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A Bayesian approach to linking archaeological, paleoenvironmental and documentary datasets relating to the settlement of Iceland (Landnám)

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Abstract

Icelandic settlement (Landnám) period farmsteads offer opportunities to explore the nature and timing of anthropogenic activities and environmental impacts of the first Holocene farming communities. We employ Bayesian statistical modelling of archaeological, paleoenvironmental and documentary datasets to present a framework for improving chronological robustness of archaeological events. Specifically, we discuss events relevant to the farm Hrísbrú, an initial and complex settlement site in southwest Iceland. We demonstrate that tephra layers are key in constraining reliable chronologies, especially when combined with related datasets and treated in a Bayesian framework. The work presented here confirms earlier interpretations of the chronology of the site while providing increased confidence in the robustness of the chronology. Most importantly, integrated modelling of AMS radiocarbon dates on *Hordeum vulgare* grains, palynological data, documented evidence from textual records and typologically diagnostic artefacts yield increased dating reliability. The analysis has also shown that AMS radiocarbon dates on bone collagen need further scrutiny. Specifically for the Hrísbrú farm, first anthropogenic footprint palynomorph taxa are estimated to around AD 830–881 (at 95.4% confidence level), most likely before the tephra fall out of AD 877 ± 1 (the Landnám tephra layer), demonstrating the use of arable fields before the first known structures were built at Hrísbrú (AD 874–951) and prior to the conventionally accepted date of the settlement of Iceland. Finally, we highlight the importance of considering multidisciplinary factors for other archaeological and paleoecological studies of early farming communities of previously uninhabited island areas.

Keywords

Bayesian outlier models, Harris matrix, Icelandic sagas, island colonisation, late Holocene, paleoecology, radiocarbon dating, tephrochronology, Viking Age

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Introduction

Archaeology as a discipline is increasingly concerned with employing scientific methods to address questions of mobility, migration, resilience and collapse, particularly under changing patterns of human–environment interactions (Kintigh et al., 2014). The timing of human settlement of previously uninhabited islands and subsequent environmental change offers exciting opportunities to understand the legacies of colonisation. The chronology of human colonisation is generally based on evidence such as radiocarbon determinations that can be modelled with Bayesian analysis. This approach allows combining multiple radiocarbon dates with archaeological information, most importantly stratigraphic relationships (e.g. Bayliss et al., 2007; Whittle et al., 2011). Vigorous debates surround the timing, scale and tempo of colonisation processes of previously uninhabited islands, such as the Norse settlements across the North Atlantic including the Faroe Islands (Church et al., 2013), Greenland (Edwards et al., 2013) and Iceland (Edwards, 2012; Schmid et al., 2017; Steinberg et al., 2016; Sveinbjarnardóttir, 2012; Sveinbjörnsdóttir et al., 2016; Vésteinsson and McGovern, 2012).

Viking Age Iceland provides one of the world's premier case studies for human interactions with pristine ecosystems because it occurred relatively late in history (9th-century AD). Furthermore, a suite of archaeological, paleoenvironmental and recorded textual information is available to define this process in Iceland. The analyses of pollen, microscopic charcoal and coprophilous fungi from natural contexts in proximity to settlement sites can inform about the time of first occupation, nature of land use and possible periodicity

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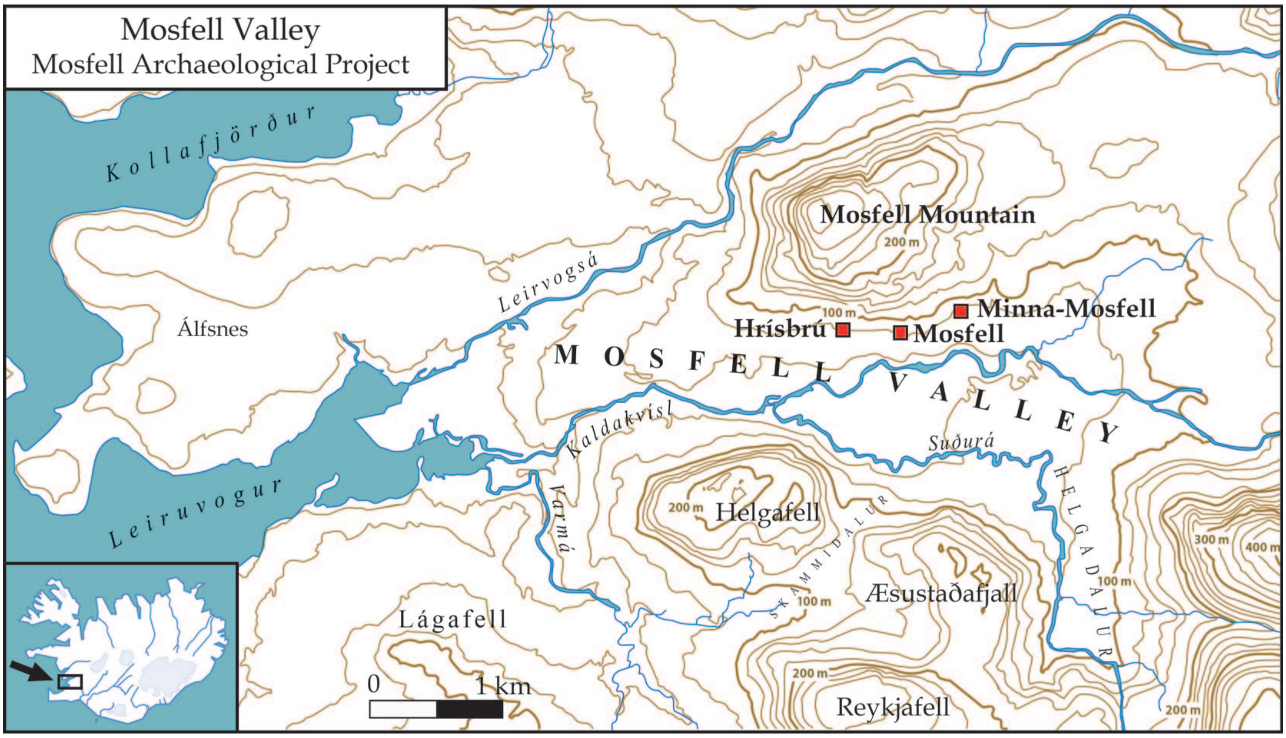

Figure 1. The Mosfell Valley in southwest Iceland. The red squares indicate the locations of the three farm sites mentioned in the text. Hrísbrú is the site of excavations that yielded the archaeological material discussed in this paper.

in habitation. These observations are particularly pertinent for Iceland where herbivorous land mammals were first introduced as part of human colonisation and where natural fires in vegetation are extremely rare (Erlendsson et al., 2006). Icelandic archaeology and paleoecology benefit from volcanic ash (tephra) deposits, which provide horizon markers (isochrons) in the stratigraphic record (Dugmore and Newton, 2012). Tephra deposits are preserved at 84% of known settlement sites in Iceland (Schmid et al., 2017), as well as in natural contexts. A key isochron is the Landnám tephra layer (LTL) that was deposited close to the time of Iceland's colonisation and is usually taken to separate wholly natural contexts from human-influenced strata; it therefore provides excellent opportunities to explore archaeological and environmental changes before and after its deposition. While archaeological evidence of 81 settlement sites occur above the LTL (Schmid et al., 2017), two turf walls in the southwest of Iceland are covered by this tephra (Jóhannesson and Einarsson, 1988; Roberts et al., 2003). In the same area, the paleoenvironmental record demonstrates that woodlands were already cleared before the deposition of the LTL (Erlendsson et al., 2014). Nevertheless, the potential usefulness of anthropogenic palynomorph footprint taxa in proximity to archaeological sites has not yet been assessed.

Our focus is on a key archaeological site in the southwest of Iceland, Hrísbrú, which provides a significant example for early Icelandic archaeology. In this paper, we assess chronological information from a variety of sources and time-periods. The site has been inhabited continually from initial settlement until today. The discussion in this paper focuses on the examination of the original settlement and occupation of Hrísbrú. The excavated component of the site consists of a Viking Age feasting hall, an early Christian church, multiple pagan and Christian burials, as well as two sediment profiles (peat monoliths) that were extracted from the original landholding and which have been palynologically analysed. The available data consist of independently dated tephra isochrons preserved both in situ in sediment profiles and around the archaeological features, palynological data, 23 AMS radiocarbon dates from various materials and multiple typologically sensitive artefacts recovered from stratified archaeological contexts. In addition, textual records from the 12th and 13th centuries mention dates regarding the establishment and abandonment of the church. The primary aim is to use these datasets to provide more robust dating of the first settlement sites of Holocene farming communities through the use of Bayesian statistical modelling. The archaeological record is reviewed and the data are discussed in a step-by-step application of the modelling. We present a framework that allows objective assessment of radiocarbon dates within the context of their stratigraphic position and in combination with other chronological information. Combining multidisciplinary datasets allows more robust dating of settlement histories of archaeological sites. This approach serves as an example for other archaeological and paleoecological studies with similar chronological constraints.

