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– ARTICLE –

Wiggles, Plateaus, and Precision: High-Resolution Radiocarbon Dating of the Transition from Early East Polynesian to Classic Māori Society

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Abstract

Achieving precise archaeological chronologies in island environments has long been hindered by plateaus and wiggles in the radiocarbon calibration curve. This study shows how to overcome these temporal bottlenecks by integrating Bayesian principles with high-precision sample selection, and demonstrates how the interpretation of archaeological context affects the results. Using two iconic Aotearoa, New Zealand sites previously dated over 30 years ago, we showcase the power of this approach and the limitations of working with legacy data. At Shag River Mouth, we reveal, for the first time, a detailed picture of site reuse starting ca. AD 1320 by considering changes ("wiggles") in atmospheric ^{14}C between AD 1290 and 1400. Similarly, at Kokohuia, we demonstrate how to achieve greater resolution between AD 1480 and 1640, a plateau in the ^{14}C calibration curve that has traditionally masked the transition between early East Polynesian and later Classic Māori culture. Our results provide unprecedented temporal resolution of economic changes over 500 years and demonstrate that these changes began much earlier than orthodox chronologies suggest.

***Keywords*:** Bayesian Chronological Modelling; Calibration Wiggles and Plateaus; East Polynesian settlement; Māori Cultural Transition

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1. Introduction

Reliable chronology is the cornerstone of archaeological interpretation. Across the globe, radiocarbon (^{14}C) dating is the primary tool for providing the temporal control necessary to understand cultural change. Currently, the established cultural sequence for the Māori settlement of Aotearoa, New Zealand, is divided into three tiers: East Polynesian settlement (~AD 1250-1400), a transitional period (~ AD 1400-1600), followed by 'Classic' [Traditional] Māori (~AD 1600-1800) as described by European explorers (see Anderson [2016] for variations on these divisions). However, archaeological evidence and iwi histories indicate that the settlement process was far more complex. As such, this three-tiered temporal structure provides few links to the traditionally recorded events that shaped Māori culture and offers little on environmental adaptation, socio-political development, changes in material culture, or social connectivity (Anderson 2014, Furey 2004, Lo and Houkamau 2012). The terms "Māori Middle Ages", "middle phase", and "middle period" (Anderson 2016) emphasise the ambiguity of this transition and the lack of chronological structure. Although ^{14}C measurement and our understanding of natural ^{14}C variation has improved over the last 20 years, the short chronology and three ^{14}C calibration "plateaus" have contributed to this imprecision, especially when combined with insufficient ^{14}C results and poor application of stratigraphic dating (i.e., Bayesian evaluation that utilises stratigraphic observations and wiggles in the calibration curve to convert ^{14}C results into calendar dates, a process which can provide "generational" precision [multi-decadal], or even better [e.g., Marciniak *et al.* 2015, Ledger *et al.* 2018], even across plateaus [Manning *et al.* 2020]).

2. Radiocarbon reversals and plateaus

Eastern Polynesian explorers settled New Zealand around 500 years before the Endeavour arrived in 1769 (Wilmshurst *et al.* 2011, Bunbury *et al.* 2022. Tomlinson *et al.* 2024, Best *et al.* 2026). Over this period, the terrestrial ^{14}C calibration curve (e.g., Hogg *et al.* 2020) is highly variable. Rapid changes in ^{14}C manifest as a steep slope in the curve and enable precise calendar ages to be given (typically multi-decadal resolution at 68% or 95% probability), assuming the precision of the radiocarbon age (CRA) is better than ±20 years (cf. Meadows *et al.* 2020, Hamilton *et al.* 2015). However, over the last 800 years, there have been three periods when this level of calendar precision is problematic. Between AD 1280 and 1400, there are reversals in ^{14}C concentration, resulting in no single clear intercept, with dates typically intersecting both peaks (Figure 1a). These wiggles rise and fall, and inversions in the CRAs are not necessarily indicators of any issue with the sample or context, as Leach *et al.* (2022, 31) suggest, but the resulting calendar dates are bimodal and ambiguous, with a calendar spread of hundreds of years. Failure to resolve these wiggles is why we see generalised statements that the East Polynesian settlement phase occurred throughout the 14th century AD (cf. Walter *et al.* 2017). Just as crucial as the points where the CRA intersects the calibration curve are periods of non-intercept. These effectively rule out calendar dates when the activity did not occur. Where a known sequence of events is available, as in the case of observed site stratigraphy or dendrochronologically dated tree rings, reasonable resolution can be achieved by "wiggle matching", but only if sample strength and context are given sufficient attention (cf., a wiggle-matched palisade post from Otāhau Pā providing a felling date of AD 1768 ± 4 [Hogg *et al.* 2017] despite dating to the AD 1675 – 1950 plateau shown in Figure 1c).

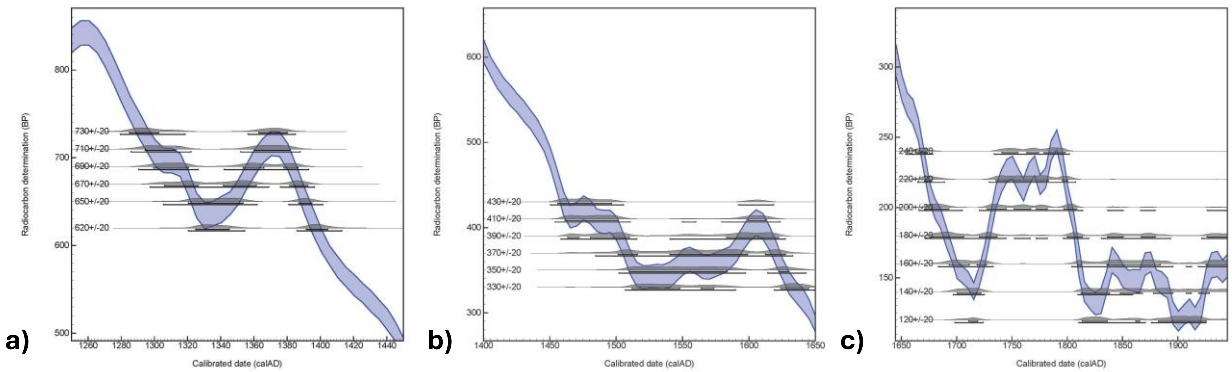


Figure 1: Calendar ages for six ^{14}C ages lying in the region of (a) ~AD 1290 – 1400, (b) ~ AD 1480 – 1640, and (c) AD 1675 – 1950 reversal/plateaus in the ^{14}C calibration curve (68.3% and 95.4% probability ranges). Plot generated by OxCal v.4.4 (Bronk Ramsey 2009) using SHCal20 (Hogg *et al.* 2020).

Between AD 1480 and AD 1640 (Figure 1b), there is little change in atmospheric ^{14}C, and while wiggles are present, their magnitude is not large. These plateaus occur because atmospheric ^{14}C concentration declines at a rate equal to radiocarbon decay, effectively cancelling out expected differences that would otherwise distinguish samples of different ages (Guilderson *et al.* 2005). Resolution across such plateaus is globally problematic (Hogg *et al.* 2019, Manning *et al.* 2020, Meadows *et al.* 2020), but in archaeological situations where sequential information is available, Bayesian modelling, which integrates the dating with archaeological observations and information on the relative order of events, can significantly improve resolution. However, between AD 1480 and AD 1640, these models are highly sensitive to the addition of new information (Holland-Lulewicz and Richison 2021, 274), and the accuracy of the archaeological observations may be more important than the precision of the ^{14}C dates (Meadows *et al.* 2020, 1279-80). Therefore, care in association and sample selection are paramount.

