Archaeological Applications of Radiocarbon Chronologies and Statistical Models:

Dating the Viking Age Settlement of Iceland (Landnám)

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Abstract

This thesis aims to refine the accuracy and precision of radiocarbon (^{14}C) datasets in order to better understand the timing of archaeological and palaeoenvironmental events relating to important issues like mobility, colonisation, human impacts and human responses to climate change. This is vital, because radiocarbon is one of the most important dating methods in prehistoric archaeology and Quaternary science and some ^{14}C determinations can be anomalously older or younger than their stratigraphy suggests. Various 'chronometric hygiene' protocols have been developed aiming at enhancing the quality of ^{14}C datasets by removing all potentially problematic ^{14}C samples, but there is no generally accepted routine approach to chronology building utilising large ^{14}C datasets. Existing practices that eliminate up to 95% of ^{14}C dates can mean that so few dates remain in some locations that a robust chronology cannot be established. Despite their foundation in sound theory, without independent tests we cannot know if established protocols are apt, too strict or too lax. This research tackles this problem utilising Bayesian statistical modelling and tephrochronology.

The Viking age settlement of Iceland (Old Norse: Landnám) is an ideal laboratory to explore the potentials and the limits of chronometric hygiene and Bayesian statistical modelling because of a remarkable conjuncture of complementary dating methods of the archaeology and palaeoenvironment of first settlement (^{14}C dates, ice core-dated tephrochronology, artefact typology, medieval literary texts and palaeoecology). The timing of Landnám is of major international significance because it represents a key stage in the greater Norse colonisation of the North Atlantic islands that led to the first European contact with North America. In recent years intensive archaeological research on the Viking age has produced significant new dating evidence and offers exciting opportunities to assess colonisation as a process. This thesis presents a first systematic and holistic cross-disciplinary regional study that critically synthesizes the spatio-temporal dynamics of settlement patterns in Viking age Iceland. The countrywide distribution of 19 tephra layers, 513 stratigraphically related ^{14}C dates and diagnostic artefacts at 550 archaeological sites (300 settlements, 140 burial sites and 110 stray finds) are reassessed.

The first research objective of this thesis *establishes a high-resolution chronology of the Viking age settlement of Iceland* that is primarily based on tephra-dated settlements and burials (n = 261). While 85 sites can only be assigned general Viking age dates, less than 1% of the remaining 185 sites are from the pre-Landnám (pre AD 877) period, 48% from the

Landnám (AD 877-938/939) and 51% from the post-Landnám (AD 938/939-1104) period. The combination of 335 reliable ^{14}C samples yielded *posterior* probabilities of *cal AD 863-881* (68%) and *cal AD 751-893* (95%) for the overall onset of colonisation. Significantly, seasonal anthropogenic activities are dated before AD 877 in the southwest, while large-scale settlement (Landnám) from the coastal to inland zones happened after that date. The data support the hypothesis that Landnám was largely completed in twenty years after the deposition of the Landnám tephra layer of AD 877 ± 1.

The second objective *establishes a new chronometric evaluation protocol that is based on Bayesian statistical modelling* and uses robust constrains provided by medieval literary texts and ice core-dated tephra layers at Icelandic archaeological sites. This protocol promotes the most parsimonious exclusion of data – bulk sediments and samples where sufficient metadata is not published (e.g. material type, isotopes), while a variety of materials – short-lived taxa, wood charcoal with inbuilt ages as well as bone samples affected by marine reservoir offsets – allow robust chronologies to be established. In fact, the higher the density of ^{14}C dates across a 'Phase', the higher the precision of *posterior* probabilities. Significantly, samples usually held to be at risk of inbuilt ages could still provide robust results in a large number of cases if appropriate *prior* assumptions are used and if the distribution of ^{14}C dates through the 'Phase' is uniform. This has critical implications for ^{14}C chronologies in world archaeology, as it means that current approaches may well be hampering investigations unneccessarily, by applying an overly prescriptive, and potentially biased, approach. In fact, this opposes current hypotheses about the robustness of uniformly distributed ^{14}C datasets: Bayesian models are in fact sensitive to the distribution of dates and they will be biased if filtered datasets have certain dates removed, most significantly if the dates are from early contexts. They are also sensitive to any dominant inclusion of biased dates, such as high numbers of charcoal dates. Although short-lived taxa are always more accurate and precise than samples with inbuilt-age, these data can have limited use if we do not assess their stratigraphic relationships, as samples may not directly relate to the event in question.

The thesis also introduces a new software program 'OxCal_parser' for rigorous data entry when dealing with large datasets in OxCal. The new analytical and methodological approaches developed and tested in Iceland are then effectively extended to the example of East Polynesia, which successfully demonstrates the potential of the approaches developed in other geographical settings, and their relevance in these contrasting locations. The project has resulted in a series of scientific publications, and has created a new common resource of Viking age archaeology in Iceland. This resource will be of significant help in spotting dating errors, simplifying the process of dating, and allowing for a new type of metadata analysis of

chronological data. This in turn will open up new avenues of research in interdisciplinary archaeological science and thus contribute to international debate on this core element of archaeological practice.

Ágrip

Markmið þessarar ritgerðar er að bæta nákvæmni og áreiðanleika greininga á söfnum geislakolsaldursgreininga til þess að skilja betur fornleifafræðileg og fornvistfræðileg álitamál á borð við fólksflutninga, landnám, gagnkvæm áhrif manns og umhverfis og viðbrögð samfélaga við loftslagsbreytingum. Þetta skiptir miklu máli því geislakolsgreining er ein mikilvægasta aldursgreiningaraðferðin í forsögulegri fornleifafræði og rannnsóknum á kvartertímabilinu, en hún er þeim annmörkum háð að einstakar geislakolsaldursgreiningar geta verið afbrigðilega gamlar eða ungar miðað við jarðlagasamhengið sem sýnin koma úr. Ýmsar forskriftir að 'tímatalslegu hreinlæti' ('chronometric hygiene') hafa verið þróaðar sem miða að því bæta heildarnákvæmni safna geislakolsaldursgreininga með því að fjarlægja öll mögulega ónákvæm geislakolssýni, en þó er engin almennt viðurkennd aðferðafræði við að byggja tímatal á stórum söfnum geislakolsaldursgreininga. Nálganir þar sem uppundir 95% allra geislakolsaldursgreininga eru útilokaðar geta leitt til þess að svo fá sýni séu tekin gild á tilteknum stað að ekki sé hægt að leggja fram ábyggilegt tímatal. Þó að slíkar uppskriftir byggi á traustum kennilegum grunni, þá er ekki hægt að meta hvort þær séu hæfilegar, of strangar eða of vægar, nema að grundvalla það á prófum á óháðum gögnum. Þessi rannsókn miðar að því að leysa þetta vandmál með líkanagerð sem styðst við bayesíska tölfræði.

Landnám Íslands hentar sérlega vel til að rannsaka kosti og galla 'tímatalslegs hreinlætis' og bayesíska líkana, því tímasetning þess byggir á nokkrun aðferðum sem styðja hver aðra (geislakolsaldursgreiningar, gjóskulög, gerðfræði og ritaðar heimildir). Tímasetning landnáms á Íslandi er mikilvæg í alþjóðlegu samhengi því það var einn helsti liðurinn í landkönnun norrænna manna í Norður Atlantshafi sem leiddi til fyrstu tengsla Evrópumanna við Norður Ameríku. Umfangsmiklar fornleifarannsóknir á íslenskum víkingaaldarminjum hafa á undanförnum árum leitt af sér nýja þekkingu á tímasetningu landnámsins og lagt grundvöll að því að rannsaka landnámið sem ferli. Í þessari ritgerð er í fyrsta skipti lagt fram heildstætt þverfaglegt gagnasafn sem gerir kleift að rýna í tímasetningu og dreifingu 550 minjastaða frá víkingaöld á Íslandi (300 bólstaðir, 140 grafreitir og 110 staðir með lausafundum). Tímasetningarnar byggja á 19 gjóskulögum, 513 geislakolsaldursgreiningum úr mannvistarlögum sem hafa samhengi við gjóskulögin, og gripum sem hægt er að aldursgreina með gerðfræðilegum aðferðum.

Öðru af tveimur meginrannsóknarmarkmiðum ritgerðarinnar var náð með því *að leggja fram tímatal landnámsins sem hefur meiri upplausn en áður hefur þekkst*. Það byggir að stærstum hluta á bólstöðum og grafreitum sem eru tímasettir út frá gjóskulögum (n = 261). 85 staði er aðeins hægt að tímasetja almennt til víkingaaldar en færri en 1% af hinum 185 stöðunum eru eldri en landnámsgjóskan frá AD 877, 48% eru frá landnámsöld (AD 877-938/939) og 51% yngri (frá AD 938/939-1104). Samanlögð niðurstaða 335 áreiðanlegra geislakolsaldursgreininga gaf *eftirá* líkindin að landnám hefði heilt yfir hafist *cal AD 863-881* (68%) og *cal AD 751-893* (95%). Máli skiptir að mannvist sem er eldri en AD 877 virðist aðeins hafa verið árstíðabundin en samfelld byggð hófst eftir þann tíma. Gögnin styðja þá tilgátu að bygging landsins alls hafi tekið innan við 20 ár eftir að landnámsgjóskan féll árið 877 ± 1.

Hitt meginmarkmið ritgerðarinnar styðst við hið heildstæða safn tímasetninga frá Íslandi til *að þróa nýja forskrift um fráviksgreiningar sem byggir á 'tímatalslegu hreinlæti' og bayesískri tölfræðigreiningu á stóru safni geislakolsaldursgreininga*. Forskriftin miðar að því að útiloka eins lítið af nothæfum upplýsingum og mögulegt er. Það eru einkum stór jarðvegssýni og sýni sem hafa verið birt án nauðsynlegra lýsigagna (t.d. efnistegund, samsætur) sem óhjákvæmilegt er að útiloka, en margskonar önnur efni – skammlífar tegundir, viðarkol með uppsöfnuðum aldri jafnt og bein lífvera sem hafa tekið upp uppsafnað kolefni úr sjó – má nota til að byggja traust tímatal. Eftir því sem fleiri geislakolsaldursgreiningar eru innan sama tímabils ('Phase') þeim mun betri eru *eftirá* líkindin. Mikilvæg niðurstaða er að sýni með uppsöfnuðum aldri draga ekki úr nákvæmni útkomunnar úr líkaninu ef viðeigandi *fyrirfram* forsendur er teknar með í reikninginn og ef dreifing geislakolsaldursgreininganna yfir tímabilið ('Phase') er jöfn. Þessi niðurstaða er í andstöðu við ríkjandi tilgátur um ábyggileika jafndreifðra geislakolsaldursgreininga: bayesísk líkön eru í raun viðkvæm fyrir dreifingum tímasetninganna og gefa villandi niðurstöður ef síun gagnasafnanna leiðir til þess að tilteknar aldursgreiningar eru útilokaðar, einkum og sérílagi ef þær tímasetningar eru úr eldri samhengjum. Þó að sýni úr skammlífum tegundum gefi alltaf áreiðanlegri og nákvæmari niðurstöðu heldur en sýni með uppsöfnuðum aldri, þá koma þau að takmörkuðu gagni ef samhengi mannvistarlaganna sem þau koma úr er ekki tekið með í reikningin, því sýnin tengjast ekki alltaf beint þeim atburði sem verið er að reyna að tímasetja.

Í ritgerðinni er sýnt fram á að þessa aðferðafræðilegu nýjung má nýta með góðum árangri utan Íslands til að varpa ljósi á aðrar grundvallarspurningar í sögu mannsins. Sýnt er fram á alþjóðlegt vægi þessarar forskriftar með því að nýta hana til að endurmeta tímasetningu

landnáms á eyjum Austur Pólynesíu. Rannsóknin hefur leitt af sér nokkrar birtar vísindagreinar og búið til nýtt heildstætt gagnasafn um tímasetningu víkingaaldarminjastaða á Íslandi sem er aðgengilegt öllum. Það mun auðvelda samanburð og stytta leiðir í tímasetningum, gagnast til að finna villur og gera kleift að greina heildstæð tímatalsgögn á nýjan hátt. Með þessu opnast leiðir til rannsókna á sviði þverfræðilegra rannsókna í fornleifavísindum sem munu stuðla að alþjóðlegri umræðu um það lykilatriði í hinni fornleifafræðilegu aðferð sem tímasetningar eru.

Acknowledgements

Every study about Vikings
creates a new saga

When this PhD was written can be easily assessed, but *how* it was done has many variables. As a wise friend once said: "One day you can radiocarbon date your PhD".

The narrative started in Budapest, where I wrote my Master's thesis about steppe nomads. This developed into 'digital nomads' – travel while doing research – which my friends referred to as "like a Viking just without a ship". One day an incident happened with an Italian visiting researcher at the *Eötvös Lórand University*, whereby he accidentally slammed a wooden door against me. Because I showed no reaction he said: "I don't understand why you study the Avars, you are such a Viking – go study them". Because of my interests in volcanic islands, and my dream to experience a volcanic eruption, I decided to write my Ph.D. about the Viking colonisation of Iceland. While visiting Reykjavík I met one of the first local archaeologists, Mjöll Snæsdóttir, and after a couple of Víking pints she said: "You are definitely a lost Viking". My decision was made and another local archaeologist, Orri Vésteinsson, agreed to be my supervisor. The Ph.D. journey began and even though it started in Iceland, I was certainly a lost Viking and ventured off course, somehow ending upon the opposite side of the world because I misunderstood the title 'Vikings of the Sunrise', written by Te Rangi Hiroa (Sir Peter Henry Buck) in 1964, which referred to the colonisation of Polynesia. Although I did not entitle my Ph.D. 'Polynesians of the North', I found many inspirations in comparative approaches in island settings.

Whilst I gathered all this data about Viking farmsteads, I realised how beautifully connected the famous sagas (*Íslendingabók*: the book of Icelanders) are with volcanic eruptions. I wondered why anybody would settle on this island soon after an enormous volcanic eruption, spitting out so much ash and blanketing almost the entire island. I arrived in Iceland one year after another enormous eruption – Eyjafjallajökull eruption in 2010 – and yet the post-eruption landscape equal to 'Mordor' had recovered beyond recognition. This was the time when I run into my second supervisor, Andrew Dugmore, who absolutely fascinated me with

his sheer knowledge about Iceland, tephra and its impact on the environment – including surviving skills during fieldwork (e.g. how to make waterproof pants out of garbage bags).

Archaeology does not go without radiocarbon dating and there has been a long discussion about the settlement date of Iceland and other islands. Orri suggested trying Bayesian analysis of radiocarbon dates, but I had never studied anything related to it. During a cold and icy winter, knee surgery, spikes on my crutches (and understanding the meaning of Iceland) and because of the never-ending issues with the radiocarbon dates, which always referred back to the Pacific islands (where the term 'chronometric hygiene' was invented), I decided to find some answers in Oceania. It took a while to get there because, after contacting lots of island archaeologists and Quaternary scientists, I received so many welcoming ideas – where I should go, who to collaborate with, which methods to apply, which conferences to visit, etc. Overall this ended in: 1) visiting and presenting at more than 40 universities, 2) visiting fellowships at six universities on four continents, 3) joint research articles and in 4) joint conference sessions.

During this time I worked actively at the *Institute of Geography and the Lived Environment* at the *University of Edinburgh* (where I met my third supervisor – Anthony Newton), the *Quaternary Research Centre* at the *University of Washington* (thanks to Ben Fitzhugh for my visit), the *Department of Archaeology and Natural History* at the *Australian National University* (thanks to Simon Haberle for my visit, and where I met my forth supervisor – Rachel Wood), the *Waikato Radiocarbon Dating Laboratory* at the *University of Waikato*, (thanks to Fiona Petchey for my visit), the *Institute of History and Archaeology* at the *Tokyo Metropolitan University* (thanks to Akira Ono and Masami Izuho for my visit) and at the *Australian Research Council Centre of Excellence for Australian Biodiversity and Heritage* at the *University of Wollongong* (thanks to Alex MacKay for my visit).

There are so many great minds to thank for a number of reasons: Atholl Anderson (for encouraging me to study in Japan), Cathy Batt (for her invitation to Bradford and research collaboration), Stuart Bedford (for inviting me to Vanuatu), Cyprian Broodbank (for research collaboration), Haraldur Bernharðsson (for his enthusiasm to combine sagas and archaeology and for inviting me to give lectures for Miðaldastofa), Damitia Brian (for discussions about quality assurance in ^{14}C dating), Jesse Byock (for research collaboration), April Cots (for putting me on the right track in radiocarbon dating and Bayesian statistics), Enrico Crema (for inspiration in statistical modelling), Mike Dee (for providing the ´Charcoal Plus Outlier

model´), Thomas Dye (for inviting me to Hawai'i), Kristina Douglass (for excellence in joint conference sessions and encouragement), Bjarni Einarsson (for discussions about the Icelandic data), Egill Erlendsson (for introducing me to paleoecology), Scott Fitzpatrick (for inviting me to the Northwest Anthropological Conference), Warren Gumbly (for teaching me Pacific fieldwork skills), Lara Hogg (for organising a joint conference session), Zenobia Jacobs (for sponsoring my participation at ^{14}C dating workshops and for evoking my interest in Australian archaeology), Martin Langer (for leading me on the road of science), Samantha Leggett (for letting me work at the *University of Sydney* and inviting me to Cambridge), Thomas Leppard (for research collaboration), Davide Lowe (for inviting me to write my first article about tephras, which lead to a Ph.D. by publication), Karen Milek (for studying the transitional period between Viking age and medieval Iceland), Clive Oppenheimer (for interest in my research), Fiona Petchey (for teaching me skills in the ^{14}C lab), Daniel Óskarsson (for any help and 'survival' related to Iceland), Neil Price (for sponsoring my participation at the Pacific Archaeology Seminar), Mads Ravn (for inviting me to Aarhus and for having the same Atlantic-Pacific travel routes), Howell Roberts (for helping me measuring SeAR at Aðalstræti), Richard Roberts (for having an enriching time at *CABAH* and for evoking my interest in Australian archaeology), Magnús Sigurgeirsson (for assessing my Icelandic tephra layers collection), Matthew Spriggs (for being my unofficial supervisor, for good travel times and for inviting me to Vanuatu), Takehiko Suzuki (for teaching me skills in the tephra lab), Davide Zori (for research collaboration and fieldwork).

My sincere gratitude goes to Luca Foresta, who saved me from going mad with Bayesian modelling and writing 'OxCal_parser' for me, as well as to my four supervisors who all contributed to this Ph.D. through their excellent skillsets: Orri for encouraging me not to give up on the Icelandic language and data, and Rachel for her inevitable contributions to ^{14}C dating and Bayesian modelling. It was an absolute privilege wrapping up my thesis at the *University of Edinburgh*, thank you Andy and Anthony for your tireless enthusiasm, encouragement and brilliant ideas.

This journey would not have been possible without the financial support from the *Icelandic Research council* (Rannís), the *Watanabe Trust fund*, two *Erasmus Traineeships*, and several travel grants sponsored by the University of Iceland, *The Sudreys Fund* (sponsored by the Society for Medieval Archaeology), several *Dialogues with the past* workshops (sponsored by the University of Oslo), workshops sponsored by *The Australian Research Council Centre*

of Excellence for Biodiversity and Heritage (University of Wollongong), and the generous financial support from my grandma and my parents.

Special thanks to my amazing parents, Josef and Clementine, as well as to my amazing sisters, Genoveva and Anastasia, who have always been a backbone for me, no matter how far away I am. Last, I want to thank everybody who I have met during my travels, who have kept me going, have given me shelter – which was a constant problem – friendship and good company. The list is endless, thanks to: Adrian, Božena, Daniel, Em, Emily, Gergö, Hannah, Jessi, Judy, Kala, Maria, Matt, Nico, Paul, Roger, Ruth and Shane. Every journey has a reward – a perfect Viking 'date'. Adam I could never ask for a better end – and beginning of a new story!

Although writing this Ph.D. was truly a rollercoaster, I feel blessed to have had this amazing journey in my life (next time maybe with a ship) – and I also experienced the volcanic eruption of Mount Yasur, where I sat right on the crater rim.

Table of Contents

List of Papers

The thesis is based on four peer-reviewed journal articles (including a fifth article attached in Appendix IV). All published papers were reproduced with permission from the journals concerned. The articles and their Supplementary Materials will be referred to in the text as the following chapters:

Chapter 4.2 [Paper 1. Supplementary Materials are attached in Appendix III]

Schmid, M.M.E., Dugmore, A.J, Vésteinsson, O., Newton, A.J. 2017. Tephra Isochrons and Chronologies of Colonisation. *Quaternary Geochronology 40. Special Issue: Tephrochronology*, 56-66. (http://dx.doi.org/10.1016/j.quageo.2016.08.002).

Chapter 5.1 [Paper 2. The paper is attached in Appendix IV]

Batt, C., Schmid, M.M.E., Vésteinsson, O. 2015. Constructing Chronologies in Viking age Iceland: Increasing Dating Resolution using Bayesian Approaches. *Journal of Archaeological Science* 62, 161-174. (http://dx.doi.org/10.1016/j.jas.2015.07.002).

Chapter 5.2 [Paper 3. Supplementary Materials are attached in Appendix V]

Schmid, M.M.E., Zori, D., Erlendsson, E., Batt, C., Damiata, B.N., Byock, J. 2017. A Bayesian Approach for Linking Archaeological, Palaeoenvironmental and Documentary Datasets relating to the Settlement of Iceland (Landnám). *The Holocene* 28(1), 19-33. DOI: 10.1177/0959683617714597.

Chapter 6 [Paper 4. Supplementary Materials are attached in Appendix VI]

Schmid, M.M.E., Wood, R., Newton, A.J., Vésteinsson, O., Dugmore, A.J. (2018). Enhancing Radiocarbon Chronologies of Colonisation: Chronometric hygiene revisited. *Radiocarbon*, 1-19. DOI:10.1017/RDC.2018.129.

Chapter 7 [Paper 5. Supplementary Materials are attached in VII]

Schmid, M.M.E., Dugmore, A.J., Foresta, L., Newton, A., Vésteinsson, O., Wood, R. (2018). How ^{14}C dates on charcoal increase precision when dating colonisation: the examples of Iceland and Polynesia. *Quaternary Geochronology* 48, 64-71. (https://doi.org/10.1016/j.quageo.2018.07.015).

Other publications not included in the doctoral thesis:

Schmid, M.M.E., Dugmore, A.J., Newton, A.J. (*submitted*). From sites to regional synthesis: collective chronologies of late Viking and early Christian activities in Iceland. In A. Pedersen & S.M. Sindbæk (Eds.). *18th Viking Congress Proceedings*.

Schmid, M.M.E., Vésteinsson, O., Newton, A.J., Dugmore, A.J. (*submitted*). Spatial and temporal patterns of large island colonisation: the Viking age settlement of Iceland. In M.F. Napolitani, J.H. Stone, & R.J. DiNapoli (Eds.), *The Archaeology of Island Colonization*. University of Florida Press.

Schmid, M.M.E. (2015). Archaeological dating evidence in Viking age Iceland: A critical review. *Ólafia V – Rit Fornleifafræðingafélags Íslands*, 97-111.

Schmid, M.M.E. (2014). Radiocarbon Dates from Igaliku Interpreted within a Bayesian Framework. In O. Vésteinsson (Ed.), *Archaeological Investigations in Igaliku. Excavations in the Meadow* 2012-2013 (pp. 99-102). Excavation report. Fornleifastofnum Íslands, Reykavík FS517-12151.

Conference activities, workshops and invited presentations as a result of this Ph.D.

Organisation of International conference panels

- 2018: co-organising (with Dr. Fiona Petchey) '*Archaeology and radiocarbon dating in Oceania: Where are we now and where to from here*' at the New Zealand/Australia Archaeological Association. Auckland, NZ.
- 2017: co-organising (with Assoc. Prof. Kristina Douglass) '*The island anthropocene*' at the 82nd Society for American Archaeology Conference. Vancouver, BC, Canada.
- 2015: co-organising (with Dr. Lara Hogg) '*North Atlantic islands: Networks, settlement, and identity*' at the 21st European Association of Archaeologists. Glasgow, UK.
- 2013: '*A stitch in time: Combining analytical chronology in a Scandinavian context*' at the 13th Nordic Tag. Reykjavík, Iceland.

Discussant at International conferences

- 2017: '*The island anthropocene*' at the 82nd Society for American Archaeology Conference. Vancouver, BC, Canada.
- 2015: '*North Atlantic islands: Networks, settlement, and identity*' at the 21st European Association of Archaeologists. Glasgow, UK.

Published conference abstracts of International conferences

- 2017: '*The chronology of the Viking age settlement of Iceland'*. Invited poster presentation, 18th Viking Congress. Jylland, Denmark.
- 2017: '*Recreating the timing and patterns of first-peopling with the Bayesian approach'*. Paper presentation, 82nd Society for American Archaeology Conference. Vancouver, BC, Canada.
- 2016: '*Multidisciplinary examination of an Avar age population from the Middle Tisza region'*. Paper presentation (in collaboration with: T. Szeniczey et al.), International Union of Anthropological and Ethnological Sciences. Dubrovnik, Croatia.
- 2015: '*Colonising North Atlantic and Pacific islands: A comparable approach'*. Poster presentation, 8th International Lapita conference. Port Vila, Vanuatu.
- 2015: '*Colonisation models of Iceland: New archaeological and environmental data'*. Paper presentation, 80th Society for American Archaeology Conference. San Francisco, CA, USA.
- 2015: '*Landnám tephra and the settlement of Iceland: Preliminary results'*. Paper presentation, 68th Northwest Anthropological Conference. Eugene, OR, USA.

- 2014: '*Colonisation of Iceland: Fast or slow*?' Paper presentation, 79th Society for American Archaeology Conference. Austin, TX, USA.
- 2013: '*Constructing new chronologies in Viking age Iceland'*. Poster presentation, 20th European Association of Archaeologists Conference. Pilsen, Czech Republic.
- 2013: '*Making the most of scientific dates in Viking age Iceland'*. Paper presentation, North Atlantic Biocultural Organization Conference. Akureyri, Iceland.
- 2013: '*New dating perspectives on Viking age Iceland'*. Paper presentation, 13th Nordic Tag. Reykjavík, Iceland.

Invited presentations

- 2018: '*Dating Vikings across the North Atlantic: Ingolf of Smoky Bay, Erik the Red, and Leif the Lucky*'. Centre for Archaeological Science Seminar Series, School of Earth and Environmental Sciences. Wollongong, Australia.
- 2017: '*The Viking age settlement of Iceland'*. Medieval Archaeology Group Seminar Series, McDonald Institute. Cambridge, UK.
- 2017: '*Enhancing radiocarbon chronologies of colonisation'*. George Pitt-Rivers seminar Series, McDonald Institute. Cambridge, UK.
- 2016: '*The settlement of Iceland in light of new archaeological data'*. Fornleifastofnum Íslands, Reykjavík, Iceland.
- 2016: '*A periodization of Iceland's Landnám in light of new archaeological data'*. Miðaldastofa. Reykjavík, Iceland.
- 2016: '*Research and travel: A Ph.D. on four continents'*. Institute of Geography and the Lived Environment. Edinburgh, UK.
- 2016: '*Chronological observations of tephra deposits at archaeological sites in Iceland'*. Department of Geography, Tokyo Metropolitan University. Tokyo, Japan.
- 2016: '*Tephra isochrons and the colonisation of Iceland'*. Department of Archaeology, Tokyo Metropolitan University. Tokyo, Japan.
- 2015: '*The chronology of the Viking age settlement of Iceland: A comprehensive reassessment'*. Andfœtinga samband. Sydney, Australia.
- 2015: '*Dating Vikings: A step-by-step guide'*. Archaeological Seminar Series. Canberra, Australia.
- 2015: '*Current research regarding Viking age archaeology'*. The Anthropology Department Occasional Talk. Honolulu, HI, USA.
- 2015: '*Constructing chronologies of Viking age settlement sites in Iceland'*. Friday Afternoon Archaeological Lecture Series. Seattle, WA, USA.
- 2015: '*Did the colonisation of Iceland happen between 870 and 930?*' Lecture series: Landnám Íslands. Fyrirlestraröð Miðaldastofu 2014-2015. Reykjavík, Iceland.

- 2013: '*The third radiocarbon revolution: using Bayesian statistics in archaeology'*. Archaeological Research Seminar. Reykjavík, Iceland.

Sponsored workshops

- 2018. '*Chronometric hygiene – what is the point?*' Paper presentation. CABAH Masterclass. **'**AustArch' database: the way forward. Bowral, Australia.
- 2018: '*Down through the ages: Radiocarbon chronologies, statistical models and sampling bias in archaeological contexts*'. Paper presentation. University of Wollongong Node day, Bundanon, Australia.
- 2017: 3rd Pacific Archaeology Seminar, University of Uppsala.
- 2014: '*Methodological problems regarding interdisciplinary research in Iceland'*. Presentation at the Seminar: "Human and environment: From multidisciplinary to interdisciplinary research." Tromsø, Norway
- 2013: '*Agrarian tools in Viking age Iceland*'. Presentation at the Seminar: 'Dynamics of Agrarian Transformation – and Research'. Rome, Italy.
- 2013: '*Trade and exchange in Viking age archaeology'*. Presentation at the Seminar: 'Interdisciplinary junior researcher workshop in Viking studies'. Rønbjerg, Denmark.
- 2012: '*The settlement of Viking age Iceland'*. Presentation at the Seminar: 'Past mirrors: Interaction and Integration in the North Sea region in the Bronze and Viking ages'. Museum of Cultural History, University of Oslo, Norway.
- 2012: '*Burial customs and artefacts in Viking age Iceland'*. Presentation at the Seminar: 'Materialities of Time: Ritual, death and the practice of archaeology'. Århus, Denmark.
- 2011: '*Methods and Methodologies in Viking age Iceland'*. Presentation at the Nordic research school in Information Studies (Norsilis). Vilnius, Lithuania.

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- 2016: Interview on '*Settlement ash layer adjusted to the year 877*' for the Icelandic TV Visir http://www.visir.is/g/2016161208649/landnamsoskulagid-leidrett-til-arsins-877.

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Abbreviations

Aeolian	–	Windblown sediment deposits
AMS	–	Accelerator Mass Spectrometry
^{14}C	–	Radiocarbon
BP	–	Before Present (before 1950 AD)
B-M	–	Bone-Mixed diet (marine and/or freshwater)
B-T	–	Bone-Terrestrial
Ch-U	–	Charcoal-Unidentified
CRA	–	Conventional ^{14}C Age (uncalibrated)
ΔR	–	Delta-R value
$\delta^{13}C$	–	Stable isotope values of carbon
$\delta^{15}N$	–	Stable isotope values of nitrogen
$\delta^{34}S$	–	Stable isotope values of sulfur
E	–	East
Eldgjá	–	Fissure of the Katla eruption in AD 939
FRE	–	Freshwater Reservoir Effect
G	–	Grímsvötn (volcanic source)
G/S	–	Grains/Seeds
H	–	Hekla (volcanic source)
HPD	–	Highest Probability Distribution
In situ	–	A tephra layer or archaeological artefact that has not been moved from its original place of deposition
Isochron	–	Spatially extensive volcanic marker horizon
K	–	Katla (volcanic source)
Landnám	–	Old Norse for ‘land-taking’. The settlement of Iceland by the Norse around AD ~877. This term can also refer to other settlements by the Norse (e.g. Greenland)
LEK	–	Local ecological knowledge
Likelihood	–	Assumptions about the radiocarbon dataset (Bayesian statistics)
LSC	–	Liquid scintillation counting (standard radiometric dating)
LTL	–	Landnám Tephra Layer. This tephra is from an eruption at approximately the same time as the settlement of Iceland
MRE	–	Marine Reservoir Effect

N	–	North
NW	–	Northwest
Ö	–	Öræfajökull (volcanic source)
Posterior	–	Posterior assumptions about hypotheses (Bayesian statistics)
Prior	–	Prior assumptions about hypotheses (Bayesian statistics)
R	–	Reykjaneshryggur (volcanic source)
SeAR	–	Sediment accumulation rates
SPD	–	Summed Probability Distributions
SW	–	Southwest
TAQ(s)	–	Terminus ante quem/termini ante quos
Tephra	–	Greek: volcanic ash (after Þórarinsson 1944)
TPQ(s)	–	Terminus post quem/termini post quos
V	–	Veiðivötn (volcanic source)
V-Sv	–	Veiðivötn (volcanic source)
W-LL	–	Wood-Long-Lived
W-SL	–	Wood-Short-Lived
Yr(s)	–	Year(s)

1. Introduction

Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration: relative, apparent, and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year.

Sir Isaac Newton 1689

1.1 The importance of accurate and precise radiocarbon chronologies

This thesis tackles a globally significant issue in archaeology and palaeoecology that is subject to fierce and long-running debate – how best to synthesize large sets of radiocarbon (^{14}C) dates to determine the most accurate and precise age ranges for key events in history. Transformative events, where the timing is crucial to our understanding, include human migrations and the colonisation of new areas (e.g. Hunt and Lipo 2006, Braje et al. 2017; Walter et al. 2017). The colonisation of the last places on Earth, the remote islands in the North Atlantic and Pacific oceans, is globally significant as island communities have the potential to teach us many things about adaptation, sustainability, how societies are established and how they survive over multi-generational timescales in constrained circumstances with finite resources (McGovern et al. 2007; Cooper and Sheets 2012; Harrison and Mather 2014). Such concerns are timely, and we need to have precise regional-scale chronologies to understand as accurately as possible when people arrived and the timing of subsequent cultural, ecological, and demographic changes.

This is important, because chronological uncertainty can lead to two unfortunate outcomes (Baillie 1991). First, a potential trigger of change, for instance an explosive volcanic eruption, may be precisely dated (e.g. to the year), but poorly-dated events within the same general time period, such as archaeological and ecological changes, are in danger of being erroneously attributed to this potential trigger. Second, events that are actually causally-related, they occur simultaneously or in a sequence, may not be seen to be linked because the necessary chronological precision and accuracy is lacking.

Chronological accuracy and precision typically rely on multiple ^{14}C dates. Radiocarbon dating is arguably the most important dating method in archaeology allowing us to use

organic material to establish chronologies for the last 55,000-60,000 years. Since its invention the method has almost changed beyond recognition with key developments often described as revolutions (Renfrew 1973; Bayliss 2009; Wood 2015). The latest revolution is the statistical analysis of multiple ^{14}C dates and other data (e.g. stratigraphy, tephra layers, incremental dating methods, typologically diagnostic artefacts, documentary and palaeoecological datasets) allowing us to test specific hypotheses about the past (Buck et al. 1996; Bayliss et al. 2007).

Bayesian statistics derive *posterior* probabilities for archaeological and palaeoenvironmental events by modifying a particular ^{14}C dataset with *prior* assumptions (e.g. the stratigraphic relationship or distribution of dates) (e.g. Bayliss et al. 2007). Such an analysis allows the maximum information to be generated from limited archaeological and palaeoecological resources. Nevertheless, the use of different *prior* assumptions in statistical modelling has been questioned (Steiner and Rom 2000) and debates continue if anomalously younger and older dates – the outliers – should be excluded in chronological models (Bronk Ramsey 2009a). Millard (2014) and Wood (2015) argue that one of the most pressing problems in ^{14}C dating is the lack of appropriate publication of individual ^{14}C determinations for quality assurance – for instance information about the material of samples, their stable isotope values, their contextual information and their pre-treatment methods.

Quality assurance of ^{14}C dates has been discussed since the 1970s (Waterbolk 1971). Protocols have been developed to eliminate dates that are most likely problematic, a process that has been described as 'chronometric hygiene' (after Spriggs 1989). While a number of different protocols have been applied to island contexts in the Pacific and Caribbean (e.g. Spriggs and Anderson 1993; Fitzpatrick 2006; Wilmshurst et al. 2011) a standardized protocol has not materialised due to the lack of independent dating. A common strategy of these protocols is to reject a large number of ^{14}C samples with the primary aim to remove dates that can be misleading, such as those of bone samples affected by reservoir effects and wood charcoal with inbuilt ages (e.g. Spriggs and Anderson 1993; Pettit 2003; Rieth et al. 2011). More precisely, wood charcoal may be influenced by 'inbuilt age' – if it originates from long-lived species, such as the heartwood of trees (Allen and Wallace 2007), or by 'storage age' – if the species selected are resistant to weathering and decay or if stored wood is burned (Schiffer 1987). However, wood charcoal can also derive from roundwood of small diameter and short lifespan or outer tree rings without large inbuilt ages. Significantly, more than 50% of ^{14}C dates (> 41,000 samples) from key databases around the world are of wood

charcoal representing >US$25 million of laboratory analysis (Chapter 7). As charcoal was most likely produced by initial settlement activities (e.g. woodland clearance, early cooking pits) chronometric hygiene protocols may therefore remove dates from first anthropogenic activities and other key contexts. Discarding many classes of ^{14}C dates drastically limits the number of places where chronologies can be established, including islands in Oceania with small datasets (e.g. Wilmshurst et al. 2011).

While dating island colonisation presents great chronological challenges, it may also provide potential solutions to a range of questions. Previously uninhabited and remote islands provide archaeological and palaeoenvironmental clarity, as they are isolated; they are naturally defined territories and their ecosystems are pristine (Streeter et al. 2015). The Viking age (AD ~800-1100) settlement of Iceland, the Landnám (Old Norse: 'land-taking'), represents a key stage in the greater Norse colonisation of the offshore islands across the North Atlantic and further west to Newfoundland (Fig. 1). Landfall in North America marked the first time that people encircled the Northern hemisphere (Fitzhugh and Ward 2000).

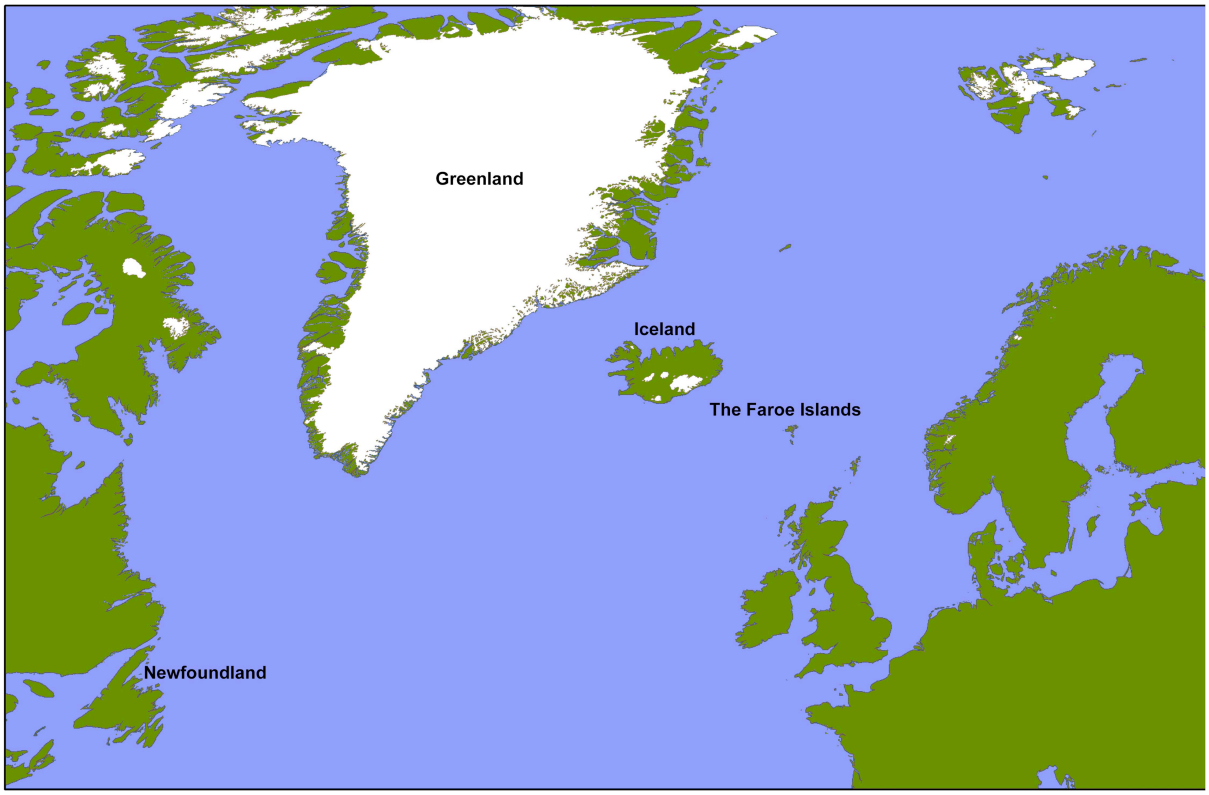

Fig. 1-1. The Norse Landnám across the North Atlantic: the Faroe Islands, Iceland, Greenland and Newfoundland.

Iceland's Landnám presents an ideal laboratory for synthesizing radiocarbon datasets because it occurred on a massive scale and multiple lines of complementary dating evidence are available (^{14}C dates, ice-core dated volcanic ash layers, typologically diagnostic artefacts, historical dates from medieval texts and palaeoecological data). The discovery and settlement of Iceland by the Norse is historically dated to between AD 870 and the emergence of social institutions, AD 930 being the traditional date for the establishment of the Alþing, a parliament serving the whole island (*Íslendingabók*: Grønlie transl. 2006). This onset of colonisation is broadly constrained by the relationship of archaeological features to distinctive volcanic ash (tephra) layers that form spatially extensive marker horizons (isochrons) in key environmental archives such as ice cores, soils and lake sediments (Þórarinsson 1944; Lowe 2011; Dugmore and Newton 2012). Around the time of Iceland´s discovery massive simultaneous eruptions of the Veiðivötn and Torfajökull volcanic systems spread a distinctive visible layer of tephra over the entire island apart from the northwest peninsula (Larsen 1984; Chapter 4.2). Traces of these deposits, called the Landnám Tephra Layer (LTL), have been found in Greenland ice cores and yielded an independent date of AD 877 ± 1 (Grönvold et al. 1995; Zielinski et al. 1997; Chapter 4.2). Additionally, the ice core-dated Eldgjá tephra of AD 939 (Sigl et al. 2015; Chapter 4.2), found mainly in central southern Iceland, and the V-Sv tephra of 938 ± 6 (Sigurgeirsson et al. 2013; Chapter 4.2), found mainly in northeastern Iceland, allow the evaluation of spatio-temporal dynamics of initially established archaeological sites. Not only are 19 tephra layers deposited above and below Viking age archaeological features in Iceland, but also 73% of the 513 ^{14}C dates from anthropogenic contexts are stratigraphically associated with such tephra isochrons (Chapter 6, Appendix VI.A). The colonisation of Iceland is therefore used as an ideal example laboratory for identifying inaccurate ^{14}C dates and testing the limits of chronometric hygiene and Bayesian statistical analyses for radiocarbon-dating events in our past.

This study, therefore, began with cataloguing a comprehensive multidisciplinary dataset of Landnám archaeological sites in Iceland that were investigated from the 18th century until 2016. In total, 300 settlement sites, 140 burials and 110 assemblages or stray finds (n = 550) have been systematically evaluated (Appendices I-II). This is the largest collection of Icelandic Landnám sites produced so far. The key focus is on archaeological sites clearly related to Viking age activity, as suggested by 19 tephra layers at 261 sites (Appendix III), associated ^{14}C dates earlier than AD 1200 (n = 513 samples at 97 sites: Appendix VI.A), as well as typologically diagnostic artefacts or house types that point to a Viking period

occupation of the landscape (Appendices I-II). Sites are excluded that do not have any secure dating evidence, such as house shapes of unknown functions or burials without diagnostic artefacts that have not yielded a scientific date (e.g. a burial with iron nails is not included: Eldjárn and Friðriksson 2016).

The core of this thesis is methodological. It aims to refine the accuracy and precision of radiocarbon datasets. First, methods used in this thesis are introduced, including radiocarbon dating, outlier theories, chronometric hygiene protocols and Bayesian statistical analysis (Chapter 2), followed by the critical analysis of the dating methods employed in Iceland (Chapter 3) with the main focus on independent dating evidence provided by tephra isochrons (Chapter 4). This faciliates hypothesis-testing of ^{14}C dataset choices enhancing routine chronology-building using Bayesian statistical analysis of multidisciplinary data (Chapter 5). The outcome of the thesis is a new standardized chronometric evaluation protocol for producing Bayesian chronological models based on ^{14}C measurements (Chapter 6). This offers significant advantages by allowing for incorporation of the largest possible amount of ^{14}C measurements into a model, by rigorously assessing the decision-making process behind their inclusion or exclusion, and validating with independent dating controls. The work from Icelandic archaeological settings are extended to East Polynesia to demonstrate the applicability of the methodological approaches developed in this thesis to other geographic settings and other archaeological questions (Fig. 2; Chapter 7). The colonisation of East Polynesia covers a similar timeframe, and chronometric hygiene has been applied in this geographic region resulting in chronologies being shifted by more than 1000 years (Chapter 7). This thesis demonstrates how robust *termini ante quos* (TAQs) for colonisation and other events can be generated – with and without independent dating of tephra isochrons. This will help to refine our understanding of island colonisation and other large-scale events in human history that have abrupt, but complex, manifestations.

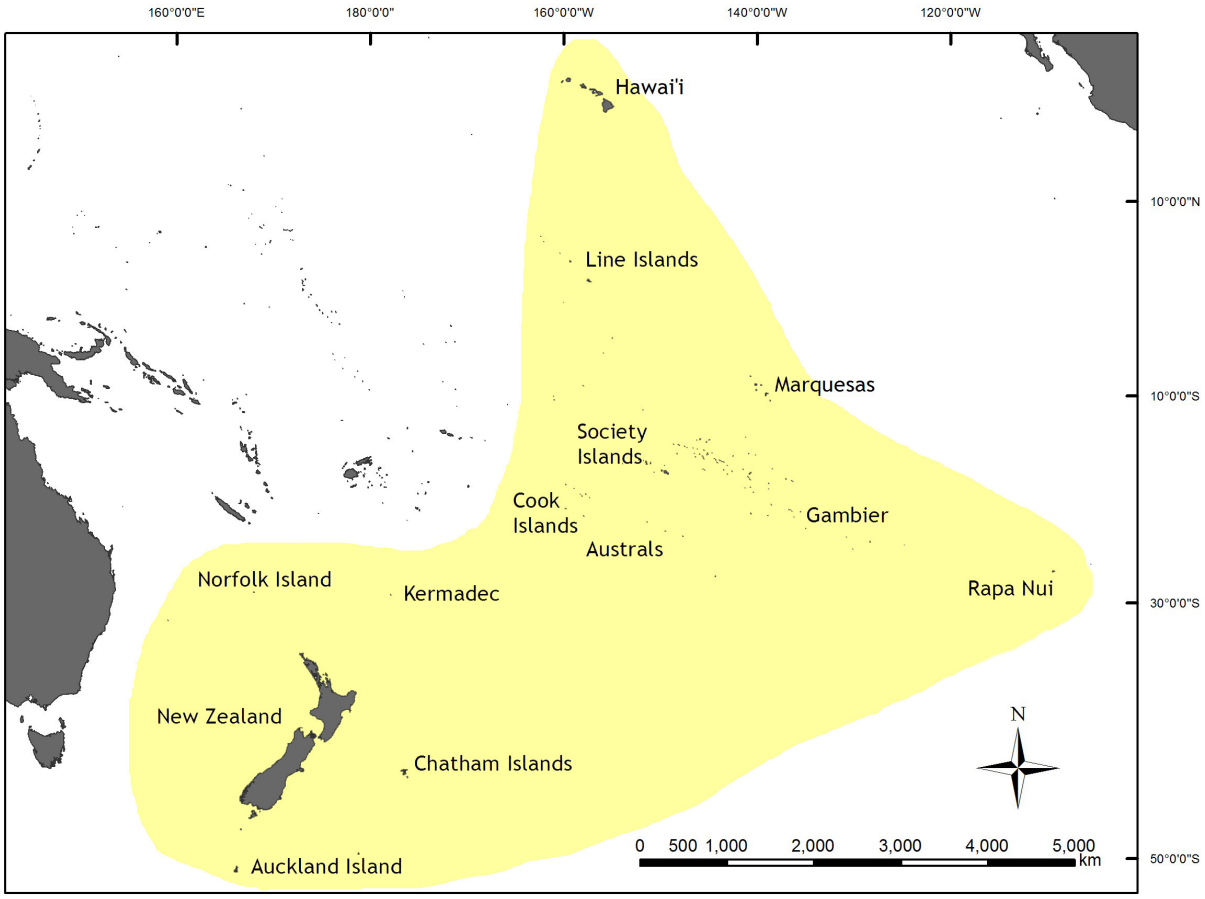

Fig. 1-2 The geographic distribution of East Polynesian islands and archipelagos along with Hawai'i, New Zealand, and Easter Island. The ^{14}C datasets from the 'Cook Islands' are separated into 'Northern Cook' and 'Southern Cook Islands'. West Polynesia includes islands of Tonga and Samoa, which are located west of the Cook Islands.

1.2 Thesis research questions

This thesis develops the statistical analysis of ^{14}C datasets using a unique case study from the settlement of Iceland. Two overall research objectives (**RO**) drive the research – one primarily specific to Iceland, and the other of global significance:

(**RO1**) **A high-resolution chronology of Iceland's Landnám.**

(**RO2**) **A new chronometric evaluation protocol that is based on Bayesian statistical modelling.**

In order to achieve **RO1** the three following research questions (**RQ**s) and one hypothesis (**H**) were addressed:

RQ1 ***What is the archaeological evidence of Landnám in Iceland*****?**

- To discuss the advantages and limitations of tephrochronology, radiocarbon dating and artefact typology.
- To identify spatial patterns of anthropogenic activities relating to colonisation in general and the earliest evidence of occupation in particular.

RQ2 ***How does the archaeology of Landnám relate to the chronology provided by tephra layers*****?**

- To evaluate tephra layers below and above archaeological features on a countrywide scale.
- To establish a high-resolution periodization of Viking age archaeology in Iceland.

RQ3 ***How can multiple lines of dating evidence be most effectively correlated to assess the onset of colonisation in Iceland*****?**

- To evaluate the contexts of radiocarbon dates.
- To identify problematic radiocarbon dates.
- To evaluate sampling bias and the impact of researchers hunting for the most attractive research.
- To establish routine chronology-building using Bayesian statistical analysis of multidisciplinary data.

Given the long-standing discussions about the timing of Iceland's settlement and the question if the settlement was 'a trickle or a flood' (Edwards 2012), this thesis tests the following hypothesis (after Vésteinsson and McGovern 2012):

H1 The settlement of Iceland was largely completed in less than 20 years after the deposition of the Landnám Tephra Layer

(a) The settlement happened before the traditional date (AD ~870) *because a number of ^{14}C dates point to the 6^{th} and 8^{th} centuries*.
(b) The settlement happened after the traditional date (AD ~870) *because none of the 6^{th} and 8^{th} centuries ^{14}C dates are from stratigraphic contexts below the LTL and none are of short-lived materials*.
(c) The settlement was a flood *because of the stratigraphic relationships of archaeological features and 9^{th}-10^{th} century tephra layers*.
(d) The settlement was a trickle *because of the stratigraphic relationships of archaeological features with multiple tephra layers*.

In order to achieve **RO2** the following **RQ** of international significance are addressed and the associated **H2** is tested:

RQ4 ***How can Bayesian approaches improve the accuracy and precision of ^{14}C datasets*****?**

- To test how ^{14}C dates choices affect age-model accuracy and precision.
- To test how the distributions of ^{14}C dataset choices affect age-model accuracy and precision.
- To establish robust *posterior* distributions for key events in the past.

RQ5 ***How many ^{14}C dates are needed for accurate and precise ^{14}C chronologies*****?**

- To test the minimum number of ^{14}C dates needed for generating robust *posterior* distributions using real-life datasets from Iceland and East Polynesia.

Given the inherent problems of ^{14}C samples with inbuilt ages, solutions are sought on how these samples can be included in chronological models without decreasing their accuracy and precision. This thesis formulates the following hypothesis (after Bayliss et al. 2007):

H2 Bayesian modelling can produce accurate age estimations for archaeological events

- **(a)** Model outcomes are sensitive if samples with inbuilt ages are used in chronological models *because they do not accurately date their contexts*.
- **(b)** Model outcomes are insensitive if samples of short-life span are used in chronological models *because they do accurately date their contexts*.
- **(c)** Model outcomes are insensitive if the sample's stratigraphic relationship to the event of interest is known *because the context of samples is fundamental knowledge*.
- **(d)** Model outcomes are insensitive to the *prior* assumption that dates are uniformly distributed across a Phase *because the distribution of ^{14}C dates is flexible and robust.*

1.3 Outline of thesis

After having defined research objectives (RO) and associated research questions (RQ) and hypotheses (H), the methodological framework of this thesis is introduced. The key attention is on archaeological application of radiocarbon dating and Bayesian statistical modelling. The results are published in peer-reviewed journal articles and are summarized in Chapters 4-7.

Chapter 2 – *Radiocarbon dating, chronometric hygiene and Bayesian statistical modelling using OxCal* – provides an introduction to the methods used in this thesis including recent developments in radiocarbon dating and the limits of the technique. It acknowledges the importance of outlier assessments in ^{14}C datasets for quality assurance with the key focus on wood charcoal with inbuilt ages and bone samples affected by reservoir effects. This chapter compares previously established chronometric hygiene protocols that have been developed for enhancing the quality of ^{14}C datasets for Pacific questions and elsewhere. It then provides an in-depth introduction about Bayesian statistical modelling of multidisciplinary datasets, which is the core of this thesis (Chapters 5-7). This chapter also provides a very detailed introduction to OxCal, the most commonly used platform for Bayesian analysis of ^{14}C data for archaeological questions. It further introduces a new software program, 'OxCal_parser', which was established during the course of this Ph.D. The aim of this program is to increase the speed and accuracy of data import in OxCal.

Chapter 3 – *The settlement of Iceland (Landnám)* – is used as a regional case study of island archaeology because the presence of multiple tephra deposits provide a unique set of independent dating control and make Iceland an important test case. This chapter introduces a comprehensive catalogue of early settlements, burials, and assemblage sites in Iceland. The chapter outlines the wealth of data observed from excavations and coring surveys from the

18th century until 2016. 550 archaeological sites have identified tephra, associated ^{14}C dates and/or typologically diagnostic artefacts. This chapter presents a summary and critical analysis of the dating tools that are applied in Iceland, particularly in archaeology, but also relevant to palaeoenvironmental reconstructions, for example sediment accumulation rates and palaeoecology (**RQ1**). The spatial distribution of archaeological sites is assessed, including an evaluation of the presence and absence of data especially associated with the earliest evidence of occupation. The data are alphabetically listed in **Appendix I**, described in detail in **Appendix II** and illustrated in various maps.

