

High inter-series correlation between ring-width series from the left- and right-centre panels suggested that both originated from the same tree and allowed derivation of a composite $XRF_{portrait}$ series. Objective crossdating of $XRF_{portrait}$ against the absolutely dated SC England chronology indicate a formation period of 1400-1480 CE. This position was the only one exceeding an objectively derived adjusted significance level within any of the oak master chronologies we tested. The significance level associated with our crossdating results exceed the adjusted threshold by an order of magnitude and exhibit an extremely low probability—less than 1 in 294,000—of having arisen by chance. Thus, while the importation of oak timber from Baltic regions of continental Europe is well recognised, the central boards of the panel under investigation appear to have been sourced within Great Britain.

A second phase of dating, against site-level chronologies using five-year moving averages generated an identical dating position and identical t-value as generated using smoothing splines within COFECHA. Mapping of t-values indicated moderate spatial variability in the strength of site-level crossdating within the oak database for England and Wales. Higher t-values suggest a provenance within a 150 km arc across several southern English counties. It is tempting, based upon the highest t-value for correlation between the $XRF_{portrait}$ series and the oak database, to attribute the panel timbers to a single site for which the associated t-value exceeded 6.50. However, high t-values associated with any one point must be considered with caution. Correlation between tree-ring series reflects both geographic proximity as well as environmental similarity between growing sites. Relative to that of continental Europe, Britain's climate exhibits a relatively high level of spatial inconsistency. That is, the relation between locations is relatively unstable and, as a consequence, site-level tree-ring chronologies contain a weaker geographic and relatively greater site-specific content than exhibited by European datasets (Fowler and Bridge 2015). Examples of living oak timbers correlating highly with locations far from their known origin (Bridge 2000a; Bridge 2012) illustrate this problem. An additional caveat is that chronologies within the oak database are the product of opportunistic sampling associated with historical investigations of built structures. Transportation of timber for large construction projects as well as subsequent recycling means that buildings, and their associated chronologies, may comprise remotely sourced timbers that do not represent their current location.

Notwithstanding the caveats raised above, the absence of significant crossdating results for either of the Hamburg or East Pomerania chronologies is highly supportive of, at the very least, a British rather than continental European provenance for the panel timbers. Further, while we express caution in over-interpretation, the spatial clustering of relatively high correlations within a set of neighbouring sites suggests a possible provenance within the central-southern counties of England.

Time of felling and completion

Consistent with the typical composition of oak panel paintings, the timbers comprising the AGNSW Henry VIII portrait lacked any obvious sapwood. Thus, only an earliest-possible felling date (*terminus post quem*) can be estimated for the panels by adding the year of the most-recent dated ring to the minimum likely number of excised sapwood rings (Miles 1997). Sapwood ring counts range widely within oaks and significant variability has been reported between European regions (Haneca et al. 2009), within trees (Hughes et al. 1981) and, for British oak, between northern and southern counties (Miles 1997). For example, while a minimum of 10 sapwood rings is appropriate for estimating *terminus post quem* for timber of unknown provenance within the British Isles (Hillam et al. 1987), a slightly lower minimum (nine rings) is acceptable for timber with a known provenance in southern Britain (Miles 1997). The latter minimum is of greater relevance in this instance given the suggested southern provenance for the timber and yields a *terminus post quem* of 1489 CE (*i.e* 1480 CE outer measured ring plus a minimum of nine sapwood rings). This date is prior to the documented date of completion for the portrait (1535–1540 CE).

The *terminus post quem* for the timber supports of the AGNSW Henry VIII portrait is earlier than that for the two portraits of King Henry VIII within the NPG collection (NPG 1376 and NPG 3638) as well as that in the Society of Antiquaries (LDSAL 333) attributed to Anglo-Netherlandish artists and of the same workshop. While documentary evidence dates the NPG portraits to 1535-1540 CE, dendrochronological dating of the panels indicate earliest-possible felling dates of 1512 (NPG 1376) and 1521 (NPG 3638) (National Portrait Gallery 2015). The Society of Antiquaries portrait felling date is given as 1507-1543 (Franklin et al. 2015). We stress, however, that caution must be applied in interpreting the apparent differences between earliest felling dates between the AGNSW and other portraits. Specifically, the number of heartwood rings excised during the panel's construction cannot be estimated and a later felling date is indeed possible.