Materials and methods

Beginning in the mid-1990s, the Mosfell Archaeological Project has conducted on-going archaeological survey and large-scale excavation in the Mosfell Valley, located about 15 km to the northeast of modern Reykjavík (Figure 1; Byock and Zori, 2014). This paper focuses on two excavated areas: (1) Tún; meaning, 'homefield'; the site of a well-preserved bow-shaped structure (TUN), and (2) Kirkjuhóll; meaning, 'Church Knoll'; the site of an early Christian church and surrounding cemetery (CK) (Figure 2). The slightly bow-shaped structure including gable rooms and a central fireplace represents a typical, albeit large, Viking Age hall (Zori et al., 2013). The hall and church are separated by just over 5 m. Furthermore, sediment (peat) profiles for pollen analysis were extracted from an area expected to be within the original landholding.

Tephrochronology

Tephrochronology is based on identifying volcanic ash (tephra), correlating tephra deposits from the same eruption to define isochrons and establishing calendar dates for these deposits (Lowe,

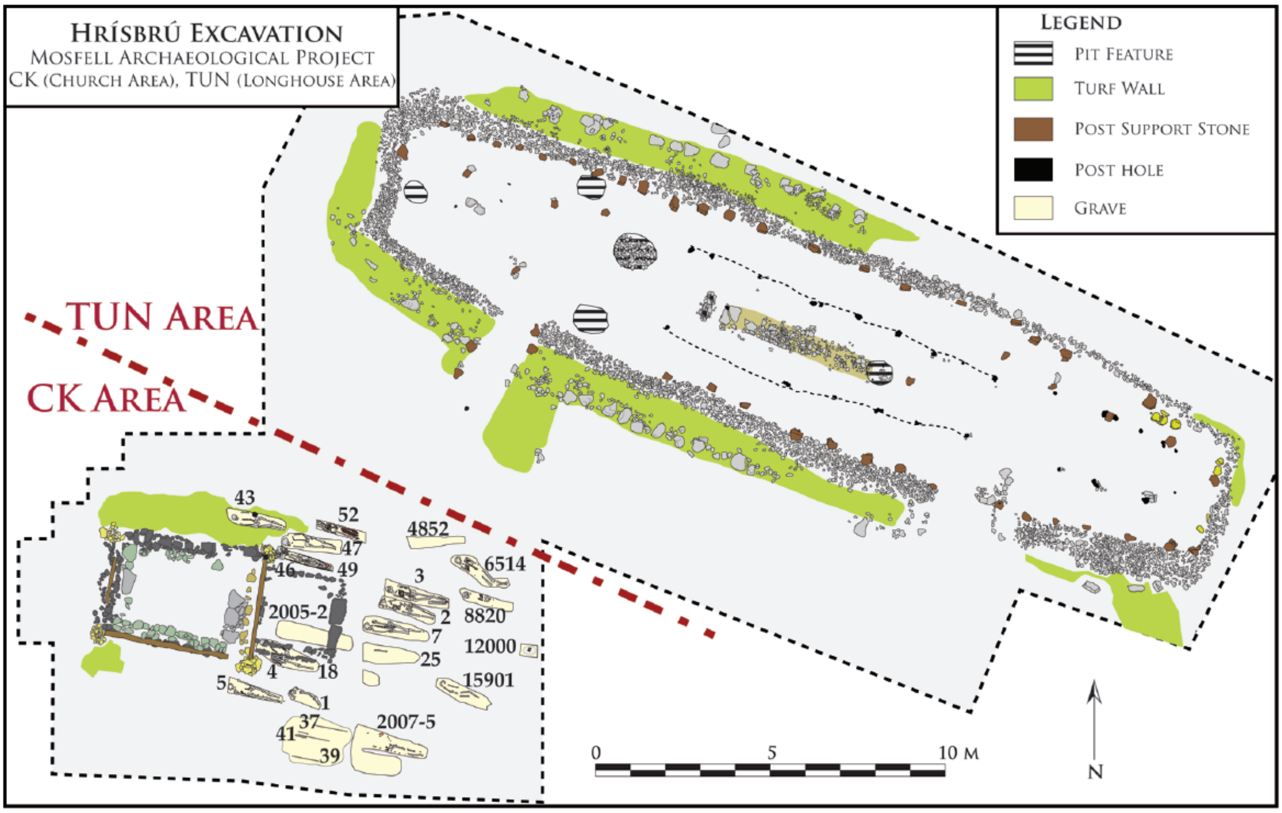

Figure 2. The location of the Viking Age hall (TUN) and the church and cemetery (CK) to the southwest of the hall.

2011; Þórarinsson, 1944). This paper follows the approach described by Schmid et al. (2017) in obtaining independent chronological frameworks for archaeological sites in Iceland. Tephra layers are named after the source volcanic system and eruption dates in years AD. Five visible tephra layers were preserved within the Hrísbrú excavation areas and sediment profiles (Sigurgeirsson, 2014). Recently, the ages of the LTL and Eldgjá tephra have been revised through high-resolution aerosol concentration records from Greenlandic ice cores. The LTL yielded an age of AD 877 ± 1 (Schmid et al., 2017), which was previously dated to 871 ± 2 (GRIP core, Grönvold et al., 1995 and GIG05 core, Vinther et al., 2006) as well as to 877 ± 4 (GISP2 core, Zielinski et al., 1997). The Eldgjá tephra yielded an age of AD 939 (NEEM-2011-S, Baillie and McAneny, 2015; Sigl et al., 2015). This tephra layer has also been correlated to documentary records; hence, it does not have an error value (Schmid et al., 2017; Sigl et al., 2015). One tephra layer of the Reykjaneshryggur source is dated to AD 1226 using textual records (Jóhannesson and Einarsson, 1988). Two tephra deposits have been correlated to annually layered sediments in lakes: the Katla tephra of around AD 920 and the Katla tephra of around AD 1500 (Haflidason et al., 1992). As described by Schmid et al. (2017), tephra layers in this paper are referred to as LTL, K~920, Eldgjá, R-1226 and K~1500.

An 'outside activity area' that accumulated throughout the lifetime of the hall (TUN) spread to the south of the house. The lower levels of this gradual accumulation extend beneath the church (CK). Within these deposits are streaks of LTL, indicating that the eruption of the LTL pre-dates the construction of the church. The LTL is also preserved in the hall's turf walls and in collapsed turfs from the walls (Byock and Zori, 2008). Additionally, the turf wall in the eastern gable room of the hall contains a 10th-century tephra, either K~920 or Eldgjá tephra. Both tephra deposits have very similar geochemical signatures that are generally hard to identify in turf (Sigurgeirsson, 2007). The presence of the 10th-century tephra in the rebuilt or repaired wall, but not in the original construction, suggests that the hall was built after the deposition of the LTL, but before the 10th-century eruption, and repaired sometime after the 930s. The same tephra layer is also preserved in the turf walls of the church. The in situ Katla tephra of AD 1500 covers the TUN hall.

Palynologically analysed sediment profiles

Sediment profiles were extracted from the Hrísbrú and Mosfell farms in areas close enough to the farmsteads for the pollen records to represent cultural activities. The Hrísbrú profile (HRI1; Figures 1 and 3a) was extracted from a cleaned section of a drainage ditch around 200 m to the south and down slope from the Viking Age hall (Erlendsson et al., 2014). About 750 m east from Hrísbrú, the Mosfell monolith (MOS; Figures 1 and 3b) was obtained by digging ca. 1 × 1 m wide pit into a drained wetland some 150 m to the southeast and down slope from where a medieval farmhouse at the current Mosfell farm is thought to have stood (Erlendsson, 2012).

Both monoliths (HRI1 and MOS) contained the LTL, R-1266 and K~1500 tephra (Figures 3a and b). The tephra layers show that the profiles cover identical periods and offer means to compare with archaeological contexts. The 10th-century Katla and Eldgjá tephras did not form visible horizons in the profiles. They could, in fact, be preserved in the profiles in the form of cryptotephras, very fine-grained tephra layers that are not visible to the naked eye (Blockley et al., 2005; Lane et al., 2013). Cryptotephras have not yet been systematically studied in Iceland; however, they could provide key additional age control (Schmid et al., 2017).

Analysis and recording of pollen and other palynomorphs were continued until reaching a total of 300 native land pollen (total land pollen (TLP)) using Moore et al. (1991) as the primary key. Andersen's (1979) methodology was used to separate cereal-type pollen (cf. *Hordeum*-type) from other Poaceae (grass family) pollen. Identification of spores of coprophilous (dung-loving) fungi relied mainly on Van Geel et al. (2003). Microscopic charcoal fragments were counted along with other palynomorphs and are presented as percentage of TLP. To enhance the signal for cereal cultivation, all pollen samples were subjected to the rapid scanning procedure (Edwards and McIntosh, 1988) until around 1500 native land pollen had been viewed. The palynological data were divided into local pollen assemblage zones (LPAZs) using CONISS (a stratigraphically constrained dendrogram) and visual assessment of the data.

The pollen data from HRI1 can be divided into five LPAZs (Figure 3a). LPAZ HRI1-I (39–36 cm) is characterised by *Betula* undiff., Cyperaceae (sedge family), Poaceae, *Angelica* undiff. (angelicas) and *Filipendula ulmaria* (meadowsweet).