Chapter 4 – *Tephrostratigraphy and spatio-temporal dynamics of settlement patterns* – establishes a systematic regional tephrostratigraphic framework that is tailored to the investigation of Iceland's settlement and subsequent events, which then is employed in the chronological models for the following chapters. 253 of 300 settlement sites are stratigraphically connected to well-dated tephra isochrons deposited between the 9th and 17th centuries. The spatio-temporal distribution of tephra layers at archaeological sites is used to define three novel periods of settlement: pre-Landnám (AD pre-877), Landnám (AD 877-938/939) and post-Landnám (AD 938/939-1104), plus a larger Viking age group overlapping with the Landnám and post-Landnám periods. This periodization has the purpose to establish a robust overarching chronology of 550 archaeological sites that are introduced in Chapter 3 focusing on **RQ2** and testing **H1**. The tephra data from individual archaeological sites are listed in **Appendix III**.

Chapter 5 – *Correlating archaeological, palaeoenvironmental and documentary datasets using Bayesian approaches* – provides a step-by-step guide to Bayesian statistical modelling for re-analysis of excavated and previously dated archaeological and palaeoenvironmental sequences. Four key large-scale multiphase excavated sites in Iceland (Reykjavík, Hofstaðir, Sveigakot and Hrísbrú) are used to show how ^{14}C dates – including bone samples affected by the marine reservoir effect – can be correlated with stratigraphy, tephra layers, typologically diagnostic artefacts, historical dates from medieval texts as well as with palaeoecological data to building robust chronological models (**RQ3**). These examples are used to demonstrate the potential of multi-phase models to improve chronological precision and to allow hypotheses to be formulated about sequences of activities where stratigraphic relationships are either unclear or missing. Lastly, it shows how soil accumulation rates between tephra layers can inform age estimates for the occupation of archaeological features. This chapter also discusses sampling bias in ^{14}C datasets, and the importance of publishing quality assurance

data to make informed decisions about whether certain materials can be incorporated into a model, a prerequisite for Chapter 6. The results are published in two research articles. Paper 2 is indirectly related to this thesis, due to alphabetical authorship, and therefore attached in **Appendix IV**. The text output of the Bayesian model discussed in Paper 3 is attached in **Appendix V**.

Chapter 6 – *Enhancing the accuracy and precision of ^{14}C datasets using a new standardized chronometric evaluation protocol* – assesses 513 Viking age and early medieval ^{14}C dates from 97 archaeological sites in Iceland introduced in Chapter 3. The reliability of individual ^{14}C dates is rigorously evaluated using independent dating control provided by tephra layers described in Chapter 4. This chapter focuses on the most parsimonious elimination of ^{14}C samples for statistical assessment and introduces a new outlier categorisation: 'non-tangible outliers'. A variety of methods introduced in the previous chapters are tested focussing on **RQ4** and testing **H2**. The outcome is a new chronometric evaluation protocol, which produces robust *posterior* probabilities for the colonisation of Iceland and may be usefully applied elsewhere, as demonstrated in the next chapter. The ^{14}C data (A) and text outputs of Bayesian models (B) discussed in this chapter are attached in **Appendix VI**.

Chapter 7 – *Applying the new chronometric evaluation protocol to other geographic settings: The examples of Polynesia* – expands on the Icelandic case study to examine the colonisation of Oceania to demonstrate the applicability of the methodological approaches developed in this thesis to other geographic settings. It assesses 282 ^{14}C dates from Viking age Iceland and 1434 dates from East Polynesia with the main focus on datasets using short-lived taxa and samples with inbuilt-age. This chapter evaluates the quality and quantity of ^{14}C datasets (**RQ5** and **H2**). It introduces a new software program 'OxCal_parser' for rigorous data entry when dealing with large datasets. This chapter demonstrates how samples with inbuilt ages can pinpoint the transformational human settlement of islands in the Atlantic, Oceania, and elsewhere. The ^{14}C data (A. Iceland; C. East Polynesia), 'OxCal_parser' (B) and text outputs of Bayesian models discussed in this chapter (D) are attached in **Appendix VII**.

Chapter 8 – *Conclusion* – summarizes the main findings and wider implications of the thesis, demonstrating the international significance of the thesis and stakes out some future research agendas.

1.4 Contribution of this thesis

This thesis refines ^{14}C chronologies for dating discreet events in the past and provides a new methodological approach for identifying outliers, simplifying sample selection, and allowing for a refined analysis of chronological data.

Firstly, this thesis provides a new and comprehensive dataset of 550 archaeological sites relating to the first ~300 years of Iceland's settlement. This dataset contributed to a high-resolution chronology of colonisation, which refutes hypotheses about Icelandic settlement prior to the late 9th century. Furthermore, independent dating control provided by ice-core dated tephra isochrons allows the testing of methodologies used in chronometric hygiene protocols and Bayesian statistical analysis.

As a result this thesis challenges current chronometric hygiene protocols and assumptions that samples with inbuilt ages (e.g. bone samples that are affected by reservoir effects and wood samples that have been long utilised after death) should be excluded in archaeological chronologies. Detailed investigations into such material classes reveal that they are much more valuable than is often assumed and may enhance the precision of archaeological chronologies if combined with short-lived materials. Thus, strict chronometric hygiene protocols may in fact obscure the full potential of large ^{14}C datasets.

By questioning the extent to which *prior* assumptions in Bayesian statistical analysis of multiple ^{14}C dates affect age-model accuracy and precision, this project recognises that the distribution of ^{14}C datasets plays a key part in establishing robust chronologies, which will be biased if dates from specific contexts are not included. This is particularly a problem when dates from early anthropogenic contexts are not available or intuitively removed. This thesis also demonstrates that early contexts, for instance in island environments, can be difficult to identify and therefore further research is needed to identify such contexts.

Lastly, this thesis introduces a new software program 'OxCal_parser' which facilitates rigorous data entry in OxCal in a timely manner. This is important for both small and large ^{14}C datasets using single-phase and multi-phase Bayesian models allowing faster data analysis of very large datasets.

2. Radiocarbon dating, chronometric hygiene and Bayesian statistical modelling

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As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality.

Albert Einstein 1921

2.1 Introduction

The first chapter introduced the study rationale, and sets out the driving hypotheses and research questions. This chapter provides a rationale behind the choices made with respect to the design of this study, methods and approaches, as well as their limitations, followed by data selection in the subsequent chapter. The main body of this chapter is structured in the following sections: it introduces key developments in radiocarbon dating, theories of outliers, previously established chronometric hygiene protocols, as well as Bayesian statistical modelling for archaeological and palaeoenvironmental questions and lastly a new software program that supplements the commonly used computer platform OxCal.

2.2 Radiocarbon dating and outlier theory

Box 2.2.A Radiocarbon dating (Libby et al. 1949)

Radiocarbon dating is a technique for determining the absolute date of organic matter. Carbon has three naturally occurring isotopes. Carbon consists of c. 98.89% of ^{12}C, c. 1.11% of ^{13}C, both of which are stable, and only about one part in a trillion of modern carbon is ^{14}C (e.g. Bronk Ramsey 2008). Unlike ^{12}C and ^{13}C, ^{14}C is unstable and slightly radioactive, hence the name 'radiocarbon'. ^{14}C is continually being formed and occurs in the upper atmosphere by the interaction of neutrons produced by cosmic rays with nitrogen atoms (^{14}N). After formation, the ^{14}C atoms rapidly combine with oxygen to form carbon dioxide, which mixes throughout the atmosphere, dissolves in the oceans and, via the photosynthesis process and the food chain, enters all plant and animal life, known collectively as the biosphere. Under certain circumstances, in particular if the production rate is constant, there is a dynamic equilibrium between formation and decay, and therefore a constant ^{14}C concentration in the atmosphere, and thus a constant ^{14}C level in all-living organisms. When the organism dies the

^{14}C is no longer replenished from the environment and what is present at the time of death decays at a constant rate back to ^{14}N. The half-life of ^{14}C was calculated by Libby as being 5568 ± 30 years (Anderson and Libby 1951). By measuring the radioactivity of the carbon remaining in a specimen its age (usually expressed as an age BP) can be calibrated to produce dates that are comparable to calendar age estimates, e.g. using curves derived from tree-ring chronologies (usually expressed as BCE or cal BP) (Bronk Ramsey et al. 2006). It is possible for an organism to take its carbon from a different reservoir than the atmosphere (e.g. marine and freshwater reservoirs) and these samples need particular consideration as explained in Chapter 2.3.2).

Material for ^{14}C dating

^{14}C determinations can be obtained on wood; charcoal; marine and fresh-water shell; bone and antler; peat and organic-bearing sediments; carbonate deposits such as tufa, caliche, and marl; and dissolved carbon dioxide (CO_2) and carbonates in ocean, lake, and ground-water sources. Each sample type has specific problems associated with its use for dating purposes, including contamination and special environmental effects.

Standard radiometric (LSC) vs. Accelerator Mass Spectrometer (AMS) dating

Radiometric methods of ^{14}C dating rely on counting the electrons emitted during beta decay. Earlier methodologies have been enhanced with Liquid scintillation (LSC) spectrometers (e.g. Povinec et al. 2009), enabling both older and smaller samples (e.g. 6 g of charcoal) to be dated. This technology is still used in some laboratories due to higher precision dating for ^{14}C samples 30,000-60,000 yrs (e.g. at the University of Waikato, New Zealand: https://www.radiocarbondating.com/). The more commonly used Accelerator Mass Spectrometers (AMS) count ^{14}C atoms (Nelsen et al. 1977) and allow smaller samples to be measured (e.g. 2 mg of charcoal and less: Wood 2015).

The inception of ^{14}C dating by Libby in the 1950s re-wrote chronologies around the world (Renfrew 1973); today this method underpins the vast majority of archaeological and palaeoenvironmental chronologies, because it allows us to date organic material (Box 2.2.A). The method has almost changed beyond recognition with key developments described as revolutions (Renfrew 1973; Bayliss 2009; Wood 2015):

- The **inception** of the method itself in the 1950s (Arnold and Libby 1949). As a result, the pace of cultural change in world archaeology was much slower; for instance, the

English Neolithic was at least a millennium older than had been suggested previously (Piggott 1949; Renfrew 1974).

- The **calibration** of radiocarbon dates in the early 1970s (Suess 1967). ^{14}C years do not directly equate to calendar years because atmospheric ^{14}C concentration varies through time due to changes in the production rate, caused by geomagnetic and solar modulation of the cosmic-ray flux, and the carbon cycle (de Vries 1958; Stuiver and Suess 1966; Reimer et al. 2013). Hence, a calibration is required, which should ideally be based on an absolutely dated record that has carbon incorporated directly from the atmosphere at the time of formation. As a result, calibrated dates appeared to be several hundred years older than uncalibrated ^{14}C measurements; for instance, the English Neolithic became earlier by another 800 yrs (Bayliss 2009).
- The development of **Accelerator Mass Spectrometry** (AMS) ^{14}C dating in the mid-1980s (Dennell 1987; Box 2.2.A). This method permits the dating of much smaller samples with greater precision for samples <30,000 yrs, which, combined with declining unit cost, has resulted in the generation of very large datasets of individual age determinations around the world (e.g. >80,000 samples from key databases: Chapter 7).
- **Bayesian statistical modelling** of multiple ^{14}C dates and other data in the early 1990s (Chapters 5-7). This method allows (re)interpreting existing archaeological and palaeoenvironmental data and facilitates an efficient, explicit and iterative hypotheses testing strategy and is therefore rapidly gaining momentum in archaeological discourse (e.g. Buck et al. 1996). The method is explained in detail in Chapters 2.4-2.6.

However, there are some key issues that still need to be addressed to improve chronologies:

Dating strategies. A large proportion of archaeological sites from around the world have only a single ^{14}C age (e.g. 31% or 30 archaeological sites in Iceland: Appendix I). Single ^{14}C dates produce probability distributions that plot around the true age and they may not necessarily capture the timing of key events.

Accuracy versus precision of ^{14}C ages. There are two interrelated concepts with any form of radiometric dating: accuracy and precision (e.g. Steier et al. 2004). The archaeologist usually asks for the *accuracy* of data, the maximum deviation from the 'true' age. This refers to the measurement of the ^{14}C/^{12}C of the sample and how well that samples dates its context. *Precision* refers to the statistical uncertainty associated with an age estimate (the error value

of a sample) – the greater the precision, the less uncertainty there is in the assessed age. Radiocarbon laboratories estimate uncertainties in numerous ways using counting uncertainties, measurements on standards and measurements on replicated samples (Ramsey et al. 2004). AMS has facilitated greater precision of ^{14}C ages <30,000 yrs allowing smaller sample sizes to be measured (Fig. 2-3); however, a precise estimate of a single grain sample could have been contaminated or may have moved from its primary context, compromising its accuracy. In this instance, a grain sample from Torfgarður (TFG 565 ± 15 yr B.P.) is stratigraphically below the Vj tephra of AD ~1000; the calibrated age, however, is *cal AD 1327-1410*.

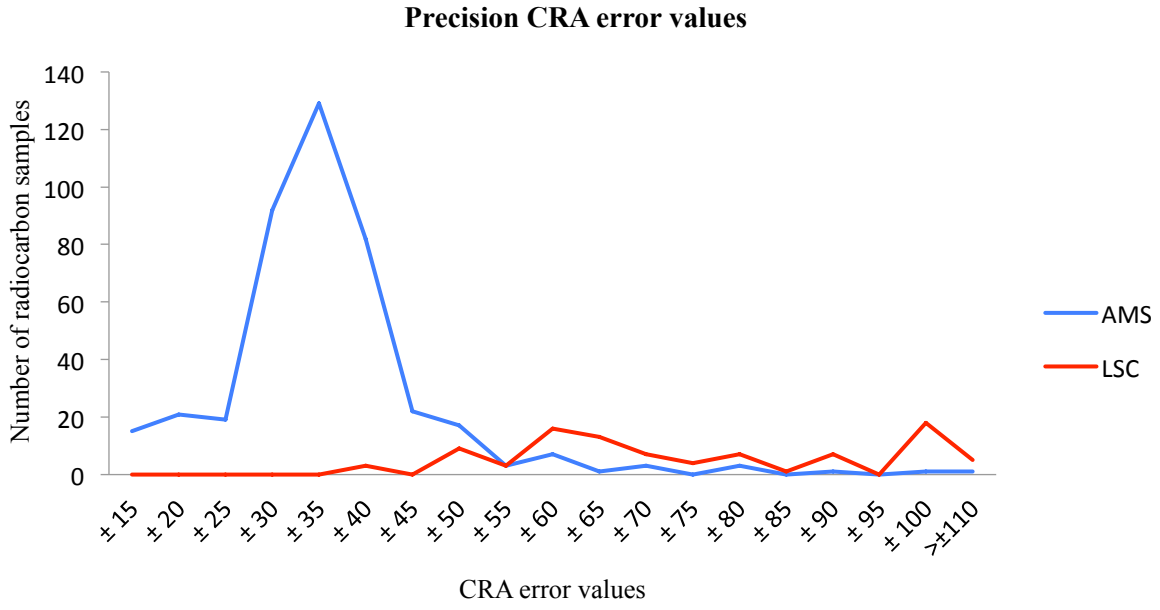


Fig. 2-3 Precision of radiocarbon ages using Liquid scintillation counting (standard radiometric dating: LSC) vs. Accelerator Mass Spectrometry (AMS). The graph is based on actual errors on 513 ^{14}C samples from Iceland (Appendix VI.A). Most of the samples with error values greater than ± 55 yrs were calibrated before the 1990s. It is important to note that high precision LSC dates can have errors <± 20 yrs; while routine LSC dates have precisions of c. ±30.

The context of ^{14}C samples. As archaeologists we are interested in the start, duration, and end of an event or occupation of a site. This knowledge can be used to evaluate if a particular site is older or younger than another site or if a particular event (e.g. a volcanic eruption) is (un)related to archaeological or ecological events (Baillie 1991). In order to evaluate any event in the past, we need to know the contexts of ^{14}C dates. Nevertheless, this information is not always published. In Iceland, for instance, detailed recording of stratigraphic relationships only became standard after the 1970s (Vésteinsson 2004).

Material classes. Any organic material can be used for radiocarbon dating; however, different material classes produce ages of different precision (Box 2.2.A). Organisms with short-life span (e.g. grains, seeds, eggshells, roundwood of small diameter, terrestrial bone), where ^{14}C concentrations are in equilibrium with the atmosphere until death, can accurately date their contexts assuming no contamination is present. Organisms with storage or inbuilt age, on the other hand, such as driftwood or the heartwood or trees, do not accurately date their contexts in which they occur (Schiffer 1987; Bronk Ramsey 2009a; Allen and Huebert 2014).

Taphonomy. In the North Atlantic, such as the Faroe Islands and Iceland, a large percentage of Norse farmsteads were never abandoned/relocated, so it can be very difficult to identify early anthropogenic contexts (e.g. Vésteinsson and McGovern 2012; Church et al. 2013; Steinberg et al. 2016). Unless an archaeological site is fully excavated and samples have been carefully selected, ^{14}C dates are more likely to come from younger contexts than older contexts. Even then difficulties can arise, for example, it has been proposed that floors from structures were regularly cleaned out and that the archaeological evidence only reliably represents the activities of the last years of occupation (Vésteinsson 2004; Lucas 2009). As a rule, early deposits have a low survival rate due to later disturbances and are easily obscured, and no protocols exist on how to securely identify these contexts. Nevertheless, uneven survival can also adversely affect younger deposits, depending upon the specific depositional system and/or contextual taphonomy.

Multiple ^{14}C ages from an archaeological site. Ideally archaeological sites should have multiple ^{14}C dates (> n = 10) from known stratigraphic sequences (Chapters 5-6). If we return to the Icelandic example, 89% of archaeological sites have less than ten samples (n = 85). More precisely, 31% of sites have one sample (n = 30), 20% both two and three samples (n = 19) and 18% between four and nine samples (n = 17). On the contrary, 9% of sites have between ten and 25 samples (n = 9), while 2% between 58 and 82 samples (n = 2; Appendix I). As such radiocarbon samples are typically taken from certain key locations considered to be of greater research interest (Michczynski and Michczynski 2006). Such 'special interest' samples can bias radiocarbon chronologies.

Multiple ^{14}C ages from a specific geographic area (e.g. single islands, archipelagos, continents) or from a discreet event in history. Single islands, archipelagos or entire continents can have very large datasets of hundreds or thousands of ^{14}C data (Rieth et al.

2011; Williams et al. 2014; Rull 2016). Discreet archaeological events, for instance the timing and spatiotemporal patterning of Neanderthal disappearance, can also be evaluated using large ^{14}C datasets (Higham et al. 2014). Evaluating such large datasets typically relies on secondary data from the grey literature, as presented in this thesis (Appendices I-II). As such, materials and contexts for ^{14}C dating cannot be chosen for the specific purpose of regional chronologies. The available dataset may not reflect the accurate timing of the archaeological event. For instance, suitable material for dating may simply not be available from early colonisation contexts due to preservation issues and taphonomy. A dataset, thus, can consist solely of wood charcoal samples with inbuilt or storage ages and may not result in an accurate timing of colonisation (Chapter 7). Or we choose to use samples that we think most likely capture the accurate timing of colonisation, such as short-lived materials (e.g. tree twigs), but realize that most samples are indeed from young settlement contexts and result in a chronology that is too young (Chapter 7). This underlines the importance of contexts of ^{14}C data.

Outliers in ^{14}C datasets. No matter if we have one or more ^{14}C dates from an archaeological site, or if we have hundreds or even thousands of ^{14}C dates from a geographic area or archaeological period, some ^{14}C dates are always anomalously younger or older than their stratigraphy suggests. Outliers in datasets may occur when samples are contaminated, they are poorly provenanced, not directly related to the archaeological context or to the event of interest, or they have considerable inbuilt age (Box 2.2.B). Other outliers may have no obvious explanation for their status because, for example, they are not published with sufficient detail to evaluate these concerns or it is not established whether methodological pre-treatment protocols were appropriate or our knowledge is limited as to the environmental corrections required. There is sufficient evidence for regional offsets in terrestrial ages in some regions of the world, and potential seasonal shifts (Reimer et al. 2013). Assessing the quality of ^{14}C datasets and removing inaccurate dates in ^{14}C datasets is crucial for accurate and precise chronological interpretation. This requires both chronometric hygiene and the application of Bayesian statistical approaches of ^{14}C datasets, which are critically assessed in the following subchapters (Fig. 2-4).

Box 2.2.B Outlier theory

I. Definition of an outlier

Barrett and Lewis (1987:4) 'define an outlier in a set of data to be an observation (or subset of observations) which appears to be inconsistent with the remainder of that set of data'. It has been suggested that chronological outliers in stratigraphic sequences are common; it is assumed that 1 in every 20 sample is an outlier (Bronk Ramsey 2009a).

II. Types of outliers (Christen 1994; Bronk Ramsey 2009a)

Type S: The ^{14}C measurement of a sample might not be correct.

Type R: The ^{14}C measurement of a sample might be different from that of the associated reservoir.

Type D: The whole set of ^{14}C measurements might be biased in some way relative to the calibration curve, either because the measurements themselves are biased, or because the reservoir from which the sample draws its carbon might not have the expected ^{14}C isotope ratio.

Type T: The sample measured might not relate to the timing of the event being dated.

III. Post-depositional disturbances (Schiffer 1983)

A date can be an outlier if an archaeological site was disturbed. Many different factors can disturb an archaeological site over time, from accidental to deliberate human activity:

Natural disturbance: Erosion and displacement: where sediments are moved, mixed and re-deposited elsewhere. Disturbance *in situ* by physical processes: shrinking and expansion of sediments caused by wetting/drying or freezing/thawing; bioturbation: biological processes that disturb a site and mix sedimentary layers – caused by animals (grazing, trampling, burrowing, digging) or plants (tree roots, vegetation overgrowth).

Cultural disturbance: Human activity such as: clearing surface, modify surface (de-turfing for construction, drainage/irrigation, manuring, digging pits, graves, etc.).

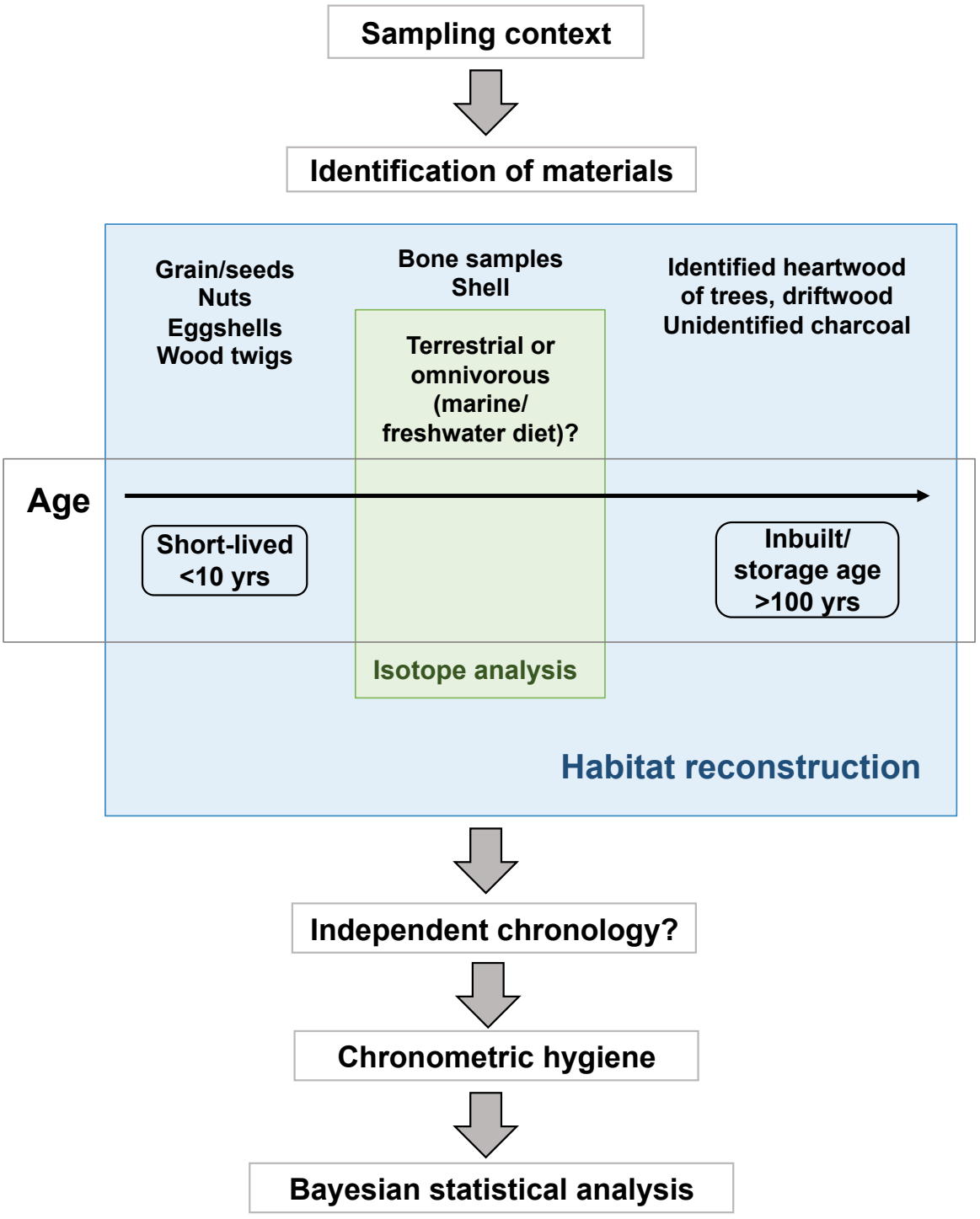


Fig. 2-4 Important steps in evaluating ^{14}C dates**.** The assessment of the context of any sample is fundamental as is choosing short-lived materials wherever possible to avoid in-built ages. The data evaluation should be performed in the following steps: 1) if applicable, against independent dating evidence (e.g. a tephra layer or a historical date), 2) by applying chronometric hygiene and 3) using Bayesian statistical analysis.

2.3 Chronometric hygiene

Debates about the reliability of ^{14}C chronologies and the use of specific material classes have been on-going since the 1970s (Waterbolk 1971). The aim has been to eliminate dates that are most likely problematic, a process that has been described as 'chronometric hygiene' (after Spriggs 1989). Today there are a number of chronometric hygiene protocols using various classifications for different ^{14}C datasets around the globe; they have been predominantly applied in the Pacific (Table 2-1). These protocols exemplify critical debates about ^{14}C chronologies all over the world, where conflicting interpretations stem from different approaches to identifying problems within collections of ^{14}C dates. Large numbers of dates have been rejected that are considered uncertain in terms of: 1) stratigraphic and archaeological context, 2) material classes and 3) methodology (Table 2-1). The most common strategy is to eliminate samples with inbuilt ages, such as wood charcoal samples (Outlier Type T) and samples affected by reservoir effects as described above (Outlier Type R), calling into question up to 95% of ^{14}C dates (Table 2-1, Rieth et al. 2011). Strict dataset choices have both reduced the places where dating can be utilized – in particular for small datasets of some Pacific islands (Chapter 7) – and shifted individual chronologies by more than 1000 years (Dye 2015; Wilmshurst et al. 2011). These methodological innovations have radically changed views of the great Polynesian voyages of discovery and colonisation of remote Pacific islands.

2.3.1 Outlier Type T: Wood charcoal samples with inbuilt ages

There has been active debate about the validity of ^{14}C dates of wood charcoal for two reasons: firstly, it may not represent anthropogenic activities (e.g. be created by natural fires); secondly, it can have misleading inbuilt-ages, such as those derived from the heartwood of trees with a long-life span, or any wood that was utilized long after its death (Schiffer 1986). In Iceland, natural fires in vegetation are extremely rare and charcoal most likely represents anthropogenic activity of some kind (Erlendsson et al. 2006). The first people to settle islands will have burnt old wood from native trees (e.g. standing dead wood), or driftwood collected upon arrival, but we are interested in the time when people made the fire and not how old the wood was that they burnt. For instance, Icelandic birch may live more than 100 years (so the heartwood may have died a century before the tree did), and European larch may live for 200 years with a potentially greater effect (Sveinbjörnsdóttir et al. 2004). Thus, it is believed that charcoal samples have limited utility in chronological models (Table 2-1; Bronk Ramsey 2010; Manning et al. 2006). To underline this problem, wood charcoal has been shown to

give earlier dates than charred barley of short life span from the same contexts (Sveinbjörnsdóttir et al. 2004). Given the uncertainities involved in interpreting dates from charcoal, this material is not used in many archaeological chronologies. Clearly there have been good reasons for discarding this data in certain circumstances, but a greater effective use of it would represent a major advance for many sites around the globe, where charcoal is the only material class numerous enough, and sufficiently well-preserved for dating (Chapter 7).

Table 2-1: Chronometric hygiene protocols around the world. Classifications refer to ^{14}C dates that are considered problematic and it is suggested to eliminate those for archaeological chronologies (marked with an 'X').

Elimination of ^{14}C dates according to:															
Stratigraphy			Material classes					Method							
No association with cultural layers	Disturbed deposits/stratigraphically inverted	Lack of stratigraphic relationship	Sample does not date the event of interest	Contamination through reservoir effects (e.g. bone, marine shell)	Wood samples with high inbuilt ages ("old wood effect") or unidentified charcoal	Mixed materials, carbons (human acids, carbonates, charcoal, sediments)	Clearly anomalous in comparison to other samples from the same material class	Inaccurate pre-treatment	Standard radiometric method (LSC)	Inaccurately published (e.g. bone fractions)	From a particular laboratory (e.g. Gak-)	Excessive standard deviation	Single dates of a site/context	Region	References
X			X	X	X	X		X						Not specified	Waterbolk 1971
X	X										X	X		East Asia	Spriggs 1989
X	X		X	X	X	X	X	X			X		X	East Polynesia, New Zealand	Anderson 1991; Spriggs and Anderson 1993

				X	X						X	X		Central Plains	Blakaslee 1994
X			X	X	X	X		X						Not specified	Pettitt 2003
X		X			X								X	Carribean	Fitzpatrick 2006
				X		X							X	Easter Island	Hunt and Lipo 2008
X			X	X	X	X						X		East Polynesia	Wilmshurst et al. 2011
X			X	X	X	X						X		Hawai'i	Rieth et al. 2011
				X		X								Papua New Guinea	Denham et al. 2012
		X			X							X		Maioro	Wallace and Green 2012
X					X								X	Pacific and Island Southeast Asia	Fitzpatrick 2013
									X	X		X		New Zealand	Perry et al. 2014
		X				X				X		X		Mimbres Region	Anyon et al. 2017

2.3.2 Outlier Type R: Samples affected by reservoir offsets

Box 2.3.2 Marine (MRE) and freshwater reservoir effects (FRE)

I. The marine reservoir effect – MRE (Stuiver et al. 1986; Petchey et al. 2008; 2009; 2013)

The surface ocean is depleted in radiocarbon compared to the atmosphere and has an apparent ^{14}C age, which is on average around 400 years older than associated materials from the terrestrial (atmospheric) reservoir – known as the marine reservoir effect. This is caused by the delay in radiocarbon exchange between the atmosphere and ocean as well as by the mixing of surface waters with upwelled, ^{14}C-depleted deep ocean water. This offset is automatically corrected when a marine shell conventional radiocarbon age is calibrated using the modelled marine ^{14}C calibration curve ('Marine13': Reimer et al. 2013). This represents a global average of the surface ocean ^{14}C. Local and regional deviations from this global average are corrected for by the use of a local correction factor called ΔR. ΔR is the difference between the modelled ^{14}C age of surface water and the actual ^{14}C age of surface water in a specific area. Organisms that derived some, or all, of their carbon from an oceanic reservoir will have been affected by this marine reservoir effect. Inclusion of this material in human and animal diets can cause bone samples to appear several hundred years older than their true age.

II. The freshwater reservoir effect – FRE (Lanting and Van der Plicht 1998; Ascough et al. 2007; 2010; 2012; Sayle et al. 2014; 2016)
Freshwater reservoir effects also occur when ^{14}C depleted carbon from reservoirs such as peat, old soils or from geothermal activity (upwelling of geological age carbon from volcanic activity) is added to the freshwater system. These reservoir effects are both significant and highly variable, but can amount to many hundreds of ^{14}C years within a single water-body, and without extensive regional work, corrections are not possible.

The stable carbon isotopic ratio is expressed as $\delta^{13}C$ and defined as a relative deviation (in ‰) of the $^{13}C/^{12}C$ ratio of a sample from that of a standard. Radiocarbon samples, whose $\delta^{13}C$ values reflect a wholly terrestrial diet and with no indication of significant admixtures of marine, freshwater or geologically-derived carbon are unlikely to have been influenced by any addition of 'old carbon' from reservoirs and normally provide reliable ^{14}C ages (Chapters 5-7).

Omnivorous animals and humans with marine diets (marine fish, mammals and shellfish) and seaweed-eating sheep (sea grapes) in coastal areas need particular consideration, because they can contain marine derived carbon and the ^{14}C age must be corrected for the marine reservoir effect (Valentin et al. 2011; Box 2.3.2). The extent of this effect can be assessed by using measurements of $\delta^{13}C$ as an indication of the percentage of marine contribution to diet, having established values that would be expected for 100% terrestrial and 100% marine diet and performing linear interpolation between the two extreme values (discussed in detail in Chapters 5-7). In the North Atlantic, the end points of $\delta^{13}C$ values are typically set to -21.0‰ for a 100% terrestrial diet and -12.5‰ for a 100% marine diet with an adjustment of +1‰ for trophic level shift (Arneborg et al. 1999; Sveinbjörnsdóttir et al. 2010). These values can be derived either by using measurements of local flora and fauna and taking account of fractionation, or by values directly measured from bone collagen within the study areas with extreme diets (Dewar and Pfeiffer 2010). They are approximately similar to those used by Ascough et al. (2012) for terrestrial and marine protein sources from sites in northern Iceland: -20.3‰ for a 100% terrestrial diet and -12.8‰ for a 100% marine diet, respectively. The data from northern Iceland were selected as they provide the closest geographical match to the archaeological material under consideration. This thesis calculated the percentage of marine carbon within the bone samples using the linear regression calculation of $y = 270.67 + 13.333x$ for Iceland, where x is $\delta^{13}C$ value and of y is % marine contribution to diet (Ascough

et al. 2012). The percentage of marine carbon can be calculated with a reasonable precision (± 10 uncertainty) (Arneborg et al. 1999; Sveinbjörnsdóttir et al. 2010). The uncertainties arising in this data are discussed in Ascough et al. (2012).

The accurate calibration of ^{14}C determinations (e.g. human bone, shell) with significant contribution of marine carbon requires an understanding of the geographical variability in the surface ocean marine ^{14}C reservoir that is caused by variations in upwelling, ocean currents, and climate (Box 2.3.2), as well as an understanding of the habitat and dietary preferences of different shellfish species (Dye 1994; Hogg et al. 1998; Petchey et al. 2018). It is neccessary to consider both the global average reservoir effect and its site-sepecific deviation from it. The global average is provided by the calibration curve, in this case "Marine13' (Reimer et al. 2013). A reservoir correction factor, commonly called a ΔR, is used to account for local marine ^{14}C variation (Reimer et al. 2002); however, ΔR values show significant spatial and temporal variation around the globe (e.g. Petchey et al. 2008).

This thesis uses the most recently calculated overall weighed mean ΔR value of 111 ± 10 ^{14}C yr for Iceland, obtained from multiple paired measurements on terrestrial mammals and marine molluscs from Norse period archaeological deposits in northern Iceland (Ascough et al. 2011). Although this is currently the best estimate, it could be improved through measurements from other parts in Iceland because there could be significant spatial variability as a result of the variable influence of different oceanic currents (Chapters 5-7).

A further area of uncertainty in ^{14}C dating concerns the effects of freshwater reservoirs (FRE) on bone collage partly arising from upwelling of geological age carbon from volcanic activity into freshwater lakes (Box 2.3.2). These reservoir offsets are both significant and highly variable; modern fish from Lake Mývatn in the north of Iceland have ^{14}C reservoirs of more than 3000 ^{14}C years, due to geothermal springs supplying ^{14}C depleted water to the lake, and this effect can vary by around 1500 ^{14}C years (Sayle et al. 2016). Stable isotope analysis of human remains from the nearby cemetery of Hofstaðir suggests that freshwater resources comprised only 5-6% of the diet of these people. However, this would cause ^{14}C offsets of between 40 and 500 ^{14}C years (Sayle et al. 2016). Calculations of these effects are still uncertain in other parts of Iceland and it is important to recognise its potential complication.

The caveat with MRE corrections is that in order to work well, it must be applied in areas, where much work has been done to characterize robust MRE/ΔR corrections, and the carbon stable isotope values of the system. Much work has also been carried out in the Pacific

(Petchey et al. 2008; 2009; 2013). Here, the dating of shellfish is of particular importance, because charcoal and bone can be highly degraded. The dating of shellfish requires robust ΔR values; however, such values show significant spatial and temporal variations (e.g. -49 ± 10 for the Norfolk Islands, 136 ± 83 for Chatham Islands, -19 ± 13 for Kermadec Islands, -7 ± 45 for New Zealand) and are affected by an uneven distribution of ^{14}C throughout the marine environments. High ΔR values are the result of carbon from peat, hardwaters, calcareous bedrock or from upwelling of ^{14}C depleted water; while low values are the result of the incorporation of freshwater, e.g. high rainfall (e.g. Southon et al. 2002). The affect of these varying sources of ^{14}C on shellfish will depend upon the degree of water exchange with the open ocean, ocean circulation, as well as the habitat and feeding habits of the marine mammal (Petchey et al. 2004).

Islands located within the Pacific Gyre – the central region that includes Tonga, Fiji, Vanuatu, New Caledonia, Samoa, etc. – have more regular ΔR values than islands along the Southland front/Subtropical front – the southeast coast of New Zealand, Chatham Islands, Auckland Islands, the Solomon/Bismarck region, the central equatorial Pacific and the eastern Pacific rim along the Peru coastline (Petchey et al. 2008). These areas can be affected by disrupted currents, upwelling, and 'hardwaters' (ancient carbon derived from limestone) and can be less ideal to use shells as dating materials. Current research for the Mariana Islands in Western Polynesia, however, shows that there are solutions to the hardwater problem by using $\delta^{13}C$ values to separate shells into estuarine and marine shellfish (Petchey et al. 2018). These approaches show potential for dating marine shells and should be applied to shellfish in other regions, such as for East Polynesia.

2.4 Bayes' theorem

Today's posterior belief becomes tomorrow's prior belief

Bayliss 2007

Box 2.4: Bayesian versus Frequentist statistics

I. Bayes' theorem

Bayesian statistics contrast with classical statistics, where probabilities are identified with relative frequencies (Mendanhall and Beaver 1994:158). Bayesian statistics are named after Thomas Bayes who formulated the Bayes' theorem in his 'Essay towards solving a problem in the doctrine of chances' and established a mathematical basis for probability interference (Bayes 1763). In mathematical terms Bayesian statistics can be described thus: *prior* beliefs about hypotheses are expressed and they are modified in the light of additional data (the *likelihood functions*) in order to arrive at *posterior* beliefs (Fig. 2-5; Lee 2012:36). In archaeological terms this involves:

Prior belief: Archaeological information about the stratigraphic relationships of ^{14}C dates, assumptions over how individual outliers are distributed, and assumptions about how the overall ^{14}C dataset is distributed.

Standardised likelihoods: The ^{14}C dataset, but also other dates such as tephra, typological data or historical dates.

Posterior belief: *Highest probability density* (HPD) ranges of *posterior* distributions (e.g. archaeological and palaeoenvironmental events as well as of individual ^{14}C dates. They typically represent a subset of data used; they are thus interpretative estimates because they are not definite or absolute and will change with additional data.

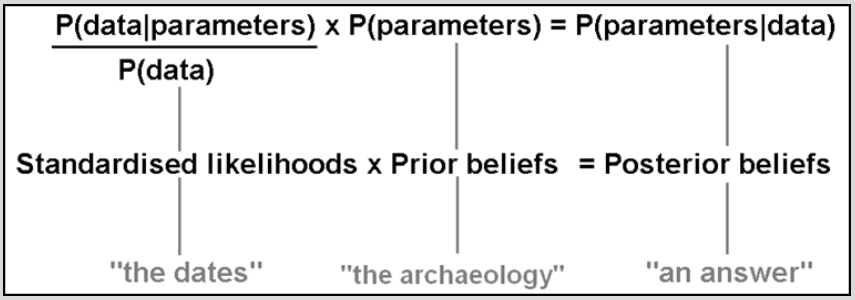


Fig. 2-5 Bayes' theorem for archaeological problems (after Bayliss 2009).

II. Summed probability distributions (SPD)
A common approach in archaeology has been to use 'data as dates' and sum probability distributions (SPD) of ^{14}C datasets. The last decade has seen an increase in the popularity of SPD methods as a proxy for prehistoric demographic change, and it has been argued that there is a dynamic relationship between population size, date density, and distribution (e.g. Crema et al. 2017; Williams et al. 2018). However, methods are still being refined and their reliability is vigorously debated (e.g. Bayliss et al. 2007, Contreas and Meadows 2014; Attenbrow and Hiscock 2015). Some of the key uncertainties include sampling error, calibration process, time-dependent (and independent) taphonomic loss, spatial and/or temporal variations in site-to-population ratios and in sampling bias, of which some have not yet been quantified. There is no control over statistical scatter and so the duration of events is always overestimated (Bayliss et al. 2007). Moreover, the approach assumes that all samples within a population have been dated, and no uncertainty term is calculated. This means it is not possible to assess whether any given peak is significant.

In the last twenty years, there has been an increasing interest among archaeologists in Bayesian and Frequentist statistics, and the use of these analyses in modelling ^{14}C dates is becoming the norm in archaeological practice (Box 2.4). Summed probability distributions (SPD) of radiocarbon datasets provide an estimate for the frequency distribution of data as they add together all the probability distributions of the calibrated dates (the approach is explained in detail in: Aitchison et al. 1991). Although researchers have attempted to improve the accuracy by selecting single-entity materials with small error values (e.g. Czebreszuk and Szmyt 2001; Wilmshurst et al. 2011; Rieth et al. 2011), Bayliss et al. (2007) highlight that statistical scatter results in the overestimation of the duration of an archaeological phase: "The more dates are included in the analysis, the more scattered will be the results and the longer the estimates for the duration of the activity […] essentially blurring the view unless additional constraints can be applied" (Bayliss et al. 2007:10). While SPD methods are still being refined and their reliability has been vigorously debated (Box 2.4), this thesis uses Bayesian statistical analysis of ^{14}C datasets to estimate the start of colonisation rather than examine the distribution of dates over time.

Buck et al. (1996) provide an in-depth introduction to the Bayesian approach from an archaeological viewpoint, while an introduction to the approach to chronological problems is introduced in a number of articles (e.g. Buck et al. 1991; 1992; 1994a; 1994b). The Bayesian

approach can be used to test hypotheses, emphasizing that the interpretation of the data is conditional on all the chronometric information available. *Posterior* distributions are generated by expressing *prior* assumptions (e.g. the stratigraphic relationships between contexts containing dated samples or the mathematical distribution of the archaeological events in the phase of activity which has been sampled for radiocarbon dating) and by modifying them with standardized *likelihood* functions (multiple ^{14}C dates and ages from tephra isochrons). Less commonly used *likelihoods* include typological data (Needham et al. 1998) or historical data (Bronk Ramsey et al. 2010). This study quotes the 68% and 95% *Highest Probability Density* (HPD) ranges of these *posterior* probability distributions. The appropriate analytical software utilises probability in assessing dates and identifies outlying samples (Bayliss and Bronk Ramsey 2004; Bronk Ramsey 2009a). This type of analysis and the resulting enhancements in both accuracy and precision can clarify our view of the past and offers a rigorous procedure for both the interpretation and re-interpretation of archaeological chronologies. An example of the crucial role of chronology is the study of colonisation events, which is the focus of this thesis.

There are clear advantages to a statistical approach that combines multidisciplinary datasets, in (re)interpreting existing data, developing routine chronology building and in planning sampling strategies. However, it is important to underline that Bayesian models produce particular images of the past that can easily be changed with additional data and the observer has to work with information and dates that are available and not with what is ideal; thus, the *posterior* distributions are interpretive estimates and not absolute. Thus, Bayesian statistics are like any other form of modelling – just as good (or bad) as the information fed into the box (Bayliss et al. 2007). However, they can be used to test hypotheses with the available dataset (the subject of this thesis) and then identify where work should focus to target future dating projects, facilitating an efficient, explicit and iterative hypothesis testing strategy (Bayliss et al. 2007; Bayliss 2009).

Classical statisticians have expressed their biggest concern about the use of *prior* information, for instance assumptions about stratigraphic relationships of ^{14}C dates, over how individual outliers are distributed, and/or assumptions about how the whole ^{14}C dataset is distributed (Steiner and Rom 2000). For chronological models in archaeology, *prior* information has been divided into two categories: *informative* and *uninformative* (Bayliss et al. 2007). Using simulated datasets, it has been argued that informative *prior* assumptions are information, which strongly affects the outputs of the models; the stratigraphic relationships

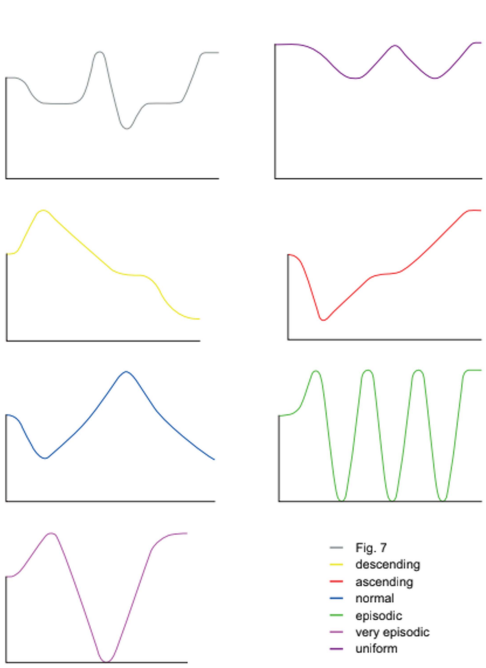


Fig. 2-6 Uninformative *prior* assumptions. A variety of distributions of dated events (after: Bayliss et al. 2007).

between ^{14}C samples or archaeological events and the ^{14}C samples themselves must be accurate (they should not be reworked, residual or intrusive). It has been argued, that this is expected, because this information is intended to be informative (Bayliss et al. 2007:14). On the contrary, uninformative prior assumptions – the distribution of ^{14}C samples – do not influence the output of the model, because they are robust and even when the distribution is grossly incorrect (Fig. 2.6), its effect is out-weighed (Bayliss et al. 2007:17). Thus, a uniform distributed dataset is robust. This thesis, therefore, tests the use of *priors* in statistical models using a real-life dataset from Iceland because of ice core-dated tephrochronology of initial settlement.

2.5 An introduction to OxCal

In this thesis, the Bayesian statistical approach was employed to estimate the most likely age ranges for archaeological and palaeoenvironmental events. Several statistical programs for modelling ^{14}C determinations are freely available online. Some are more suitable for archaeological (e.g. BCal: Buck et al. 1999) others more for palaeoenvironmental applications (DateLab: Jones and Nicholls 2002; BPeat: Blaauw and Christen 2005; BChron: Haslett and Parnell 2008; CLAM: Blauuw 2010; StalAge: Scholz and Hoffmann 2011; Bacon: Blaauw and Christen 2011). OxCal contains a variety of applications both for archaeology and palaeoenvironment (e.g. Bronk Ramsey 1994; 1995; 1998; 2001; 2008; 2009a; 2009b; 2017: Bronk Ramsey and Lee 2013; Bronk Ramsey et al. 2006: Dee and Bronk Ramsey 2014), and is therefore used in this thesis.

OxCal is structured in an output module and input module (Tables 2-2 and 2-3). The output module is the opening page that allows the calibration of single dates and the presentation of the results. The input module realizes the calibration of multiple dates and the input of Bayesian models. Both modules use the 'Chronological Query Language2' ('CQL2': Bronk Ramsey 1998). This universal language enables the models to be easily replicated and published. The commands used for output and input modules are explained in Tables 2 and 3 since the commands are explained in a number of papers; terms written in 'CQL2' are indicated using single quotation marks (').

Tab. 2-2: Commands on the output module. 'Chronological Query Language2' ('CQL2') for Bayesian models constructed in OxCal.

Lab code	#	Enter the 'Lab code' of the radiocarbon sample.
Date	#	Enter the radiocarbon 'Date' in uncalibrated form.
±	#	Enter the error value '±'of the radiocarbon date.
Curve	#	Use the scroll down list next to 'Curve' in order to select a calibration curve. Enter the most recent atmospheric calibration curve 'IntCal13' for the northern hemisphere. Choose 'ShCal13' for the southern hemisphere.
Calibrate	#	Press 'Calibrate' and wait. The default view is a table, which shows the calibrated date range at 68% and 95% probability.
Format	#	Found on the menu bar. The command 'Format' allows you to change the data that is given in the table.
Show	#	Found under 'Format'. The command 'Show' allows you to change the data that is given in the table: e.g. the 'Ranges' and 'Style'.
Ranges	#	Found under 'Format'. Change the 'Range' (68%, 95% and 99% probability).
Date reporting	#	Found under 'Format'. Change the 'Style' of the calibrated dates. Here you can change the calibrated dates, e.g. 'cal BP' to 'BC/AD (yrs)'.

Rounded by	#	Found under 'Format'. Here you can round the dates, e.g. to the nearest 5 or 10 years.
View	#	Found on the menu bar. 'View' dates in different ways, e.g. single plots, multiple plots, etc.
Single plot	#	Found under 'View'. The command allows you to view the calibrated date as a distribution plot. The brackets below the probability distribution represent the probability range you have chosen (95% probability recommended). It is possible to display more than one probability range.
Plot on curve	#	Found under 'View'. The command allows you to view the calibrated date on the atmospheric curve.
File	#	Found on the menu bar. The command 'File' allows you to 'Save' or 'Download' a 'Plot'.
Save as	#	Found under 'File'. Tick 'Save as' and a new screen will open. Create a 'Folder', assign a 'Name' and press 'Save'. The 'Plot' will be saved in your OxCal folder as .csv files.
Download	#	Found under 'File'. Repeat the same step under 'Save as'. However, instead of pressing 'Save' press 'Download'. The 'Plot' will be saved in your download folder as '.csv' files. They are in high resolution. Alternatively choose the scroll down 'Format' list and choose '.png' or '.pdf', then press 'download'. These files are low resolution.
@	#	Found on the menu bar. Click on '@' to return to the screen where you enter a single radiocarbon date.
Options	#	Found on the menu bar. The command 'Options' allows you to calibrate a radiocarbon date from the marine environment with the appropriate 'curve'. Click on 'curve'.
Curve	#	Found under 'Options'. 'Curve' lets you choose the '^{14}C Calibration Curve' and the "Marine/mixed curve'.
^{14}C Calibration Curve	#	Found under 'Options'. Use the scroll down list next to 'Atmospheric' in order to select a calibration curve: e.g. for the Northern Hemisphere choose 'IntCal13', for the Southern Hemisphere use 'ShCal13'.
Marine/mixed curve	#	Found under 'Options'. Use the scroll down list next to 'Marine' in order to select a calibration curve: e.g. the latest version is 'Marine13'.
Marine %	#	Found under 'Options'. Include the percentage of marine diet of the sample including its error value, e.g. 45 ± 10.
Delta_R	#	Found under 'Options'. Set the 'Delta_R' to, e.g. 111 ± 10 for Icelandic data. The individual values can be found at: http://calib.qub.ac.uk/marine/
Plots dates	#	Choose 'Plot dates' in order to view the calibrated radiocarbon dates as a multiple plot. Change the view using the 'Zoom', 'Centre' and 'Span' buttons on the right hand side menu bar. A more controlled way to change the view is under 'Format' on the menu bar.
Adjust	#	Found under 'Format'. You can change the scale of the size of the font, the axes, the 'X Axis' etc. In order to change the size of the font click on '$_{A}$' (for small letters) or 'A' (for big letters). To change the image style, press the arrow button on the top left side.
PPP	#	Found under 'Adjust'. The number at 'PPP' allows you to change the space between samples, e.g. choose '30' for up to twenty dates; choose '40' or '50' for more than twenty dates. Press the arrow button.
X Axis	#	Found under 'Adjust'. The 'X Axis' lets you change the time span of

		the dates. You can select 'centre' and 'span'. Press the arrow button.
Plot	#	Found under 'Adjust'. 'Plot' can be found under 'Format'. Here you can add and remove certain data on the plot. It is useful to tick 'Agreement' as individual agreement indices for each sample will be displayed on the graph. For 'Outlier models' it is useful to tick 'Outlier'. Press the arrow button.
A	#	The agreement index value ('A' values) quantifies the degree to which the data support the proposed model; they are calculated for the posterior distributions. 'A': Individual agreement index > 60.
A_{model}	#	An 'Agreement model' is used to see if the model is likely to given the data > 60. If the posterior distribution of the model falls below 60% there is some clear error in the stratigraphic position of the samples and/or the 'Phases' and 'Sequences'. In this case the model has to be revised.
$A_{overall}$	#	Similar to 'A_{model}'. Product of the individual 'Agreement indices' > 60.
A_{comb}	#	An 'Agreement model' that is used for combined samples. Individual agreement index > 60.
C	#	The Convergence integral (C) tests whether the analysis has provided a representative posterior probability distribution by examining how similar different attempts to perform the analysis are. It should be above 95% (arbitrary cut-off).
O	#	'Outlier'. This command is used for 'Outlier_models' only. It tests how likely the sample is an 'Outlier'. The prior and posterior probability of each sample is demonstrated.

Tab. 2-3: Commands on the input module using CQL2.