Baltic timber was a preferred source of timber for panel paintings during the period as a consequence of the stability associated with its slow-grown, fine-grained texture (Haneca et al. 2005b). The English provenance of the AGNSW portrait contrasts with the Baltic origin of the timber used as supports for the two similar paintings in the NPG collection and the majority of English panel paintings (Hillam and Tyers 1995). However, the panel to which the AGNSW portrait bears the most striking resemblance—the Society of Antiquaries (LDSAL 333)—is also of southern English provenance (Franklin et al. 2015). That observation offers an important link between the AGNSW portrait and the others in the Tudor group and supported decisions to base subsequent reconstruction of excised parts of the original panel on the compositionally similar Society of Antiquaries panel.

CONCLUSION

Advances in sensor platforms and imaging techniques have greatly enhanced the capability of XRF for investigations of historical artworks. While these advances have led to a flourishing of studies aimed at artistic components, we are unaware of any study prior to this one that has relied solely upon XRF-derived data for dendrochronological dating and provenancing. While alternative non-destructive techniques such as CT tomography are relatively well established for dendrochronological investigation of wooden artefacts, our results suggest that XRF offers a new pathway for conservators seeking data on the age and source of materials to support qualitative stylistic assessments of the painting itself. Importantly, our investigations revealed an evident consistency in the provenance and time period of the timbers used in the portrait under study and similar paintings with which it appears art-historically associated, shedding light on the panel’s construction and history as well as helping guide restoration treatment.

While spatial analysis indicates a provenance of the timbers used in the panels examined in this study within southern Britain, we note that the provenancing for oak timbers of British origin has previously proven to be misleading. Nevertheless, the absence of crossdating between the ring-width series derived in this study and western European or Baltic master chronologies is highly suggestive of a British origin for the timber used in the AGNSW portrait. The apparent consistency in provenance of the portrait and a painting with which it has been previously associated is additionally suggestive of a common origin.

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DECLARATION ON INTEREST STATEMENT

No potential conflict of interest was reported by the authors

Table 1. Crossdating threshold values and summary statistics for position of best fit with the continental Europe and British Isles master chronologies. Bonferroni-adjusted significance (α_B) and critical values for r (r_{crit}) and t (t_{crit}) reflect the number of possible dating positions (m) between each chronology and the XRF*portrait* series. Calculated values for r ($r_{\max}$) and t ($t_{\max}$) are reported for the dating position of highest correlation for the entire span of the indexed XRF*portrait* series. Significance associated with this best fit is also reported. Bold text denotes dating positions exceeding the Bonferroni-adjusted threshold.

Chronology	m	α_B	t_{crit}, r_{crit}	Span (CE)	$t_{\max}$, $r_{\max}$	α
Hamburg	548	9.1×10^{-5}	4.12, 0.42	1458-1538	3.76, 0.39	3.2×10^{-4}
East Pomerania	910	5.5×10^{-5}	4.26, 0.43	1326-1406	3.76, 0.39	3.2×10^{-4}
South-central England	1267	3.9×10^{-5}	4.35, 0.44	**1400-1480**	**5.20, 0.50**	$\mathbf{3.4 \times 10^{-6}}$

Table 2. Summary statistics for matches with regional and site-level English tree-ring chronologies. Span reflects the range between the first and last measured rings within each series. Overlap and t-value associated with the 1400-1480 CE best match with the XRF$_{portrait}$ series are reported. Chronology file names and citations associated with superscripted numerals are reported for each chronology below the table.

