Journal of Archaeological Method and Theory
https://doi.org/10.1007/s10816-020-09444-z

Dating Medieval Masonry Buildings by Radiocarbon Analysis of Mortar-Entrapped Relict Limekiln Fuels—a Buildings Archaeology

Mark Thacker[1]

Abstract

This paper considers how the data returned by radiocarbon analysis of wood-charcoal mortar-entrapped relict limekiln fuels (MERLF) relates to other evidence for the construction of medieval northern European masonry buildings. A review of previous studies highlights evidence for probable residuality in the data and reflects on how this has impacted on resultant interpretations. A critical survey of various wood-fired mortar materials and lime-burning techniques is then presented, to highlight evidence suggesting that a broad spectrum of different limekiln fuels has been exploited in different periods and that growth, seasoning, carriage and construction times are variable. It is argued that radiocarbon analysis of MERLF fragments does not date building construction directly and the heterogeneity of the evidence demands our interpretations are informed by sample taphonomy. A framework of Bayesian modelling approaches is then advanced and applied to three Scottish case studies with contrasting medieval MERLF assemblages. Ultimately, these studies demonstrate that radiocarbon analysis of MERLF materials can generate reasonably precise date range estimates for the construction of medieval masonry buildings which are consistent with other archaeological, historical and architectural interpretations. The paper will highlight that these different types of evidence are often complementary and establish that radiocarbon dated building materials can provide an important focus for more holistic multidisciplinary interpretations of the historic environment in various periods.

Keywords Medieval buildings archaeology radiocarbon Bayesian limekiln

---

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10816-020-09444-z) contains supplementary material, which is available to authorized users.

✉ Mark Thacker
mark.thacker@stir.ac.uk

[1] University of Stirling, Stirling, UK

Introduction

A remarkably high number of medieval masonry buildings survive throughout northern and western Europe, and these structures present a valuable record of the interaction between different groups of medieval people and their surrounding environments. Contemporary documentary evidence relating to the initial construction of these buildings is rare, however, and chronological resolution often relies on late incidental historical references from which we can deduce that a building of some kind probably already existed on the site. Ultimately, this has engendered a multidisciplinary typological approach to establishing constructional dates, in which all available documentary, architectural and archaeological evidence from within and between particular sites is compared, to present increasingly consistent relative chronologies. The strength of the relationships between these different sources of evidence is highly variable, however, and a widespread lack of precision often continues to limit our understanding of how the construction of these buildings relates to the historical record, and to changes in the wider cultural and physical environment. Indeed, in Scotland, this includes several important upstanding medieval castle buildings with ascriptions ranging from the thirteenth to the sixteenth centuries.

A number of building investigators around the world have responded to similar issues with variously successful attempts to date masonry fabric through the radiocarbon analysis of lime mortar materials, exploiting the fact that this fundamental component of the construction process is included within two interconnected carbon cycles. Lime mortar manufacture is predicated on a process called the ‘lime cycle’, which begins when a carbonate-rich material, such as limestone or marine shell, is heated in a kiln to temperatures over 750 °C, to drive off carbon dioxide and form the very reactive oxide known as ‘quicklime’ (Gibbons 2003, 9–10). Once ‘slaked’ and tempered with water and aggregate, the resultant mortar mixture will be deposited within and upon masonry walls in a variously fluid or plastic state and in this position will absorb carbon dioxide from the air to form a solid carbonate matrix, and so set. The fuel component of the limekiln charge, used to heat the carbonate-rich lime source, forms part of another carbon cycle between source materials and the surrounding atmosphere. Where wood fuel is used, then that material is part of a multi-scalar process by which trees (as autotrophs) acquire carbon from the air through photosynthesis, store it by wood formation and finally release carbon back into the atmosphere through respiration, decomposition and combustion (*cf.* Mahli *et al.* 1999, 715).

Investigations of the carbon dating potential of historic mortar materials have been ongoing for over 40 years and have generally followed one of two methods: In the ‘matrix method’, the radiocarbon age of carbon dioxide fractions released from constructional mortars by acid digestion has been analysed, on the basis that this contains atmospheric carbon absorbed during matrix formation, when the mortar initially set (Folk and Volastro, 1976; Ambers 1987; Mathews, 2001; Lindroos *et al.* 2007; Al-Bashaireh 2008, 2013; Pesce *et al.* 2013). In the ‘fuel method’, by contrast, small wood-charcoal fragments entrapped within constructional lime mortars have been subject to radiocarbon analysis, on the basis that this material has been incidentally included (from the limekiln charge) during the mortar’s initial manufacture (Berger 1992, 1995; Bonani *et al.* 2001). Both of these approaches, however, present particular challenges of interpretation associated with potential residuality, suggesting the materials under analysis (or components of them) may have been formed long before the layer in which they were found (Harris 1989, 121). With the 'matrix method', these challenges are largely predicated on the extent to which the released carbon can be considered a purely pyrogenic material, 'indigenous' to the constructional mortar layer (*ibid.* 121) and free of residual geogenic or biogenic carbonate contaminants which have sometimes led to obviously very early radiocarbon results (*e.g.* Mathews, 2001). No such wildly inaccurate results have been reported using the 'fuel method' but, when compared to interpretations predicated on other types of buildings evidence, then a number of published studies have reported some strikingly early results.

This paper will consider how the data returned by radiocarbon analysis of wood-charcoal mortar-entrapped relict limekiln fuels (hereafter MERLF) relates to other evidence for the construction of medieval northern European masonry buildings. It will begin with a short summary of previous attempts to date MERLF samples through radiocarbon analysis, in Ireland, Egypt, Italy and France, before examining wider evidence for these materials within the historical and archaeological record. Evidence for fuel types, lime-burning techniques, limekiln designs, materials transport and masonry construction in medieval and early modern Britain and Ireland will be considered, to investigate how the depositional histories of these materials might inform our interpretations of the radiocarbon data. More recent approaches to the characterization of MERLF fragments and the modelling of radiocarbon data using Bayesian techniques will then be discussed, before presenting three case studies focussing on three different medieval castle buildings from Scotland. Ultimately, within a wider multidisciplinary framework, this paper will present a robust methodology for the dating of medieval buildings by radiocarbon analysis of MERLF fragments and propose a protocol for future investigations of these materials.

Berger and Beyond

The most significant mortar dating project undertaken in north-west Europe, in terms of its influence on the archaeology of the region, emerged from the work of Rainer Berger. Berger's research developed from devising successful techniques for radiocarbon dating surviving timbers from English and continental European medieval structures (Berger 1970), to dating a series of (generally pre-Romanesque) Irish churches and chapels whose constructional chronologies were only very broadly understood. Given the lack of surviving timbers in these masonry structures, and the failure of his initial attempts to date surviving lime mortars by the 'matrix method' described above, his attention was caught by the acid-digested remains of these earlier trials, within which he noticed '…many charcoal particles...from the original fuel used to produce burned lime…[which had not been] …totally consumed in the heating process' (Berger 1992, 881). The experimental focus of the project was subsequently shifted to radiocarbon dating these very small charcoal fuel relicts, and beginning with four control structures with ostensibly well-documented histories (Berger 1992, 882; 1995, 163), the project ultimately reported apparently reasonable date ranges for a further 20 undocumented medieval Irish ecclesiastical building contexts.

The radiocarbon measurements presented by Berger were all produced by gas proportional counting; initially calibrated using data from Stuiver and Pearson (1986) and published at '1-sigma error' (1σ; effectively 68.2% probability), and subsequently calibrated using data from Stuiver and Reimer (1993) and published at wider 95% (2σ) probability ranges (Berger 1992, 884; 1995, 172). The historiography of these publications is important, as Berger's innovative work has continued to have a significant impact on Irish medieval church archaeology. It was this radiocarbon data which prompted Peter Harbison to group together a number of particularly small 'tomb-shrine' chapels and suggest they were probably the first ecclesiastical mortared stone structures in Ireland (Harbison 1992, 149–152), and it is interesting to compare this multidisciplinary discourse with his (pre-Berger) four-part pre-Romanesque typological scheme in which 'the problem of their dating' largely relied on historical sources (Harbison 1982, 618–620; see also Ó Carragáin 2003, 2010, 66–70). But various challenges to Berger's interpretations have subsequently emerged, and four somewhat problematic examples from across the country will be briefly summarized here:

1. Berger believed that the round tower at Clonmacnoise was a multiphase building, and a mid-tenth century constructional date was initially ascribed to the structure's lowest courses on the basis of a single radiocarbon measurement (UCLA-2727A; 1080 ± 60BP) which calibrated to 891–1012 cal AD at '1-sigma error' (Berger 1992, 884, 887–888; 1995 162). Berger subsequently published a much wider 780–1150 cal AD date range for this measurement, calibrated at 95% probability, but his mid-tenth century ascription remained unchanged (Berger 1995, 170). Subsequent analysis of the building by Conleth Manning, however, suggested that the upstanding tower was predominantly single phase with typologically twelfth century architectural features and, although there may have been an earlier building on the site, this re-interpretation is consistent with historical sources reporting that the building was 'completed' in c.1124 (Manning 1997; *Chronicum Scotorum*, CS1124). Manning found it 'comforting' that the 'true date' of the tower remained just within Berger's more recently calibrated 95% probability range, but re-calibration based on current datasets (Reimer *et al.* 2013) now suggests Berger's sample dates to 770–1040 cal AD (95% probability) or 1100–1120 cal AD (0.4% probability), probably 890–1020 cal AD at 68.2% probability (see Fig. 1). Ultimately, therefore, there is only a 0.4% probability that this sample dates to the twelfth century, and the reported c.1124 completion date of Clonmacnoise round tower now lies just outside of the calibrated date range returned by UCLA-2727A.
2. Berger's analysis of a mortar sample from the chapel of *Teach Molaise* (Inishmurray) returned a radiocarbon age of 1215 ± 45 BP (UCLA-2725D), which he calibrated to 724–736 cal AD at 68.2% (1σ) and 690–980 cal AD at 95% probability (Berger 1192, 884;1995, 170, 172). These calibrated date ranges informed the early medieval 'tomb-shrine' and 'shrine-chapel' typological framework noted above, within which several buildings across Ireland and Scotland were situated (Harbison 1992, 150; Ó Carragáin 2003), but the (east wall) context from which this mortar sample was removed is now thought to have been rebuilt, leading to a suggestion that 'the dated mortar may not have been in a primary context when sampled' (O'Sullivan & Ó Carragáin 2008, 76). This suggestion implies that the sample was in a context of re-use although, given the general lack of turnover associated with lime-bound materials (see below), it is more likely this was a secondary mortar. Using the methodology outlined in Fig. 1, Berger's

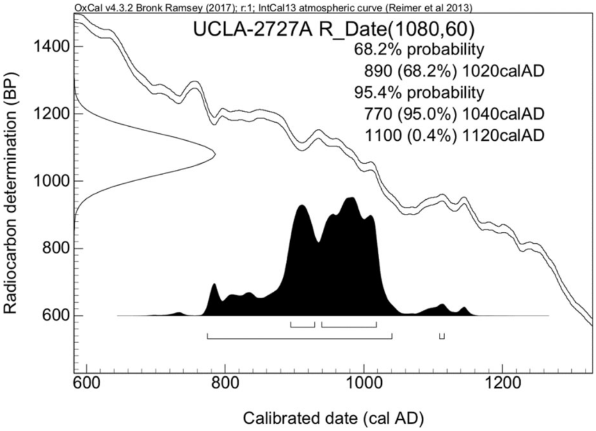

Fig. 1 Re-calibration of Berger's radiocarbon measurement returned by a MERLF sample removed from the lower courses of Clonmacnoise round tower. Sample UCLA-2727A (1080 ± 60BP) has been calibrated using OxCal v4.3.2 software (Bronk Ramsey 2017), using the probability method against the dataset of Reimer *et al.* (2013), with results rounded out to 10 years

reported measurement from *Teach Molaise* (UCLA-2725D; 1215 ± 45 BP) calibrates to 680–900 cal AD at 93.2% probability or 920–950 cal AD at 2.2% probability, although the 'relevance' of this measurement for our understanding of the primary structure (*cf.* Dean 1978) is now open to question.

3. Berger interpreted St Columb's House, Kells as a multiphase structure and radiocarbon analysis was undertaken on two samples he associated with construction of the building's earliest phase. These samples returned radiocarbon ages of 1270 ± 125 BP (UCLA-2714A) and 1295 ± 80 BP (UCLA-2714B), which he calibrated to 650–890 cal AD and 654–786 cal AD at 68.2% (1σ) probability, and 540–1020 cal AD and 610–980 cal AD at 95% probability respectively (Berger 1992, 882–883; 1995, 164). As this data appeared to confirm the building's ninth century origins, these results were listed within Berger's 'historically datable buildings' and used to suggest this was 'one of the oldest mortared structures in Ireland designed as an oratory' (*ibid.*), although more recent analysis has suggested that St Columb's House is a predominantly single-phase structure which, on typological grounds, should probably be ascribed to a date of around 1100 (Ó Carragáin 2003, 165, n19; 2010, 255, 263–265). Using the methodology outlined in Fig. 1, Berger's measurements from this building now calibrate to 550–1020 cal AD (95.4% probability; UCLA-2714A), and 600–900 (94.1% probability) or 920–950 cal AD (1.3% probability) (UCLA-2714B), suggesting they are both much earlier than the currently accepted constructional date of the building.
4. Berger also undertook radiocarbon analysis of two mortar samples from the west wall of the chapel on High Island, Co. Galway. These returned radiocarbon ages of 1395 ± 195 BP (UCLA-2570) and 1090 ± 105BP (UCLA-2792), which he calibrated to 430–852 cal AD and 810–1020 cal AD at 68.2% (1σ) probability, and 240–1020 cal AD and 690–1210 cal AD at 95% (2σ) probability (Berger 1992, 884; 1995, 166–167). On the basis of these measurements, Berger ascribed a pre-eleventh century constructional date to the structure, although subsequent excavation and analysis of this building suggests that almost all of the upstanding fabric

> represents the third phase of a building whose second phase post-dates an eleventh century grave, whilst the third phase itself 'is possibly mid to late eleventh or even perhaps twelfth century' (White Marshall & Rourke 2000, 121). Using the methodology outlined in Fig. 1, Berger's measurements from this site currently calibrate to 220–1030 cal AD (UCLA-2570) and 680–1160 cal AD (UCLA-2792) at 95.4% probability, but more work is required to assess how these dates relate to the most recent interpretation of the chapel. At present, these date ranges appear to contrast with the recent re-phasing of the west wall (see White Marshall & Rourke 2000, 78), but once more this chronology is outside or overlaps with the upper end of these ranges at 95.4% probability.

It is salient that the challenges to Berger's interpretations presented above have generally emerged from re-analysis of the fabric of each structure, so clearly demonstrating the importance of structural phasing and sample context for the interpretation of radiocarbon data. The historiography of the studies presented above, however, also highlights how precision in calibrated radiocarbon date ranges relates to other types of buildings evidence. Calibrated date ranges for single samples in this period often extend over hundreds of years at 95.4% probability, and the single radiocarbon measurement (UCLA-2727A) from Clonmacnoise round tower presented by Berger calibrated to such a broad chronological range, that it appeared to remain accurate despite Manning's (1997) radical re-interpretation of the masonry fabric. Ultimately, a lack of precision significantly limits the potential for independent interpretation of the building's age or phasing from the radiocarbon data alone, whilst that data is itself subject to re-interpretation on the basis of a multidisciplinary re-evaluation of the wider building evidence. If convincing and precise estimates for building construction could be generated from the radiocarbon data, it would enable this type of inter- or multidisciplinary discourse to be much more meaningfully iterative.

The lack of precision in Berger's calibrated data is compounded by a plateau in the calibration curve around the early second millennium focus of his study (Ó Carragáin 2010, 116), but the challenges to his interpretations presented above also suggest some of his date ascriptions are early, so questioning whether his samples from these particular sites are affected by residuality. Berger did briefly consider whether an 'old wood effect' might bias his interpretations, if coal, peat or 'bog-oak' had been used as a limekiln fuel, but the wider significance of this issue for his case studies was broadly dismissed by 'assuming that …the normal procedure in the past was to use short-lived fuel' (Berger 1992, 881; 1995, 161). This issue needs re-visiting.

The assumption that lime-burning techniques can be characterized by a 'normal [*i.e.* ahistorical] procedure' is not uncommon, and where early radiocarbon results have been reported elsewhere then this has led to some remarkable interpretations. For example, the Jewish catacomb complex at *Villa Torlonia* in Rome had been ascribed to the third/fourth century AD on the basis of comparative typology, before investigating archaeologists submitted five 'rare small bits of charcoal encased into the mortar' for AMS radiocarbon analysis (Rutgers *et al.* 2002). These samples returned radiocarbon ages ranging from 2144 ± 46BP (UtC-6719) to 1753 ± 33BP (UtC-6718), which were calibrated against Stuiver and Reimer (1993) to present date ranges reported at 68.2% (1σ) probability (*ibid*, 544). These authors accepted that the oldest of these measurements must be affected by old-wood bias, since this returned a historically unacceptable BC calibrated date range. But by then 'assuming' that the remaining measurements 'originated from short-lived vegetation', and were therefore 'reasonably unaffected by "old wood" biases', the archaeologists suggested that the four structures associated with these measurements should be re-ascribed to constructional dates beginning in the first century AD (Rutgers *et al.* 2002, 545). It is worth noting here that, using the methodology presented in Fig. 1, the youngest measurement from this group of dates (UtC-6718; 1753 ± 33BP) calibrates to 170–200 cal AD (1.4% probability) or 210–390 cal AD (94% probability), so is consistent with the previously accepted, typologically informed, third/fourth century AD interpretation ascribed to the wider group.

Further south, the American Research Center in Egypt undertook an ambitious project to 'establish a radiocarbon chronology' for buildings associated with the Old and Middle Kingdoms by analysis of organic materials used during their construction (Bonani *et al.* 2001). The project ultimately removed over 450 samples from 33 monuments (including such culturally significant structures as the Great Pyramid and the Sphinx), and 78% of this assemblage was comprised of mortar materials apparently manufactured in 'massive fires' (Bonani 2001, 1297). Bulk samples of MERLF fragments were released from selected mortars by acid digestion and submitted for a combination of conventional and AMS radiocarbon analysis (depending on sample weight). Calibrated date ranges from 30 monuments were subsequently reported at 68.2% (1σ) probability, but many were much older than the accepted historical context of each monument's construction, and this trend persisted even when the data is re-calibrated at 95% probability (Bonani *et al.* 2001, 1302–1320; Dee *et al.* 2009, 1062).

Returning to Ireland, Paul Naessens explicitly adopted 'Rainer Berger's technique' in an attempt to establish the constructional chronology of a rare, mortar-bonded, sub-circular fortification on the island of *Iniscremha*, Connaught (Neassens 2009). In this study, mortar samples from a section of collapsed wall core were 'broken down manually' to release 0.6 g of 'Residual charcoal flecks from the limeburning process', and this returned a single AMS radiocarbon age of 932 ± 33 BP (UB-6789) which calibrated at that time (against Reimer *et al.* 2004) to 1020–1180 at 95.4% probability (Naessens 2009, I, 63). It is possible this focus on the wider 95.4% probability range reflects increasing concern in Ireland regarding some of Berger's narrower 68.2% probability dates, and the reported UB- (rather than UBA-) code is curious if indeed this measurement was the result of AMS analysis, but in any case, the result was suggested to confirm 'that Iniscremha was built between 1020 and 1180…prior to the arrival of the Anglo-Normans in the region' (Naessens 2009, 63). The calibrated date range reported during this study has been regarded as typologically consistent with the monument's masonry style and used to support that typology, but considering that the Normans arrived in Ireland in 1169 and had conquered large areas of western Connaught by 1230 (O'Conor and Naessens, 2012), wider interpretation relies heavily on the 'accuracy' and precision of that single bulk-charcoal radiocarbon date, and in particular on the 1180 cal AD upper limit of the calibrated age range at 95.4% probability. Using the methodology described in Fig. 1, 932 ± 33BP (UB-6789) now calibrates to 1020–1190 cal AD at 95.4% probability.

Finally, in this section, a multidisciplinary team of building investigators named *Terres cuites architecturales et Datation* applied a suite of different scientific analyses to the fabric of St Martin's church in Angers, north-west France, with a particular concern to establish the constructional date of the crossing tower (Blain *et al.* 2011). Construction of this building had previously been ascribed to a date in the early eleventh century, on the basis of architectural typology and a pre-1020 charter document, but radiocarbon analysis of four MERLF charcoal samples removed from the transept and tower, returned radiocarbon ages of 1110 ± 25BP (Ly-3922), 1135 ± 30BP (Ly-10,781), 1202 ± 34BP (Ly-7857) and 950 ± 40BP (Ly-7856) (*ibid*, 57, Table 1). By disowning the youngest measurement (Ly-7856) removed from the upper storey of the tower, and calibrating the remaining measurements using 'Intcal.04', these investigators reported that 'the wood used to make the charcoal [in the lower levels of the tower] grew between the 8th and the 10th century' (*ibid*, 57). Since these measurements appeared consistent with data returned by thermoluminescence (TL) analysis of ceramic materials from the tower piers, the accepted results from all materials analyses were combined and the 'final date for the bell tower' estimated to a date range of 825–900 AD at 95% probability (Blain *et al.* 2011, 57, 62). This work, therefore, presents a radical re-interpretation of the constructional context of this important building.

Each of the studies presented above raises several important issues for our understanding of the wider relationships between MERLF radiocarbon data and other types of building evidence. The European studies, in particular, are characterized by widespread assumptions that MERLF materials have no inherent residuality and on this basis have often presented chronological interpretations which are earlier than those previously accepted on basis of architectural typology, historical evidence or archaeological phasing. Indeed, it has often been accepted that calibrated radiocarbon date ranges accurately bracket constructional chronologies and therefore, notwithstanding issues of precision and apparently very obvious 'outliers', where a range of dates has emerged then this has been regarded as retrospective evidence for revised multiphase interpretations.