File	#	Found on the menu bar. To open the input module press 'File' in the menu bar.
New	#	Found under 'File'. Press 'New', a new window will be displayed and the input module will open including a new menu bar.
Tools	#	Found on the menu bar. 'Tools' lets you select 'Options', 'Curves', 'Models' and 'Import'.
Import	#	Found under 'Tools'. Use the scroll down list under the menu bar and choose the command 'R_Date' (Radiocarbon date). 'Import' lets you copy and paste the 'name' ('Lab code') the '14C date' ('Date') and the uncertainly' ('±') from an Excel sheet into the text box. Click '>>' in order to paste the radiocarbon dates into the plot on the right hand side. Your dates should now appear in the right hand of the screen in the format 'R_Date'. Alternatively, you can add individual dates under 'Insert'.
Insert	#	Found on the menu bar. 'Insert' allows entering any type of date to the 'Plot'. Use the scroll down list under the menu bar in order to select a date/type, e.g. this can be a 'R_Date'. Additional information is needed: 'Name', ^{14}C date' and 'Uncertainty'. Click '>>' to add the dates to the plot.
Sequence	#	Found under 'insert'. Name the 'sequence'. A 'Sequence' is an ordered group from contexts that have clear stratigraphic relationships. Within a 'Sequence' the individual elements can

		themselves be ‘Sequences’ or ‘Phases’.
Phase	#	Found under ‘Insert’. Assign a ‘Name’ to the ‘Phase’. A ‘Phase’ is an unordered group of elements for which there are no fixed relations; thus no assumptions are made. A ‘Phase’ represents the archaeological context. Within a ‘phase’ the individual elements can themselves be ‘Sequences’ or ‘Phases’.
Boundary	#	Found under ‘Insert’. Assign a ‘Name’ to the ‘Boundary’. ‘Boundaries’ are used at points in the stratigraphy where the archaeological evidence suggests a hiatus in deposition; e.g. the start/end age for an archaeological context. A ‘Phase’ that has been given definite ‘Boundaries’ assumes a uniform distribution of data.
Tau_Boundary	#	Found under ‘Insert’. A ‘Tau_Boundary’ is used for to define an exponentially defined group or a phase of activity that does not have a definite start and end event. It assumes that the density of results is likely to be greatest toward the younger end of the phase. The dates are all earlier than the event in question and are distributed exponentially, meaning events either build up to or decay away from some defining event, e.g. samples under a destruction layer.
Sigma_Boundary	#	Found under ‘Insert’. A pair of ‘Sigma_Boundary’ states a normal distribution of the ‘Phase’ that does not have a definite start and end event. It can also be combined with a simple ‘Boundary’.
Zero_Boundary	#	Found under ‘Insert’. It is used to define the start or end of the group where the event rate has a ramped distribution.
Interval	#	Found under ‘Insert’. An ‘Interval’ can be added to events. It calculates the duration of the ‘Phase’.
R_Date	#	Found under ‘Insert’. Type in ‘Lab code’, ‘Date’, and ‘±’. ‘R_Dates’ (Radiocarbon dates) are incorporated in the model in their uncalibrated form with uncertainties as appropriate; they calculate the likelihood distribution for the calibrated date as a function of radiocarbon concentration.
R_Combine	#	Found under ‘Insert’. Type in ‘Lab code’, ‘Date’, and ‘±’. ‘R_Dates’ are combined with a χ^2 test. This can be a set of ‘R_Dates’ where all determinations have the same true mean and any differences between ^{14}C measurements were due to changes in the circumstances under which the determination was made (Ward and Wilson 1978:20). .
C_Date	#	Found under ‘Insert’. Type in ‘Name’, ‘Date’, and ‘±’. ‘C_Dates’ are true calendar dates without errors or uncertainties, such as ‘C_Date(“Colonisation” 877)’.
C_Simulate	#	Found under ‘Insert’. Type in ‘Name’, ‘Date’, and ‘±’. Tephra, historical, numismatic and typological dates are incorporated in the model as ‘C_Simulate’ with uncertainties as appropriate plotted as a normally distributed range with a mean value and assessment of the error, citied at the 68.2% confidence level. A bead that is dated between 960 and 1000 AD is incorporated in the model as 980±10. A historical date that is assumed to lie somewhere between 1090 and 1150 is incorporated in the model as 1120±15.
Combine	#	Found under ‘Insert’. Dates of different sources are combined, e.g. ‘R_Date’ and ‘C_Date’.
Date	#	Found under ‘Insert’. A ‘Date’ allows the HPD range of the date of the event to be entered directly. It provides a generic date likelihood

		of data, such as object types.
Color	#	Found under 'Insert'. Type in the name of the 'Color'. There is no rule which 'Color' to choose for what material/dating technique.
Label	#	Found under 'Insert'. Different type of samples can be labelled, e.g. 'bone samples'.
After	#	Found under 'Insert'. Elements, which determine a TPQ, e.g. a tephra layer. The 'After' function employs a prior that only allows solutions to be drawn for the associated parameter that are from the younger end of the likelihood or younger.
Outlier	#	Found under 'Insert'. In case the posterior distribution of a sample falls below 60%, the sample is considered an 'Outlier'; either it is a statistical 'Outlier' or a residual/inverted sample. The command Outlier defines specific radiocarbon dates: 'Outlier ([name] [prior]);' 'Name': 'Charcoal' or 'General'. The term 'General' is used for any material apart from 'Charcoal'. 'Prior': the prior probability that the sample is an outlier. The typical value is set to 0.05 for a 1 to 20 chance that the measurement needs to be shifted.
Outlier_Model	#	Found under 'Insert'. 'Outlier models' are mostly used for charcoal samples ('Charcoal'), but can be also used for any other material ('General'). The following commands are used for outlier models: 'Outlier_Model ([name] distribution [scale [type]]);' The command 'Outlier_Model' defines the model; the command 'Outier' defines specific radiocarbon dates. 'Name': the name of the model: either Charcoal or General (for any other material). 'Distribution': the definition of how the outliers are distributed: it can be Exp, T, U or N. 'Exp': Exponential distribution with an exponential constant τ of 1 taken over the range -10 to 0. 'T': Student's t distribution 5 degrees of freedom. 'U': Uniform distribution. 'N': Normal distribution range 0-1. 'Scale': this defines the scaling of the outliers, expressed in powers of 10. This can be a number or a distribution. 'Type': this defines the type of outlier: either because of a time variable ("t"), because of the uncertainty in the ^{14}C concentration ("s"), or because of the ^{14}C isotope rations ("r").
Trapezoid model	#	Found under 'Insert'. The trapezoid model can be used for artefacts that show a gradual increase (introductory period), then, a period of constant rate of activity (blooming period); and finally, a gradual decrease (period of decline).
File	#	Found on the menu bar. 'File' lets you calibrate the dates.
Run	#	Found under 'File'. Select 'Run'. In case there is a problem with the dates the running process will be screened in a single red bar; in case the data is fine the running process will be screened in three blue bars representing 'Done', 'Convergence' and 'Ok'. Once the calibration process is finished the Output module is opened and a table is shown. The menu bar is now identical to the one that is used to calibrate the single date.

^{14}C dates are calibrated using the 'IntCal13' (Reimer et al. 2013) and 'ShCal13' (Hogg et al. 2013) curves representing the mid-latitude Northern and Southern Hemisphere atmospheric reservoirs. However, the Northern and Southern Hemisphere division is debated for geographic areas below the South Tropical Convergence Zone (Petchey et al. 2009; Marsh et al. 2018). Reservoir-affected bone samples in Iceland were corrected using a mixed curve approach using the 'IntCal13' and the 'Marine13' curve (Reimer et al. 2013) – the latter represents the 'global' marine reservoir – as well as the regional deviations from it, known as ΔR (for Iceland the ΔR value of 111 ± 10 is used). All of the modelled ^{14}C estimates are presented using the 68% and 95% confidence level.

Within this thesis, single-phase, multiple-phase and age-depth models are used for appropriate datasets (Chapters 5-7, Appendices V, VI.B, VII.D). Single-phase models are used for an unordered group of ^{14}C dates, which are modelled as a 'Phase' (e.g. multiple dates from the same archaeological context or from contexts that were stratigraphically equivalent). A 'Phase' is bracketed by 'Boundaries', within a 'Sequence' – an ordered group of events (Fig. 2-7; Bronk Ramsey 2009b). This model assumes that all dates are uniformly distributed between the two 'start' and 'end' 'Boundaries'.

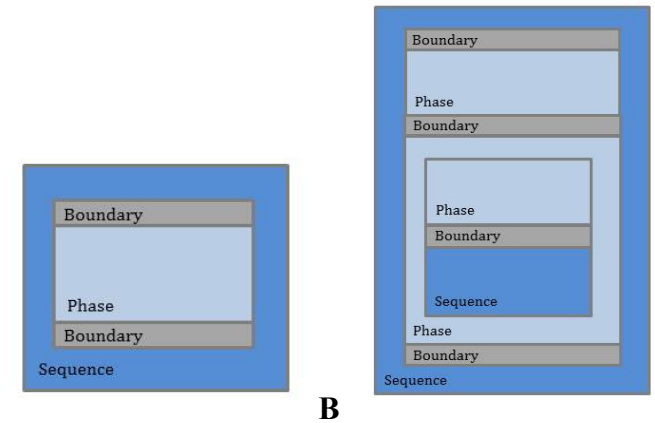


Fig. 2-7 Single-phase and multi-phase models using OxCal. **A**. Single-phase model. **B**. An example of a multiple-phase (B) model using a variety of 'Phases' and 'Sequences'. The ^{14}C dates were incorporated into the models as 'R_Dates' in their uncalibrated form.

Multi-phase models are used for ^{14}C dates where stratigraphic relationships between samples are known. This typically relates to archaeological sites, where contexts are recorded and have yielded a sufficient number of ^{14}C dates (>n = 10). Such models consist of both 'Phases' and 'Sequences' depending on whether archaeological contexts had clear stratigraphic relationships. Age-depth ('Poisson Sequence') models are used for sedimentary sequences (Chapter 5.3, Appendix V). This type of analysis allows for variability in deposition

processes of sediments giving approximate proportionality to 'z', which refers to the depth of samples. The command 'P_Sequence' is used, which provides a robust model to account for random sediment deposition.

Where relevant, tephra isochrons and artefact typological dates were included as 'C_Dates' (calendar dates) with uncertainties as appropriate, plotted as a normally distributed range with a mean value and assessment of error cited at the 68% confidence level (Chapters 5 and 7). Tephra isochrons can also be included using the 'After' command, for a TPQ of archaeological features above a tephra layer, or using the 'Before' command, for a TAQ of archaeological features below a tephra layer (Chapter 5). Uniform distribution of calendar dates can also be included using the 'Date' command, such as for bead typologies (Chapter 5). The modelled estimates have been given in italics when discussed within this thesis to differentiate them from the raw calibrated age ranges. The 'Boundary' before the 'Phase' provides a HPD range of the *posterior* distributions. These HPDs generate secure TAQs for archaeological events. This thesis compares the 'Agreement Index' and 'Outlier models' to assess whether dates are statistical outliers within a model constructed in OxCal.

2.5.1 Agreement Index

Originally, models produced in OxCal relied on the 'Agreement Index' values ('A' values) to objectively identify outliers. This index quantifies the degree to which the data support the proposed model; it is calculated for the *posterior* distributions of each date in the model and for the overall model itself. The critical value defined for the 'Agreement Index' is set at c. 60%; values below this level were indicative of a high likelihood (>95%) that there is a problem within a 'Sequence' and may indicate the presence of residual or intrusive material or errors in the stratigraphic interpretation or ^{14}C measurements (Chapters 5 and 6). If dates were highlighted as being anomalous, the security of the material and the context were reassessed using the site records. Samples below this value were manually removed until the overall model had an 'A' value of >60% (Bronk Ramsey 1995; Bayliss and Bronk Ramsey 2004). This approach is time consuming when dealing with large datasets.

2.5.2 Outlier models

Box 2.5.2 'General' and 'Charcoal (Plus) Outlier models'
(Bronk Ramsey 2009a, Christen and Pérez 2009, Dee and Bronk Ramsey 2014)

Outlier_Model ("General",T(5),U(0,4),"t");

The most common model used in archaeology is the General t-type 'Outlier_Model'. It draws the outlier from a Student T distribution with 5 degrees of freedom ['T(5)']; the scale of the offset is allowed to range anywhere between 10^0 and 10^4 years ['U(0,4)']; the type used is "t" where the samples measured might not relate to the timing of the event being dated (Bronk Ramsey, 2009b). The Student T distribution is bell-shaped like a normal distribution, but with longer tails to account for extreme outliers and is therefore very flexible (Fig. 2-8.A). The command 'Outlier("General", 0.05)' is used defining the prior probability to 5%.

Outlier_Model ("Charcoal",Exp(1,-10,0),U(0,3),"t");

This model is recommended by Bronk Ramsey (2009b) for wood charcoal samples with inbuilt ages. The distribution used is 'Exp(1, -10,0)'. Such a distribution is exponential, but with an unknown time constant: longer than a year but shorter than a thousand years. The scale is 'U(0,3)' which lies anywhere between 10^0 and 10^3 years; the type used is "t" where the samples measured might not relate to the timing of the event being dated. The command 'Outlier("Charcoal", 1)' is used defining the prior probability of 100%.

Prior ("charcoal_plus","charcoal_plus.prior");
Outlier_Model ("Charcoal_Plus",Prior("charcoal_plus"),U(0,3),"t");

This model is built on the Charcoal Model using the same exponential distribution, scale and type (Fig. 2-8.B). This model additionally allows a small number of samples to be intrusive. The command 'Outlier("Charcoal Plus", 1)' is used defining the prior probability of 100% (Dee and Ramsey 2014).

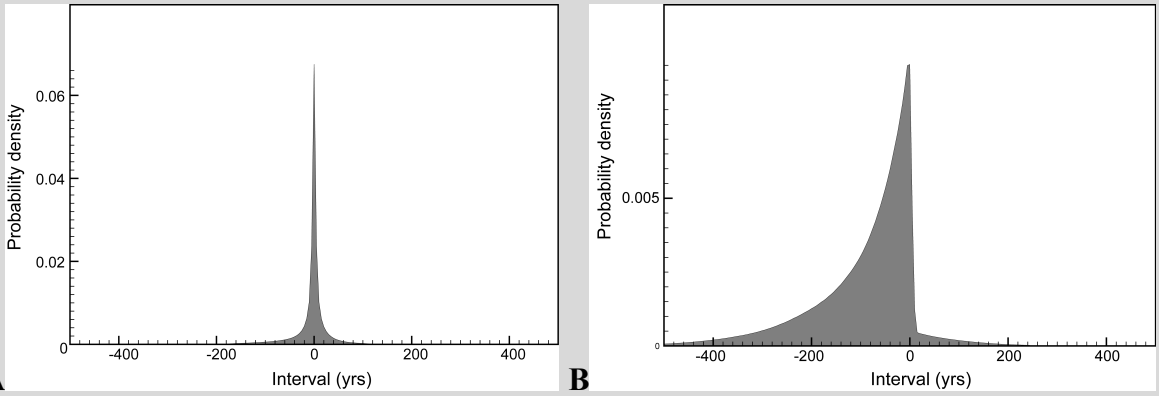


Fig. 2-8: Distribution curves of 'General' and 'Charcoal Plus Outlier models'. **A**. The 'General Outlier models' use a Student T distribution with 5 degrees of freedom. **B**. 'Charcoal Plus Outlier models' use an exponential distribution of individual outliers and shift the whole sequence towards the younger end range. They also allow a small percentage of intrusive material to be included.

Bronk Ramsey (2009a) introduced a Bayesian outlier analysis approach; the model identifies and downweights dates that are inconsistent with the surrounding data. To do this, the distribution of outliers must be described (the 'Outlier Model'), and the *prior* probability of each sample within this Outlier model assessed (Box 2.5.2). For dates on short-lived materials, the 'General t-type Outlier model' is recommended, which assumes that outlying dates are due to movement between stratigraphic units, and are distributed according to a 'Student T' distribution (Fig. 2-8.A). This is a flexible model and assumes that, although most samples are not outlying, a minority may be much too young or much too old. All short-lived materials were given a 5% prior probability of being an outlier within this distribution. The model generates a posterior outlier probability for each sample, and downweights the significance of the sample within the model accordingly. For example, a sample found to have an 80% chance of being an outlier will only be included in 20% of the model runs.

Bronk Ramsey (2009a) suggests treating samples with inbuilt age, such as charcoal from heartwood, differently (Chapter 2.3.1). The 'Charcoal Outlier model' uses an exponential distribution for outliers to account for samples where the distribution relates to the lifespan and growth habit of trees assuming that outliers are most likely to be too old due to their inbuilt age. Here, samples with inbuilt age are assigned a 100% likelihood of being an outlier and the distribution is less flexible – it only shifts towards the younger end. This model does not eliminate odd erroneous dates, but it shifts the whole sequence in one direction.

A recent modification of this model has allowed a small number of samples to also be younger than the context they represent – such as intrusive material ('Charcoal Plus Outlier model': Fig. 2-8.B) (Dee and Ramsey 2014). Unlike previous syntheses in OxCal ('A' values) none of the dates have to be removed, despite the inevitable presence of outlying dates, because the age offsets of charcoal samples are successfully corrected (Chapters 6-7).

2.5.3 An introduction to 'OxCal_parser'

Box 2.5.3 Installation of 'OxCal_parser' (https://bitbucket.org/luca_foresta/oxcal_parser)

'OxCal_parser' reads an input spreadsheet file (.xlsl or .csv) and automatically generates a text output (.txt) in 'CQL2' for OxCal. The program can be installed on your computer in the following steps (Fig. 2.9):

1. Download the code 'OxCal_parser.py' (https://bitbucket.org/luca_foresta/oxcal_parser) and copy it into a new file on the your Desktop. The file should be given a name, for instance 'OxCal'. Do not use any space for file labelling.
2. Use a spreadsheet file (.xlsl or .csv) with the same optional and mandatory fields from Appendix V and copy it into the folder 'OxCal'. The folder should not be closed. In Figure 2-9 I use the spreadsheet 'Iceland all dates'.
3. Login to 'Terminal' on your computer.
4. On Terminal notify your computer where your folder is located. Type: cd Space Location/Name of folder/. It is important to use "Space" correctly
In our example this would be: Magdalenas-MacBook-Pro:~ Magda$ cd Desktop/OxCal/
5. Type in the name of the code: python Space 'name of code'
In our example this would be: Magdalenas-MacBook-Pro:Pythons Magda$ python OxCal_parser.py
6. Press enter. The spreadsheet file is automatically converted into a text output (.txt). In this case it is 'Iceland all samples.txt'
7. Copy this text into the input model in OxCal (https://c14.arch.ox.ac.uk/oxcal/OxCal.html?Mode=Input&).
8. Run the model.

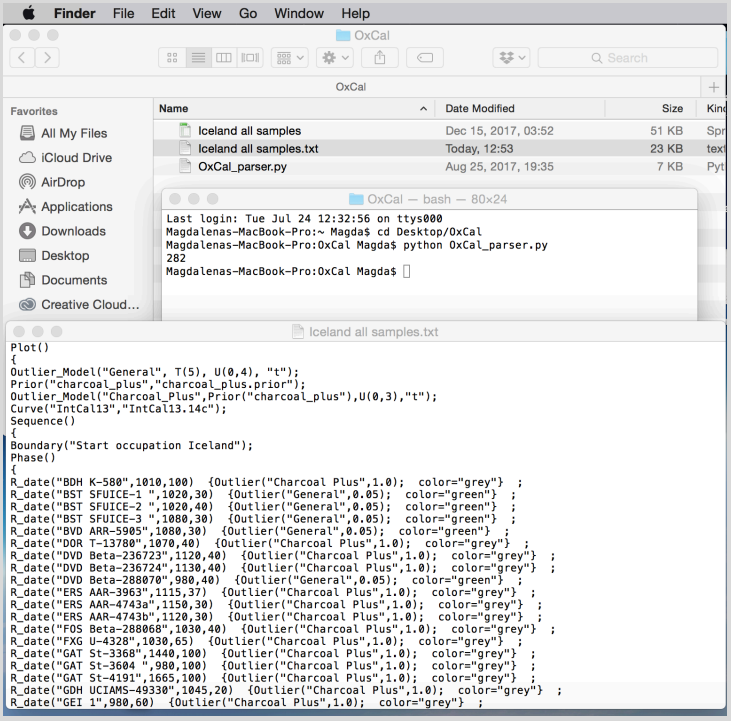


Fig. 2-9 Installation of 'OxCal_parser' for applications in OxCal.

OxCal currently allows uploading spreadsheets including 'Sample ID', 'CRA' and 'error value'. In this thesis more than 1000 Outlier model runs on OxCal were performed, each with some tens to hundreds of ^{14}C samples arranged in different 'Phases', 'Sequences' and 'Boundaries', where information – such as the type of outlier and the 'P value' had to be manually entered. Not only is this time consuming, but also can lead to significant errors in the dataset. As an example, I accidently included a mixed sediment sample as a 'General', short-lived date in a number of models (GAT St-4191: 1665 ± 100). Models would either not converge at all or the whole process was extremely slow and resulted in inaccurate *posterior* probabilities. It took me several months to find the mistake after building hundreds of Outlier models using different datasets and different 'Boundaries' and I almost gave up on Outlier models. Therefore, rigor is required in uploading ^{14}C datasets.

To increase the speed and accuracy of data import to OxCal, this thesis therefore introduces a program (OxCal_parser), which I commissioned from Dr. Luca Foresta (Chapter 7). It reads an input spreadsheet file (.xlsl or .csv) and automatically generates a text output (.txt) in 'CQL2' (Box 2.5.3). The program runs instantaneously and the output can be copied in the OxCal text browser to run models without adding any additional information (Fig. 2-8). It allows automatic data entry of small to very large datasets with simple and complex stratigraphy in a timely manner, but does not perform any computation. 'OxCal_parser' is available on Bitbucket (https://bitbucket.org/luca_foresta/oxcal_parser); users can freely download or clone the program and alter it according to individual needs. 'OxCal_parser' is written in Python 2.7, which is an open access programming language.

This thesis provides six examples with datasets from the Northern and Southern hemispheres (Iceland and New Zealand) that demonstrate how 'OxCal_parser' works (Chapter 7, Appendix VII.B and D). It can be used to produce both single-phase and multi-phase models using the same structure with mandatory and optional fields (columns). Mandatory fields are Sample ID ('Lab Code'), Conventional ^{14}C Age ('Date') and Error ('±'), together with their Date Type ('radiocarbon') and the calibration curve ('IntCal13' or 'ShCal13') (Table 2-4). The Start Boundary Label is the HPD of the model and can be assigned a label, for instance 'Start occupation'. Optional fields are the type of outlier model ('General' or 'Charcoal Plus'), the type of outlier for each individual ^{14}C sample, together with its related P Value (e.g. p = 0.05 for short-lived material; p = 1 for wood charcoal samples), and a 'Color'. If optional fields are not used for a specific model, the columns should be empty, as demonstrated in Appendix VII.B.

Table 2-4 Mandatory and optional fields using 'OxCal_parser'. Mandatory fields are highlighted in grey. It is important to keep the labeling of columns otherwise the program will not run.

Start Boundary Label	Calibration Curve	Sample ID	Conventional Radiocarbon Age	Error	Date Type	Outlier Model	P Value	Color	Stratigraphic Block	Block Label	Stratigraphic Block 2	Block Label 2
Start occupation	IntCal13	LTL	877	1	calendar			red	1	Sequence	1	Sequence
		RKV-AST AAR-7622	1262	35	radiocarbon	Charcoal Plus	1	grey	2	Phase	1	Sequence(Hearth)
		RKV-AST AAR-7614	1218	40	radiocarbon	General	0.05	green	2	Phase	1	Sequence(Hearth)
		RKV-AST AAR-7620	1184	35	radiocarbon	Charcoal Plus	1	grey	2	Phase	1	Sequence(Hearth)
		RKV-AST AAR-7612	1150	36	radiocarbon	General	0.05	green	2	Phase	1	Sequence(Hearth)
		RKV-AST AAR-7621	1210	33	radiocarbon	Charcoal Plus	1	grey	2	Phase	1	Sequence(Hearth)
		RKV-AST AAR-7613	1087	35	radiocarbon	General	0.05	green	2	Phase	1	Sequence(Hearth)
		RKV-AST AAR-7619	1282	35	radiocarbon	Charcoal Plus	1	grey	2	Phase	1	Sequence(Hearth)
		RKV-AST AAR-7611	1092	39	radiocarbon	General	0.05	green	2	Phase	1	Sequence(Hearth)
		RKV-AST AAR-7623	1226	33	radiocarbon	Charcoal Plus	1	grey	2	Phase	2	Phase(Floor)
		RKV-AST AAR-7624	1192	36	radiocarbon	Charcoal Plus	1	grey	2	Phase	2	Phase(Floor)
		RKV-AST AAR-7625	1236	35	radiocarbon	Charcoal Plus	1	grey	2	Phase	2	Phase(Floor)
		RKV-AST AAR-7615	1153	36	radiocarbon	General	0.05	green	2	Phase	2	Phase(Floor)
		RKV-AST AAR-7616	1129	35	radiocarbon	General	0.05	green	2	Phase	2	Phase(Floor)
		RKV-AST AAR-7617	1152	36	radiocarbon	General	0.05	green	2	Phase	2	Phase(Floor)

In scenarios with complex stratigraphy, the user can divide the samples in multiple 'Phases' and/or 'Sequences' (Table 2-4, Fig. 2-7). This is achieved through the 'Stratigraphic Block' field and the 'Block Label' field. Each 'Sequence' or 'Phase' is given a number, where 1 represents the oldest archaeological event. 'Boundaries' are automatically added by the program. In cases where a 'R_Date' or 'C_Date' is not part of any 'Sequence' or 'Phase', these samples can be placed in an independent stratigraphic block. More information is provided in Chapter 7 and Appendix VII.B and D.

2.5.4 The 'Difference' function

This thesis uses various Bayesian approaches (using the 'Agreement Index', the 'General Outlier model' and the 'Charcoal Plus Outlier model') in order to assess different strategies for assessing groups of ^{14}C dates after the applications of chronometric hygiene. Dataset choices include:

Multi-phase models of:

- Individual archaeological sites (Chapters 5 and 6).

Single-phase models of:

- A whole dataset of an island (Chapters 6 and 7)
- Samples from archaeological periods (Landnám, post-Landnám, and Viking age contexts: Chapters 4 and 7)
- Short-lived taxa (e.g. grains/seeds, tree twigs, terrestrial bone: Chapter 7)
- Wood charcoal with inbuilt ages (Chapters 6 and 7)
- Bone samples affected by MRE (Chapter 6).

The aim is to assess whether the dataset yield a colonisation age which is consistent with independent tephrochronological dating using the Landnám Tephra Layer (LTL) of AD 877 ± 1 for the Icelandic dataset (Chapters 6 and 7) and the Kaharoa tephra of AD 1314 ± 12 (Hogg et al. 2002) for the New Zealand dataset (Chapter 7). In order to be considered different, the 'Difference' range does not overlap with zero. That is, the model generates a colonisation age range either earlier or later than the tephra layer in question.

3. The settlement of Iceland (Landnám)

Iceland was first settled from Norway in the days of Haraldr the FineHaired, son of Hálfdan the Black, at the time […] when Ívarr, son of Ragnarr lo[brók, had St Edmund, king of the Angles, killed; and that was 870 years after the birth of Christ, according to what is written in his [Edmund's] saga […].

Wise men have also said that Iceland was fully settled in sixty years, so that no further settlement was made after that. At about that time Hrafn, son of Hængr the settler, took up the office of lawspeaker after Úlfljótr, and held it for twenty summers;34 he was from the Rangá district. That was sixty years after the killing of King Edmund, and one or two years before Haraldr the Fine-Haired died, according to the reckoning of wise men.

Íslendingabók AD 1122-1133, Grønlie translation 2006: Chapters I and III

This chapter presents a summary and critical analysis of the dating tools that are applied in Iceland, particularly in archaeology, but also relevant to palaeoenvironmental reconstructions. For example, sediment accumulation rates and palaeoecology are introduced as methods. It considers the spatial distribution of excavated and identified archaeological sites, and potential biases in recovery of material, versus actual spatial patterning in a dataset. This refers to the potential uneven survival probability of older versus younger deposits, and the impact of this upon age measurements and Bayesian models outputs. However, uneven survival can also adversely affect younger deposits, depending upon the specific depositional system and/or contextual taphonomy.

3.1. Introduction – history of archaeological research in Iceland

The dating of Iceland's Landnám has been subject to both academic controversy and wide public interest. Iceland has produced one of the world's richest collections of medieval vernacular literature (Kristjánsson 1988); traditionally, these texts provided the framework for dating Iceland's Landnám to AD 870-930. The traditional dates are derived from the chronicle *Íslendingabók* written in AD 1122-33 (Grønlie transl. 2006). A comprehensive analysis of the typology of grave goods from pagan burials carried out in the mid-20th century, as well as typological dates from buildings, found that the assemblages had a '10th century' or 'Viking age' character and did not contradict the historical dates regarding the onset of colonisation in the late 9th century (Eldjárn and Friðriksson 2016). Until recently, any Viking age date in Iceland tended to be considered as synonymous with the Landnám and the whole period has tended to be regarded as a single indivisible block, despite variation

becoming apparent through the increasing application of radicarbon dates, tephrochronology and typology (beads and coins) since the 1970s.

By the late 1980s, there were 79 ^{14}C dates on material related to early human activities in Iceland (Vilhjálmsson 1991). Some of these dates extended back in time to the 6th and 8th centuries, but the relationship between these dates and human activities were not always clear and the result was a vigorous debate about the timing of Landnám (e.g. Hermanns-Auðardóttir 1989, Rafnsson 1990, Vilhjálmsson 1991, Kaland 1991, Mahler and Malmros 1991, Theodórsson 1998, 2009, 2012). Some of these ^{14}C dates were probably misleading, but it was difficult to argue the merits or limitations of individual dates in an objective manner. Methodological criticism of the interpretation of ^{14}C samples applies to archaeology globally rather than just to Iceland (e.g. the colonisation of New Zealand based on ^{14}C dates: Chapter 7; Anderson 1991; Higham and Hogg 1997; Sutton et al. 2008; Wilmshurst et al. 2008; 2011; Jacomb et al. 2014; Dye 2015). Significantly, numerous investigations into the chronology of Landnám have relied either on the typology of artefacts found in burials (Eldjárn and Friðriksson 2016) or on a few ^{14}C samples from an individual archaeological site (e.g. Reykjavík or Herjólfsdalur: Hermanns-Auðardóttir 1989). The investigations are typically discussed in isolation, whilst referring to other dating evidence uncritically (e.g. the stratigraphic relationships between ^{14}C dates and tephra layers and diagnostic artefacts).

In recent years a number of significant archaeological excavations and surveys in Iceland have illuminated new aspects of Viking age settlement, the Landnám. In particular, data have been systematically collected to assess colonisation as a process on a regional scale in two areas in the north (e.g. Vésteinsson and McGovern 2012; Bolender et al. 2011; Steinberg et al. 2016). Based on the Mývatnssveit data, it has been argued that the settlement process was rapid; in fact that the country was largely settled in less than 20 years (Vésteinsson and McGovern 2012). In contrast, surveys in the Skagafjörður region have suggested a gradual infilling of the landscape until the end of the 10th century (Bolender et al. 2011). Was colonisation a trickle or flood (Edwards 2012)? Figure 3-10 illustrates two models of colonisation that apply in particular to island settings. What are the implications of the timing, rate, and scale of colonisation? This is important, because the settlement of Iceland obviously persists to this day and can teach us important lessons about adaptation, sustainability, and how the Norse survived over multi-generational timescales in constrained circumstances with finite resources. These lessons are rooted in historical ecology, the

relationship between humans and their environments and the concept of landscapes (e.g. Crumley 1994).

The concept of a 'trickle', a slow diffusion, implies gradual change and potentially a better understanding of the local environment (local ecological knowledge: LEK) and settlement, and subsequent to a better resource management, which can lead to long-term sustainability of the environment and settlement (Fig. 3-10). For instance, cereal cultivation depends on the soil chemistry and external drivers – such as climate and weather, volcanic eruptions and competing people can have strong influence on a system's maintenance of the ecosystem (Walker et al. 2004). In Iceland, for instance, there is a volcanic eruption every five years (Larsen and Eiríksson 2008).

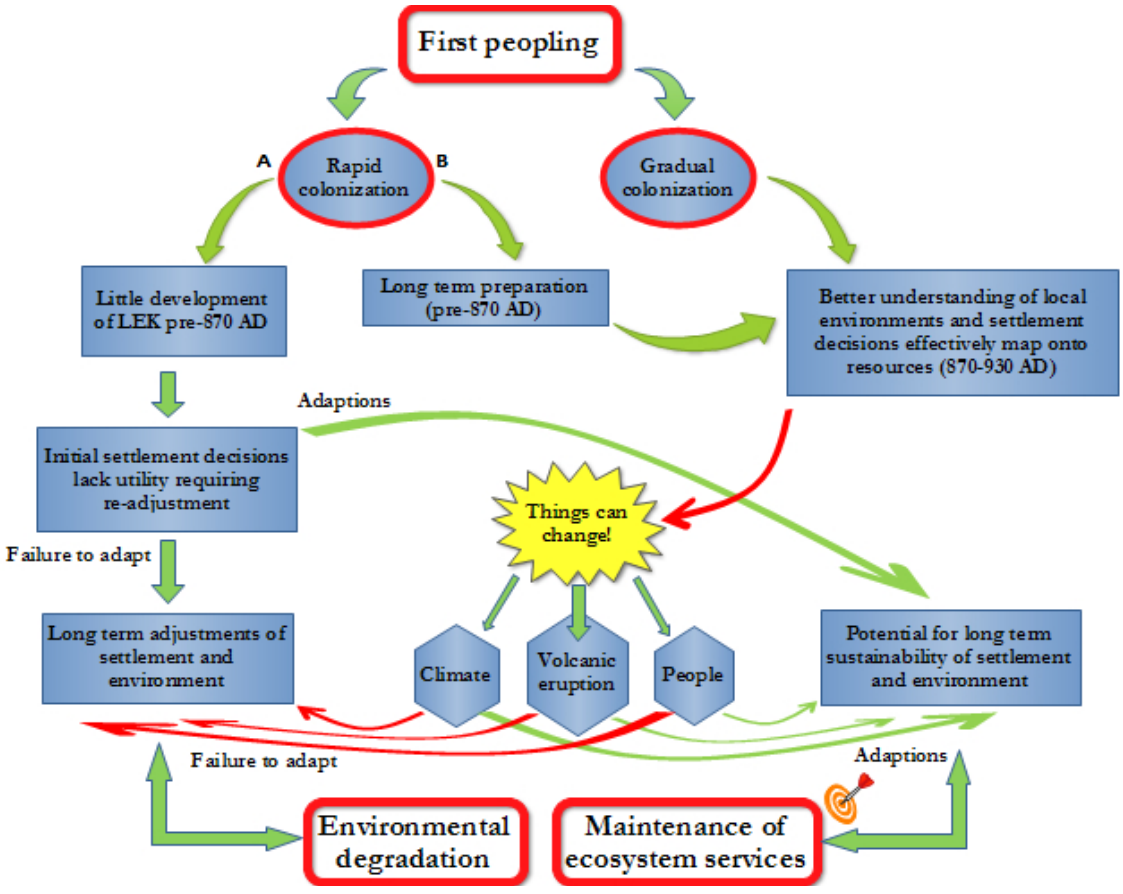


Fig. 3-10 Rapid ('a flood') vs. gradual ('a trickle') colonisation of pristine environments in island contexts and implications for settlement and environment. LEK: Local Ecological Knowledge.

The concept of a 'flood', or punctuated equilibrium, implies fast changes of state of progress (Folke 2006). In fact, without long-term preparations (Scenario A: Fig. 3-10), little

development of LEK may lead to failure of adaptation requiring long-term adjustments of settlement and environment. Long-term preparations for a successful settlement in Iceland (Scenario B: Fig. 3-9) include deforestation and leveraging of the landscape for the construction of farmsteads and animal husbandry. This implies that exploration of a new territory is a necessary first step of colonisation and equipped settlers with the knowledge needed for a secondary explosive colonisation. Nevertheless, external drivers can still affect adaptation leading to either long-term adjustments or sustainability of settlement and environment (Dugmore et al. 2006). This illustrates how precise chronologies could help understanding the spatio-temporal settlement dynamics in Iceland.

The wealth of multidisciplinary data on a countrywide scale, generated since the late 20th century, as well as a greater understanding of the basis of tephrochronology, ^{14}C dating, chronometric hygiene and Bayesian statistical modelling offers an excellent opportunity to shed new light on the understanding of settlement dynamics.

3.2 Establishing a holistic and multidisciplinary dataset

There are clear advantages in a multidisciplinary dataset for establishing high precision chronologies. A comprehensive dataset is important, because each piece of scientific knowledge is one part of a long chain that has to remain stable and reversible (LaTour 1988).

The first step in establishing a robust chronology of Viking age sites in Iceland involved the systematic collection of data demonstrated in Figure 3-11. This new compilation of data derives from more than 600 field reports, journal articles, and academic monographs, as well as from previously unassessed data that relate to anthropogenic activities. Data was gathered through a systematic search of the corpus of field reports site-by-site, including direct questioning of the excavators involved (in particular Magnús Sigurgeirsson for tephra layers) to achieve a dataset as comprehensive and accurate as possible (Appendices I-II). The target was secondary source data; archaeological sites that have been investigated from the 18th century to 2016 (n = 550) from all habitable parts of the island.

Archaeological interventions include large-scale excavations, multiple or single trenches and surface collections with dating evidence of different precisions, accuracy and bias that may range from excellent to problematic. The catalogue only includes dates that are related to or interpreted as human activity and excludes non-cultural, historical data, place names and sites where dating is unsecure – for instance where no tephra layer has been identified, no ^{14}C data taken or no typologically diagnostic artefacts or house shapes identified. Detailed recording

of stratigraphic location and relationships only became standard after the 1970s and the majority of burials were investigated before the routine application of tephrochronology (Vésteinsson 2004).

The data are summarized in tables including both descriptive and interpretative aspects (tephra layers: Appendix III, ^{14}C dates: Appendix VI.B, typologically diagnostic artefacts and house shapes: Appendices I-II). The descriptive part includes information about the site (the type of site, the geographic area, the type of intervention, the date(s) of intervention, and the location of the site). The interpretive section analyses the dating implications of those activities with the main focus being the earliest evidence of occupation (Appendices I-II).

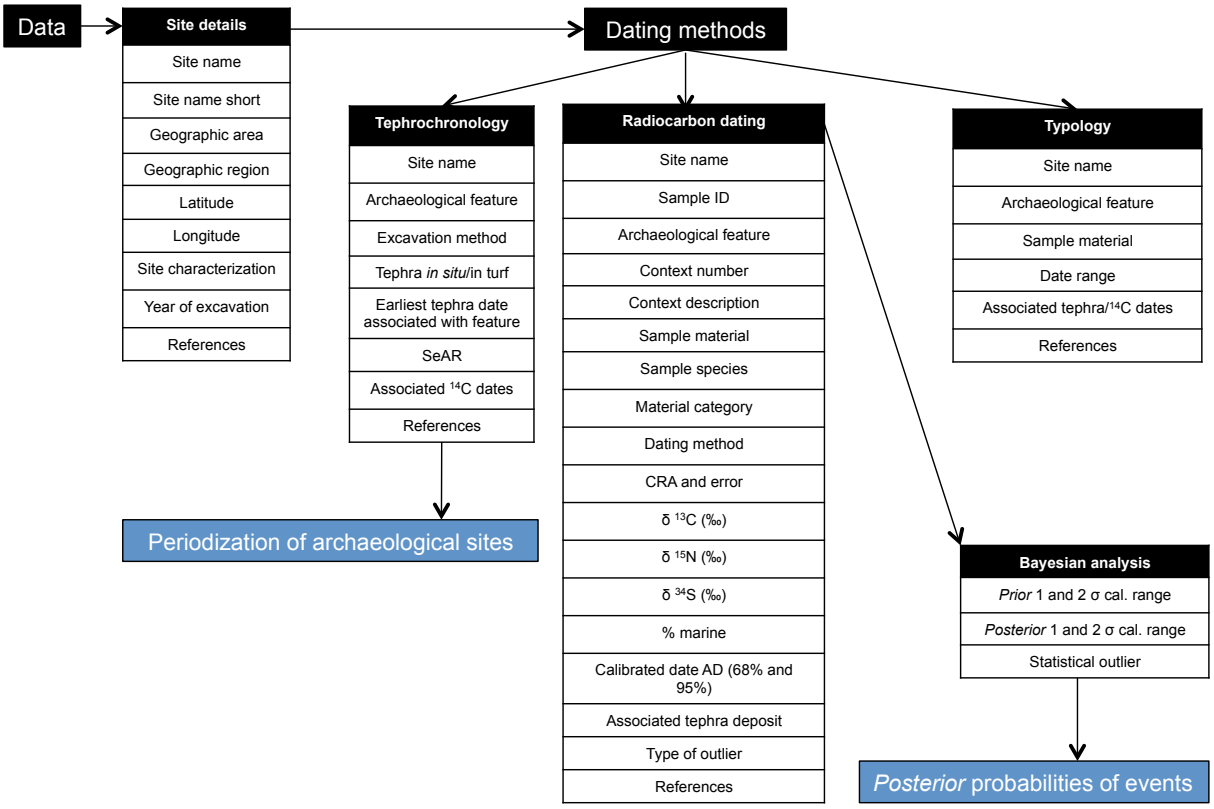


Fig. 3-11 Steps in establishing a high-precision chronology of anthropogenic activities in Viking age Iceland. The data are summarized in Appendices I-II. The blue boxes refer to the outcome of multidisciplinary data analysis.

3.2.1 Categorization of archaeological sites

550 archaeological sites are systematically classified into three basic categories – settlement sites, burial sites and assemblages. The systematic and minimal grouping of sites is used as a foundation for analytical work.

S = Settlements (n = 300)

B = Burials (n = 140)

A = Assemblages or stray finds (n = 110).

Settlement sites are defined as places where people resided and these can include both farms occupied year-round, and seasonally or intermittently occupied sites like shielings or iron making facilities as well as structures associated with farming in the outfields, anthropogenic burning or midden deposits. Archaeological features typically include dwellings (halls), pit houses, animal stalls, smithies, middens, caves, earthworks systems that encircle farm properties and early churches. Burials can consist of single or multiple internments. In some cases they can be associated with deposits or structures, primarily churches or enclosure walls. Some archaeological sites have features related to both settlement and burial. If they have been assigned the same name, they are not separated and are categorized under settlement. A loose find through surface collection without contextual information can represent a settlement, burial, hoard, or accidental loss. This is highly interpretative and depends on the expertise of the investigator; therefore, all loose finds are categorized as assemblages.

This thesis does not include classifications of archaeological sites, such as ´historic farm´ ‘large/medium/small abandoned farm’ and ‘shieling’ that have been used by Vésteinsson and McGovern (2012) for the Mývatn area and by Boldender et al. (2011) for the Skagafjörður area. Applying such classifications to the data under discussion here would require systematic evaluation of other geogroaphic areas in Iceland which is not yet possible. This dissertation also does not describe stylistic details – the number, shape and type – of archaeological features and objects neither does it evaluate the length of occupation of archaeological sites. This thesis focuses on the start of occupation of individual sites, which refers to the earliest archaeological feature that is securely dated (by tephra layers, ^{14}C dates and/or typologically diagnostic artefacts).

3.2.2 Geographic areas

The data are separated into four geographical areas within Iceland, the southwest (SW), the northwest (NW), the north (N) and the east (E). These areas are based on the administrative division of Iceland into quarters around AD 965 (*Íslendingabók* – Grønlie transl. 2006), when areas were divided by natural barriers to settlement and travel: glaciers, interior highlands and major rivers that remain stable reference points in the landscape. The thesis uses these geographical divisions to structure the discussion of the data.

Sites are also categorized into districts ('hreppur', pl. 'hreppar'); however their definition is not straightforward (Appendix II). The hreppar division of 1847 is used (Johnsen 1847); however some of these hreppar were split at different stages. For instance, Helgastaðahreppur became Aðaldæla- and Reykdælahreppar in the 1890s; Ljósavatnshreppur became Bárðdæla- and Ljósavatnshreppur in 1907. This thesis uses mostly the older hreppar divisions.

The coordinates were derived from excavation reports where this kind of information is available. When co-ordinates are not included in the report, the coordinates from LMI (the National Land Survey of Iceland: https://www.lmi.is/en/) maps are used. Altitude is not included in this study as this kind of information is not frequently reported, but could be estimated from the coordinates if required in future studies (as demonstrated in Fig. 4-16).

3.2.3 Date(s) of excavation

The dates of intervention (the timing of the research activity) for the 550 sites provide evidence for the shifting of regional archaeological activity and allow assessments of the quality of the data (Appendices I-II). Interventions are defined as year(s) of (re-)excavation or find accession. Accession year(s) are used when excavation/find years are not known, and this primarily refers to assemblages of artefacts. Less than 1% of the sites were investigated in the 18th century (n = 3), 16% in the 19th century (n = 91), 50% in the 20th century (n = 274) and 33% since the year 2000 (n = 182). Almost all burials and assemblages were discovered in the 19th and 20th centuries (96%). In contrast, 95% of excavated settlements were investigated in the 20th and 21st centuries. Significantly, the majority of settlements studied by archaeologists in the 20th century were investigated in the southwest (36%), while the majority of settlements investigated in the 21th century are from the north of Iceland (59%). The density of excavated settlements reflects modern priorities in terms of fieldwork activity. In the areas of most intensive fieldwork, the figures also indicate settlement density and population levels. It has been proposed that regional differences in burial frequencies are both an effect of discovery bias and differences in burial practices (Vésteinsson 2011). The

discovery of Viking age burials is more likely in areas where soil erosion has been active and where road sites coincide with burial locations (Eldjárn and Friðriksson 2016). On the other hand, there are differences in the visibility of burial rites resulting in the overrepresentation of furnished burials which seem to have been less prevalent in the western part of the country.

3.3 The spatial distribution of archaeological sites

Forty-eight percent of 550 Viking age sites are located in the north (n = 266), 28% are in the southwest (n = 157), 17% in the east (n = 93) and 7% in the northwest (n = 37). This distribution primarily reflects modern archaeological fieldwork priorities and is unlikely to reflect inherent archaeological contrasts.

The distribution of 300 settlement sites is shown in Figure 3-12. The majority of settlements (60%) are in the north (n = 182). Almost equal numbers are in the southwest and east (n = 50-58), while the northwest is underrepresented (n = 13). The distribution of 140 burials is shown in Figure 3-13, which shows that 46% of burials are found in the north (n = 65), 27% in the southwest (n = 37), 19% in the east (n = 27) and 8% in the northwest (n = 11). The distribution of 110 assemblages is presented in Figure 3-14 with 54% of assemblages in the southwest (n = 60), while the other areas are evenly distributed.

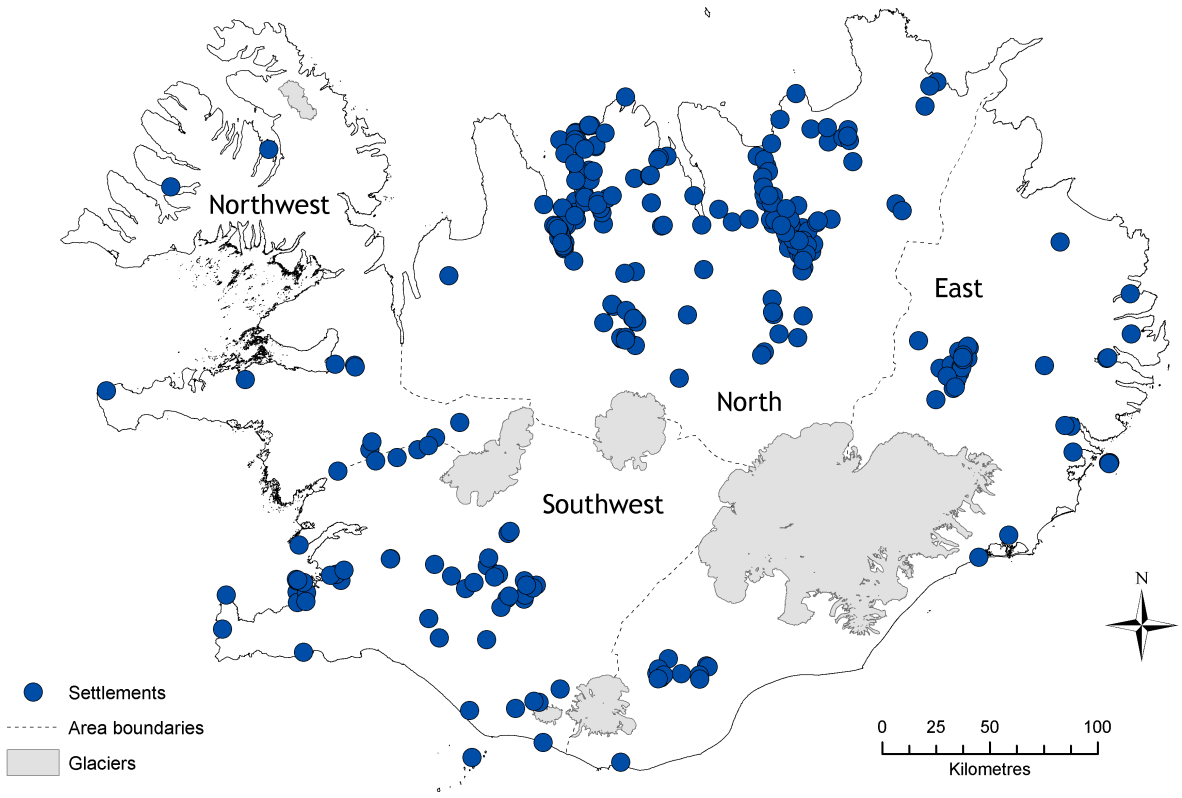


Figure 3-12 The distribution of 300 settlement sites in Iceland. 60% of the sites are located in the north of Iceland. The map was created by Anthony J. Newton.

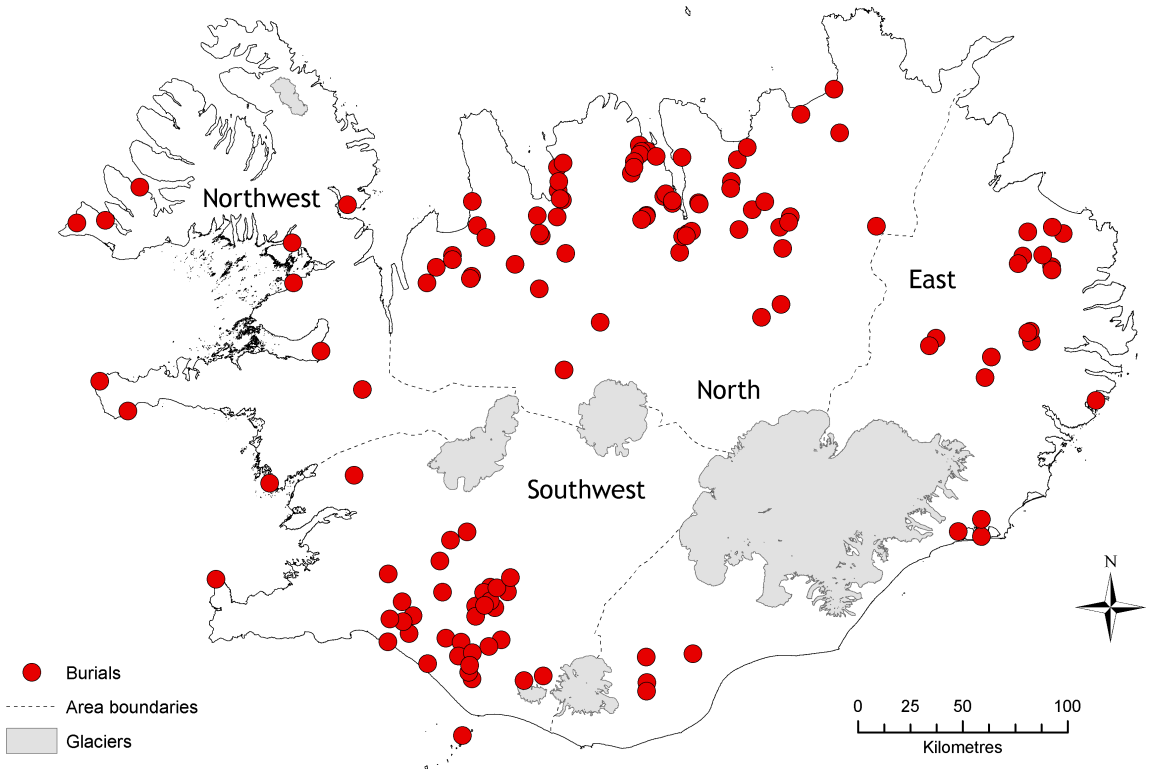


Figure 3-13 The distribution of 140 burials in Iceland. 46% of the sites are located in the north of Iceland. The map was created by Anthony J. Newton.

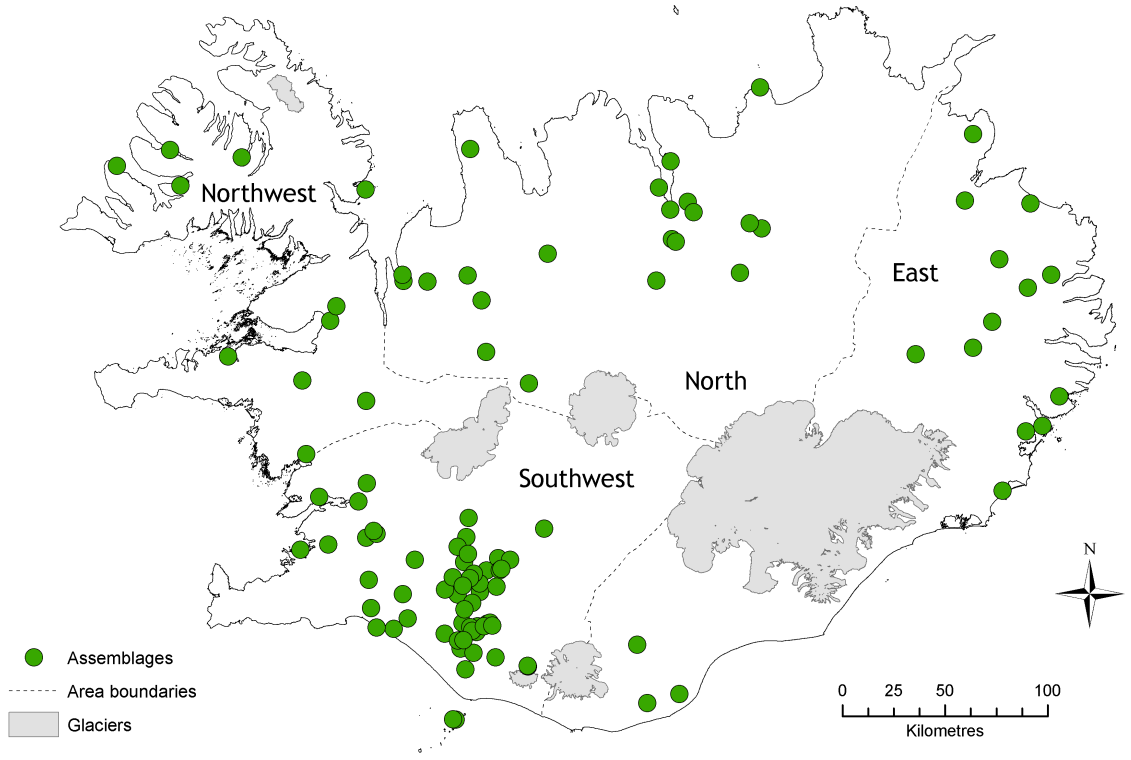


Figure 3.14 The distribution of 110 assemblages in Iceland. 54% of the sites are located in the southwest of Iceland. The map was created by Anthony J. Newton.