In LPAZ HRI1-II (36–33.5 cm), cereal-type pollen (e.g. barley; through rapid scanning), microscopic charcoal, coprophilous fungi (*Sordaria*-type, *Sporormiella*-type and *Podospora*-type) and replacement of *Betula* undiff. by Poaceae become apparent within the first centimetre immediately below the LTL. These features remain prominent throughout LPAZ HRI1-II, until 33.5 cm.

In LPAZ HRI1-III (33.5–29.5 cm), the values for microscopic charcoal, coprophilous fungi, cereal-type pollen and Poaceae are reduced, while *F. ulmaria* and Cyperaceae increase, and in LPAZ HRI1-IV (29.5–26.5 cm), microscopic charcoal, coprophilous fungi and Poaceae resume prominence. The record for cereal-type pollen is consistent within this LPAZ. Cyperaceae and *F. ulmaria* decrease.

In LPAZ HRI1-V (26.5–17 cm), Cyperaceae, *Thalictrum alpinum* (alpine meadow-rue) and *Selaginella selaginoides* (lesser clubmoss) become increasingly prominent and replace grazing-sensitive taxa such as *Betula* undiff., *F. ulmaria* and *Angelica* undiff. The record for cereal-type pollen becomes reduced and sporadic. Percentages of microscopic charcoal and coprophilous fungi are also reduced from the previous zone.

The MOS profile is divided into three LPAZs (Figure 3b). LPAZ MOS-I (55–50 cm) is characterised mainly by *Betula* undiff., Cyperaceae, Poaceae and *F. ulmaria*.

In LPAZ MOS-II (50–37 cm), cultural indicator taxa (cereal-type pollen, microscopic charcoal and dung-loving fungi) become prominent. Poaceae increases in place of Cyperaceae. The increase in *Betula* undiff. and Pteroposida (monol.) indet. is probably because of reworked soil (cf. Gathorne-Hardy et al., 2009) which is also indicated by reduced organic matter.

In LPAZ MOS-III (37–22 cm), Cyperaceae, *T. alpinum, Plantago maritima* (sea plantain) and *S. selaginoides* become prominent. They replace mainly *Betula* undiff., and Pteroposida (monol.) indet., which were considered to be contaminants in previous zone. Values for microscopic charcoal dwindle and recordings of cereal-type pollen become reduced and sporadic.

Radiocarbon dating

This study employs 23 published and previously unpublished AMS radiocarbon dates with well-defined contexts in the stratigraphic matrix (Tables 1 and 2; Byock et al., 2005; Byock and Zori, 2014; Grimes et al., 2014; Zori et al., 2013). Ten samples are of short-lived, single-entity materials (*Hordeum vulgare* and identified wood as tree twig). Twelve samples are from human bones of which the $\delta^{13}C$ (‰) values of 11 samples point to mixed diets (Grimes et al., 2014). The final sample is a fragmented piece of pine wood from a mostly disintegrated sill beam in the church's nave. The stratigraphic relationships of radiocarbon samples in the deposits are illustrated using the commonly applied format of a Harris Matrix (Harris, 1989). Harris Matrices show the stratigraphic order of deposits and inter-relationship of samples and stratigraphic units over time at archaeological sites. Dye and Buck (2015) discuss in detail the usefulness of Harris Matrices for the use of Bayesian modelling and their development into archaeological sequence models to show stratigraphic relationships more clearly. These developments have been incorporated in Figure 4.

TUN (eight ^{14}C samples). The floor layers of the hall are well preserved, and throughout the house 38 floor layers with separate context numbers were distinguished (Zori, 2010). Three dated *H. vulgare* seeds are from floor layers designated as contexts 11, 19 and 95 (Figure 4). Floor layer 11 lay on the raised northern aisle – or bench – of the central room of the hall. Floor 19 lay directly under the turf collapse and is the upper-most context in a deep sequence of floors in the middle of the central room. Floor layer 95 was the top floor layer in a pantry room adjacent to the central room. No stratigraphic relationship exists between the three floor layers and they may have accumulated contemporaneously, as shown in the Harris Matrix; their stratigraphic positions all represent the last occupation of the hall. Five *H. vulgare* samples came from midden or rubbish deposits that accumulated on top of the turf collapse after the original hall was abandoned. The sampled midden deposits have a documented stratigraphic relationship with each other, and context 39 is below 8 and 34 (Figure 4). Context 36, however, has no documented stratigraphic relationship with the sequence and may be contemporaneous in the Harris Matrix.

CK (15 ^{14}C samples). One hay sample derives from a pit deposit below the church (CK 8); one twig sample is from a midden deposit (CK 10) below a burial (CK 6); one pine wood sample comes from the southern wall of the chancel of the church (CK 19); 12 samples of bone collagen were taken from nine burials around the church and one was taken from a burial lying above the southern wall of the church chancel (CK 18) (Figure 4). As schematically illustrated in Figure 2, two of the skeletal remains (CK 4 and 46) were disarticulated indicating that they are re-deposited secondary burials (see Figure 2). Burial 18 is stratigraphically above the foundations of the church and post-dates its abandonment. The specific stratigraphic relationships that pertain to radiocarbon dates from the site can be seen in the Harris Matrix (Figure 4).

Documentary evidence

The textual record suggests that the current farmstead named Hrísbrú was the location of the original Mosfell farm. The original Mosfell farm broadly utilised the southern slopes of the Mosfell mountain. Subsequently, this large farmland on the mountain slopes was subdivided into three farms: Mosfell, Hrísbrú and Minna-Mosfell (Figure 1). The Old Mosfell farm (located at modern Hrísbrú) was the main farm of chieftains recorded in multiple sagas, including Egil's Saga, Hallfred's Saga and The Saga of Gunnlaug Serpent-tongue. These sagas recount stories of chieftains and their families who lived at Mosfell in the late 10th and early 11th centuries (see Byock et al. (2005) and Byock (2014) for more on the textual sources concerning the Mosfell chieftains). Egil's Saga explains that Grímr Svertingson built a church at Hrísbrú at the time of Iceland's conversion to Christianity, an event conventionally dated to AD 999/1000 (the *Íslendingabók* text provides the basic chronology). Gunnlaug's Saga mentions this church as the inhabitants of Mosfell sought sanctuary in their church during an attack on their farm sometime around AD 1015. Egil's Saga recounts the abandonment of the church and graveyard and the relocation of the chieftain's farm at Hrísbrú to the current Mosfell farm in the time of the priest Skafti Þórarinsson (Egil's Saga in Nordal 1933, ch. 86, pp. 298, 299). Other written sources indicate that Skafti was alive in AD 1121 (Jóhannesson et al., 1946; *Sturlunga Saga*, 1988: 45) and in AD 1143 (Nafnaskrá Íslenzkra Presta in *Diplomatarium islandicum* I, 186). Sturlunga Saga suggests that in AD 1121 Skafti was a person of importance, therefore more likely to be middle aged than young. This suggests a possible date range for the relocation of the church between ca. AD 1090 and 1150. The existence of a church at the new Mosfell farm is verified by Bishop Páll's AD 1200 register of churches in the southern Icelandic diocese of Skálholt (Nafnaskrá Íslenskra Presta in *Diplomatarium islandicum* XII, 9). The textual records, therefore, provide two dates for the Mosfell/Hrísbrú farm that have been included in the Bayesian analysis: AD 1015 as a *terminus ante quem* for the establishment of the church and