The measurements presented by these studies have emerged over two decades, were produced using a variety of pretreatment and analysis methods and, as the historiography of Berger's study highlights, were calibrated using different (published and ratified) calibration datasets (Karlsberg 2006, 13–19). Radiocarbon analysis does generally generate date estimates which are consistent with tree rings of known (dendrochronological) age, however, and the uncalibrated results reported above are very likely to be 'accurate' within the stated error margins. Crucially for our discussion, however, all of these radiocarbon measurements are contingent upon the date at which the living wood in the surviving MERLF sample stopped exchanging carbon with the atmosphere, when each annual tree ring in the sample was formed (Dean 1978). Understanding how these radiocarbon measurements should be interpreted, therefore, requires an understanding of the potential time interval between the formation of the growth ring in the analysed MERLF sample, and the cultural event we are investigating (in most of these cases the construction of the building). This potential offset was characterized by McFadgen (1982) as the sample's 'inbuilt age' or 'IA' (the sum of its 'growth IA' and 'storage IA'), whilst Dean (1978, especially 225-9) defined this as a chronological 'disjunction', and urged archaeologists to consider the interval between the 'dated event' (the formation of the tree rings in the MERLF sample), the 'reference event' (the terminal ring of the parent tree), various 'bridging events' (such as wood fuel seasoning) and the 'target event' (the construction of the building). These useful terms will be employed variously throughout this paper, as we seek to evaluate possible sources of disjunction in the processes associated with lime manufacture and mortar deposition, and the potential effect of these events on the IA of the surviving MERLF sample assemblage.

Ultimately, if we are to present robust estimates for the construction of our northern European medieval buildings by radiocarbon analysis of Mortar-Entrapped Relict Limekiln Fuels, we have to investigate the depositional histories of those materials as well as the phasing of the building itself (*cf.* Bayliss 2009, 129). In the second part of this study, therefore, we will evaluate wider evidence for the character of limekiln fuels; consider how this evidence relates to limekiln design and burning technique; examine how lime, fuel and aggregates were transported; how the mortar itself was finally mixed and deposited and how long buildings took to construct.

Limekiln Fuels

Several studies have demonstrated that the relatively long- and slow-burn times associated with wood-fired (rather than coal-fired) kilns results in a more reactive quicklime product and wood fuel has long been regarded as particularly suited for the manufacture of lime (Toft 1988, 82–4). Within a discourse in which fuel performance was clearly an important consideration, the main criteria for wood-fuel selection relates to size/morphology (twig, branch, trunk; sawn and/or split), taxon (particularly genus), density (growth characteristics) and condition (green, seasoned or rotten; wet or dry), and each of these interrelated characteristics will impact on the IA associated with a surviving MERLF sample.

Historical accounts reporting that 'brushwood' was used as a lime-burning fuel are particularly widespread across Europe in more recent periods (*e.g.* eighteenth century France (Young [1794] 1909); nineteenth century Spain (Morris 1815), nineteenth century England (Young 1813; Brayley & Britton 1814; Johnson 2010) and twentieth century Greece (Forbes 2002). In southern England, this evidence can be extended into the medieval period, with oft-quoted references from the thirteenth century accounts of Henry III providing valuable evidence for lime-burning practices in the face of increasing regulation of dwindling woodland resources. Several authors have highlighted an order for sea-coal to fuel limekilns at Windsor Castle in 1264 (Brindlecombe 1975, 1976, 2012; Galloway *et al.*1996) and compared this with an earlier order for a boatload of wood to argue that previously 'Traditionally lime was burnt in a kiln with oak brushwood' (Brindlecombe 1975, 389), but the wide distribution of these reports does not preclude the possibility that alternative fuel sources were exploited elsewhere. Indeed, it is probable that the oft-quoted medieval reference to '*Ad calcem et ad prasternendum et cariandum vetera robora*' (Colvin 1971, 345) noted above should probably be translated as 'old pollard' rather than 'brushwood oak', and it is likely that this term relates to dead or exhausted stocks (now useless to commoners with wood-cutting rights) which reverted to the king (*cf.* Rackham 2003, 182; Bond 2007, 277). There are, moreover, many other reports in the English royal accounts for the use of large and aged wood fuel sources for lime-burning, including an order for 30 individual *robora* from the king's forest at Hainault to fuel limekilns at the Tower of London (Rackham 2003, 182), an order for 8 tree trunks from Windsor Forest to fuel a limekiln at the castle there (Johnson 2010b, 72), and 'the Hundred Rolls of 1275 complain that the king's two lime-kilns (*rees calcis*) had between them devoured 500 oaks in the forest of Wellington' (Salzman 1952, 150). Johnson concluded that these royal accounts tended to specify either brushwood *or* timber and suggested that brushwood was probably used 'as the sole kiln fuel' on occasion (Johnson 2010b, 72). The examples from medieval England highlighted above, however, clearly indicate that brushwood was not always required for lime manufacture.

These accounts do suggest that oak was a commonly used limekiln fuel in this particular medieval social context, but the most salient theme to emerge from documentary sources throughout this period is that a wide range of different taxa were employed (Thacker 2016). An increasing number of archaeobotanical studies undertaken in association with limekiln excavations across northern Europe are also consistent with that suggestion, and the evidence is chronologically broad. This includes a second century limekiln excavated in Northamptonshire (England) which contained 'twigs and branches up to 40mm in original diameter' of beech, poplar, oak, hawthorn-type, hazel and field maple (Jackson *et al.* 1973); a group of second to third century limekilns excavated in Iversheim (Germany) which contained only willow and poplar (Sölter 1970, 19); and the excavated assemblages from two Gallo-Roman limekilns in Normandy and Brittany (both western France), one of which was completely dominated by oak, whilst the other included over 30% ash (with lower concentrations of hazel, birch and *Prunus*), and both of these assemblages were almost completely dominated by large-diameter morphologies (Marguerie 2002). In the medieval period: a twelfth century limekiln excavated close to St Michael's church in *Betws yn Rhos* (Wales) contained 'coppiced alder' (Grant 2007); a large assemblage of limekiln fuel associated with the construction of an early fifteenth century castle in Co. Meath (Ireland) was completely dominated by ash wood (O' Donnell 2009); a fifteenth to seventeenth century limekiln excavated in Co. Galway (also Ireland) contained a single fragment of *Pomoideae* (McMorran & Tierney 2010); and a group of seven fifteenth to seventeenth century clamp kilns excavated in Yorkshire (northern England) included mixed assemblages of alder, ash, oak and willow (Johnson 2010b, 72). Even the remarkably layered fuel assemblage discovered during the excavation of two seventeenth century limekilns in Provence (southern France), which was certainly dominated by small-diameter oak fragments (including bark and leaves), also included some 'roundwood' pine (Vaschalde *et al.* 2013).

No evidence for the use of pre-prepared wood charcoal to fuel the limekilns of Britain and Ireland has yet been noted by this author in the documentary sources, and yet un-pyrolyzed wood has only rarely been noted in the archaeological buildings evidence. This may be a taphonomic issue since charcoal is a much more durable material, but with full pyrolysis generally complete by 400 °C and limekiln temperatures exceeding 750 °C, it is more likely that the kiln environment was controlled to maximize fuel conversion as far as possible. Indeed, it is possible that wood fuel was deliberately 'coaled' within mixed-feed limekilns (see below) during a period of pre-heating with reduced airflow, although in a northern European context, this technique would not generally have enabled the deliberate use of very green (freshly cut) wood so imposing a minimum pre-kiln seasoning (storage) IA upon any resultant MERLF (*contra.* Russell & Dahlin 2007). This 'hiatus' period (Dean 1978, 229) may be less than a year where limited diameter living wood has been harvested and deliberately seasoned, but might be increased significantly where standing or downed deadwood

(Coarse Woody Debris – CWD) or driftwood have been incorporated in the charge. Studies from boreal forests in Russia and Finland, which report that individual CWD fragments can contain IAs of over 500 years (Shorohova & Kapitsa 2014), clearly highlight the potential for northern European wood fuels to be associated with very old biogenic carbon in particular contexts. CWD accumulation rates are directly related to variations in environmental context, successional stand development and taxa-specific life cycles, however, and much lower residence times are generally reported in warmer temperate woodland biomes (Harmon *et al.* 1986) such as those covering much of Britain and Ireland.

The exploitation of some CWD or driftwood probably formed a part of many limekiln fuelling strategies, but the overall significance of this issue is likely to be site-specific and highly dependent on prevailing ecology and management regimes. The discussion above indicates that lime-burning evidence includes a variety of wood-fuel taxa and morphologies, but the reasonably high calorific value required to reach and maintain calcination temperatures within any limekiln imposes certain general conditions on the character of the fuel. Given this requirement, it is important here to distinguish between post-mortem ageing processes of decomposition and the 'seasoning' associated with drying environments and characterized by 'a decrease in moisture, shrinkage and formation of checks or cracks' (Harmon *et al.* 1986, 151). Shorohova and Kapitsa (2016, 597) report that the 'initial density of woody CWD components increases in the order: roots, stems and branches…[and that]…. With some exceptions, the wood density of a component determines its decomposition rate'. Given that calorific value is also a function of wood density, these studies highlight the fuel value of dry and seasoned tree branches, whether freshly cut or standing post-mortem CWD with a higher storage IA.

Limekilns and Lime-Burning Technique

The variety of limekiln fuel evidence highlighted above is paralleled by a diversity in lime-burning and mortar making technique. The early nineteenth century author of the *Encyclopaedia Londinensis* (1814) reported that 'Limekilns are built of different forms or shapes according to the manner in which they are to be wrought, and the kinds of fuels which are to be employed', and this applied in earlier periods also. In other words, limekiln design, fuel availability, carbonate availability, mortar specification and craft tradition are contingent upon each other and that variability is reflected in the range of historic terminology (*cf.* Salzman 1952, 150) as well as in the surviving archaeology of kiln and mortar. Kiln studies often divide these structures into two contrasting types, such as 'open-firing' or 'kiln-firing' (Livingston-Smith 2001), 'intermittent' or 'continuous' (Cowper [1927]) and 'flare' or 'mixed-feed' (Dix 1982; Jackson *et al.* 1973; Rutgers *et al.* 2002), but the most important factor for this discussion is whether the fuel and carbonate fractions of the charge are separated or mixed, and that will form the basis of the discussion below.

In the 'separated' method, the carbonate is suspended over the fire by a grate within the kiln superstructure, and this practice is always associated with intermittent firing as the kiln must be extinguished to allow removal of the quicklime. These kilns can often be recognized by an internal scarcement intake designed to support the grate/arch (*e.g.*

Dix 1982), with the fire accessed through low-level vents in the side of the kiln and maintained by repeated cycles of stoking and burning. This technique therefore requires fast-burning wood fuels with a long hot flame—to fully penetrate the carbonate above—as described in a twentieth century account from Persia wherein 'The [kiln] shaft was filled up with the rock material...and a fire was maintained in the tunnel [below] for 12 hours, the *fuel shrubs* being pushed in...with a rake' (Wulff 1966, 126; my italics). It is salient that most of the excavated limekiln structures noted above which presented evidence for very small diameter wood fuel (in southern England, Germany and France) have also been interpreted as kilns in which the lime source and fuel were separated (see especially Vaschalde *et al*. 2013).

By contrast, in the 'mixed feed' technique, the fuel and carbonate elements are stacked in alternate layers and the whole mixed charge allowed to burn through without any significant fuel additions. This technique can be open or enclosed, and intermittent or continuous, although the continued requirement for low-level ventilation presents a form which can be very similar to that described for the separated method, and this has led to some problematic interpretations resulting from terminological confusion. The success of the mixed-feed technique, however, ultimately relies on the lime-burner correctly predicting material behaviour as the layered charge is stacked, in order that sufficiently high temperatures are maintained (for calcination) for enough time (depending on carbonate type and size) (Thacker 2016).

Descriptions of the mixed-feed technique survive from several post-medieval northern English, Scottish and Irish contexts, and significantly from an archaeological perspective, these accounts also indicate that a wide range of different lime-burning fuels may be used. In seventeenth century Galloway, for instance, layers of shell and peat 'a foot thick or more' were laid '*stratum super stratum*' upon a 'circumference' of ground 'till they bring it to an head like a pyramis' and the 'fire kindles the whole kilne... in twentie-four hours space' (Symson [1684]; my italics; see also MacIntyre 1993 and Thacker 2011, 2015 for similar practice in the Western Isles; see Fig. 2). In seventeenth century Connaught and Munster, however, general practice reportedly required 'a great pit, round or square' to be excavated and filled with alternate layers of limestone and 'wood, turf or comb...which being done, the kiln is set afire until all be burnt' (Boate 1652, 86–87). A 1285 account from Corfe which describes payment 'for making the pit for a kiln (rogam)' (Salzman 1952, 150) suggests a similar process to that described by Boate may have pertained close to the south coast of England in the medieval period, and several 'pit-kilns' have now been subject to archaeological excavation across Ireland. This includes structures at Cullenagh More (Co. Galway), where a fifteenth to seventeenth century limekiln 'comprised a roughly square, earth-dug, subterranean chamber', and the base of the southern flue was 'covered in successive layers of charcoal and burnt/scorched clay, lime and charcoal' (McMorran & Tierney 2010, 8, 11); at Rath Lower (Co. Louth), where a fifteenth to sixteenth century 'stone-built circular limekiln' which had been 'cut directly into the natural sub soil' contained a mixture of 'burnt timber, ash and lumps of limestone and lime' (Clutterbuck 2002, 13–15), and at Killeen Castle (Co. Meath), the base of another circular stone-built limekiln had been 'cut into bedrock' and was 'sealed with a hard coating of lime...containing the charcoal remains of burnt timber' (Baker 2009, 79). Moreover, at Dundrum Castle (Co. Down), a circular stone-built pit-kiln thought to date to the twelfth century has been excavated, and the twelfth century annals of Armagh

(1145) and Derry (1163) also both report the construction of enormous limekilns ‘sixty feet every way’, the latter of which took 20 days to construct (*Annals of the Four Masters*, M1145.4, M1163.8). There is little doubt these were also mixed-feed type structures.

No closely dated limekilns from the medieval period are known in Scotland, although possible examples have been reported at the west coast castle sites of Dunstaffnage, Tioram and Dun Scaith (Thacker 2016). Each of these structures is circular, with the Dunstaffnage site presenting two very similar adjacent examples, one of which has been subject to limited excavation around a probable vent revealing a ‘0.22-0.24m deposit of lime with some disturbed charcoal flecking’ (Breen *et al*. 2010, 175). Recent petrographic analysis of loose materials from around this kiln suggests that (as in some particular phases of the castle) a meta-limestone lime source was exploited here, and these materials are now subject to further analysis and possible radiocarbon dating. Where the fuel from excavated medieval pit-kilns in Britain and Ireland have previously been subject to radiocarbon analysis then these have returned calibrated date ranges which appear to overlap with other buildings evidence. A wood-charcoal sample discovered during excavation of a limekiln close to St Michael’s church, *Betws yn Rhos Wales*, for example, returned a radiocarbon age which reportedly calibrated to between the late tenth and early twelfth century cal AD, whilst the church building itself is recorded from the 1250s (CAT 2008, 7; see also Grant 2007). Elsewhere, a sample of wood charcoal from the base of a limekiln excavated on the site of Killeen Castle, co Meath in Ireland, returned a radiocarbon age of 588 ± 33 BP (calibrating at that time to 1300–1440 cal AD) which appears consistent with the early fifteenth century date ascribed to the earliest surviving phase of the castle and neighbouring church, and ‘an intense period of historically recorded construction on the site’ (Baker 2009, 66, 82). Using a similar methodology to that presented in Fig. 1, this latter 588 ± 33 BP radiocarbon age now calibrates to 1290–1420 cal AD at 95.4% probability and so the parallel between this comparative evidence and Berger’s 95%

Fig. 2 A replica limekiln constructed on the Isle of Barra in 2014 and fired using the mixed-feed technique. This circular kiln was constructed and charged with alternate layers of peat and shell; relict evidence for which was noted in multiple phases of the nearby Castle Kisimul (Thacker 2014; Ostrich 2015, 416–7). Photograph: M. Thacker

data from the *in situ* mortar fuel of Clonmacnoise round tower (in an earlier period) is striking.

Various accounts list sieves amongst the tools required by a lime-burner, hinting at various levels of post-burn processing and refinement. Ultimately, however, there is much greater potential for significant quantities of relict fuel to become entrapped within a lime material manufactured by the mixed-feed technique, where carbonate and slower-burning fuels are intimately associated, than where fire and carbonate are effectively separated and fast-burning fuels are preferred. In this regard, the mixed-feed technique also appears suited to the use of organic fuels such as peat and turf (Radcliff 1803), where lower calorific levels and flame heights pertain but dating potential is much reduced. Importantly for this paper, however, where mixed-feed wood-fired limekilns remain in use in different parts of the world, then ethnographic descriptions also often suggest that a range of wood taxa and sizes are required, including relatively large diameter pieces. The hundreds of unenclosed lime-burning 'heaps' of Tanzania, for instance, are fuelled by 'coconut poles...15-25cm diameter and 1m in length' (Muhegi & Schilderman 1995, 15), whilst in Mexico a variety of wood taxa and morphologies up to 20–30-cm diameter are reportedly required—to 'sustain very high temperatures for several hours' (Russell & Dahlin 2007, 410–13). Offering some further explanation, Wingate (1985, 45) reports from Africa that '...where fast burning woods like coconut have been used they have been mixed with a slower burning wood. The former maintains the combustion of the latter' (see also Ryan 1961 who describes a mix of fuels including 'logs').

Carriage, Mixing and Deposition

Management of lime-burning resources throughout the duration of construction would have been crucial to the successful completion of the building process. Where, as in the examples noted above, limekiln evidence survives close by and can be related to a constructional phase of the building by materials analysis (see below), then we can be secure in the knowledge that the raw carbonate (limestone or shell) was carried to the site. Identifying the location of the limekilns with respect to both the building under construction and the source materials, however, remains a significant challenge to our understanding of the depositional history of many mortar materials. In contrast to the limestone-rich south of Ireland, much of Scotland is geologically diverse and relatively non-calcareous, and the distance between carbonate sources and medieval sites varies widely. If the building site is not situated close to available carbonate or fuel sources, then the form in which the lime, limestone or fuel was transported, and the distance covered, has implications for our understanding of the character and dating potential of the surviving mortar. The long-distance carriage of limestone, pre-prepared lime or fuel to the construction site are bridging events, which have the potential to increase MERLF IA and, perhaps more significantly, dissociate the character of the limekiln fuel and carbonate source from the environment immediately surrounding the building.

Quicklime is a much lighter material than limestone and so, all else being equal, may have been preferred for overland transport, but the distance to a navigable waterway from the building site is also an important consideration, as this allowed access to coastal exposures of shell or limestone which (like sandstones) were often the first outcrops to be exploited in any given region (Thacker forthcoming). The frequent use of waterways to distribute lime throughout Scotland suggests that the very reactive quicklime from the kiln may often have been slaked to the more stable hydroxide powder before transportation, as was clearly described in seventeenth century Galloway Symson [1684] and eighteenth century Edinburgh (Alston 1752). Harrison (1992) characterizes the lime that was brought 'fra the boit to the castle' at Stirling in 1543 as 'boat lime', but the form of material carried is not clear from this account.

The most detailed description of the logistics of lime manufacture and transport in medieval Scotland emerges from a set of early fourteenth century accounts describing a period of construction at Tarbert Castle in Argyll. These report that 760 chalders of lime were burnt between May/June 1325 and June 1326 and transported to the castle site 'both by land and sea', with additional costs for canvas bags, a horse-drawn cart and boards for two boats to carry both lime and gravel (Stuart & Burnett 1878, 53–7). Although the location of the lime-burning site was not reported, the accounts indicate that it took 10–23 days to construct, load, fire and empty the kiln for the first batch of transported material, so suggesting the kilns were situated somewhere in the surrounding Loch Fyne area. We might speculate whether these first burns made use of CWD or freshly cut wood which had been previously stockpiled, but it is clear that lime production was almost constant during the course of construction, and the lime was deposited within the building almost immediately. The Tarbert accounts require more work in conjunction with analysis of the *in situ* materials (Thacker in prep. a), but a preliminary reading of the text does suggest it was the lime, rather than the limestone, which was transported for this constructional event.

Whether the raw carbonate materials or the lime itself was carried to the building site is context specific and subject to wide variation across medieval and later Europe depending on the physical and cultural context of the constructional event. Given the administrative role of many masonry buildings in the period, it is perhaps unsurprising that lime or limestone was often transported by tenants from surrounding settlements in payment of rent or services. Estate management of this type could result in regular payments (to the early tenth century monastery of St Ambrose, Milan (Hilton 2003, 66), twelfth century Abbey of Stavelot, Belgium (Halkin & Roland 1909), and sixteenth century Abbey of Iona, Scotland (Iona Club 1847, 3)), or during a particular construction project as at the Scottish castles of Dunstaffnage (Simpson 1958, 47) and Ruthven during the seventeenth century where:

'…the Baillie decernes the Tennentis and vassellis…[must]…carie & transport to the castell of Ruthwen of Badyenoch so monie Lymstones as may sufficientlie suffice for rebuilding and repairing of the said castle…ane transport the said Lymestaine from the quarrell nixt adjacent to thair owen dwellings' (NAS,GD,44/27/3/137x, in Ross 2015, 164).

Regular payment of rent or services in fuel by tenants is also very common, and also often likely to have dictated that the different components of the limekiln charge were transported to the kilns from separate locations (Thacker forthcoming; see Case Study 2 below).

The 'slaking' and mixing of masonry mortars generally proceeds by one of two ways: water can be added to the quicklime from the kiln to form a dry powder or plastic putty, which is then tempered with sand and gravel and mixed with more water during a secondary process; or the quicklime can be mixed directly with a wet temper aggregate in a single-stage process to produce a so-called ‘hot-lime mortar’, which can be deposited immediately (Forster 2004). Historic depictions of building sites often include images of mortar being mixed with hoe-like hand tools (see, for example, ‘The Art and Craft of Building c.1450’; Saltzman 1952, frontispiece), but some 59 (possibly animal driven) mechanical mixers have also been discovered close to medieval buildings across northern Europe, and most have been ascribed dates between the eighth and tenth century (Stelzle-Heuglin 2007, with gazetteer). Indeed, radiocarbon analysis of several pieces of mortar-entrapped wood charcoal from a mixer discovered in Basel, Switzerland, reportedly returned measurements whose ‘weighted average… gives a calibrated radiocarbon-age between AD 936-1018 (with a probability of 71.8%)’ (*ibid*, 2). On this basis, it was suggested that ‘the mortar mixing device and with it a major building in stone was most probably erected in the 10th or beginning of the 11th century AD’ (Stelze-Heuglin 2007, 2). Mortar mixers have been discovered at a number of early medieval sites in England, but no unambiguous medieval examples are known to this author in Scotland or Ireland.