3.4 Accuracy, precision, and bias of multidisciplinary chronological datasets

Chronologies for Icelandic archaeological sites have been primarily based on tephrochronology, ^{14}C dating and typology (Schmid 2015). This thesis correlates for the first time such multidisciplinary datasets. It also introduces the concept of sediment accumulation rates (SeAR) that describe relationships between geological and historical events (e.g. archaeological features between two well-dated tephra layers) as well as key palaeoecological data that describe anthropogenic activities in the original landholding of archaeological sites (e.g. the burning of woodlands, the cultivation of barley). Each method produces dates of different precision, accuracy and bias, which are briefly described in this subchapter.

The dating methods are used to answer the following research question:

RQ1) ***What is the archaeological evidence of Landnám in Iceland*****?**

3.4.1 Tephrochronology

Box 3.4.1 Tephra nomenclature

Tephra: The term tephra (gr. *τέφρα* ash) is of Greek origin and is used as a collective term for pyroclasts (gr. *πῦρ* fire and *κλαστός* broken) – including both airfall and pyroclastic flow materials regardless of composition, shape, and size (Þórarinsson 1944). Tephra does not occur in Greek in plural form and in compound English words based on Greek roots, the vowel ´a´ is always replaced with ´o´ to form derivatives (Lowe and Hunt 1991).

Isochrons: Isochrons (gr. ίσος same and κρόνος time) are deposits of identical ages that allow high-precision dating and correlation of geological, palaeoenvironmental and archaeological events (Dugmore et al. 2004).

Tephrochronology: Tephrochronology is based on (a) identifying tephra deposits, (b) correlating separate deposits from the same eruption to define isochrons, and (c) establishing calendar dates for the tephra isochrons (Þórarinsson 1944; Lowe 2011). The development of tephrochronology as a geochronological technique was pioneered in Iceland by Sigurður Þórarinsson, who described the theoretical foundations of this dating technique and developed its applications through studies of archaeology, historical sources, geomorphology and environmental change (Þórarinsson 1944; 1958; 1967; 1975). The advantage of the technique is the correlation of tephra layers with historic volcanic events, which allows precise dating control – to the year and sometimes to the month or day. If such records are not available, tephra may be aged through ^{14}C dating of associated organic material or

wiggle-matched (e.g. the Kaharoa tephra in New Zealand: Hogg et al. 2002), through a combination of ice core correlations, or through construction of age-depth models in sediment (aeolian or lacustrine) sequences (Dugmore and Newton 2012).

Tephrostratigraphy: Tephrostratigraphy is based on the correlation of archaeological deposits with tephra isochrones through their stratigraphic position to provide relative ages (Lowe and Hunt 2001; Lane et al. 2017).

Proximal tephra: The application of tephrochronology usually involves proximal areas (lat. *proximus* nearest) typically preserved around 10 km from the vent, with tephra layers being visible with the naked eye (Þórarinsson 1981).

Cryptotephra: A terminology adapted by Lowe and Hunt (2001) and first described as 'teleconnections' by Þórarinsson (1981). Cryptotephra (gr. *χρυπτός* to hide) can be preserved in deep-ocean sediments, ice sheets, lake sediments or in peat bogs at the microscopic level (less than 100 μ) and are usually distal from the volcanic source (Lowe 2011; Lane et al. 2014).

Landnám tephra layer (LTL): The LTL (or landnámslag: 'the settlement layer') was first described by Þórarinsson (1944); it is associated with the earliest anthropogenic deposits in Iceland.

Landnám sequence (LNS): *Landnámssyrpa* or LNS is a series of 12 distinctive tephra layers forming a group below and above the LTL (Sigurgeirsson et al. 2013). Within this sequence are five firmly dated tephra isochrones: the LTL, V-Sv of AD 936 ± 6, H-1158, V-1159, H-1300 and V~1477, as well as several estimated tephra layers: K(8) of AD ~734, K(7) of AD ~777, G(6) of AD ~783 and G(5) of AD ~805.

Sediment accumulation rates (SeAR): SeAR refer to aeolian accumulation in non-uniform depositional environments. They are used to estimate the age of unknown tephra layers between firmly dated ones (e.g. Sigurgeirsson et al. 2013; Streeter and Dugmore 2013). They can also be correlated with archaoelogical deposits: SeAR are used to estimate the time elapsed between the deposition of a particular tephra layer and anthropogenic disturbance, such as structures, midden or cultivation, and ^{14}C dates (e.g. applied by Chruch et al. 2007).

Iceland's location on the mid-Atlantic ridge means it is subject to frequent volcanic activity (Larsen and Eiríksson 2008). Iceland has many effusive, basaltic fissure eruptions that become explosive due to interaction between water and magma (Larsen 1981). Explosive eruptions typically last short periods of time and generate large volumes of ash (tephra) that

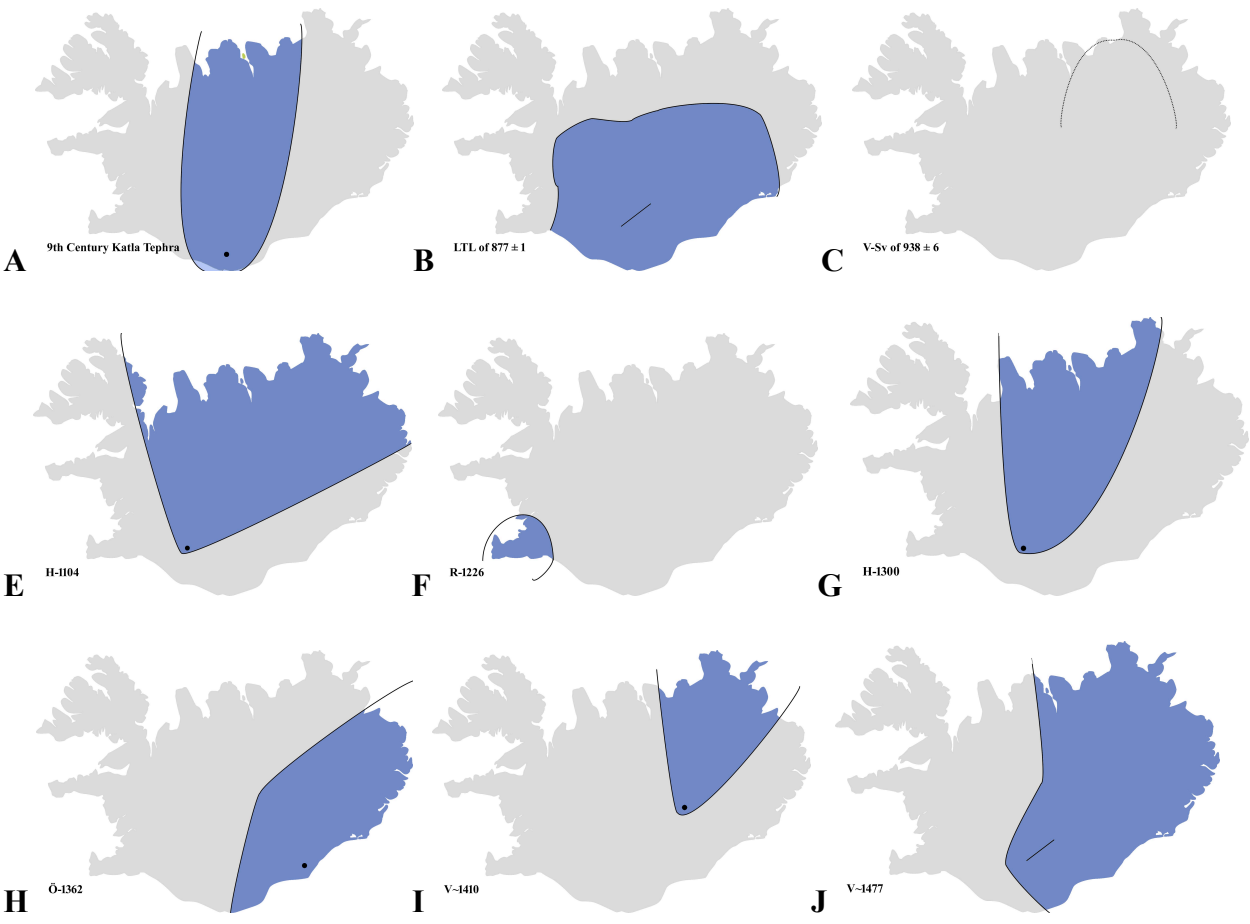
can be rapidly transported within the atmosphere and are deposited onto the landscape (Lowe 2011). Because of their rapid deposition, tephra layers represent single moments in time. Layers have identical ages that form age-equivalent marker horizons known as 'isochrons' (Box 3.4.1). The volcanic tephra from these eruptions can be identified, correlated and dated, and occur frequently within the stratigraphy of archaeological sites and, thus, have the strongest impact on Viking age chronology in Iceland. Nineteen tephra layers are included in this study that are associated with Viking aarchaeological features and that have been investigated between 1944 and 2016 (Table 3-5, Appendix III). Eighty-four percent of settlement sites (n = 253) and 7% of burial sites (n = 9) are in stratigraphic relationship with tephra layers (n = 261). Ideally, an archaeological feature is sandwiched between two tephra layers of close years of deposition, such as between the Landnám Tephra Layer (LTL) of AD 877 ± 1 and the Eldgjá/V-Sv tephra of AD 938 ± 6 (e.g. Sveigakot), or between the latter and the Hekla tephra of AD 1104 (e.g. Hofstaðir) (Chapter 5.3).

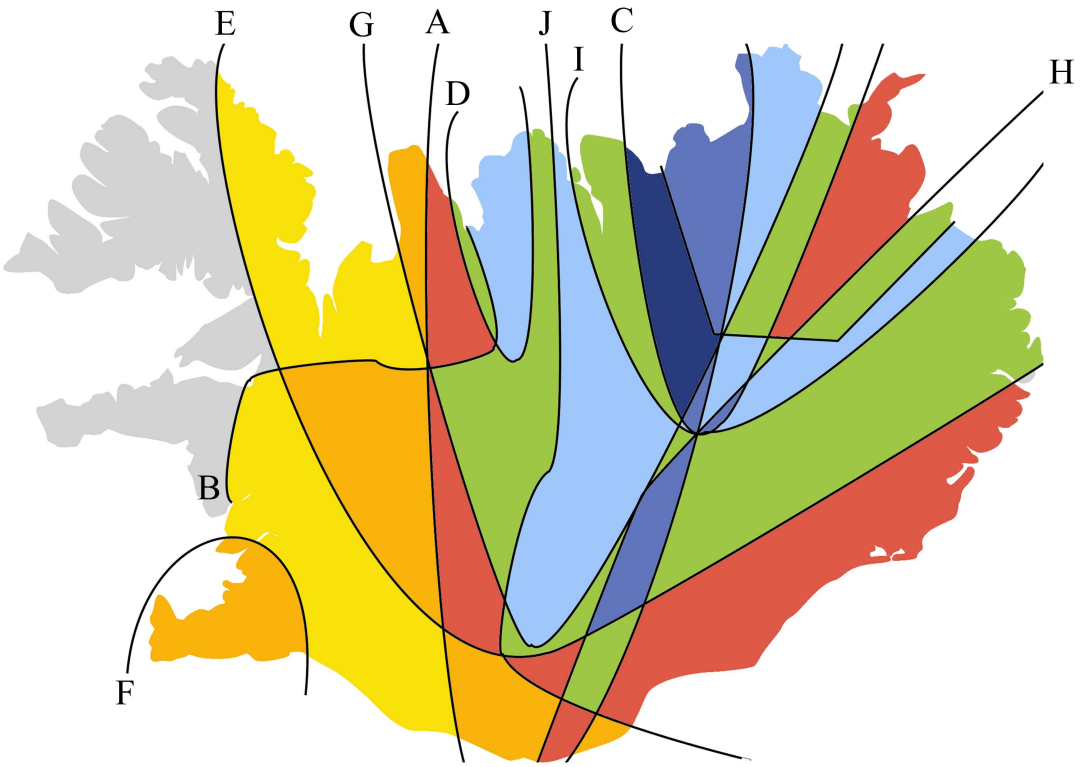
Table 3-5 Tephrostratigraphy in Iceland (between LTL of AD 877 ± 1 and H-1693). The tephra layers are named after the source volcanic system and the eruption date in years AD. The volcanic source systems are: E: Eldgjá, G: Grímsvötn, H: Hekla, K: Katla, Ö: Öræfajökull, R: Reykjaneshryggur and V: Veiðivötn (Fig. 3-14). Historically dated tephra layers are named after the source volcanic system and the eruption date in years AD ('-' symbol). Some tephra layers that have obtained age independent estimates have been given age independent names, as the date of the eruption can change ('~' symbol for estimated ages and '±' symbol for quantifiable error values). References for individual tephra layers are published in Chapter 4.2.

Tephra ID	*Previous ID*	*Year in AD*	*Dating method*
LTL	´VIIa/b´ ´LAL´ ´Vö´	877 ± 1	Greenland ice cores
K~920	´Katla-R´	~920	SeAR rates
V-Sv	´V~950´ ´V~940´	938 ± 6	SeAR rates
Eldgjá	´K~1000´ ´E1'	939	Greenland ice cores
Vj	/	~1000	SeAR rates
H-1104	´H1´	1104	Historical date
H-1158	/	1158	Historical date
V-1159	/	1159	Historical date
H-1206	/	1206	Historical date
R-1226	´Medieval layer' 'R-9'	1226	Historical date
K-1262	/	1262	Historical date
H-1300	/	1300	Historical date
G~1320	/	~1320	SeAR rates
H-1341	/	1341	Historical date
Ö-1362	/	1362	Historical date
V~1410	/	1410	SeAR rates
V~1477	´a´	~1477	Historical dates/SeAR rates
K~1500	/	~1500	SeAR rates
H-1693	/	1693	Historical date

The use of tephrochronology for establishing archaeological periodization also has limitations, which are demonstrated in the following examples:

Tephra fallout. The use of tephrochronology as a dating tool varies in geographic areas in Iceland. Some areas have no proximal tephra (the northwest peninsular), or they have one or two deposits, while others have multiple deposits (e.g. in northeastern areas with six or seven isochrons) allowing a fine-grained chronology over long periods of time to be established here (Fig. 4-15). While the LTL covers almost the entire island, other key tephra layers – in particular the 10th century tephras (Eldgjá and V-Sv) – are not present in many parts of the country and cannot be used for a countrywide comparison. Medieval tephra layers, therefore, have to be included to bracket Viking age sites, if they are in stratigraphic relationship with one of the 9th-10th century tephra layers; however, the time gap can be large (e.g. between LTL and K~1500).





K

Fig. 3-15 Dispersal of key tephra layers in Iceland. The lines show the outermost approximate isopach of each layer as known as present. An isopach connects points beneath which a particular stratum or group of strata has the same thickness. The dot within the blue shaded area represents the volcanic source. The outmost isopach line is:

- **A.** 0.1 cm for a 9th century Katla tephra, stratigraphically below the LTL (Larsen et al. 2012);
- **B.** 0.5 cm for the LTL (Larsen 1984); the distribution is extended according to archaeological data from Appendix VII.
- **C.** 0.5 cm for the estimated direction of tephra fall out of V-Sv according to Sigurgeirsoon 2001.
- **D.** Vj~1000: The distribution is estimated according to archaeological data from Appendix VII.
- **E.** 0.2 cm for H-1104 (Þórarinsson 1967);
- **F.** 0.5 cm for R-1226 (Sigurgeirsson 1992; Sæmundsson and Sigurgeirsson 2013);
- **G.** 0.1 cm for H-1300 (Þórarinsson 1967);
- **H.** 0.5 cm for Ö-1362 (Þórarinsson 1967);
- **I.** 0.1 cm for V-1410 (Larsen et al. 2012);
- **J.** 0.5 cm for the V-1477 (Þórarinsson 1967).
- **K.** The density of tephra layers in Iceland. Grey: no proximal tephra, yellow: one tephra layer; orange: two; red: three; green: four; light blue: five; blue: six; dark blue: seven tephra layers.

Preservation of tephra at complex archaeological sites. Complex archaeological sites consist of multiple features (e.g. midden, structures), of which a tephra date may reflect some part of this depending on how comprehensively the site has been excavated. The absence of tephra may be a result of household activities and construction that removed sediments (e.g. at Hofstaðir: Lucas 2009), but it can reflect the limitations of past excavation strategies where walls and the surroundings of features were not excavated (e.g. at Granastaðir: Einarsson 1995). Furthermore, tephra isochrons discussed in this thesis only focus on earliest occupational layers and not on the full range of tephra layers preserved at a particular archaeological site.

Geochemical fingerprinting of tephra layers at archaeological sites. Geochemical fingerprinting involves three stages of analysis of tephra layers: 1) macroscopic observation in the field, 2) microscopic analysis of samples in the lab and 3) chemical analysis of samples in the lab (Lowe 2011). There are only a few cases where tephra from archaeological sites in Iceland have been geochemically fingerprinted (Appendix II). Tephra is typically identified through its morphology and position in the stratigraphic sequence (similar at Cross Creek in New Zealand: Furey et al. 2008). A series of layers in the north forms a group named the Landnám Sequence (LNS: Box 3.4.1); this sequence includes both the LTL and the V-Sv tephra. Both tephra layers can be identified in the field with the naked eye, due to the fact that the LTL contains crystals of plagioclase, which are missing from the V-Sv tephra. However, the tephras around Landnám can be disturbed and sometimes only one layer of the Landnám Sequence is present and misidentification of this tephra is possible. As an example, the V-Sv tephra was only identified in 1999; tephra layers excavated prior to 1999 in the north may have been misidentified as LTL, which has become suspicious in light of more recent discoveries (e.g. Granastaðir was excavated 1987-1991 and the tephra layer at the site was interpreted as the LTL. This tephra layer may in fact be the V-Sv tephra: pers. com. Magnús Sigurgeirsson). Furthermore, deposits that are from the same volcanic source, but from different eruptions, can have very similar trace element chemistry, and thus appear similar in the field (Larsen and Eiríksson 2008). Thus, closely spaced deposits of Hekla AD 1104 and AD 1158 as well as of K~920 and Eldgjá tephra can sometimes not be separated, in particular when layers are too thin (e.g. at Hrísbrú: Chapter 5.2; other sites: Appendices I-III). Ideally, the analysis of cryptotephra would enhance the dating of such deposits (Box 3.4.1).

Precision of ages of tephra layers. Tephra layers have calendar ages of different precision (Table 5). In Iceland, strategies to obtain independent age estimates of tephra layers utilize written sources, correlation to annually layered sediments in lakes, the ice core records in

Greenland and age depth profiles constructed using sediment accumulation rates, or SeAR (Chapter 4.2). SeAR rates refer to annual accumulation in different depositional environments and can be used to estimate the age of undated tephra layers that occur between well-dated ones within suitable stratigraphic sequences. Here accuracy and precision is closely controlled by the approach used. For instance, the 'Vj~1000' tephra has been identified in association with early settlement sites in Skagafjörður, in northern Iceland (e.g. Bolender et al., 2011), but this estimate has significant uncertainty as it uses SeAR over more than 227 years. Tephra dates derived from ice-core stratigraphies in Greenland can also be somewhat ambiguous. Sigl et al. (2015) claim to have produced high resolution ice-core analyses through annual-layer counting, re-interpretation of tephra and sulphate spikes, and using tree ring, historical records and other independent age information. A chronological offset has been explained through the use of volcanic fallout in the ice believed to originate from the historic eruption of AD 79 (Vesuvius) as a fixed reference horizon to constrain the Greenland ice core chronologies. All tephra dates that are based on 'Greenland Ice Core Chronology 2005' (CICC05: Vinther et al. 2006) need adjusting. This has important implications for eruptions that rely on ice core chronologies, as well as for key tephra layers in Iceland, in particular the LTL and Eldgjá tephra. As such, the LTL has been corrected in this thesis to AD 877 ± 1 and the Eldgjá to AD 939. In light of this research the V-Sv tephra could also be corrected to AD 938 ± 6, which is discussed in detail in Chapter 4.2.

Taphonomy of tephra (in situ/in turf). In Iceland, turf is a commonly used building material and turf blocks can include tephra layers that were near to the surface when the turf was cut. As a result, tephra layers can be moved around the landscape within building materials and incorporated into structures. It has been estimated that tephra can last up to 100 years in turf (Milek 2012) providing a TPQ for the archaeological feature. Tephra *in situ* above or below any cultural feature is much more reliable and inferences can be made about the length of time elapsed from the deposition of the tephra to the archaeological event in question (p sequence: Chapter 5). More precisely, tephra needs to be continuous over a large area, larger than any conceivable piece of turf or it has to be undisturbed in an undisturbed matrix (Schmid 2015). The later is more difficult, but often essential, because small patches are often the only evidence found with a possibility of re-deposition. For instance, in New Zealand tephra markers, such as the Kaharoa tephra of AD 1314 ± 12 (Hogg et al. 2002), are often disregarded in chronological interpretation of archaeological sites because of the possibility of re-deposition. This is crucial because this tephra layer is in fact found in many archaeological sites in Coromandel (Furey et al. 2008).

3.4.2 Soil accumulation rates (SeAR)

Tephra layers are frequently found in sediments below and/or above archaeological features. Therefore, tephra isochrons provide secure TAQs and TPQs for archaeological features. Nevertheless, the time that elapsed between the deposition of the tephra and any cultural layer is often unclear. This is particularly problematic when a site was established between the LTL and H-1500 tephra, which are separated by more than 600 years (e.g. Reykjavík: Chapter 5).

Our understanding of these issues can be improved through an assessment of soil accumulation rates, or SeAR (Streeter and Dugmore 2014). SeAR are based on tephrochronology to describe local stratigraphic and chronological relationships of archaeological features (Dugmore and Erskine 1994; Dugmore et al. 2009). This information can be used as a proxy to evaluate the length of time between the tephra deposit and anthropogenic activity (Appendix II). However, the evidence needs rigorous assessment as SeAR are temporally and spatially variable (Streeter and Dugmore 2014). Dugmore et al. (2007:5) assess: "After settlement this rate increases by an order of magnitude to average 0.38mm/yr in the period AD 877–939. Accumulation rates are similar, if somewhat lower, in the later 10th century and decline marginally after the AD 1104 eruption. Reworked tephra on top of the primary airfall deposits indicate periods of instability following both the AD 1104 and AD 1300 tephra falls." Although SeAR rates vary considerably from one site to the next (Streeter and Dugmore 2014) – making averages very difficult to use on individual sites and requiring methodological innovations – they should not be ignored. They are significant for archaeological sites that are based on large-scale excavation, for example Reykjavík-Aðalstræti (Chapter 5.2).

3.4.3 Palaeoecology

Tephra layers in Iceland can also be found in pollen profiles in proximity to archaeological sites. In recent years, pollen analysis below and above the LTL, in particular, has been of interest in Iceland in order to investigate long and continuous environmental change due to anthropogenic activities in Iceland (Erlendsson et al. 2006). The aim is to identify first cultural indicators, such as *Hordeum*-type pollen (cereals), microscopic charcoal and coprophilous (dung-loving) fungi within the original landholding of a farmstead. Such indicators can inform about the time of first occupation, nature of land use and possible periodicity in habitation. These observations are particularly pertinent for Iceland (McGovern

et al. 2007, Dugmore et al. 2005) and other previous uninhabited islands (e.g. Faroe Islands: Church et al. 2013) because prior to colonisation there:

1) Were no indigenous people and agriculture had not yet been practised; *Hordeum*-type pollen grains (e.g. *Hordeum vulgare*: barley grains) are not native to Iceland and must have been brought to the island by the Norse.
2) Was little to disturb vegetation cover and there is no record of naturally occurring fires. Microscopic charcoal, therefore, demonstrates the use of fire, for example, in clearing the woodland.
3) Were very few land-mammals, only the arctic fox and possibly field mouse, although there were colonies of seals and walrus and occasional visits by polar bears. No record of pre-settlement herbivorous land mammals exists, as they were first introduced as part of human colonisation (a biozone: Furey et al. 2008). The identification of spores of coprophilous (dung-loving) fungi, therefore, is considered to be reliant on herbivore dung for germination.

Although *Hordeum*-type pollen, microscopic charcoal and dung-loving fungi are not infrequently reported below the LTL (Chepstow-Lusty 2003; Erlandsson and Edwards 2009); such evidence has only recently been correlated with archaeological sites (Chapter 5.3). The key limitation of this method is that most sites reveal a small number of pollen. The amount of pollen needed to reliably demonstrate anthropogenic activites has not yet been quantified. Uncertainty is also present when distinguishing between domesticated and natural species within the Hordeum group which includes both cultivated barley (*Hordeum vulgare*), introduced by the Norse and native lyme grass (*Leymus arenarius*). It has been argued that developing methodologies, such as rapid cereal-type scanning, may aid in separation (Erlandsson and Edwards 2009). Early human activities below (and above) the LTL, are thus most reliable if a combination of *Hordeum*-type pollen, microscopic charcoal and dung-loving fungi are all present, currently just at Hrísbrú in southwest Iceland (Chapter 5.3).

3.4.4 Radiocarbon dates

The ^{14}C samples from Iceland are from both published and previously unassessed data collected between 1959 and April 2016. All ^{14}C dates are included that have a median age before AD ~1200. AD ~1200 is defined as a reasonable cut-off because of the presence of the H-1104 tephra, while also accounting for statistical scatter. ^{14}C dates that date after AD ~1200, but are from clear stratigraphic contexts below the H-1104 tephra layer, are also

included. They provide evidence of intrusive materials (statistical outliers: Appendix VI.A). 513 ^{14}C dates from 97 sites dating to the Viking age and early medieval period have been gathered (Fig. 3-16; Chapter 6).

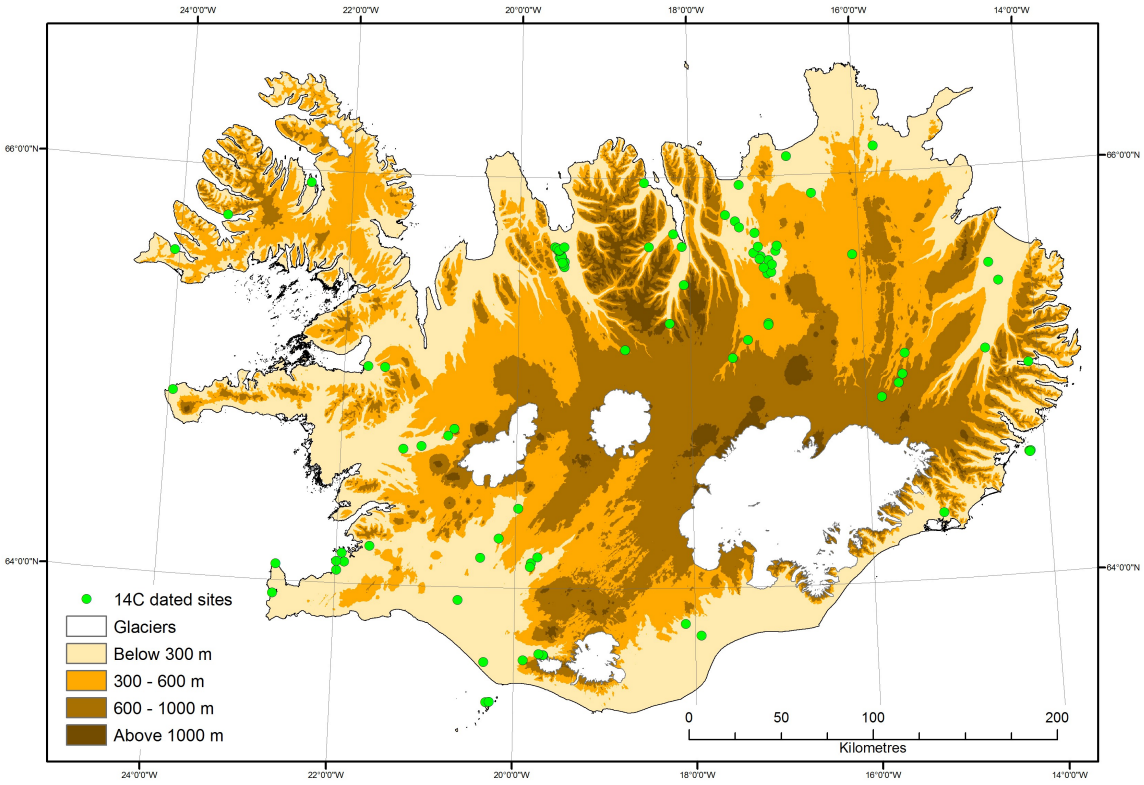


Fig. 3-16 The distribution of 97 archaeological sites that yielded radiocarbon data in Iceland. Most sites have an altitude below 300m. The map was created by Anthony J. Newton.

There have been rapid methodological developments in the field of ^{14}C calibrations. This thesis does not use any previously published calibrated ages. Terrestrial and marine calibrations and reservoir offsets have changed with past work; valid at the time of publication they are now superseded. The ^{14}C dates are listed according to current publication standards (Table 3-6; Reimer et al. 2013: e.g. 'Marine13' and 'IntCal13') and the chronological models used in this thesis are explicitly defined in the Supplementary Materials section, facilitating replication, comparison, and further interdisciplinary research (Appendices V-VII). Pre-treatment methods and quality assurance data (e.g. C:N ratio), however, are only discussed in Chapter 5.3 for ^{14}C samples from Hrísbrú as this kind of information is not available for any other Icelandic ^{14}C samples.

Table 3-6 Summary of data collated with each ^{14}C date. This information refers to the excavation report/publication and is based on the expertise of the investigator.

Data heading in Spread sheets	Description
Site name	The name of the archaeological site dated. Sites can have two names, which are both mentioned in order to identify the identical site. Arnavatnssel (Helluvað): Arnarvatnssel is the name of the site and Helluvað the name of the farm property on which Arnarvatnssel is found. If two different archaeological sites have the same name, they have also been assigned an area (e.g. Höskuldsstaðir í Reykjadal), a number (e.g. Hólar I, Hólar II) or a core name: Langanes I (REU 23), Langanes II (CP1)
Site name short	Site name short: e.g. HST for Hofstaðir. This category is useful for ^{14}C dates, where the laboratory code was not published: Geirstaðir is labelled GEI 1 and GEI 2
Sample ID	A combination of 'site name short' using three letters (following conventions where possible) and the unique laboratory code. A list of radiocarbon laboratories is available at http://www.radiocarbon.org/Info/lablist.html. According to the publishers of the 'Radiocarbon' journal, as of September 2016, there were 152 active radiocarbon labs in 50 countries (http://www.radiocarbon.org/Info/Labs.pdf).
Area	The data are separated into four geographic areas in Iceland: SW, NW, N, E. The division follows Chapter 4.2 and its purpose is the spatial analysis of the data
Latitude/Longitude	The spatial location of the site where the date was recovered (decimal degrees)
Archaeological feature and number	Systematic and minimal grouping of sites the date was recovered from: e.g. burial, structure of unknown function, pit house, annexe of hall, midden deposit, church site, cave deposit, byre, hall, charcoal pit, smithy, animal pen, ship burial
Context number	The context number helps to refer to the stratigraphic context of the sample; it aids to find the context in the associated publication.
Context description	Stratigraphic information about the archaeological feature: e.g. lower midden fill, upper floor layer, burial around church, turf collapse, etc.
Sample material	The type of material dated is divided into: Ch-U (unidentified charcoal), B-T (terrestrial bone), B-M (bone mixed diets), G/S (grains/seeds), W-SL (identified short-lived wood, such as twigs and bark), W-LL (identified heartwood of trees), T (Textile), MS (marine shell)
Sample species	The sample species have a set vocabulary: Charcoal/wood: *Betula pubescens* (birch), burnt bark, hardwood, roundwood, *Salix* sp. (willow), *Picea* sp. (spruce), *Pinus pumila* (pine), *Larix decidua* (larch), 'mixed material'. Bone: *Homo sapiens* (human), *Equus* sp. (horse), *Canis* sp. (dog), *Phocid* sp. (seal), *Bos* sp. (cow), *Ovis* sp. (sheep), *Capra* sp. (goat), *Sus* sp. (pig), *Salvelinus alpinus* (Arctic char), *Salmo trutta* (brown trout).

	Marine shell: *Mytilus edulis* (blue mussel), *Mya* sp. (mussel). Grain/seeds: *Hordeum sativum* (barley), *Stellaria media* (chickweed seeds), *Caryophyllaceae* (carnation plant).
Material category	1. Short-lived taxa (W-SL, G/S, B-T) 2. Samples with inbuilt age (Ch-U, W-LL) 3. Bone samples corrected for MRE (B-M) 4. Marine shell
Dating method	Standard Radiometric (LSC) or Accelerator Mass Spectrometry (AMS)
CRA	Conventional ^{14}C Age (uncalibrated) before AD 1950
Error	The error value of the uncalibrated ^{14}C age
$\delta^{13}C$	If available, the stable isotope value of carbon is provided
$\delta^{15}N$	If available, the stable isotope value of nitrogen is provided
$\delta^{34}S$	If available, the stable isotope value of sulphur is provided
% marine diet	The percentage of marine diet according to calculations in Chapter 2.3.2 (bone samples affected by MRE)
Calibrated date AD	68% and 95% probability ranges
Associated tephra deposit	Three categories: Tephra *in situ* below an archaeological feature: e.g. post-LTL Tephra *in situ* above an archaeological feature: e.g. pre-LTL Tephra below and above an archaeological feature: e.g. between LTL and V-Sv Abbreviations for tephra layers are described in Table 5
Type of outlier	If applicable, the type of outlier is described (Chapter 7): None-tangible outliers: Uncertain reservoir (FRE), insufficient documentation of isotopic composition (bone samples), bulk sediment, insufficient metadata (unspecified material type) Statistical outliers: Extreme outlier, erroneous date
References	The publication the age was sourced from

3.4.5 Typological dates

For many archaeological sites (e.g. burial and assemblage sites), artefact and house typologies either provide the only available dating evidence, or complement other dating methods. In terms of chronology there are three categories of typologies for Viking age contexts in Iceland:

1. Artefacts which either give no, or only the broadest, dating indication (e.g. objects of stone or iron) (Appendix II).
2. Artefacts and house shapes that provide reasonably robust 'Viking age' dates. These include several types of weapons and jewellery. Some burial practices, such as the presence of a horse, as well as diagnostic house types (e.g. pit houses or halls with bow-shaped long-walls) may also be reasonably attributed to the Viking age (Appendices I-II).

3. Diagnostic artefacts which can be ascribed a specific date or a date range of decades rather than centuries. These consist of coins, imported glass beads and other decorative objects with a limited period of circulation. Examples are glass beads of type B and E, which are dated to AD 960-1000 (Appendices I-II).

Diagnostic artefacts can provide TPQs for the associated archaeological feature. However, many artefacts show signs of long usage and may have been in circulation for some time (Eldjárn and Friðriksson 2016). The largest category of diagnostic artefacts are glass beads in Iceland (Hreiðarsdóttir 2005). Nevertheless bead typology is problematic; there are no independent scientific dates and the typology is based on the co-occurrence of objects such as oval brooches decorated in Viking age animal styles and datable coins. These dates provide an indicative period; however, there is often no clear link between the date obtained and the bead in question and assumptions must be made about the period of possible circulation (Chapter 5). Furthermore, diagnostic artefacts are frequently associated with sites that have neither ^{14}C nor tephra isochrons (e.g. burials and assemblages), therefore the comparisons are less valuable. There are a few examples where diagnostic artefacts are stratigraphically associated with ^{14}C samples and tephrochonology; such data are included in statistical models (Chapters 5). Typological data, therefore, do not contribute directly to the analysis in this thesis, and are only briefly discussed in Chapters 5, but they are consistent with the findings of the thesis and complement the picture of spatio-temporal distributions of archaeological sites discussed in Chapter 3.

4. Tephrostratigraphy and spatio-temporal dynamics of Iceland's settlement

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ἐν ταύτῃ γάο ἐξανώδει τι τής γής, καί άνήει οίον λοφώης όγκος μετά ωόφον τέλος δέ ραγέντος ἐξήιθε΄, πνεδμα πολύ κάι τόν φέωαλον κάι τήν ***τέφραν*** *άνήκε, κάι τήν τε Λιπαροίων πόλν ούσαν ού πόρρω πάσαν κατετέφρωσε, κάι είς ένιας τών ἐν Ιταλία Πόλεων ήλθευ*

[There was a piece of the ground swollen up and grown higher with a tremendous rumble and formed a kind of hill, and almost directly afterwards it fell apart and threw out a lot of air, sparks and ***tephra****. Ash covered the Lipardian town not far away, and also reached some towns in Italy]*

Aristotle 350 BC

4.1 Introduction

This chapter establishes a detailed tephrostratigraphic framework that is tailored to the investigation of Iceland's settlement and subsequent events, which then is employed in the chronological models for the following chapters. This confirms the abrupt start of the settlement in all areas, even those in which data coverage has previously been very sparse. The study indicates spatial patterning to settlement archaeology; however, the earliest evidence is clustered in the southwest. A key finding of this study is the likelihood that the proportion of initial settlement sites in this process is underestimated in the currently available corpus of information in Iceland. There is a full and frank consideration of the possibility of over- and underrepresentation in the dataset, and the potential impact/limitations of these upon interpretations. This emphazises the advantages of an approach that is as rigerous as possible, and that also integrates multiple strands of dating evidence rather than relying on a single strand (in this case: tephra), but also raises the prospect of targeting particular areas of the Icelandic landscape for excavation, to expand our knowledge in a systematic way.

4.2 Paper 1: 'Tephra isochrons and chronologies of colonisation'

Schmid, M.M.E., Dugmore, A.J, Vésteinsson, O., Newton, A. 2017. Tephra Isochrons and Chronologies of Colonisation. *Quaternary Geochronology 40. Special Issue: Tephrochronology*, 56-66. http://dx.doi.org/10.1016/j.quageo.2016.08.002.[1]

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The first paper is motivated by the fact that until now tephrochronology has not been used to full effect in dating archaeological sites in Iceland. This paper illustrates the spatio-temporal distribution of 19 tephra layers at 253 Viking age settlement sites across the country. The aim is to evaluate the presence and absence of regional tephra layers at archaeological sites focusing on the following research question:

Q2) ***How does the archaeology of Landnám relate to the chronology provided by tephra layers*****?**

Four tephra layers are of particular importance because of their relationship to the initial settlement period and because of their dating independent of the ^{14}C method (Table 4-7):

- The LTL of AD 877 ± 1 (dated in the Greenland ice-cores).
- The Eldgjá tephra of AD 939 (dated in the Greenland ice-cores).
- The V-Sv tephra of AD 938 ± 6 (dated by interpolation in relation to layers dated in the Greenland ice-cores).
- The Hekla tephra of AD 1104 (dated by written sources).

[1] The role of the doctoral student (Magdalena M.E. Schmid) in this paper was to carry out all of the research activity including the research design, the collection of data, the collection of GIS, the analysis of data, the creation of figures and the writing of the text. Prof. Andrew J. Dugmore, Prof. Orri Vésteinsson, and Dr. Anthony Newton guided the doctoral student during the writing process. The maps were created by Dr. Anthony Newton.

Table 4-7 Three consecutive periods of the Viking age settlement of Iceland: pre-Landnám, Landnám and post-Landnám, as well as a larger Viking age group. Two additional periods include uncertain categories based on tephrochronology alone. These uncertain categories are not used in the rest of the thesis, because data is merged with ^{14}C samples and typology.

Period	*Name of period*	*Description of period*	*Tephra correlation of deposits/dates*	*Age range*
1	*pre-Landnám*	Before widespread settlement	Below the LTL	AD pre-877
2	*Landnám*	Early widespread settlement	Sandwiched between the LTL and any tenth century Tephra (Eldgjá or V-Sv tephra)	AD 877-938/939
3	*post-Landnám*	Late widespread settlement	Sandwiched between a tenth century tephra (Eldgjá or V-Sv) and the H-1104 tephra	AD 938/939-1104
4	*Viking age*	/	Sandwiched between the LTL and H-1104	AD 877-1104
5	*Landnám/Viking age?*	/	Above the LTL or between LTL and a 12th-17th century tephra	/
6	*post-Landnám*	/	Above a 10th century tephra (Eldgjá or V-Sv) or between those and a 12th-17th century tephra	/

Definitions of the pre-Landnám and Landnám periods depend on the distribution of the LTL. Archaeological evidence is consistently found above this tephra isochron (n = 81), with the notable exception of two sites in the southwest where turf-walls occur immediately below this tephra. The age of the LTL (AD 877 ± 1) by reference to annual snowmelt in the Greenland icecap effectively demolishes the early settlement hypothesis. The post-Landnám period is defined by two 10th century tephras, the Eldgjá and V-Sv tephra. The regional patterns are biased because of:

- The distribution of tephra layers.
- Different fieldwork intensities in different regions.
- An uneven distribution of (identified) tephras *in situ* below and/or above archaeological features.

More of the excavations in the north in the past 25 years have involved methodologies that maximise the likelihood of successfully utilizing tephra layers for archaeological chronologies, e.g. by excavating turf walls and observing tephra layers *in situ* below archaeological structures.

Another important conclusion of this study is that the early Landnám sites in the north are entirely sub-surface features such as pit houses, middens or traces of cultivation, while later

post-Landnám sites have upstanding remains like turf walls of houses or earthwork systems. Such upstanding features are easier to identify on the surface. Thus, it is likely that the number/proportion of pre-Landnám and Landnám sites currently known is significantly underestimated. This highlights fundamental limitations of tephrochronology if used as a single strand of evidence for colonisation events. This study suggests targeting regions with 10^{th} century tephras (and potentially the application of cryptotephra) in the future, as well as underlining the necessity of correlating tephra with ^{14}C dates using Bayesian statistical analyses. This data collection confirms the abrupt start of the settlement in all areas, even those in which data coverage has previously been very sparse. It demonstrates that the earliest evidence is clustered in the southwest. This research used the Landnám as a test case for chronological development using an archaeological event with a clearly defined start.

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Tephra isochrons and chronologies of colonisation

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ABSTRACT

This paper demonstrates the use of tephrochronology in dating the earliest archaeological evidence for the settlement of Iceland. This island was one of the last places on Earth settled by people and there are conflicting ideas about the pace and scale of initial colonisation. Three tephra layers, the Landnám ('land-taking') tephra layer (A.D. 877 ± 1), the Eldgjá tephra (A.D. 939) and the recently dated V-Sv tephra (A.D. 938 ± 6) can be found at 58% of 253 securely-dated early settlement sites across the country. The presence of the tephras permits both a countrywide comparison, and a classification of these settlement sites into pre-Landnám, Landnám and post-Landnám. The data summarised here for the first time indicate that it will be possible to reconstruct the tempo and development of the colonisation process in decadal resolution by more systematically utilising the dating potential of tephrochronology.

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1. Introduction

Understanding the pattern and timing of the peopling of a landscape is a difficult task, because evidence is scattered across sites where the potential for dating may vary from excellent to problematic. Without effective integration, dates of different precisions, accuracy and bias derived from a range of different media may give a misleading sense of either synchronous or time-transgressive change, a problem aptly described by Baillie (1991) as 'suck in and smear'. The isochrons formed by tephra layers offer a rigorous way to avoid these problems when the volcanic ash (tephra) falls occur around times of colonisation, cover extensive areas, have distinctive properties that are well-characterised, and have good independent dating (Þórarinsson, 1944; Dugmore and Newton, 2012; Lowe and Alloway, 2015). While tephrochronology has been successfully applied to studies of the first human settlement in areas such as Iceland (Vésteinsson and McGovern, 2012) and New Zealand (Lowe et al., 2000), it can be further developed to produce routine high-resolution dating of the pattern and tempo of human occupation. Elsewhere in the world, such as the western parts of the Americas, this approach has great and currently unrealised potential applications to the study of colonisation phases (both human and non-human) across the widespread areas affected by visible or crypto tephra falls.

Iceland was one of the last places on Earth settled by people and yet despite a rich history of academic study, the timing and pattern of the late 9th to early 10th century A.D. Viking settlement of Iceland (the 'Landnám' or 'land-taking') is still debated vigorously (e.g. Vésteinsson and McGovern, 2012; Edwards, 2012; Sveinbjarnardóttir, 2012a). Based on later written sources, the onset of Landnám has traditionally been put at A.D. 870 (Benediktsson, 1968); this is broadly supported by the relationship of early archaeological evidence to a tephra from the A.D. 870s named the Landnám tephra layer (LTL). However, controversy over the timing of the settlement has been generated by a dozen or so radiocarbon dates linked to human activity at around A.D. 700 (e.g. Hermanns-Auðardóttir, 1989; Theodórsson, 1998, 2009, 2012). The relevance of these 'early' dates to Iceland's settlement history is problematic because either their stratigraphic positions are unsecure or their interpretation is demonstrably incorrect—for example an 'early' date from a secure context above LTL of A.D. 877 ± 1 indicates that the dates are misleading and could, for example, be a result of the use of old timber for fires (Sveinbjörnsdóttir et al., 2004, 2016). Given the widespread occurrence of old dead timber in wooded areas at the time of first human settlement there will always be an element of uncertainty over 'early' charcoal dates in Iceland even if they are from native species and secure stratigraphic locations.

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While the overwhelming majority of archaeological evidence occurs above LTL, a small number of archaeological features in the southwest of Iceland are overlain by this tephra horizon (Jóhannesson and Einarsson, 1988; Roberts et al., 2003). In addition paleoenvironmental data in the same region suggest first anthropogenic disturbances (human and livestock) some time between A.D. 830-877 (Erlendsson et al., 2014).

Understanding when people arrived is part of the puzzle, but understanding *how* they arrived, in a trickle, a steady flow or a torrent (Edwards, 2012) is key, but in addition to the timing of colonisation, the pattern of settlement is also unclear and this too is a difficult question to resolve. Two different narratives have emerged from key areas in the north of Iceland: Bolender et al. (2011) see a gradual infilling of the landscape in Skagafjörður between the LTL and Hekla 1104, however Vésteinsson and McGovern (2012) argue that Mývatnsveit was rapidly settled between the LTL and V-Sv tephra of A.D. 938 ± 6. The V-Sv tephra is closely related in time to the Eldgjá tephra and both are mid-tenth century tephra layers of Icelandic origin that are of great importance to the colonisation debate; while the recently discovered V-Sv tephra is distributed over large parts of northeast Iceland the Eldgjá tephra is distributed in the southwest and east.

Tephrochronology, in conjunction with other dating methods such as radiocarbon, offers an effective and rigorous way to resolve debates over the timing and tempo of settlement, because of the presence of tephra layers at around the time of first settlement and in the centuries both before and afterwards.

This paper reassesses the chronology of 300 Viking period settlement sites in Iceland (A.D. ~800-1100), of which 253 can be dated with well-established tephra isochrons. We discuss the dating of tephra deposits in Iceland and the application of tephrochronology with a focus on eighteen tephra horizons ranging between LTL and Hekla 1693. This new analysis suggests there is a distinct spatial patterning to the archaeology of the settlement of Iceland, with the earliest phases clustered in the southwest and a rapid colonisation both in coastal and inland areas by the mid 10th century.

2. Materials and methods

2.1. Archaeological data

Chronologies for Viking settlement sites in Iceland have been based on tephrochronology, radiocarbon and artefactual dating. However, prior to the last decade of the 20th century, these methods rarely produced dates more precise than the 'Viking Age' (Eldjárn, 2000; Grímsdóttir, 1997; Vilhjálmsson, 1991). The wealth of new archaeological data in Iceland, as well as methodological advances in Bayesian analysis, now make it possible to critically reassess the chronological evidence relating to the settlement of Iceland and to aim for a much improved resolution of the timing and pattern of colonisation within the Viking Age (e.g. Batt et al., 2015).

This discussion is based on a new catalogue of 543 archaeological sites that have been dated to the Viking period (Schmid, forthcoming). In this work, secondary source data was gathered from field reports (e.g. reports published by FSÍ, the Institute of Archaeology in Iceland, accessible at: www.nabohome.org) and academic monographs (e.g. Lucas, 2009; Sveinbjarnardóttir, 2012b). The catalogue consists of archaeological interventions including large-scale excavations, trenches and surface collections from the 19th century to 2016. Data was gathered through a systematic search of the corpus of field reports site-by-site, supplemented with direct questioning of the researchers involved. The complete catalogue includes all Viking Age sites in Iceland that contain direct evidence of human activity. The discussion in this study is, however, restricted to the sites dated through tephrochronology.

The Icelandic archaeological sites related to early human activity can be separated into three categories: 55% of the sites are settlements (n = 300), 24% are burials (n = 132) and 21% are assemblages (loose finds, n = 111). Since tephra is hardly ever documented at burial sites and is absent from assemblages of loose find, these categories are not considered in this tephrochronological study and we focus exclusively on archaeological evidence that is related to settlement. 253 out of 300 settlement-related sites have associated tephra layers and are listed in SI Table 1 (Fig. 1). These sites can be either a single feature or a cluster of features, such as anthropogenic disturbances associated with farming, charcoal layers, midden deposits, iron production pits, or they can be structures below ground (pit houses or caves), or structures above ground (dwellings, halls, smithies, animal stalls or boundary earthworks). Each archaeological feature or cluster of features is considered a 'site' when it has been given a separate name by the investigator.

The Viking Age settlement sites considered in this study are primarily dated by reference to three tephra isochrons, the LTL, Eldgjá and V-Sv tephras. Where these tephras are not present, sites are dated by reference to the Hekla tephras from 1104 or 1158 that provide secure *termini ante quos* for the archaeological site. Tephra layers dating between Hekla 1202 and Hekla 1693 are taken into account if they are in combination with one of the 9th or 10th centuries tephra horizons described above because in most cases the archaeological structure or deposit is immediately on top of the 9th and 10th century tephra layers and thus likely represents human occupation within the Viking Age. In order to discuss settlement patterns, we separate the data into four geographical areas, the southwest, the northwest, the north and the east (Fig. 1).

2.2. Tephrochronology

Tephrochronology is based on (a) identifying tephra deposits, (b) correlating separate deposits from the same eruption to define isochrons, and (c) establishing calendar or sidereal dates for the tephra (þórarinsson, 1944; Lowe, 2011). The development of tephrochronology as a geochronological technique was pioneered in Iceland by Sigurður þórarinsson, who described the theoretical foundations of this dating technique and developed its applications through studies of archaeology, historical sources, geomorphology and environmental change (þórarinsson, 1944, 1952; 1954, 1956; 1957). In addition to considering proximal areas with visible tephra layers, þórarinsson also drew attention to the possibility of creating precise teleconnections using ultra-distal tephra deposits—very fine grained deposits that are not visible to the naked eye due to their low concentrations (þórarinsson, 1981a). These deposits, now known as *cryptotephras* (Lowe and Hunt, 2001), can be used to both extend the geographical coverage of tephrochronology (Davies, 2015), and also enhance stratigraphic resolution (Dugmore et al., 1992).

In this paper, eighteen tephra layers ranging from A.D. 877 to 1693 are used to establish a chronological framework for Viking period features (Table 1). Historically dated tephra layers in Iceland are named after the source volcanic system and the eruption date in years A.D. (-symbol). Some tephra layers that have obtained age independent estimates have been given age independent names, as the date of the eruption can change (~symbol for estimated ages and ± symbol for quantifiable error values).

2.3. Dating of tephra deposits in Iceland

In Iceland, strategies to obtain independent age estimates of tephra layers utilize written sources, correlation to annually layered

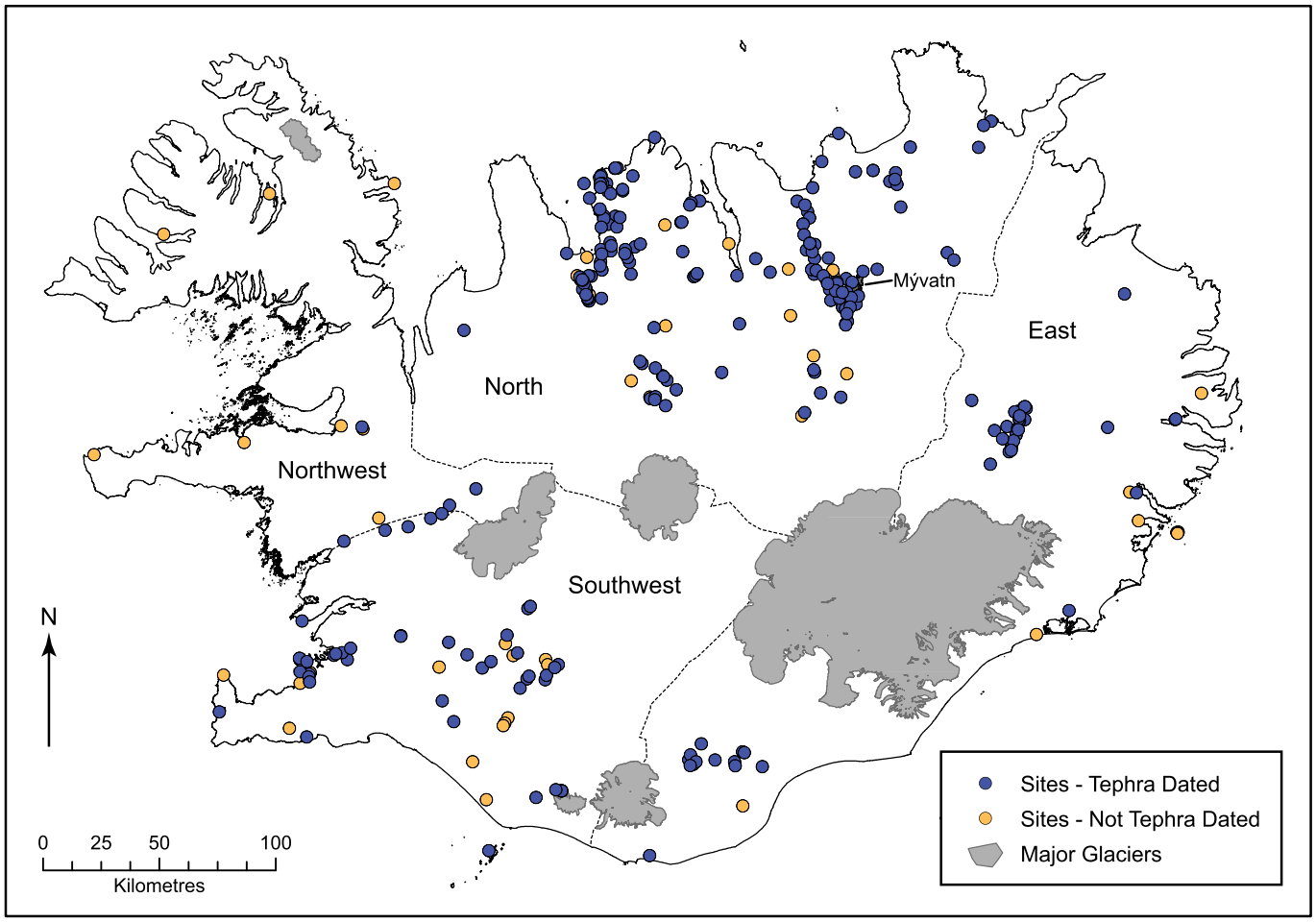

Fig. 1. The distribution of 300 settlement sites considered in this study. 85% sites are dated by tepha layers (n = 253).

sediments in lakes, the ice core records in Greenland and age depth profiles constructed using sediment accumulation rates constrained by other chronological evidence, such as radiometric dates and written sources (e.g. Þórarinsson, 1967; Grönvold et al., 1995; Zielinski et al., 1997; Dugmore and Newton, 2012; Streeter and Dugmore, 2014).