In this paper, we reinvestigate the chronologies of the SM/C:Dune excavation at Shag River (Waihemo) Mouth (NZAA site no. J43/2) in the South Island, and the Area 3 midden at Kokohuia (O06/317) in the North Island of New Zealand (Figure 2). These two sites were used to test ^{14}C methods and reservoir offsets 30 years ago (Anderson *et al.* 1996; Schmidt 1996a; Higham *et al.* 2004) and date to ^{14}C reversals and plateaus between AD 1290 – 1400 and AD 1480 – 1640, respectively. By evaluating legacy data and applying new dating protocols and statistical analyses, we demonstrate how significant refinements can be made not only to the timing and duration of site use, but also to the temporal structure of each site and, by implication, to the three-tiered structure of New Zealand archaeology. Moreover, these new site chronologies enable us to identify where established sampling and interpretation protocols (i.e., dating strength) no longer hold up under scrutiny.

Figure 2: Map showing the location of Shag River (Waihemo) Mouth and Kokohuia. Image generated by Google Gemini (2026) based on the original outline supplied by FP.

3. Methodology

We collated information from each site from published and archived records (Petchey *et al.* 2022). For both sites, these established chronological frameworks were based on artefactual and faunal remains (e.g., butchered *vs* worked moa bone, changes in other taxa, fishhook styles) and on "eyeballing" the calibrated age distributions. From these legacy ^{14}C datasets, we prepared preliminary Bayesian models to identify where new information would be most beneficial. For both sites, it soon became apparent that the legacy dates were not only too imprecise (e.g., an individual date precision of ±45 years) but, in some instances, completely inaccurate due to built-in age, heirloom storage, and/or stratigraphic displacement. Consequently, we sought new sets of sequential radiocarbon dates. A detailed breakdown of the legacy dates for Shag River Mouth and Kokohuia is given in Supplementary Information 1.

New samples were obtained from the University of Otago Archaeology stores, the Institute of Geological and Nuclear Sciences, where some samples had previously been analysed, and the University of Waikato radiocarbon stores, which housed spare material from Higham's (1993; Shag River Mouth) and Schmidt's (1996a; Kokohuia) PhD research. All charcoal samples were identified, and single twigs, preferably of short-lived shrub species, rather than small trees, were selected (see Supplementary Table 3 for possible issues with charcoal taxa). Samples came from all cultural layers, and all dates were duplicated where possible, using different materials or taxa from different squares or features to test comparability of results and mitigate the risk that samples may be residual (reworked) or intrusive (c.f., David *et al.* 2025). This enabled us to assess the reproducibility of the radiocarbon ages, the possibility of heirloom effects and disturbance affecting the chronology, and the context/layer interpretation.

High-precision (better than ±20 years) Accelerator Mass Spectrometry (AMS) dates were processed at the University of Waikato using protocols outlined in WRD (2017). The modelling used in this paper employs OxCal v.4.4 and the SHCal20 calibration dataset (Hogg *et al.* 2020). To reduce the risk of producing an inaccurate chronology, we also assessed the consistency of replicate results – whether they are statistically identical (see Ward and Wilson 1978) and the fit of calendar results with the stratigraphic information and the terrestrial calibration curve (e.g. Bronk Ramsey 2009a, 2009b, Bronk Ramsey *et al.* 2010). For each site, dates were grouped into multiple phases (layers) based on stratigraphy, with either contiguous or sequential boundaries depending on the stratigraphic information. Outlier analysis was used to assess whether the radiocarbon data were consistent with prior information. This methodology provides a probabilistic measure of how likely dates are to be outliers and downweighs outliers accordingly (Bronk Ramsey *et al.* 2009a, 2010). Throughout the process, we ran multiple models to assess how the new chronology may have changed our interpretation of the site and whether additional dates were required (cf., Bayliss and Marshell 2022, fig 11).

The results are presented at 68% probability throughout the text to limit the calendar age spread and aid interpretation. The calendar ages are rounded to 10 years to avoid spurious precision because of the inclusion of non-twig small diameter charcoal samples (see estimated possible maximum inbuilt age in Tables 1 and 3) and because much of SHCal20 for the period of interest is constructed from dendrochronologically dated 5-year blocks. The success of each model run is assessed according to A_{model} and $A_{overall}$ being ≥60% and "convergence" being ≥95%, with lower values indicating many different incompatible solutions to the model (see Bronk Ramsey 2009b). The model code is provided in Supplementary Information 2.

4. The AD 1290 – 1400 reversal and impact on the SM/C:Dune (J43/2) chronology

The site of Shag River Mouth is located on the east coast of the South Island at the mouth of the Waihemo River (Figure 2). Until relatively recently, Shag River Mouth was one of the best-dated archaeological sites in New Zealand, with occupation considered to span 20 to 50 years in the 14th century AD, though Anderson and Smith (1996, 278) suggested it may have been much shorter (cf., Figure 1a). With Bayesian modelling, we should have achieved greater resolution, but upon reinvestigation, several problems were apparent in the extant dataset (see Supplementary Information 1). Theoretically, all previous evaluations of the site chronology have assumed the samples come from secure contexts, primarily the SM/C:Dune excavation (see Higham *et al.* 2005, Higham and Horn 2000). However, during our evaluation, it was apparent that few specific features of SM/C:Dune were dated, with many samples instead coming from a layer within a square or by combining material from multiple squares (Supplementary Table 1), a methodology necessary to achieve the sample weights required for ^{14}C analysis at the time.[1] The reliability of these contextual interpretations (and the samples selected for our new chronology) was difficult to assess because detailed sections and field notes for each square are no longer available. Published plans of the different layers clearly indicate disturbances between layers; most features cut only into the immediate layer below, but some cut into much older layers (Figure 3). Of note, the large oven in the NNE corner of Layer 5 cut down through multiple layers, and a precursor oven was found in the same location. This penecontemporary disturbance, combined with the complexity of dune stratigraphy and sand mobility, makes sample displacement likely. Following careful examination of the terrestrial legacy dates, it became apparent that mixing between layers had occurred (Supplementary Table 1) and that older material was typically "brought up" (residual) rather than younger material moving down into the older deposits (intrusive) (Figure 4).

While there are Bayesian statistical methods specifically designed for dealing and assessing the fit of different types of noisy data (see Bronk Ramsey *et al.* 2010), a combination of the short time period, complexity of evaluating samples from different ^{14}C reservoirs (i.e., marine, terrestrial and mixed), storage and/or heirloom effects, context disturbance, the nature of dune excavation and low precision legacy dates, made any improvements to the extant chronology using Bayesian tools, impossible (cf. Bronk Ramsey *et al.* 2010, 954). Critically, a key piece of information was missing – cultural Layer 9 had never been dated, which meant our analysis of legacy data could not refine the age of Layers 11 to 7 across the wiggles. Therefore, we acquired a series of new high-precision, short-lived samples for dating.

[1] In the mid-1990s the Waikato Radiocarbon Dating laboratory recommended sample sizes were 10g for charcoal and 30g for shell standard radiometric dating.