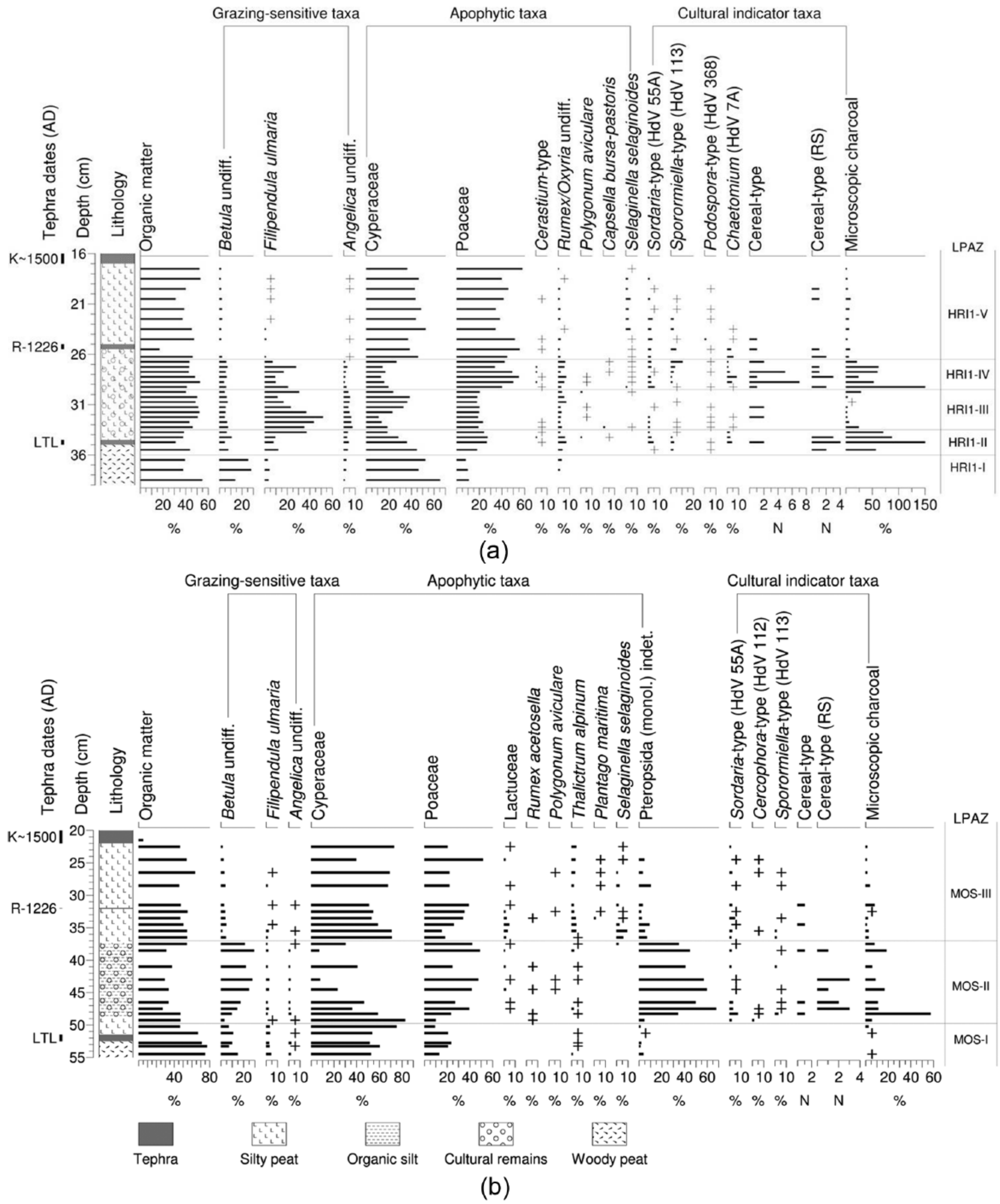

Figure 3. Pollen percentage diagrams from (a) Hrísbrú (HRI1) and (b) Mosfell (MOS). The diagrams show selected pollen, spore and fungal taxa, along with microscopic charcoal, lithology and organic matter content of sediment. Crosses signify values below 1% TLP.
RS: rapid scanning.

AD 1150 as a *terminus ante quem* for the relocation of the church. The application of these constraints of course relies on conclusions that the old Mosfell farm was located at the current Hrísbrú farm (Byock and Zori, 2014; Byock et al., 2005).

Artefact typology

Thirty-six imported glass beads were recovered within the floor layers of the hall excavated at Hrísbrú. The majority of these beads can be typologically dated generally to the Viking Age. A third of these beads are dated to the second half of the 10th to the early 11th centuries (Hreiðarsdóttir, 2014). Among these are four so-called ‘eye- or sun-beads’ imported from the Caspian Sea area of Callmer’s type Bh, which are dated to AD 960–1000, and one segmented bead, Callmer’s type Ea, which is dated to AD 950–1000 (Callmer, 1977). The beads were found within the upper floor layers of the hall [floor layer 11] and therefore suggest that the site was occupied in the late 10th to early 11th centuries.

Table 1. Summary data of unmodelled and modelled ages of 'Boundaries', radiocarbon determinations ('R_Dates'), tephra ('After') and typological data ('Date') for the Viking Age hall (TUN) stratigraphic sequence in OxCal (Bronck Ramsey, 2017). All data are given as both the 68.2% and 95.4% highest probability density ranges. Modelled ages are calibrated using the IntCal13 calibration curve in OxCal (Reimer et al., 2013). Fields with no entry are due to not applicable, not analysed or not reported previously.

OxCal command	Archaeological feature/deposit	Context no.	Context description	AMS lab. no./typological date	Sample material[1]	Treatment[2]	C (wt%)	^{14}C age (BP) ± 1σ	Unmodelled 95.4% probability range (cal. AD)		Modelled 68.2% probability range (cal. AD)		Modelled 95.4% probability range (cal. AD)		Posterior outlier probability %
									From	To	From	To	From	To	
Boundary	Start anthropogenic signal	–	–	–	–	–	–	–	–	–	839	876	830	881	–
After	Tephra (LTL)	–	In turf of the wall and in turf of the outside activity area	–	–	–	–	877 ± 1	–	–	876	877	876	877	–
Boundary	Earliest use of site	–	–	–	–	–	–	–	–	–	879	926	874	951	–
Boundary	Latest use of site	–	–	–	–	–	–	–	–	–	934	966	910	970	–
R_Date	Hall, floor deposit	95	Upper floor	UCIAMS-64171	ChB	ABA	74.5	1125 ± 20	885	980	950	971	926	976	3
R_Date	Hall, floor deposit	19	Upper floor, under turf collapse, stratigraphically above 11	UCIAMS-64173	ChB	ABA	57.4	1145 ± 20	777	973	948	971	929	974	3
R_Date	Hall, floor deposit	11	Floor on northern side aisle, under turf collapse	UCIAMS-64172	ChB	ABA	51.0	1140 ± 15	780	973	948	970	929	973	3
Date	Hall, floor deposit	80	Fill of western gable room	Bead type BO88 and BO90 (Bh)	–	–	–	–	960	1000	960	967	960	977	4
Date	Hall, floor deposit	11	Floor on northern side aisle, under turf collapse	Bead type E030 (Ea)	–	–	–	–	950	1000	955	969	950	974	3
Boundary	Transition floor-midden deposits	–	–	–	–	–	–	–	–	–	963	978	959	984	–
R_Date	Midden deposit	8	Infill above hall, stratigraphically contemporary with 34	UCIAMS-64175	ChB	ABA	63.8	1115 ± 15	891	978	969	983	963	990	6
R_Date	Midden deposit	36	Infill above hall	UCIAMS-64170	ChB	ABA	60.2	1085 ± 20	895	1014	972	988	964	998	3
R_Date	Midden deposit	44	Infill above hall, stratigraphically below 39	UCIAMS-64174	ChB	ABA	59.2	1080 ± 25	895	1018	972	989	964	1002	3
R_Date	Midden deposit	39	Infill above hall, stratigraphically below 34, above 44	UCIAMS-64168	ChB	ABA	68.8	1040 ± 20	976	1025	975	996	968	1010	4
R_Date	Midden deposit	34	Infill above hall, stratigraphically above 39	UCIAMS-64169	ChB	ABA	62.7	1055 ± 20	905	1023	974	994	967	1010	3
Boundary	End use midden	–	–	–	–	–	–	–	–	–	978	1006	971	1026	–

[1]ChB: charred barley seed; H: hay.
[2]ABA: dilute acid/dilute alkali/dilute acid treatment.

Table 2. Summary data of unmodelled and modelled ages of 'Boundaries', radiocarbon determinations ('R_Dates'), tephra ('After' and 'Before') and recorded historical information ('Before') for the church and cemetery (CK) stratigraphic sequence in OxCal (Bronck Ramsey, 2017). All data are given as both the 68.2% and 95.4% highest probability density ranges including quality assurance data. Modelled ages are calibrated using the IntCal13 and Marine13 calibration curves in OxCal (Reimer et al., 2013). The LocalMarine value is set to 111 ± 10. Fields with no entry are due to not applicable, not analysed or not reported previously.