2.3.1. Sediment accumulation rates (SeAR)

Sediment accumulation rates (SeAR) refer to annual accumulation in different depositional environments. They can be used to estimate the age of undated tephra layers that occur between well-dated ones within suitable stratigraphic sequences (Haflidason et al., 2000; Streeter and Dugmore, 2014; Sigurgeirsson et al., 2013).

1) Some Icelandic tephra dates have been derived from annually resolved ice-core stratigraphies in Greenland. Some of these dates are, however, somewhat ambiguous. Sigl et al. (2015) claim to have resolved the discrepancies between ice cores chronologies with multi-parameter aerosol concentration records from Greenland (NEEM-2011-S1, TUNU2013 and NGRIP) and Antarctic (WDC) ice cores. High resolution ice-core aerosol analyses are achieved through improved annual–layer counting, reinterpretation of tephra and sulphate spikes, and using tree ring, historical records and other independent age information. A chronological offset has been explained through the use of volcanic fallout in the ice believed to originate from the historic eruption of A.D. 79 (Vesuvius) as a fixed reference horizon to constrain the Greenland icecore dating (Sigl et al., 2015). All tephra dates that are based on ice core chronologies using, or referencing, GICC05 (Vinther et al., 2006) therefore need adjusting. This has important implications for the dating of not only Icelandic tephra layers, but also other eruptions that rely on ice core chronologies. Baillie and McAneny (2015) discuss issues (tree rings, ice cores and historical records) surrounding the dating of the Eldgjá eruption, which they suggest could be responsible for climatic flucuations observed in A.D. 939-940. Previously, the Eldgjá tephra had been dated to A.D. 938 ± 4 (GISP2 core: Zielinski et al., 1995) and to A.D. 933 ± 1 (GICC05 chronology: Vinther et al., 2006). An adjustment of 6 years is suggested by Baillie and McAneny (2015) and the date of A.D. 939 is used by Sigl et al. (2015). This implies that the age of the LTL tephra layer should also be reassessed. The LTL has previously been dated to A.D. 871 ± 2 (GRIP core/GICC05 chronology: Grönvold et al., 1995; Vinther et al., 2006) and to A.D. 877 ± 4 (GISP2 core: Zielinski et al., 1997). The revised age of the Eldgjá tephra allows bringing forward the often quoted GISP2 age of the LTL by six years to A.D. 877 ± 1 and is therefore in agreement with the mean age of the GRIP chronology.
2) Tephra dates have been derived from regular or rhythmically deposited lacustrine sediments. A series of layers forming a group named the Landám tephra sequence (LNS) has been analysed from lacustrine sediment cores extracted from Lake Mývatn in the north of Iceland (McGovern et al., 2007; Sigurgeirsson et al., 2013). The date of a distinctive olive-green

Table 1
Tephrochronological record in Iceland.

Name of tephra layer	Origin (volcanic system)	Year A.D.	References
LTL [VIIa, VIIb]	Veiðivötn	877 ± 1	Haflidason et al., 1992; Grönvold et al., 1995; Zielinski et al., 1997; Larsen et al., 1999; Vinther et al., 2006; this study
K~920 [Katla-R]	Katla	~920	Hafliðason et al., 1992
Eldgjá [K~1000]	Katla	939	Hammer et al., 1980; Larsen, 1984; Hafliðason et al., 1992; Zielinski et al., 1995; Sigl et al., 2015; Baillie and McAneny, 2015; this study
V-Sv [V~950, V~940]	Veiðivötn	938 ± 6	Sigurgeirsson, 2001; Sigurgeirsson et al., 2013; this study
Vj	Veiðivötn	~1000	Sigurgeirsson, 2010
H-1104 [H1]	Hekla	1104	þórarinsson, 1967; Larsen and þórarinsson, 1977; Larsen et al., 1999; Sigurðsson, 1982; Haflidason et al., 2000
H-1158	Hekla	1158	þórarinsson, 1967; Einarsson et al., 1988; Larsen et al., 1999
V-1159	Veiðivötn	1159	Einarsson et al., 1988; Haflidason et al., 2000
H-1206	Hekla	1206	þórarinsson, 1967
R-1226 ['R-9']	Reykjaneshryggur	1226	Hafliðason et al., 1992; Sigurgeirsson, 1995
K-1262	Katla	1262	Larsen, 1982; Streeter and Dugmore, 2014
H-1300	Hekla	1300	þórarinsson, 1967; Einarsson et al., 1988; Haflidason et al., 2000
H-1341	Hekla	1341	þórarinsson, 1967; Larsen et al., 1999
Ö-1362	Öræfajökull	1362	þórarinsson, 1958; Sigurðsson, 1982
V~1410	Veiðivötn	1410	Larsen, 1982; Haflidason et al., 2000
V~1477 ['a']	Veiðivötn	~1477	þórarinsson, 1958, 1976; Larsen, 1982, 1984; Haflidason et al., 2000
K~1500	Katla	~1500	Hafliðason et al., 1992
H-1693	Hekla	1693	þórarinsson, 1967

basaltic tephra layer (V-Sv) found in the LNS was dated using sediment accumulation rates from nine cores from Lake Mývatn and is also found in many terrestrial sediment sequences (Fig. 2). This tephra was erupted from Veiðivötn volcanic system after the LTL and before Hekla 1158 tephra layers. The presence of these well-dated tephra layers provided the chronological control to calculate the age of the V-Sv tephra. The name V-Sv was adopted by Sigurgeirsson et al. (2013), as it is age independent and allows for further revision of the estimate of the dating of its deposition.

The age of the 10th-century Veiðivötn tephra (V-Sv) was estimated by Sigurgeirsson et al. (2013) using the sedimentation rate between the LTL and H-1158 and they calculated the age of the V-Sv tephra by using both Greenland ice core dates (GRIP and GISP) for the LTL. Therefore, if the age of LTL is assumed to be A.D. 871 ± 2 (the GRIP date), then the 10th century Veiðivötn tephra was estimated to be A.D. 933 ± 6 and if the LTL was assumed to be A.D. 877 ± 4 (the GISP2 date), the age of the V-Sv tephra was A.D. 938 ± 6 (Sigurgeirsson et al., 2013). However, the revision of the GICC05-based ice core chronologies (e.g. GISP2) suggested by Baillie and McAneny (2015) and Sigl et al. (2015) means that the resultant A.D. 877 ± 1 age for LTL produces an average age estimate of A.D. 938 ± 6 for the V-Sv tephra. Based on the same approach using sedimentation rates and assuming an age of A.D. 877 ± 1 for the LTL, other tephra layers in the north have been dated to mean ages of A.D. 1239, A.D. 824, A.D. 803, A.D. 795 and A.D. 710 (Sigurgeirsson et al., 2013). Elsewhere, a similar method has been applied to derive calendar dates for K~920 and K~1500 (Hafliðason et al., 1992).

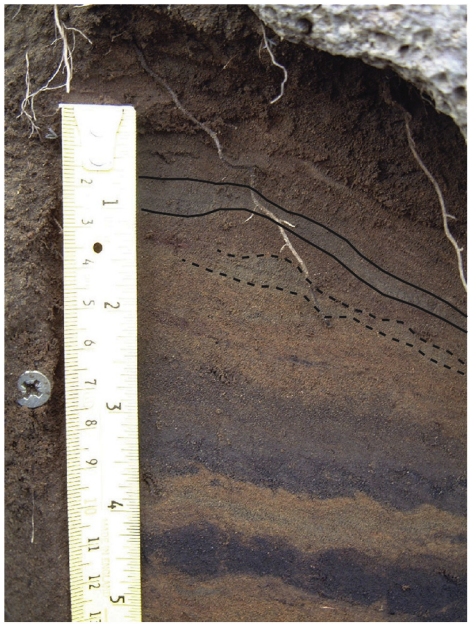

Fig. 2. The preservation of the LTL and V-Sv tephras *in situ* below a structure at. Sveigakot, Myvatnsveit in northern Iceland (picture: Anthony Newton).

3) Accumulation rates within aeolian sediments have also been used to infer tephra dates; here accuracy and precision is closely controlled by the approach used. For example, Streeter and Dugmore (2014) estimated the age of two 15th century Grímsvötn tephra layers using aeolian sediment accumulation rates between K-1416 and V-1477 in an area of rapid aggradation. Multiple high-resolution measurements of sediment thickness (n = 1960) were used to infer ages of A.D. 1432 ± 5 (mean ± 1SD) and A.D. 1457 ± 5 (mean ± 1SD) and the accuracy was evaluated by using the same method to date a tephra of known age – that of K-1262 (Streeter and Dugmore, 2014). The test used calculations of SeAR between tephras H-1206 and H-1300 (time interval between control points 96 years), and measurements to an accuracy of ± 2.5 mm; the age inferred for the A.D. 1262 tephra was A.D. 1264 ± 10 (mean ± 1SD, n = 97). A 'Vj~1000' tephra has been identified in association with early settlement sites in Skagafjörður (e.g. Bolender et al., 2011; Zoëga et al., 2013), but this estimate has significant uncertainty, as it uses SeAR over more than 227 years as opposed to c. 60 years for Streeter and Dugmore's (2014) Grímsvötn dates or 96 years for their test of the Katla layer.

2.3.2. Written sources

Tephra layers that were deposited at times for which written records survive can be dated with both precision and accuracy, sometimes to the year, on occasion to a month, week or day of the eruption (Þórarinsson, 1967). Þórarinsson's seminal works focused on Hekla (Þórarinsson, 1967) and Öræfajökull (Þórarinsson, 1952), he compiled a catalogue of Katla eruptions (Þórarinsson, 1977) and identified layers from other systems such as Grímsvötn (Þórarinsson, 1981b). The approach is not without its critics (e.g. Vilhjálmsson, 1991), but dates derived from written sources for tephra layers such as H-1104, H-1158 and H-1300 have withstood the test of time and are frequently used as reliable *termini post quos* for Viking age sites.

2.4. Identification of tephra deposits

The application of tephrochronology in Icelandic archaeology first began with the use of major tephra layers such as those formed by the A.D. 1104 eruption of Hekla in Þjórsádalur and pre-settlement plinian tephras such as Hekla 3 and Hekla 4 (Þórarinsson, 1944, 1967). Initially reference to a few clearly developed marker horizons can achieve a lot, but in order to engage with crucial detail—such as the decadal scale pattern and timing of initial settlement—greater temporal resolution is needed. Þórarinsson created some of this with his magisterial work on the historic eruptions of Hekla (Þórarinsson, 1967) and this has since been developed through work on other volcanic systems (e.g. Larsen, 2000; Óladóttir et al., 2008). Further enhancement can be achieved by the careful utilization of thin and weakly developed or poorly provenanced tephra layers that occur between the major, well-constrained marker horizons (Dugmore and Newton, 2012).

Rigour is required because fine layers have poorly developed layer colours and may have the same physical appearance as other tephras; deposits that are from the same volcanic source, but from different eruptions, can have a very similar major, minor and indeed trace element chemistry, and thus appear similar in the field. Silicic tephra layers from two 12th century eruptions (H-1104 and H-1158) are both found in the north, where they form very thin horizons. Although they may be confused in the field, it has been demonstrated that they have distinctly different chemistries (Larsen et al., 1999; Newton, 2008). In a comparable way, tephras with similar major element chemistry from K~920 and Eldgjá overlap in the south where either one or both may appear in sections (e.g. at Hrísbrú: Sigurgeirson, 2014). Veiðivötn tephras formed in the 9th and 10th centuries have a very similar chemistry, with overlapping compositions, but the crucial LTL of A.D. 877 ± 1 is unique as it includes crystals resulting from the interaction of the Veiðivötn and Torfajökull volcanic systems and their simultaneous activity (Larsen, 1982). Silicic tephra layers from Katla (the 'SILK layers of Larsen et al., 2001) can be confidently identified in the field when only a few mm thick because of a combination of a distinctive 'needle grain' shard morphology and their stratigraphic context in relation to other tephra layers (e.g. SILK-un in Dugmore et al., 2000). Thus, confident identification of thin, weakly developed or poorly provenanced tephra layers relies on a combination of precise stratigraphy, the identification of a crystal fraction or distinctive shard morphologies, chemical analysis of the glass fraction, and integration within a well-known local and regional tephrostratigraphic framework.

2.5. Dating archaeological sites using tephra deposits

The presence of well-dated tephra isochrones within the archaeological stratigraphy is a major asset when building site chronologies (Lane et al., 2014; Riede and Thastrup, 2013). Tephra can be preserved *in situ* below and/or above anthropogenic layers where the area has been exposed to atmospheric fallout and aeolian sediment accumulation has not been disturbed (Fig. 3). These sites may include turf structures and layers of midden. Turf is a commonly used building material in Iceland and turf blocks can include tephra layers that were near to the surface when the turf was cut (Fig. 3). As a result, tephra layers can be moved around the landscape within building materials and incorporated into structures. Tephra layers *in situ* above anthropogenic features give secure *termini ante quos*; tephra layers *in situ* below anthropogenic features as well as tephra in turf generally give secure *termini post quos*.

3. Results and discussion

3.1. Presence/absence of tephra at archaeological sites

This study considers a total of 300 archaeological sites related to settlement; 59% are located in the north (n = 176), 20% are in the southwest (n = 60), 17% in the east (n = 51) and 4% in the northwest (n = 13) (Fig. 1). It is important to note that these numbers do not reflect the density of settlement, rather they reflect fieldwork activity. In the north 92% of sites include *in situ* tephra layers (162 out of 176), as do 77% in the southwest (46 out of 60 with tephra), 78% in the east (40 out of 51), and proportionally less (38%) in the northwest (5 out of 13) (Table 2).

This regional pattern is biased, because more of the excavations in the north have involved methodologies that maximise the likelihood of successfully using tephrochronology. In contrast, many of the earlier excavation methods employed in the south did not excavate turf walls and thus any tephra deposits *in situ* beneath them were not documented. The absence of tephra for an archaeological site may be a result of impacts of household activities and

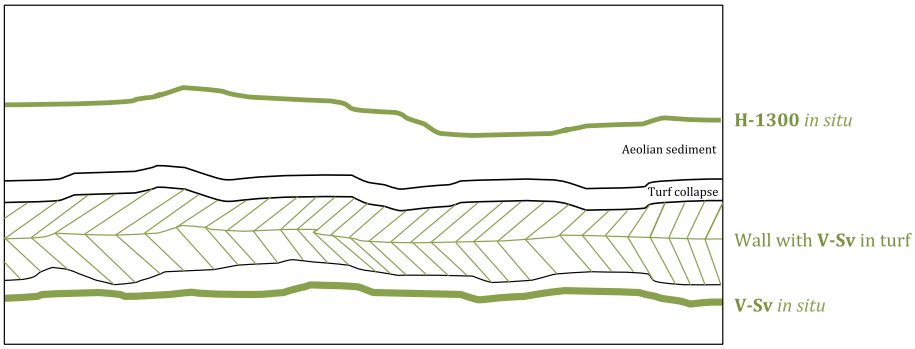

Fig. 3. V-Sv tephra *in situ* below the wall of a hall at Hofstaðir, as well as in turf of the wall (reconstruction after Lucas, 2009).

Table 2
Tephrochronological record of archaeological sites.

Tephra dates	Southwest	North	East	North west	No. of sites
Pre-LTL	2	–	–	–	2
Post-LTL	10	2	2	5	19
Between LTL and K~920/Eldgjá	1	–	1	–	2
Between LTL and V-Sv	–	7	–	–	7
Between LTL and Vj	–	5	–	–	5
Between LTL and H-1104/H-1158	5	17	2	–	24
Between LTL and R-1226	8	–	–	–	8
Between LTL and H-1262	–	1	–	–	1
Between LTL and H-1300	–	5	–	–	5
Between LTL and H-1341	2	–	–	–	2
Between LTL and Ö-1362	–	–	2	–	2
Between LTL and V-1477	–	1	–	–	1
Between LTL and H-1500	3	–	–	–	3
Between LTL and H-1693	2	–	–	–	2
Between K~920 and Eldgjá	1	–	–	–	1
Pre- Eldgjá	1	–	3	–	4
Between Eldgjá and H-1104	3	1	–	–	4
Between Eldgjá and H-1206	–	–	7	–	7
Between Eldgjá and K-1341	6	–	–	–	6
Between Eldgjá and V~1477	–	1	–	–	1
Post- V-Sv	–	1	–	–	1
Between V-Sv and Vj	–	6	–	–	6
Between V-Sv and H-1104/H-1158/V-1159	–	26	1	–	27
Between V-Sv and K-1262	–	1	–	–	1
Between V-Sv and H-1300	–	18	–	–	18
Between V-Sv and Ö-1362	–	–	1	–	1
Between V-Sv and V-1410	–	1	–	–	1
Between V-Sv and V~1477	–	12	–	–	12
Pre-Vj	–	7	–	–	7
Between Vj and H-1104	–	12	–	–	12
Pre-H-1104/H-1158	2	38	21	–	61
LTL	**33**	**38**	**7**	**5**	**83**
Eldgjá	**11**	**2**	**10**	**-**	**23**
V-Sv	**-**	**65**	**2**	**-**	**67**
Vj/H-1104/H-1158	**2**	**57**	**21**	**-**	**80**
Recorded tephra	**46**	**162**	**40**	**5**	**253**

building construction that removed sediments including tephra layers. Alternatively the absence may be as a result of a lack of tephra layers. In the west, for example, the low frequency of tephra records is a reflection of the location of volcanoes to the east and prevailing westerly winds, which results in a much lower frequency of tephra falls, especially in the West Fjords. Modern excavation techniques, including the identification of cryptotephras, may yet reveal tephra layers at sites, which currently have no record of them.

The tephra layers used to date Viking Age deposits are listed in Table 2. One third of the sites are dated with medieval tephra layers ranging between A.D. 1206 and 1693 (n = 71). This highlights one fundamental limitation of tephrochronology as a means of dating archaeological sites in Iceland and elsewhere; tephra layers have to be present and identifiable. Some sparse records, such as sites that only contain tephras produced in late 9th century (LTL) and at the turn of the 17th century (H-1693) may reflect an environmental reality, alternatively cryptotephras may be present but currently unidentified. Cryptotephras represent an untapped potential in Icelandic archaeology, but one that would require further methodological innovations to extract sparse numbers of fine-grained volcanic glass shards from a matrix of volcanically-derived andisols of a similar particle size.

3.2. Spatial distribution of the LTL, Eldgjá and V-Sv tephras

The LTL, Eldgjá and V-Sv tephras cover substantial parts of Iceland and are associated with 58% of early settlement sites (n = 173). Isopach maps are available from the LTL and Eldgjá tephra and are illustrated in Fig. 4. The LTL is preserved at 83 sites, of which 33 are located in the southwest, five in the northwest, 38 in the north and seven sites are located in the east (Table 2). The distribution of the LTL at archaeological sites in the north goes beyond the borders mapped by Larsen (1984; Fig. 4B) and shows how distributions may be extended by additional detailed study. The Eldgjá tephra is primarily found associated with sites in the southwest (n = 11) and east (n = 10) and is also documented in the north (n = 2) (Fig. 4C, Table 2). The V-Sv tephra is primarily found in the north (n = 65), but also in the east (n = 2) (Fig. 4C, Table 2).

3.3. Chronology of archaeological sites

The range of tephra layers allows a secure periodization of settlement sites in Iceland (SI Table 1). The pre-Landnám period summarizes sites where human activity occurred before the LTL was deposited (Period 1 = 1%); the Landnám period refers to sites that are sandwiched between the LTL and Eldgjá or V-Sv tephras (Period 2 = 6%) and the post-Landnám period covers sites that are sandwiched between the Eldgjá or V-Sv tephras and the Hekla tephras of A.D. 1104 or 1158 (Period 3 = 19%) (Fig. 5). Archaeological sites that were occupied before the deposition of the Vj or Hekla tephras of A.D. 1104 or 1158 are categorized as Viking age (Period 4 = 38%). Sites considered as potential Viking age are dated post-LTL or between LTL and a 12th-17th century tephra layer (Period 5 = 17%). Sites are considered as potential post-Landnám are dated post-Eldgjá/V-Sv or between one of these 10th century tephras and

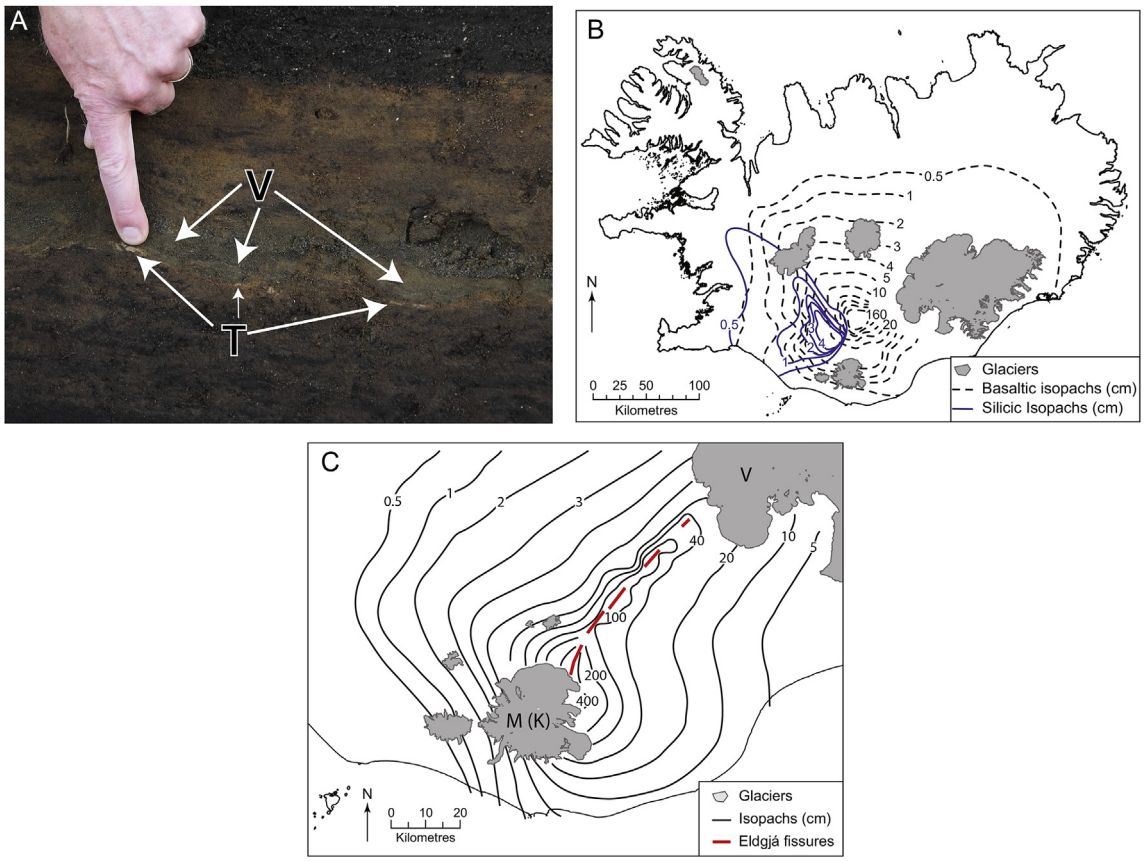

Fig. 4. A: The preservation of the LTL at Langanes in southwestern Iceland. 'T' points to the white silicic Torfajökull component (discontinuous) and 'V' points to the olive-green basaltic Veiðivötn component. B:Isopach map of the silicic and basaltic components of LTL (after Larsen, 1984). C: Isopach map of the Eldgjá tephra in southern Iceland. M= Mýrdalsjökull (K)= Katla; V=Vatnajökull (after Larsen, 2000). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a 12th-17th century tephra (Period 6 = 19%).

There is a pattern to the regional distribution of settlement-related sites connected to the LTL, Eldgjá and V-Sv tephra layers. The two sites with evidence for occupation before the deposition of LTL are both in the southwest (Period 1: Fig. 6A). Sites that are dated between the deposition of the LTL and Eldgjá/V-Sv tephra layers are scattered around the southwest, east and north and found equally in coastal as well as inland regions (Period 2: Fig. 6B). Sites that were occupied after the deposition of the V-Sv tephra are mostly located in the north (Period 3: Fig. 6C) – a function of the

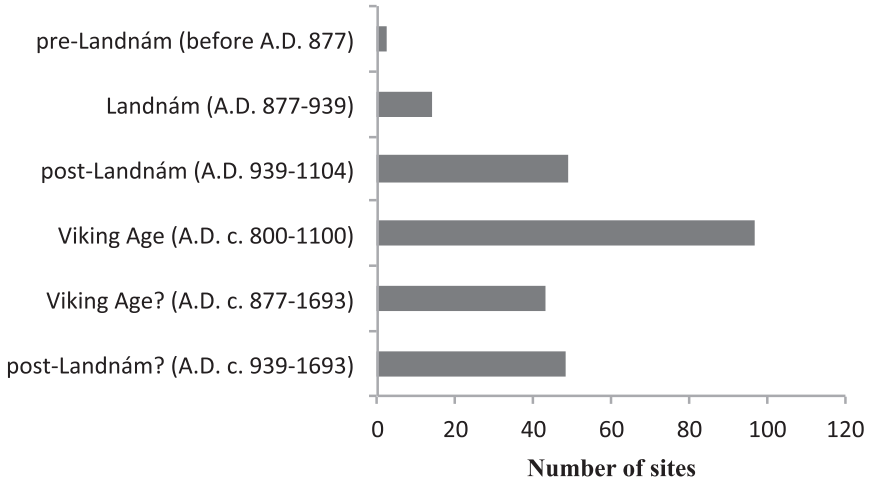

Fig. 5. The number of Viking age settlements whose periods can be defined by tephrochronology (n = 253).

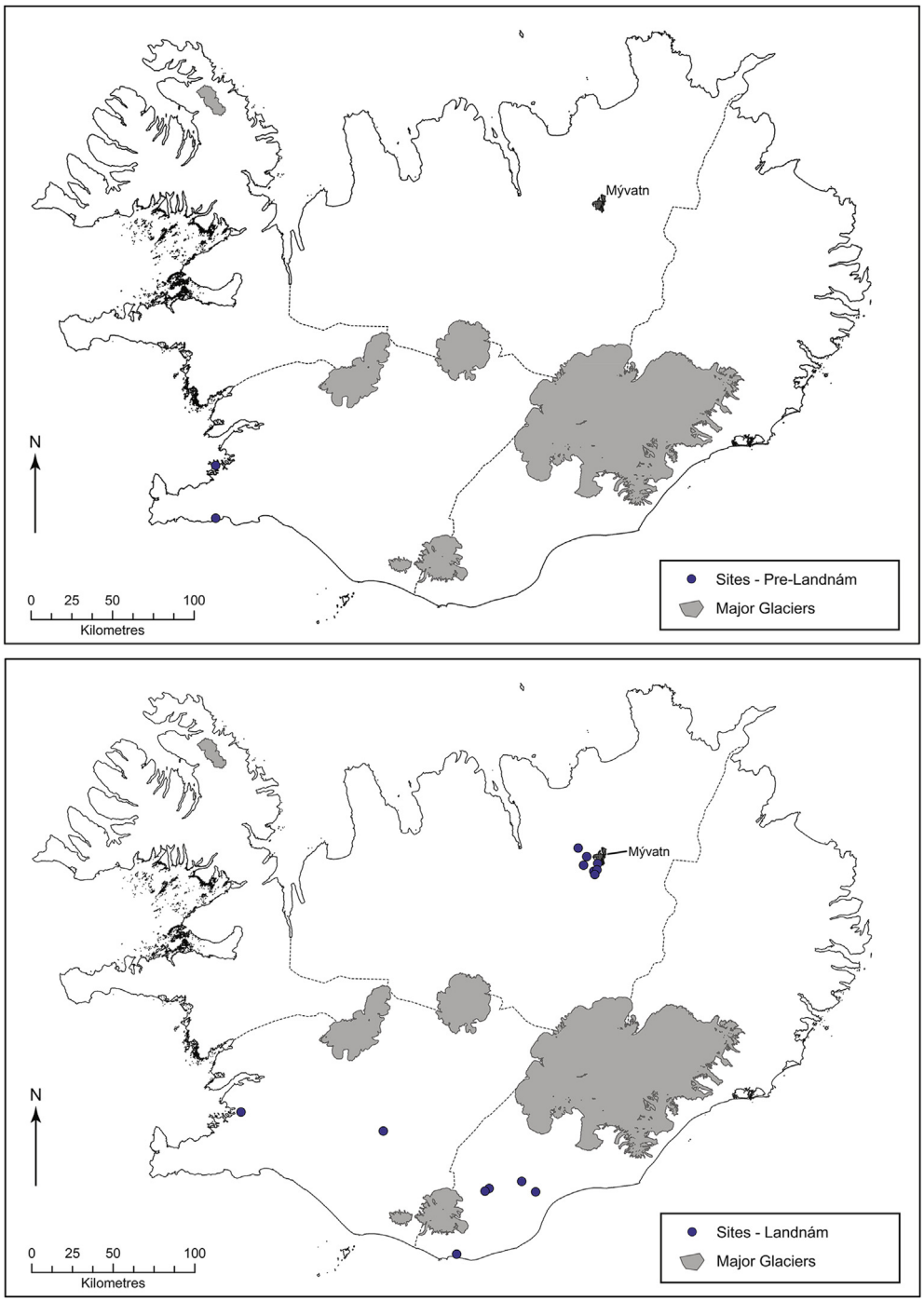

Fig. 6. A: The periodization of Viking Age settlement sites in Iceland. Pre-Landnám (A.D. pre-877; n = 2); **B**. Landnám (A.D. 877-939; n = 14); **C**. Post-Landnám (A.D. 939-1104; n = 47).

distribution of that tephra. Fig. 6 illustrates continuity of settlement in the south and north. The distribution of Viking Age sites shows that all inhabitable parts of the island were most likely occupied by the 10th and 11th centuries and the next phase of Viking expansion to Greenland (Period 4: Fig. 7).

The presence of both the LTL and V-Sv tephra layers in the north and the LTL and Eldgjá tephras in the southwest and east has allowed better dating than is possible in regions where tephra layers from the early settlement period have not been identified and the closest available isochrons are formed by H-1104 and H-1158 or even later tephras. This situation could be improved through the application of other dating methods, in particular radiocarbon dating within a Bayesian framework (e.g. Church et al., 2007; Batt et al., 2015).

These results suggest that although colonisation had started before the 870s in the southwest, the bulk of first settlement happened after that date. Other patterns in the data reflect different fieldwork intensities in different regions and the uneven distribution of (identified) tephras. Within the regions where the A.D. 939 Eldgjá and A.D. 938 ± 6 V-Sv tephras have been identified there are

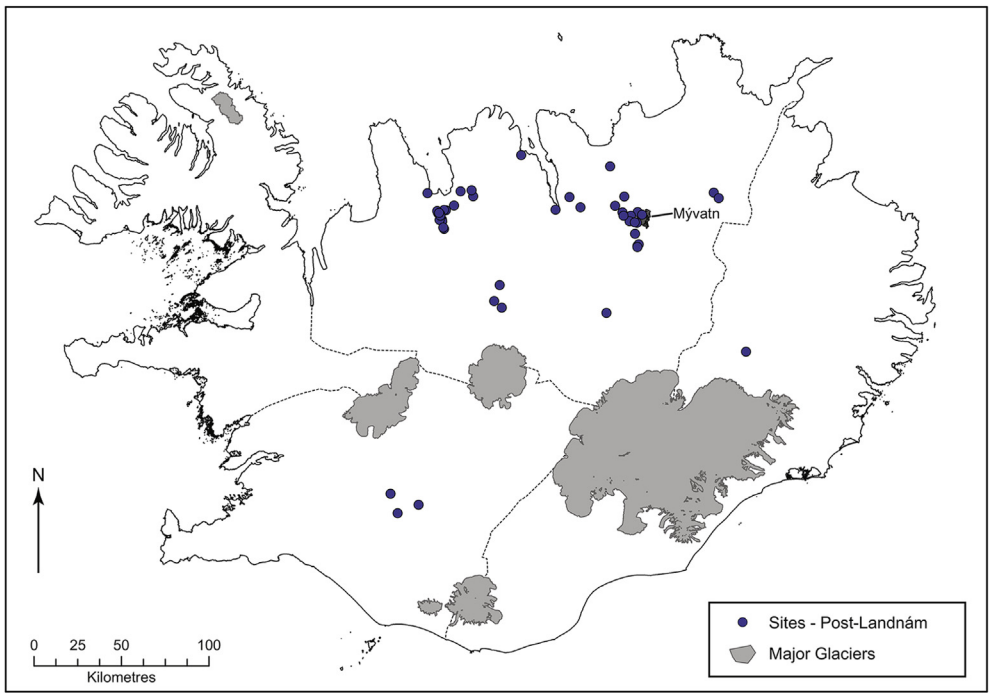

Fig. 6. (*continued*).

a significant number of sites with deposits below those horizons. Indeed, in open area excavation around Lake Mývatn, where the identification of the tephra is far more certain than in limited exposures, anthropogenic layers are below the V-Sv in two out of three sites. Vésteinsson and McGovern (2012) argue that many of these pre-A.D. 938 ± 6 sites represent satellite occupations on less than optimal land, or indeed main occupation sites that are themselves in marginal areas, and this indicates a rapid process of colonisation and near complete occupation of the landscape, encompassing ideal sites and far less than ideal ones, all before the mid-930s.

The new catalogue of early settlement sites shows that none of the pre- A.D. 938 ± 6 archaeological features identified so far in the north are from currently upstanding remains like turf walls. They are all entirely sub-surface features such as pit houses, middens or traces of cultivation. In contrast, most of the post mid-930s dates

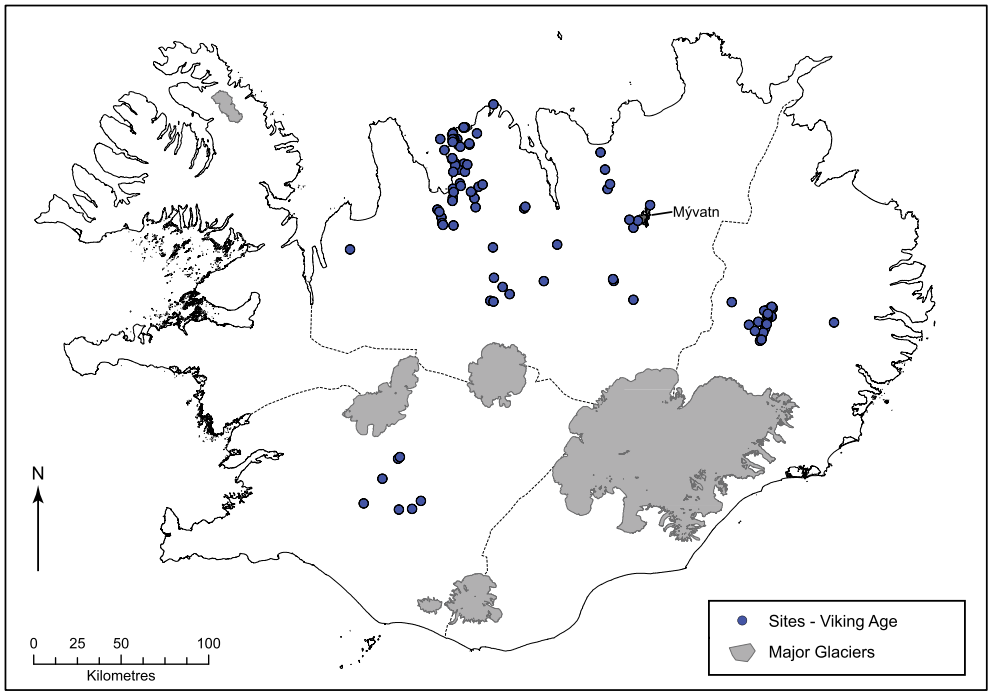

Fig. 7. The periodization of Viking Age settlement sites in Iceland: Viking age (A.D. c. 800-1100; n = 97).

relate to archaeological remains that are still visible as positive features of relief, such as turf-walls of houses and earthwork systems. Such upstanding features in the modern landscape are much more easily identifiable that buried remains; feature of field surveys and are more likely to be targeted for excavation. Furthermore, when excavated they are more likely to preserve tephra layers by sealing them below archaeological remains or providing obstacles against which tephras can accumulate. As sunken-features such as pit houses and midden spreads are more difficult to detect they are most likely under-represented in the data (Vésteinsson, 2014). If this is the case then it opens up the possibility that sites dating to just before or after the LTL may be under-represented in the data set.

Only in recent decades has the potential to use multiple tephra layers to precisely date archaeological deposits from the Icelandic colonisation period been widely recognised. While the majority of available tephra dates demonstrate a clear contrast in the number of settlements known between the pre-LTL and the post-LTL most were obtained using methodologies that do not allow further refinement of the dates. Archaeologists have been pre-occupied with the possibility that pre-LTL deposits might be identified, but they have only just begun trying to systematically collect evidence to date the colonisation as a process (e.g. Bolender et al., 2011; Vésteinsson and McGovern, 2012). The data presented here demonstrates the potential to build a much more nuanced understanding of the sequence of colonisation of Iceland, and whether it was a trickle, steady flow or torrent (Edwards, 2012). It suggests that targeting regions with early 10th century tephras would be particularly useful and that dense spatial coverage of sampling points is key to success. The majority of early tephra dates come from trenching campaigns conducted in the last 20 years (see SI Table 1). They have transformed the distribution maps and further work is likely to clarify the picture. Improving the known geographical extent of 9th and 10th century tephras would also help, as this would improve the number of isochrons available at specific locations. Use of either poorly defined layers (Dugmore and Newton, 2012) or cryptotephras (Lowe, 2008) could achieve this – but across much of Iceland the latter would require methodological innovations to isolate low concentrations of very fine-grained tephras within sedimentologically-similar volcanically-derived andosols (Davies, 2015; Ponomareva et al., 2015).

4. Conclusion

Icelandic archaeology benefits from the presence of multiple tephra layers deposited at around the time of initial settlement by the Norse and in the decades and centuries that followed. The tephras are well-dated and have been identified at 253 archaeological sites related to settlement (84% of the known total). The recent revision of the Greenlandic ice core chronologies has improved tephrochronology in Iceland; most importantly the ages of three key tephra isochrons have been revised: the LTL is now dated to A.D. 877 ± 1, the Eldgjá tephra to A.D. 939 and the V-Sv tephra to A.D. 938 ± 6. Tephra layers that are not historically dated are therefore best referred by a name that is independent of a date, e.g. V-Sv.

The LTL allows us to confidently group archaeological sites into two periods, two from before A.D. 877 ± 1 and 81 from after that date. The earliest sites are exclusively located in the southwest of Iceland. After the deposition of the LTL, continuous and large-scale settlement commenced in all inhabitable parts of the island. The identification of the A.D. 938 ± 6 V-Sv tephra in the north and the A.D. 939 Eldgjá tephra in the southwest and east allows further division of the archaeology of settlement sites into the period of Landnám as well as in the period after the Landnám.

Considerable potential exists to apply the tephrochronology of Landnám across regions where key tephra are known to exist. The isochrons defined by tephra layers provide a very effective way to constrain and quantify the timing, scale and tempo of settlement, and thus gain a better understanding of the processes driving colonisation both in Iceland and many other parts of the world affected by tephra deposition, such as the western parts of the Americas and the Pacific Rim. Methodological innovations to isolate low concentrations of very fine grained tephras within sedimentologically similar volcanically-derived andosols would allow cryptotephrochronology to further enhance both the temporal resolution and geographical extent of dating using tephra.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quageo.2016.08.002.

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4.3 Correlating multidisciplinary datasets

After having established three consecutive periods of Iceland's settlement this chapter focuses on comparing tephra evidence, ^{14}C samples and typologically diagnostic artefacts. Archaeological sites are primarily dated by tephrochronology. The chronology of a site is revised if ^{14}C dates show a later occupation than the earliest tephra. For example, Selhagi is dated by tephrochronology to between LTL of AD 877 ± 1 and the H-1104/1158. Two terrestrial bone samples have CRA of 960 ± 45 BP (*cal AD 1023-1152* at 68% probability) and 995 ± 45 BP (*cal AD 991-1148* at 68% probability). Although quality assurance data is not published for these bone samples, the site is still considerd as post-Landnám. If tephra is not preserved or recorded at an archaeological site, the age of the site is established with reliable ^{14}C dates, excluding eleven statistical and 118 non-tangible outliers due to their current inaccuracy (n = 384; Chapter 6). If ^{14}C samples are also absent, the site is dated using typology. The earliest feature dated at an archaeological site that yielded one or more dates provides the earliest evidence of occupation at that particular site. The chronology of 550 sites is summarized in Figure 4-17 and in Appedix I. Generally <1% of archaeological sites are from the pre-Landnám period (n = 2), 15% from the Landnám period (n = 84), 33% from the post-Landnám period (n = 182) and 51% of the dataset cannot be assigned more narrow age ranges than the Viking age (n = 282).

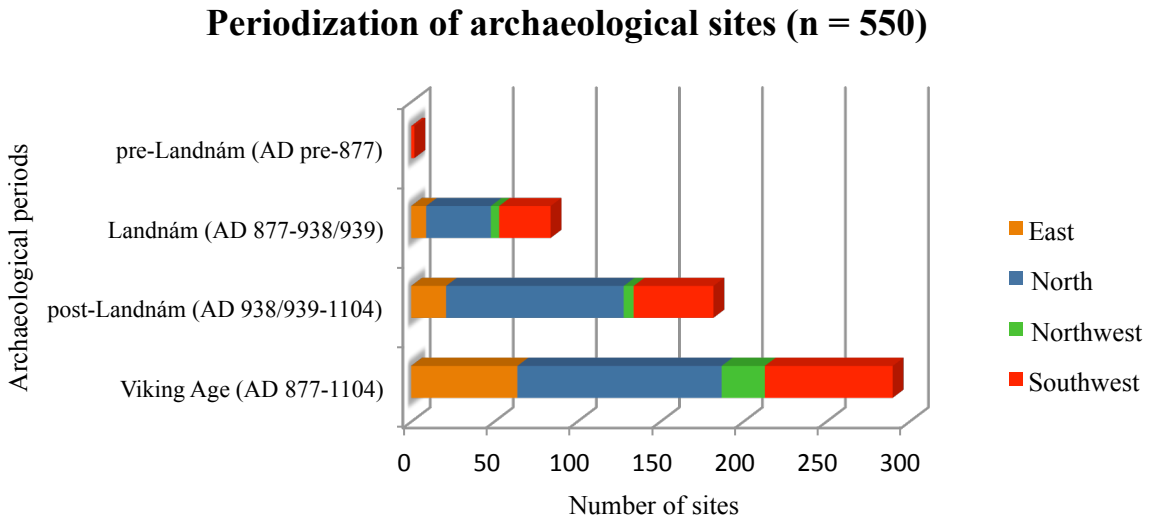

Fig. 4-17 The chronology of 550 archaeological sites in Iceland. The data are separated into four geographic areas.

4.3.1 pre-Landnám (AD pre-877)

The pre-Landnám (AD pre-877) period refers to sites where earliest observed human activity satisfies one or more of four criteria:

1) Archaeological features occur stratigraphically below the LTL of AD 877 ± 1:
    - There are only two features covered by the LTL. These features are turf walls, which will have served as fences rather than roofed structures, at sites, which had developed into permanent settlements later in the Landnám period (Figure 4-18). There are no middens, burials or dwellings sealed by the LTL.
2) Contexts related to such deposits have yielded ^{14}C ages with probability distributions before the AD 870s (e.g. RKV U-2672: *cal. AD 641-766* at 68% probability)
    - Although 37 ^{14}C dates date to the AD 6-8th centuries, they are from stratigraphic contexts above the LTL. This is not surprising at all, considering that none of these 'early' ^{14}C dates are of short-lived materials such as grains or terrestrial bone, but they are of wood charcoal with inbuilt age.
3) Contexts related to such deposits have yielded artefacts dated to AD pre-870s.
    - The oldest artefacts found in Iceland are four Roman coins, Antoniniani from around AD 300, and a few early artefacts dating to the late 8th century. Significantly, none of the objects were sealed by the LTL.

Two settlement sites belong to this early period of settlement; they are both located in the Reykjanes peninsula in SW Iceland (Fig. 4-18). The sites cannot be interpreted as permanent settlement; they most likely represent seasonal activities. Significantly, there are no midden deposits, burials, abandoned buildings or artefacts found sealed by the LTL.

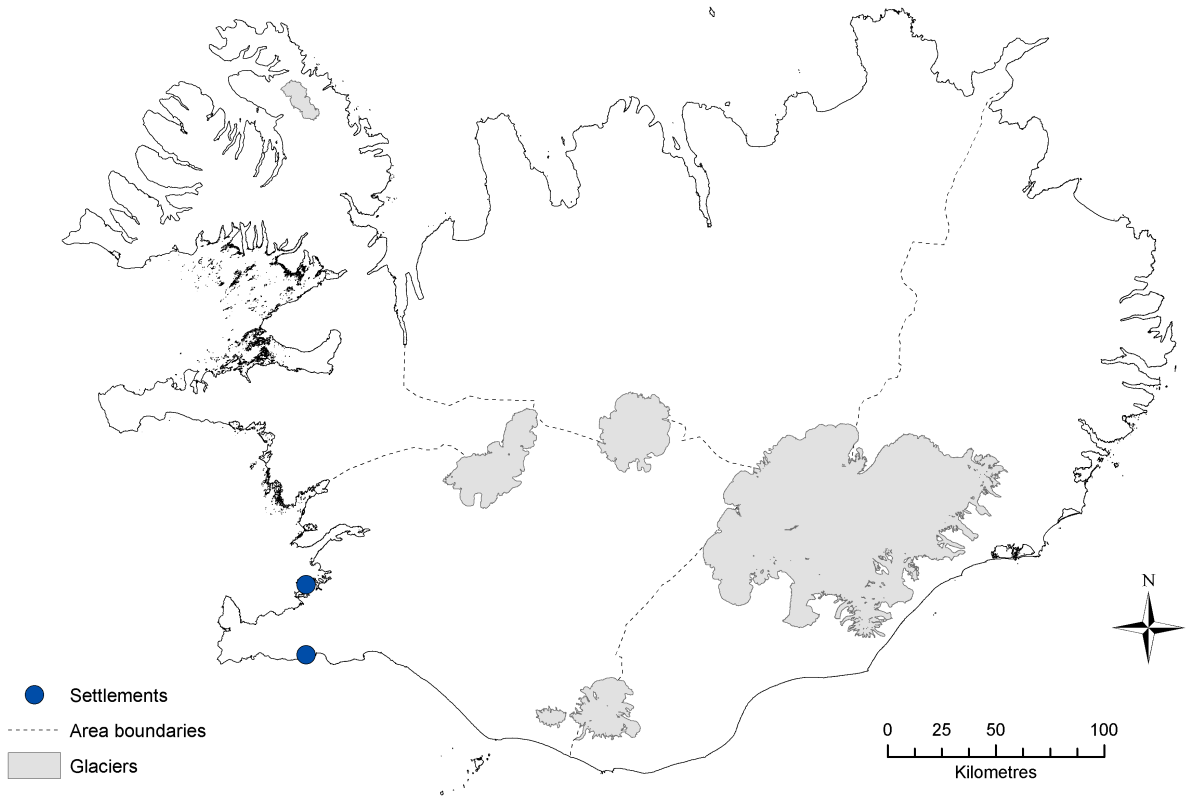

Fig. 4-18 The distribution of two pre-Landnám (AD pre-877) sites in the southwest of Iceland. Source: Anthony J. Newton.

4.3.2 Landnám (AD 877-938/939)

The Landnám (AD 877-938/939) period refers to sites where earliest observed human activity satisfies one or more of three criteria:

1) Archaeological features occur stratigraphically above the LTL of AD 877 ± 1 or below a 10th century tephra (Eldgjá of AD 939 or V-Sv of AD 938 ± 6). They can also be sandwiched between the K~920 and Eldgjá tephra:
    - There are 81 settlement sites of all sorts of functions that belong to this period; they are interpreted as permanent settlements (Figure 4-19). Furthermore, graves at one burial site were covered by the Eldgjá tephra.
    - None of the archaeological features identified in the north are from upstanding remains like turf walls. They are all entirely sub-surface features such as pit houses, middens or traces of cultivation.

2) Contexts related to such deposits have yielded ^{14}C ages with probability distributions before the AD 940s (e.g. RKV-AST ARR-7620: *cal. AD 777-885*)
    - 68 ^{14}C dates have clear cut-offs before the AD 940s; they are mostly of wood charcoal with inbuilt age.
3) Contexts related to such deposits have yielded artefacts dated to AD pre-950s.
    - There are two assemblage sites dating to this period because of beads that are dated to AD pre-915 an AD pre-950.

In total, 81 settlement sites, one burial site and two assemblage sites are dated to the Landnám period (n = 84). These sites are found across the entire island, equally in coastal and inland areas, apart from the northwest peninsula, although 46% of sites are located in the north (n = 39), 37% in the southwest (n = 31), 11% in the east (n = 19) and 6% in the northwest (n = 5; Fig. 4-19).

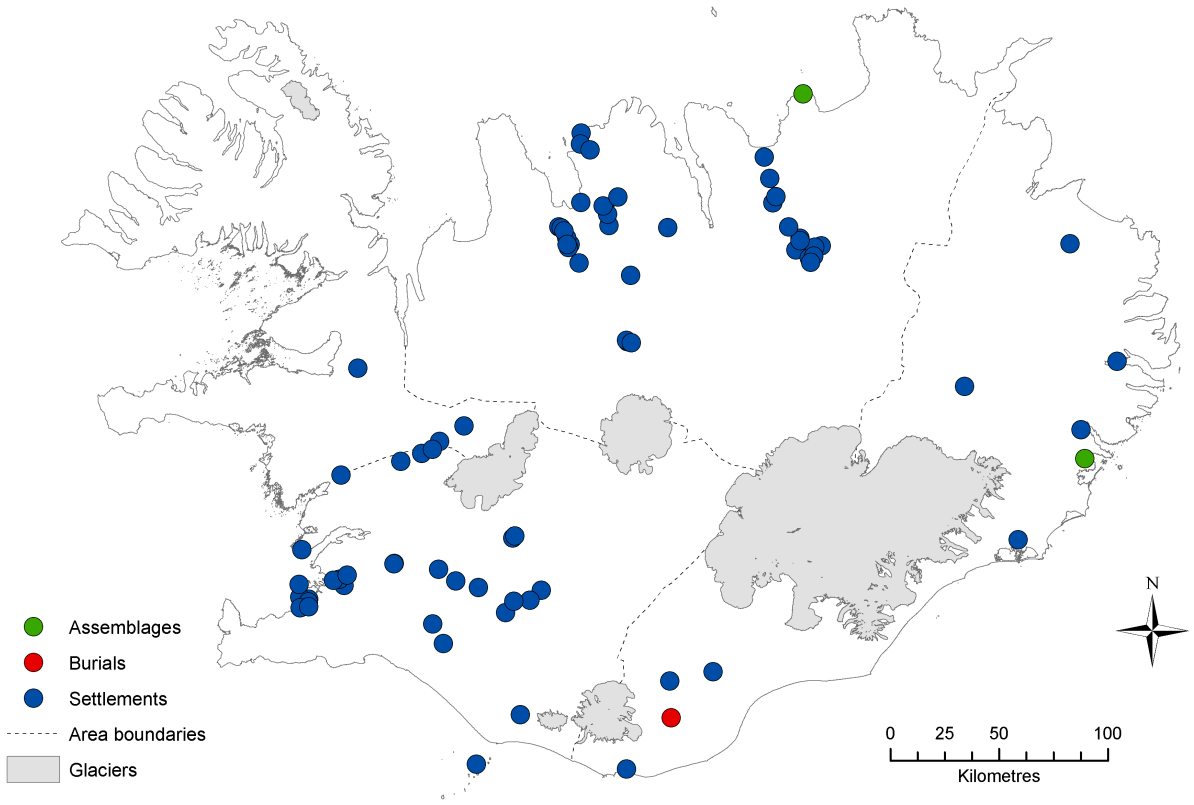

Fig. 4-19 The distribution of 84 Landnám (AD 877-938/939) sites across the country. The distribution is based on tephra layers, ^{14}C dates and typology and differs from that given in Chapter 4.2, Figure 6B, which is only based on sites that are sandwiched between the LTL and a 10th century tephra (Period 2: Table 4-7). The map was created by: Anthony J. Newton.

4.3.3 post-Landnám (AD 938/939-1104)

The post-Landnám (AD 938/939-1104) period refers to sites where the earliest observed human activity satisfies one or more of three criteria:

1) It occurred above one of the tenth century tephras, the Eldgjá tephra of AD 939 or the V-Sv tephra of 938 ± 6 or below the H-1104 tephra.
    - There are 116 archaeological sites of all sorts of functions that belong to this period; they are interpreted as permanent settlements (Fig. 4-20).
    - There are distinctive earthwork systems established in the north of Iceland.
2) Contexts related to such deposits have yielded ^{14}C ages with probability distributions after the AD 940s (e.g. RKH SUERC-5123a: *cal. AD 997-1147*).
    - 132 ^{14}C dates have clear cut-offs after the AD 940s; they are from both settlement and burial sites. These ^{14}C dates are of all material classes.
    - ^{14}C samples in the north are all of short-lived materials and bone samples affected by MRE.
3) Contexts related to such deposits have yielded artefacts dated to AD post-950 or post-960, or they are dated to the 11th century.
    - Most of the narrow typological dates (e.g. a variety of beads) from burial and assemblage sites belong to the mid to late 10th century; while a few are dated to the 11th century (Vésteinsson and Géstsdóttir 2016; Appendix I).

116 settlement sites, 29 burial sites and 37 assemblage sites are dated to the post-Landnám period (n = 182). The sites are distributed across the whole island; however, 59% are located in the north (n = 107), 26% in the southwest (n = 48), 12% in the east (n = 9) and 3% in the northwest (n = 6; Fig. 4-20).