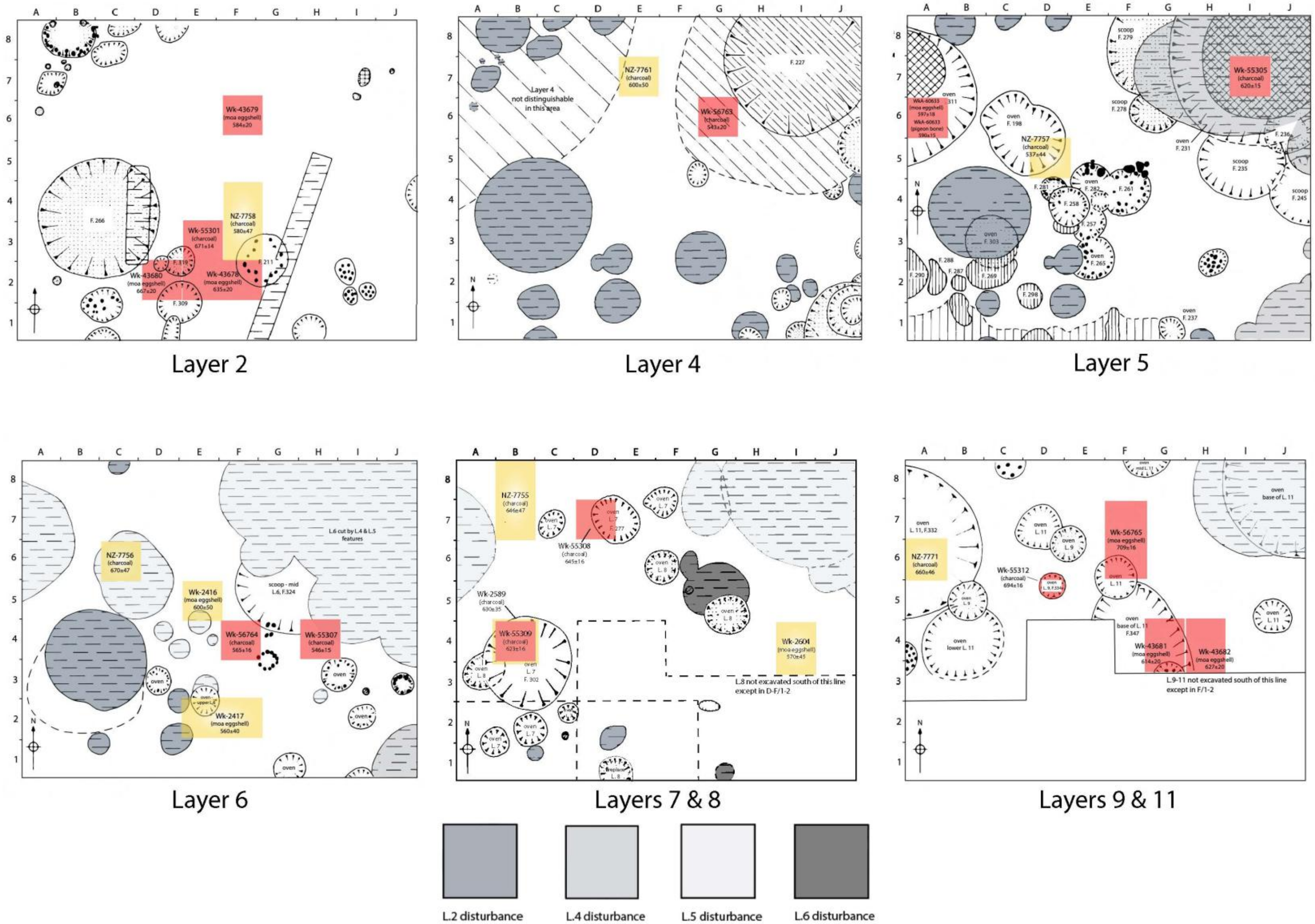


Figure 3: Excavation plans from SM/C:Dune (after Anderson and Allingham 1996, 43-46, figures 5.5-5.10. Reproduced with permission) showing disturbance between the layers and position of terrestrial radiocarbon dates (legacy date locations highlighted in yellow and new AMS sample locations in red).

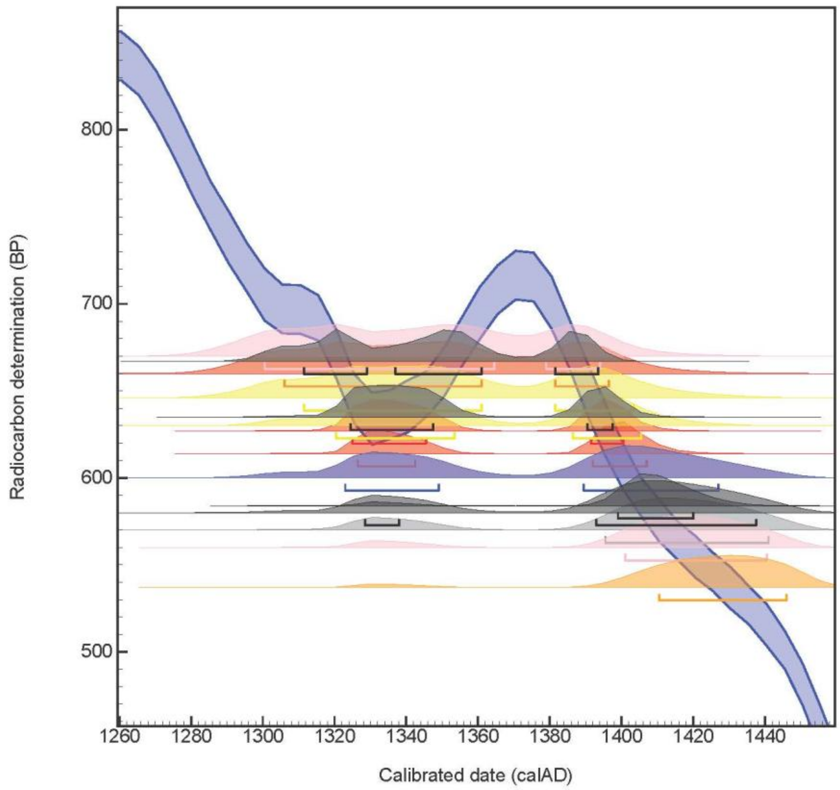
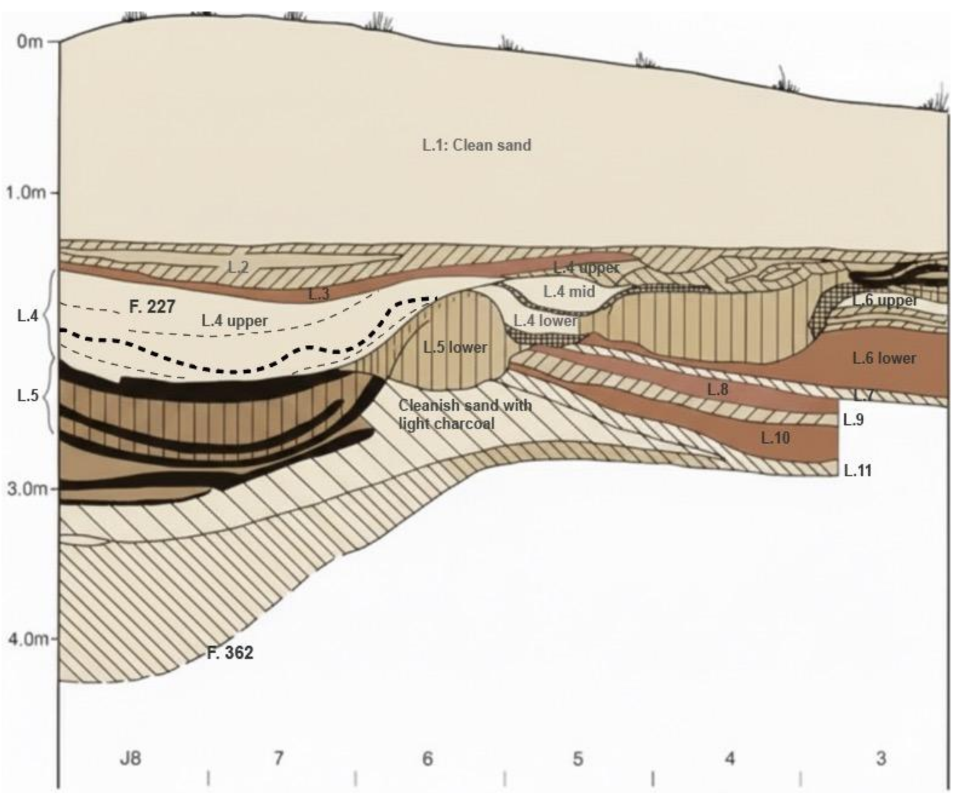


Figure 4: OxCal plot showing how terrestrial (moa egg and charcoal) legacy dates intersect the calibration curve (68.3% prob.), colour-coded by layer; Red = Layer 11 (oldest), Grey = Layer 8, Yellow = Layer 7, Pink = Layer 6, Orange = Layer 5, Blue = Layer 4, Black = Layer 2 (youngest).