Rare seventeenth century evidence for the storage of pre-prepared mortar in a specially constructed rectangular subterranean maturation pit was reported during excavation at Park’s Castle Co. Leitrim in Ireland (Foley & Donnelly 2012, 68), and a maturation period of 12 weeks has been specified more recently (Gibbons 2003, 29). The fourteenth century Tarbert accounts indicate that the ‘hiatus’ period between firing and deposition of MERLF materials can be very short, however, and (although the distinction requires more discussion than is possible here) it is possible that the Park’s Castle features might be more accurately described as ‘slaking pits’. The likelihood of residual wood charcoal from earlier anthropogenic activity becoming included within masonry mortars during burning or mixing is generally remote but must be considered, particularly where materials appear to have been recycled (*e.g.* Salzman 1952, 151–2). In general, however, the relatively swift *in situ* hardening up of lime mortar within masonry walls effectively precludes introduction of ‘infiltrated remains’ (Harris 1989, 121), or subsequent turnover of the mortar and its component materials (until release when a mortar eventually degrades, or a context is demolished or collapses), thereby presenting an unambiguous direct link between coherent mortar layers and a moment during building construction.

Interpreting the Building

The above evidence suggests that anthropogenic processes of conversion, carriage, firing and deposition are likely to have only a limited impact on the pre-existing IA of the wood fuel, but that building construction itself is a variously ‘temporally thick’ process must also be acknowledged. The importance of this issue for our understanding of the relationship between different forms of evidence was well understood by Manning (1997), when he highlighted that the 1124 annal reference to Clonmacnoise round tower specifically reported that:

‘The great bell-tower of Cluaín moccu Nóis was *completed* by Gilla Críst ua Maíleoin and Tairdelbach ua Conchobuir’ (my italics; *Chronicum Scotorum*, CS1124).

Where ‘completion’ of the masonry building is the cultural event of interest, and build times are extended, then the hiatus period between MERLF deposition (perhaps in a foundation) and target event can be significant. Dendrochronological analysis of surviving scaffold timbers within the walls of the donjon at Loches in France, for instance, indicate this building was constructed over a 25-year period (Creighton 2012, 68) and the RCAHMS (1982a, 22) have suggested that the early thirteenth century nunnery church on Iona was also built within a 25-year timeframe. Returning to Tarbert Castle in a later period, it would appear that 'building operations' associated with the construction of a late fifteenth to mid-sixteenth century tower house on the site 'may have extended over a considerable period of time' (RCAHMS 1971, 184), whilst the later medieval fabric at Spynie Palace appears to display a programme of 'remodelling' that was 'spread over several decades, continuing as and when funds were available' (Lewis and Pringle 2002, 29). Indeed, many medieval cathedral churches have been associated with build times that have extended over centuries and, as at St Andrews Fife and St Magnus Orkney, this may be evidenced by changes in architectural style as the masonry progressed westward from the eastern focus.

Characterizing the development of upstanding masonry buildings, such as these cathedral churches, generally proceeds from close examination and recording of the surface stonework to identify discrete phases of construction from stone sources, dressing techniques, emplacement patterns, coursing and moulding profiles, before establishing how this fabric relates to other phases through recognition of abutments, insertions, overbuilding *etc.* A thorough investigation of how the mortar evidence is distributed within the masonry fabric of a building in three dimensions, however, is also important for characterizing building phasing and evaluating how particular phases have developed. Close examination can establish whether or not the complete plan-form was raised course-by-course, whether or not through-courses indicate the internal and external wall faces were raised in level lifts, and crucially, whether or not the core, bedding and coating mortars are continuous and compositionally consistent. It is questionable whether medieval buildings in continental Europe were always mortar coated (Armi 1996) and evidence elsewhere across Britain and Ireland is tentative (although see Cramp 2006; Gem 2009). Widespread survey by this author over the last decade, however, has demonstrated that almost all Scottish medieval and later masonry buildings present some surviving *in situ* evidence for internal and external mortar coatings and, although differences in fluidity and post-deposition taphonomy can promote textural contrasts, compositional continuity from core to coat in exposed sections indicates these materials have generally been deposited during the same phase of construction (Thacker 2011, 2012, 2013a, 2013b, 2015; 2016). These *in situ* interpretations have been supported at a number of sites by petrographic and radiocarbon analysis of comparative core, bedding and coating samples from particular phases, as well as comparative characterization of mortars from all three wall contexts in multiphase buildings with phase-specific mortar compositions (*e.g.* Knott & Thacker 2011; Thacker 2016; see below).

Characterizing mortar materials *in situ* precedes analysis of samples in the lab (see below) and is analogous to that process. Potential (carbonate and fuel) kiln relicts and added tempers are identified through close inspection of the fabric with the naked eye and a hand lens, and where possible, interpretations are informed by comparative examination of potential material sources from the surrounding landscape (including semi-natural woodlands, limestone outcrops, riverine sands and marine shell deposits) (Thacker 2011, 2012). In many cases, this process reveals phase-specific contrasts in mortar compositions which are very striking, whilst multiperiod layering of external coatings, direct abutment between mortars associated with different phases, and textural variation between construction breaks can provide a relative chronology for mortar deposition and thereby inform sampling and analysis strategies. As we might expect, such evidence is very often also associated with concomitant changes in stone sources, dressing techniques, emplacement patterns, coursing and moulding styles; but the process is iterative—between analysis of the stonework, analysis of the mortar and analysis of potential material sources surviving in the surrounding landscape.

Emerging evidence suggests phase-specific contrasts in carbonate and temper sources, which in north-west Scotland appear to relate to wider regional compositional trends (Thacker 2016), extend to the use of different lime-burning fuels. Evidence for peat, coal and wood MERLF materials has been noted throughout the British and Irish corpus in different contexts although, as many of Berger's studies demonstrate, the evidence for wood fuel appears to have a wider distribution than might be expected from local vegetational histories (*ibid*; Thacker 2019a). It is fuel availability, and the interrelated issues of carriage, which determines to what extent a carbonate source can be exploited and where it will be burnt. In the face of increasing demand, these issues would eventually lead to the emergence of more centralized regional lime production centres across Europe, in different places at different times, and ultimately thereby the widespread transport of pre-prepared lime over much longer distances. In some contexts, such as at Strathbogie in north-east Scotland, the roots of these regional centres can be traced back to the end of the medieval period and to tenants paying their rent in lime (Shepherd 2011). Elsewhere, however, changing resource availability (such as the decline of a particular fuel) would result in further phase-specific contrasts in the mortar biography of particular multiphase buildings and to wider regional trends, as the relationship between (pre-existing) craft skills and the emerging (cultural and physical) environment is re-negotiated. The ability of medieval craftspeople to adapt their techniques in response to changing material availability is clearly demonstrated by the royal lime-burners of thirteenth century England (discussed above) who needed to respond to a variety of materials from dispersed locations. We might reasonably expect the archaeological evidence to be particularly heterogeneous where masonry construction across a region is discontinuous (perhaps as a result of economic downturn) and itinerant lime-burners are constantly responding to different local resources, as was probably the case in fourteenth century Tarbert. That the standing buildings on Iona display such striking phase-specific contrasts in mortar compositions between major thirteenth and fifteenth to sixteenth century phases are of great interest, therefore considering the relative political stability of the island and the later medieval manufacture of lime by the tenantry on Mull (Thacker 2016, I, 176–7; III, 393–443; Iona Club 1847). Such contrasts in mortar compositions, whether through time at a particular site or between different sites, clearly reflect contrasting resource exploitation strategies. Importantly, however, these different materials also present contrasts in interpretive potential.

Interpreting the Sample

In summary, lime mortars have some very important characteristics which closely associate MERLF materials with the construction of particular masonry phases and allow those materials some radiocarbon potential. These include:

- A wide geographical distribution of wood-fired materials;
- Phase-specific compositions;
- A relatively quick set which generally precludes infiltration and turnover.

In order to select samples for radiocarbon analysis from wider MERLF assemblages and interpret the resultant radiocarbon measurements, however, any possible temporal disjunction in this process caused by 'bridging events' must be evaluated (*cf.* Dean 1978, 228). The discussion above has highlighted many of these, including:

- The possible use of old-wood fuel derived from the inner rings of long-lived trees or CWD;
- Conversion, seasoning, carriage, firing, mixing, maturation and deposition times; and
- Construction times before building completion.

As described above, the last of these bridging events might be evaluated during buildings analysis, but estimating the potential hiatus associated with these other events generally relies on analysis of the sample assemblage and further comparison with samples of potential material sources collected from the surrounding environment. That subject will form this next section of the paper, before we consider how the radiocarbon data itself might be interpreted and finally move on to the case studies.

Pre-industrial lime mortars are complex composite materials which generally betray evidence of each stage of their production in partially converted 'relict' source materials, including part-calcined carbonate clasts and wood charcoal, both of which often retain some textural or structural characteristics of the parent carbonate or tree source. Indeed, archaeological mortar analysis largely relies on characterizing these relict inclusions (and any added temper) through various microscopic techniques, to enable comparison with (current and historic) geological and vegetational evidence for potential material sources (*e.g.* Hughes & Cuthbert 2000; Thacker *et al.* 2019). It is therefore striking that, although microscopic analysis of historic mortars is fast becoming general practice in the building conservation industry and archaeobotanical analysis is often now employed during limekiln excavations, analysis of relict limekiln fuels removed from the *in situ* mortar materials themselves does not appear to have been employed in any of the previous studies discussed above. One more recent exception to this trend was the analysis of two MERLF fragments associated with an assemblage of mortars curated during the survey and excavation of All Saints church, Brixworth (England), which had previously been subject to both 'matrix method' and bulk fuel radiocarbon analysis (Parsons & Sutherland 2013, 141–144; Millard 2013). It is important (and perhaps no coincidence) that this re-analysis was undertaken along with other biogenic materials from excavated contexts such as post-holes and ditch-fills, but the mix of taxa presented by this very limited assemblage (which included a lens of hazel (OxA-22276), and a fragment of oak (OxA-22336)) is clearly consistent with the wider evidence for European limekiln fuels set out above.

Accepting that compositional contrasts emerge from variations in lime-burning and processing techniques, another probable reason for the lack of published MERLF archaeobotanical studies is sample size. Archaeobotanical (or anthracological) characterization of wood-charcoal taxon and morphology is generally predicated on relatively low-powered microscopic examination of ≥ 1cm^3 samples in three different planes, in comparison with reference material and anatomical literature (Schweingruber 1990), and the size and condition of MERLF samples can place limitations on this procedure. The evidence from Scotland suggests this is a very valuable exercise, however, and although examination is generally limited to transverse sections, genus-specific characteristics such as porosity, pore size, ray conformation and growth boundary character are often clearly visible. These observations generally enable sample taxa (so important for evaluating life cycle and habit) to be confidently characterized, even in very small fragments, but interpretation of wood-charcoal morphology is often more challenging. Without bark evidence, it is generally impossible to estimate how much wood from outer stem layers has been lost during sample taphonomy and so the vital relationship between the sample fragment and the growing edge of the tree (McFadgen's (1982) growth IA, or Dean's (1978) 'gap') is difficult to quantify. Ring-porous trees, such as oak, deposit an ever-expanding core of heartwood surrounded by a living and maturing sapwood of 10–46 years old (Haygreen & Bowyer 1989, 29–32; Barbaroux & Bréda 2002) but it is often not possible to distinguish sapwood from hardwood fibres in small highly altered pyrolyzed wood fragments.

Characterizing sample curvature can also be challenging in small fragments, and environmental factors or structural features can result in taxa-specific taphonomic biases. It has been demonstrated by experimentation that oak charcoal can suffer from particularly high fragmentation rates (Chrzazvez *et al.* 2014) and the tendency of this taxon to split along closely spaced radial rays often results in very narrow charcoal lenses which makes curvature characterization difficult. Although degree of curvature has been accepted as a proxy for age in a number of anthracological studies (see Dillon *et al.* 2008; Marguerie 2002, 188), this relationship is also problematic and ambiguous descriptors (such as roundwood and branchwood) are now avoided by this author. Where biostructural curvature can be characterized, however, then this can provide valuable information on the relationship between the sample fragment and the stem centre, since low or no curvature samples are very unlikely to represent early growth whilst very high curvature wedged-shaped fragments generally do. Within any given stem, therefore, the fragments with the lowest curvature are generally closest to the bark edge, and so the youngest. Annual growth rates and time depths (number of annual rings) within individual samples can often be assessed during microscopic analysis, and even where only a few growth boundaries are visible then an approximation of time depth can be made from sample size. These parameters can provide useful comparative information on the growing environment but, more importantly for this discussion, growth rate and time-depth measurements provide further circumstantial information on the potential relationship between the radiocarbon evidence and the date of building construction.

The size, botanical character and radiocarbon dating potential of a sample are interrelated in various ways. As above, the fragment should be large enough to allow botanical characterization if possible, and there must be enough surviving carbon in the sample (following pretreatment) to allow measurement to proceed. Soon after Berger's Irish study was published, however, Patrick Ashmore also argued that only whole 'single-entity' wood-charcoal samples should be submitted for radiocarbon analysis and suggested that 'all [radiocarbon] dates for bulk charcoal samples must be reevaluated and it seems likely that scholars will wish to use them with even more caution than previously seemed sensible' (Ashmore 1999, 128). This recommendation clearly has implication for those studies, such as Berger's, which took place before AMS analysis techniques allowed the measurement of much smaller samples. Whether Berger's (1992) 'particles', Bonani *et al.*'s (2001) 'fragments' or Naessen's (2009) 'flecks', however, most previous MERLF studies appear to have been predicated on bulk samples comprised of very small wood-charcoal fragments, and this may also have effectively precluded archaeobotanical characterization. Whilst turnover and infiltration (which were Ashmore's primary concerns) are not significant issues with regard to *in situ* mortar-entrapped materials, radiocarbon analysis of uncharacterised MERLF samples clearly precludes selection of the shortest-lived fragments, so increasing the statistical probability of including long-lived material (Bayliss 2015, 688) and further decreasing the interpretative potential of the resultant data. Simple allometric calculation (see below) suggests that a considerable volume of older material is likely to be included in any randomly submitted wood-charcoal assemblage.

Finally, in this section, and with reference to the discussion of wood fuel diameters earlier in this paper, it is important to note here that annual ring width in oak charcoal is generally submillimetric and often as narrow as 0.3 mm/year. More experimental work is required, but allowing for an average of 20% radial shrinkage during pyrolysis (Ludemann 2008, 148) would suggest that even a 20-cm-diameter piece of wood (from our mixed-feed kiln above) could be over 200 years old if used in the round, and a 20–30-cm-wide piece of split wood fuel might conceivably contain a time depth of 400 years. Moreover, even where the limekiln charge is composed of wood fuel in the round, it is the oldest high curvature centres of these stems (with the greatest IA or temporal 'gap') which are most likely to survive as MERLF fragments.

Interpreting the Radiocarbon Evidence

The inclusion of high IA 'old wood' within uncharacterised MERLF wood-charcoal fragments has the potential to increase the disjunction between radiocarbon data and building completion dates significantly, and with reference to the English medieval documentary evidence discussed above, we should expect a clear interpretive contrast between the pyrolyzed tree trunk fragments presumably entrapped within the constructional mortars of Windsor Castle and the fragments of brushwood that fuelled the limekilns for the construction of the city walls of Oxford. In this regard, the report that 500 oaks from Wellington Forest were 'devoured' for lime-burning is particularly evocative, since this appears to imply that the radiocarbon profile of the limekiln fuel charge matched that of the woodland, and allometric calculations would therefore indicate that (due to the increasing diameter of the ageing tree) more than 50% of the fuel volume would be composed of the outer 30% of the tree rings (Manning *et al.* 2018, 4). Accepting that MERLF assemblages will not fully reflect the age distribution of the associated limekiln charges, these three examples—tree trunks, brushwood and mixed morphology—parallel the revised interpretative framework developed for the final section of this paper.

Without positive *a priori* evidence suggesting that the IA associated with an analysed MERLF sample is very limited then, as with the Clonmacnoise round tower and St Columb's Kells studies discussed above, building completion dates may not be constrained within the resultant radiocarbon calibrated date range. Given the temporally thick process of building construction, however, the concept of building 'completion' does usefully allow for a clear understanding of how the radiocarbon measurements associated with MERLF fragments relate to a particular socio-political 'event' rather than an extended 'phase', and it is generally reasonable to suggest that a calibrated radiocarbon date range presents an effective *terminus post quem* (TPQ) for building completion (Dee *et al.* 2009; Millard 2013). Using the terminology proposed by Dean (1978), the dated event (MERLF wood formation) pre-dates the target event (building completion), and this approach is likely to be accurate for all of the various limekiln fuelling strategies highlighted above—whether oak tree trunks or brushwood, local or transported, fresh cut and seasoned or CWD—irrespective of extended bridging events such as build times. Given the potential for MERLF samples (whether bulk or single entity) to contain significant IA, however, it is not reasonable to suggest that the upper end of a calibrated date range represents an effective *terminus ante quem* (TAQ) for building completion, and this is a significant issue for studies predicated on uncharacterised samples which have implicitly accepted this premise to argue for particularly early building dates (*e.g.* White Marshall and Rourke 2000, 121; Berger 1995, 167; Naessens 2009, 63). A radiocarbon TPQ from an uncharacterised sample of primary phase MERLF material, however, can very usefully constrain the chronological range of a building where a documentary reference already presents a convincing TAQ. These different types of building evidence are complementary and will effectively bracket the date of primary construction, although precision relies on the survival of an early documentary reference (such as that for Clonmacnoise round tower) and an incidentally low IA MERLF sample.

A more robust approach to investigating the relationship between MERLF radiocarbon data and the chronology of building construction, however, can be made by incorporating the data from multiple radiocarbon measurements within a Bayesian model, including all of the known evidence that can confidently be related to the structure and its component materials. By combining new independent 'prior' dating evidence (such as MERLF radiocarbon measurements) with 'prior' archaeological beliefs (including sources of relative dating evidence such as site phasing, the rate at which we would expect the individual samples to have been deposited within a particular phase, and the character of those samples), Bayesian techniques can generate 'posterior' distributions which include altered date ranges for each radiocarbon measurement as well as quantitative estimates for the dates of archaeological events that are not directly measurable—such as the completion of a masonry building (Karlsberg 2006; Bayliss *et al.* 2007; Bronk Ramsey 2009a; Bayliss 2009, 130; 2015). Informed by the discussion presented above regarding MERLF depositional histories, it is vital for our interpretations to understand how these parameters relate to one another within a Bayesian model:

- Phasing—Radiocarbon measurements from a period of cultural activity are generally grouped within a modelled 'phase' in order to reflect relative chronological relationships between samples (Bayliss *et al.* 2007, 5). There is no inherent direct stratigraphic relationship between individual MERLF radiocarbon measurements from different phases, however, and it is entirely possible that a high IA MERLF sample could 'predate' a measurement from an earlier period of construction.

- Distribution—A uniform (non-informative) distribution is generally incorporated into a modelled phase and, by reducing statistical 'scatter' and the effect of measurement error margins, this will often refine the probability distributions associated with each measurement quite considerably (Bayliss *et al.* 2007, 5). The overall distribution of unmodelled MERLF radiocarbon measurements (relative to structural completion), however, will reflect the number of samples selected, the pre-depositional IA of those samples, the duration and rate of construction and the precision of the radiocarbon measurements themselves (Dee & Ramsey 2014, 85; Dee *et al.* 2009, 1065; *cf.* Gavin 2001).
- Boundaries—Completion of a period of masonry construction is an 'event' represented by the Boundary probability distribution generated by the Bayesian model at the end of each phase (Dee *et al.* 2009, 1065–6) and, unlike the individual radiocarbon measurements, these generated end boundary probability distributions can be interrelated stratigraphically.

Of these parameters, the radiocarbon measurements and phasing information are generally regarded as the most important 'informative priors' for robust posterior estimates, since this information is firmly situated within the site archaeology and any erroneous information here will make the model 'importantly wrong' (Bayliss *et al.* 2007, 5–6). Informed by the radiocarbon evidence reported in previous MERLF studies and by the heterogeneous depositional histories of the limekiln fuel materials and buildings themselves, however, the modelled relationship between the assemblage distribution and phase boundary is also of clear significance. Within the 'OxCal' program employed for the case study data in this paper, an allowance for potential disjunction in the sample assemblage can be made by situating the radiocarbon data within various 'outlier models' which themselves have distinctive distributions, and within which each radiocarbon date can be tagged with an individual 'outlier probability' according to its IA potential (Bronk Ramsey 2009b). Utilizing this capability for the interpretation of MERLF materials, a framework of three different Bayesian approaches is presented below:

Approach A is specified where the sub-assemblage from a particular phase selected for radiocarbon analysis is dominated by MERLF samples of relatively short-lived archaeobotanical character (Thacker in prep. d). In this approach, the OxCal 'General' outlier model and a 'Tau' Start Boundary are imposed upon the model (Bronk Ramsey 2009a, 346–7, Fig. 5; 2009b). The General outlier model 'draws from a long-tailed student distribution …so will not be too affected by the odd extreme outlier…' (Bronk Ramsey 2009b, 1027–8) and each measurement can be tagged with a full range of outlier probabilities from 100 to 1% depending on sample character. Following Dee *et al.* (2009, 1066), an exponentially distributed Tau boundary is included to 'focus on the latter portion of the individual [radiocarbon date] calibrations' which are likely to be situated closer to the building completion date.

Approach B is specified where the sub-assemblage selected for radiocarbon analysis is dominated by MERLF samples that are not of a demonstrably short-lived archaeobotanical character. In this approach, an OxCal 'Charcoal' outlier model is imposed on the data and (as demanded by the model) each radiocarbon measurement is tagged with a 100% outlier probability (Bronk-Ramsey 2009b). This model imposes an exponential distribution on tagged radiocarbon measurements (which heavily downweights the effect of older calibrated date ranges), with a time constant of 1–1000 years (reflecting the potential IA of very mature woodlands), and all measurements are considered older than the date of deposition (so particularly suitable for *in situ* MERLF assemblages where infiltration is precluded; Harris 1989, 121) (Bronk-Ramsey 2009b, Nicholls & Jones 2001; Dee & Ramsey 2014, 83–4).