OxCal command	Archaeological feature/ context	Context no.	Context description	AMS lab. no.	Sample material[1]	Treatment[2]	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	Collagen yield (%)	N (wt%)	C (wt%)	C/N[3] (atomic)	^{14}C age (BP) ± 1σ	Marine ^{14}C years (%)	Unmodelled 95.4% probability range (cal. AD)		Modelled 68.2% probability range (cal. AD)		Modelled 95.4% probability range (cal. AD)		Posterior outlier probability %
															From	To	From	To	From	To	
Boundary	Start anthropogenic signal	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	839	876	830	881	–
After	Tephra (LTL)	–	In turf of the outside activity area	–	–	–	–	–	–	–	–	–	877 ± 1	–	–	–	876	877	876	877	–
Boundary	Early use of site	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	881	918	874	963	–
R_Date	Deposit	8	Pre-church activity	Beta-175675	H	ABA	−23.9	–	–	–	–	–	1070 ± 40	–	890	1025	897	952	892	979	3
R_Date	Deposit	10	Under burial 6 (not ^{14}C dated)	Beta-165332	W	ABA	−26.4	–	–	–	–	–	1100 ± 40	–	778	1022	895	953	891	976	3
R_Date	Pagan burial	46	Burial around church	Beta-244590	B	Collagen B	−19.3	15.9	–	–	–	–	1270 ± 40	13 ± 10	676	965	893	942	886	973	5
R_Date	Pagan burial	4	Burial around church	Beta-244587	B	Collagen B	−18.4	12.1	–	–	–	–	1150 ± 40	25 ± 10	881	1161	896	953	892	978	4
R_Date	Pagan burial	4	Burial around church	Beta-203867	B	Collagen B	−19.4	7.6	–	–	–	–	1080 ± 40	12 ± 10	889	1160	897	954	892	980	4
Boundary	Christian activity	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	907	964	901	987	–
Before	Historical date	–	Gunnlaug's Saga	–	–	–	–	–	–	–	–	–	1015 ± 0.5	–	–	–	–	–	–	–	–
R_Date	Church	19	Sample from southern chancel wall foundation	Beta-175676	WP	ABA	−27.8	–	–	–	–	–	1150 ± 40	–	774	978	937	986	917	1009	5
R_Date	Christian burial	15901	Burial around church	UCIAMS-134936	B	Collagen UF	−18.0	12.9	4.1	16.6	45.8	3.22	1265 ± 20	31 ± 10	778	1015	942	997	919	1017	4
R_Date	Christian burial	49	Burial around church	UCIAMS-134937	B	Collagen UF	−17.0	13.5	6.4	17.0	46.6	3.20	1250 ± 15	44 ± 10	887	1121	966	1019	922	1037	3
R_Date	Christian burial	2	Burial around church	Beta-165331	B	Collagen B	−17.4	–	–	–	–	–	1360 ± 40	39 ± 10	702	985	936	991	917	1016	5
R_Date	Christian burial	2	Burial around church	AA-93254	B	Collagen	−17.2	11.3	–	15.4	49.3	3.7	1207 ± 44	41 ± 10	Omitted	Omitted	Omitted	Omitted	Omitted	Omitted	–
R_Date	Christian burial	1	Burial around church	UCIAMS-107239	B	Collagen UF	−18.8	11.4	8.9	–	–	3.22	1190 ± 15	20 ± 10	778	1025	949	1004	919	1020	3
R_Date	Christian burial	3	Burial around church	UCIAMS-107238	B	Collagen UF	−17.4	13.0	7.3	–	–	3.23	1235 ± 15	39 ± 10	881	1120	963	1017	922	1032	3
R_Date	Christian burial	43	Burial above turf wall north of church	Beta-244589	B	Collagen B	−19.7	11.3	–	–	–	–	1120 ± 40	8 ± 10	772	1047	960	1013	919	1027	3
R_Date	Christian burial	5	Burial around church	UCIAMS-134935	B	Collagen UF	−19.3	10.1	6.5	17.2	46.9	3.19	1020 ± 20	13 ± 10	990	1189	996	1053	962	1102	15
Boundary	End of Christian activity	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	996	1053	962	1102	–
Boundary	Hiatus in occupation	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1149	1150	1149	1150	–
Before	Historical date	–	Abandonment (Skafti Þórarinsson)	–	–	–	–	–	–	–	–	–	1015 ± 0.5	–	–	–	–	–	–	–	–
Boundary	Burial above church	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1272	1420	1136	1436	–
R_Date	Christian burial	18	Burial lying on wall foundation	Beta-244588	B	Collagen B	−21.9	11.6	–	–	–	–	530 ± 40	–	1310	1445	1322	1431	1303	1444	5
Boundary	End occupation	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1335	1472	1326	1498	–
Before	Tephra (H~1500)	–	–	–	–	–	–	–	–	–	–	–	1500 ± 0.5	–	–	–	–	–	–	–	–

[1]B: human bone; Ch: charcoal (birch/Betula); H: hay; W: wood; WP: wood (pine).
[2]Collagen B: collagen extraction included alkali (base) treatment; collagen UF: collagen extraction included ultrafiltration (>30 kDa collagen); ABA: dilute acid/dilute alkali/dilute acid treatment.
[3]Wt% C/N values were converted to atomic C/N values by multiplying by atomic masses of nitrogen (14)/carbon (12) = 1.16667.

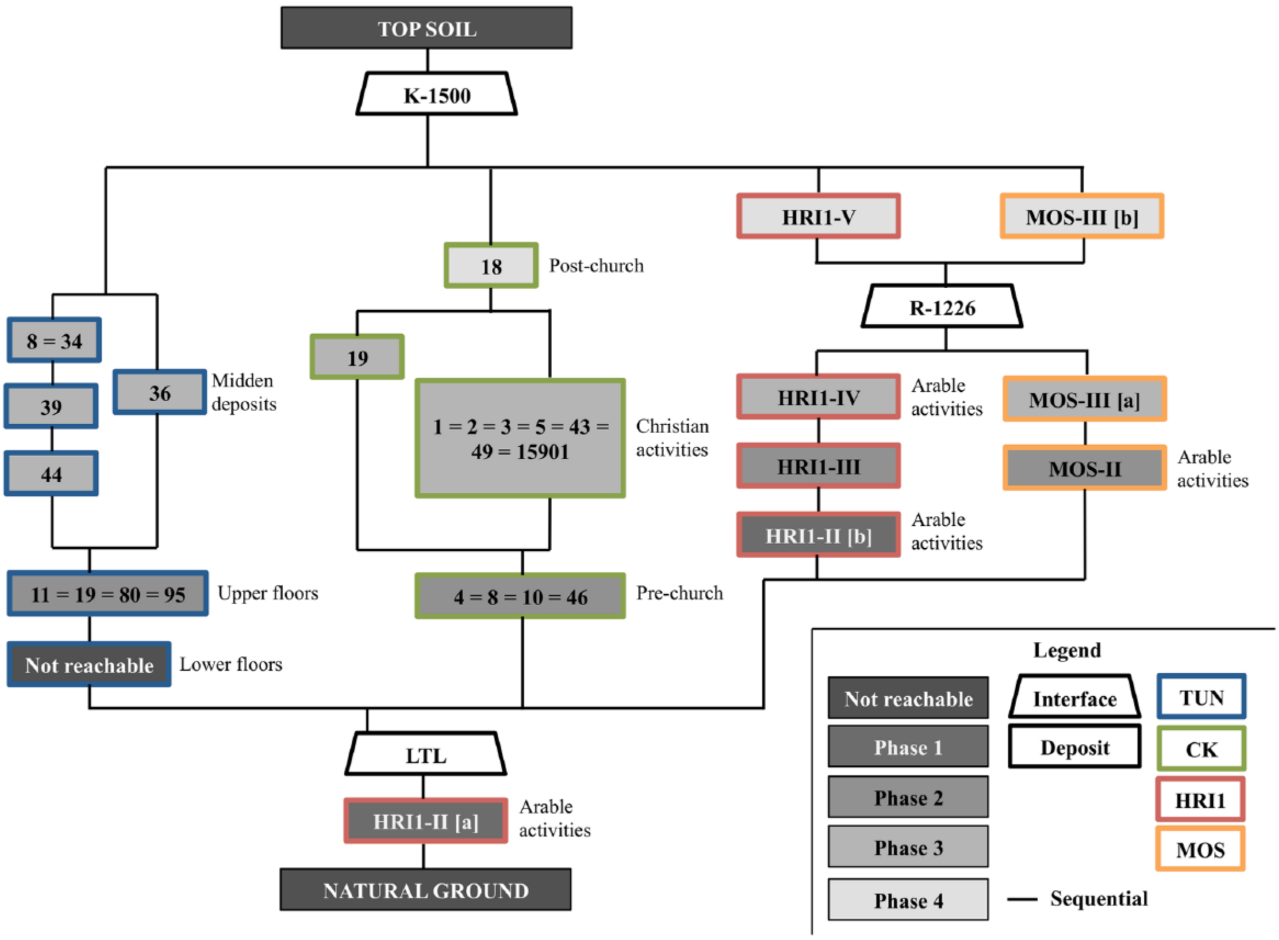

Figure 4. Harris Matrix showing relationships of radiocarbon samples, beads and tephra layers for TUN and CK and for the sediment cores HRI1 and MOS (after Dye and Buck, 2015). LPAZ HRI1-II and MOS-III are split into [a] and [b], because they occur below and above a particular tephra layer.

Bead type Ea comes from the same floor layer [11] as the radiocarbon sample UCIAMS-64172; bead type Bh is from the fill of the western gable, which is likely contemporary with the radiocarbon samples UCIAMS-64171, UCIAMS-64172 and UCIAMS-64173 as all three radiocarbon samples derive from contexts representing the upper floor layers (Figure 4).

Bayesian statistical analysis: A step-by-step application

Bayliss and Bronk Ramsey (2004: Figure 2.2) suggested an approach to building chronologies that is applicable for complex archaeological sites. We have modified their framework to suit the Icelandic evidence. Figure 5 demonstrates the steps in the process.

Step 1: Define site stratigraphy. The stratigraphic relationships between samples and other site information provide the prior information that is built into Bayesian modelling. For the present case, the stratigraphy suggests that the hall was in use contemporaneously with the church; however, they were not built at the same time nor necessarily ended synchronously (Byock et al., 2003; Zori and Byock, 2014). Because the stratigraphies of the structures are not in direct relationship with each other, the two sites are linked with the shared tephra layers; most importantly, with the LTL.