4.1. A new chronology for SM/C:Dune

To simplify and reduce ambiguity, we focused on short-lived, single-element charcoal dates and, when suitable charcoal was unavailable, on moa eggshell or terrestrial bird bone (2 dates per layer). We obtained 12 new terrestrial dates (plus 4 eggshell AMS dates measured in 2016) to ensure coverage of all cultural layers, including the first dates ever for different contexts within Layer 9, and carefully evaluated their placement relative to potential disturbance from overlying layers (Table 1, Figures 3 and 5). We also highlight that two dates from discrete identified features in different areas of the excavation were sourced from Layer 7 (WkA-55308 from Square D7, oven F.277 and WkA-55309 from Square B4, oven F. 302). Of note, uncalibrated Layer 9 radiocarbon ages are “older” than dates from Layer 11 and Layers 8 to 4, even though Layer 9 is younger than Layer 11. This apparent inversion in age does not indicate disturbance but is caused by the wiggle in the calibration curve (Figure 6a and b). The four dates from Layer 2; eggshell samples WkA-43680 (667 ± 20 BP), WkA-43679 (584 ± 20 BP) and WkA-43678 (635 ± 20 BP), and charcoal sample WkA-55301 (671 ± 14 BP) are problematic (Figure 6), being both statistically distinguishable ($\chi 2$ 3:0.05 = 14.10<7.81) and three being contextually older than dates from Layers 4, 5, 6 and 7. Upward movement is consistent with other material finds at the site, but additional dates would be required to determine the age of Layer 2. The limited availability of samples from secure contexts led us to exclude the Layer 2 dates from further analysis.



Generalised Stratigraphy

Layer 1: Clean sand.

Layer 2: charcoal- blackened sand rich in cultural material.

Layer 3: Clean sand.

Layer 4: Shell midden lenses and blackened sand within large oven.

Layer 5: Black sand layer with ovens indicating repeated use.

Layer 6 upper: Rich in cultural material.

Layer 6 lower: Comparatively sterile.

Layer 7: Charcoal darkened sand rich in cultural material.

Layer 8: Clean yellow sand. Four oven scoops and minimal cultural material.

Layer 9: Charcoal-stained sand.

Layer 10: Clean yellow sand with minimal evidence of cultural deposits.

Layer 11: Lowest cultural material and a few cooking pits.

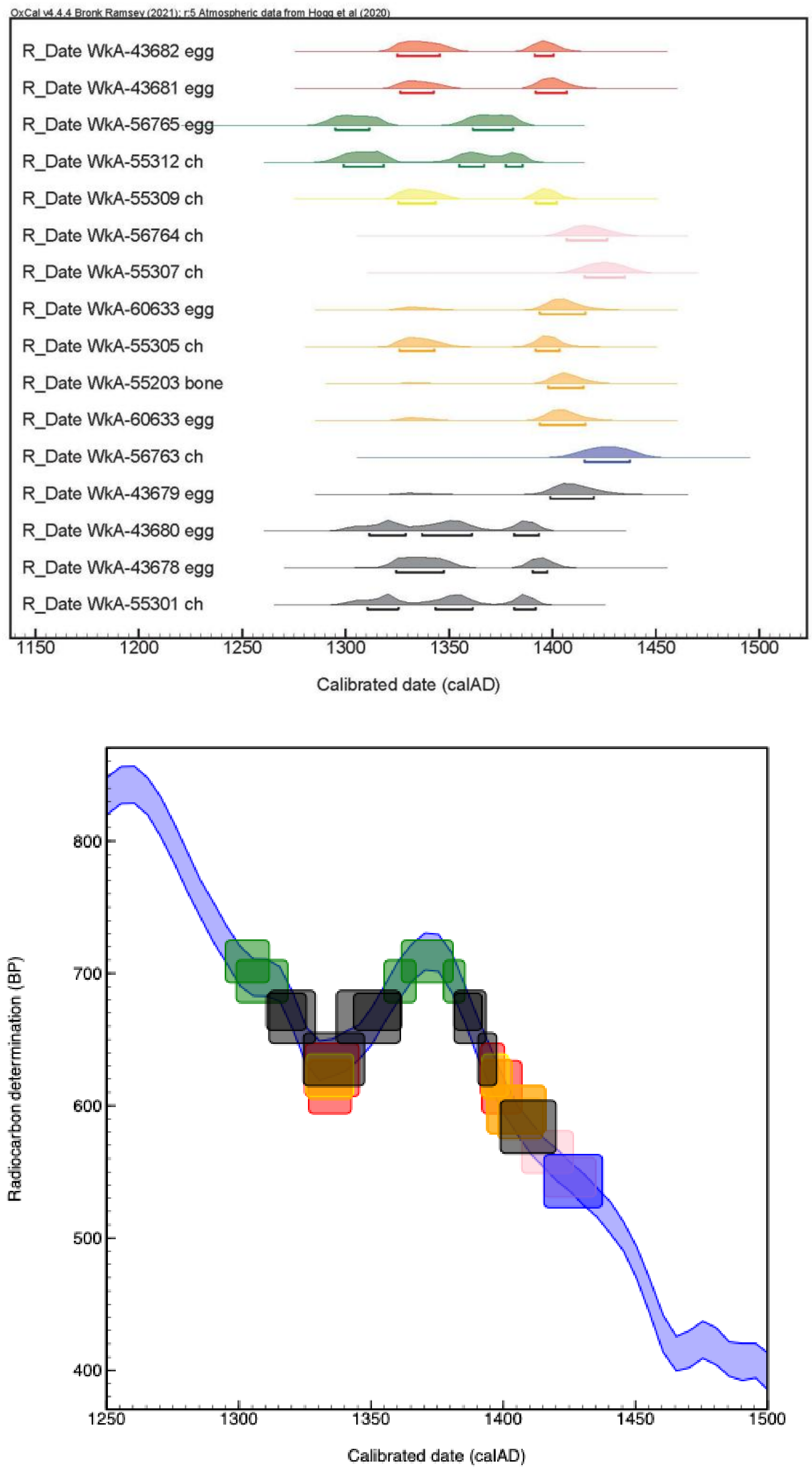
Layer 12: Sterile yellow dune-sand.

Figure 5: SM/C:Dune stratigraphic profile of the east wall of Squares J1-J8. Brown layers indicate a hiatus in cultural activities (adapted from Anderson and Allingham 1996, 42, Figure 5.4a. Colourised with Gemini Feb 2006. Reproduced with permission). Stratigraphic information from Anderson and Allingham (1996, 39-50). Grey shading indicates non-cultural deposits.

Table 1. New radiocarbon dates from SM/C:Dune. Material and context information from Anderson, Allingham and Smith (1996).