Approach C is specified where a mixture of short-lived and potentially long-lived MERLF samples has been selected for radiocarbon analysis. In this approach the ‘General’ and ‘Charcoal’ outlier models described above are used in tandem, and individual radiocarbon measurements can be tagged against either model depending on sample character (Dee & Ramsey 2014).

Each of these approaches is illustrated in three Scottish case studies presented below, selected for this paper from two much wider programmes of investigation on the basis of the different evidence associated with their construction (see Acknowledgements for further details). The masonry buildings which form the focus of these studies are located in different parts of the country (see Fig. 3), were constructed at different scales, present MERLF assemblages of different character and are associated with variously refined date ascriptions predicated on architectural and historical evidence. Case Study 1 (Castle Fincharn) is typologically and historically ambiguous, whilst Case Study 2 (Lochindorb Castle) has previously been ascribed to a very refined historically informed typological date range. Case Study 3 (Kincardine Castle) has also been ascribed to a refined date range and has been included to demonstrate a modelling approach to sub-assemblages containing a mixture of short-lived and long-lived taxa. In order to further investigate the relationship between MERLF radiocarbon data and these other types of building evidence, two Bayesian models have been constructed for all three studies, with a ‘standalone’ model predicated on building stratigraphy and materials analysis only, followed by a ‘multidisciplinary’ model which also includes

Fig. 3 Locations of the three Scottish Medieval case study sites. Map annotated using Edina digimap software. Contains OS data © crown copy and database rights Ordnance Survey (100025252)

documentary evidence. Further details of these models (including the coding) are also presented in the Electronic Supplementary Material (ESM).

Case Study 1—Castle Fincharn, Mid-Argyll

Castle Fincharn is located on the south bank of Loch Awe, an important waterway connecting central Scotland to south-west Argyll (Thacker 2017; Figs. 3 and 4). The name Fincharn first emerges in the documentary record within a long list of settlements granted to Gillescop MacGillechrist by the Scottish Crown in 1240, but there is no clear reference to a castle building of this name until a 1563 retour confirming '…the lands of the lordship and barony of Glasre…with the messuage or manor place of the said lordship named Nether Fincharn…' (MacPhail 1916, 206). Previous architectural interpretations of the ruinous predominantly single-phase two- to three-storey masonry block surviving on the site have varied between these same thirteenth to sixteenth century dates (*e.g.* RCAHMS 1992; Coventry 1997), with some suggestion that the nearby ruins at *Caol Chaorunn* are more likely to relate to the earlier period (Campbell & Sandeman 1962).

Castle Fincharn was the first medieval building in Scotland to be dated by radiocarbon analysis of MERLF fragments (Thacker 2016, 2017). Survey and sampling strategies at this small (approx. 12 × 5.5 m internally) ruinous multi-storey structure were informed by examination of large areas of constructional fabric in full wall cross-section (1.4–2.15 m wide), now exposed by adjacent collapse. Buildings and on-site mortar analysis confirmed that this structure was predominantly single-phase (RCAHMS 1992) and had been constructed from lime-bonded rubble blocks in a series of level through-courses, in a formal masonry style with some dressed sandstone features. A well-distributed assemblage of mortar, limestone and single-entity wood-charcoal MERLF samples was removed from the monument (Fig. 5), and subject to a suite of geoarchaeological, archaeobotanical and radiocarbon analyses that included

Fig. 4 Castle Fincharn is located on a narrow peninsula on the freshwater loch of Loch Awe in Mid-Argyll, Scotland (Thacker 2017). Photograph M. Thacker

comparative analysis of limestone and temper materials collected from the surrounding region. Final archaeobotanical analysis of the MERLF assemblage from this site was undertaken by Mike Cressey (CFA Archaeology, Musselburgh), and the assemblage, which included high quantities of *Corylus* (9/12) with very minor quantities of *Betula* and *Quercus,* reflects the vegetational history of the locality quite closely. None of these samples presented evidence for bark, however, and only the two oak samples displayed no biostructural curvature at all. Five well-distributed single-entity fragments of *Corylus* were submitted to the Scottish Universities Environmental Research Centre (SUERC) for AMS radiocarbon analysis (see Dunbar *et al.* 2016 for details of the pretreatment and analysis methodologies), and the results are presented in Table 1 below.

Petrographic analysis indicates that the constructional mortar at Castle Fincharn had been manufactured from very local limestone and temper materials, consistent with material deposits located less than a mile from the castle building. A walkover survey of the semi-natural woodlands currently surrounding Loch Awe also highlighted that the hazel growing in this locality generally presents a ‘self-coppicing’ shrub habit, in which multiple stems are produced on a 30- to 50- year cycle from a much longer lived root-stock (*cf.* Rackham 2003, 209), with some standing deadwood stems but very little coherent CWD surviving on the wet woodland floor (Thacker 2017). The generally high curvature morphologies of the small *Corylus* samples in the castle assemblage are consistent with this short-lived multi-stemmed habit and strongly suggest that these MERLF fragments were formed during early stem growth. Although the lack of bark evidence in the assemblage precludes an identification of the exact interval between the formation of these fragments and the death of the tree stem, the generally short-lived character of the *Corylus* taxon suggests that this radiocarbon data is unlikely to be significantly affected by high IA ‘old wood’. The very narrow range of radiocarbon results presented here, which are statistically consistent at the 5% significance level (T

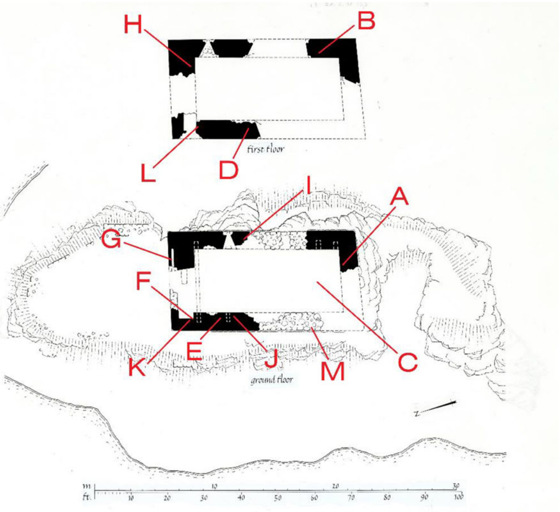

Fig. 5 MERLF sample contexts plotted onto ground and first-floor level plan drawings of Castle Fincharn. Plotted by the author on to a plan drawing prepared and hatched by the RCAHMS (DP_172541; © Crown Copyright: HES)

Table 1 Site context, archaeobotanical character, radiocarbon measurements and calibration date ranges for selected MERLF samples from Castle Fincharn

Site context			Sample character				Radiocarbon measurements and calibrated date ranges			
Phase	Feature	Code	Taxa	Curve	Rings	Bark	Lab. Code	$\delta^{13}C$ (‰)	^{14}C Age (BP)	Calibrated date range (cal AD) at 94.5% probability
1	South Wall	FCA.A	*Corylus* sp.	Low	< 20	No	SUERC-54796	− 26.4	744 ± 36	1210–1300
1	West Wall	FCA.D	*Corylus* sp.	Mod.	< 20	No	SUERC-54795	− 27.5	777 ± 36	1190–1290
1	North Wall	FCA.H	*Corylus* sp.	High	< 20	No	SUERC-54794	− 28.7	777 ± 36	1190–1290
1	East Wall	FCA.I	*Corylus* sp.	High	< 10	No	SUERC-54793	− 26.6	837 ± 36	1050–1080 (4.1%), or 1150–1270 (91.3%).
1	West Wall	FCA.J	*Corylus* sp.	High	< 10	No	SUERC-54800	− 26.9	808 ± 36	1160–1280

All samples were removed from in situ core mortars consistent with phasing. All samples were single entity. δ C values are all reasonably close to the expected − 25‰ level. Calibrated date ranges were calibrated by the probability method using OxCal v.4.3.2 (Bronk Ramsey 2017) and the IntCal13 atmospheric curve (Reimer et al. 2013). Calibrated date ranges have been rounded out to 10 years

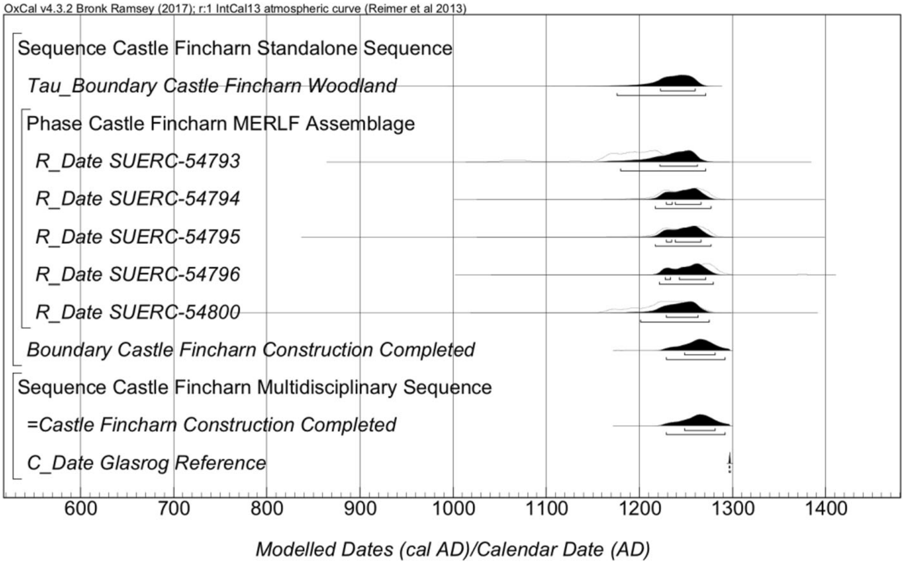

Fig. 6 Probability distributions of dates from Castle Fincharn using modelling approach A and 'multidisciplinary' data, including phasing interpretations, radiocarbon data and the earliest available (1297) convincing documentary reference. Plotted in OxCal v4.3.2 (Bronk Ramsey 2017), calibrated using IntCal13 atmospheric curve (Reimer *et al*. 2013). All five radiocarbon dates have been situated within a single phase and all five tagged with a 5% outlier probability within the 'General' outlier model (Bronk Ramsey 2009b). Each distribution represents the relative probability than an event occurs at a particular time and for each of the radiocarbon dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration, and a solid one, which is based on the chronological model. The Boundary distribution '*Castle Fincharn Construction Completed*' situated at the end of this phase is an estimate of the date when construction of Castle Fincharn was completed, and a second sequence defines that this distribution pre-dates a calendar date of 1297 (predicated on a documentary reference to Glasrog Castle). The large squared brackets down the left-hand side define the model, and the smaller brackets beneath each distribution represent the highest probability distributions at 68.2% and 95.4% probability

$' = 3.8$, $T'(5\%) = 9.5$, $\nu = 4$) and even 10% significance level ($T' = 3.8$, $T'(10\%) = 7.8$, $\nu = 4$; Ward & Wilson 1978), indicates these MERLF fragments could all be of the same actual age and there is clearly a large mid-thirteenth century overlap in the calibrated data.

With knowledge of the short-lived taxonomical character of the submitted samples, and the likely local provenance of that material, this radiocarbon data suggests various other strands of archaeological and documentary evidence can be confidently considered (Thacker 2016, 2017). The formal masonry style displayed at Castle Fincharn, for example, is similar to the nearby parish church, which can be ascribed to the thirteenth century on the architectural form of a twin-lancet east window and trefoil-headed piscina. These buildings appear to have represented the dual administrative focus of the co-extensive lordship and parish of Glassary until the sixteenth century, and the similar biographies of these structures suggest that Castle Fincharn is indeed likely to be the '...certain castle and barony by the name of Glasrog...' noted by Alexander of the Isles in 1297 (Stevenson 1870, 191; Barrow & Royan 1985, 168) and one of the three castles held by the MacDougalls on Loch Awe in the very early fourteenth century (Fisher 2005). Elsewhere, I have argued that Castle Fincharn was constructed soon after the surrounding lordship was confirmed to Gillescop MacGillechrist in the 1240 royal grant (Thacker 2017).

Constructing a Bayesian model around this data allows us to consider further how the radiocarbon results from these MERLF materials might be distributed with respect to other evidence for the castle's construction. Modelling approach A (see text above) was selected on the basis that the MERLF assemblage submitted for radiocarbon analysis was dominated by relatively short-lived samples of very local provenance and a 5% individual outlier probability was imposed on each of the five radiocarbon dates to reflect this low IA interpretation. As indicated above, two separate models were constructed using this approach including a 'standalone' model that generated end boundary posterior densities on the basis of radiocarbon data and archaeological phasing interpretations alone (ESM 1.1), and a 'multidisciplinary' model that constrained the end boundary distribution from the single phase of radiocarbon data relative to the earliest surviving (1297 AD) documentary reference (ESM 1.2). This standalone model has generated an estimate suggesting that construction of Castle Fincharn was completed *1220–1305 cal AD* (*95.4% probability*), probably *1245–1285 cal AD* (*68.2% probability; Castle Fincharn Construction Completed*; ESM Fig. S1 & Table S1), whilst the multidisciplinary model suggests construction of the building was completed in *1225–1295 cal AD* (*95.4% probability*), probably *1245–1285 cal AD* (*68.2% probability*; *Castle Fincharn Construction Completed*; Fig. 6). These probability distributions, which have been rounded out to 5 years in both models, will be considered further in a comparative section below.

Case Study 2—Lochindorb Castle, Highland

Lochindorb Castle is located on a small island high in the Grampian Mountains, close to an important historic SW-NE routeway across the central Highland region of Badenoch to the cathedral city of Elgin (Thacker 2019b; Figs. 3 and 7). The site is closely associated with various very high-status personalities, including Edward I of England, and the upstanding masonry buildings on the island are extensive. These include a primary phase quadrangular enclosure measuring 54 × 57.5 m within curtain walls up to 2 m thick (Anderson and Dixon 2011, 6) with rounded angle towers; a secondary curtain wall ('outer-works') in the east and the fragmentary remains of a secondary multi-cellular east range. The distinctive mid-late thirteenth century architectural form of the primary enclosure castle is consistent with a 1279 reference to 'Robert of Lochindorb', and on this basis, a very narrow 1258–1275 constructional chronology for this structure has been widely accepted (Cruden 1960; Barrow 1988, 9; Anderson & Dixon 2011). Although clearly abutting the primary enclosure, the constructional date or dates of both main secondary buildings are more speculative. No consensus of opinion on these secondary structures had been reached by the time of the recent materials study undertaken during the Scottish Medieval Castles and Chapels C14 Project (SMCCCP), although it is generally accepted that a 1455 royal charter ordering the slighting of the complex (Innes 1859, 21–22; Anderson & Dixon 2011, 3, 16 n.7), which was reportedly completed by 1458 (Burnett 1883, 486; MacGibbon & Ross 1887, 71; Thacker in prep. c), post-dates all significant upstanding constructional evidence.

Long stretches of largely complete wall faces and areas of secondary calcite deposition limited mortar visibility in some areas of the monument, but mortar survey did suggest the building fabric was bound with limestone lime mortars presenting some phase-specific textural contrasts. A limited sample assemblage comprising three mortar fragments (one representative core sample from each main structure), a relict limestone inclusion, a fragment of sandstone and 12 MERLF fragments (plus one loose wood-charcoal sample) was removed from well-distributed contexts around the Lochindorb Castle site (Fig. 8). These samples are currently subject to a suite of geoarchaeological, archaeobotanical and radiocarbon analyses that includes comparative analysis of regional material sources. These analyses suggest that each of the three main surviving structures had been constructed with distinctive compositionally contrasting mortar materials, and the assemblage appears to include two different lime sources. Whilst the mortars of the secondary outer works and primary curtain present some close similarities, contrasts in the relict limestone associated with the secondary outer-works and south end of the east range suggests these structures may not be contemporaneous, and on this basis, these structures are ascribed to phases 2 and 3 in interim. Archaeobotanical botanical analysis of the MERLF assemblages from this site was undertaken by the author under some supervision from Mike Cressey who verified all taxonomic interpretations. Phase 1 (enclosure) and phase 3 (east range) assemblages were completely dominated by fragments of *Quercus* sp. (oak), however, with only a single loose fragment of *Pinus* sp. (pine) from the core of (phase 2) outer-works contrasting (Thacker 2019b).

These analyses suggest the limestone and sandstone materials necessary to construct Lochindorb Castle had been transported (overland) to the site from a considerable distance away, and the taxonomical profile of the *Quercus*-dominated MERLF assemblage presents a striking contrast with fragments of suspected semi-natural birch and pine dominated woodland in the locality (Thacker 2019b). The MERLF assemblage from this site was also dominated by amorphous morphologies, with no surviving evidence for bark, visible sapwood/heartwood boundaries, or very high curvature

Fig. 7 Lochindorb Castle from the east. The building is situated on an island in a freshwater loch of the same name, in the Grampian Mountains of north-east Scotland. Photograph: J. Thacker

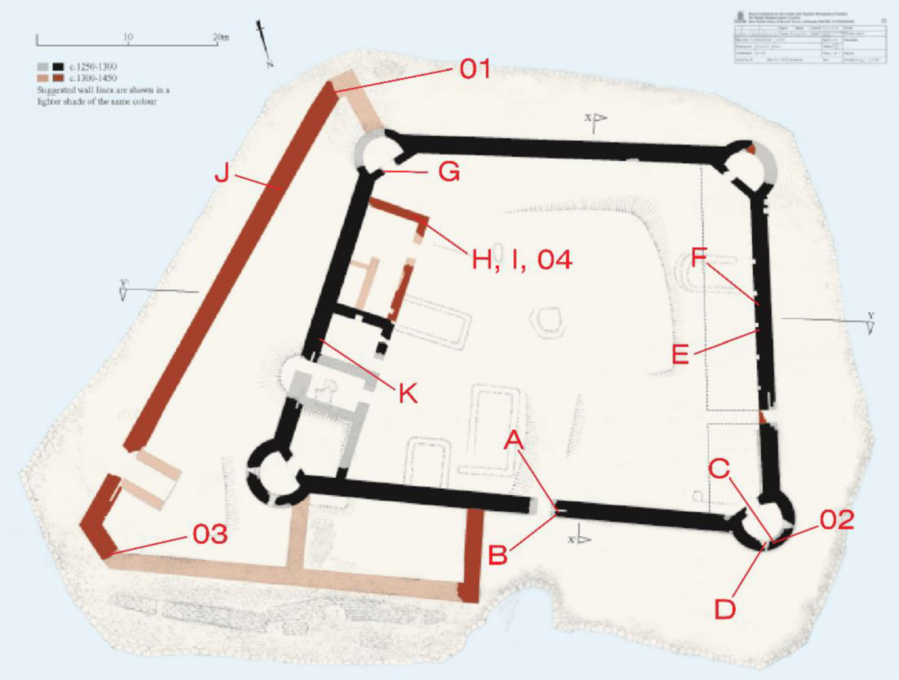

Fig. 8 MERLF and other material sample contexts plotted onto a plan drawing of Lochindorb Castle. Contexts plotted by the author on to a ground floor plan drawing prepared with hatching by RCAHMS (GV_004942; © Crown Copyright: HES). Primary phase fabric (ascribed by RCAHMS to 1250–1300) has been hatched in black and secondary fabric (ascribed by RCAHMS to 1300–1450) in red. Suggested wall lines in lighter shades. Scale bar in metres × 10

biostructural conformations, and 8 of the 12 charcoal fragments displayed no biostructural curvature at all. In the absence of more demonstrably short-lived material, eight variously curved *Quercus* fragments from phases 1 and 3 were submitted to the Scottish Universities Environmental Research Centre (SUERC) for radiocarbon analysis (see Dunbar *et al.* 2016 for details of pretreatment and analysis methodologies), and the results are presented in Table 2 below.

The submitted assemblage from Lochindorb Castle has returned set of results which further demonstrate the importance of various interrelationships between MERLF taxa, sample context, building phasing, possible sources of disjunction and radiocarbon data distribution. The five MERLF samples from the phase 1 enclosure, for example, were removed from a widely distributed series of curtain wall and angle tower locations, and these have returned a set of radiocarbon results which are also widely spread. Taken altogether, the five radiocarbon determinations are clearly not statistically consistent at 5% significance level ($T' = 2013.8$, $T'(5\%) = 9.5$, $\nu = 3$; Ward & Wilson 1978). Manually removing the extremely early LCB.D (SUERC-75752) from consideration narrows the distribution considerably, however, and the four remaining youngest radiocarbon determinations from phase 1 are at least statistically consistent at the 2.5% significance level ($T' = 8.4$, $T'(2.5\%) = 9.3$, $\nu = 3$; Ward & Wilson 1978). The data from the east range is, by contrast, very narrowly distributed, and these three radiocarbon determinations are statistically consistent at 5% ($T' = 1.5$, $T'(5\%) = 6.0$) and even 10%

Table 2 Site context, sample character, radiocarbon measurements and calibrated date ranges for selected MERLF samples from Lochindorb Castle

Site context			Sample character				Radiocarbon measurements and calibrated date ranges			
Phase	Feature	Code	Taxa	Curve	Rings	Bark	Lab. Code	$\delta^{13}C$ (‰)	^{14}C age (BP)	Calibrated date range at 95.4% probability
1	North Curtain	LCB.A	*Quercus* sp.	Mod.	10+	No	SUERC-75747	−26.5	835 ± 31	1150–1270 cal AD
1	NW Tower	LCB.C	*Quercus* sp.	Low-Mod.	10	No	SUERC-75751	−25.3	862 ± 31	1040–1090 (12%), or 1120–1260 (83.4%) cal AD
1	NW Tower	LCB.D	*Quercus* sp.	Mod.	–	No	SUERC-75752	−26.7	2368 ± 31	540–380 cal BC
1	West Curtain	LCB.E	*Quercus* sp.	Low	6	No	SUERC-75753	−24.7	932 ± 31	1020–1170 cal AD
1	SE Tower	LCB.G	*Quercus* sp.	None	8	No	SUERC-75754	−26.1	940 ± 31	1020–1160 cal AD
3	East Range	LCB.Ia	*Quercus* sp.	None	18	No	SUERC-75755	−26.5	842 ± 31	1050–1080 (2.4%), or 1150–1270 (93%) cal AD
3	East Range	LCB.Ib	*Quercus* sp.	None.	7	No	SUERC-75756	−26.5	891 ± 31	1040–1220 cal AD
3	East Range	LCB.Ic	*Quercus* sp.	None.	8	No	SUERC-75757	−26.7	848 ± 31	1050–1080 (5%), or 1150–1270 (90.4%) cal AD

Modified from Thacker 2019b (© Rilem 2019). All samples were removed from fixed *in situ* core mortars consistent with phasing. All samples were single entity. Samples LCB.A, C and D were characterized as roundwood on the basis of relative sample curvature. δ^{13}C values are all reasonably close to the expected −25‰ level. Radiocarbon measurements were calibrated by the probability method using OxCal v.4.3.2 (Bronk Ramsey 2017) and the IntCal13 atmospheric curve (Reimer *et al.* 2013). Calibrated date ranges have been rounded out to 10 years significance levels ($T' = 1.5$, $T'(10\%) = 4.8$, $\nu = 2$; Ward & Wilson 1978). This very narrow range, however, highlights that (unlike the phase 1 samples) these MERLF fragments were removed from an east range south wall context which is also of very limited physical distribution (Fig. 8), and since these samples were all *Quercus* of similar morphology, it is at least possible that these results lack independence (and may be from the same plant and radiocarbon reservoir).