Location	Chronology name	Span (CE)	Overlap (yrs)	t-value
Regional chronology				
England	Southern Central England[1]	663–2009	81	5.2
Site chronologies				
Surrey	Picketts Farm, Salfords[2]	1347–1451	52	6.7
Hampshire	Winchester Deanery roof [3]	1264–1499	81	6.1
Wiltshire	The Old Mansion, Clarendon[4]	1315–1625	81	5.9
West Sussex	Field Place Barn[5]	1309–1465	66	5.6
Hampshire	Old Stables, Pilgrims Hall, Winchester [6]	1245–1478	79	5.5
Sussex	Avery's Farm Barn, Cowfold [7]	1377–1535	81	5.2
Berkshire	Round Tower, Windsor Castle [8]	1385–1468	69	5.1
West Sussex	St Andrew's Church, Ford[9]	1286–1511	81	5.1
West Sussex	Gaskyns, Slinfold[10]	1321–1488	81	4.9
Hampshire	Burhunt Barn[11]	1377–1506	81	4.8
Surrey	Home Farm, Newdigate[12]	1261–1483	81	4.8

[1]SCENG (Wilson et al., 2013); [2]PICKETTS (Miles et al. 2006); [3]DWCx1 (Bridge and Miles 2016); [4]CL TOM (Tyers 1999); [5]FIELDPB (Bridge 1993); [6]PILGRIM2 (Alcock 2009); [7]COWFOLD (Tyers 1990); [8]WINDSOR2 (Miles and Haddon-Reece 2003); [9]FORD (Bridge 2000b); [10]GASKYNS1 (Miles and Worthington 2002); [11]BURHUNT (Alcock and Tyers 2013); [12]NEWDIG1 (Bridge 1998)

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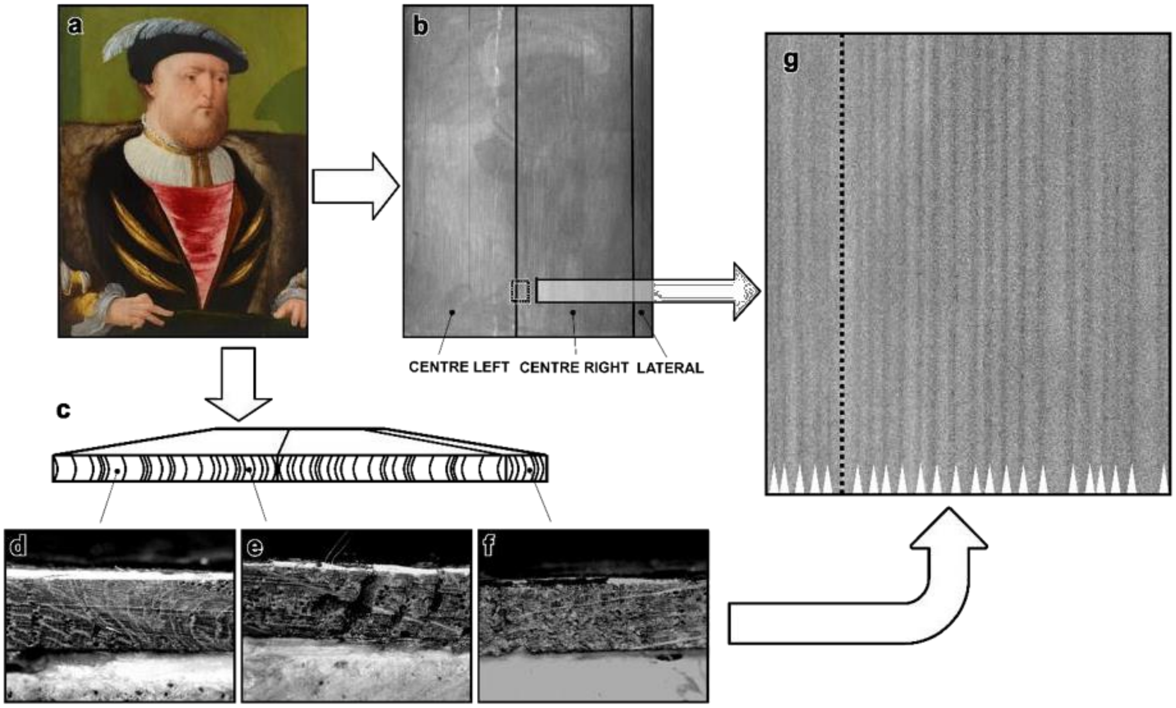

Figure 1 Three vertically alignd oak boards comprising the support of the AGNSW Henry VIII portrait.