Step 2: Define archaeological questions/hypotheses. Bayesian statistical analysis can be used to test hypotheses. Given the techniques, material and resources of the datasets, the following questions were addressed:

1. When did anthropogenic activities start at Hrísbrú?
   - Consistent with wider hypotheses about the settlement of Iceland, we posed the question of whether the Hrísbrú site was settled before or after the deposition of the LTL tephra of AD 877 ± 1. Apparent anthropogenic activity in the form of microscopic charcoal, spores of coprophilous fungi and cereal-type pollen is evident in the sediment profile 1 cm underneath the LTL tephra and would suggest activity before this volcanic eruption, followed by the subsequent building of the turf structures including LTL.
2. Is there a continuous occupation history of TUN and CK?
   - The hypothesis proposed by Byock and Zori (2014) is based on stratigraphical observations, artefact typology, individual 14C dates and documentary data; it suggests that the hall was built first, followed by the church. The two were in use simultaneously for a period before the hall was abandoned while the church continued to be used until the 12th century as suggested by texts.
3. Do the scientific dates support the typological dates as well as the historical dates?
   - If all the dating methods are robust, they should be consistent with each other and improve chronological control. The prior information should reflect the archaeological information; inconsistency therefore would reflect a problem either with the dating or with the archaeological interpretation.

Step 3: Obtain radiocarbon and other scientific data. Pollen data were previously acquired from Hrísbrú (Erlendsson et al., 2014; Zori et al., 2013) and Mosfell (Erlendsson, 2012). Rapid scanning

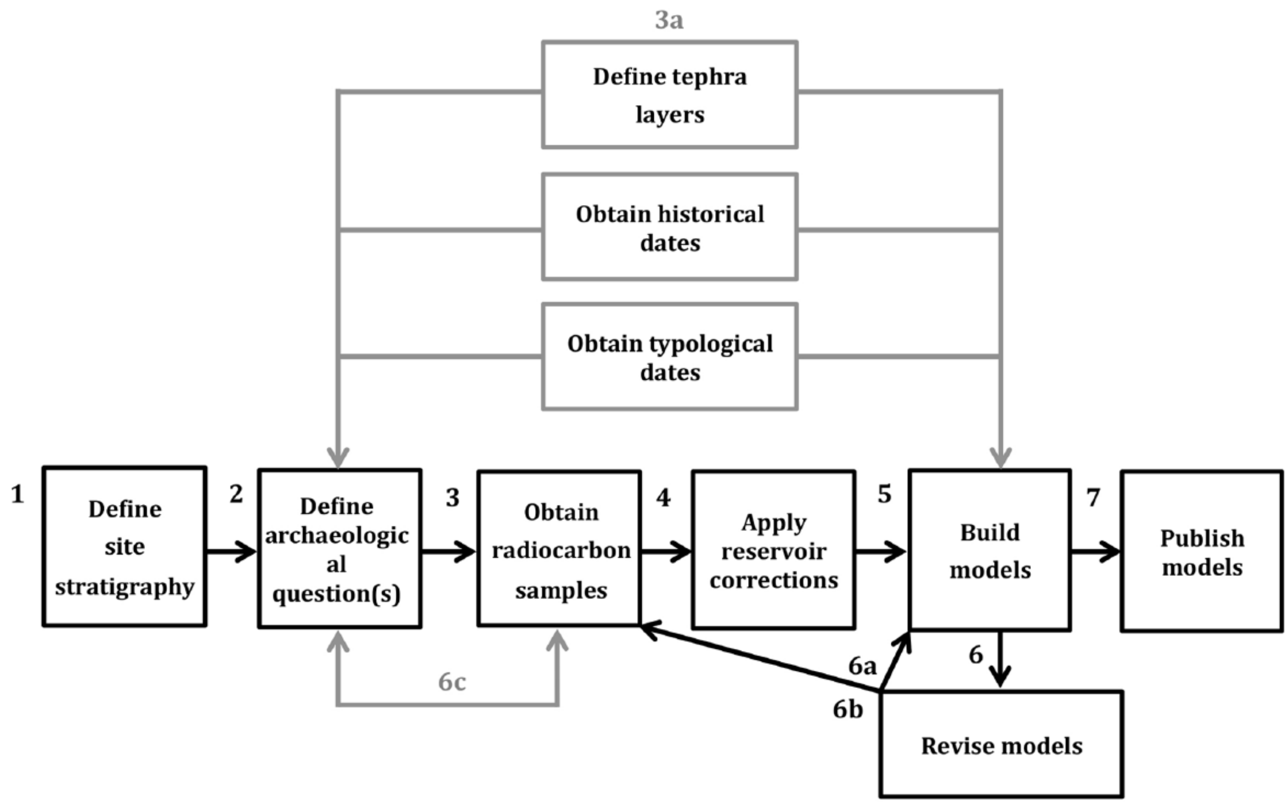

Figure 5. Routine Bayesian application for chronological models based on Bayliss and Bronk Ramsey (2004: Figure 2.2). The black boxes and arrows are essential; the grey boxes and arrows are optional, but improve the robustness of the models.

for cereal-type pollen was undertaken for the purpose of this paper, and the data were employed in the model (Tables 3 and 4). Radiocarbon samples had been previously taken and dates had been obtained (Tables 1 and 2). The stratigraphic relationships between the radiocarbon dates are schematically illustrated in Figure 4 and are discussed in section 'Radiocarbon dating'.

Step 4: Apply reservoir corrections. It is well known that human and animal diets rich in marine organisms, such as marine fish, mammals and shellfish, can affect radiocarbon determinations and can cause bones to appear up to several hundred years older than their true age (e.g. Arneborg et al., 1999; Barrett et al., 2000). Affected radiocarbon samples, therefore, have to be corrected accordingly. Following the approach taken in Batt et al. (2015), the percentage of non-terrestrial carbon within the bone samples was calculated using the linear regression calculation $y = 270.67 + 13.333x$ (Ascough et al., 2012), where x is $\delta^{13}C$ value and y is the percentage of marine contribution to diet, which assumes the $\delta^{13}C$ end-members of −20.3‰ and −12.8‰ for 100% terrestrial and marine diets, respectively. These values are based on measurements of terrestrial and marine protein sources from sites in northern Iceland, with adjustments for trophic level shift (Ascough et al., 2012). These values are approximately similar to those used by Sveinbjörnsdóttir et al. (2010) based on Arneborg et al. (1999) for material from Greenland (i.e. values of −21‰ and −12.5‰, respectively). The data from northern Iceland were selected as they provide the closest geographical match to the archaeological material under consideration.

When calibrating radiocarbon ages where there has been a significant contribution from marine carbon, it is also necessary to consider both the global average reservoir effect and site-specific deviations from it (delta_R). This study used a delta_R value of 111 ± 10 ^{14}C years obtained from multiple paired measurements on terrestrial mammals and marine molluscs from Norse period archaeological deposits in northern Iceland (Ascough et al., 2007). This value is slightly different from that adopted by Sveinbjörnsdóttir et al. (2010) who used a delta_R of 50 ^{14}C years. Both the selection of end-members for marine and terrestrial diets and the value of delta_R are estimates made from the best available data, but further site-specific characterisation of these factors would be helpful (Batt et al., 2015). A further area of uncertainty in radiocarbon dating concerns the effects of freshwater reservoirs on bone collagen (Ascough et al., 2011, 2012). Sayle et al. (2014, 2016) have identified this effect in samples from north-eastern Iceland based on analysis of $\delta^{34}S$ and have reported freshwater offsets of between ca. 40 and 500 ^{14}C years for individuals with 5–6% (±4%) dietary protein from freshwater sources (Sayle et al., 2016). Although it is not possible to correct for this effect at Hrísbrú with the currently available data, it is important to recognise the potential complication.

Step 5: Build models. Radiocarbon ages were calibrated using OxCal Version 4.3 (Bronk Ramsey, 2017), which incorporates the Intcal13 and Marine13 curves (Reimer et al., 2013). Uncertainties are presented approximately equivalent to a 95.4% (2σ) confidence level (Bronk Ramsey, 2012). Bayesian models in general relied on agreement index values ('A' values) that quantify the degree to which the data support the proposed model and they were calculated both for individual dates and for the model itself (Bronk Ramsey, 2000). The critical value for both agreement indices was set to 60% and samples that are below this value had to be manually removed until the model passes >60%; however, this value has been criticised as being arbitrary (Bronk Ramsey, 2008). In 2009, Bronk Ramsey introduced a 'Bayesian outlier analysis approach', in which the model identifies and downweights dates that are inconsistent with the surrounding data. Here, the distribution of outliers must be described and the prior probability of each sample within this Outlier Model assessed. The data are described by the General t-type model [Outlier_Model('General',T(5),U(0,4),'t'] and are often assigned a 5% prior probability of being an outlier using the command 'Outlier ["General," 0.05]' (Bronk Ramsey, 2009b). This General outlier model uses the symmetrical Student's *t* distribution 'T(5)' centred on each calibrated date. A shift can occur in either direction to younger or older calendar years allowing 5 degrees of freedom; the scale of the offset ranges anywhere between 10^0 and 10^4 years; the type 't' refers to samples that might not relate to the timing of the event being dated (Bronk Ramsey, 2009b). The type in particular refers to data that are assumed to date the event of interest, although a few may be outlying because of, for example, stratigraphic disturbances.