The individual calibrated dates returned by MERLF samples from both phases of Lochindorb are all early, however, with none of the results post-dating the 1458 calendar date at which the whole complex was apparently decommissioned, and none of the phase 1 results clearly post-dating the accepted 1258–1275 constructional chronology of the primary phase main enclosure. Whilst two of the phase 1 results do at least overlap with the accepted date of the primary enclosure, all of the phase 3 results are earlier than would have been expected for short-lived material in this secondary context, and the lack of clear distinction between the unmodelled calibrated date ranges of the assemblages from the two submitted phases is salient. Indeed, the overlap in the data from these phases is such that (discounting the extremely early sample LCB.D; SUERC-75752) the remaining seven multiphase samples are statistically consistent at 5% significance level ($T' = 11.7$, $T'(5\%) = 12.6$, $\nu = 6$; Ward & Wilson 1978).

These results and their distributions hint at high levels of disjunction, for which there are several possible causes. With ‘bog-wood’ widely reported in the area, it is possible that the extremely early result returned by sample LCB.D (SUERC-75752) represents the use of CWD, but once again the most important consideration for the rest of the assemblage relates to the archaeobotanical character of the submitted samples and the potential for *Quercus* sp. to live for hundreds of years. The short time depths and small size of the submitted samples clearly indicate that fragmentation of the relict limekiln materials is advanced and the early radiocarbon dates are generally inconsistent with survival from the outermost (youngest) rings of the harvested wood. The inversely proportional relationship between sample curvature and radiocarbon age evident in the four youngest phase 1 results also suggests a range of wood diameters were harvested for inclusion within the kiln charge (Thacker 2019b). The distribution presented by these youngest phase 1 results prompts further questions about outlier recognition and whether 5% significance should always be accepted as the critical value for consistency evaluation, but the overall results indicate that even this small sub-assemblage probably contained a considerable time depth and the lack of high curvature early wood and late bark in these limited assemblages suggest that the overall time depths of the kiln charges themselves were probably even broader (see below).

On the basis of the character of the *Quercus*-dominated submitted samples and the potential for increased disjunction caused by the apparent lack of locally available resources and the size of the building, modelling approach B (see text above) was adopted for the Bayesian analysis of the Lochindorb Castle radiocarbon measurements. For the purposes of these models, the extremely early date returned by sample LCB.D (SUERC-75752) is not included and the phase 3 east range samples (SUERC-75755, SUERC-75756 & SUERC 75757) are regarded as independent (so are not combined before calibration). As with the first case study, two models were constructed, including a ‘standalone’ model which incorporates the radiocarbon data and phasing interpretations

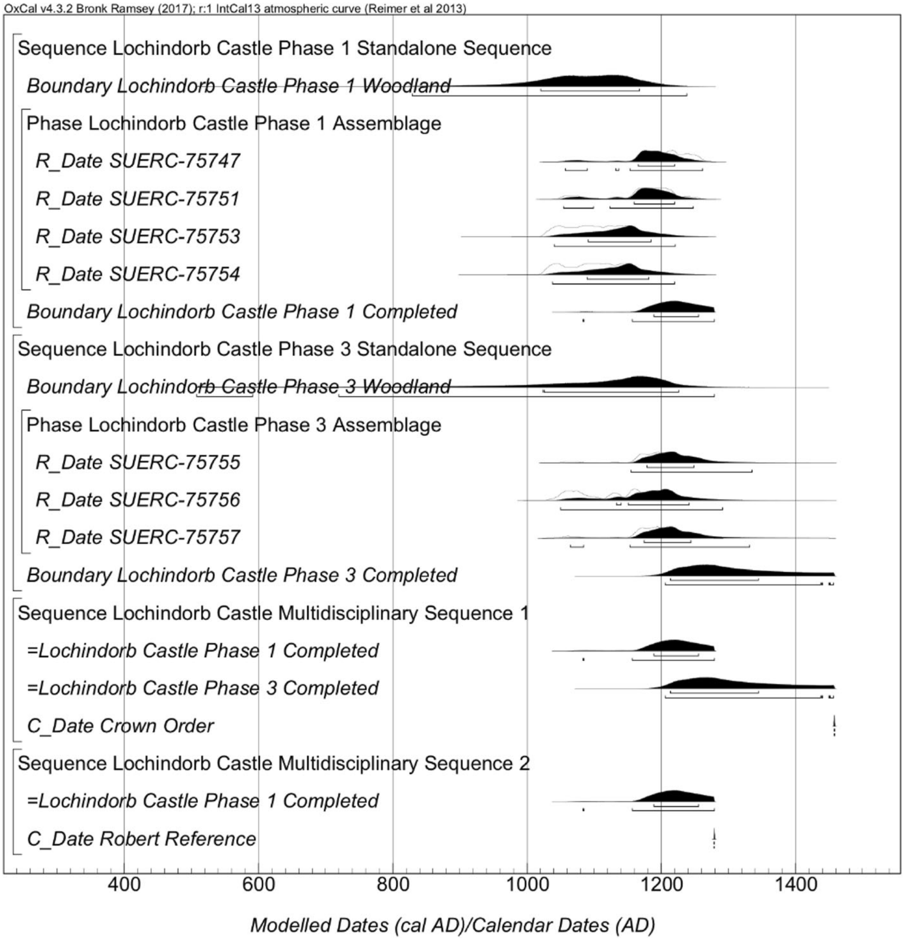

Fig. 9 Probability distributions from Lochindorb Castle using modelling approach B and incorporating multidisciplinary data, including phasing interpretations, radiocarbon measurements and documentary evidence. Plotted in OxCal v4.3.2 (Bronk Ramsey 2017) and calibrated using the IntCal13 atmospheric curve (Reimer *et al*. 2013). The MERLF radiocarbon measurements have been situated within two bounded phases, and all seven radiocarbon measurements, from both phases, have been tagged with 100% outlier probabilities within separate 'Charcoal' outlier models (Bronk Ramsey 2009b). Each distribution represents the relative probability than an event occurs at a particular time and for each of the radiocarbon dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration; and a solid one, which is based on the chronological model. The Boundary distributions ' *Lochindorb Castle Phase 1 Completed*' and '*Construction Lochindorb Castle Phase 3 Completed*' represent the estimated dates at which construction of these structural phases (curtain wall and east range) were completed. Two further sequences constrain these Boundary distributions according to stratigraphic interpretation and documentary evidence. The third sequence constrains both end boundary distributions relative to each other and to a 1458 AD calendar date (representing documentary evidence that the slighting of the Castle was completed), and in the fourth sequence, the end boundary distribution '*Lochindorb Castle Phase 1 Completed*' is defined as earlier than a 1279 AD calendar date (representing the historical reference to Robert of Lochindorb). The large squared brackets down the left-hand side define the model, whilst the smaller squared brackets beneath each distribution represent the highest probability distributions at 68.2% and 95.4% probability

(ESM 2.1), and a 'multidisciplinary' model which includes the thirteenth and fifteenth century documentary references noted above (ESM 2.2). The standalone model suggests construction of the Phase 1 enclosure at Lochindorb Castle was completed in *1070–1415 cal AD* (*95.4% probability*), probably *1175–1280 cal AD* (*68.2% probability; Lochindorb Castle Phase 1*; ESM Fig. S2 & Table S2), and construction of the phase 3 south end of the east range was completed in *1200–1695 cal AD* (*95.4% probability*), probably *1205–1440 cal AD* (*68.2% probability*; *Lochindorb Castle Phase 3*; ESM Fig. S2 & Table S2). The multidisciplinary model suggests construction of phase 1 at Lochindorb Castle was completed in *1080–1085 cal AD* (*0.1% probability*) or *1155–1280 cal AD* (*95.3% probability*), probably *1185–1260 cal AD* (*68.2% probability*; *Lochindorb Castle Phase 1 Completed*; Fig. 9) and construction of the phase 3 east range was completed in *1205–1440 cal AD* (*94.2% probability*), probably *1210–1345 cal AD* (*68.2% probability; Lochindorb Castle Phase 3 Completed;* Fig. 9). These probability distributions, all of which have been rounded out to 5 years, will be considered further in a comparative section below.

Case Study 3—Kincardine Castle, Aberdeenshire

The site of the medieval county town of Kincardine is located approximately 4 miles NW of Laurencekirk, on the edge of the fertile Howe of the Mearns valley and close to an important historic north-south routeway to and from Deeside (Fig. 3). The position of this settlement and burgh in the late medieval period is attested to by various fragments of documentary, archaeological, cartographic, and place-name evidence, including a chapel site and burial ground, deer park, relocated market cross and gallows site (RCAHMS 1982b, nos. 250, 213, 275 & 247; Ordnance Survey 1868). Almost all of the upstanding buildings relating to Kincardine have now disappeared beneath ploughed fields, although the highly ruinous remains of a quadrangular enclosure castle (defined by turf-covered footings) are still visible on a prominent woodland-covered escarpment overlooking the former settlement and valley below (Fig. 10).

A plan of this building was first published on the Ordnance Survey (1868) 1st Edition map, depicting a medium sized (approx. 35 m × 35 m with walls 2.4 m thick) sub-square curtain-walled enclosure with a main entrance in the south (through what appears to be a gatehouse range), with further internal ranges to the north and east and another gate in the north (Fig. 11). A nineteenth century commentator reported that Kincardine Castle 'is supposed to be of great antiquity, and to have been occupied by Kenneth III, Alexander the Lion, Alexander III, Edward I and Robert II' (MacGibbon & Ross 1889, 112) implying a royal foundation of tenth to eleventh century origin (see also Cruden 1960, 51). Some support for this tradition is afforded by the Crown charters which were issued from or relate to Kincardine during the late 12th and early thirteenth century (here variously recorded as Kincard, Kincarden, Kinkardyn & Kin[…]), beginning with the confirmation of a grant made to St Andrews Cathedral Priory by Hugh Giffard dated to somewhere between 1189 and 1195, although the lack of earlier evidence prompted Barrow to suggest this reflected more focussed exploitation (indeed feudalisation) of royal demesne lands north of the Tay during the reign of King William than had previously pertained (Barrow 1971, 5, 29, nos. 358, 410, 428,

Fig. 10 The fragmentary upstanding remains of Kincardine Castle, just visible in the trees to the left of this image, are situated on a raised ridge overlooking the former burgh, and on the edge of an extensive deer park. Photograph: M. Thacker

494, 496; 1973, 259–60; Gilbert 1975, 25). A fourteenth century account reports that Guthred MacWilliam, leader of a Highland rebellion and rival claimant of the throne, was beheaded at Kincardine in 1212 (Corner *et al*. 1994, 466–6; Duncan 1989, 196–7; 2002, 37) and Crown occupation and investment in the site continued with William's heirs after his death in 1214. Importantly for later commentators, this includes three charters issued from the site during the reign of Alexander II between 1226 and 1231, although at least three surviving acts associated with Alexander III (in 1251 and 1277), two documents with King John (1294 and 1296) and two with David II (both in 1360) are also place dated to Kincardine in the later thirteenth and fourteenth centuries (Scoular 1959, nos. 109, 137 & 144; Simpson 1960, nos. 12, 102, 108; Webster 1982, nos. 243 & 245; Neville & Simpson 2012, 36, nos. 12, 101 & 107). Indeed, it is during the later thirteenth century that contemporary evidence for a sheriffdom and deer park at Kincardine finally emerges in the Crown accounts, with a chaplain (presumably associated with St Catherine's chapel and burial ground noted above) recorded in 1330 (Stuart & Burnett 1878, 18, 21 & 321).

The historical evidence highlighted above clearly demonstrates a long history of Crown occupation and regional administration at Kincardine. None of these documentary sources describe a specific building, however, and current work suggests the first direct report of a castle here relates to a 1359 account reporting that the thanage, 'parco' and 'castro' of 'Kyncardyn' were in the hands of the Earl of Sutherland (Stuart & Burnett 1878, 585). It is of course likely that the earlier Crown charter place dates also relate to some kind of castle structure, although a simple association with the surviving masonry building is problematicised by evidence for a nearby earthwork structure (now known as 'Green Castle'), which is of probable medieval date and located only 1.4 km NNE of the masonry complex under discussion (RCAHMS 1982b, no. 226; Oram 2012, 250; Malloy & Hall 2018). Indeed, the RCAHMS assert that this earthwork structure 'is probably the remains of an *early-medieval* castle' (*ibid*; my italics), whilst the masonry building to the south has been attributed to a very narrow 1217–1227 AD date range, on the basis of perceived similarities in plan-form with other supposedly thirteenth century buildings occupying royal castle sites across Scotland and Alexander II's visit to the Kincardine site in 1226 (Dunbar & Duncan 1971, 10–11). Fragments of deer and pig bone, discovered above the gatehouse floor during a small excavation undertaken in 2013, returned dates of 277 ± 30 (SUERC-49788) and 885 ± 34BP (SUERC-48047) (Hall & Malloy 2013, 43), with the earlier of the two samples was reportedly from the lower layer of mixed 'sandy clay' and stone (3009) described as 'demolition material' (Hall 2013). Using the methodology outlined in Fig. 1, this earlier sample (SUERC-48047) now calibrates to 1030–1230 cal AD (95.4% probability), and the early thirteenth century date range ascribed to this masonry building by Dunbar and Duncan (1971) remains widely accepted (RCAHMS 1982b, no. 238; Oram 2012, 249–50; Malloy & Hall 2018).

A preliminary survey of the fragmentary and overgrown remains of the masonry building at Kincardine suggested the main enclosure wall was single phase (although the internal ranges require further work), and a sample assemblage comprising three mortars (KCA.01–03), and 13 MERLF fragments was subsequently removed from the site (Fig. 11). These samples are currently subject to a suite of geoarchaeological, archaeobotanical and radiocarbon analyses, and interim results suggest the mortar was manufactured from a wood-fired weakly metamorphic limestone lime source, tempered with a quartz-rich angular to rounded lithic aggregate grading to 7 mm. Archaeobotanical analysis of the MERLF assemblage was undertaken by the author under supervision of Mike Cressey (CFA Archaeology, Musselburgh) who verified all taxonomic interpretations, and the assemblage was found to be dominated by *Quercus*

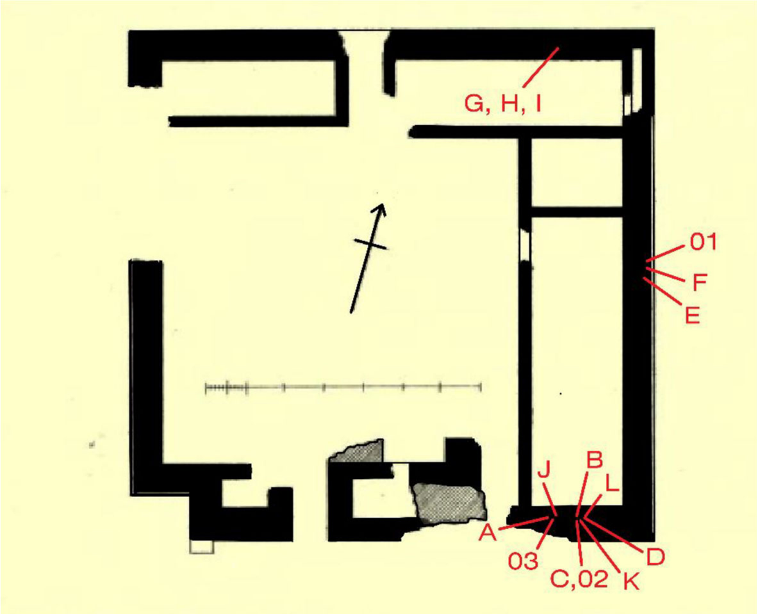

Fig. 11 MERLF and other sample contexts plotted onto a plan drawing of Kincardine Castle. Annotated by the author on a plan drawing by J. Crabb Watt, Esq., F.S.A (MacGibbon & Ross 1889, 111–2, Fig. 63). Scale in feet and feet × 10

(11/13) with single samples of *Betula* (1/13) and *Corylus* (1/13). Three MERLF samples from the enclosure wall (including one loose core sample interpreted as an inclusion released by mortar degradation), none of which presented bark evidence, were submitted to Scottish Universities Environmental Research Centre (SUERC) for AMS radiocarbon analysis (see Dunbar *et al*. 2016 for details of pretreatment and analysis methodologies) and the results are listed in Table 3 below.

The three MERLF samples submitted for radiocarbon analysis each represent different taxa, and so, even though samples KCA.A (SUERC-84391) and KCA.J (SUERC-84393) were removed from *in situ* wall core locations in reasonably close proximity, these were clearly derived from different individuals/radiocarbon reservoirs. The uncalibrated radiocarbon determinations presented here are evenly distributed between 850 ± 21 and 949 ± 24BP but are not statistically consistent at 5% ($T' = 9.8$, $T(5\%) = 6.0$, $\nu = 2$) or even 1% significance level ($T' = 9.8$, $T'(1\%) = 9.2$, $\nu = 2$; Ward & Wilson 1978). This indicates that the small submitted sub-assemblage contained a significant time depth, and it is notable that the (apparently short-lived taxon) *Corylus* sample has returned the earliest (BP) radiocarbon age. At 95.4% probability, the lower Figure in all three calibrated age ranges is below the 1217–1227 AD date previously ascribed to the building, and two of the samples (KCA.A and KCA.J) have returned calibrated date ranges which are completely below this previously suggested constructional date range. Loose sample KCA.G (SUERC-84392) was the only measurement which returned a calibrated date range that brackets that suggested period.

The vegetational history of Kincardineshire and comparative limestone samples from the region are yet to be evaluated. Although not unproblematic considering the very limited number of dates currently available (Bronk Ramsey 2009b), modelling approach C (see text above) is adopted here for the Bayesian analysis of these radiocarbon measurements on the basis of the mixed character of the MERLF sample assemblage submitted for analysis and the moderate size of the building. Within this approach, the radiocarbon date returned by *Quercus* sample KCA.A (SUERC-84391) was tagged with a 100% outlier probability within a Charcoal outlier model, and the radiocarbon dates returned by *Betula* sample KCA.G (SUERC-84392) and *Corylus* sample KCA.J (SUERC-84393) were tagged with 10% outlier probabilities within the General outlier model.