Lab Number	CRA ± Error	Material / Element	Max Inbuilt Age#	Context	Comment
WkA-55301	671 ±14	Charcoal: *Coprosma* small dia.	< 30 years	Layer 2, Square E3	Corner of F.319, which cuts down to the base of Layer 6.
WkA-43678	635 ±20	Eggshell fragment (Moa)	—	Layer 2, Square E/F2 scoop; western end of baulk.	Near F.309 (cuts Layer 7), F.211 (cuts Layer 4), and F.319 (cuts Layer 8).
WkA-43680	667 ±20	Eggshell fragment (Moa)	—	Layer 2, Square D2, oven scoop feature.	Near F.309 that cuts down below Layer 8.
WkA-43679	584 ±20	Eggshell fragment (Moa)	—	Layer 2, Square F6	No intercutting between layers at this location.
WkA-56763	543 ±20	Charcoal: *Plagianthus* twig	< 5 years	Layer 4 upper: Square G6	Associated with F.227.
WkA-60633	597±18	Eggshell fragment (Moa)	—	Layer 5 upper, Square A6	Associated with F.311, which cuts down to Layers 9/11.
WkA-56203	590±15	Bone: *Hemiphaga novaeseelandiae* (Pigeon)	—	Layer 5, Square A6	Associated with F.311, which cuts down to Layers 9/11.
WkA-55305	620 ±15	Charcoal: *Veronica*	< 25 years	Layer 5 lower, Square I7	Associated with F.231 (mixing in Layer 4/5 ovens?). Ovens cut down to Layer 11.
WkA-55307	546 ±15	Charcoal: *Olearia* small dia.	< 25 years	Layer 6, Square H4	Possibly F.324 (may be introduced from Layer 4/5 ovens).
WkA-56764	565 ±16	Charcoal: *Coprosma* small dia.	< 30 years	Layer 6, Square F4	Possibly associated with F.324 or F.199.
WkA-55308	645 ± 16	Charcoal: *Coprosma* small dia. <1cm	< 30 years	Layer 7, Square D7, Sample 31	Possibly associated with oven F.277
WkA-55309	623 ±16	Charcoal: *Myrsine* small dia.	< 30 years	Layer 7, Square B4	From oven F.302.
WkA-55312	694 ±16	Charcoal: *Coprosma* small dia.	< 30 years	Layer 9, Square D5, Sample 54	From oven F.334.
WkA-56765	709 ±16	Eggshell fragment (Moa)	—	Layer 9, Square F/6-7	Possibly associated with oven F.346.
WkA-43681	614 ±20	Eggshell fragment (Moa)	—	Layer 11, Square G3/4	From oven F.347.
WkA-43682	627 ±20	Eggshell fragment (Moa)	—	Layer 11, Square H3/4	Possibly associated with oven F.347.

A "twig" or "stem" is where part of the outside surface is preserved, the curvature of which allows an estimation of the original size. When the outside surface is not present, but the medullary rays converge towards what would have been the pith of the stem, the sample is described as "small diameter". These small-diameter samples may have come from the oldest part of a larger-diameter limb.



a)

b)

Figure 6: (a) OxCal plot showing the 68.3% probability distributions for the new high-precision terrestrial ^{14}C data from SM/C:Dune (no model applied). (b) Schematic showing dates plotted against the calibration curve (68.3% prob.) (no model applied). Red = Layer 11, Green = Layer 9, Grey = Layer 8, Yellow = Layer 7, Pink = Layer 6, Orange = Layer 5, Blue = Layer 4, Black = Layer 2.

4.2. The Bayesian model

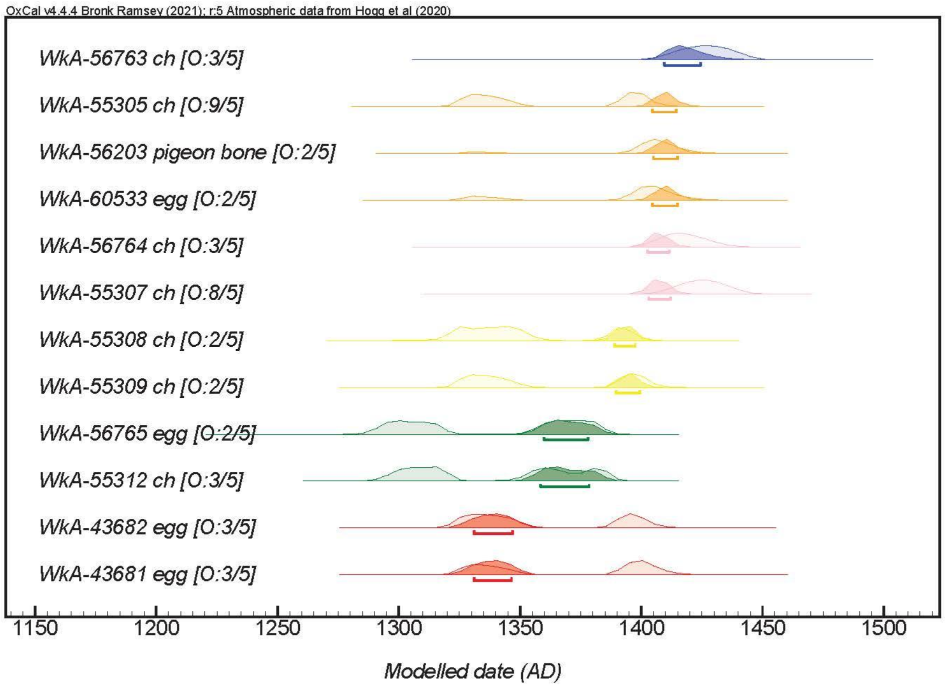
Layers 3, 8, and 10 contained minimal cultural evidence and, in our model, are treated as activity gaps, with no prior assumption about their length. A General t-type Outlier Model ("General",T(5), U(0,4), "t") was assigned to all dates with a prior outlier probability of 0.05 (c.f., Bronk Ramsey 2009b). This specific outlier code works best where context disturbance is responsible for any offsets and will also counter any minor inbuilt age in the charcoal samples (Supplementary Information 2, Table 1).

By Layer 5, issues with the model start to appear. WkA-55305 is a minor outlier (9%), returning a result that is slightly too old for the context, while WkA-55307 from Layer 6 is too young (minor outlier = 8%). The overall agreement indices for the model are also poor (A_{model}=38.4; $A_{overall}$=46.0), though the convergence values are >95%, suggesting a reasonable solution has been found. Visually, we can see that the Layer 5 date (WkA-55305) is offset from the curve (Figure 7b) and could be residual material from earlier layers (i.e., oven F.362 at the base of Layer 11 in the same location) or reflect the upper estimate of 25 years of inbuilt age for this sample (i.e., a t-type outlier following Bronk Ramsey 2009) (Figures 4 and 5, Table S3). Removing both WkA-55307 and WkA-55305 improves the agreement indices (A_{model}=93.7; $A_{overall}$=97.3), but Layers 5 and 6 remain visually inverted; the complexity of lensing observed in the section drawing (Figure 5) may have led to an incorrect layer attribution during excavation. Regardless, removing these two dates doesn't alter the conclusion that activity in the high dune area occurred between AD 1320 and 1440.