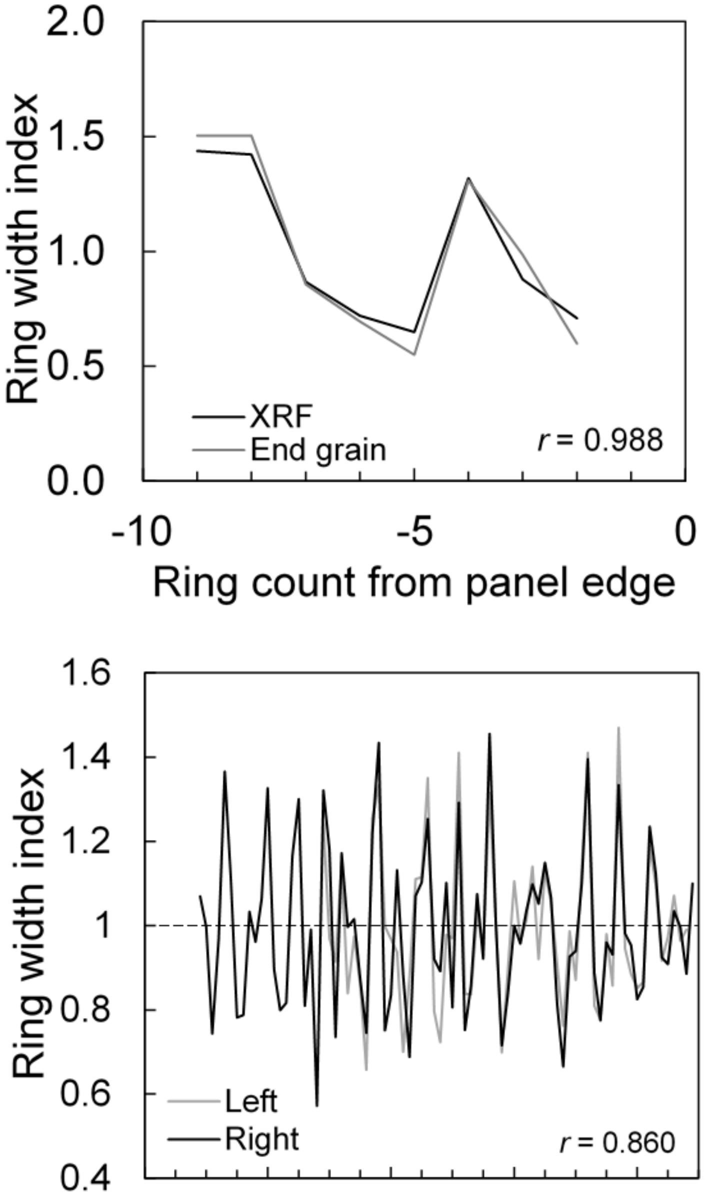

Figure 2 Upper: Panel end grains indicating dark banding in the 18.5 keV elastic scatter map, apparent as wood granularity; and Lower: XRF mean ring-widthy series for left and right pahnels indiating that the timbers were sourced from the same treee.