It is hoped that radiocarbon analysis of further MERLF samples can add to this model in future work. From this perspective, it is notable that the radiocarbon age returned by the pig bone sample (SUERC-48047), discovered in demolition material during previous excavation, is statistically consistent at 5% significance level with the youngest two MERLF samples—KCAG (SUERC-84392) and KCA.A (SUERC-84391) but the lack of a clear stratigraphic link with the castles' construction currently precludes the inclusion of this measurement within the model (*i.e.* This measurement may lack 'relevance'; Dean 1978, 229). In line with the general methodology presented above, two models were also constructed for Kincardine Castle: one standalone model containing the MERLF radiocarbon measurements and phasing interpretations only (ESM 3.1), and a second 'multidisciplinary' model (ESM 3.2) including the 1226 documentary reference to King Alexander II's visit to the site highlighted by Dunbar and Duncan (1971). With reference to the probability distributions generated by these models; the standalone model suggests construction of Kincardine castle was completed in *1135–1505 cal AD* (*95.4% probability*), probably *1165–1280 cal AD* (*68.2%*

Table 3 Site context, archaeobotanical character and radiocarbon measurements and calibrated date ranges for selected MERLF samples from Kincardine Castle

Site context			Sample character				Radiocarbon measurements and calibrated date ranges			
Phase	Feature	Code	Taxa	Curve	Rings	Bark	Lab. Code	$\delta^{13}C$ (‰)	^{14}C Age (BP)	Calibrated date range (cal AD) at 95.4% probability
1	South Curtain	KCA.A	*Quercus* sp.	Low	16	No	SUERC-84391	−26.3	903 ± 24	1035–1110 (48.8%) or 1115–1210 (46.5%)
1	North Curtain	KCA.G	*Betula* sp.	None	5	No	SUERC-84392	−24.7	850 ± 21	1155–1250
1	South Curtain	KCA.J	*Corylus* sp.	Low	12–14	No	SUERC-84393	−26.6	949 ± 24	1025–1155

KCA.A and KCA.J were removed from fixed *in situ* core mortar contexts; KCA.G was a loose sample interpreted as released from core mortar. All samples were single entity. δ^{13}C values are all reasonably close to the expected −25‰ level. Radiocarbon measurements were calibrated by the probability method using OxCal v.4.3.2 (Bronk-Ramsey 2017) and the IntCal13 atmospheric curve (Reimer *et al*. 2013). Calibrated date ranges have been rounded out to 5 years

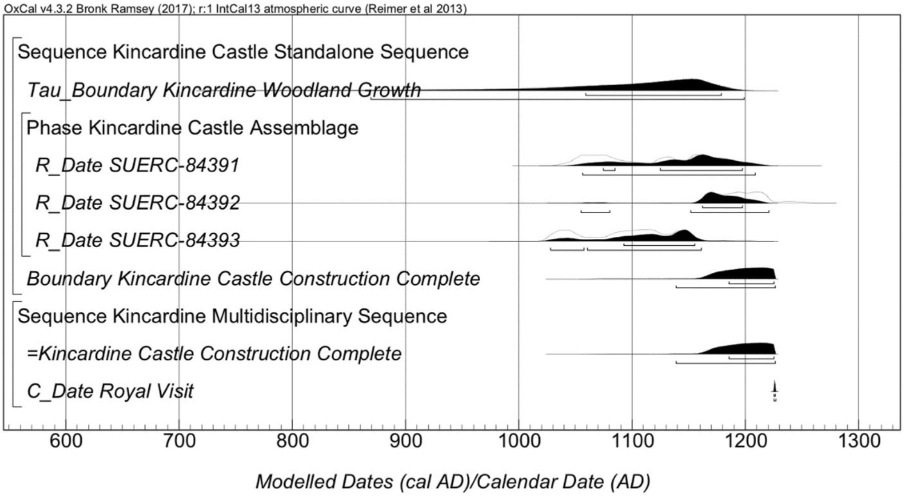

Fig. 12 Probability distributions from Kincardine Castle using modelling approach C and incorporating multidisciplinary data, including phasing interpretations, radiocarbon measurements and documentary evidence. Plotted in OxCal v4.3.2 (Bronk Ramsey 2017) and calibrated using the IntCal13 atmospheric curve (Reimer *et al*. 2013). The MERLF radiocarbon measurements have been situated within a single bounded phase. Measurements SUERC-84392 and SUERC-84393 have been tagged with 10% outlier probabilities within a 'General' outlier model, and measurement SUERC-84391 has been tagged with a 100% outlier probability within a separate 'Charcoal' outlier model (Bronk Ramsey 2009b). Each distribution represents the relative probability than an event occurs at a particular time and for each of the radiocarbon dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration; and a solid one, which is based on the chronological model. The Boundary distribution '*Kincardine Castle Construction Complete'* represents the estimated date at which construction of this primary upstanding phase of the building was completed. A second sequence in the model constrains this Boundary distribution to a period before the calendar date 1226 (representing the reported date of the royal visit). The large squared brackets down the left-hand side define the model, whilst the smaller squared brackets beneath each distribution represent the highest probability distributions at 68.2% and 95.4% probability

probability; *Kincardine Castle Construction Complete*; ESM Fig. S3 & Table S3), whilst the multidisciplinary model suggests construction of Kincardine Castle was completed in *1135–1230 cal AD* (*95.4% probability*), probably *1185–1225 cal AD* (*68.2% probability; Kincardine Castle Construction Complete*; Fig. 12). These probability distributions, which have all been rounded out to 5 years, will be considered further in the comparative section below.

Comparative Discussion of Scottish Case Study Evidence

The work described above has presented the first absolute chronological evidence relating to the construction of three widely distributed and culturally significant Scottish medieval castle buildings. The scale of masonry construction at these sites varies from a small domestic block constructed from very local materials (at Fincharn), to a large enclosure castle which has exploited resources from across the region (at Lochindorb), with a moderately sized building (at Kincardine) situated somewhere between these two extremes. The constructional date ranges to which these buildings have been ascribed (on the basis of their architectural character and historical evidence) also contrasts in precision quite markedly; with scholarly opinion associating the two larger, higher-status and apparently more typologically distinctive buildings at Kincardine and Lochindorb with particularly refined date ranges, whilst the more architecturally ambiguous structure at Fincharn has been ascribed to a very broad range of dates. The MERLF sample assemblages currently associated with these buildings also present striking taxonomical contrasts, however, ranging from an assemblage dominated by *Corylus* (at Fincharn), to one dominated by *Quercus* (at Lochindorb). The extent to which these contrasts in MERLF character are predicated on the status and size of these buildings (rather than environmental constraints, taphonomical survival or other considerations) requires more comparative work across the country. With regard to the three studies included in this particular paper, however, we might expect the radiocarbon data to complement these other types of building evidence; such that the MERLF radiocarbon data from Castle Fincharn can inform our interpretations of the architectural and documentary evidence relating to this previously little-understood site, whilst the refined art-historical date ranges ascribed to the primary upstanding phases of Lochindorb and Kincardine can inform our interpretation of the (potentially higher IA) MERLF radiocarbon data. With this as our starting position, the discussion below will initially evaluate how the character of the MERLF samples, the statistical consistency of the radiocarbon data and the selected outlier framework have affected the distribution of posterior estimates in the standalone models across the study, before reflecting further on how these estimates relate to other types of building evidence.

The relative precision of the standalone constructional estimates generated by our three case studies is initially predicated on the distribution of the unmodelled radiocarbon determinations. The Castle Fincharn study, for example, is based on five relatively short-lived *Corylus* wood-charcoal MERLF samples, whose radiocarbon ages correlate with a steep area of the calibration curve. These measurements are of such limited distribution that they are statistically consistent at 10% significance level, indicating they are all likely to contain similar levels of radiocarbon and so may be the same age. Modelling these measurements using Approach A, within a single-phase standalone model, has generated precise constructional (end boundary) estimates of *1220–1305 cal AD* (*95.4% probability*) and *1245–1285 cal AD* (*68.2% probability; Castle Fincharn Construction Completed*; ESM 1.1 & Table S1). I would reiterate previous discussion highlighting the importance of imposing stratigraphy on the radiocarbon data as prior information, and the dangers of using measurements from uncharacterised samples to impose phasing interpretations on the archaeology; but the reasonable size of the Castle Fincharn MERLF sub-assemblage, its wide physical distribution, short-lived character and high level of statistical consistency, supports the on-site interpretation that these samples derived from a single-phase mortar layer.

The Castle Fincharn MERLF sub-assemblage was limited to a selection of relatively short-lived MERLF fragments, however, whose distribution may not be representative of the larger and more taxonomically diverse assemblage removed from the building. Where samples are characterized by higher IA potential, then increased numbers of analyses are more likely to widen radiocarbon data distributions (decreasing precision), and the indirect relationship between radiocarbon data and phasing noted in the Castle Fincharn study is less likely to pertain. The lack of a direct relationship between MERLF radiocarbon measurements and phasing is clearly demonstrated by the Lochindorb Castle study, which includes an extremely early primary phase measurement as well as date ranges from separate phases which overlap. To compound matters (perhaps also as a result of high IA), the Lochindorb Castle determinations correspond with a more complex area of the calibration curve. Modelling these measurements using Approach B has generated less precise (end boundary) constructional estimates of *1070–1110 cal AD (1.7% probability) or 1130–1415 cal AD (93.8% probability)* and *1175–1280 cal AD (68.2% probability; Construction Lochindorb Castle Phase 1*; ESM 2.1.1 & Table S2), in a standalone model which does not include the extremely early sample LCB.D (SUERC-75752).

Such manual post-analysis removal of extreme dates will certainly increase data precision and consistency within a given phase, and it is possible that identification and removal of another so-called ‘outlier’ from the already reduced Lochindorb primary phase sub-assemblage would raise consistency above the widely accepted 5% significance critical value. This approach may be valid where MERLF sub-assemblages are believed to be binary mixtures of short-lived and long-lived fragments only (rather than a continuous spectrum), but where sub-assemblage sizes are already very limited then relatively wide ranging measurement distributions inevitably lead to an apparent lack of statistical consistency. The three radiocarbon determinations currently associated with Kincardine Castle, for example, do not appear to be statistically consistent (even at 1% significance), and modelling these measurements using Approach C in a standalone model has generated end boundary constructional estimates of *1135–1505 cal AD (95.4% probability)* and *1165–1280 cal AD (68.2% probability;* Kincardine Castle Construction Complete; ESM 3.1.1 7 Table S3).

Statistical consistency at 5% significance cannot, therefore, be regarded as a proxy for phasing in either the Lochindorb or Kincardine studies. Statistical consistency reduces with sample size across this comparative study, as data distribution widens. Quantitative estimates for this last variable have been generated within each standalone model (using the OxCal Span and ‘Difference’ functions) and are summarized in Table 4 below. Unsurprisingly, the ‘Range’ distributions in all models closely parallel the Span distributions, and with IA distributions of *−5 to 105 years* (*95.4% probability*), probably *−5 to 45 years* (*68.2% probability*; *Fincharn IA*; ESM 1.1.1 & Table S1), the precision in the Castle Fincharn model is clearly apparent once more. Interestingly, however, the Range and IA distributions associated with the Lochindorb (reduced phase 1) and Kincardine studies also include zero values at 95.4% probability, and so a lack of consistency cannot be clearly demonstrated in these modelled distributions. It is also possible that these sub-assemblages ‘Range’ up to *185 years* (*95.4% probability*; *Lochindorb Phase 1 Range*; ESM 2.1.1 & Table S2) and *190 years* (*95.4% probability*; *Kincardine Range*; ESM 3.1.1 & Table S3) respectively, however, and the ‘IA’ distributions for these two sites are wider still; with a Kincardine Castle IA distribution of *−5 to 365 years* (*95.4% probability*) probably *30–195 years* (*68.2% probability*; *Kincardine IA*; ESM 3.1.1 & Table S3) the broadest of all.

It is important to understand how the end boundary constructional estimates generated from these studies relate to the measurement distributions within each modelled phase and the selected outlier Approach. Unsurprisingly, where samples within a phase are statistically consistent and tagged with a 5% outlier probability in a General outlier model, as in the (Approach A) Castle Fincharn study, then end boundary distributions are very similar to those generated without using any outlier model at all (Thacker in prep. d). In line with our pre-case study discussion, the effects of scatter and error

Table 4 Primary phase MERLF Span, Range and IA calculations from standalone models associated with Castle Fincharn, Lochindorb Castle* and Kincardine Castle

Primary phase structure	Number of Samples	Statistical consistency	Span at 95.4% probability	Range at 68.2% probability	Range at 95.4% probability	IA at 68.2% probability	IA at 95.4% probability
Castle Fincharn	5	10%	0 to 95 years	−10 to 35 years	−30 to 90 years	−5 to 45 years	−5 to 105 years
Lochindorb Castle*	4	2.5%	0 to 185 years	−10 to 100 years	−40 to 185 years	−5 to 130 years	−5 to 265 years
Kincardine Castle	3	–	0 to 195 years	20 to 120 years	−10 to 190 years	30 to 195 years	−5 to 365 years

‘Span’ distributions were generated within each primary phase; ‘Range’ distributions were also generated within each primary phase using the Difference function to calculate the difference between the earliest and latest modelled R-date distributions; IA distributions were generated within the sequence using the Difference function to calculate the difference between the end boundary distribution and earliest modelled R-date distribution. Radiocarbon measurements were calibrated by the probability method using OxCal v.4.3.2 (Bronk-Ramsey 2017) and the IntCal13 atmospheric curve (Reimer *et al.* 2013), and date ranges have been rounded out to 5 years. Note* the Lochindorb Castle data relates to the primary upstanding phase and does not include the extremely early sample LCB.D (SUERC-75752)

Table 5 Comparison of different evidence types for each case study site

Site name	Earliest historical reference to the site	Architectural interpretation of upstanding building	Archaeological estimate for completion date of primary phase upstanding fabric (standalone model)	Multidisciplinary estimate for completion date of primary phase building (multidisciplinary model)
Castle Fincharn	1240	Thirteenth to sixteenth century	***1245–1285 cal AD*** *(68.2%) 1220–1305 cal AD (95.4%)*	*1245–1285 cal AD (68.2%) 1225–1295 cal AD (95.4%)*
Lochindorb Castle	1279	Mid-thirteenth century	***1175–1280 cal AD*** *(68.2%) 1070–1110 cal AD (1.7%)* *or 1130–1415 cal AD (93.8%)*	*1185–1260 cal AD (68.2%) 1080–1058 cal AD (0.1%) or 1155–1280 cal AD (95.3%)*
Kincardine Castle	1189 × 1195	Early thirteenth century	***1165–1280 cal AD*** *(68.2%) 1135–1505 cal AD (95.4%)*	*1185–1225 cal AD (68.2%) 1135–1230 cal AD (95.4%).*

margins have been reduced, and as a result, the highest density distribution of each modelled radiocarbon date is more precise than its unmodelled calibrated counterpart (with earlier upper limits and later lower limits). The Range distribution is thereby also significantly narrower—shifting from −30 to 220 years (95.4% probability) and 10–100 years (68.2% probability) in the unmodelled data, to *−30 to 90* (*95.4% probability*) and *10 to 35 years* (*68.2% probability; Fincharn Range*; ESM 1.1.1 & Table S2) in the modelled distributions. Where samples are tagged with a 100% outlier probability in a Charcoal outlier model (as in Approach C; Lochindorb Castle), however, then the posterior distributions associated with each individual radiocarbon measurement are wider and later; Span, Range and IA distributions are wider; and thereby end boundary distributions are also wider and later at both 68.2% and 95.4% probability (see ESM Table S2). The scale of the outlier model distribution itself can be reduced to modify this effect where samples are believed to be shorter-lived, but from scales of between 0 and 500 ($0,10^{2.7}$) and 0–1000 years ($0,10^{3}$), this has no effect on posterior estimates. Comparison of the Lochindorb standalone model with an alternative 'comparative' model (similar in all other respects but not including an outlier model in phase 1) indicates that imposing Approach C on the phase 1 'standalone' model sequence for Lochindorb Castle has shifted the 'IA' distribution from *−5 to 225 years* (*95.4% probability*; *Lochindorb Phase 1 IA*; ESM 5.1.1 & Table S4) to *−5 to 265 years* (*95.4% probability*; *Lochindorb Phase 1 IA*; ESM 2.1.1 & Table S2), and the end boundary distribution from *1165 to 1250 Cal AD* (*68.2% probability; Construction Lochindorb Castle Phase 1*; ESM 5.1.1 & Table S4) to *1175–1280 Cal AD* (*68.2% probability; Construction Lochindorb Castle Phase 1*; ESM 2.1.1 & Table S2). Seeking accuracy in the generated end boundary distribution, rather than precision in the measured radiocarbon distributions, we are using the model to compensate for potential IA in the Lochindorb Castle MERLF sub-assemblage, and at historical scales of enquiry that apparently minor chronological shift to a later date range is significant.

Although the MERLF sub-assemblages across this study are of limited size and the samples themselves are of contrasting character, the three modelling approaches advanced in this paper have generated 'standalone' primary phase end boundary distributions for each of our three case study sites which are consistent with surviving historical and architectural evidence (see Table 5). Indeed, generated by Bayesian techniques from building archaeology and materials analysis evidence alone, the degree of comparative consistency between these different types of evidence is particularly striking in the standalone models at 68.2% probability.

These 68.2% probability standalone date ranges are often very similar to the 95.4% probability estimates generated by the multidisciplinary models, and the effect of historical evidence on these interpretations is best considered by comparison of the 'standalone' and 'multidisciplinary' end boundary plots (Figs. 13, 14, and 15). These demonstrate that the precise probability distributions generated by the standalone model for Castle Fincharn are almost unchanged by the inclusion of historical evidence in the multidisciplinary model (Fig. 13a, b), whilst the long positive tails in the Lochindorb and Kincardine standalone distributions have allowed the documentary evidence to have a large effect on multidisciplinary estimates—particularly at 95.4% probability (Figs. 14a, b and 15a, b).

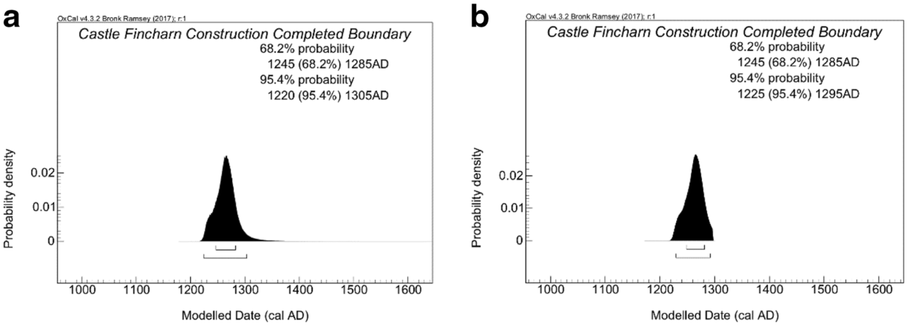

Fig. 13 **a**, **b** End boundary probability distributions for Castle Fincharn, reproduced from the 'standalone' model (on the left) and 'multidisciplinary' model (on the right). Rounded out to 5 years, the narrow range and symmetrical form of both distributions is clearly evident. The inclusion of the 1297 documentary reference in the 'multidisciplinary' model has slightly narrowed the distribution at 95.4% probability (truncating the slight positively skewed tail), but the 68.2% distribution remains unchanged

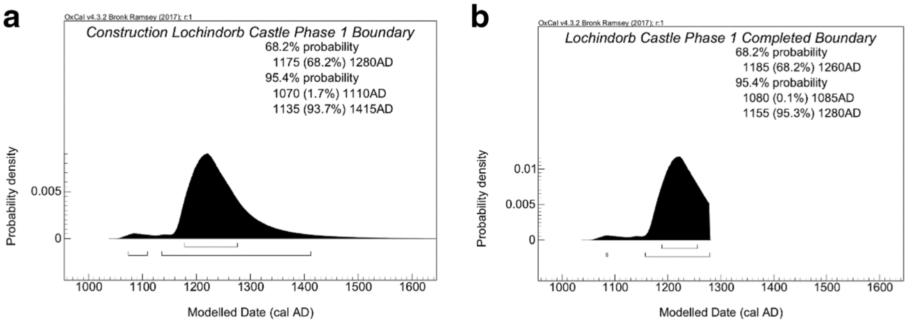

Fig. 14 **a**, **b** End boundary probability distributions for phase 1 of Lochindorb Castle, reproduced from the 'standalone' model (on the left) and 'multidisciplinary' model (on the right). Rounded out to 5 years, the broader range and long tails in the distribution from the standalone model is evident. The long positively skewed tail is truncated by the 1279 documentary reference included in the multidisciplinary model

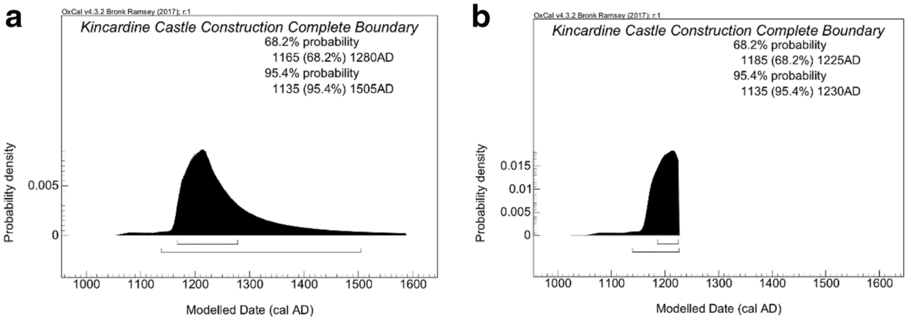

Fig. 15 **a**, **b** End boundary probability distributions for Kincardine Castle, reproduced from the 'standalone' model (on the left) and 'multidisciplinary' model (on the right). Rounded out to 5 years, the inclusion of the 1226 documentary reference in the multidisciplinary model has truncated the positively skewed tail of the distribution and increased precision at both 68.2% and 95.4%

These comparative plots confirm that the standalone constructional estimates presented in the current study are consistent with previous chronological interpretations, but also highlight various issues relating to the archaeological, historical and architectural evidence upon which those previous ascriptions were based; drawing comparisons with other studies from the wider research programme. It remains salient, for example, that none of the first contemporary historical references associated with our three case study sites explicitly mention a castle building, let alone a particular surviving structure. It is, however, notable that the probable *1245–1285* (*68.2% probability*) chronological estimate generated by the Castle Fincharn standalone model has allowed more confident interpretation of the 1240 Crown charter relating to Glassary (in which Fincharn is simply listed along with other settlements without reference to a castle building) and the 1297 and early fourteenth century documents which refer directly to a castle structure here (without mentioning Fincharn). This remarkable level of chronological consistency between the standalone model estimate and historical sources is very similar to the evidence presented in a recent investigation of Achnaduin Castle, Lismore (see Thacker in prep. d), and it is notable that in both of these Argyll studies, the first documentary reference to the site probably preceded castle construction.

The earliest references associated with both Lochindorb and Kincardine, however, are very likely to be associated with a castle building of some sort, and the standalone estimates generated in each of these studies highlight the more commonly encountered difficulty of ascribing a building construction TPQ from historical evidence alone. Indeed, the 1258 lower limit of the (widely accepted) constructional date range for Lochindorb is predicated on an assumption that the upstanding enclosure castle was founded by John Comyn (Barrow 1988, 9), although prominent members of this kinship were granted the lordship of Badenoch (to which Lochindorb was certainly attached in the fourteenth century) in or around 1229 (Young 1997, 26–30, 205). The lower limit of the (also widely accepted) 1217–1227 art-historical range for Kincardine, meanwhile, is predicated on an assumption that Alexander II would not have patronized castle construction until after the recent war with England (Dunbar & Duncan 1971,11), although (as highlighted above) charter evidence indicates the site was frequented by King William from the later twelfth century. On the basis of current standalone end boundary distributions, an earlier date of construction than has been previously accepted cannot be ruled out for either building.

In at least two of the case studies presented above (at Fincharn and Kincardine), however, the earliest historical evidence has also been related to other buildings; either structures located nearby and suggested to have been constructed in an earlier period, or to the potential for an earlier underlying building on the same site. The multiplicity of upstanding buildings in these locations presents issues similar to that discussed in greater detail during the recent study of Abernethy Castle, Speyside (Thacker in prep. c), although in this latter example, previous excavation had at least demonstrated that the upstanding masonry building was unlikely to have been constructed on an earlier earthwork. With regard to the studies presented in this paper, however, even in the absence of excavation, the standalone constructional estimates generated for Castle Fincharn dispel almost all ambiguity relating to the identification of this upstanding structure. This study has allowed us to look again at the architectural, historical and environmental context of this building from a position of much greater chronological confidence (Thacker 2016, 2017), and in future work this data may be used to inform our understanding of similar structures surviving elsewhere across Britain and Ireland.