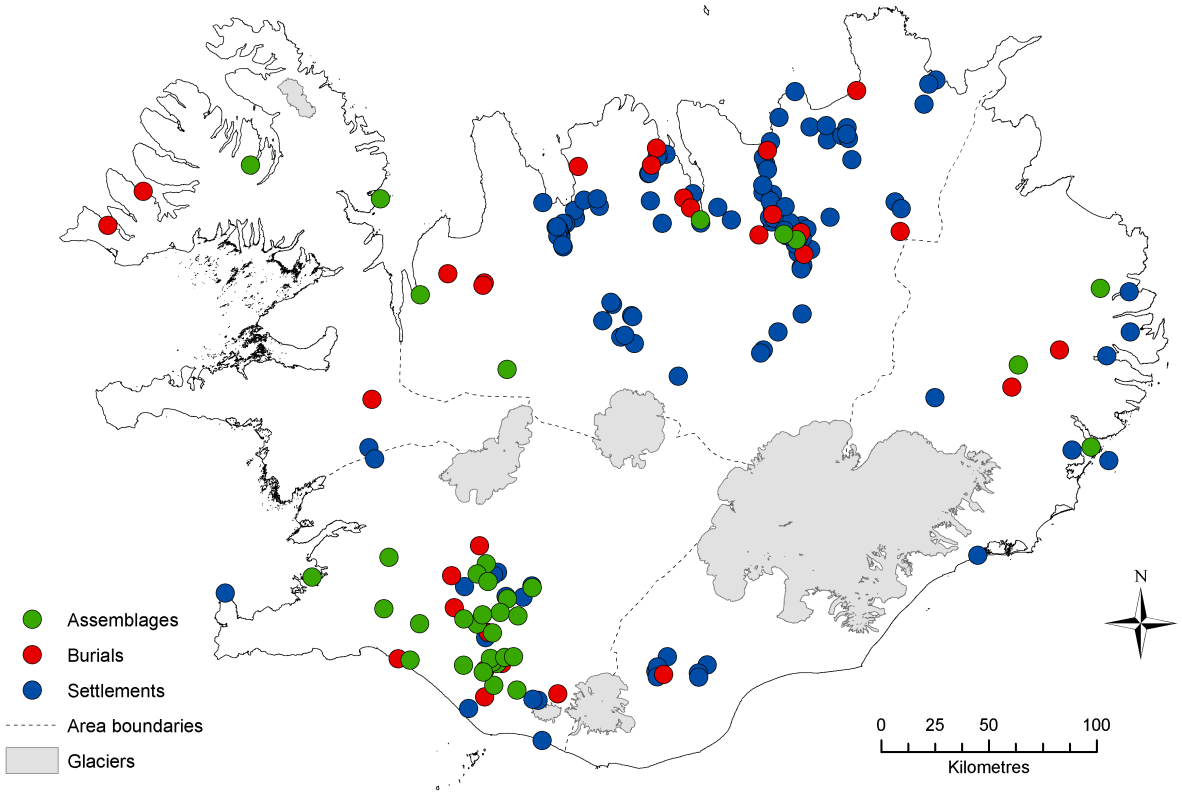

Fig. 4-20 The distribution of 182 post-*Landnám* (AD 938/939-1104) sites across the country. The distribution is based on tephra layers, ^{14}C dates and typology and differs from that given in Chapter 4.2, Figure 6C, which is only based on sites that are sandwiched between a 10th century tephra and the H-1104 tephra (Period 3: Table 4-7). The map was created by: Anthony J. Newton.

4.3.4 Viking age (AD 877-1104)

The Viking Age (AD 877-1104) period refers to sites where earliest observed human activity satisfies one or more of three criteria:

1) Earliest observed human activity cannot be constrained by the LTL or a 10th century tephra. For instance, an archaeological feature is below the Vj tephra.
    - There are 101 settlement sites of all sorts of functions that belong to this period; they are interpreted as permanent settlements (Fig.4-21).
2) Contexts related to such deposits have yielded ^{14}C ages with probability distributions overlapping with periods 2-3 (e.g. RKH SUERC-5123b: AD 893-975 at 68%)
    - 184 ^{14}C dates from settlements and burials of all material classes.
3) Contexts related to such deposits have yielded artefacts broadly dated to the 'Viking Age' or '10th century'

- Mostly swords and bead finds from burial and assemblage sites (Eldjárn and Friðriksson 2016, Appendix I).

101 settlement sites, 110 burial sites and 71 assemblages are dated to the Viking Age (n = 282). The sites are distributed across the whole island (Fig. 4-21).

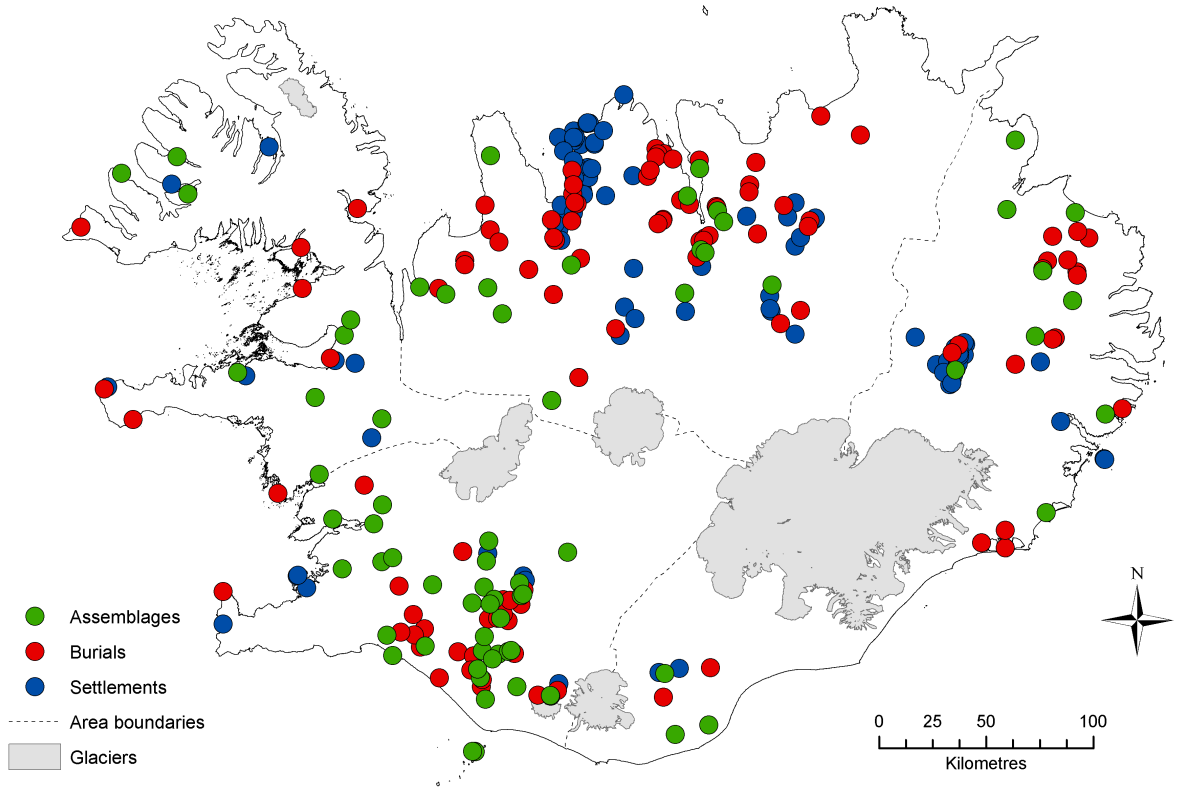

Fig. 4-21 The distribution of 232 Viking age (AD 877-1104) sites across the country. The distribution is based on tephra layers, ^{14}C dates and typology and differs from that given in Chapter 4.2, Figure 7, which is only based on tephra dated sites. The map was created by: Anthony J. Newton.

5. Correlating archaeological, palaeoenvironmental and documentary datasets using Bayesian approaches

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Quand le sol aura été interrogé, il répondra.
When the soil has been questioned, it will answer.

L'Abbé Jean Cochet 1866

5.1 Introduction

This chapter assesses the potential for how re-analysis of excavated and previously dated archaeological sequences, using the methods developed in the thesis, can result in chronological improvements. This is shown to offer new insights into activities such as site occupation histories. The work assesses how multiple, potentially powerful, strands of dating evidence can be best combined. This is primarily directed at the timing of Icelandic settlement, but has much wider implications as a statement of how such investigations can be approached in other regions and other time periods. This paves the way for future chapters that show how material that would likely be excluded from standard models can, in fact, provide robust results.

The chapter summarizes two research papers and focuses on the following research question:

Q3) ***How can multiple lines of dating evidence be most effectively correlated to assess the onset of colonisation in Iceland*****?**

The first research paper explores the use of 'Agreement Index' in Bayesian approaches to model chronologies for archaeological sequences (Chapter 2.5.1). Materials and methods combined include ^{14}C dates, stratigraphy, tephra layers, typologically diagnostic artefacts, and sediment accumulation rates (Chapter 3.4).

The second research paper explores the use of 'General Outlier models' and Age-depths models in Bayesian approaches to model chronologies for both archaeological and palaeoenvironmental sequences (Chapter 2.5.2). This draws upon a comprehensive range of dating evidence including ^{14}C dates, stratigraphy, tephra layers, typologically diagnostic artefacts, textual resources and palaeoecology (Chapter 3.4). The outcome of this chapter is that the scientific dates support the typological and historical dates. The chapter builds upon previous work in the thesis, building a framework for a robust approach to chronology

building. It also focuses on aspects of available collagen-quality indices to make informed decisions about weather certain materials can be incorporated in a model.

Conventional ^{14}C ages of bone samples affected by MRE were converted into calendar years by using a mixed calibration curve interpolated between the terrestrial curve 'IntCal13' and the marine curve 'Marine13' with the fraction of marine diet as an input parameter. The percentage of marine diet was calculated by linear interpolation ($y = 270.67 + 13.333x$) between the end-point values 12.8‰ for a 100% marine diet and -20.3‰ for a 100% terrestrial diet, where x is $\delta^{13}C$ value and of y is % marine contribution to diet (Chapter 2.3.2). An uncertainty of 10% in the percentage value was included. Furthermore, a ΔR value of 111 ± 10 ^{14}C yrs was used.

5.2 Paper 2: 'Constructing chronologies in Viking age Iceland: Increasing dating resolution using Bayesian approaches'

Batt, C., Schmid, M.M.E., Vésteinsson, O. 2015. Constructing chronologies in Viking age Iceland: Increasing dating resolution using Bayesian approaches. *Journal of Archaeological Science* 62, 161-174.[2]

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The second paper (Appendix IV) evaluates three large-scale excavated sites in Iceland (Reykjavík-Aðalstræti, Sveigakot, and Hofstaðir) using Bayesian statistical analysis of multiple ^{14}C dates, associated tephra layers, artefact typologies and soil accumulation rates (SeAR).

Reykjavík-Aðalstræti is one of the earliest sites occupied in southwest Iceland. A turf-wall is abutted by the LTL of AD 877 ± 1 and demonstrates that people had been on the island before this volcanic eruption (Chapter 4.2). How long before the AD 870s people arrived cannot be estimated. The key focus in this paper is on the well-preserved remains of a hall that is associated with this turf wall. The hall was sandwiched between the LTL and K~1500

[2] The role of the doctoral student (Magdalena M.E. Schmid) in this paper was to carry out all of the research activity including research design, the collections of data, the analysis of data, as well as writing of the text. SeAR were measured at Aðalstræti by the doctorate student and Dr. Howell Roberts. Dr. Cathy Batt and Prof. Orri Vésteinsson guided the doctoral student during the writing process. The authors agreed on alphabetical oder.

tephra; unfortunately no 10th century tephra is preserved at the site. In 2013, Howell Roberts and myself measured the accumulation of sediments below and above the cultural remains in relation to the two tephra layers *in situ* in order to date the occupation and abandonment of the hall more precisely. The accumulation between the LTL *in situ* and the foundations of the hall is between 1-3 cm on the eastern side and between 3-8 cm on the western side. The accumulation varies because the hall, facing northeast, was constructed at the bottom of a steep slope starting on the western site of the hall. The soil was deposited through fluvial processes, which accumulate faster than through aeolian processes. 78 cm of soil was deposited between the two tephra constrains; if we assume that soil accumulated at a constant rate, we have an average of 1.24 mm/yr, suggesting that the time elapsed between the LTL and the construction of the hall could have been between 12 and 99 years, according to less accumulation on the eastern side, potentially, between 12 and 37 years.

These estimates have been tested with a Bayesian model of seven ^{14}C dates of barley seeds from well preserved floor and hearth deposits within the hall. The modelled date for the earliest occupation is estimated to *cal. AD 865-890*. The constrained dates of the model also propose that the hall was constructed within a few years of the deposition of the LTL (before AD 890) making this hall one of the earliest dwelling sites in Iceland. The model also indicates that the hall was abandoned by AD 1020, which adds detail and precision to previously proposed site-specific chronologies (Roberts et al. 2003). Nevertheless, floors and hearths were regularly cleaned in the past and most likley do not represent initial deposits. The date of the earliest occupation of the hall is therefore constrained by the underlying LTL and the proposed length of occupation is around 150 years maximum.

Bayesian models can also either incorporate established artefact typologies or be used to test them. This study, therefore, incorporated a diagnostic glass bead (B610) in the model with a *prior* probability of AD 860-950. Viking age bead typologies are problematic; there are no independent scientific dates and the typology is based on the co-occurrence of oval brooches decorated in Viking age animal styles – which have chronological problems themselves – and datable coins. Considering these uncertainties, the *posterior* probability of this bead is *cal. AD 875-950*; which is in excellent agreement with the ^{14}C date from the same context (AAR-7616: *cal. AD 875-955*) and does not contradict the scientific date. In fact, the inclusion of the bead makes a slight improvement to the precision of the date of first occupation. This demonstrates that bead typologies have the potential to be systematically assessed in Iceland in future studies.

Two sites in the north (Hofstaðir and Sveigakot) consist of multiple anthropogenic features, where stratigraphic relationships between individual features as well as tephra layers are discontinuous and demostrate challenges in cross correlation between different areas.

Hofstaðir, for instance, has a complex stratigraphy and several phases of activities. There are large, open spaces between most of the structures, and connecting layers are thin or discontinuous, making it difficult to establish a secure overall site stratigraphy. Although the chronology of the site is well constrained (sandwitched between the V-Sv and H-1104), only two out of five structures were ^{14}C dated: a pit house and a well-preserved hall. This again is a result of 'special interest' sample selection.

The chronological models for the pit house and hall are based on 23 ^{14}C dates from animal bone collagen, of which some were adjusted for marine reservoir effects. On the evidence available, it was not possible to reliably estimate the date of first occupation of the site, only for the use of the pit house (*cal AD 930-945*, shortly after the V-Sv tephra), which is, however, a much more precise date than previously obtained. It was also possible to identify that the hall had been abandoned by *cal AD 1015-1095*, which concurs with the existing archaeological interpretation (Lucas 2009:67, Table 3.1).

The adjustments made for reservoir effects were largely successful in the sense that most changes produced calibrated dates that were in accordance with other dated material from the same context. However, there remain two examples where the adjustments still give ^{14}C dates that are apparently anomalous when compared with samples from the same context. This demonstrates that bone samples are less valuable if the quality assurance data, such as the C:N ratio, are unavailable. This is discussed in more detail in the following chapter.

In Sveigakot, there are no overall linking deposits and it is not possible to create an overall stratigraphic sequence, despite comprehensive excavation, due to erosion of the substrata. Two tephra layers are preserved at the site, the LTL and V-Sv of 938 ± 6 tephra; however, features are typically connected to one tephra layer or in some cases features are not connected to any tephra at all. This discontinuous nature of the stratigrpahic record makes in necessary to construct short sequences, reflecting different areas of the site, as well as to focus on specific questions, for instance the first occupation of the site.

Four chronological models consits of 21 ^{14}C dates, predominantely from animal bone, of which some are corrected for marine reservoir effects. The impact on calibrated date ranges is limited due to the fact that they are all short sequences with a small number of dates.

Although the *posterior* estimates do not contradict the archaeology; for instance a cow bone sandwiched between the LTL and V-Sv tephra yielded a posterior estimate of *cal AD 875-940*; they do not improve the precision of the chronology either. We still do not know how long after the deposition of the LTL the Norse occupied the site. This is a result of sample selection; samples were taken from key locations considered to be of greater research interest (Chapter 2.2); here these are locations stratigraphically above the V-Sv tephra because there is no other tephra layer preserved at the site that is younger than the V-Sv tephra. Furthermore, 'special interest' sampling strategies may result in ^{14}C datasets where early anthropogenic activities are most likely underrepresented. This is primarily directed at the timing of Iceland's settlement, but has much wider implications as a statement of how such investigations can be approached in other regions and other time periods – setting up discussions in Chapters 5.3 and 6-7.

5.3 Paper 3: 'A Bayesian Approach to linking archaeological, palaeoenvironmental and documentary datasets relating to the settlement of Iceland (Landnám)'

Schmid, M.M.E., Zori, D., Erlendsson, E., Batt, C., Damiata, B.N., Byock, J. 2018. A Bayesian Approach for Linking Archaeological, Palaeoenvironmental and Documentary Datasets relating to the Settlement of Iceland (Landnám). *The Holocene* 28(1), 19-33. (https://doi.org/10.1177/0959683617714597).[3]

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The third paper is motivated by the fact that the timing of early anthropogenic activities in Iceland (e.g. the use of arable fields, or the clearing of woodlands) has previously not been correlated with archaeological sites and modeled using Bayesian statistical analysis. This paper uses a large-scale excavated site in southwest Iceland, Hrísbrú, as a case study to test previous assumptions about anthropogenic activities and to evaluate multidisciplinary datasets (^{14}C dates, stratigraphy, tephra layers, typologically diagnostic artefacts,

[3] The role of the doctoral student (Magdalena M.E. Schmid) in this paper was to carry out all of the research activity including research design, the collections of data, the analysis of data, as well as writing of the text. Dr. Davide Zori, Dr. Egill Erlendsson, Dr. Cathy Batt, Dr. Brian Damitia and Prof. Jesse Byock guided the doctoral student during the writing process. The figures were done by the doctoral student and by Dr. Davide Zori.

documentary texts and palaeoecology) from multiple-periods including a Viking age hall and Christian church and cemetery.

The palaeoenvironmental rationale for a pre-Landnám occupation at the site includes a series of potential cultural indicators 1 cm below the LTL. They consist of microscopic charcoal (evidence for woodland clearance), the appearance of dung-loving fungi (the introduction of herbivorous animals) as well as *Hordeum*-type pollen (the introduction of agriculture). The onset of agricultural activities are estimated to *cal. AD 839-876* (68%) and *cal. AD 830-881* (95%); before the first known structure – the hall – was built at the site (after the LTL). This is consistent with anthropogenic activities in the southwest of Iceland that started before the deposition of the LTL (Chapter 4.2).

This study shows sampling bias in ^{14}C dates across large-excavated sites as demonstrated in the previous paper (Chapter 5.2). The hall was built after the LTL, but ^{14}C samples were only observed from late occupation contexts, shortly before the hall went out of use. It was not possible to reliably estimate the date of first occupation of the site. This has wider implications for both the settlement of Iceland as well as for other geographic regions and time periods and again shows that dates from early contexts are most likely underrepresented – a prerequisite for the following Chapters.

Furthermore, this study discusses ^{14}C dates of bone collagen that appear to be affected by MRE. 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. The most widely used criterion for identifying contamination is the C:N ratio and values within an empirically derived range of 2.8-3.3. are robust cut-offs for archaeological studies, while values above 3.4 may indicate contamination with carbon-rich substances such as humic acid or glues such as PVA. The use of available collagen-quality indices to make informed decisions about whether certain materials can be incorporated in a model has wider implication for bone samples from other archaeological features in Iceland as well as from other geographic areas and time periods. Therefore, sample AA-93254 is suspect based on the quality of collagen; the sample yielded an atomic ratio of 3.7 and is therefore omitted from analysis.

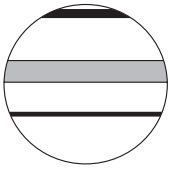
This study also tested typologically sensitive materials. 36 imported glass beads were found in the upper floor layers of the hall. Two types of diagnostic glass beads were incorporated in the model with a *prior* probability of AD 960-1000 (Bh) and of AD 950-1000 (Ea). The 95%

HPDs are *cal. AD 960-977* and *cal. AD 950–974* respectively; they constrain the chronology of the site, more so than the ^{14}C date from the same context (UCIAMS-64172: *cal. AD 929-973*).

Additionally, dates from medieval literary texts are included in the model in order to test assumptions about the construction date of the church (e.g. after the conversion to Christianity in AD 999/1000). One pine wood sample from the nave of the church was constrained to *cal. AD 917–1009*, while the unmodelled date is AD 770–980, which does not account for the inbuilt age of pine wood. Christian activity at the site, however, is modelled to *cal. AD 901–987*, because most burials around the church yielded tenth century dates. It is therefore likely that the church and Christian burials may predate the conventionally accepted AD 999/1000 date for the conversion of Iceland.

The key conclusion is that palaeoecological, textual and typological datsets fit well with the archaeological evidence based on stratigraphy, multiple tephra layers and ^{14}C dates. This is also the first example of an archaeological site where a pine wood sample of considerable growth could be incorporated in the model, which sets up the discussion of the value of ^{14}C samples with inbuilt ages as presented in the next two chapters.

Research paper



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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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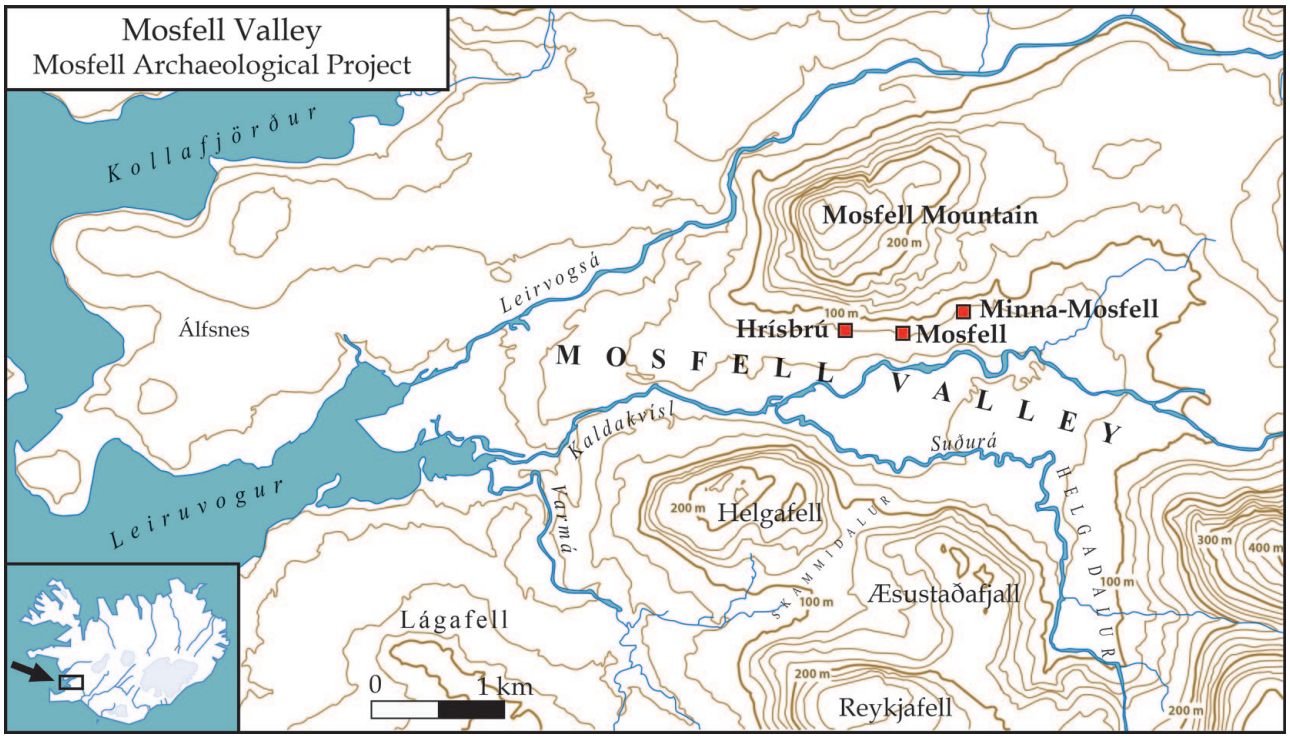

Figure 1. The Mosfell Valley in southwest Iceland. The red squares indicate the locations of the three farm sites mentioned in the text. Hrísbrú is the site of excavations that yielded the archaeological material discussed in this paper.

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,

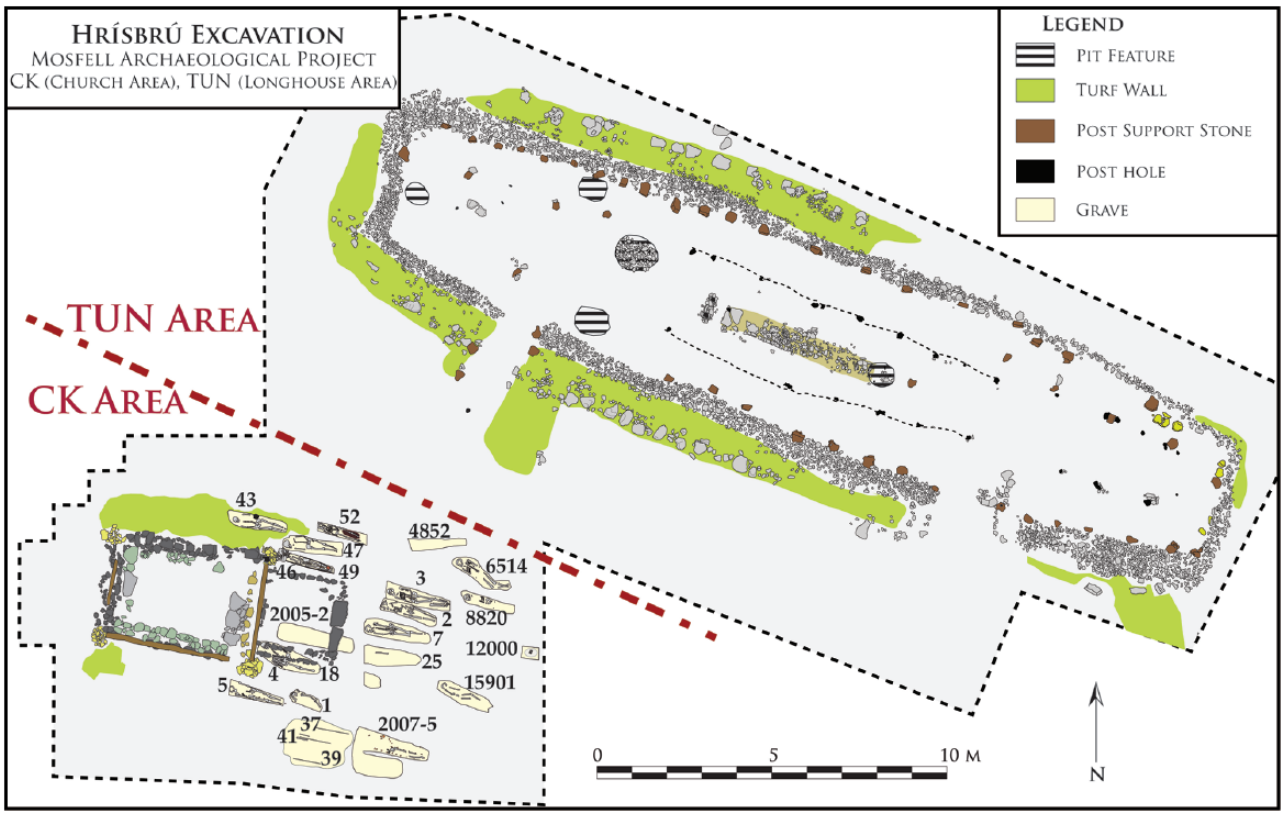

Figure 2. The location of the Viking Age hall (TUN) and the church and cemetery (CK) to the southwest of the hall.

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

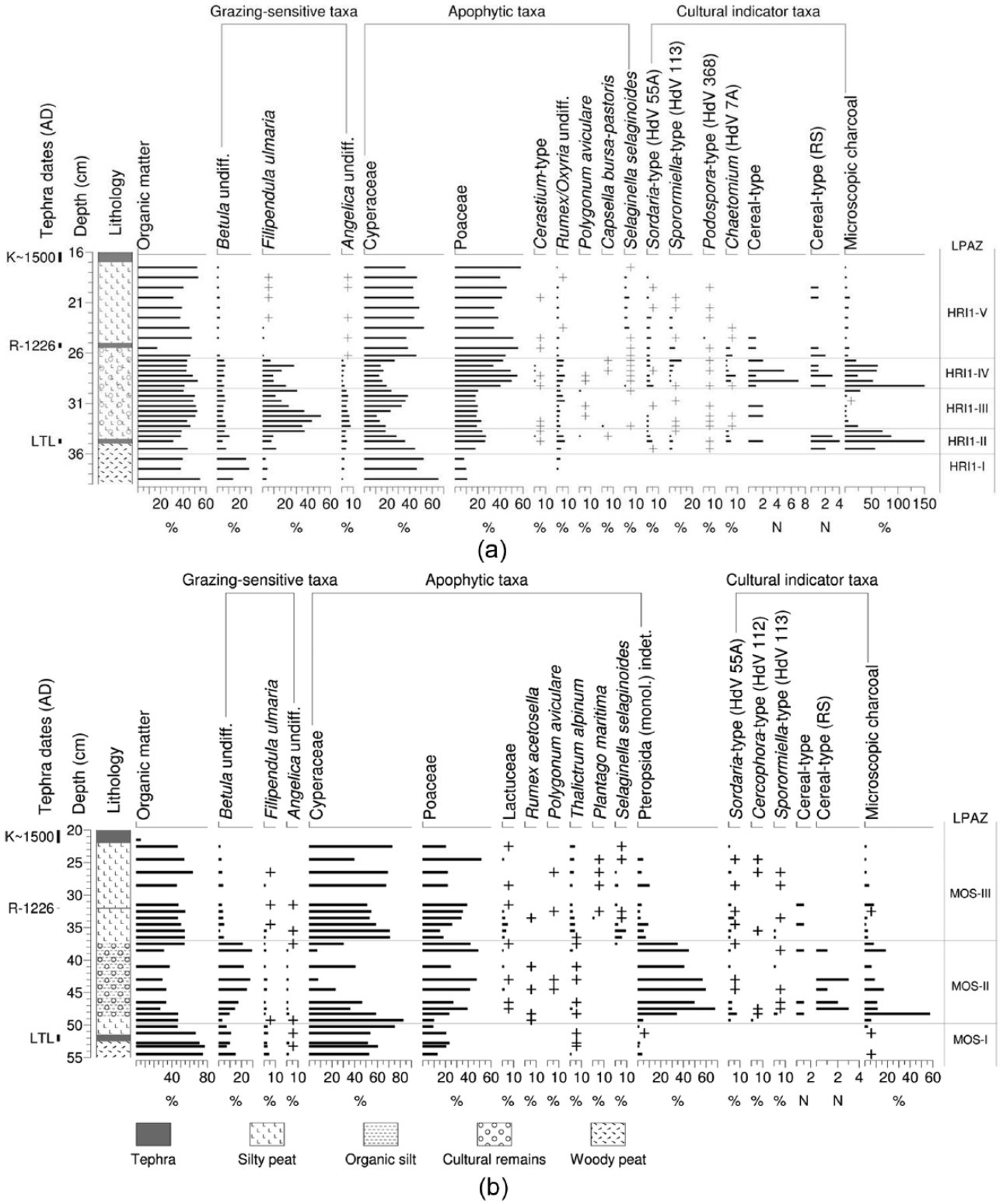

Figure 3. Pollen percentage diagrams from (a) Hrísbrú (HRI1) and (b) Mosfell (MOS). The diagrams show selected pollen, spore and fungal taxa, along with microscopic charcoal, lithology and organic matter content of sediment. Crosses signify values below 1% TLP.
RS: rapid scanning.

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.

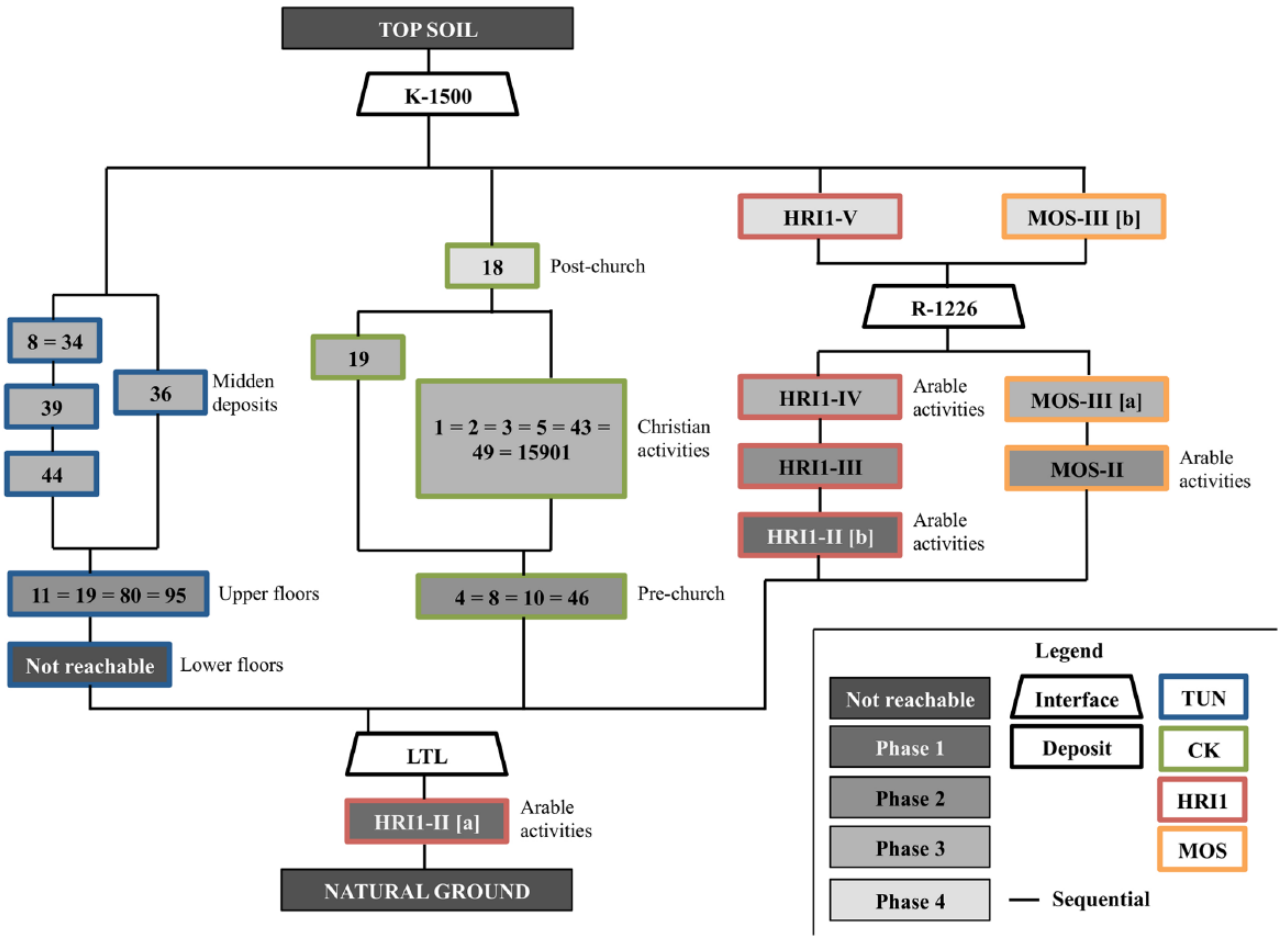

Figure 4. Harris Matrix showing relationships of radiocarbon samples, beads and tephra layers for TUN and CK and for the sediment cores HRI1 and MOS (after Dye and Buck, 2015). LPAZ HRI1-II and MOS-III are split into [a] and [b], because they occur below and above a particular tephra layer.

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

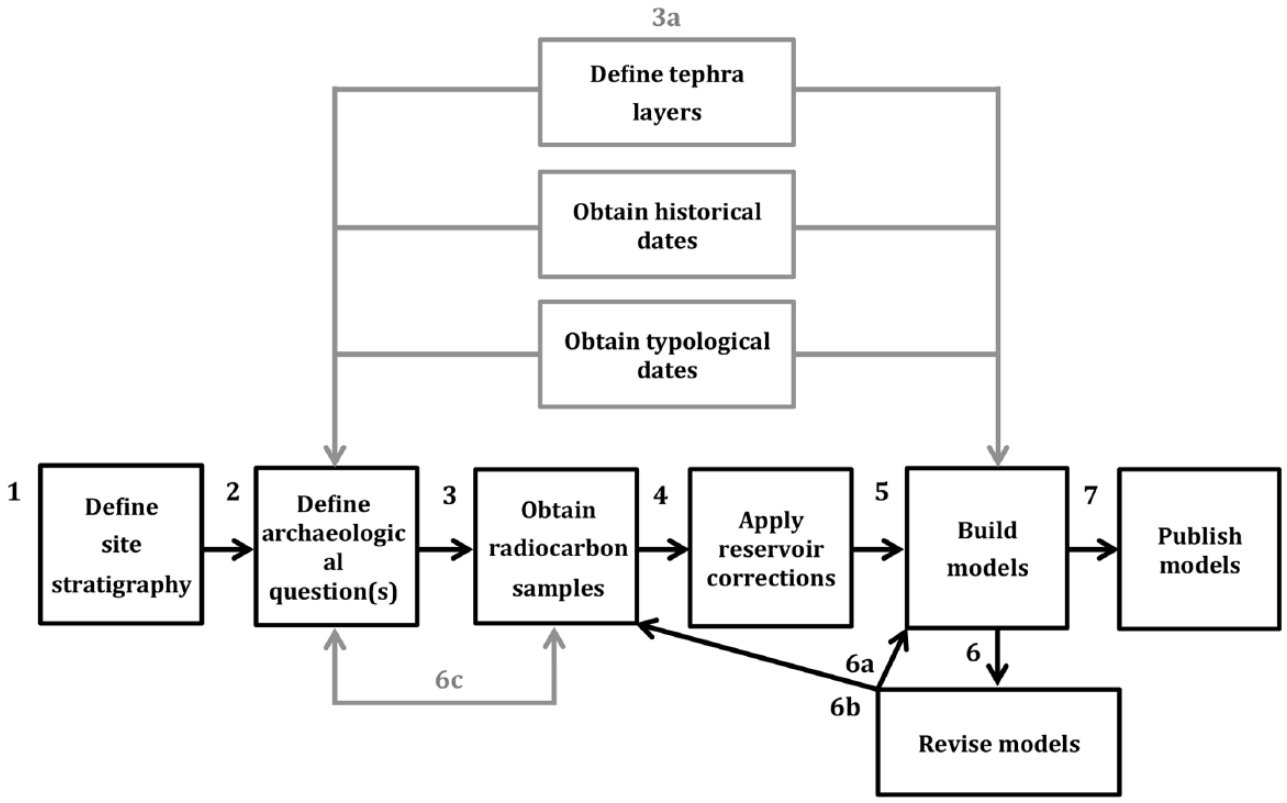

Figure 5. Routine Bayesian application for chronological models based on Bayliss and Bronk Ramsey (2004: Figure 2.2). The black boxes and arrows are essential; the grey boxes and arrows are optional, but improve the robustness of the models.

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

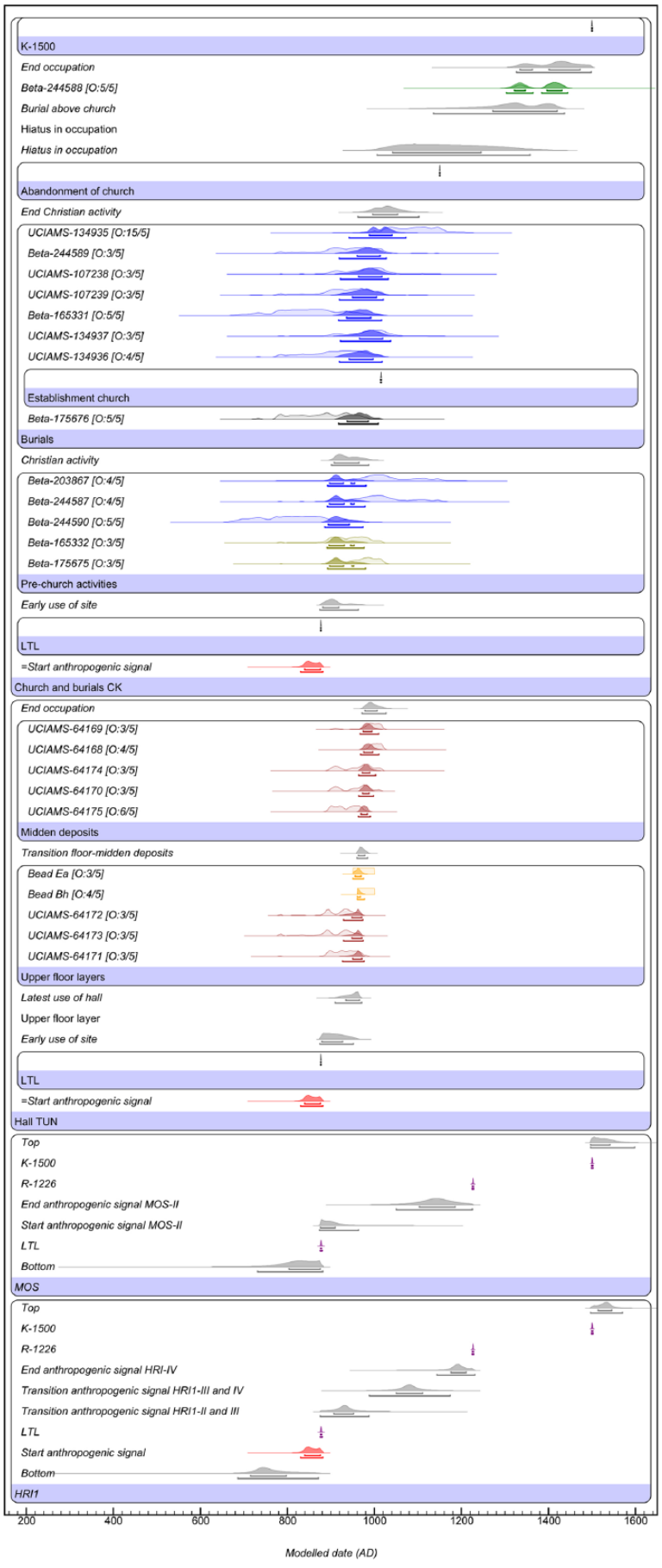

Figure 6. The output plots from the Bayesian model in stratigraphic order incorporating the TUN and CK sites and the HRI1 and MOS sediment cores. Boundaries are in grey; tephra dates in purple; radiocarbon dates of barley grains in dark brown, of short-lived wood in light green and of long-lived wood 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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6. Enhancing the accuracy and precision of ^{14}C datasets using a new standardized chronometric evaluation protocol

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Island Southeast Asia has produced very few radiocarbon-dated sites compared with adjacent regions […]. The paucity of dates has led archaeologists […] to accept uncritically almost any ^{14}C result. In Island Southeast Asia the first Neolithic dates run were by chance often surprisingly early. Now that many more dates are becoming available, these early results appear questionable. It is both possible and questionable to examine anew the corpus of ^{14}C dates, as has been done for other regions where chronology is critical, in order to assess their reliability, to weed out those which cannot be dependent on, and to build a secure chronology with those that remain

Matthew Spriggs 1989

6.1 Introduction

This chapter makes an important research contribution in archaeology by presenting a new standardized protocol for producing Bayesian chronological models based on ^{14}C measurements. This offers significant advantages by allowing for incorporation of the largest possible amount of radiocarbon measurements into a model, by rigorously assessing the decision-making process behind their inclusion and exclusion, and validating with independent dating controls. This makes it possible to accommodate even material where there will be the inevitable possibilities of outlier dates. Models such as the 'Charcoal Plus Outlier' are successfully applied, and methods introduced previously in the thesis are properly evaluated. This chapter highlights the importance of exploring the tension between being vigilant against problem materials, and not being over-cautious and comprising models unnecessarily. It further stresses that marine reservoir (MRE) corrections must be applied in areas (such as Iceland), where much work has been done to characterize a robust MRE/ΔR correction, and the carbon stable isotope values of the system.

6.2 Paper 4: 'Enhancing ^{14}C Chronologies of Colonisation: Chronometric hygiene revisited'

Schmid, M.M.E., Wood, R., Newton, A.J., Vésteinsson, O., Dugmore, A.J. (2018). Enhancing ^{14}C Chronologies of Colonisation: Chronometric hygiene revisited. *Radiocarbon*, 1-19 (DOI:10.1017/RDC.2018.129).[4]

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The fourth paper has two principle motivations:

1) To assess the whole ^{14}C dataset relating to the settlement of Iceland.

2) To successfully integrate samples affected by marine reservoir effects (MRE) and wood charcoal with inbuilt ages into Bayesian statistical models (Chapter 5), although these types of samples are generally excluded in chronological models around the globe after strict applications of 'chronometric hygiene' (Chapter 2.3).

The aim of this paper is to revisit chronometric hygiene and develop a standardized protocol for producing Bayesian chronological models based on a wide range of ^{14}C measurements. This offers significant advantages by allowing for incorporation of the largest possible amount of ^{14}C measurements into a model. The decision-making process behind the inclusion or exclusion of specific data is rigorously evaluated and validated using independent chronological controls provided by ice-core dated tephrochronology (Chapter 4.2). This makes it possible to accommodate even material where there will be the inevitable possibilities of outlier dates. Bayesian models were constructed using the 'Agreement Index', the 'General Outlier model' and 'Charcoal Plus Outlier model' to model chronologies for archaeological sequences (Chapter 2.5).

The research question and hypothesis addressed in this paper are:

Q4) ***How can Bayesian approaches improve the synthesis of ^{14}C dates*****?**

[4] The role of the doctoral student (Magdalena M.E. Schmid) in this paper was to carry out all of the research activity including research design, the collections of data, the analysis of data, as well as writing of the text. Dr. Rachel Wood, Dr. Anthony Newton, Prof. Orri Vésteinsson, and Prof. Andrew J. Dugmore guided the doctoral student during the writing process. The figures were done by the doctoral student and by Dr. Anthony Newton.

H2: Bayesian modelling can produce accurate age estimates for archaeological events

This study focuses on the most parsimonious exclusion of ^{14}C dates. It introduces a new concept of outliers and differentiates between two types: 1. 'non-tangible' and 2. 'statistical' outliers. It suggests excluding non-tangible outliers in statistical models: samples that are not directly associated with evidence of human activity and where key information about e.g. context, sample type and $\delta^{13}C$ values, is unpublished, or where it is very likely that accuracy is poor e.g. for sediment with mixed carbons or bone affected by freshwater reservoir effects (FRE: Chapter 2.3.2). This study underlines, however, that if additional metadata is forthcoming some of the samples may have potential in future studies.

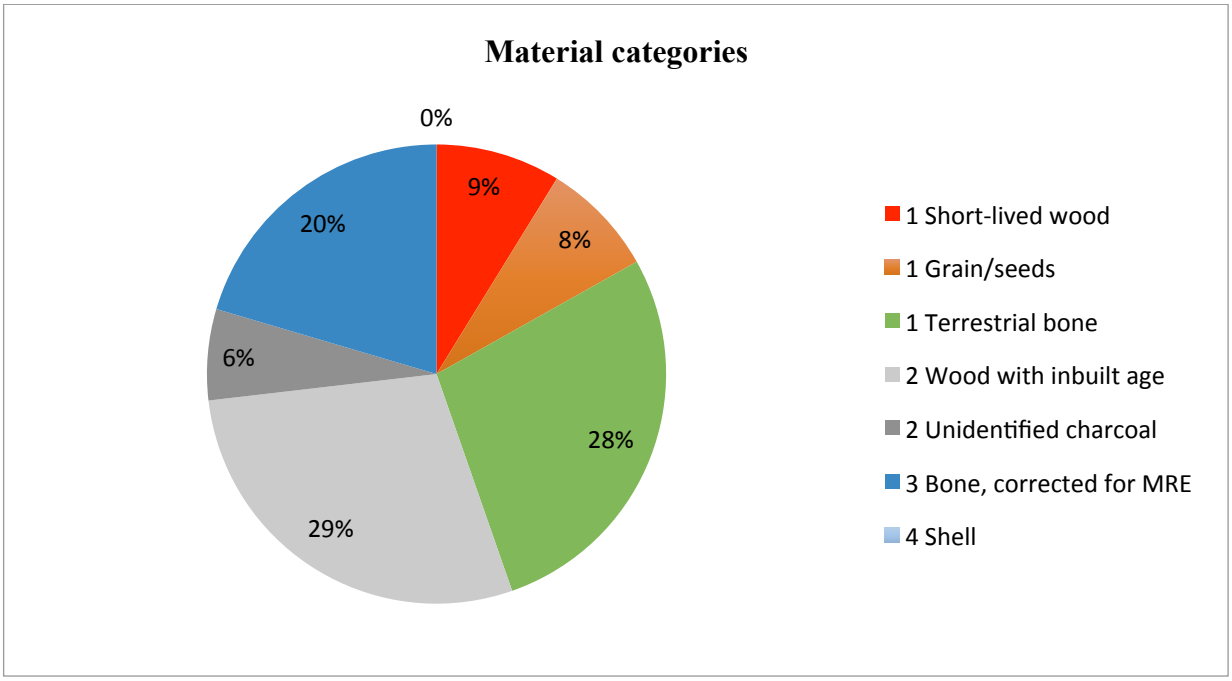

Fig. 7-22 Material categories after applying chronometric hygiene. Material categories: 1. short-lived taxa (short-lived wood: n = 37; grains: n = 34; terrestrial bone: n = 117), 2. samples with inbuilt ages (identified heartwood: n = 120; unidentified charcoal: n = 27), 3. bone samples affected by MRE (n = 86) and 4. shell (n = 0).

After eliminating 129 non-tangible outliers, the remaining 384 samples are categorized into material categories (Fig. 7-22):

1. Short-lived taxa (grains and seeds, identified tree twigs, terrestrial bone).
2. Samples with inbuilt ages (identified heartwood of trees, unidentified charcoal).
3. Samples affected by MRE (bone).
4. Shell.

This study evaluates different statistical methods (the 'Agreement Index', 'General Outlier model' and 'Charcoal Plus Outlier model') and datasets choices (individual stratified sites introduced in Chapter 5, datasets using a combination of material categories 1 and 2, as well as a combination of categories 1, 2 and 3).

The outcome of this study is a set of robust HPDs for the colonisation of Iceland (*cal. AD 863-881*) using both multi-phase models of stratified samples from archaeological sites as well as single-phase models combining material categories 1 and 2 (n = 335), which are convincing because they are consistent with ice-core dated tephrochronology. The requirements, however, are that 1) appropriate *prior* assumptions are used, and 2) the distribution of ^{14}C dates through the 'Phase' is uniform. As such, 'General Outlier models' could be used with confidence to create chronologies from multiple ^{14}C dates on short-lived plant materials, terrestrial bone, and bone affected by MRE. 'Charcoal Plus Outlier models' could be used with confidence for synthesizing sets of ^{14}C dates based on wood/charcoal with inbuilt age and displacement. Furthermore, these new assessments have demonstrated that Bayesian models are sensitive to the uniform *prior* assumption. First, adding 49 dates from the 10th century (material category 3 in Fig. 7-22: HPD of *cal. AD 932-973*) to the previously assessed 335 samples (material categories 1 and 2 in Fig. 7-22) decreases the precision of *posterior* colonisation age estimate to *cal. AD 815-885*, because there is a comparable lower density of data towards the start of a 'Phase'. Second, where dates from early settlement contexts are not available (e.g. Chapter 5), the model will be affected and the *posterior* colonisation age estimate will most likely underestimate early human activity (e.g. *cal. AD 889-950*).

This new chronometric evaluation protocol encourages the use of a variety of ^{14}C categories compared to previous chronometric hygiene protocols (Chapter 2.3). As a result a greater range of materials than currently accepted can be used with confidence for ^{14}C analysis, provided that certain conditions are met, including the dissemination and full publication of contextual data (including detailed sample metadata). The utilization of a wide range of samples benefits chronological models, because it is more likely to capture initial phases of settlement and dating can potentially be applied more widely, especially relating to the chronology in coastal areas and on small islands (e.g. Nuun and Petchey 2013; Petchey et al. 2015), which needs to be tested further (Chapter 7).

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ENHANCING RADIOCARBON CHRONOLOGIES OF COLONIZATION: CHRONOMETRIC HYGIENE REVISITED

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ABSTRACT. Accurately dating when people first colonized new areas is vital for understanding the pace of past cultural and environmental changes, including questions of mobility, human impacts and human responses to climate change. Establishing effective chronologies of these events requires the synthesis on multiple radiocarbon (^{14}C) dates. Various "chronometric hygiene" protocols have been used to refine ^{14}C dating of island colonization, but they discard up to 95% of available ^{14}C dates leaving very small datasets for further analysis. Despite their foundation in sound theory, without independent tests we cannot know if these protocols are apt, too strict or too lax. In Iceland, an ice-core dated tephrochronology of the archaeology of first settlement enables us to evaluate the accuracy of ^{14}C chronologies. This test demonstrated that the inclusion of wider range of samples for ^{14}C dates in Bayesian models improves the precision, but does not affect the model outcome. Therefore, based on our assessments, we advocate a new protocol that works with a much wider range of samples and where outlying ^{14}C dates are systematically disqualified using Bayesian *Outlier Models*. We show that this approach can produce robust *termini ante quos* for colonization events and may be usefully applied elsewhere.

KEYWORDS: Bayesian outlier models, east Polynesia, Iceland, marine/freshwater reservoir effect, wood charcoal with inbuilt age.

INTRODUCTION

This paper advocates a new protocol for synthesizing multiple radiocarbon (^{14}C) dates that utilizes a much wider range of ^{14}C samples than currently accepted within strict applications of "chronometric hygiene." Our approach is rigorously tested using independent chronological controls provided by ice-core dated tephrochronology.

The development of AMS ^{14}C dating meant that very small samples can be analyzed which, combined with a lower unit cost, has resulted in the generation of very large datasets of individual age determinations relating to major historical (Bronk Ramsey 2010) and archaeological events, such as the colonization of large islands (Rieth et al. 2011; Williams 2012; Rull 2016). However, more dates do not necessarily result in improved clarity, as with a large dataset ambiguities can multiply with the production of significant numbers of anomalously younger and older dates. These anomalies may occur when samples are poorly provenanced, not directly related to the archaeological event of interest, or have considerable inbuilt age (Bronk Ramsey 2009a). Other outliers may have no obvious explanation for their status because, for example, they are not published with sufficient detail to evaluate these concerns or establish whether methodological protocols were appropriate (Millard 2014; Bayliss 2015; Wood 2015).