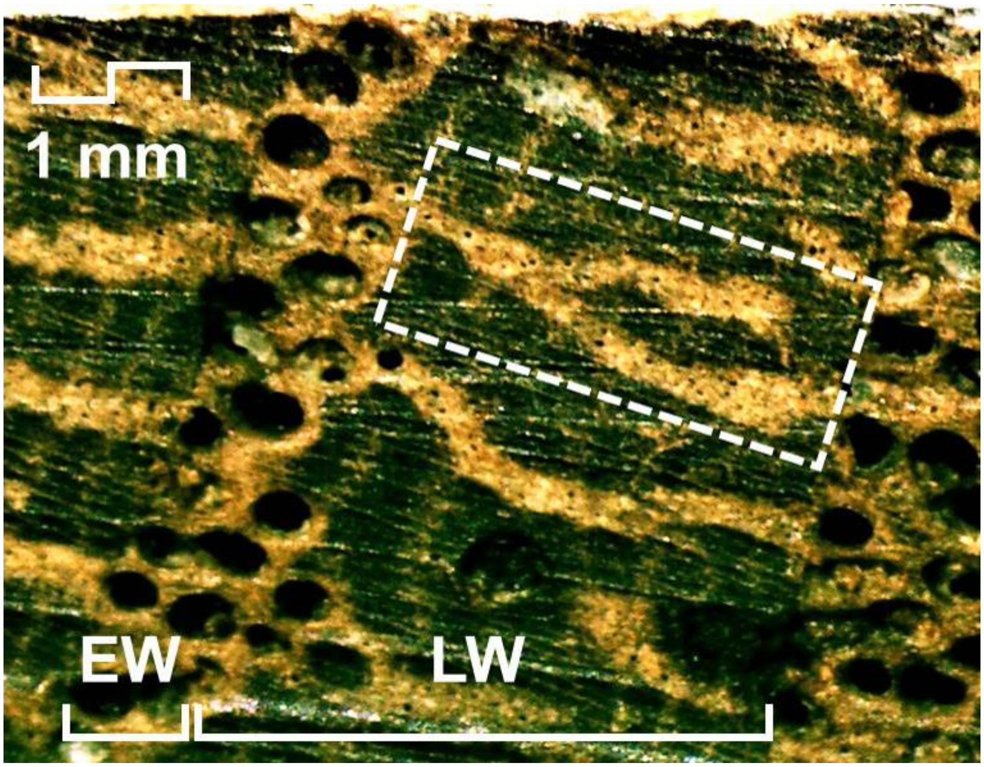

Figure 3 Latewood vessel bands exhibit a narrow strap-like form with occasional bifurcations that are more consistent with *Q. petraea* than *Q. robur*.

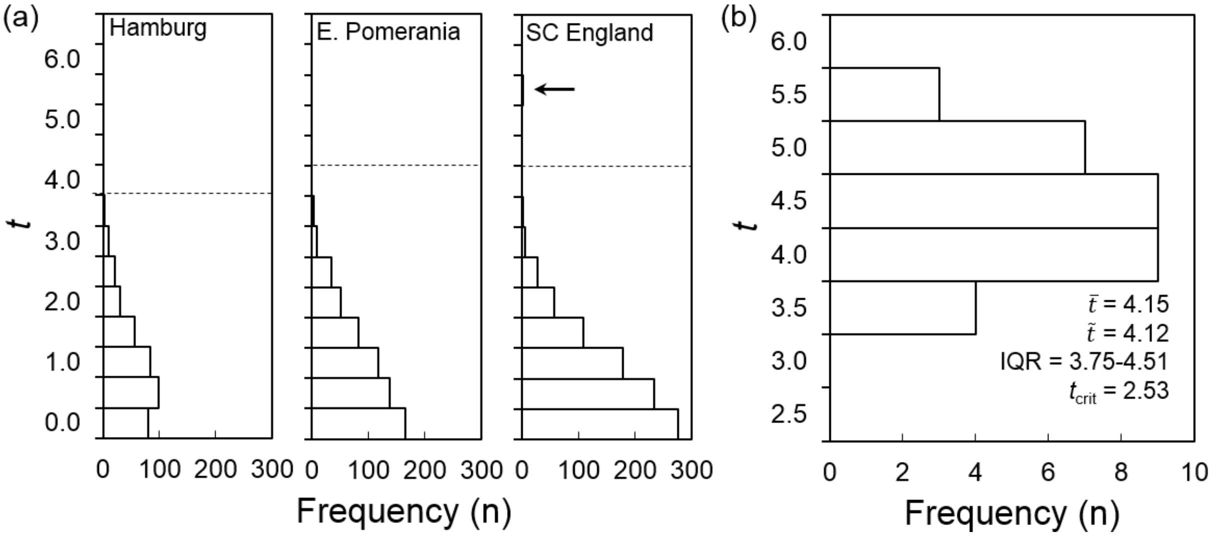

Figure 4 (a) While correlation between the SC England chronology and the entire length of the $\text{XRF}_{portrait}$ series is moderate (*r* = 0.50) the 1400-1480 CE date is an extreme outlier within the distribution of *t*-values for all positively correlated overlaps with the SC England chronology; (b) The distribution of the associated *t*-values is relatively normally distributed, ranging between 3.10-5.42 with an almost identical mean and median.