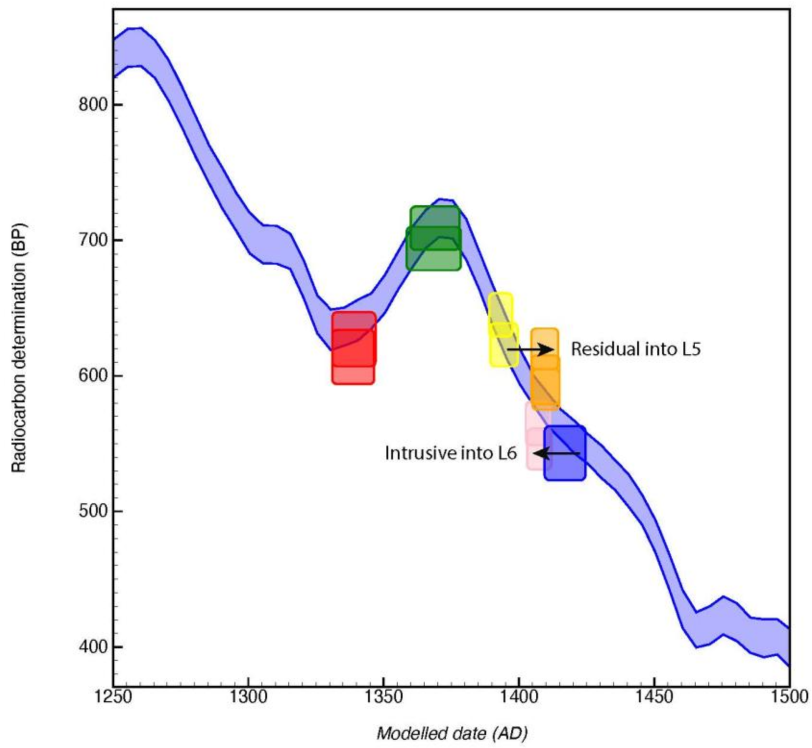
As we inspect ^{14}C results for older layers, the value of dating all layers becomes obvious. When constrained by Layers 11 and 7 (Figure 7a), the most likely age for Layer 9 is between AD 1350 and 1390, at the peak of the calibration wiggle (Figure 7b). Layer 7 dates to between AD 1380 and 1410, following a hiatus represented by the Layer 8 sand. We can further query the model to assess the possibility of distinct periods of activity at the site using the OxCal "difference" command, which assesses the overlap between probability ranges (c.f., Bronk Ramsey 2009a). The calculated difference between the end of Layer 11 and the start of Layer 9 ranges from 2 to 25 years (68.3% probability; unrounded). Because the result does not cross zero, a hiatus in deposition is a possible explanation for the Layer 10 sand. Similarly, the difference between the end of Layer 9 and the start of Layer 7 ranges from 1 to 21 years, supporting the idea that the Layer 8 sand represents a period of partial abandonment of the high dune. Layers 6, 5, and 4 cannot be separated in time and likely represent near-continuous activity between AD 1400 and 1440 at the resolution presented here.

Our new chronology also provides a temporal measure of change in economic activity and material culture. The last period of near-continuous activity, spanning Layer 5 to Layer 4, dates to between AD 1400 and 1440 and was centred on a large oven, starting in Layer 5, with an economy focused on shellfish, fish, dogs, and open-country birds. The lower layers (11, 9, and 7) date to between AD 1320 and 1410, when activity focused primarily on moa and seal butchery and cooking. Layer 6 cannot be temporally separated from the late activity but had a high proportion of moa and seal remains and lower proportions of shellfish.

The Bayesian model indicates this economic shift took place over nearly a century. This longer chronology allows for the gradual evolution of material culture and resolves a long-standing paradox where Anderson and Smith (1996, 281-2) noted that artefacts considered typical of the early East Polynesian phase and those belonging to an "intermediate" period were found at the same supposed short-term site. The extended chronology also implies that key "Transitional" features were emerging by the early 15th century AD, and that a persistent, but not continuous, human presence was evident on the high dune between AD 1320 and 1410. This new chronology for SM/C:Dune provides a basis for reassessing what we know of this early period.



a)



b)

Figure 7: (a) Bayesian sequence model showing 68.3% probability distributions of the new high-precision terrestrial ^{14}C data from SM/C:Dune. Darker distributions represent ages after applying model constraints. The notation [e.g. O:2/5] indicates a 2% posterior probability of being an outlier in the model. Values >5 may be problematic (Bronk-Ramsey 2009b). (b) Schematic showing new dates plotted against the calibration curve following the Bayesian age model for SM/C:Dune. Red = Layer 11, Green = Layer 9, Grey = Layer 8, Yellow = Layer 7, Pink = Layer 6, Orange = Layer 5, Blue = Layer 4. Layer 5 material (residual arrows) is redeposited from earlier deposits. Layer 6 material indicated by the intrusive arrow is from later deposits (cf., Bronk Ramsey *et al.* 2010).

Table 2. Modelled Chronology: SM/C:Dune

Stratigraphic Level	Modelled Start Date (68% Prob.)	Modelled End Date (68% Prob.)	Archaeological Content
Site Occupation	AD 1320 – 1350	AD 1410 – 1440	SM/C:Dune settlement
Span	70 – 110 years		
Layer 11	AD 1320 – 1350	AD 1330 – 1360	Primary moa and seal butchery
Interval Layer 9/11 (Layer 10)	0 – 30 years		
Layer 9	AD 1350 – 1380	AD 1360 – 1390	Primary moa and seal butchery
Interval Layer 7/9 (Layer 8)	0 – 20 years		
Layer 7	AD 1380 – 1400	AD 1390 – 1410	Primary moa and seal butchery
Interval Layer 6/7 (Layer 6 lower)	0 – 10 years		
Layer 6 upper	AD 1390 – 1410	AD 1400 – 1420	Primary moa and seal butchery
Layer 5	AD 1400 – 1420	AD 1400 – 1420	Mixed economy (big game and fish)
Layer 4	AD 1400 – 1420	AD 1410 – 1440	Specialised fishing processing. Fewer large animal remains.
Layer 2	Excluded	Excluded	Dropped from the model due to disturbance

4.3. Implications

These results significantly refine previous conclusions about the age and nature of occupation at SM/C:Dune. Previously thought to have been occupied for between 20 and 50 years in the 14th century AD, our new model now indicates activity at the site lasted at least 70 years (span = 70 – 110 years at 68.3% prob.). Moreover, these new results support discrete phases of activity, starting ca. AD 1320, with each phase separated by sand layers (Layers 10, 8 and 6 lower). Unlike the previous chronological assessment, we can confirm that these gaps are short but likely represent several years' worth of sand accumulation rather than a single season of windblown sand or a storm event. Because our date sequence comes from a small section of a poorly dated archaeological landscape, more work is required to ascertain whether the site was left for short periods or whether activities simply shifted off the high dune. Layer 9, previously undated and assumed to be temporally indistinguishable, is now dated to between AD 1350 and 1390 and is confirmed as a distinct phase of activity.

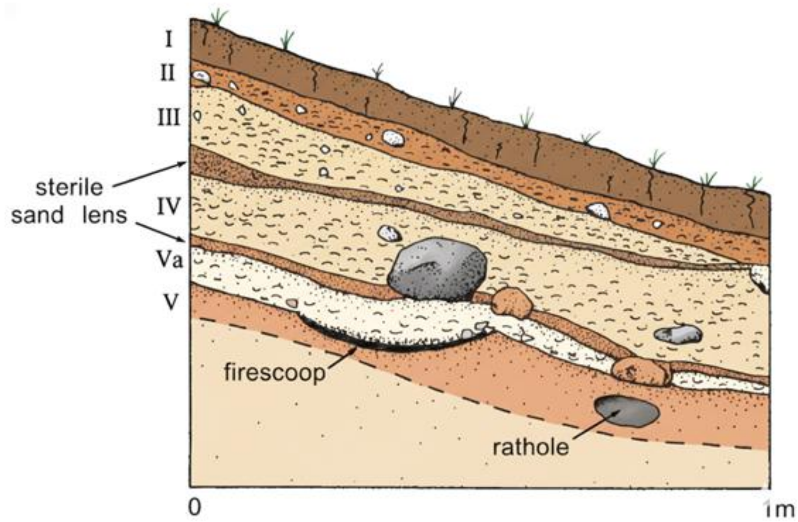
5. The AD 1480–1640 plateau and impact on the Kokohuia (O06/317) chronology