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These challenges were realized early in the history of radiocarbon dating (Waterbolk 1971), and in response numerous protocols have been developed to help evaluate the quality of ^{14}C dates in large datasets, and to eliminate dates that are most likely problematic, a process which has been subsequently described as "chronometric hygiene" (after Spriggs 1989). One of the early protocols used in the Pacific rejected large numbers of dates that were considered uncertain because of issues with stratigraphic and archaeological context and material types (Anderson 1991; Spriggs and Anderson 1993). Subsequently, this approach has been extended by other chronometric hygiene protocols that favor using only short-lived plant materials and terrestrial bone (e.g. Rieth et al. 2011; Wilmshurst et al. 2011). The number of different protocols has increased (e.g. Pettitt et al. 2003; Rodriguez-Rey et al. 2015) and each protocol has been used to date colonization events. Significantly, the analysis has become increasingly selective and may reject up to 95% of available ^{14}C analyses (e.g. Rieth et al. 2011). Despite their foundation in sound theory, without independent tests we cannot know if these protocols are apt, too strict or too lax. We aim to test new outlier detection capabilities of the Bayesian software package OxCal (Bronk Ramsey 2009a; Dee and Ramsey 2014). In particular, we want to know if bone samples affected by marine reservoir effects (MRE), such as omnivorous animals and humans with marine diets (e.g. including marine mammals, fish, and shellfish) and seaweed-eating sheep in coastal area can be used in accurate analysis. If this greater range of materials can be used to create chronologies, synthesized dates may become more precise, and dating may be applied more widely, especially for questions relating chronology in coastal areas and on small oceanic islands.

Iceland provides a remarkable opportunity to evaluate the utilization of large ^{14}C datasets because 513 ^{14}C dates are related to the abrupt 9th century AD Norse colonization that can also be dated independently of the ^{14}C method using an exceptional tephrochronology tied to dates from both medieval written sources and the Greenland ice cores. The crucial Landnám Tephra Layer (LTL) constrains the initial settlement of Iceland, is found across virtually the whole island, and has a combined ice-core date of AD 877 ± 1 (Grönvold et al. 1995; Zilinski et al. 1997; Schmid et al. 2017a). While there is abundant archaeological evidence of settlement immediately above the extensive LTL on a countrywide scale, there are sparse anthropogenic activities below this isochron in the southwest of Iceland (Figure 1). Two turf-built enclosures or boundary walls are recorded just below this tephra demonstrating that people created shelters before this volcanic eruption (Jóhannesson and Einarsson 1988; Roberts et al. 2003; Schmid et al. 2017b). Significantly, no ^{14}C samples related to archaeological evidence in stratigraphic contexts have been found below the LTL. Later tephra isochrons help to refine the rate and scale of Viking Age settlement: these include the ice-core dated Eldgjá tephra of AD 939 (Sigl et al. 2015; Schmid et al. 2017a), the V-Sv tephra of AD 938 ± 6 (Sigurgeirsson et al. 2013), whose age has been estimated from lacustrine sediment cores, and the historically dated Hekla tephra of AD 1104 (Þórarinsson 1967). 73% ^{14}C samples ($n = 377$) are stratigraphically associated with widespread tephra isochrons.

Using Iceland as a world-class testing ground for developing ^{14}C synthesis, our aim is to develop a robust and accurate protocol that can be applied to any colonization event and uses the largest number of ^{14}C dates possible, including charcoal samples and bone samples with known marine reservoir effects. This protocol systematically identifies outliers in large ^{14}C datasets within a Bayesian framework using the software OxCal (Bronk Ramsey 2017), as well as tests different *priors* in Bayesian statistical modeling.

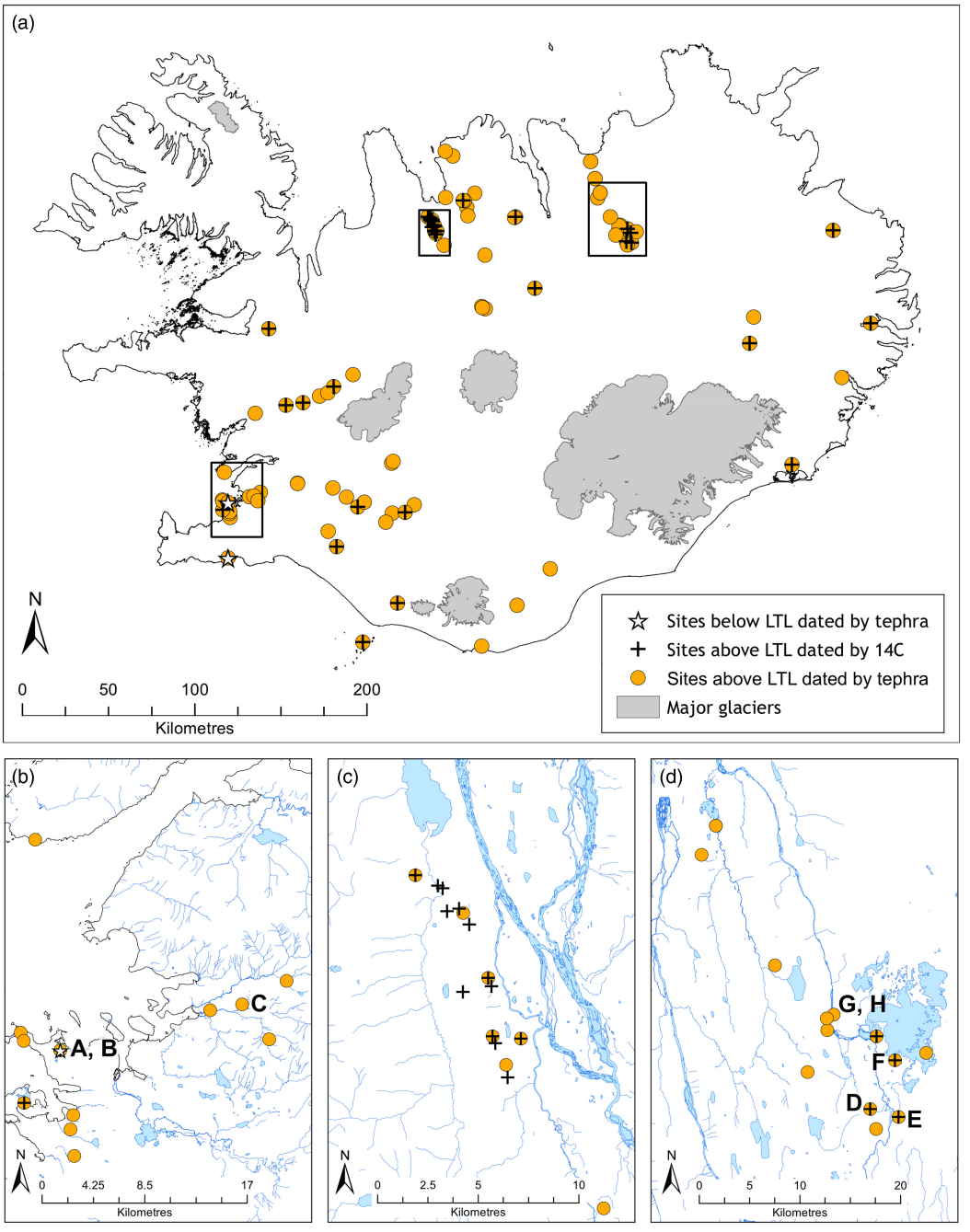

Figure 1 The distribution of archaeological sites in stratigraphic relationships to the Landnám Tephra Layer (LTL) on a countrywide scale (a) and on a regional scale around Reykjavík (b), Skagafjörður/Langholt (c) and Mývatn (d). Two sites are below the LTL (stars) and 85 settlement sites (dots) as well as 181 related radiocarbon dates from 35 burial and settlement sites are above this tephra isochron (crosses). Archaeological sites that are discussed in this paper are: a) A. Reykjavík-Suðurgata, B. Reykjavík-Aðalstræti, C. Hrísbrú; c) D. Hrísheimar, E. Sveigakot, F. Skútusstaðir, G. Hofstaðir-pit house and H. Hofstaðir-hall.

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METHODOLOGY

The Outlier Protocol

We have developed an outlier protocol that can be used to successfully estimate colonization events using small stratified and large unstratified ^{14}C datasets. This protocol involves five steps that are summarized in Figure 2.

Step 1: Define dataset

The first step is to create a set of ^{14}C dates in direct association with cultural materials that define colonization events. For instance, Wilmshurst et al. (2011) included a wide range of ^{14}C dates from 3000 to 300 ^{14}C years BP for the colonization of East Polynesian islands. In our example we used 18 independently dated tephra layers ranging from AD 877 to AD 1693 to define Viking-medieval period settlements and burials (Table 1). In Iceland age estimates of tephra layers—independent of the ^{14}C methods—utilize written sources, correlations with annually layered ice core records in Greenland, as well as annually-laminated lacustrine and aeolian sediment accumulation rates projected over decades (Schmid et al. 2017a). These various age estimates of tephra horizons vary in quality from written sources accurate to the hour, to natural archives with annual to multiannual uncertainties. We have used the following symbols in Table 1: "-" for historically dated tephra, "$\pm$" for age independent estimates in ice cores and "$\sim$" for estimates from sediment accumulation rates in different depositional environments.

We have collected 513 ^{14}C dates that refer to Viking Age settlement and burials sites (AD $\sim$ 800–1100) (see supplemental appendix). Some of the settlement sites are also from the transitional period following the Viking Age.

Step 2: Apply "chronometric hygiene": Remove non-tangible outliers

The next step is to remove dates that cannot be confidently used for statistical analysis, as there is either a high probability that they are inaccurate, or their accuracy cannot be verified. Barrett and Lewis (1978:4) "define an outlier in a set of data to be an observation (or subset of observations) which appears to be inconsistent with the remainder of that set of data". There are two types of outliers: "non-tangible" (non-statistical) and "statistical" (samples that are outlying in relation to probability models) (Barrett and Lewis 1978). We define non-tangible outliers as:

1. Inaccurately or published data with insufficient documentation.
2. Bulk sediments.
3. Samples that have inbuilt ages from mixed dietary sources that cannot be adequately corrected.

Insufficient Sample Documentation

We have discarded from our analysis age estimates whose publication lacks sufficient metadata. For example, the material dated (e.g. charcoal, seed, bone) is not specified for three ^{14}C dates in the Icelandic dataset. Knowledge of the material type is crucial for Bayesian Outlier analysis, as short-lived samples and samples with inbuilt ages are assigned different *priors* in the model (more information under step 4). Other critical information required for analysis includes stable isotopic data from bone samples, or other information necessary to assess collagen quality (e.g. collagen yield, C:N ratio) ($n = 26$). Any samples lacking contextual data are labeled

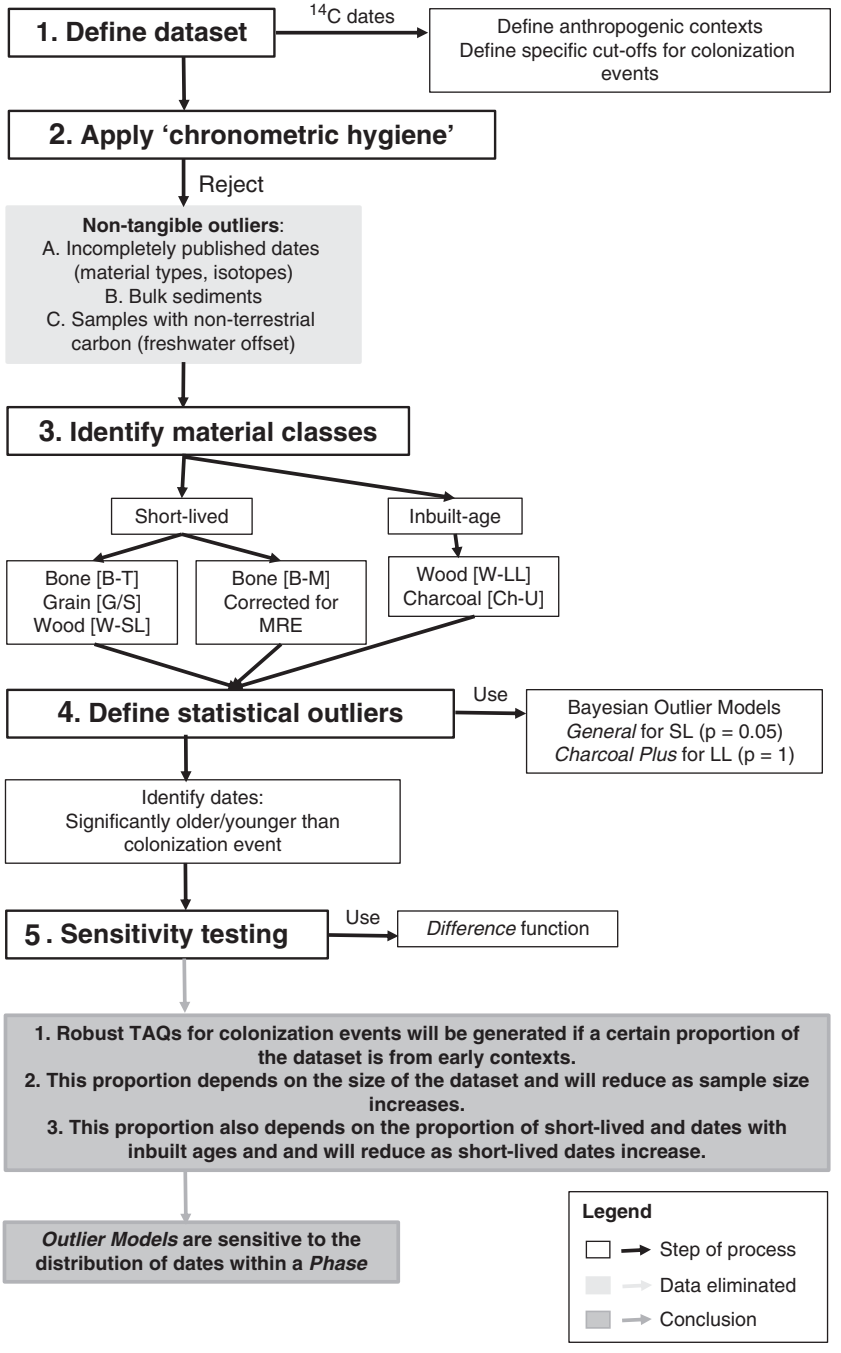

Figure 2 Outlier protocol for ^{14}C datasets demonstrating the importance of stratigraphic relationships of ^{14}C samples. Bayesian *Outlier Models* will be affected if 'chronometric hygiene' protocols preferentially remove dates from early contexts. Key: B-M: Bone-Marine, B-T: Bone-Terrestrial, G/S: Grains/Seeds, LL: Long-Lived, MRE: Marine Reservoir Effect, SL: Short-Lived, W-SL: Wood-Short-Lived.

Table 1 Tephrostratigraphy in Iceland. The tephra layers are named after the source volcanic system and the eruption date in years AD. The volcanic source systems are: E: Eldgjá, G: Grímsvötn, H: Hekla, K: Katla, Ö: Öræfajökull, R: Reykjaneshryggur and V: Veiðivötn.

Name of tephra layer	Year AD	Dating method	References
LTL	877 ± 1	Greenland ice cores	Grönvold et al. 1995; Zielinski et al. 1997; Schmid et al. 2017a
K~920	~920	Sediment accumulation rates	Hafliðason et al. 1992
V-Sv	938 ± 6	Sediment accumulation rates	Sigurgeirsson et al. 2013; Schmid et al. 2017a
Eldgjá	939	Greenland ice cores	Sigl et al. 2015; Schmid et al. 2017a
Vj	~1000	Sediment accumulation rates	Sigurgeirsson, 2010
H-1104	1104	Historical date	Þórarinsson 1967
H-1158	1158	Historical date	Þórarinsson 1967
V-1159	1159	Historical date	Hafliðason et al. 2000
H-1209	1209	Historical date	Þórarinsson 1967
R-1226	1226	Historical date	Hafliðason et al. 1992
K-1262	1262	Historical date	Þórarinsson 1975
H-1300	1300	Historical date	Þórarinsson 1967
G~1320	~1320	Sediment accumulation rates	Þórarinsson 1974
H-1341	1341	Historical date	Þórarinsson 1967
Ö-1362	1362	Historical date	Þórarinsson 1958
V~1477	~1477	Sediment accumulation rates	Þórarinsson 1958
K~1500	~1500	Sediment accumulation rates	Hafliðason et al. 1992
H-1693	1693	Historical date	Þórarinsson 1967

"insufficient metadata" and "insufficient documentation of isotopic composition" in the folder "non-tangible outliers" in the supplemental appendix (Table 2).

Bulk Sediments

Bulk samples of sediments can contain carbon from multiple sources, with different ^{14}C ratios to the event or context that they are intended to date. Three samples of bulk sediment are excluded from our dataset. They are labeled "bulk sediments" in the folder "non-tangible outliers" in the supplemental appendix (Table 2).

Reservoir Offsets

Bone samples whose $\delta^{13}C$ values reflect wholly terrestrial atmospheric carbon sources, with no indication of significant admixtures of marine or geologically-derived carbon, are unlikely to have been influenced by any addition of "old carbon" from reservoirs and normally provide reliable ^{14}C ages.

Organisms growing in ocean surface waters will produce anomalously old ^{14}C ages because of marine reservoir effects caused by a delay in ^{14}C exchange between the atmosphere and ocean, as well as by the mixing of surface waters with upwelled ^{14}C-depleted deep ocean water (Struiver et al. 1986; Petchey et al. 2008). Organisms that derived some, or all, of their carbon from an oceanic reservoir will have been affected by this marine reservoir effect (MRE).

Table 2 "Chronometric hygiene": 513 ^{14}C dates and their reason for exclusion/inclusion in chronological models. Statistical outliers were identified using *Agreement Indices* (>60% cut off) and *General Outlier models*.

Outlier type	Reason	Description	Excluded [E] Included [I]	Erroneous dates?	Number of samples
Non-tangible outliers	Insufficient metadata	Material types are not published	E	Not possible to assess	3
Non-tangible outliers	Insufficient documentation of isotopic composition	Isotopes are not published	E	Not possible to assess	26
Non-tangible outliers	Bulk sediment	—	E	Mixed carbon	3
Non-tangible outliers	Unknown reservoirs	Marine and freshwater contribution to diet	E	No, however, very high probability that these samples show freshwater contribution to diet (samples are from contexts around lake Mývatn)	86
Statistical outliers	Anomalously old or young	Contamination?	E	Yes, because they lie outside the distribution probability	10
Statistical outliers	Erroneous	Contamination?	E	Yes, because the date is erroneous	1
Other	Potentially "accurate" dates	Viking Age contexts	I	If charcoal samples, they do not date the event in question. If samples are short-lived, the date can represent human activity (unless the samples is contaminated, e.g. PVA)	335
Other	Potentially "accurate" dates with marine reservoir offsets	Viking Age contexts	I	Potential freshwater reservoir offsets (samples are from contexts that are not close to lake Mývatn)	49

The Marine13 calibration curve represents a global average of the surface ocean ^{14}C as it changes over time (Reimer et al. 2013). However, there are pronounced local deviations from this global average—known as ΔR (Stuiver et al. 1986). In the North Atlantic, for example, ΔR values show spatial and temporal variation (Ascough et al. 2006; Russell et al. 2010). A ΔR value of 111 ± 10 ^{14}C years has been obtained from multiple paired measurements on terrestrial mammals and marine molluscs from Viking Age archaeological deposits in northern Iceland, and is used here (Ascough et al. 2007). Although 111 ± 10 ^{14}C is currently the best estimate, Batt et al. (2015) suggest it could be improved through evaluation of other parts in Iceland.

Omnivorous animals and humans can incorporate carbon from different reservoirs in their diet and may be affected by marine carbon, resulting in an overestimation of their true age (e.g. Arneborg et al. 1999; Ascough et al. 2011; Petchey et al. 2013). $\delta^{13}C$ can be used to estimate percentage of marine contribution to the diet using linear interpolation, where values have been established for 100% terrestrial diet and 100% marine diet. For Iceland, the end points can be calculated using the linear regression calculation of Ascough et al. (2012), $y = 270.67 + 13.333x$, where x is $\delta^{13}C$ value and y is % marine contribution to diet. For the North Atlantic, the $\delta^{13}C$ end values are typically set to –21.0‰ for a terrestrial diet and –12.5‰ for a marine diet (Arneborg et al. 1999; Sveinbjörnsdóttir et al. 2010), with an adjustment of + 1‰ for trophic level shift (Ascough et al. 2012). The percentage of marine diet can be included in OxCal using "Mixed curves" and "Delta_R" (ΔR).

Freshwater reservoir effects (FREs) also occur when ^{14}C-depleted carbon from reservoirs such as peat, old soils, or from geothermal activity is added to the freshwater system (Ascough et al. 2010). These reservoir effects are highly variable but can amount to many hundreds of ^{14}C years within a single water body, and without extensive regional work, corrections are not possible (Sayle et al. 2016). For example, modern fish from Lake Mývatn in the north of Iceland have ^{14}C reservoirs of more than 3000 ^{14}C years, which vary by around 1500 ^{14}C years (Sayle et al. 2016). Stable isotope analysis of individuals from the nearby cemetery of Hofstaðir suggests they ate just 5–6% freshwater resources, but this would cause offsets of between 40 and 500 ^{14}C years (Sayle et al. 2016). Given the current uncertainties involved in the ^{14}C dating of organisms that have consumed significant amounts of freshwater carbon around Lake Mývatn, 12 dates on shell, four on arctic char and 70 dates on human and animal bone have been excluded from this analysis. The samples are labeled "uncertain reservoir" in the folder "non-tangible outliers" in the supplemental appendix.

Step 3: Classify remaining samples according to potential inbuilt age

After having eliminated 118 non-tangible outliers, we categorized all samples according to material classes, for which we use three basic categories:

1. Short-lived taxa: grains, seeds, identified tree bark and twigs and bone samples where the $\delta^{13}C$ values reflect a 100% terrestrial diet.
2. Samples with potential or actual inbuilt age: unidentified charcoal and identified heartwood of trees.
3. Bone samples that are affected by MRE with known ΔR.

Step 4: Apply Bayesian statistical modeling and define statistical outliers

Bayesian statistical modeling is now routinely used to analyze large sets of ^{14}C dates (Bayliss 2015). The Bayesian approach can be used to test hypotheses, emphasizing that the

interpretation of the data is conditional on all of the chronometric information available. *Posterior* distributions are generated by modifying *prior* beliefs (e.g. from stratigraphy, assumptions over how outliers are distributed or how dates are distributed across a *Phase*) with *likelihoods* (the ^{14}C dataset).

We used OxCal version 4.3.2 for our analysis (Bronk Ramsey 2017). Here, all terms relating to OxCal are given in italics. We used both single-phase and multiple-phase models for our data. For single-phase models, the ^{14}C dates are modeled as a *Phase* – an unordered group of events – bracketed by *Boundaries*, within a *Sequence* – an ordered group of events (Bronk Ramsey 2009b). This model assumes that all dates are uniformly distributed between the two "start" and "end" *Boundaries*. It does not include any stratigraphic relationships between samples from the same site. Where sufficient numbers of radiocarbon dates (>10) were available from a single site, stratigraphic information could be incorporated in a multiple-phase model. The *Boundary* before the *Phase* provides an age estimate for colonization. These *posterior* distributions generate secure *termini ante quos* (TAQs) for archaeological events. ^{14}C dates are calibrated using the IntCal13 curve (Reimer et al. 2013) for the Northern Hemisphere and the Marine13 curve (Reimer et al. 2013) for samples affected by MRE. Throughout the paper, we use both the 68% and 95% *posterior* distributions for *Boundaries*. We used *Agreement Index* and *Outlier models* to assess whether dates are statistical outliers within a model constructed in OxCal.

Agreement Index

Originally, models produced in OxCal relied on the *Agreement Index* values ("A" values) to objectively identify outliers. This index quantified the degree to which the data support the proposed model. Values of less than ca. 60% indicate a high likelihood (>95%) that there is a problem (Bayliss and Bronk Ramsey 2004). Samples below this value were manually removed
Q4 until the overall model had an "A" of >60% (Bronk Ramsey 1995; Bayliss and Bronk Ramsey 2004). This approach is time consuming when dealing with large datasets.

General Outlier Model

Bronk Ramsey (2009a) introduced a Bayesian outlier analysis approach, in which the model identifies and downweights dates that are inconsistent with the surrounding data. To do this, the distribution of outliers must be described (the *Outlier Model*), and the prior probability of each sample within this *Outlier Model* assessed. For dates on short lived materials, we use the *General t-type Outlier Model*, which assumes that outlying dates are due to movement between stratigraphic units, and are distributed according to Student's T distribution (Bronk Ramsey 2009;
Q5 Christen and Pérez 2009). This is a flexible model and assumes that although most samples are not outlying a minority may be much too young or much too old. All short-lived materials were given a 5% prior probability of being an outlier within this distribution. The model generates a *posterior* outlier probability for each sample, and downweights the significance of the sample within the model accordingly. For example, a sample found to have an 80% chance of being an outlier will only be included in 20% of the model runs.

Charcoal Plus Outlier Model

Some ^{14}C samples can have misleading inbuilt ages, such as those derived from the heartwood of trees with a long-life span or any wood that was utilized long after its death. For example, the first people to settle islands may have burnt old wood from native trees or driftwood collected upon arrival (Sveinbjörnsdóttir et al. 2004). The *Charcoal Outlier Model* (Bronk Ramsey 2009a; Dee and Ramsey 2014), assumes that outliers are most likely to be too old due to their

inbuilt age, and that they are derived from an exponential distribution. A small number of samples may be intrusive, and are drawn from an exponential distribution towards younger ages (the *Charcoal Plus Outlier Model*: Dee and Ramsey 2014). In this model all dates are assigned a 100% prior probability of being an outlier, and the effect is to shift the model towards younger ages.

Assess Statistical Outliers

Statistical outliers refer to dates that are outlying in relation to probability models. The Icelandic dataset has one clearly anomalous date (St-4192: 260 ± 245 BP) and 10 extreme outliers, of which two are exceptionally old (AA-55487: 5179 ± 43 BP and AA-55488: 4110 ± 700 BP) and eight young (HAR-2093: 150 ± 70 BP, U-4030: 305 ± 100 BP, Beta-339966: 520 ± 30 BP, TFG: 565 ± 15 BP and U-2618: 685 ± 110 BP; RKV-SUD U-2535: 810 ± 70 BP, STG K-4488: 840 ± 50 BP and STG K-5366: 800 ± 50 BP). These samples are labeled "error" or "extreme outlier" in the folder "statistical outliers" (supplemental appendix).

We therefore conclude that 188 short-lived samples (37 short-lived wood, 34 grains/seeds, and 117 terrestrial bone), 147 samples with inbuilt age (120 long-lived wood, 27 unidentified charcoal) and 49 bone samples that are affected by MRE directly apply to the colonization of Iceland. These 384 samples are in the folder "other data" (supplemental appendix). All subsequent statistical analyses are based on this assumption.

Step 5: Analysis

The *Difference* function was used to assess whether the *Outlier Models* affect the posterior estimate for the colonization of Iceland. We tested which approach is consistent with the independent tephrochronology using the Landnám Tephra Layer (LTL) of AD 877 ± 1 (Schmid et al. 2017a). In order to be considered different, the *Difference* posterior probability range should not overlap with zero, and the function generates a colonization start *posterior* distribution either earlier or later than the LTL. The results are summarized in Table 3.

RESULTS

We built Bayesian models using both large unstratified and small stratified ^{14}C datasets. The results are summarized in Table 3 and all OxCal model codes are available in supplementary materials.

Unstratified Radiocarbon Samples

Model 1: Agreement Index ($n = 335$): The *Agreement Index* was used to assess whether any of the short-lived and charcoal samples were outliers. 18 samples, or 5% of the Icelandic dataset, had an *Agreement Index* <60% and were manually removed from analysis using the command *Outlier( )* (Table 3). The 68% *posterior* distribution for the onset of colonization is estimated to cal AD 851-870, between 11 and 31 years earlier than the LTL.

Model 2: General Outlier Model ($n = 335$): Each date was assigned an equal prior probability of 0.05 within the *General Outlier Model*. The 68% *posterior* distribution for the onset of colonization extends the range of the calibration curve (Table 3). Samples that were heavily downweighted in this model (assigned a posterior outlier probability of 7–100%) were also identified as outliers using the *Agreement Index* (Table 3).

Table 3 Sensitivity testing of single- and multiple-phase models from Iceland evaluating potentially accurate dates using the *Agreement Index* (>60% cut off), *General Outlier models* and *Charcoal Plus Outlier models* (greater than 7% outlying).

Approach number	Approach detail	Nr ^{14}C	Boundary (1σ)	Boundary (2σ)	Difference to LTL in years (1σ): from	Difference to LTL in years (1σ): to	Difference to LTL in years (2σ): from	Difference to LTL in years (2σ): to	Short-lived %	Early contexts %
1	Agreement Index	317	851-870	797-876	-31	-11	-82	-2	60	57
2	General Outlier Model	335	753-…	736-…	-88	…	-82	…	56	54
3	General Charcoal Plus Outlier Model	335	863-881	751-893	-20	1	-128	12	56	54
4	General Outlier Model	49	932-973	893-991	49	93	11	112	100	0
5	General Charcoal Plus Outlier Model	384	815-885	733-890	-65	7	-134	11	62	47
6	Reykjavík-SUD	20	779-897	779-897	-102	17	-180	75	5	77
7	Reykjavík-AST	16	802-885	723-895	-68	4	-140	14	50	100
8	Hrísheimar	13	828-881	758-893	-57	2	-135	14	100	16
9	Sveigakot	18	884-961	848-980	3	79	-33	100	100	6
10	Skútustaðir	17	838-938	803-954	-46	59	-80	74	100	6
11	Hrísbrú	10	889-950	867-965	11	70	-16	86	100	0
12	Hofstaðir pit house	11	874-948	810-969	-6	68	-70	89	100	0
13	Hofstaðir hall	13	951-988	915-1009	99	127	85	138	100	0
14	Archaeological sites prior	118	799-864	728-880	-83	-17	-150	0	/	/
15	Archaeological sites prior including LTL and V-Sv tephra	118	875-883	870-894	/	/	/	/	/	/

Model 3: General and *Charcoal Plus Outlier Model* ($n = 335$): We performed analysis using the *General Outlier Model* for short-lived materials (0.05 *prior* probability) and the *Charcoal Plus Outlier Model* for charcoal samples (1 prior probability). The *posterior* distribution for the onset of colonization is estimated to cal AD 863–881 (68%) and to cal AD 751–893 (95%). These age ranges provide a TAQ for the colonization of Iceland consistent with ice-core dated tephrochronology: shortly before, but more likely after AD 877 ± 1 (Figure 3A).

Model 4: Bone samples affected by MRE ($n = 49$): We modeled 49 bone samples affected by MRE using the *General Outlier Model*. A 68% *posterior* distribution for the onset of colonization was generated to cal AD 932–973, demonstrating that burials in Iceland are mostly from the late Viking Age.

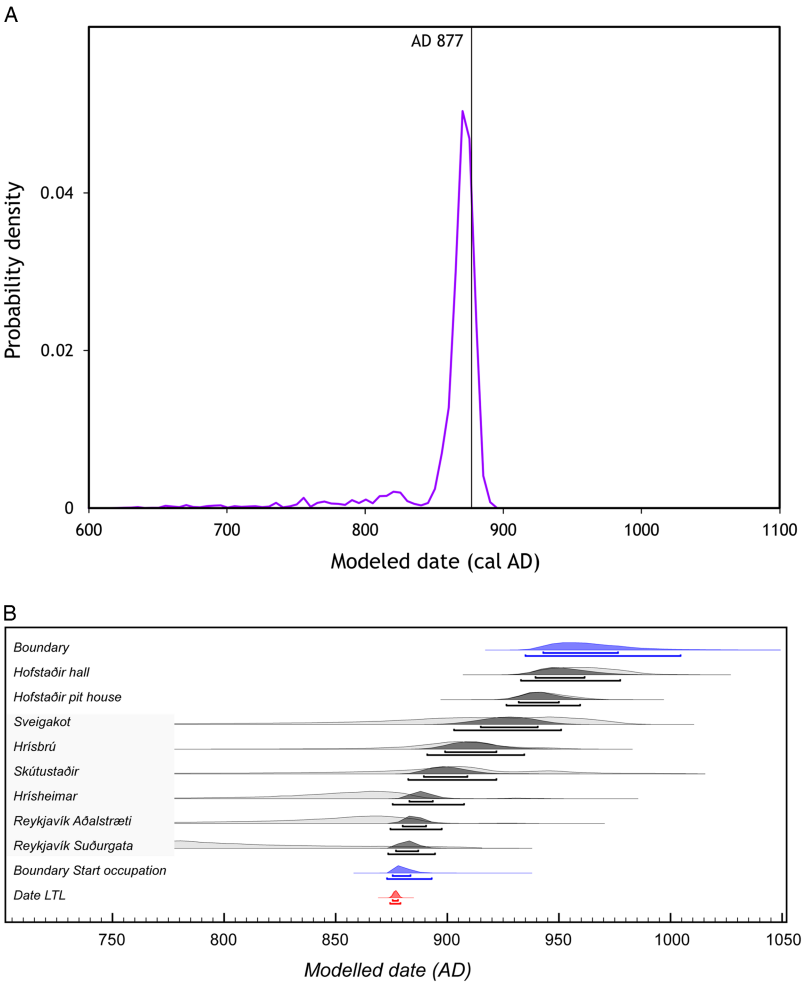

Figure 3 Estimated *posterior* distributions for the timing of Iceland's colonization using unstratified (A) and stratified (B) datasets (95.4% probability curves). (A) The combination of 190 short-lived and 144 charcoal samples ($n = 335$). (B) Multiple stratified ^{14}C samples from eight archaeological sites (>10). The *posterior* distribution is constrained by the LTL to cal AD 874–883.

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Model 5: General and *Charcoal Plus Outlier Model* ($n = 384$): We then combined all 384 samples. The *posterior* distribution for the onset of colonization is estimated to cal AD 815–885 (68%) and to cal AD 733–890 (95%) demonstrating that inclusion of the large number of younger dates on human bone decreases the precision of posterior colonization age estimate (in comparison with Model 3).

Stratified Radiocarbon Samples

Multiphase models were built for sites where more than 10 ^{14}C dates on stratigraphically related samples were available. This approach allows us to determine if samples for dating are likely to be in situ, and if there is an "old wood" problem. It removes difficulties encountered where large numbers of dates fall towards the end of a long single *Phase* (as seen when many relatively young dates on human bone were included in Model 5). Six archaeological sites are stratigraphically above the LTL of AD 877 ± 1 (Reykjavík-Suðurgata, Reykjavík-Aðalstræti, Hrísheimar, Hrísbrú, Skútustaðir, Sveigakot) while two are above the V-Sv tephra of AD 938 ± 6 (Hofstaðir-pit house and Hofstaðir-hall). The estimated *Boundaries* for the start of occupation of each site are shown in Figure 3B.

Model 6: Reykjavík-Suðurgata ($n = 14$): The site consists of a hall and a smithy built over an activity area which had come into use after the deposition of the LTL. At least four phases of structures were built on top of these remains, before K ~ 1500 blanketed the site (Nordahl, 1988). We excluded samples that are statistical outliers (Table 4). One of the samples used in the model is of short-lived taxa and 13 are charcoal samples. Nine charcoal samples are from early contexts (equivalent to 77% of the whole dataset). The 68% *posterior* distribution is estimated to cal AD 779-897, immediately after the LTL. We demonstrate that a high proportion of charcoal samples can be used in chronological models (here 95%).

Model 7: Reykjavík-Aðalstræti ($n = 16$): The site consists of a hall that was built on top of the LTL. The K ~ 1500 was deposited long after the hall was abandoned (Sveinbjörnsdóttir et al. 2004). We excluded samples that are statistical outliers (Table 4). Eight samples included in the model are short-lived and eight are charcoal samples. Six samples come from floor and 10 from stratified hearth deposits inside the hall. Both deposits are likely contemporary and represent early settlement (equivalent to 100% of the whole dataset). The 68% posterior distribution is estimated to cal AD 802–885, immediately after the LTL. The charcoal samples are consistently older than short-lived materials, but their age offsets are successfully corrected.

Model 8: Hrísheimar ($n = 11$): The site consists of excavated structures and midden deposits (Vésteinsson and McGovern 2012). Two pit houses and midden deposits are sandwiched between the LTL and V-Sv, while hall structures were built after the deposition of the V-Sv. The model consists of eleven short-lived materials. Two samples come from stratified midden deposits before the V-Sv tephra (equivalent to 16% of the whole dataset), six after this tephra deposit and four are not connected to any tephra layer. The 68% *posterior* distribution is estimated to cal AD 828–881, immediately after the LTL.

Model 9: Sveigakot ($n = 18$): The site consists of several pit houses, a byre and a hall, as well as extensive midden deposits (Vésteinsson 2010). The model consists of 15 short-lived materials. One sample is from a midden deposit stratigraphically below the V-Sv tephra (equivalent to 7% of the dataset), five samples above the V-Sv tephra (midden and hall) and 12 are from pit houses that are not connected to tephra deposits. The 68% *posterior* distribution is estimated to AD 884–961, or between 3 and 79 *later* than the LTL (Table 3). The 95% *posterior* distribution,

Table 4 Identified outliers using the *Agreement Index* (18 samples) and *General Outlier model* (21 samples). Outliers identified in Bayesian models using the *Agreement Index* are below 60%, while outliers identified in *General Outlier models* are between 6 and 100% outlying (posterior probability).

Site name	Sample ID	Conventional radiocarbon age	Error	Associated tephra deposit (after Schmid et al. 2017a)	Agreement index	General outlier model
Herjólfsdalur (Vestman island)	U-2660	1390	60	Post-LTL	<60%	44%
Herjólfsdalur (Vestman island)	U-2661	1340	65	Post-LTL	<60%	13%
Herjólfsdalur (Vestman island)	U-2663	1300	60	Post-LTL	<60%	9%
Hólmur	Beta-143635	1450	70	Post-LTL	<60%	69%
Reykjavík: Althingisreiturinn	Beta-346805	1295	25	Between LTL and R-1226	<60%	46%
Reykjavík: Aðalstræti 14-18	AAR-7619	1282	35	Between LTL and H-1500	<60%	19%
Reykjavík: Aðalstræti 14-18	AAR-7622	1262	35	Between LTL and H-1500	<60%	9%
Reykjavík: Aðalstræti 14-18	K-940	1340	100	Post-LTL	<60%	17%
Reykjavík: Aðalstræti 14-18	U-2530	1330	80	Post-LTL	<60%	8%
Reykjavík: Grjótagata	K-949	1340	100	Post-LTL	<60%	7%
Reykjavík: Suðurgata 3-5	U-2672	1345	60	Between LTL and H-1500	<60%	17%
Reykjavík: Suðurgata 3-5	U-2676	1260	55	Between LTL and H-1500	<60%	6%
Reykjavík: Suðurgata 3-5	U-2680	1375	70	Post-LTL	<60%	21%
Reykjavík: Suðurgata 3-5	U-2719	1360	60	Between LTL and H-1500	<60%	24%
Reykjavík: Suðurgata 3-5	U-2739	1310	70	Post-LTL	<60%	8%
Reykjavík: Suðurgata 3-5	U-2740	1280	65	Between LTL and H-1500	<60%	6%
Reykjavík: Suðurgata 3-5	U-2741	1330	40	Post-LTL	<60%	39%
Reykjavík: Suðurgata 3-5	U-2745	1275	60	Between LTL and H-1500	<60%	6%

however, is estimated to cal AD 848–980 and is consistent with the LTL. The 68% *posterior* distribution is slightly later than the LTL, because the ^{14}C samples are from mid-end 10th century contexts and do not relate to the actual arrival date associated with this initial colonization. Nevertheless 3–79 years are still early in terms of colonization and not every site will have been occupied immediately after the deposition of the LTL.

Model 10: Skútustaðir ($n = 17$): The site consists of a farm mound with several structures and well-stratified midden deposits (Hicks et al. 2013). The middens began to form immediately on top of the LTL and accumulation has persisted until modern times. The model consists of 12 short-lived materials. One ^{14}C sample is below the V-Sv tephra (equivalent to 6% of the whole dataset), 12 samples are above the V-Sv tephra and four samples are not associated with any tephra layer. The 68% *posterior* distribution is estimated to cal AD 838–938, consistent with the LTL.

Model 11: Hrísbrú ($n = 11$): The site consists of a hall, midden deposits, a church and multiple burials. The model consists of eleven stratified samples, of which 10 are short-lived and one charcoal sample. Although anthropogenic deposits at Hrísbrú are stratigraphically above the LTL, all ^{14}C samples are from contexts that also post-date a 10th century tephra (either K ~ 920 or Eldgjá) (Schmid et al. 2017b). Four samples are from upper floor layers under a turf collapse (representing the last use of the house) and another four samples come from the midden deposits on top of the hall. One sample is from the church, which was built after the deposition of a 10th century tephra and two samples are from midden deposits from before the church was constructed. The 68% *posterior* distribution is estimated to cal AD 889-950, or between 11 and 70 years *later* than the LTL; the 95% *posterior* distribution, however, is estimated to cal AD 867–965 and is consistent with the LTL (Table 3). This 68% *posterior* distribution is slightly later than the LTL because all ^{14}C samples are from mid-end 10th century contexts (like Model 9) and do not relate to the actual arrival date associated with this initial colonization.

Model 12: Hofstaðir-pit house ($n = 11$): The site consists of a pit house infilled with stratified midden deposits. The pit house is sandwiched between the V-Sv and H-1104 tephras (Lucas 2009). The site consists of eleven short-lived samples. One sample is from the turf collapse of the pit house, the rest are from the midden layers. The 68% *posterior* distribution is estimated to cal AD 874–948 and consistent with the LTL, and also with the V-Sv tephra.

Model 13: Hofstaðir-hall ($n = 13$): The site consists of a hall with annexes that are sandwiched between the V-Sv and H-1104 tephras (Lucas 2009). The samples are from floor layers and from the turf collapse on top of the floor. The model consists of eleven short-lived materials and none are from early settlement contexts. The *posterior* distribution is estimated to cal AD 951–988 (68%) and to cal AD 915–1009 (95%), or up to 127 years *later* than the LTL (Table 3). This *posterior* distribution is, however, consistent with the V-Sv tephra, which is not surprising, because the ^{14}C samples come from mid-end 10th century contexts.

We then combined the *posterior* distributions produced above to determine the most likely timing of overall colonization. This approach can also be used for comparing *posterior* distributions and determining the spatiotemporal relationships between archaeological sites across the country.

Model 14: Priors of archaeological sites: Eight archaeological sites yielded an age range of cal AD 799–864 (68%), or between 17 and 83 years earlier than the LTL; the 95% *posterior* distribution, however, is estimated to cal AD 728–880 and is consistent with the LTL (Table 3).

Model 15: Priors of archaeological sites including LTL and V-Sv tephra: We can constrain the same dataset (Model 14) when we include the LTL as *Calendar Date* (*C_Date*). The tephra layers constrain the *posterior* distribution to cal. AD 875–883 (68%) and to cal AD 870–894 (95%); however, this model can only be applied in geographic areas where tephra layers exist (Figure 3C).

DISCUSSION

Using the colonization of Iceland as a critical test of ^{14}C methodology, we find that stratified archaeological sites with more than 10 ^{14}C samples provide an age estimate for colonization, which is consistent with ice-core dated tephrochronology, and thus deemed accurate, providing that appropriate *prior* assumptions are used and the distribution of ^{14}C dates through the *Phase* is uniform. As such, *General Outlier Models* could be used with confidence to create chronologies from multiple ^{14}C dates on short-lived plant materials, terrestrial bone, and bone affected by marine reservoir effects. *Charcoal Plus Outlier Models* can be used with confidence for synthesizing sets of ^{14}C dates based on wood/charcoal with inbuilt age. Furthermore, our new assessments have demonstrated that that Bayesian models are sensitive to the uniform *prior* assumption. First, the inclusion of the large number of younger dates decreases the precision of posterior colonization age estimate (e.g. Model 5), because there is a comparable lower density of data towards the start of a *Phase* (I comparison to Model 3). Second, if dates from early contexts are removed, the *posterior* colonization age estimate will most likely underestimate early human activity (Models 4, 9, and 11).

The dating of island colonization in Oceania has undergone radical reassessment since the 1980s (Dye 2015). These cases exemplify critical debates about colonization and chronology all over the world. Competing "long" and "short" chronologies of island settlement have been proposed that are based on selective ^{14}C datasets, which have been filtered using differing "chronometric hygiene protocols." In this paper, we show that a new outlier protocol can provide a reduced need for the initial rejection of ^{14}C dates compared to previous protocols. We argue that it is preferable to only exclude a minimum number of samples, where key information about e.g. context, sample type and pretreatment quality, is unpublished, or where it is very likely that accuracy is poor e.g. for sediment or bone affected by a FRE. On this basis, 129 out of 513 samples (24%) were removed from analysis. We note that some of the samples may have potential to be used for future studies, if additional metadata is forthcoming.

Elsewhere, we (Schmid et al. 2018) have reviewed the ^{14}C data from 15 archipelagos in East Polynesia (published in Wilmshurst et al. 2011). While independent dating control is generally absent in Oceania, the North island of New Zealand is an exception. Here, environmental impacts and human activities first occur just below the Kaharoa tephra isochron, which is ^{14}C-dated to cal AD 1314 ±12 through the use of wiggle matching (Hogg et al. 2002). We have synthesized 265 ^{14}C dates using a combination of short-lived plant materials, terrestrial bone, and (un-)identified charcoal and generated a *posterior* distribution for colonization of cal AD 1260–1314 (68%), which is consistent with the stratigraphic distribution of palaeoenvironmental evidence related to the Kaharoa isochron. Both in Iceland and East Polynesia, the inclusion of a wider range of ^{14}C samples in Bayesian models improves the precision of the combined age determination. Significantly, the inclusion of tephra layers in chronological models does not affect the accuracy of the model outcome (e.g. Model 15). Thus, we find that our chronometric hygiene protocol may be usefully applied elsewhere and in areas where tephra isochrons are absent. The utilization of a wide range of samples benefits chronological models, because it most likely captures initial phases of settlement, enhances precision and

dating can be applied more widely, especially relating to the chronology in coastal areas and on small islands.

CONCLUSION

This study uses a clearly defined and independently dated archaeological event—the initial human colonization of Iceland—to evaluate the best ways to assess small stratified (>10) and large unstratified (>280) ^{14}C datasets based on the analysis of different materials, and to identify the most parsimonious exclusion of dates from synthesis. We demonstrate that, when combined with appropriate *priors* in *Outlier Models* within OxCal, ^{14}C dates on the majority of sample types, most notably charcoal with its potential inbuilt age and samples affected by marine reservoir effects, can be used in chronological models. At present, dates produced on samples with insufficient metadata (e.g. no published record of material types or stable isotope values) or samples affected by unknown freshwater reservoir effects cannot be used. This result is important because it shows that a greater range of materials than currently accepted might be used with confidence for ^{14}C analysis provided that certain conditions are met including the dissemination of contextual data (including detailed sample metadata), which have to be fully published.

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SUPPLEMENTARY MATERIAL

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7. Applying the new chronometric evaluation protocol to other geographical settings: The examples of Polynesia

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The Ocean Maid in her tumultuous moods vented her wrath against inanimate rock and reef, for no conqueror had yet appeared to mark her heaving bosom with the wake of the voyaging canoe or to dig into her yielding body with the dripping blade of the deep-sea paddle

Peter Buck (Te Rangi Hiroa), Vikings of the Sunrise, 1938

7.1 Introduction

This chapter extends the work from Icelandic archaeological settings to East Polynesia to demonstrate the applicability of the methodological approaches developed in the thesis to other geographic settings and other archaeological questions. This provides further emphasis to findings already highlighted for Iceland, such as the impact of selective preservation, excavation, and finally, over-rigorous chronological hygiene, upon age model outputs.

7.1 Paper 5: 'How ^{14}C dates on wood charcoal increase precision when dating colonisation: the examples of Iceland and Polynesia'

Schmid, M.M.E., Dugmore, A.J., Foresta, L., Newton, A., Vésteinsson, O., Wood, R. (2018). How ^{14}C dates on charcoal increase precision when dating colonization: the examples of Iceland and Polynesia. *Quaternary Geochronology* 48, 64-71. (doi: 10.1016/j.quageo.2018.07.015).[5]

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[5] The role of the doctoral student (Magdalena M.E. Schmid) in this paper was to carry out all of the research activity including research design, the collections of data, the analysis of data, as well as writing of the text. Prof. Andrew J. Dugmore, Dr. Luca Foresta, Dr. Anthony Newton, Prof. Orri Vésteinsson and Dr. Rachel Wood guided the doctoral student during the writing process. The figures were done by the doctoral student and by Dr. Anthony Newton. Dr. Luca Foresta wrote OxCal_parser, which was tested by the doctoral student.

The fifth paper is motivated by the possibility that the methodology developed in the previous chapter may not work for other ^{14}C datasets from different geographic regions where 300-400 ^{14}C dates are not available. As such, some islands in the Pacific currently have ten or fewer ^{14}C dates relating to colonisation, and a large percentage of these dates may be on wood charcoal with potential inbuilt ages. This chapter highlights that charcoal is the most common material class utilized globally, comprising more than 50% of samples recorded in key databases around the world (> 81,000). The aim of this study is to find ways to utilize both smaller datasets from both Iceland and East Polynesia without compromising their precision and accuracy. This approach is rigorously tested using independent chronological controls provided by the LTL of AD 877 ± 1 in Iceland and the Kaharoa Tephra of AD 1314 ± 12 in New Zealand, while independent dating control is generally absent elsewhere in Oceania.

The research question and hypotheses addressed in this paper are:

RQ5) ***How many ^{14}C dates are needed for accurate and precise ^{14}C chronologies***?

H2: Bayesian modelling can produce accurate age estimates for archaeological events

This paper explores how the quality and quantity of ^{14}C datasets affect age model accuracy and precision using datasets from Iceland (n = 282) and from 15 archipelagos in East Polynesia (n = 1434) (Appendix VII.A and C). The results are compared with summed approaches previously applied in East Polynesia. To achieve this in a timely manner this paper introduces a new open access program ('OxCal_parser') to speed data entry and minimize errors, a prerequisite for correct modeling of hundreds of ^{14}C dates (Appendix VII.B).

The key tasks in this paper are to provide comparable datasets from two geographic areas that focus on the same material categories. In Chapter 6, four material categories were assessed:

1) Short-lived taxa.
2) Wood charcoal with inbuilt ages.
3) Bone samples affected by MRE.
4) Shell samples.

The Icelandic dataset only consists of material categories 1-3.

The dataset published by Wilmshurst et al. (2011) focuses on the same material categories. A new category is terrestrial bird eggshell. The publication of ^{14}C samples, however, is incomplete: 1) contexts of ^{14}C samples are not described; 2) crucial information of sample taxa is not defined. For instance, samples are classified as 'bone' and taxa cannot be evaluated; 3) stable isotopic analysis of bone samples are not published and MRE/FRE cannot be evaluated; 4) the taxa of shell is not published and feeding habits cannot be evaluated. In total, 346 bone and shell samples are classified as 'non-tangible' outliers and are removed from analysis (Chapter 2.2). This demonstrates the significance of publishing ^{14}C dates after standardized protocols. It is important to note, however, that such samples can be used in future analysis. The possibility of including shell samples in Outlier models is particularly important in Pacific contexts (Chapter 2.3.2); however, this requires some potentially complicated applications of different ΔR values across the Pacific (e.g. Nunn and Petchey 2013; Petchey et al. 2008; 2018).

This study is, therefore, based on two material categories: 1) short-lived taxa and 2) wood charcoal with inbuilt ages. The Icelandic dataset is additionally filtered using samples from well-defined archaeological contexts – Landnám, post-Landnám and Viking age – because contexts are well described (Appendices II and VI.A). Here, short-lived taxa are further filtered into identified short-lived wood, grain/seeds and terrestrial bone. The aim is to assess whether these filtered datasets yielded a colonisation age that is consistent with the LTL.

The *accuracy* of models is determined by the context of ^{14}C samples and their distribution within a 'Phase'. There are no systematic biases within specific material classes. Nevertheless, the 68% HPD of short-lived wood yielded a slightly younger age range than the LTL (*cal AD 897-951*), because the samples are almost exclusively from late 10th century contexts and there is a very low density of data towards the start of a 'Phase' (Chapter 6). ^{14}C samples from secure contexts of archaeological periods confirm that a combination of Landnám contexts and wood samples with inbuilt age, or a combination of post-Landnám contexts and short-lived taxa, result in correspondingly older or younger colonisation age ranges than the LTL. The key result is that the accuracy of *posterior* probability distributions depends upon the context and uniform sampling density across the entire span and does have an effect on the synthesized age rage (Chapter 6). As such, the distribution is often biased because ^{14}C samples are typically chosen to answer specific questions with no consideration of a Bayesian framework (Chapter 5). It is hoped that Bayesian models will be used to inform sample selection considering their material and contexts.

The accuracy of models from East Polynesia can only be tested with the dataset from New Zealand because of independent dating control provided by the Kaharoa tephra of AD 1314 ± 12. This dating control is limited as the tephra is only preserved in the northeast area of the North Island. The colonisation date for New Zealand has undergone radical assessments since the 1980s and this exemplifies critical debates for islands all over the world.

The 'longest' chronology is dated to AD 0-500 and stems from Kirch's (1986) revision of other East Polynesian sequences. The hypothesis is based on wood charcoal samples from environmental contexts that may be related to minor anthropogenic deforestation. This early settlement hypothesis persists (Sutton et al. 2008), although such disturbances are indistinguishable from those resulting from natural background events (e.g. fires) (McGlone and Wilmshurst 1999). Another early settlement hypothesis is based on radiocarbon dates on rat bones, a human commensal species. It has been suggested that transient visitors brought rats, which remained and multiplied, more than 1000 years before the formation of the first archaeological and other paleoecological evidence for the presence of humans (Holdaway 1996, 1999).

The 'long' or 'orthodox' settlement model of New Zealand settlement is estimated to around AD 800-1000. The chronology is based on the paleoecological record, raising the possibility of a small, but 'archaeologically invisible', population of early colonists (Green 1975; Davidson 1984; Roberts 1991). These predate *marae-ahu* structures built in the 13th century, fortified *paa* sites from the 15th century and were before local artefact types were developed and exchanged (Groube 1968).