The following commands are used in the models: 'R_Dates' for radiocarbon dates in uncalibrated form [R_Date, year, error]; 'After' for a *terminus post quem*, such as the LTL [After, year, error]; 'Before' for a *terminus ante quem*, such as the K~1500 tephra [Before, year, error]; as well as 'Date' for uniform distribution of calendar dates, such as beads [Date (U(AD(year), AD(year)))] (Bronk Ramsey, 2009a). A collection of these dates are modelled in 'Phases' which describes an unordered group that spans a period of time, while 'Sequences' are used to describe ordered events and groups of events. 'Boundaries' apply to the start and end of phases of activity or deposition (Bronk Ramsey, 2009a). Age–depth models ('Poisson models') are used for sedimentary sequences in general; this type of analysis allows for variability in deposition processes of sediments giving approximate proportionality to 'z', which refers to the depth of samples (Bronk Ramsey, 2008). The command 'P_Sequence("P," 1,3,U(-2,2))' is used in this study which provides a robust model to account for random sediment depositions (Bronk Ramsey and Lee, 2013). Tephra layers in Poisson models are included as 'C_Date' [C_Date, AD(year), error].

Step 6: Revise models. Bayesian models typically have to be generated a number of times before producing a version suitable for publication.

Step 7: Publish models. Recent papers by Millard (2014) and Wood (2015) stress the need to properly publish radiocarbon data, and any chronological models used need to be explicitly defined (Supplementary Information, available online). Specifically, they advocate inclusion of the following information (Tables 1 and 2):

- Laboratory code;
- Uncalibrated radiocarbon age (BP);
- Calibrated date range, calibration curve and calibration program; any non-standard settings (delta_R);
- Material type, including identification of genus or species if possible;
- Context and justification of the sample's relationship with the event being dated;
- Quality assurance data: %C in charcoal, C:N ratio and carbon and nitrogen stable isotopes in bone collagen.

Results

The model consists of four separate 'Sequences' that are cross-linked in the model through the Boundary 'Start anthropogenic signal' and the LTL (Figure 6). One 'Sequence' represents the HRI1 sediment profile, another the MOS sediment profile, one the Viking age hall and one the church and cemetery (Supplementary Information, available online).

Poisson model (HRI1)

The 'Bottom boundary' for the HRI1 sediment profile refers to the bottom of the profile at 39 cm; the 'Top boundary' is at 15 cm (Table 3). The LTL is between 34.5 and 35 cm, the R-1226 tephra between 25 and 25.5 cm and the K~1500 tephra between 16 and 17 cm. The bottom depth of tephra layers is chosen in sedimentary models. Anthropogenic signals (dung-loving fungi, microscopic charcoal and cereal-type pollen) are reported from 1 cm below (at 36 cm) to 1 cm above the LTL of AD 877 ± 1 (at 33.5 cm) (HRI1-II). The events of interest are labelled as 'Start anthropogenic signal', which is estimated to AD 830–881, and the 'Transition HRI1-II and III' is estimated to AD 875–987. Arable activities are reduced up to around 29.5 cm ('Transition HRI1-III and IV') and cultivation increases again between 29.5 and 26.5 cm (HRI1-IV) ('End arable signal'), from where signals for cultivation drastically decline between 26.5 and 17 cm (HRI1-V). The modelled age of 'End of major arable signal' is AD 1144–1231.

Poisson model (MOS)

The same approach is applied for the MOS sediment profile; the 'Bottom' is at 55 cm, the 'Top' at 19 cm, the LTL at 51.5–52.5 cm, the R-1226 tephra at 32 cm and the K~1500 tephra at 20–22 cm (Table 4). The 'Start anthropogenic signal' is above the LTL at 50 cm; this event is estimated to AD 873–963; the 'End anthropogenic signal' is at 37 cm and estimated to AD 1050–1224. Cultivation stops just below the R-1226 tephra.

General Outlier Model (Hall TUN)

The LTL provides a *terminus post quem* for the hall 'Sequence'. The 10th-century tephra (K~920 or Eldgjá tephra) could not be included in the model because of its poor preservation in the turf. The 'Sequence' consists of three 'Phases': the first represents the lower floor layers without available samples ('The start of settlement'), the second the upper floor layers including three *H. vulgare* grains and two typological data and the third the subsequent midden deposits including five *H. vulgare* grains (Figure 6). Bead type Bh (AD 960–1000) is incorporated in the model as 'Date U(AD(960), AD(1000))' and bead type Ea (AD 950–1000) as 'Date U(AD(950), AD(1000))'. The LTL and all 'Phases' are separated by 'Boundaries'. The specific events of interest for this model are the 'Start of anthropogenic activity' below (AD 830–881) and above (AD 874–951) the LTL; the latter is labelled 'Early use of site'. The Boundary 'Transition floor to midden' (AD 959–984) suggests that there is no evidence of a hiatus in occupation, as well as the 'End of use of the midden' is estimated to AD 971–1026.

General Outlier Model (church and cemetery CK)

The 'Sequence' consists of three periods of activity that are modelled in 'Phases' pre-church, church and cemetery, and post-church. The chronological model is based on 14 radiocarbon dates from hay, charcoal and bone collagen, two tephra layers (LTL and K~1500) and two textual records that are estimates for the construction and abandonment of the church. The 10th-century tephra is only found in the turf of the church, and the lack of stratigraphic connection to the burials does not allow the inclusion of this tephra in the model. Eleven radiocarbon dates of bone collagen appear to show reservoir effects because of diet based on the values of $\delta^{13}C$, and appropriate corrections were applied, as discussed in section 'Bayesian statistical analysis: A step-by-step application'. There are two burials that were re-deposited along the chancel of the church (CK 4 and 46) of which burial 4 included a whalebone amulet. This artefact may be an indicator of pre-Christian burial before the bones were moved to the Hrísbrú church. Burial 2 yielded two radiocarbon samples; the combination of both samples failed the chi-squared test (6.6). Sample AA-93254 shows a problem of the C:N ratio (3.7) and is, therefore, not included in the model. This is discussed in section 'Do the scientific dates support the typological and textual dates?'

The 'Early use of the site' is modelled to AD 874–963 suggesting activity during the time when the hall was in use. The

Figure 6. The output plots from the Bayesian model in stratigraphic order incorporating the TUN and CK sites and the HRI1 and MOS sediment cores. Boundaries are in grey; tephra dates in purple; radiocarbon dates of barley grains in dark brown, of short-lived wood in light green and of long-lived wood in black; radiocarbon dates of human bone with terrestrial diet in dark green; radiocarbon dates of human bone that are corrected for diet with marine component in blue; historical dates in pink; typological dates in orange; and the 'Boundary Start anthropogenic signal' in red.

Table 3. Summary data from the Poisson process ('P_Sequence') age–depth model, HRI1 sediment core. Modelled ages of environmental events ('Date' and 'Boundaries') as well as tephra isochrons ('C_Date') in OxCal (Bronk Ramsey, 2017). All data are given as both the 68.2% and 95.4% highest probability density ranges.

OxCal command	Archaeological feature/deposit	Depth (cm)	^{14}C age (BP) ± 1σ	Modelled 68.2% probability range (cal. AD)		Modelled 95.4% probability range (cal. AD)	
				From	To	From	To
Boundary	Bottom	39	–	715	797	686	871
Date	Start anthropogenic signal (HRI1-I and II)	36	–	839	876	830	881
C_Date	LTL	35–34.5	877 ± 1	876	878	875	879
Date	Transition anthropogenic signal HRI1-II and III	33.5	–	906	952	875	987
Date	Transition anthropogenic signal HRI1-III and IV	29.5	–	1050	1111	988	1174
Date	End arable signal HRI1-IV	26.5	–	1176	1211	1144	1231
C_Date	R-1226	25.5–25	1226 ± 0.5	1225	1227	1225	1227
C_Date	K~1500 (also End HRI1-V)	17–16	1500 ± 0.5	1499	1501	1499	1501
Boundary	Top	16	–	1514	1545	1497	1570

Table 4. Summary data from the Poisson process ('P_Sequence') age–depth model, MOS sediment core. Modelled ages of environmental events ('Date' and 'Boundaries') as well as tephra isochrons ('C_Date') in OxCal (Bronk Ramsey, 2017). All data are given as both the 68.2% and 95.4% highest probability density ranges.