Excavations at Kokohuia on the southern shore of the Hokianga Harbour revealed a possible house and associated areas for food storage, cooking, food preparation, and midden dumping on the slope of a ridge (Taylor 1993). The age of the archaeological evidence was initially based on a pipi shell (Wk-1086; 880 ± 50 BP)[2] from Layer IV of the Area 3 midden (Taylor 1993, 26), while a separate excavation 60 m to the northeast (NZAA 2026) returned a similar age (Wk-2564 [cockle]; 790 ± 60 BP), the relationship between the two locations hasn't been established. The Area 3 midden had four cultural layers (II, III, IV, and Va) overlying a natural sand layer (Layer V). Thin deposits of yellow sand were observed on the surfaces of IV and Va, and pitting in Layer IV, suggesting exposure for a short period – perhaps only a few years (Taylor 1993, 19) (Figure 8). Taylor (1993, 27-28) concluded, based on fishhook and adze technology, the diversity of food, fragmentary pieces of moa bone, and the single radiocarbon date, that the site was occupied at the end of the "Archaic" period with the lower midden layer dating to the late fourteenth or early fifteenth century AD.

Thirty-seven additional ^{14}C dates (18 charcoal) were obtained by Schmidt (1996a) from a small excavation unit in Area 3 (the "lower midden"; Squares I-J/11-12) with bulk samples (shell and charcoal) taken from each layer specifically to assess changes in the marine ^{14}C reservoir (Supplementary Table 2). The results suggested occupation began in the late 15th century and continued until the mid-17th century AD. Critically, Schmidt (1996a, 122), following Wilson and Ward's (1981) method for identifying temporal breaks, suggested a break in occupation between Layers IV and III, with Layers II and III being contemporary (Figure 8). This differed from Taylor's (1993) view that the midden was deposited over a short period. Subsequent analysis of fish bone remains by Leach et al. (1997, 107) indicated that the "later" Layer II and III and "earlier" Layers V, Va, and IV assemblages were very similar – "more so than any other pair of assemblages we have studied in New Zealand before," suggesting either consistency in fishing practice over time or problems with the ^{14}C chronology. The chronology received further attention when Higham *et al.* (2004)[3] applied Bayesian sequence analysis to the extant chronology, broadly confirming Schmidt's (1996a) calendar age range (AD 1420 – 1670 [95% prob.]), with an occupation span of 121 to 230 years.

[2] Taylor (1993:26) reports this as 550 ± 50 BP. Although no information is provided as to the calibration of this sample in the report, this is likely to be a calendar age converted with the available calibration curve at that time.

[3] Several *Rattus exulans* bone dates originally returned ages spanning 1200 years because of contamination introduced during the ultrafiltration of bone gelatin. Redating without ultrafiltration produced age estimates considered to be consistent with the other radiocarbon dates from Kokohuia, except for one sample that was older than expected (OxA-12629; 495 ± 27 BP) possibly due to a mixed terrestrial and marine diet (Higham *et al.* 2004:142-144). Variability introduced by different ^{14}C pretreatments, especially for small (mg) samples, has complicated the evaluation of dietary offsets and sample type reliability and remains an unresolved variable in some chronologies.



Generalised Stratigraphy

Layer I: Black, sandy topsoil.

Layer II: Black sand with dense shell, charcoal and fire cracked rock.

Sterile lens

Layer III: Brown sandy soil with thick shell, stone, and charcoal.

Layer IV: Dense clean shell. Limited yellow/black sandy matrix.

Sterile lens

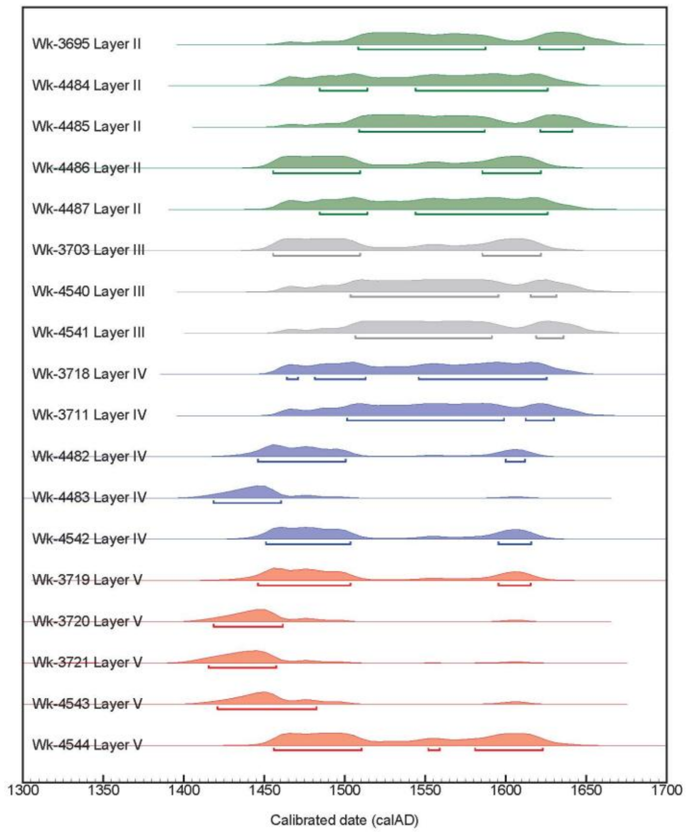
Layer Va: Midden and remains of intercutting fires in yellow sand.

Layer V: Orange/brown weathered sand.

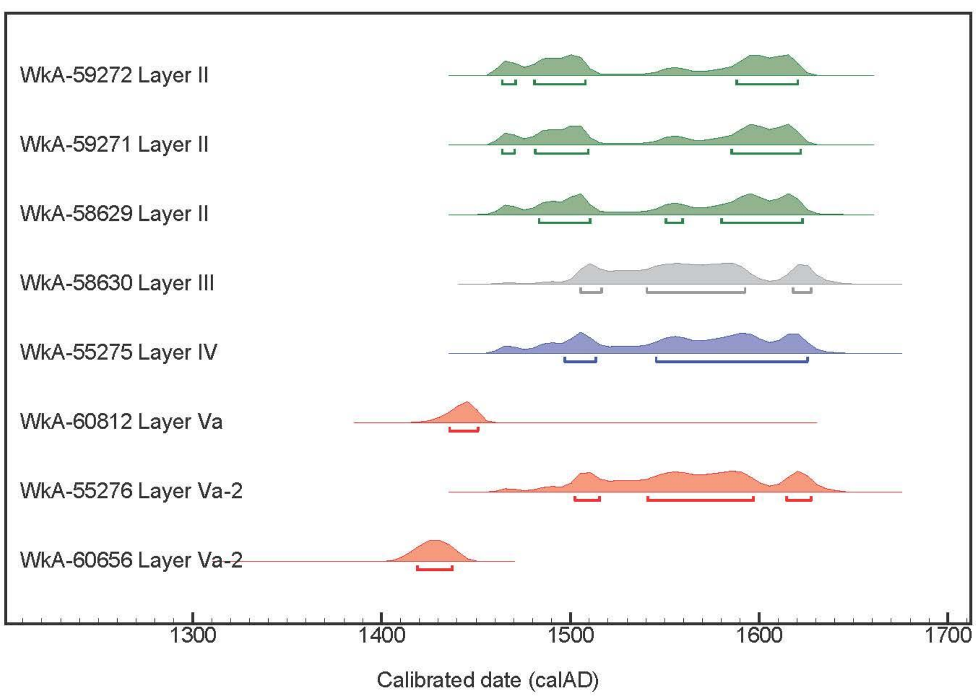
Figure 8: Cross-section, South elevation of Square Il2, "lower midden" (from Leach et al. 1997. Reproduced with permission). Generalised stratigraphy from Taylor 1993, 13-16). Colourised with Gemini Feb 2026.