A 'short' chronology of settlement has been estimated dating into the AD 13th century. This model is based on the first comprehensive assessment of around 300 radiocarbon dates using 'chronometric hygiene' process to filter out unreliable dates (Anderson 1991). Furthermore, a number of other age ranges have been proposed: AD 1250-1300 based on >270 radiocarbon dates on charcoal and shell samples (Higham and Hogg 1997); AD 1288-1300 based on typologically diagnostic artefacts from early archaeological sites (Higham et al. 1999); AD 1200-1400 based on paleoecological data (McGlone and Wilmshurst 1999). The Kaharoa tephra of AD 1314 ± 12 has also been used to constrain the onset of colonisation (Anderson 1991; Lowe et al. 2000; Hogg et al. 2002; Walter et al. 2006; Furey et al. 2008). As in Iceland, the earliest sustained periods of human deforestation occur at around or just prior to this tephra deposition (Newnham et al. 1998; Lowe et al 2000; Holdaway et al. 2014). Lowe

et al. (2002) suggest that pre-Kaharoa sediments represent a maximum of about fifty years, which has been used as a TAQ for the initial colonisation of New Zealand.

Recently, the age *cal AD~1280* (68% probability) has been used as a TAQ for late human settlement, based on the radiocarbon dating of around 100 rat-gnawed seeds (Wilmshurst et al. 2008) and the application of cumulative and summed probabilities of 112 short-lived radiocarbon dates (Wilmshurst et al. 2011). A similar age range of *cal AD 1270-1309* (95.4%) has been proposed by Dye (2015) and *cal AD 1294-1330* (95.4%) based on 93 Moa eggshell samples using Bayesian statistical modelling (Holdaway et al. 2014). These *posterior* estimates all rely on filtered datasets.

In this study, the 68% HPD yielded an age range of *cal AD 1260-1314*, which is consistent with the stratigraphic distribution of vegetation disturbance just prior to the Kaharoa isochron.

The *precision* of Bayesian models (for both Iceland and East Polynesia) is determined by the interplay of both the quality and quantity of dates used. Precision decreases using only wood charcoal with inbuilt age; it increases using short-lived taxa; however, the highest precision is achieved using a combination of wood charcoal and short-lived taxa. This coincides with the number of samples: precision is greatest (> 20 years) where ~280 samples are used, and lowest (> 160 years) where 10 samples are used.

To conclude, accurate and precise chronologies for colonisation events can be established when ^{14}C datasets choices do not have a low density of data towards the start of a 'Phase', requiring knowledge about their contexts, and when they have a certain percentage of short-lived taxa. Chapters 6-7 have both successfully included charcoal samples (both short-lived and those with inbuilt age) in chronological models. Most of these charcoal samples with inbuilt ages are from early contexts in datasets and may shift previously accepted chronologies. In turn, this may revise ideas about the timing and impacts of great migrations of people across the planet, not just the Vikings across the North Atlantic, or the Polynesians across the Pacific, but also many other cases as varied as the peopling of the Arctic, the Americas and other Oceanic islands.

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How ^{14}C dates on wood charcoal increase precision when dating colonization: The examples of Iceland and Polynesia

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ABSTRACT

Archaeological chronologies use many radiocarbon (^{14}C) dates, some of which may be misleading. Strict 'chronometric hygiene' protocols, which aim to enhance the overall accuracy and precision of ^{14}C datasets by removing all potentially problematic samples, mean that so few dates remain in some locations that accurate chronologies cannot be established. ^{14}C dates on charcoal can be affected by an 'old-wood' effect, and so they are often removed from analyses, despite > 40,000 being available worldwide, representing > $25 million. We show that when a Bayesian chronological model is used, which incorporates an Outlier Model specific to wood charcoal, the ^{14}C dataset of Iceland's Viking Age settlement agrees well with ice core-dated tephrochronology and written sources. Greatest accuracy comes from an even temporal distribution of ^{14}C dates and more dates lead to greater precision (< 20 years). This shows how charcoal-based ^{14}C chronologies can pinpoint the transformational human settlement of islands in the Atlantic, Oceania, and elsewhere.

1. Introduction

Our aim is to improve the use of large radiocarbon (^{14}C) datasets to establish the most accurate and precise age ranges for archaeological events. ^{14}C dating is one of the most significant chronometric discoveries of the 20th century, allowing us to use organic material to establish accurate chronologies for the last 50,000 years. However, individual ^{14}C dates are probability distributions that plot around the true age and do not necessarily capture the timing of key events (Wood, 2015). This is a particular problem when trying to recognize and understand rapid changes in human history that occur over a matter of decades or less. Transformative events, where the timing is crucial to our understanding, include human migrations and the colonization of new areas – topics that are often subject to vigorous debate (e.g. Braje et al., 2017; Mellars, 2006).

Our ancestors spread overland across Africa and migrated across Eurasia and into the Americas on foot, but to settle in Australia people had to cross the sea. The development of seafaring has played a key part in human history and finally enabled people to colonize some of the last settled places on Earth, including the islands of the deep oceans. Island communities are globally significant as they have the potential to teach us many things about adaptation, sustainability, how societies are established and how they survive over multi-generational timescales in constrained circumstances with finite resources. Such lessons are timely, as globally our appetites and numbers continue to grow and our collective environmental impacts become significant on a planetary scale. In order to gain the most effective understanding of various 'completed experiments' on islands around the world, we need to have precise regional-scale ^{14}C chronologies to understand as accurately as possible when people arrived and the timing of subsequent cultural, ecological, and demographic changes.

Efforts to construct accurate and precise ^{14}C chronologies from many dates typically rely on 'chronometric hygiene' protocols (after Spriggs, 1989) eliminating dates that are most likely problematic (Bayliss, 2015). Currently, protocols favour organisms with short-life spans, where ^{14}C concentrations are in equilibrium with the atmosphere

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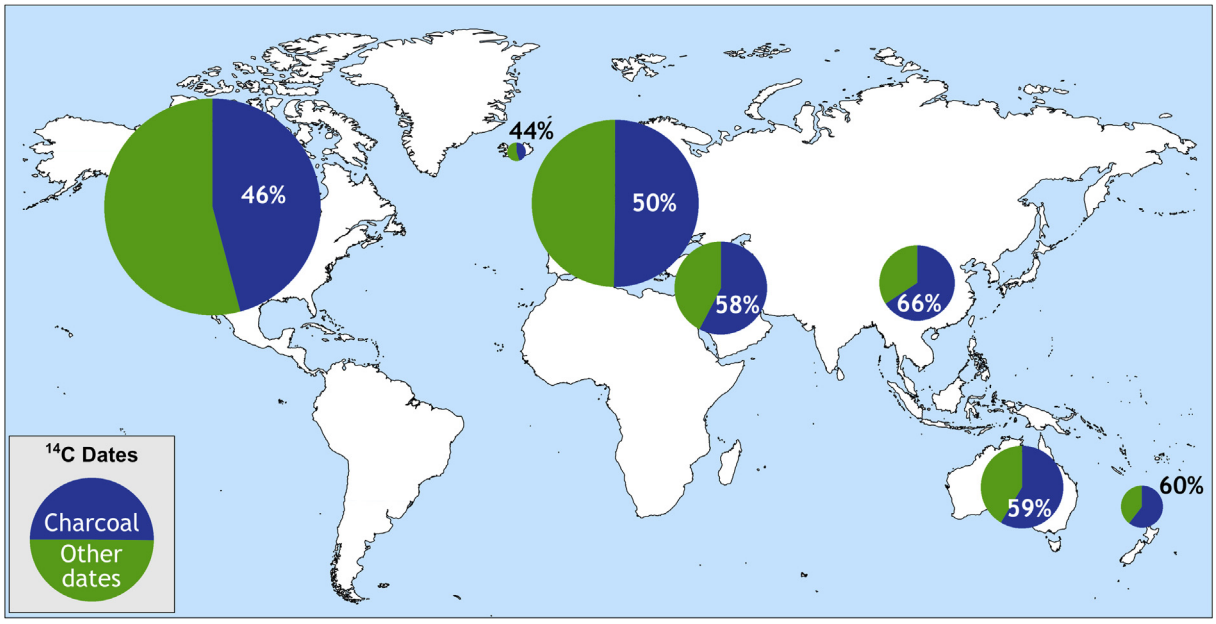

Fig. 1. The distribution of 79,809 (40,254 wood charcoal samples) ^{14}C samples from cultural layers recorded in key databases (CARD, RADON, ^{14}C Paleolithic Europe, CONTEXT, AustArch) around the world (Table 1).

until death (Bronk Ramsey et al., 2010; Wilmshurst et al., 2011; Rieth et al., 2011). Such strict protocols have both reduced the number of places where dating can be utilized, and shifted individual chronologies by up to 1000 years in East Polynesia (Dye et al., 2015). Significantly, they largely ignore the use of wood charcoal samples. This is despite charcoal samples of indeterminate age being the most frequently dated material (> 40,000 samples) in a global inventory of archaeological ^{14}C dates (Fig. 1, Table 1). In modern values, these samples represent over $25 million of laboratory analysis. Clearly there have been good reasons for discarding this data in certain circumstances, but a greater effective use of it would represent a major advance for many sites around the globe, where wood charcoal is the only significant material class sufficiently well preserved for dating (Dee and Bronk Ramsey, 2014).

The need for dating controls independent of the radiocarbon method make alternative approaches a challenge to asses. The wide range of complementary dating methods (^{14}C dates, ice core-dated tephrochronology and medieval texts), which can be employed to date the Viking Age colonization of Iceland (the Landnám), allows us to clarify the long-standing debates about how ^{14}C dataset choices can affect age-model accuracy and precision. These provide a chronological 'Rosetta stone', which enables us to perform novel assessments of alternative approaches. This in turn will help us to better understand other examples of island colonization and other large-scale events for human history that have an abrupt, but complex, manifestation.

With independent dating control, we examine 282 Icelandic ^{14}C dates using Bayesian Outlier analysis (Bronk Ramsey, 2009; Dee and Ramsey, 2014) with OxCal v.4.3 (Bronk Rasmey, 2017). Subsequently, we applied our new insights from Iceland to re-assess 1088 ^{14}C dates for 15 archipelagos in East Polynesia (Wilmshurst et al., 2011). To achieve this in a timely manner we developed a new open access program ('OxCal_parser') to speed data entry and minimize errors, a prerequisite for correct modeling of hundreds of ^{14}C dates.

2. Materials and method

2.1. Iceland: archaeological periods and data

Iceland has produced one of the world's richest collections of medieval vernacular literature and these texts pinpoint key historical events that notably include the first settlement of Iceland, which is dated to AD 870–930 according to the chronicle *Íslandingabók* written in AD 1122-33 (Grønlie, 2006). Texts also date many of Iceland's frequent explosive volcanic eruptions, which deposit widespread tephra (ash) layers that form spatially extensive marker horizons (isochrons) in key environmental archives such as ice cores, soils and lake sediments (Streeter and Dugmore, 2014; Sigh et al., 2015; Schmid et al., 2017a). Around the time of Iceland's settlement, simultaneous eruptions of the Veiðivötn and Torfajökull volcanic systems spread a distinctive two-coloured visible tephra layer over the entire island apart from the northwest peninsula. Traces of this layer, called the Landnám Tephra Layer, have been found in the Greenland ice cores, and it is precisely

Table 1
Databases and geographic areas summarizing 79,809^{14}C samples from cultural layers presented in Fig. 1.

Region	Total number of ^{14}C dates	Total number of wood charcoal dates	References
United States/Alaska	38,119	17,482	Gajewski et al., 2011
Iceland	282	125	This study
Europe	22,760	11,426	Veermeersch, 2015; Hintz et al., 2012
Near East	7036	4054	Flohr et al., 2015; Böhner and Schyle, 2002–2006
China	4656	3063	Wang et at., 2014
Australia	5522	3238	Williams et al., 2014
East Polynesia	1434	867	Wilmshurst et al., 2011
	79,809	**40,255 (> 50%)**	

dated to AD 877 ± 1 (Grönvold et al., 1995; Zielinski et al., 1997; Schmid et al., 2017a). Three sites have little evidence of anthropogenic activities immediately below this tephra (Jóhannesson and Einarsson, 1988; Roberts et al., 2003; Schmid et al., 2017b). In contrast, the archaeology of 81 settlement sites and 132 related ^{14}C dates are known from stratigraphic contexts above this isochron (Appendix A). This combination of archaeology and ice-core dated tephrochronology places countrywide settlement directly before, but mainly after, AD 877. Similarly, medieval texts place the end of early settlement to AD 930, when the Althing, the world's oldest parliament, was established

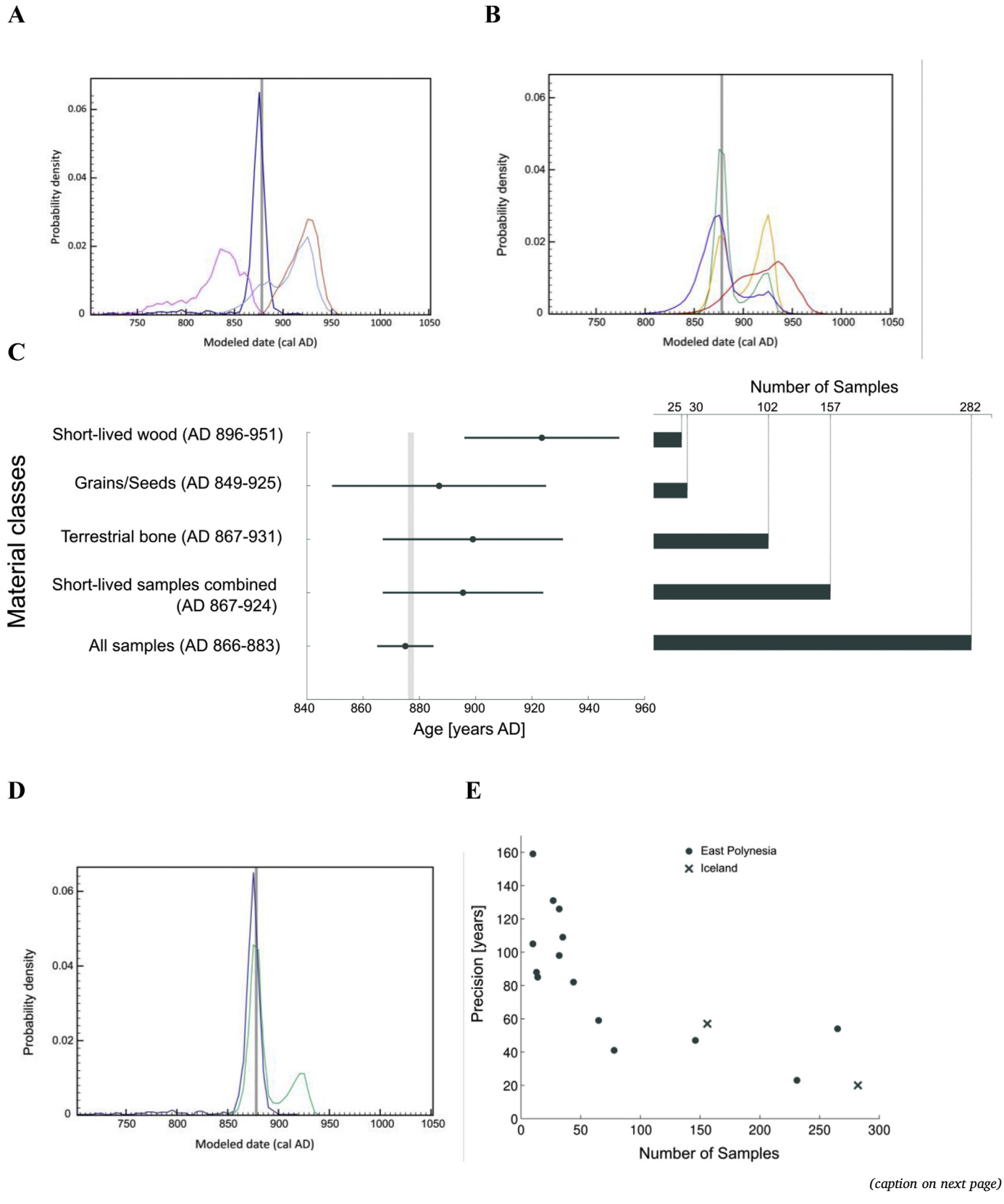

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Fig. 2. Accuracy and precision of Bayesian Outlier models. Boundary probability distributions provide a modeled date for initial occupation at 95% probability (A, B, D) and 68% probability (C, E). The grey bar denotes the Landnám Tephra Layer of AD 877 ± 1 (A–D). (**A**) ^{14}C samples and independently dated, tephra defined archaeological periods in Iceland: the whole dataset (blue line) and dates from Viking Age contexts of cal AD 877–1104 (light blue line) show agreement; while dates from early Landnám contexts of cal AD 877–939 (pink line) and late post-Landnám contexts of cal AD 939–1104 (purple line) are inconsistent. (**B**) Material classes of ^{14}C samples in Iceland: grain (blue line), terrestrial bone (yellow line), short-lived wood (red line) and a combination of grain, bone, and short-lived wood (green line) provide accurate age ranges. (**C**) Distribution of ^{14}C samples: Short-lived wood provides an inaccurate age range. (**D**) Precision is enhanced using a combination of short-lived samples and charcoal samples of indeterminate age (blue line) in comparison to short-lived samples only (green line). (**E**) The number of short-lived ^{14}C dates and charcoal samples of indeterminate age from Iceland and East Polynesia in comparison to the precision of age ranges in years. The highest precision is generated using ~280 samples (17 years), the lowest using 10 samples (160 years). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(*Íslandingabók*: Grønlie, 2006). This historical juncture coincides with tephra isochrons including the key layer from Eldgjá dated in the ice cores to AD 939 (Sigl et al., 2015; Schmid et al., 2017a) and a tephra layer from Veiðivötn dated to AD 938 ± 6 (Sigurgeirsson et al., 2013). The widespread Hekla volcanic eruption of AD 1104 provides an effective early 12th century marker horizon for the end of the Viking Age in Iceland (Þórarinsson, 1967).

In total, we have gathered 282 ^{14}C dates that relate to the Viking Age (AD ~800–1100) (Appendix A). We include ^{14}C dates that are from unambiguous stratigraphic contexts below the H-1104 tephra, or are associated with direct evidence of human activity and have a median age before AD 1100. We did not include dates on human bone with possible marine/freshwater reservoir effects due to uncertainties associated with marine and freshwater calibration (e.g. Ascough et al., 2011; Sayle et al., 2016). Significantly, 89% of our newly compiled ^{14}C dataset are from dates stratigraphically associated with tephra isochrons. To begin our assessment we use independently-dated tephra isochrons to divide 282 ^{14}C samples into two well-defined periods of colonization and a general Viking Age group (Appendix A):

1. Landnám (AD 877–939): early widespread settlement (n = 132)
2. Post-Landnám (AD 939–1104): late widespread settlement (n = 90)
3. Viking Age (AD 877–1104) (n = 60).

We then categorize 282 ^{14}C samples according to material types, for which we use two basic categories: short-lived taxa (157 samples: grains/seeds, identified short-lived wood and terrestrial bone) as well as charcoal samples of indeterminate age (125 samples: unidentified charcoal and identified wood with large inbuilt age).

2.2. East Polynesia: archaeological data

We revisit the dataset for 15 archipelagos in East Polynesia. Wilmshurst et al. (2011) published 1434 ^{14}C dates that are in direct association with cultural materials from 300 to 3000 ^{14}C y BP. We exclude 346 bone and shell samples with known marine/freshwater reservoir effects to provide a comparable dataset with Iceland (e.g. Petchey et al., 2013). We categorize 1088 ^{14}C samples according to material types, for which we use the same categories: short-lived taxa (n = 222) and charcoal samples of indeterminate age (n = 866).

In Oceania, independent dating evidence is limited to the North Island of New Zealand, where environmental impacts and human activities first occur just below the Kaharoa tephra isochron, radiocarbon-dated to cal AD 1314 ± 12 through the use of wiggle matching (Hogg et al., 2002).

2.3. Bayesian analysis

In this paper we used the Bayesian outlier analysis approach to estimate the most likely time frame for historical events in the OxCal v4.3 software (Bronk Ramsey, 2017). These age ranges (the *posterior* beliefs) depend on the distribution of data (our *prior* beliefs) and the ^{14}C dataset (the *likelihoods*) (Bayliss et al., 2007). The *prior* beliefs include: the stratigraphic relationships of samples, the distribution of samples, the overall distribution of the dataset, and also the likelihood each sample has of being an outlier.

We define accuracy through the reproducibility of *priors* in Bayesian models, and we define precision through the quality and quantity of ^{14}C dates. For accuracy, we used single-phase Outlier models for our data that assume that all dates are uniformly distributed within the bounded time range. Using the *General Outlier Model*, short-lived samples are given a 5% *prior* probability and are individually downweighted with a Student T distribution (Bronk Ramsey, 2009). This has a normal distribution, but with longer tails, that allows dates to be outliers without affecting the outputs. Using the *Charcoal Outlier Model*, charcoal samples of indeterminate age are given a 100% *prior* probability and are individually downweighted with an exponential distribution that relates to the lifespan and growth habit of trees and the distribution only shifts towards the younger end (Bronk Ramsey, 2009). This model does not eliminate odd erroneous dates, but it shifts the whole sequence in one direction. A recent modification of this model, the *Charcoal Plus Outlier Model*, has allowed a small number of samples to also be younger than the context they represent, such as intrusive material (Dee and Ramsey, 2014).

We used various approaches in order to assess different strategies for evaluating groups of ^{14}C dates, and assess whether they yield a colonization age, which is consistent with independent tephrochronological dating using the Landnám Tephra Layer of AD 877 ± 1 for Iceland and the Kaharoa tephra of AD 1314 ± 12 for New Zealand. In order to be considered different, the *Difference* probability range does not overlap with zero. The model generates a colonization age range either earlier or later than the tephra layer in question. Uncertainties are presented throughout the Supplementary Materials approximately equivalent to 95% and 68% confidence levels.

2.4. Summing approach

We compare our Bayesian results with current Summing approaches. For the East Polynesian dataset, cumulative and summed probabilities have been used to evaluate large datasets of ^{14}C dates (Rieth et al., 2011; Wilmshurst et al., 2011). When summing, researchers have attempted to improve accuracy by selecting single-entity material and by a small standard error. First, the datasets were subjected to a chronometric hygiene protocol. Only samples from short-lived plant materials and terrestrial bone, where the standard error for the conventional ^{14}C ages is < 10% of the age determination, were accepted. These approaches removed 80–95% of the dates. The summing method has been criticized because it is likely to overestimate the age of colonization as statistical scatter is not accounted for (e.g. Attenbrow and Hiscock, 2015; Bayliss et al., 2007; Culleton, 2008; Chiverell et al., 2011; Bamforth and Grund, 2012; Contretas and Meadows, 2014).

2.5. 'OxCal_parser'

OxCal was first released in 1994 and it is a very powerful tool for the analysis of complex stratigraphies of multiple ^{14}C samples (Bronk Ramsey, 2017). We performed more than 300 model runs, each with

Table 2
Accuracy of Bayesian models: sensitivity testing of single-phase models from Iceland.

^{14}C datasets			Age ranges (outlier models)				LTL model difference			
Model	Approach description	No of ^{14}C	Posterior (68%)		Posterior (95%)		from (68%)	to (68%)	from (95%)	to (95%)
1	The whole dataset	279	866	883	748	909	−16	4	−134	28
2	Landnám contexts†	135	819	867	759	874	−54	−12	−105	−1
3	post-Landnám contexts*	90	907	939	888	946	25	59	6	67
4	Viking Age contexts	185	875	935	853	944	−26	4	−56	34
5	Identified short-lived wood*	25	896	951	865	965	14	70	−18	86
6	Grains and seeds	30	849	925	838	937	−32	4	−62	38
7	Terrestrial bone	102	867	931	860	935	−15	50	−21	55
8	Charcoal samples of indeterminate age combined	126	710	928	633	945	−172	48	−198	64
9	Short-lived taxa combined	156	867	924	862	933	−16	45	−21	53

Key: The models generate a colonization age range that is: accurate (no symbol), or inaccurate. Here, the age range is: earlier than the LTL (†) or later than the LTL (*).

some tens to hundreds of ^{14}C samples arranged in different stratigraphic phases and sequences. Additionally, we specified different Outlier Models (*General* and *Charcoal Plus*) for ^{14}C samples (*R_Dates*) and assigned specific colors to groups of samples (e.g. green for short-lived materials, grey for long-lived materials and red for calendar dates, such as tephra layers).

To increase the speed and accuracy of data import to OxCal, we developed a program (OxCal_parser), which reads an input spreadsheet file (.xlsl or. csv) and automatically generates a text output (.txt) in *Chronological Query Language2* (CQL2), the latest format used by OxCal. Our program runs instantaneously and the output can be copied in the OxCal text browser to run models without adding any additional information. Our program allows automatic data entry of small to very large datasets with simple and complex stratigraphy in a timely manner, but does not perform any computation. At present OxCal_parser can be used for single- and multiple-phase models (Supplementary Materials, Fig. S1). Since OxCal provides extensive options in data analysis (e.g. the use of different *Boundaries*), we made OxCal_parser available on Bitbucket (https://bitbucket.org/luca_foresta/oxcal_parser). Users can freely download or clone the program and alter it according to individual needs. OxCal_parser is written in Python 2.7, which is an open access programming language. Instructions on how to download and use the code are provided online.

For this work, we provide six examples with datasets from Iceland and New Zealand that are used to demonstrate how OxCal_parser works (Fig. S1, Appendix B). All examples, using complex or simple stratigraphy, have the same structure, with mandatory and optional fields (columns). If optional fields are not used for a specific model, the columns should be empty, as demonstrated in Appendix B. Mandatory fields are presented in Example 1 (Fig. S1A-B), where the input file contains three basic fields (*Sample ID*, *Conventional Radiocarbon Age* and *Error*), together with their *Date Type* ('radiocarbon') and the calibration curve (e.g. 'IntCal13': Reimer et al., 2013). The *Start Boundary Label* can be assigned an optional label; in our examples, we use 'Start occupation' as the age range for the occupation of an archaeological site in question.

Optionally, other information can be included, such as the type of Outlier model (*General* or *Charcoal Plus*), the type of outlier for each individual ^{14}C sample, together with its related *P Value* (e.g. p = 0.05 for short-lived material (Fig. S1C-D); p = 1 for charcoal samples of indeterminate age), and a *Color* when displaying the model output (Fig. S1E-F).

In scenarios with complex stratigraphy, the user can divide the samples in different *Phases* (unordered group of samples) and/or *Sequences* (ordered group of samples). This is achieved through the 'Stratigraphic Block' field and the 'Block Label' field (*Sequence* or *Phase*) (Appendix B). Each *Sequence* or *Phase* is given a number, where 1 represents the oldest archaeological event. *Boundaries* – implying a uniform distribution of dates – are automatically added by the program. In cases where a ^{14}C or calendar date (*C_Date*) is not part of any *Sequence* or *Phase*, these samples can be placed in an independent stratigraphic block. In Example 4 this primarily accounts for calendar dates, which are tephra isochrons in our examples (Fig. S1G-H).

Furthermore, the user can specify multiple *Sequences/Phases* within the same stratigraphic block as shown in Example 5 where one *Sequence* (hearth samples) and one *Phase* (floor samples) are part of the same overall *Phase* (Fig. S1I-J). Our program also supports using the Southern Hemisphere Calibration Curve 'ShCal13' (Hogg et al., 2013) as shown in Example 6 using samples of short lived wood from New Zealand (Fig. S1K-L; https://bitbucket.org/luca_foresta/oxcal_parser).

3. Results and discussion: accuracy and precision of Bayesian models

3.1. Iceland

We used the whole dataset, samples from archaeological periods – Landnám (AD 877–939), post-Landnám (AD 939–1104), and Viking Age (AD 877–1104) contexts – as well as individual material classes. The results are summarized in Table 2, Fig. 2 and in Supplementary Materials (including both 68% and 95% confidence levels). We excluded three ^{14}C dates of bulk materials, because Bayesian models would not converge if they are included in models (Supplementary Materials).

It is possible to use a range of short-lived samples and charcoal samples of indeterminate age to achieve an age range for the colonization of Iceland (cal AD 866–883 at 68% probability) (Fig. 2A, 2C-D) that is consistent with both medieval literary texts, which date the initial settlement of Iceland to the year AD 870, and ice core-dated tephrochronology of archaeology, which confirms sparse traces of human settlement immediately below, and very extensive countrywide settlement immediately above the crucial Landnám Tephra Layer of AD 877 ± 1 (Appendix A). The important conclusion is that key historical events can be dated with both accuracy and precision using a wide range of ^{14}C dates. We note that the accuracy of this age range is, however, dependent upon a uniform sampling density across the entire period.

Bayliss et al. (2007) argue that while the accuracy of ^{14}C dates and their stratigraphic relationships may be fundamental for correct synthesis and chronological modelling, uniformly distributed datasets can be flexible, robust and insensitive to these factors as long as individual dates are not too inaccurate. To test this hypothesis we used filtered datasets that are based on archaeological periods and material classes to assess whether they yielded a colonization age that is consistent with the LTL (Supplementary Materials). We find that there are no systematic biases within specific material classes, and all material categories can provide accurate age ranges (Fig. 2B, Table 2).

Nevertheless, we find that model accuracy is sensitive to the assumption that a uniform distribution of dates is flexible and robust, because this does have an effect on the synthesized age range. A higher percentage of late or early dates in models results in correspondingly older (up to 54 years) or younger synthesized colonization age ranges (up to 70 years) (Table 2). Indeed, end-member dates dominate the probability distributions and the collective result can underestimate the beginning and duration of initial settlement (Fig. 2A and C). As such short-lived wood yielded a slightly younger age range than the LTL (Fig. 2C), because the samples are almost exclusively from late tenth century contexts. As a result care is needed to ensure that the filtering of ^{14}C datasets does not bias the overall distribution of dates.

The precision of models is determined by both the quality and quantity of dates used. For example, using 282 dates from a combination of both short-lived materials and charcoal samples of indeterminate age generates a very narrow age range of 17 years for the onset of colonization (cal AD 866–883). When using short-lived samples only, precision decreases to 76 years, and shifts towards the younger end of the time frame (Fig. 2C–D). In contract, when using charcoal samples of indeterminate age only, precision drastically decreases to 218 years (Table 2) and can shift towards the older end of the time frame (Fig. 2A pink lane). Thus, we conclude that robust chronologies can be constructed if 1) the contexts of ^{14}C samples, 2) the distribution of the overall ^{14}C dataset, and 3) the material classes are critically evaluated.

3.2. East Polynesia

We use our new approach to re-assess chronologies for first settlement from 15 archipelagos in East Polynesia (Supplementary Materials). We excluded 21 erroneous dates of bulk sediments (from Australs, Marquesas, Hawai'i and Rapa Nui) and 64 charcoal samples of indeterminate age that are too young to represent colonization events (from Hawai'i and Rapa Nui). If included, these ^{14}C dates distort the distribution of Bayesian models, because Outlier models ony allow a small number to be intrusive (Dee and Ramsey, 2014). The excluded samples are fully acknowledged in Supplementary Materials.

In Oceania, the accuracy of Bayesian age ranges is generally difficult to assess. One exception is the North Island of New Zealand. Our Bayesian model of 265 radiocarbon dates from archaeological sites generated an age range of cal AD 1260–1314, which is consistent with the stratigraphic distribution of vegetation disturbance just prior to the Kaharoa isochron (cal AD 1314 ± 12) (Furey et al., 2008).

To evaluate precision in the Oceania dataset, we compared models using short-lived materials only (total n = 222) and models including charcoal samples of indeterminate age (total n = 867) (Supplementary Text, Table 3). In Oceania, precision is greater the higher the quality and density of dates used (Fig. 2E, Table 3). For example, the precision is 91 years for a combined date produced from 76 short-lived samples from New Zealand (cal AD 1262–1353), but it is enhanced to 54 years if 189 charcoal samples are added to the same dataset (cal AD 1260–1314). Adding charcoal samples of indeterminate age to the dataset, therefore, has the potential to shift the date of initial settlement at least 39 years earlier and just before the deposition of the Kaharoa tephra. We argue that this model is more likely, as the use of short-lived taxa alone may underrepresent early human activities. The influence of the number of ^{14}C samples on precision is further illustrated by a range of 23 years obtained when using 231 dates from Hawai'i (cal AD 1353–1376) and 41 years when using 78 dates from Marquesas (cal AD 1224–1265). Bayesian modeling using multiple charcoal samples not only provides reasonable precision, but also allows reliable chronologies to be established in new areas, for example Norfolk (cal AD 1176–1274), Kermadec (cal AD 1380–1465) and Northern Cook islands (cal AD 1455–1586). Overall, we find that Bayesian Outlier models including charcoal samples of indeterminate age may shift previously accepted chronologies by more than 87 years, and the scale of change depends on the distribution of the dataset (Table 4). Although we can use charcoal samples of indeterminate age in chronological models, we

Table 4
Age ranges from East Polynesian archipelagos using Bayesian Outlier models (this study) and summing (Wilmshurst et al., 2011).

East Polynesian island	OUTLIER MODELS (68% probability)*†		SUMMING (68% probability)°	
New Zealand	1260	1314	1230	1280
Hawai'i	1353	1376	1219	1266
Rapa Nui	1221	1268	1200	1253
Marquesas	1224	1265	1200	1277
Southern Cooks	1231	1290	1250	1281
Society	997	1079	1025	1121
Gambier	1099	1208	1108	1275
Australs	1391	1517	/	/
Norfolk	1176	1274	/	/
Northern Cooks	1455	1586	/	/
Kermadec	1380	1465	/	/
Line	1327	1415	1275	1293
Auckland is.	1195	1300	1190	1258
Chathams	1451	1610	/	/

Key: The age ranges are based on: *short-lived taxa and charcoal samples of indeterminate age, †charcoal samples of indeterminate age, and °short-lived taxa.

Table 3
The timing of colonization from East Polynesian archipelagos using Bayesian Outlier models. Models are tested using short-lived taxa and charcoal samples of indeterminate age.

^{14}C DATASETS			AGE RANGES (OUTLIER MODELS)					
Model	Island	No. of ^{14}C Dates	Posterior 68% (excluding wood charcoal)		Precision in years	Posterior 68% (including wood charcoal)		Precision in years
10	New Zealand*	265	1262	1353	91	1260	1314	54
11	Hawai'i*	231	1331	1371	40	1353	1376	23
12	Rapa Nui*	153	1221	1268	47	1245	1280	35
13	Marquesas*	78	1224	1268	44	1224	1265	41
14	Southern Cooks*	65	1250	1310	60	1231	1290	59
15	Society*	44	1002	1075	73	997	1079	82
16	Gambier*	35	1035	1182	147	1099	1208	109
17	Australs*	32	–	–	–	1391	1517	126
18	Norfolk†	31	–	–	–	1176	1274	98
19	Northern Cooks†	27	–	–	–	1455	1586	131
20	Kermadec†	14	–	–	–	1380	1465	85
21	Line*	13	1316	1414	98	1327	1415	88
22	Auckland island*	10	–	–	–	1195	1300	105
23	Chathams*	10	–	–	–	1451	1610	159

The age ranges are based on: *short-lived taxa and charcoal samples of indeterminate age, †charcoal samples of indeterminate age.

underline the importance of using short-lived material from the same contexts when generating new datasets wherever possible.

4. Conclusions

This paper demonstrated that accurate and precise age ranges for historical events can be generated using Bayesian Outlier models for small and large datasets that combine ^{14}C dates on short-lived samples and charcoal samples of indeterminate age. These models are sensitive to the distribution of dates, and they will be biased if filtered datasets have dates from early contexts are preferentially removed. Accuracy is greatest where the sampling density is uniform. Precision is greatest (17 years), where the sampling density is high, and ~280 ^{14}C samples give the best results. Precise datasets, therefore, could be achieved using far more of the available samples, including more than 50% of around 80,000 ^{14}C samples of cultural layers recorded in a series of key databases around the globe. A more inclusive use of such samples is very important in areas where charcoal is the only material class sufficiently well preserved for dating. Utilizing marginalized charcoal samples of indeterminate age could modify presently accepted chronologies for many important events and processes in human history and may confirm or subtly, but importantly, revise ideas about the timing and impacts of great migrations of people across the planet, not just the Vikings across the North Atlantic, or the Polynesians across the Pacific, but also many other cases as varied as the peopling of the Arctic, the Americas and other oceanic islands.

Enhanced ^{14}C chronologies allow for more nuanced understanding of historical drivers of change, such as long-distance migration (Braje et al., 2017), human-induced landscape modification (Hunt and Lipo, 2006), causes of societal collapse (Middleton, 2017), extinctions (Higham et al., 2014; Holdaway and Jacomb, 2000), and post Ice Age reoccupation (Riede and Borre Petersen, 2018). Developments in Bayesian analyses of ^{14}C datasets, tested here using independent chronological controls that apply to the Viking Age settlement of Iceland, can allow controversial archaeological and anthropological questions to be tackled using a more diverse range of ^{14}C dates.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quageo.2018.07.015.

Author contributions

MMES, AJD and RW designed research; MMES performed research and analyzed data; MMES collected the GIS data, which was tested by AJN; AJN created the maps; MMES, AJN and LF the figures; LF wrote OxCal_Parser, which was tested by MMES and MMES, AJD, AJN, OV, and RW wrote the paper.

Conflicts of interest

Authors declare no competing interests.

Data and materials availability

All data is available in the main text or the Supplementary Materials.

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8. Conclusions

The mere formulation of a problem is far more often essential than its solution, which may be merely a matter of mathematical or experimental skill. To raise new questions, new possibilities, to regard old problems from a new angle requires creative imagination and marks real advances in science.

Albert Einstein 1938

8.1 Introduction

This thesis has refined ^{14}C age-model accuracy and precision in order to enhance the dating of archaeological and palaeoenvironmental events in the past. This chapter summarizes the key findings of this study. Two main research objectives have been tackled: *a high-resolution chronology of the Viking age settlement of Iceland* and *a new chronometric evaluation protocol that is based on Bayesian statistical modelling*. The research objectives are related to two hypotheses introduced in Chapter 1 and tested using real-life datasets from Iceland and East Polynesia. This chapter reflects on how this work has achieved these outcomes and evaluates wider implications arising from the data in this thesis.

8.2 Increased dating resolution of Iceland's Landnám

The Viking age settlement of Iceland has previously been regarded as one single period, often conflated with the Landnám, due to the fact that investigations into the chronology tended to rely on a single methodology (primarily typological data from burials and assemblages: Eldjárn and Fridriksson 2016), and because multidisciplinary data had not been systematically assessed on a countrywide scale. This thesis evaluated the spatio-temporal dynamics of Landnám covering the first ~300 years of settlement. This required a higher resolution of the chronology of Landnám including an original periodization of this period. The implications of these results are summarized along the lines with **RQ1-3** and **H1** addressed in this thesis.

1. A new and extensive multidisciplinary dataset of the archaeological record. Iceland has a minimum of 550 archaeological sites relating to Landnám comprising 300 settlement sites, 140 burial sites and 110 assemblages. These sites are clearly related to Viking age activity as suggested by 19 tephra layers below and/or above 261 archaeological sites, associated ^{14}C dates earlier than AD 1200 (n = 513 at 97 sites) as well as by

typologically diagnostic artefacts or house types. These sites represent the minimum number of the rich archaeological record and limited scope of archaeological activity in Iceland, because sites were excluded that do not have secure dating evidence, but can be targeted in future analysis. Although each dating methodology (tephrochronology, ^{14}C dating, typology) produces dates of different precision, accuracy, and bias, this thesis demonstrated that each date is a piece of scientific knowledge that should not be ignored and can, and should, be effectively integrated.

2. Early anthropogenic activities are most likely underrepresented (tephra). Settlement dynamics in four geographic areas were evaluated through the analysis of regional patterns of the presence and absence of anthropogenic activities relating to colonisation with the main focus on the earliest evidence of occupation. The dating of settlement sites is primarily a function of the distribution of 19 tephra layers below and above archaeological features. The improvement of excavation techniques (e.g. excavating turf-walls) and fieldwork intensities (e.g. regional focus) in the last 25 years have mostly been applied in the North of Iceland and not only bias the distribution pattern of colonisation, but also produces data of different accuracy and precision in geographic areas.

The evaluation of four tephra layers in particular – the LTL of AD 877 ± 1, the Eldgjá tephra of AD 939, the V-Sv tephra of AD 938 ± 6 and the Hekla tephra of AD 1104 – faciliated a periodization of archaeological sites on a countrywide scale into:

1. pre-Landnám of AD pre-877: before widespread settlement
2. Landnám of AD 877-938/939: early widespread settlement
3. post-Landnám of AD 938/939-1104: late widespread settlement.

Where applicable, radiocarbon samples and typologically diagnostic artefacts from settlement, burial, and assemblage sites were systematically classified within these periods. The assessment of 550 archaeological sites has demonstrated that 282 sites can only be assigned general Viking age dates. The remaining 268 sites can be assigned robust periods, of which <1% are from the pre-Landnám period in the southwest (n = 2), 31% are from the Landnám period (n = 84) and 68% are from the post-Landnám period (n = 182) across the country. However, the Landnám period almost exclusively exists of settlement sites (n = 81) with only one securely dated burial site and two assemba sites. The post-Landnám period includes a few more settlements (n = 116), and significantly many more dated burial sites (n = 29) and assemblage sites (n = 37). Nevertheless, the sheer amount of artefacts can be

categorized into the Viking age period, therefore the distribution of typological data is highly biased and does not mean, for instance, the construction of burials happened only during post-Landnám.

The data is therefore assessed using tephra layers. The pre-Landám period consists of seasonal structures and there are no middens, burials, artefacts, or ^{14}C dates sealed by the LTL. Such temporary structures are few (n = 2), but there are almost equal numbers of established settlement sites dating to the Landám period (n = 81) and post-Landám period (n = 90). Significantly, Steinberg et al. (2016) collected 4000 cores from modern farms in Langholt in northern Iceland. They identified 17-20 Viking age settlements of which 12-20% did not have any surface signs. As such, early anthropogenic contexts are difficult to identify in island contexts, due to later disturbances; they are easily obscured and are most likely underrepresented. Furthermore, the nature of the impacts – temporary buildings, scattered and short time periods of occupation leave little impact to start off with. These visible impacts can then be obscured by subsequence human activities.

3. Radiocarbon dates from early contexts are underrepresented. Analysing secondary data has the inherent disadvantage that materials and contexts of ^{14}C samples cannot be chosen. But they also have the advantage that when a holistic dataset is assessed, as demonstrated in this thesis, knowledge about sampling bias can be overcome in the future with re-dating key contexts.

Prior to the early 1990s, 79 ^{14}C samples had been published. The number of ^{14}C dates has increased 6-fold (n = 513). Eighty-nine percent of archaeological sites have less than ten samples (n = 85). More precisely, 31% of sites have one sample (n = 30), 20% both two and three samples (n = 19) and 18% between four and nine samples (n = 17). On the contrary, 9% of sites have between ten and 25 samples (n = 9), while 2% between 58 and 82 samples (n = 2). As such, site-specific Bayesian models can be produced for eleven archaeological sites. After applying chronometric hygiene and eliminating 129 outliers from the overall dataset, only six sites have sufficient numbers of dates for multi-phase modelling. From the remaining overall dataset, 188 samples are of short-lived taxa, 147 of wood charcoal with inbuilt and 49 samples of bone samples affected by MRE (Chapter 6). If we choose to build chronologies solely using short-lived taxa, five sites would remain for analysis (Hrísheimar, Sveigakot, Skútusstaðir, Hrísbrú and Hofstaðir). Even more significantly, the earliest dated contexts at three of these sites are from mid- to late-10th centuries (Chapter 5). To conclude, only two

sites (Hrísheimar and Skútusstaðir) date early anthropogenic activities, the *posterior* probabilities are estimated to cal *AD 828-881* and *cal AD 838-938* (Chapter 6). This thesis, therefore, advatises utilizing a greater variety of ^{14}C materials.

8.2.1 Hypothesis 1: The settlement of Iceland was largely completed in less than 20 years after the deposition of the Lándnam Tephra Layer

Based on the evidence presented it was possible to evaluate the first hypothesis. The hypothesis that best matches the timing, rate and scale of Iceland's settlement is a combination of (b) *the settlement happened after the traditional date (AD ~870)* and (c) *the settlement was a flood*. Permanent settlement indeed happened after the AD 870s, which is based on the stratigraphic relationships of 84 sites above the Landnám Tephra Layer (LTL). The combination of 335 ^{14}C samples yielded *posterior* probabilities of *cal AD 863-881* (68%) for the overall onset of colonisation. The settlement of Iceland was homogeneous across the entire island, it is comparable on a countrywide scale and all habitable parts of the island were occupied by the 10th century. This shows that the colonisation of Iceland was extremely rapid and extensive.

Nevertheless, the hypothesis that the settlement happened before the traditional date in the AD 870s can be only partially refuted. This is a question of the definition of 'settlement'. There is a difference between very low numbers of settlers who could not create a sustainable population (demographic models would indicate that is less than 600 people) and a large, potentially sustainable population with high probability of prolonged growth (Keegan 1987). Iceland was visited before that date, currently evident at three sites in the SW with sparse traces of anthropogenic activities. Two of the sites consist of seasonal structures of unknown function and one site shows potential woodland clearance and barley cultivation before the LTL. How long before the LTL the Norse arrived on the island cannot be established with the current dataset, because there are no burials, middens, artefacts, or ^{14}C samples (and potentially suitable organic material to date) from secure stratigraphic archaeological contexts below the LTL, suggesting a transient or very short-term occupation.

The hypothesis that the colonisation was a trickle can be refuted. Nevertheless, there are almost equal numbers of settlement sites above the LTL (n = 81) and the Eldgjá/V-Sv tephras (n = 90). Do these sites demonstrate internal or external mobility? It has been argued that people still migrated to Iceland in the 10th century (Price and Gestsdóttir 2006; Vésteinsson & Gestsdóttir 2016), however, it is not known on what scale. Vésteinsson and McGovern (2012)

propose that the colonisation of Iceland was largely completed in less than 20 years (e.g. 24,000 people) and that this could be the cause of a further push to Greenland in the late 10th century (Vésteinsson et al. 2014).

8.3 Enhancing the accuracy and precision of small and large ^{14}C datasets using a new chronometric evaluation protocol

The second research goal was to establish a new methodology for synthesizing ^{14}C datasets using Bayesian statistical analysis, with the overall aim to improve age-model accuracy and precision. This was achieved by promoting a new protocol to assess the quality of ^{14}C datasets, which is tested using ice-cored dated tephrochronology. The main findings of international significance can be summarized along with **RQ4-5** and **H2.**

1. Chronometric hygiene should not be too strict. The quality of ^{14}C datasets depend on chronometric hygiene aiming at removing samples that are most likely problematic. This thesis showed that previous chronometric hygiene protocols are overly strict and remove too many samples. This drastically restricts:

1) Opportunities for robust statistical analysis of data that require a certain amount of samples.
2) The establishment of chronologies in many parts of the world, where unfavourable material classes are sufficiently well preserved for dating (e.g. wood charcoal with inbuilt age).
3) Most significantly, the rejection of many data can underestimate the beginning and duration of significant events in archaeology as many samples provide some information about past activities.

2. Non-tangible outliers can be avoided. Non-tangible outliers can currently not be used in statistical analysis (Chapter 2.2). Such outliers are primarily a result of sample choice (e.g. bulk sediment), but can also be the lack of appropriate publication of metadata. These include the material type of samples and isotope values to evaluate dietary intake of bone samples. Furthermore, stratigraphic relationships of ^{14}C data and their contexts, quality assurance data of bone samples and pre-treatment methods are not always described and thus the reliability of such ^{14}C data is uncertain (Chapters 5 and 7). It is hoped that this information can become available.

3. Multiple *priors* in Bayesian statistical analysis should be tested. Robust *posterior* distributions of archaeological chronologies depend on testing *priors* in Bayesian statistical analysis. While 'Outlier models' have shown to be robust, single- and multi-phase models of different datasets can be tested evaluating if there are inherent biases within specific material classes or the distribution of datasets (Chapters 5-7). The results should be compared to formulate hypotheses about the most likely *posterior* probabilities of events.

4. The number of ^{14}C samples and their contexts are key for robust chronological models. Both single-phase and multiple-phase models can be used to establish robust *posterior* probabilities on a site-, region-, or island-scale and, as demonstrated in this thesis with Iceland and East Polynesia and this depends on the availability of data (Chapters 5-7). A large dataset has obvious advantages over a small dataset. The *accuracy* and *precision* of Bayesian models can be enhanced by the interplay of both the quality and quantity of dates. Multi-phase models can be robust if at least ten samples are available per archaeological site (Chapters 5-6). Single-phase models highly depend on the quantity of samples and this depends on the percentage of short-lived materials and materials with inbuilt age. Precision decreases using only wood charcoal with inbuilt age (e.g. Norfolk Island, Northern Cook Islands and Kermadec in East Polynesia); it increases using short-lived taxa (e.g. Iceland); however the highest precision is achieved using a combination of wood charcoal and short-lived taxa (e.g. Iceland and the other islands in East Polynesia). This coincides with the number of samples: precision is greatest (> 20 years) where ~280 or more samples are used, and lowest (> 160 years) where 10 samples are used.

5. Improved routine chronology building is facilitated through a new chronometric evaluation protocol. The outcome of this thesis is a new standardized chronometric evaluation protocol for producing Bayesian chronological models based on ^{14}C measurements. This offers significant advantages by allowing for incorporation of the largest possible amount of ^{14}C measurements into a model, by rigorously assessing the decision-making process behind the inclusion or exclusion, and validating with independent dating controls. This makes it possible to accommodate even material where there will be the inevitable possibilities of outlier dates (Chapter 6). Models, such as the 'General Outlier model' and the 'Charcoal Plus Outlier model' are successfully applied, and methods introduced previously in this thesis are properly evaluated (Chapters 2, 4-5). This new standardized chronometric evaluation protocol is summarized in the following steps:

1) Define the context of an event (e.g. the colonisation of a remote and pristine island) and collect ^{14}C samples that relate to the event in question.
2) Produce Excel spreadsheets of the data using mandatory and optional fields that can be used for computer software such as 'OxCal_parser'.
3) Apply chronometric hygiene to ^{14}C datasets and carefully eliminate non-tangible outliers.
4) Categorize the remaining, and potentially, accurate ^{14}C samples into three categories (short-lived taxa, wood charcoal with inbuilt ages, bone samples affected by MRE).
5) Apply reservoir corrections to bone samples affected by MRE.
6) Statistically assess ^{14}C dates using 'General Outlier models' for short-lived taxa ($p = 0.05$) and 'Charcoal Plus Outlier models' for wood charcoal with inbuilt ages ($p = 1$).
7) If applicable, include other multidisciplinary data (e.g. stratigraphy, typology, historical dates, palaeoecology).
8) Remove statistical outliers.
9) Apply different statistical models to evaluate if there are inherent biases within specific material classes or the distribution of datasets. Compare the results and formulate hypotheses about the most likely *posterior* probabilities of events.
10) Re-date significant contexts at archaeological sites, and choose short-lived taxa wherever possible.

8.3.1 Hypothesis 2: Bayesian modelling can produce accurate age estimations for archaeological events

Based on a real-life ice-core dated ^{14}C dataset from Iceland, it was possible to evaluate the second hypothesis. The dataset refutes (a) *model outcomes are sensitive if samples with inbuilt ages are used in chronological models* but supports (b) *model outcomes are insensitive if samples of short-life span are used in chronological models* – as long as appropriate *prior* assumptions are used and the distribution of ^{14}C dates through the 'Phase' is *uniform*. As such, the context and distribution of ^{14}C measurements are more important than the material type. Therefore scenario (c) *model outcomes are insensitive if the sample's stratigraphic relationship to the event of interest is known* is inevitable for chronological modelling, while scenario (d) *model outcomes are insensitive to the prior assumption that dates are uniformly distributed across a Phase* is also refuted.

To conclude, 'General Outlier models' could be used with confidence to create chronologies from multiple ^{14}C dates on short-lived plant materials, terrestrial bone, and bone affected by MRE. 'Charcoal Plus Outlier models' can be used with confidence for synthesizing sets of

^{14}C dates based on wood/charcoal with inbuilt age, because the age offset is accurately corrected. Nevertheless, the inclusion of a high percentage of younger dates decreases the precision of *posterior* colonisation age estimate, because there is a comparable lower density of data towards the start of a 'Phase'. Second, where dates from early contexts are preferentially removed, the model will be affected and the *posterior* colonisation age estimate will most likely underestimate early human activity.

8.4 Closing statement

A robust chronology depends on the accuracy and precision of the ^{14}C dataset, and how well that date is associated with the event being dated. For example, a radiocarbon date may be *precise* and *accurate* (as an appropriate pretreatment method has fully removed contamination), but it may:

- Have a substantial inbuilt age (e.g. be from heartwood of a long-lived species or have a FRE).
- Come from an occupation context, which occurred long after colonisation.
- Not be functionally related to what we are trying to date. For instance, charcoal in a burial fill is not functionally related to a human burial, while charcoal in a hearth of an archaeological feature is functionally related to that hearth.

This thesis demonstrates that a large variety of samples could, and should, be used in chronological models, because:

- If too many samples are removed the dataset can be very small and is likely to obscure the dates from early colonisation contexts.
- A large dataset allows assessing various archaeological and environmental questions including functional reasons, such as the successful cultivation of cereals.
- There are now statistical models that account for inbuilt ages.

Therefore, as a community we could, with the appropriate methodology, refrain from eliminating so many individual analyses from ^{14}C datasets, and thus, collectively make better use of research funding, and answer more questions with greater confidence, accuracy and precision.

This thesis concludes that no matter how much we work on improving the accuracy and precision of individual ^{14}C samples, these data have limited use if we neglect their

stratigraphic relationships and interpretation of association with the event. This thesis casts new light on how best to treat many other ^{14}C datasets related to distinct events in the past.

This study has important implications for our understanding of ^{14}C dating within both archaeology and Quaternary sciences. The analysis of stratigraphic contexts of ^{14}C dates can lead to a better understanding of statistical assessments of large datasets and suggest revised future sampling protocols. The findings of this study will benefit chronological work in several research areas including archaeological excavation, palaeoenvironmental reconstruction, tephrostratigraphy, and the application of Bayesian statistics. In particular, it allows assessing both large and small, underutilized datasets that was not possible before.

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Appendices

Appendix I. List of Viking age sites in Iceland

Appendix II. Detailed catalogue of Viking age sites in Iceland

Appendix III. Paper 1 (Chapter 4.2): Supplementary Materials

Appendix IV. Paper 2 (Chapter 5.1): 'Constructing chronologies in Viking Age Iceland: Increasing dating resolution using Bayesian approaches'

Appendix V. Paper 3 (Chapter 5.2): Supplementary Materials

Appendix VI. Paper 4 (Chapter 6): Supplementary Materials

- **A. 513 ^{14}C dates from Iceland**
- **B Bayesian OxCal models using ^{14}C datasets from Iceland**

Appendix VII. Paper 5 (Chapter 7): Supplementary Materials

- **A. 282 ^{14}C dates from Viking age contexts in Iceland**
- **B. 'OxCal_parser'**
- **C. 1434 ^{14}C dates from East Polynesia**
- **D. Bayesian OxCal models from Iceland and East Polynesia**