From this wider comparative perspective, it is reasonable to suggest that construction of the masonry building generally identified as Kincardine Castle post-dated construction of the nearby earthwork structure (now known Green Castle). The chronologically refined early thirteenth century architectural typology within which that masonry building has been situated is now beginning to look much less secure, however; with emerging work indicating the form and phasing of the royal castle at Tarbert has previously been mis-interpreted, whilst another building in the group (Achanduin) can be very securely dated to the very late thirteenth or early fourteenth century (Thacker in prep. a, in prep. d). Indeed, this also undermines previous suggestions that round-towered buildings such as Lochindorb are a development from the square-towered buildings more closely associated with Kincardine, and the standalone end boundary distributions generated for Lochindorb and Kincardine are currently very similar. More work is required to inform our constructional chronological interpretations at individual medieval buildings across the corpus, including at Kincardine and Lochindorb, before the relationship between these architectural typologies and end boundary distributions can be more usefully modelled.

Conclusion

Lime-burning techniques are historically, regionally and socially contingent, but also technically and environmentally constrained, as craftspeople in different contexts responded to contrasts in material availability in different ways. Assumptions that lime manufacture has remained technically static have limited our understanding of the surviving archaeological resource, and the documentary, ethnographic, archaeobotanical and radiocarbon evidence discussed in this paper challenges previous interpretations suggesting northern European wood-fired limekilns were always charged with short-lived fuel. Indeed, all three Scottish case studies presented above displayed some variation in wood taxon and morphology, and (despite limited numbers of analyses and a general aspiration to analyse charcoal fragments of relatively short-lived character where possible) two of the three are associated with radiocarbon determinations which are not statistically consistent at the 5% significance level, and with modelled distributions spanning up to almost two centuries at 95.4% probability.

Understanding how different types of dating evidence relate to one another is crucial for multidisciplinary interpretation of the built environment, and the material in which MERLF fragments were deposited imbues them with particular interpretative advantages over wood-charcoal materials excavated from occupational contexts; *in situ* masonry mortars are sedimentary materials that generally preclude post-depositional material infiltration and turnover, often betray phase-specific compositional contrasts, are generally deposited reasonably quickly after manufacture and can be directly related to particular constructional events. As with occupational evidence, however, documentary references generally relate to a completed building whose date of construction remains ambiguous, and architectural typology often ultimately relies on those same sources. Importantly then, these contrasting characteristics lend a complementarity to the evidence, since the primary phase MERLF radiocarbon data (as a TPQ) and robust documentary references to the wider building (as a TAQ) effectively bracket the constructional chronology of the primary phase structure. From this perspective, despite the critique of the accepted architectural typologies presented above, it is notable that the two Scottish case studies associated with less statistically consistent radiocarbon measurements discussed in this paper include individual calibrated date ranges which are significantly earlier than the documentary evidence relating to the sites from which they were removed, but none are later. This pattern is also consistent with the data presented by previously reported studies and is a relationship that pertains even for radiocarbon measurements returned by bulk samples of uncharacterised wood-charcoal MERLF fragments, such as those previously investigated by Berger (1992, 1995), Bonani *et al.* (2001), Naessens (2009), and this author (Thacker 2016, III, 313–392). The calibrated date ranges returned by these measurements do not therefore independently represent the constructional chronology of the building under investigation and, even where such measurements are apparently consistent with documented dates or other types of evidence, the heterogeneity of the wider resource precludes simply accepting such data as a robust statistical 'control' for studies where other types of evidence are absent.

The evidence presented in this paper suggests that MERLF assemblages can be associated with high levels of inbuilt age. The range of diameters and increased time depth of the Lochindorb assemblage is consistent with the technical discussions around mixed-feed limekilns, including some of the documentary evidence reported from England in this same thirteenth century period and elsewhere, and the scale of the different Span, Range and IA distributions presented in these studies (Table 4) also appears to parallel previously reported data. Further evaluation of Berger's radiocarbon measurement from Clonmacnoise round tower (UCLA-2727A; Fig. 1 above), for example, suggests this single bulk MERLF sample is *80–350 years* (*95% probability*) older than the building's c.1124 documented date of completion, and this has significant implications for some of the other studies with which this paper began (Thacker in prep. b). Re-calibration of Berger's (1992, 1995) radiocarbon measurements associated with the Irish and Scottish shrine-chapel typology, for example, indicates that the upper end of some of these date ranges can often be reduced significantly (*ibid.*), but the data from Clonmacnoise presented above (a cathedral site within which the shrine chapel of Temple Ciaran is also situated) cautions against accepting these Figures as TAQs for the construction of these very small chapel buildings. Whether these measured date ranges are calibrated to 68% or 95% probability is not directly relevant to the accuracy of chronological interpretation, and since the scale of disjunction is currently unknown, these measurements should be interpreted as TPQs only. Ultimately, our limited knowledge of the character of these MERLF samples currently places greater weight on documentary references relating to specific buildings within this typology, and for St Columba's shrine chapel on Iona, that reference appears to be eleventh century (RCAHMS 1982a, 42; Thacker in prep. b).

In many ways, the chronological evidence relating to these Scottish and Irish chapels reflects that relating to St Martin's church in Angers (NW France) in a similar period, and the team investigating this building also very clearly privileged the independent ninth century MERLF radiocarbon and ceramic TL measurements over an early eleventh century (pre-1020) charter; concluding their 'work shows the importance of being cautious towards written records…their chronological interpretation to a specific architectural structure…[and]…consequently the dating of other buildings displaying similar architectural and artistic features' (Blain *et al.* 2011, 62). That other types of independent evidence were cross-dated during this project is an important development, but even adopting Approach A to the three earliest reported MERLF measurements generates a 'standalone' end boundary distribution which is very consistent with previous early eleventh century ascriptions; suggesting the tower at St Martin's was constructed in *885–1235 Cal AD* (*95.4% probability*) probably *900–1020 Cal AD* (*68.2% probability*; *St Martins Tower Construction Completed*; ESM 4.1 and Fig. S5). Further information on the character of the MERLF assemblage and mortars associated with these radiocarbon measurements would enable the reported inconsistencies with the documentary evidence and the effect of the TL measurements on their final interpretation to be more fully considered. Also from this same early medieval period, the recent re-analysis of two MERLF fragments from the (probably eighth to ninth century) All Saints church at Brixworth (England) provides a very limited quantity of data and it is not certain how these samples relate to the character of the wider mortar assemblage, but this study is important in presenting botanically informed interpretations of the radiocarbon measurements and modelling those results within a wider sequence of data from non-masonry contexts such as burials (Millard 2013).

The case study work discussed in this paper has presented the first independent chronological evidence relating to the construction of three culturally significant Scottish medieval buildings. By adopting a framework of Bayesian models informed by the archaeobotanical character of each MERLF sample, material availability at the site and the scale of masonry construction, convincing estimates for the constructional dates of each of these variously ruined buildings have also been generated. These studies demonstrate that Bayesian analysis can generate 'standalone' date estimates for building completion (from radiocarbon measurements, phasing interpretations and materials analysis) which are consistent with other types of dating evidence, even where those radiocarbon measurements are associated with very small MERLF assemblages of widely contrasting character. Moreover, where there is evidence that the inbuilt age associated with the MERLF assemblage is likely to be limited, and 'standalone' probability distributions for building completion are reasonably precise, then these estimates can inform a reflexive re-interpretation of any available documentary and architectural evidence to generate even more refined 'multidisciplinary' date ranges. Whilst it can be challenging to unpack where previous building investigators have implicitly privileged architectural or historical evidence, the process of constructing separate 'standalone' and 'multidisciplinary' models advanced here very effectively illustrates how these different types of evidence have informed interpretations. Indeed, like all other types of building evidence—whether independent, archaeological, architectural or historical—radiocarbon data requires re-interpretation when new information about a site emerges, and Bayesian techniques usefully allow an ongoing reflexive approach to any changing relationships between different sources.

As centres of religious, judicial and fiscal administration at various geographical scales throughout medieval and later northern Europe, lime-bonded masonry structures were often a significant focus for the investment of regional cultural and material resources. This paper has focused on the chronological relationships between the archaeological, architectural and documentary evidence relating to various buildings but, with standalone interpretation of the radiocarbon data best achieved through iterative cycles of landscape, building and materials analysis, the potential for radiocarbon-dated buildings to provide a material focus for multi- and interdisciplinary studies of the wider environment is also now emerging. It is not yet completely clear why the *Quercus*-dominated character of the small medieval MERLF assemblage from Lochindorb Castle presents such a striking contrast with the surviving semi-natural vegetation of the surrounding land, or why the *Corylus*-dominated assemblage from Castle Fincharn appears to represent one particular population of the surrounding vegetation so strongly. It is more certain, however, that these buildings were all constructed within a prolonged period of political and climatic stability that was to come to an end very shortly (Lamb 1977; Oram & Adderley 2008; Thacker 2019b), and the evidence emerging from the wider research project suggests that change is visible in the character of the MERLF and other building materials surviving in Scotland from the later medieval period. Re-casting our upstanding medieval masonry buildings, as fossilized environments above the ground which can be dated with some precision, allows us to present increasingly refined interpretations of the wider cultural and physical environments in which they were constructed.

Acknowledgements Particular thanks to Mike Cressey (CFA Archaeology, Musselburgh) for various degrees of archaeobotanical analysis, teaching and supervision; to Alex Bayliss (Historic England & University of Stirling) and Derek Hamilton (Scottish Universities Environmental Research Centre, East Kilbride) for useful discussion of Bayesian techniques and feedback on preliminary models; Angus Wilson (Fincharn), Angelika Cawdor (Lochindorb) and Brian Carnegie (Kincardine) kindly gave permission to work at the three case study sites; Rilem gave permission to re-use modified Tables and Figures from Thacker 2019b, as did Historic Environment Scotland for the Castle Fincharn and Lochindorb Castle plan drawings. Emma Drye proofread various drafts. Radiocarbon analysis was undertaken at the Scottish Universities Environmental Research Centre (SUERC), East Kilbride, Scotland, and was funded through the Historic Scotland/Historic Environment Scotland Radiocarbon Call-off Contract. Materials analysis for the Castle Fincharn study was undertaken during doctoral research at the University of Edinburgh, supervised by Geoffrey Bromiley (School of Geosciences, Grant Institute) and part-funded through a History, Classics and Archaeology McMillan Award. Materials analysis for the Lochindorb Castle and Kincardine Castle studies is being undertaken during postdoctoral research at the University of Stirling, under the aegis of the Scottish Medieval Castles & Chapels C14 Project (SMCCCP). The SMCCCP is funded by Historic Environment Scotland (Archaeology Programme & Cultural Resources Team) and the University of Stirling (Centre for Environment, Heritage & Policy). The comments of three anonymous peer reviewers contributed enormously to the paper. Any errors are my own.

Funding The research in this paper has received funding from the University of Edinburgh (McMillan Award); University of Stirling (CRT/9999/2018/); Historic Environment Scotland Archaeology Programme (AMK/408/18); Historic Environment Scotland Cultural Resources Team; and Historic Scotland/Historic Environment Scotland's Radiocarbon Call-off Contract.

Compliance with Ethical Standards

Conflict of Interest The author declares no conflicts of interest.

Appendix. A Protocol for Radiocarbon Analysis of Mortar-Entrapped Relict Limekiln Fuel (MERLF)

1. Phasing—MERLF sample contexts should be informed by detailed characterization of all the masonry and mortar materials throughout the building (Thacker 2016). Interim materials analysis (including radiocarbon dating) can also usefully inform further analysis of the building fabric.

2. Contexts—MERLF samples should be removed from compositionally consistent demonstrably constructional mortars, continuous with core materials if possible, and preferably of a distinctive phase-specific character (Thacker 2016). The provenance of these mortar materials should be investigated.
3. Single entity—MERLF samples should be single entity, if at all possible, to allow for botanical characterization (Ashmore 1999). Samples with reduced IA potential can then be selected for radiocarbon analysis, allowing more precise interpretations.
4. Multiple samples—Multiple MERLF samples from well-distributed locations should be analysed from each phase, if possible, to enable statistical modelling and outlier detection (Bronk Ramsey 2009a, 2009b). Where possible, samples from a single context/phase with very limited physical distribution should be of different taxa (Derek Hamilton pers. com) to ensure independence.
5. Multiple phases—MERLF samples from multiple phases should be sampled, analysed and modelled, where possible, to further constrain boundary distributions.
6. Standalone modelling—Standalone Bayesian models of MERLF materials should be constructed separately, to illustrate how other archaeological, historical and architectural information has impacted on final interpretations.

References

Al-Bashaireh, K. (2008). *Chronology and technological production styles of Nabatean and Roman plasters and mortars at Petra (Jordon).* Unpublished PhD Thesis, University of Arizona.

Al-Bashaireh, K. (2013). Plaster and mortar radiocarbon dating of Nabatean and Islamic structures, south Jordon. *Archaeometry, 55*(2), 329–354.

Alston, C. (1752). *A dissertation on quick-lime and lime-water.* W. Sands, A. Murray, & J. Cochran: Edinburgh.

Ambers, J. (1987). Stable carbon isotope ratios and their relevance to the determination of accurate radiocarbon dates for lime mortars. *Journal of Archaeological Science, 14*, 569–576.

Anderson, I., & Dixon, P. (2011). Inverlochy and Lochindorb castles – A comparative study. *Architectural Heritage, 22*, 1–17.

Annals of the Four Masters, 1145.4 & 1163.8. Electronic edition compiled by M. Priour & S. Beechinor for the CELT Project. Can be viewed at https://celt.ucc.ie/published/T100005B.html last viewed 09-10-2019.

Armi, C. (1996). Report on the destruction of Romanesque architecture in Bergundy. *Journal of the Society of Architectural Historians, 55*(3), 300–327.

Ashmore, P. (1999). Radiocarbon dating: Avoiding errors by avoiding mixed samples. *Antiquity, 73*, 124–130.

Baker, C. (2009). *The archaeology of Killeen Castle, co. Meath*. Dublin: Wordwell.

Barbaroux, C., & Bréda, N. (2002). Contrasting distribution and seasonal dynamics of carbohydrate reserves in stem wood of adult ring-porous sessile oak and diffuse-porous beech trees. *Tree Physiology, 22*(17), 1201–1210.

Barrow, G. (ed.) with the collaboration of W. Scott (1971). Regesta Regum Scottorum, II. The acts of William I, king of scots 1165–1214. Edinburgh University Press: Edinburgh.

Barrow, G. (1973). *The kingdom of the scots. Government, church and society from the eleventh to the fourteenth century* (2nd ed.). Edinburgh University Press: Edinburgh.

Barrow, G. (1988). Badenoch and Strathspey, 1130-1312. Part 1: Secular and political. *Northern Scotland, 8*(1), 1–15.

Barrow, G., & Royan, A. (1985). James fifth Stewart of Scotland, 1260(?) – 1309. In K. Stringer (Ed.), *Essays on the nobility of medieval Scotland* (pp. 166–190). Edinburgh: John Donald.

Bayliss, A. (2009). Rolling out revolution: Using radiocarbon dating in archaeology. *Radiocarbon, 51*(1), 123–147.

Bayliss, A. (2015). Quality in Bayesian chronological models in archaeology. *World Archaeology, 47*(4), 677–700.

Bayliss, A., Bronk Ramsey, C., van der Plicht, J., & Whittle, A. (2007). Bradshaw and Bayes: Towards a timetable for the Neolithic. *Cambridge Archaeological Journal, 17*, 1–28.

Berger, R. (1970). The potential and limitations of radiocarbon dating in the middle ages: The Radiochronologists view. In R. Berger (Ed.), *Scientific Methods in Medieval Archaeology* (pp. 89–139). Los Angeles: University of California Press.

Berger, R. (1992). 14C dating mortar in Ireland. *Radiocarbon, 34*(3), 880–889.

Berger, R. (1995). Radiocarbon dating of early medieval Irish monuments. *Proceedings of the Royal Irish Academy. Section C: Archaeology, Celtic Studies, History, Linguistics, Literature, 95C*(4), 159–174.

Blain, S., Guibert, P., Prigent, D., Lanos, P., Oberlin, C., Sapin, C., Bouvier, A., & Dufresne, P. (2011). Combined dating methods applied to building archaeology: The contribution of thermoluminescence to the case of the bell tower of St Martin's church, Angers (France). *Geochronometria, 38*(1), 55–63.

Boate, G. (1652). *The Natural History of Ireland*. Can be viewed at http://www.ucc.ie/celt/published/E650002-001/ last viewed 22/07/2016.

Bonani, G., Hass, H., Hawass, Z., Lehner, M., Nakhla, S., Nolan, J., Wenke, R., & Wölfli, W. (2001). Radiocarbon dates of old and middle kingdom monuments in Egypt. *Radiocarbon, 43*(3), 1297–1320.

Brayley, E., & Britton, J. (1814). *The beauties of England and Wales, or delineations, topographical, historical & descriptive, of each county*. Wiltshire: T. Maiden.

Breen, C., Forsyth, W., Raven, J., & Rhodes, D. (2010). Survey and excavation at Dunstaffnage Castle, Argyll. *PSAS, 140*, 165–178.

Brindlecombe, P. (1975). Industrial air pollution in thirteenth century Britain. *Weather, 30*(12), 388–396.

Brindlecombe, P. (1976). Attitudes and responses towards air pollution in medieval England. *Journal of the Air Pollution Control Association, 26*(10), 941–945.

Brindlecombe, P. (2012). *The big smoke: A history of air pollution in London since medieval times*. London: Routledge.

Bond, J. (2007). Medieval charcoal-burning in England. In J. Klápšte & P. Sommer (Eds.), *Arts and crafts in medieval rural environment*, *Ruralia* (Vol. 6, pp. 277–294). Turnhout: Brepols.

Bronk Ramsey, C. (2009a). Bayesian analysis of radiocarbon dates. *Radiocarbon, 51*(1), 337–360.

Bronk Ramsey, C. (2009b). Dealing with outliers and offsets in radiocarbon dating. *Radiocarbon, 51*(3), 1023–1045.

Bronk Ramsey, C. (2017). Methods for summarizing radiocarbon datasets. *Radiocarbon, 59*(2), 1809–1833.

Burnett, G. (Ed.). (1883). *The Exchequer Rolls of Scotland. Vol. VI. A.D. 1455–1460. H.M.* General Register House: Edinburgh.

Campbell, M., & Sandeman, M. (1962). Mid-Argyll: A field survey of the historic and prehistoric monuments. *Proceedings of the Society of Antiquities of Scotland, 95*, 1–125.

CAT. (2008). Clwyd-Powys archaeological trust newsletter. *Autumn, 2008*.

Chronicum Scotorum, CS1124. Author Unknown. Translated by William M. Hennessy, Gearóid Mac Niocaill. Electronic edition compiled by Beatrix Färber and Ruth Murphy, Funded by University College, Cork and Professor Marianne McDonald via the CELT Project. Can be viewed at https://celt.ucc.ie//published/T100016/index.html last viewed 05-10-2019.

Chrzazvez, J., Théry-Parisot, I., Fiorucci, G., Terral, J., & Thibaut, B. (2014). Impact of post-depositional processes on charcoal fragmentation and archaeobotanical implications: Experimental approach combining charcoal analysis and biomechanics. *Journal of Archaeological Science, 44*, 30–42.

Clutterbuck, R. (2002). Preliminary report on the rescue excavation at Rath lower, grange*, Co. Louth.* Unpublished report prepared for Oliver Murphy, Chairman, Grange Parish Committee.

Colvin, H. (1971). *Building accounts of Henry III*. Oxford: Clarendon Press.

Corner, D., Scott, A., Scott, W., & Watt, D. (Eds.). (1994). *Scotichronicon by Walter Bower. Vol 4, books VII & VIII*. Edinburgh: The Mercat Press.

Coventry, M. (1997). *The castles of Scotland*. Goblinshead: Edinburgh.

Cowper, A. (1927). *Lime and lime mortars*. Donhead: Shaftsbury.

Cramp, R. (2006). *Wearmouth and Jarrow, monastic sites* (Vol. 2 vols). English: Heritage.

Creighton, O. (2012). *Early European castles*. London: Bloomsbury.

Cruden, S. (1960). *The Scottish Castle*. Nelson: Edinburgh.

Dean, J. (1978). Independent dating in archaeological analysis. *Advances in Archaeological Method and Theory, 1*, 223–255.

Dee, M., Bronk Ramsey, C., Shortland, A., Higham, T., & Rowland, J. (2009). Reanalysis of the chronological discrepancies obtained by the old and middle kingdom monuments project. *Radiocarbon, 51*(3), 1061–1070.

Dee, M., & Ramsey, C. (2014). High-precision Bayesian modeling of samples susceptible to inbuilt age. *Radiocarbon, 56*(1), 83–94.

Dillon, M., Newman, C., Molloy, K., & Connell, M. (2008). Environment and ritual in a late Iron age context: An example from Raffin fort, co Meath, Ireland. In G. Fiorentino & D. Magri (Eds.), *Charcoals from the past: Cultural and Palaeoenvironmental implications*, *BAR international series* (Vol. 1807, pp. 75–92). Oxford: Archaeopress.

Dix, B. (1982). The manufacture of lime and its uses in the Western Roman provinces. *Oxford Journal of Archaeology, 1*(3), 331–345.

Dunbar, E., Cook, G., Naysmith, P., Tripney, B., & Xu, S. (2016). AMS ^{14}C dating at the Scottish universities environmental research Centre (SUERC) radiocarbon dating laboratory. *Radiocarbon, 58*(1), 9–23.

Dunbar, J and Duncan, A. (1971). Tarbert Castle: A contribution to the history of Argyll. *The Scottish Historical Review* 50 (149, part 1): 1-17.

Duncan, A. (1989). *Scotland. The making of the Kingdom. The Edinburgh history of Scotland volume 1*. First published 1975. Mercat Press: Edinburgh.

Duncan, A. (2002). The kingship of the Scots 842–1292. In *Succession and Independence*. Edinburgh: Edinburgh University Press.

Encyclopaedia Londinensis. (1814). *Encyclopaedia Londinensis, or, universal dictionary of arts, sciences and literature* (Vol. 12). London: John Wilkes.

Fisher, I. (2005). The heirs of Somerled. In R. Oram & G. Stell (Eds.), *Lordship and Architecture in Medieval and Renaissance Scotland* (pp. 85–96). Edinburgh: John Donald.