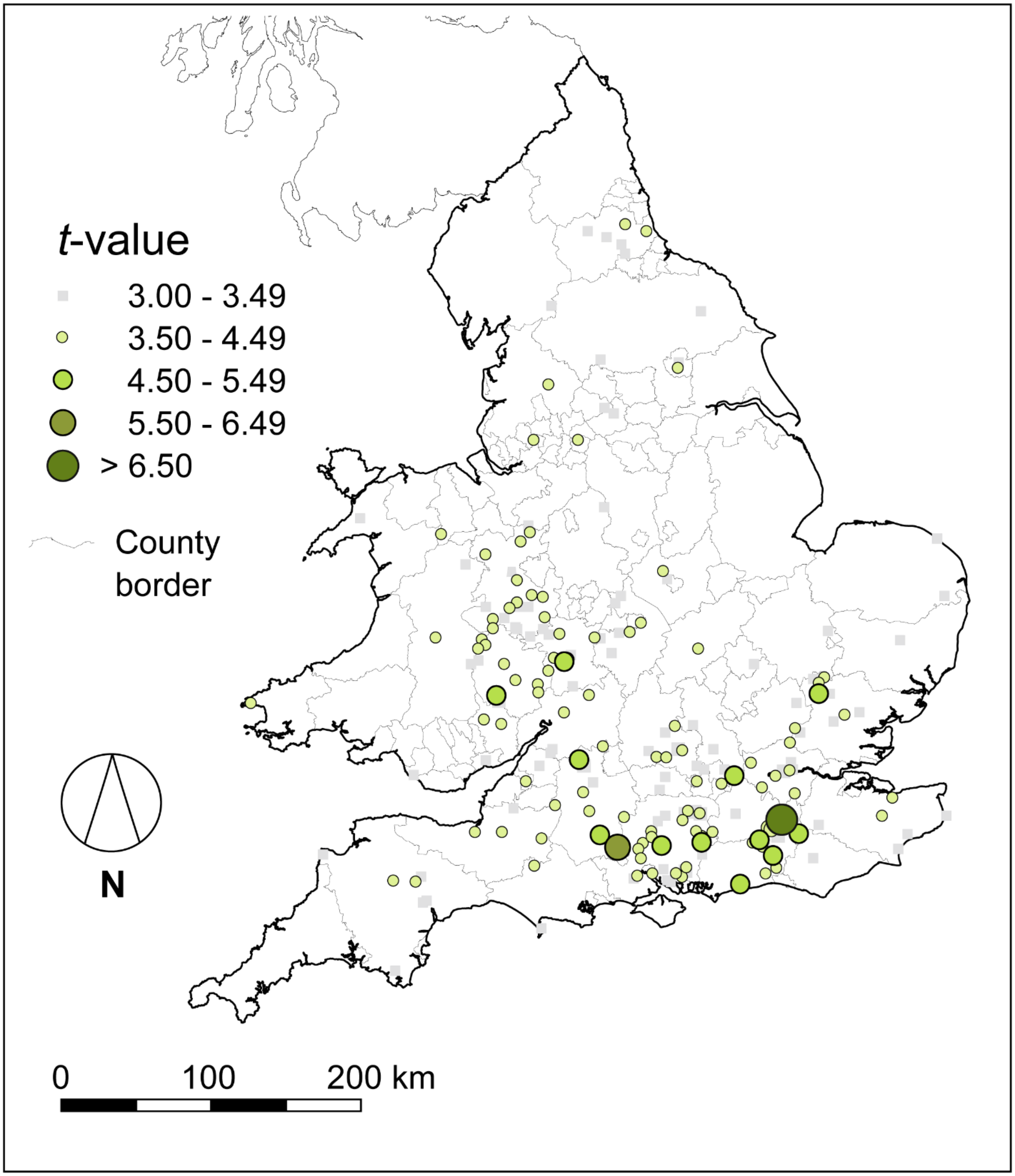

Figure 5 Crossdating with English and Welsh site-level chronologies generated *t*-values exceeding 3.0 for 218 unique sites.