OxCal command	Archaeological feature/deposit	Depth (cm)	^{14}C age (BP) ± 1σ	Modelled 68.2% probability range (cal. AD)		Modelled 95.4% probability range (cal. AD)	
				From	To	From	To
Boundary	Bottom of sediment core	55	–	803	875	731	881
C_Date	LTL	51.5	877 ± 1	876	878	875	879
Date	Start anthropogenic signal (MOS-II)	50	–	876	910	873	963
Date	End anthropogenic signal (Transition MOS-II and III)	37	–	1103	1185	1050	1225
C_Date	R-1226	32	1226 ± 0.5	1225	1227	1225	1227
Date (not included in model)	End MOS-III	22	–	1497	1502	1497	1513
C_Date	K~1500	20	1500 ± 0.5	1499	1501	1499	1501
Boundary	Top of sediment core	19	–	1497	1541	1497	1598

'Start Christian activity' including the construction of church and burials is estimated to AD 901–987, while the 'Construction date of the church' is set as 'Before' AD 1015; the 'End of Christian activity' is estimated to AD 962–1102. The modelled age for the pine wood sample from the nave of the church (Beta-175676) is AD 917–1009 (unmodelled date: AD 770–980). A possible explanation for the pine wood material – giving a date that is too old for its archaeological context – is that the wood has been recycled drift wood since pine trees did not grow in Iceland and may have been collected from the coast.

The start of occupation of the hall is based on the LTL and 'Start anthropogenic signal' Boundary, since no radiocarbon dates were obtained from early occupational layers of the hall, such as from the lower floor layers. The LTL and 'Start anthropogenic signal' link all four sequences. The 'Start anthropogenic signal' is estimated to AD 830–881 (Figure 6). The hall was built immediately after the deposition of the LTL (AD 874–951) and the church site was occupied around the same time at AD 874–963. The major farming activity at HRI1 ceases around AD 875–987 (End of HRI1-II) and increases again around AD 988–1174 (Start of HRI1-IV). Farming activity at MOS starts around AD 873–963 (Start of MOS-II). The model supports the contention that anthropogenic traces are continuous. The relatively high counts of charcoal and cereal-type pollen at the end of the 9th (HRI1) as well as between the 9th and 10th centuries (MOS) probably indicate field fertilisation for cereal cultivation. At HRI1, another period of high charcoal and cereal-type pollen counts arises in the 11th and 12th centuries.

Discussion

The archaeological, paleoenvironmental and documentary data from Hrísbrú were used to test the following hypotheses.

When did anthropogenic activity start at Hrísbrú?

Anthropogenic activity can be tested with both archaeology and paleoecology. While the archaeology of the site relies on a fixed point (e.g. the earliest use of the hall) and gives a relatively short period, palynology offers the means to investigate a long, continuous environmental trajectory, which is sensitive to alterations from a wide(r) area. The paleoenvironmental rationale for a pre-LTL occupation at Hrísbrú (Figure 3a) includes a series of potential cultural indicators. The microscopic charcoal demonstrates use of fire, for example, in clearing the land, where no record of naturally occurring fires exists, and there is no evidence for woodland fire prior to the LTL at Mosfell (Figure 3b), or the nearby Helgadalur (Riddell, 2014). The appearance of coprophilous fungi below the LTL at Hrísbrú includes three different taxa of dung-loving fungi, *Sordaria*-type, *Sporormiella*-type and *Podospora*-type, all considered to be reliant on herbivore dung for germination. No record of pre-settlement herbivorous land mammals in Iceland exists. Finally, the rapid scanning process uncovered cereal-type pollen 1 cm below the LTL, signifying arable activity prior to the deposition of the tephra. The cultural indicators found below the LTL are not isolated features; they represent the onset of agricultural activity at the site, including cereal (most likely barley) cultivation, which continues over the duration of LPAZ HRI1-II.

The LTL is embedded in the turf from which the oldest known structure at the site, the hall, is built. This of course signifies that the walls of the hall are younger than the eruption. The people who cultivated the fields at Hrísbrú before the LTL deposition event therefore must have lived in another earlier and not yet excavated house. Based on the currently available data, we conclude that anthropogenic activity began at the Hrísbrú site at some point between AD ca. 830 and the time of the LTL of AD 877 ± 1.

What is the occupation history of TUN and CK?

The Bayesian models are consistent with the stratigraphic observations that concluded that the hall and the church were in use contemporaneously (Figure 6; Byock and Zori, 2014). The dating also supports the hypothesis (Byock and Zori, 2014) that the church continued to be used after the abandonment of the hall. Although the abandonment of the hall at Hrísbrú seems to coincide with cessation of cultivation there (Transition between HRI1-II and III), subsequent midden deposits show that activity continues at the site. The cultivation signal at Hrísbrú reappears in the 11th and early 12th centuries (HRI1-IV). The beginning of cultivation at modern Mosfell at a similar time (MOS-II) would seem to add further evidence that agricultural activity expanded or shifted from Hrísbrú to Mosfell and that this may be linked to the abandonment of the hall. A change certainly takes place, but the data do not allow definite conclusions about the nature or significance of this change in terms of occupation history. It could be that the chieftain's residence was moved from Hrísbrú to Mosfell (LPAZs HRI1-III and MOS-II) with associated arable activity or that a new hall in an unknown location was built at Hrísbrú and cultivation expanded or moved over to modern Mosfell – perhaps in an attempt to invest more in cereal cultivation at this time. In any case, and importantly, the two pollen datasets combined suggest continuous habitation and cereal cultivation within the Mosfell landholding from the onset of settlement until at least the end of the 12th century (HRI1-II and III, MOS-III), around the time when the Mosfell farm and church were moved from Hrísbrú to their current location.

Do the scientific dates support the typological and textual dates?

TUN. It is suggested that the hall was abandoned in the mid- to late 10th century (AD 959–984), which is based on *H. vulgare* seeds that in general yield reliable dates. The artefact assemblage (imported beads) suggests an occupation of the house between cal. AD 950 and 1000 (Figure 6). In particular, one radiocarbon date (UCIAMS-64172) and one bead of type E030 are from the same context [floor layer 11]. The beads are estimated to AD 950–974 and AD 960–977, respectively, and show consistency with the radiocarbon dates. Tephrochronology would be consistent with the history of the site; however, it only tells us that the house was built after the LTL, repaired in the 930s and had been abandoned for some time before the K~1500 tephra fell.

CK. The relocated and potential Viking Age burials at Hrísbrú are constrained to around AD 874–963, the Christian burials to AD 901–987 and the construction date of the church to AD 917–1009. The unmodelled date of the wood sample of the church yields an earlier date (AD 770–980), which is not surprising considering a potentially large biological age of the pine wood sample.

There are two re-deposited secondary burials (CK 4 and 46) along the nave of the church, which Byock and Zori (2014) proposed as predating the construction of the church. This hypothesis has been tested with multiple radiocarbon samples from burials 2 and 4. After correcting for reservoir offsets, the two unmodelled samples from burial 4 yielded similar ages of AD 881–1161 and AD 889–1160. The calibrated date ranges for burial 2, however, show a small overlap of AD 702–985 and AD 888–1173 (Table 2).

In general, the purity of extracted collagen from bone samples, and thus the reliability of its radiocarbon date, is evaluated using three criteria: the C:N ratio, the collagen yield and the wt% concentrations of C and N (see section 'Bayesian statistical analysis: a step-by-step application'; Ambrose, 1990; Ambrose and Norr, 1992). The most widely used criterion for identifying contamination and/or digenetic alteration is the C:N ratio (Table 2). Modern collagen has an atomic ratio of 3.21. The values within an empirically derived range of 2.8–3.3 are robust cut-offs for archaeological studies (Hedges, 2000). Values above 3.4 may indicate contamination with carbon-rich substances such as humic acid or glues such as PVA (Kennedy, 1988). Modern bone has around 25% weight collagen, and archaeological bones that have >1% collagen are generally considered for dating (Van Klinken, 1999). For the third criterion, modern collagen is around 43% C and 16% N by weight. For those samples where data were reported by the laboratory, the criteria were satisfied. Therefore, sample AA-93254 (burial 2) is suspect based on the quality of collagen using the values stated above for the stable isotopes. The sample yielded an atomic ratio of 3.7, which is well outside the normally accepted range and is therefore omitted from analysis.

Conclusion

Reassessing multidisciplinary datasets using Bayesian statistical modelling offers a way to test previous dating assumptions and provide further nuanced understanding of specific archaeological events. In general, the work presented here confirms earlier interpretations of the chronology of the Hrísbrú site (Byock and Zori, 2014). Importantly, though, this new work has provided increased confidence in the accuracy of the chronology. Furthermore, it has allowed a sharpening of estimates of particular events. First, anthropogenic footprint palynomorph taxa extracted from sediment profiles within the original landholding demonstrate that people had arrived in Iceland before the deposition of the LTL of AD 877 ± 1. As a result, it seems more likely to us now that people were farming on the slopes of the Mosfell Mountain before the LTL tephra fell. Second, the Bayesian models consistently yielded 10th-century dates for many burials surrounding the Hrísbrú church. We, therefore, find it more likely than previously that the Hrísbrú church may predate the conventionally accepted AD 999/1000 date for the conversion of Iceland (Byock and Zori, 2014).

The environmental, textual and typological datasets fit well with the archaeological evidence based on stratigraphy, multiple tephra layers and radiocarbon dates. On the other hand, radiocarbon dates of bone collagen are less valuable if quality assurance data, such as the C:N ratio, are unavailable. The approaches taken here demonstrate the utility of interpreting high-precision multidisciplinary datasets within Bayesian frameworks. These frameworks provide a way to cross-check datasets, yield more robust dating and increase dating reliability.

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