Foley, C., & Donnelly, C. (2012). *Parke's Castle, Co. Leitrim: archaeology, history and architecture. (Archaeological monograph series, 7)*. Dublin: The Stationery Office, Dublin.

Folk, R., & Volastro, S. (1976). Successful technique for dating of lime mortar by Carbon-14. *Journal of Field Archaeology, 3*, 203–208.

Forbes, H. (2002). The uses of the uncultivated landscape in modern Greece: A pointer to the value of the wilderness in antiquity? In J. Salmon & G. Shipley (Eds.), *Human landscapes in classical antiquity: Environment and culture* (pp. 68–97). London: Routledge.

Forster, A. (2004). Hot-lime mortars: A current perspective. *Journal of Architectural Conservation, 10*(3), 7–27.

Galloway, J., Keene, D., & Murphy, M. (1996). Fuelling the city: Production and distribution of firewood and fuel in London's region, 1290-1400. *The Economic History Review, New Series, 49*(3), 447–472.

Gavin, D. (2001). Estimation of inbuilt age in radiocarbon ages of soil charcoal for fire history studies. *Radiocarbon, 43*(1), 27–44.

Gem, R. (2009). Gruffudd ap Cynan and the Romanesque church of Penmon, Anglesey. In N. Edwards (Ed.), *The archaeology of the early medieval Celtic churches* (pp. 301–312). Leeds: Maney.

Gibbons, P. (2003). *Preparation and use of lime mortars*. Historic Scotland: Edinburgh.

Gilbert, J. (1975). *Hunting Reserves in Medieval Scotland*. Unpublished PhD Thesis. University of Edinburgh.

Grant, I. (2007). *Archaeological Excavation of Land Opposite the Llais Afon Inn, Betws-yn-Rhos, Conwy.* Unpublished report by the Clwyd-Powys archaeological trust. CPAT report no. 872.

Halkin, J., & Roland, C. (Eds.). (1909). *Recuil des Chartes de l'Abbaye de Stavelot-Malmedy.* Brussels: Academie Royale de Belgique.

Hall, D. (2013). Kincardine Castle; excavation. *Discovery and Excavation in Scotland, New series, 14*, 21–22.

Hall, D. & Malloy, K. (2013) Always chasing deer – Excavations at Buzzart Dykes, Kincardine Park and Kincardine Castle in 2013. Unpublished fieldnotes kindly forwarded by Derek Hall.

Harbison, P. (1982). Early Stone Churches. In H. Lowe (ed.), *Die Iren und Europa im Frvheren Mittelalter.* Stuttgart. 618-629.

Harbison, P. (1992). *Pilgrimmage in Ireland: The monuments and the people*. London: Barrie and Jenkins.

Harrison, J. (1992). Lime supply in the Stirling area from the 14th to the 18th centuries. *The Forth Naturalist & Historian, 16*, 82–89.

Harmon, M., Franklin, J., Swanson, F., Sollins, P., Gregory, S., Lattin, J., Anderson, N., Cline, S., Aumen, N., Sedell, J., Lienkaemper, G., Cromack, K., & Cummins, K. (1986). Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research, 15*, 133–302.

Harris, E. (1989). *Principles of archaeological stratigraphy* (2nd ed.). London: Academic Press.

Haygreen, J., & Bowyer, J. (1989). *Forest products and wood science. An introduction*. Iowa: Iowa State University Press.

Hilton, R. (2003). *Bond men made free: Medieval peasant movements and the English rising of 1381*. London & New York: Routledge.

Hughes, J., & Cuthbert, S. (2000). The petrography and microstructure of medieval lime mortars from the west of Scotland: Implications for the formulation of repair and replacement mortars. *Materials and Structures, 33*, 594–600.

Innes, C. (Ed.). (1859). *The book of the thanes of Cawdor. A series of papers selected from the charter room at Cawdor*. The Spalding Club: Edinburgh.

Iona Club (ed.). (1847). *Collectanea de Rubus Albanicus*: consisting of original papers and documents relating to the history of the Highlands and Islands of Scotland.

Jackson, D., Biek, L., & Dix, B. (1973). A Roman limekiln at Weekley, Northants. *Brittania, 4*, 128–140.

Johnson, D. (2010). Hushes, delfs and river stonary: Alternative methods of obtaining lime in the gritstone Pennines in the early modern period. *Landscape History, 31*(1), 37–52.

Johnson, D. (2010b). *Liming and agriculture in the Central Pennines: the use of lime in land improvement from the late thirteenth century to c. 1900. BAR British Series* (p. 525).

Karlsberg, A. (2006). *Flexible Bayesian Methods for Archaeological Dating*. Unpublished PhD. thesis. University of Sheffield.

Knott, C. and Thacker, M. (2011). Eaglais na h'Aoidhe. Archaeological Survey. Unpublished document prepared for *Urras Eaglais na h'Aoidhe.*

Lamb, H. (1977). *Climate: past, present and future*, *Volume 2: Climatic history and the future*. Oxon: Routledge.

Lewis, J. & Pringle, D. (2002). *Spynie Palace and the bishops of Moray: history, architecture and archaeology.* Society of Antiquaries of Scotland monograph series no. 21: Edinburgh.

Lindroos, A., Heinemeier, J., Ringbom, Å., Braskén, M., & Sveinbjörnsdóttir, Á. (2007). Mortar dating using AMS 14C and sequential dissolution: Examples from medieval, non-hydraulic lime mortars from the Åland Islands, SW Finland. *Radiocarbon, 49*(1), 47–67.

Livingstone Smith, A. (2001). Bonfire II: The return of pottery firing temperatures. *Journal of Archaeological Science, 28*, 991–1003.

Ludemann, T. (2008). Experimental charcoal-burning with special regard to anthracological wood diameter analysis. In G. Fiorentino & D. Magri (Eds.), *Charcoals from the past: Cultural and Palaeoenvironmental implications*, *BAR Int series* (Vol. 1807, pp. 147–157).

MacGibbon, D. & Ross, T. (1887). The castellated and domestic architecture of Scotland from the twelfth to the eighteenth century. Volume 1. David Douglas: Edinburgh.

MacGibbon, D. & Ross, T. (1889). The castellated and domestic architecture of Scotland from the twelfth to the eighteenth century. Volume 3. David Douglas: Edinburgh.

MacIntyre, M. (1993). Making Hydrated Lime from Seashells: As recalled by Domhnall lain Monk, Benbecula. Recorded December 1992 by Martin MacIntyre. Transcript published in *Comunn Eachdraidh nan Eilean mu Dheas*. No. 4. p. 8.

MacPhail, J. (1916) Highland papers II. **The Scottish History Society**.

Mahli, Y., Baldocchi, D., & Jarvis, P. (1999). The carbon balance of tropical, temperate and boreal forests. *Plant, Cell and Environment, 22*, 715–740.

Malloy, K., & Hall, D. (2018). Archaeological excavations of the medieval Royal Kincardine Landscape, Aberdeenshire, Scotland. *Medieval Archaeology, 62*(1), 157–176.

Manning, C. (1997). The date of the round tower at Clonmacnoise. *Archaeology Ireland, 11*(2), 12–13.

Manning, S., Birch, J., Conger, M., Dee, M., Griggs, C., Hadden, C., Hogg, A., Ramsey, C., Sanft, S., Steier, P., & Wild, E. (2018). Radiocarbon re-dating of contact-era Iroquoian history in northeastern North America. *Science Advances, 4*(12), 1–10.

Marguerie, D. (2002). Fuel from protohistorical and historical kilns in North-Western France. In I. S. Thiébault (Ed.), *Charcoal Analysis: Methodological approaches, Palaeoecological results and wood uses. BAR international series 1063*. Oxford: Archaeopress.

Mathews, J. (2001). Radiocarbon dating of architectural mortar: A case study in the Maya region, Quintana Roo, Mexico. *Journal of Field Archaeology, 28*(3/4), 395–400.

McFadgen, B. (1982). Dating New Zealand archaeology by radiocarbon. *New Zealand Journal of Science, 25*, 379–392.

McMorran, T. & Tierney, J. (2010). Lime kiln. Cullenagh More Co. Galway. Final archaeological excavation report E3881. *Eachtra Journal* 8.

Millard, A. (2013). The radiocarbon dates. In D. Parsons & D. Sutherland (Eds.), *The Anglo-Saxon Church of All Saints Brixworth Northamptonshire. Survey, excavation and analysis 1972-2010* (Vol. 6, pp. 271–282). Oxford: Oxbow.

Morris, A. (1815). On Spanish peasantry, their improved lime-kilns and economical cooking stoves. *Memoirs of the Philadelphia Society for Promoting Agriculture* 4. Philadelphia: Benjamin Warner. Pp 9-10.

Muhegi, B., & Schilderman, T. (1995). *Lime and alternative binders in East Africa*. Rugby/: Practical Action Publishing.

Naessens, P. (2009). *The Ui Fhlaithbheartaigh Gaelic Lordship of Iarchonnacht: Medieval Lordly Settlement on the Atlantic Seaboard*. Unpublished PhD thesis, 2 Vols. NUI Galway.

Neville, C., & Simpson, G. (Eds.). (2012). *Regesta Regum Scottorum IV part 1: The acts of Alexander III king of scots 1249–1286*. Edinburgh: Edinburgh University Press.

Nicholls, G., & Jones, M. (2001). Radiocarbon dating with temporal order constraints. *Journal of the Royal Statistical Society: Series C: Applied Statistics, 50*, 503–521.

Ó Carragáin, T. (2003). The architectural setting of the cult of relics in early medieval Ireland. *The Journal of the Royal Society of Antiquaries of Ireland, 133*, 130–176.

Ó Carragáin, T. (2010). *Churches in early medieval Ireland*. New Haven and London: Yale University Press.

O'Conor, K., & Naessens, P. (2012). Pre-Norman fortification in eleventh and twelfth-century Ireland. In P. Ettel, A.-M. Flambard Héricher, & K. O'Conor (Eds.), *L'origine du château médiéval, actes du colloque de Rindern, Allemagne 25* (pp. 259–268). Château Gaillard: Caen.

O' Donnell, L. (2009). Analysis of the Charcoal. In C. Baker (Ed.), *The Archaeology of Killeen Castle, Co. Meath* (pp. 113–124). Dublin: Wordwell.

Oram, R. (2012). *Alexander II. 1214–1249 king of scots*. John Donald: Edinburgh.

Oram, R., & Adderley, P. (2008). Lordship and environmental change in Central Highland Scotland c.1300-c.1400. *Journal of the North Atlantic, 1*(1), 74–84.

Ordnance Survey. (1868). Six inch 1st edition 1843-1882 map, Kincardineshire sheet XIX (includes Fettercairn and Fordoun). Survey date 1863-4. Can be viewed at www.maps.nls.uk last viewed 14-04-2017.

O'Sullivan, J. & Ó Carragáin, T., T. (2008). Inishmurray: Monks and pilgrims in an Atlantic landscape. Volume 1: Archaeological survey and excavations 1997–2000. The Collins Press: Cork.

Ostrich, S. (2015). Post-medieval fieldwork in Britain, Ireland and the Channel Islands in 2014. *Post-Medieval Archaeology, 49*(3), 359–418.

Parsons, D., & Sutherland, D. (2013). *The Anglo-Saxon Church of All Saints Brixworth Northamptonshire. Survey, excavation and analysis 1972–2010*. Oxford: Oxbow.

Pesce, G., Micheletto, E., Quarta, G., Ugge, S., Calcagnile, L., & Decri, A. (2013). Radiocarbon dating of mortars from the baptismal font of the San Lorenzo cathedral of Alba (Cuneo, Italy) : Comparison with thermoluminescence dating of related bricks and pipes. *Radiocarbon, 55*(2–3), 526–533.

Rackham, O. (2003). *Ancient woodland: Its history, vegetation and uses in England*. Dalbeatie: Castlepoint Press.

Radcliff, J. (1803). *On burning lime with peat. Prize essays and transactions of the Highland Society of Scotland* (pp. 160–163). Edinburgh: William Creech.

RCAHMS. (1971). *Royal Commission of the ancient and historic monuments of Scotland: Argyll: An inventory of the ancient monuments: Vol. 1: Kintyre*. RCAHMS: Edinburgh.

RCAHMS. (1982a). *Royal Commission on the ancient and historical monuments of Scotland. An inventory of the monuments in Argyll* (Vol. 4: Iona). Edinburgh: RCAHMS.

RCAHMS. (1982b). *Royal commission on the ancient and historical monuments of Scotland. The archaeological sites and monuments of Scotland 15: South Kincardine and Deeside District, Grampian region*. RCAHMS: Edinburgh.

RCAHMS. (1992). *Royal Commission on the ancient and historical monuments of Scotland. An inventory of the monuments in Argyll* (Vol. 7: Mid-Argyll & Cowal). Edinburgh: RCAHMS.

Reimer, P., Bard, E., Bayliss, A., Beck, J., Blackwell, P., Bronk Ramsey, C., Grootes, P., Guilderson, T., Haflidason, H., Hajdas, I., Hattž, C., Heaton, T., Hoffmann, D., Hogg, A., Hughen, K., Kaiser, K., Kromer, B., Manning, S., Niu, M., Reimer, R., Richards, D., Scott, E., Southon, J., Staff, R, Turney, C., &

van der Plicht, J. (2013). IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP. *Radiocarbon, 55*(4), 1869–1887.

Reimer, P., Baillie, M., Bard, E., Bayliss, A., Beck, J., Bertrand, C., Blackwell, P., Buck, C., Burr, G., Cutler, K., Damon, P., Edwards, R., Fairbanks, R., Friedrich, M., Guilderson, T., Hogg, A., Hughen, K., Kromer, B., McCormac, G., Manning, S., Ramsey, C., Reimer, R., Remmele, S., Southon, J., Stuiver, M., Talamo, S., Taylor, F., van der Plicht, J. & Weyhenmeyer, C. (2004). IntCal04 Terrestrial Radiocarbon Age calibration, 0-26 Cal Kyr BP. *Radiocarbon, 46*(3), 1029–1058.

Ross, A. (2015). *Land assessment and lordship in northern medieval Scotland*. Brepols: Belgium.

Russell, B., & Dahlin, B. (2007). Traditional burnt-lime production at Mayapán, Mexico. *Journal of Field Archaeology, 32*(4), 407–423.

Rutgers, L., De Jong, A., & der Borg, K. (2002). Radiocarbon dates from the Jewish catacombs of Rome. *Radiocarbon, 44*(2), 541–547.

Ryan, W. (1961). Coralite for cheaper building in the islands. *South Pacific Bulletin July, 1961*, 44–49.

Salzman, L. (1952). *Building in England down to 1540. A documentary history*. Oxford: Clarendon Press.

Scoular, J. (1959). *Regesta Regum Scottorum. Handlist of the acts of Alexander II 1214–1249*. Edinburgh: Edinburgh University Press.

Schweingruber, F. (1990). *Microscopic Wood Anatomy. Structural variability of stems and twigs in recent and subfossil woods from Central Europe*. Swiss Federal Institute for Forest, snow and landscape research: Switzerland.

Shepherd, C. (2011). Agrarian and settlement characterisation in post-medieval Strathbogie, Aberdeenshire, 1600-1760. *Rural History, 22*(1), 1–30.

Shorohova, E., & Kapitsa, E. (2014). Influence of the substrate and ecosystem attributes on the decomposition rates of coarse woody debris in European boreal forests. *Forest Ecology and Management, 315*, 173–184.

Shorohova, E., & Kapitsa, E. (2016). The decomposition rate of non-stem components of coarse woody debris (CWD) in European boreal forests mainly depends on site moisture and tree species. *European Journal of Forest Research, 135*, 593–606.

Simpson, G. (1960). *Regesta Regum Scottorum. Handlist of the acts of Alexander III, the guardians, John 1249–1296*. Edinburgh: Edinburgh University Press.

Simpson, W. (1958). *Dunstaffnage and the stone of destiny*. Edinburgh: Oliver and Boyd.

Sölter, W. (1970). *Römische Kalkbrenner im Rheinland*. Düsseldorf: Rheinland-verlag GMBH.

Stelzle-Hueglin, S. (2007). "Renovatio imperii" on the Meunsterhuegel of Basle? A reappraisal of mechanical mortar mixers. http://medieval-europe-paris-2007.univ-paris1.fr/Stelzle-Hueglin.pdf last accessed 07-10-2019.

Stevenson, J. (1870). *Documents illustrative of the history of Scotland from the death of king Alexander the Third to the accession of Robert Bruce. Volume II*. HM General Register House: Edinburgh.

Stuart, J., & Burnett, G. (1878). *Rotuli Scaccarii Regum Scotorum. The Exchequer rolls of Scotland I 1264–1359. H.M.* General Register House: Edinburgh.

Stuiver, M., & Pearson, G. (1986). High precision calibration of the radiocarbon time scale AD 1950-500 BC. In, M. Stuiver & R, Kra (eds.). Proceedings of the 12th International ^{14}C Conference. *Radiocarbon, 28*(2B), 980–1021.

Stuiver, M., & Reimer, P. (1993). Extended ^{14}C data base and revised calib. 3.0 ^{14}C age calibration program. *Radiocarbon, 35*, 35–66.

Symson, A. (1684). *(1823). A Large Description of Galloway*. Edinburgh: W & C. Tait.

Thacker, M. (2011). *An archaeology of the lime and Shell-lime mortars of the Western isles*. University of York: Unpublished MA Dissertation.

Thacker, M. (2012). Towards an on-site mortar archaeology of the Isle of Lewis. *Journal of the Building limes Forum, 19*, 38–44.

Thacker, M. (2013a). *Making lime at the edge of the world. Proceedings of the 3rd Historic Mortars Conference*. Paris: Rilem.

Thacker, M. (2013b). *The late Norse 'coral' or maerl-limes of Orkney – An on-site mortar-archaeology of Cubbie Roo's castle and chapel. Proceedings of the 3rd Historic Mortars Conference*. Paris: Rilem.

Thacker, M. (2014). Kisimul Castle. *Barra. Survey. Discovery & Excavation in Scotland, 15*, 195–196.

Thacker, M. (2015). Cille Donnain revisited: Negotiating with lime across Atlantic Scotland from the 12th century. *Journal of the North Atlantic, 901*, 45–66.

Thacker, M. (2016). *Constructing Lordship in North Atlantic Europe: the archaeology of masonry mortars in the medieval and later buildings of the Scottish North Atlantic*. 3 Vols. Unpublished PhD. thesis. University of Edinburgh.

Thacker, M. (2017). MacGillechrist's castle: An environmental study in medieval buildings archaeology from Argyll. In P. Martin (Ed.), *Castles and Galleys. A re-assessment of the historic galley-castles of the Norse-Gaelic seaways* (pp. 157–171). Laxay: IBT.

Thacker, M. (2019a). From dry-stone to Shell-lime bound: High medieval contrasts in masonry technique at Skellig Michael, High Island and north Rona. In J. Hughes, J. Válek, & C. Groot (Eds.), *Historic mortars: Advances in research and practical conservation* (pp. 61–77). Berlin: Springer.

Thacker, M. (2019b). An Ecology of Castle Construction: geoarchaeology, archaeobotany and radiocarbon analysis in the ecotone of Lochindorb Castle. In, RILEM PRO 130; *Proceedings of the 5th Historic Mortars Conference, Pamplona*. RILEM publications: Paris. ISBN: 978–2–35158-221-3, e-ISBN: 978–2–35158-222-0, pages 808–826.

Thacker, M. Hughes, J. & Odling, N. (2019). Animal, vegetable or mineral? Characterising shell-lime, maerl-lime and limestone-lime mortar evidence form the late Norse and medieval site of Tuquoy, Orkney. In, RILEM PRO 130; *Proceedings of the 5th Historic Mortars Conference, Pamplona*. RILEM publications: Paris. ISBN: 978-2-35158-221-3, e-ISBN: 978-2-35158-222-0, pages 758-777.

Thacker, M. forthcoming. The Shell-lime Mortars of Scotland – the South & East. *Journal of the Building Limes Forum* 2019.

Thacker, M. in prep. a. Tarbert Castle. Landscape, Buildings & Materials Analysis. *Discovery and Excavation in Scotland 2019.*

Thacker, M. in prep. b. The Early Church in Scotland and Ireland [working title].

Thacker, M. in prep. c. The Castle of Abernethy: Investigating Medieval Cultural Landscapes, Buildings and Materials in Badenoch and Mar.

Thacker, M. in prep. d. The Castle of Achanduin, Lismore – A Point of Reference for the Radiocarbon Analysis of Mortar-Entrapped Relict Limekiln Fuels.

Thacker, M. in prep. e. Castle Camus, Isle of Skye – Buildings, Materials & Radiocarbon Analysis in the Borderlands of Medieval Sleat.

Toft, L. (1988). Lime burning on the Gower Peninsula's Limestone Belt. *The Industrial Archaeology Review, 11*(1), 75–85.

Vaschalde, C., Durand, A., Figueiral, I., & Thiriot, J. (2013). Charcoal analysis of lime kiln remains in southern France: An original process of mediaeval and modern traditional lime burning. In F. Damblon (Ed.), *Proceedings of the Fourth International Meeting of Anthracology Brussels, 8–13 September 2008 Royal Belgian Institute of natural sciences*, *BAR international series* (Vol. 2486, pp. 251–258).

Ward, G., & Wilson, S. (1978). Procedures for comparing and combining radiocarbon age determinations: A critique. *Archaeometry, 20*, 19–32.

Webster, B. (Ed.). (1982). *Regesta Regum Scottorum VI. The acts of David II, king of scots 1329–1371.* Edinburgh: Edinburgh University Press.

White Marshall, J., & Rourke, G. (2000). *High Island: An Irish monastery in the Atlantic*. Dublin: Town and Country House.

Wingate, M. (1985). *Small-scale lime-burning. A practical introduction*. London: Intermediate Technology Publications.

Wulff, H. (1966). *The traditional crafts of Persia*. Massachusetts: The M.I.T. Press.

Young, A. (1813). *A general view of the agriculture of the county of Sussex*. London: Richard Phillips.

Young, A. (1909). *Travels during the years 1787, 1788 and 1789*. London: George Bell.

Young, A. (1997). *Robert the Bruce's rivals: The Comyns, 1212–1314*. East Linton: Tuckwell Press.