Overall, the chronological resolution for Kokohuia is poor, spanning the mid-15th to late 17th centuries AD. Within this time frame, researchers either favour a short occupation, primarily based on the available archaeological information (Taylor [1993] and Leach et al. [1997]) or a longer use of the site based on the calendar spread in radiocarbon ages (Schmidt [1996a] and Higham *et al.* [2004]), which implies significant hiatuses between layers. These two pictures of site use are incompatible. Part of the problem with determining the age and duration is that Kokohuia dates to the calibration plateau between AD 1480 and 1640. Under such circumstances, precision, sample integrity and deposit sequence are critical.

We obtained new ^{14}C samples from stored bags of bulk midden from all four cultural layers (II, III, IV, and Va), in squares J11, I12 and H11 of Area 3 (Table 3). The new dates from Layers II to IV are statistically indistinguishable ($\chi^2_{4:0.05} = 2.33 < 9.49$) and could easily be interpreted as representing a single short occupation. However, two dates on single seeds from Layer Va, bulk midden, confirm earlier activity. Although a large number of charred seeds were recovered during the sorting of the midden (Taylor 1993:19), no specific contextual source for these seeds was noted.

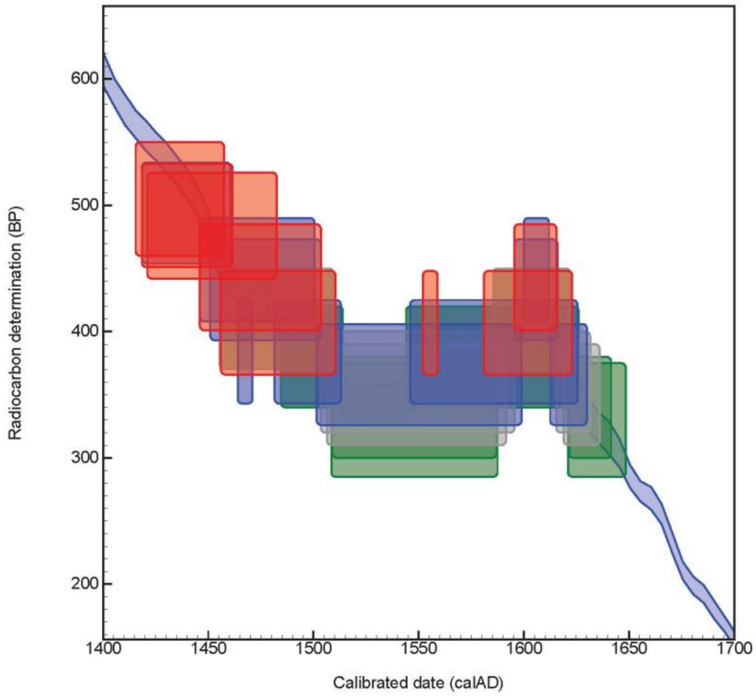


a)

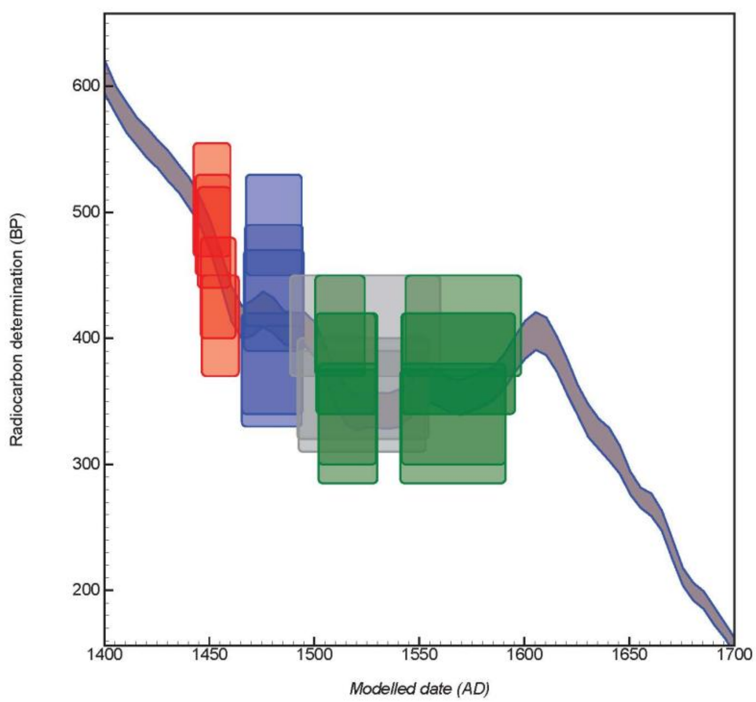


b)

Figure 9: OxCal plots showing 68.3% probability distributions of the legacy terrestrial ^{14}C data from Kokohuia, Area 3 (no model applied). Red = Layer V and Va, Blue = Layer IV, Grey = Layer III, Green = Layer II. (a) Legacy dates. (b) New dates.



a)



b)

Figure 10: (a) Schematic showing legacy dates plotted against the calibration curve (68.3% prob). A. No model constraints. (b) After applying model constraints. Red = Layer V and Va, Blue = Layer IV, Grey = Layer III, Green = Layer II.

Table 3. New radiocarbon dates from Kokohuia, Area 3 "lower midden"

Lab Number	CRA ± Error	Material / Element	Max Inbuilt Age#	Context*	Comment
WkA-58629	386 ± 16	Charcoal: *Coprosma* sp.**	< 40 years	Layer II, Sq. H11 (S297, 335, 336)	Chi-square test confirms consistency $\chi^2_{2:0.05}$ = 0.09<5.99, μ = 390 ± 11
WkA-59272	393 ± 17	Charcoal: *Veronica* (2mm dia. twig)	2–3 years	Layer II-1, Sq. J11W (S88)	
WkA-59271	390 ± 16	Charcoal: *Veronica* (2mm dia. twig)	2–3 years	Layer II-2, Sq. J11W (S118)	
WkA-58630	362 ± 16	Charcoal: *Veronica*	< 25 years	Layer III, Sq. H11 (S304, 309, 338)	
WkA-55275	372 ± 19	Charcoal: *Plagianthus* (3mm stem)	< 5 years	Layer IV, Sq. H11 (S318, 341)	
WkA-60812	502 ± 17	*Alectryon excelsus* (Titoki) seed (?), charred	1 year	Layer Va-1, Sq. I12 N+W (S230, 232, 233)	
WkA-55276	368 ± 19	Charcoal: *Plagianthus* (3mm stem)	< 5 years	Layer Va-2, Sq. I12 (S263, S264)	Outlier
WkA-60656	540 ± 15	*Elaeocarpus dentatus* (Hīnau) seed, charred	1 year	Layer Va-2, Sq. I12 (S263, 264)	same bag as above

* -1 and -2 indicate ~5-10 cm spits.
** *Coprosma* charcoal may have ~15–40 years inbuilt age for a branch (~15 mm diameter).
\# See footnote to Table 1 for definitions of "twig" and "small diameter."

5.1. The Bayesian model

The new chronology now relies on dates on single seeds, twigs and short-lived charcoal (Table 3). This has been built into a Bayesian sequence that uses information from field observations (Figures 11a and b; model code is given in Supplementary File 2). In this model, only one sample is a major outlier (WkA-55276; 25%) and is of a similar age to the Layer IV results, so it is likely intrusive. Also of note, Layer II results yielded slightly older ^{14}C ages than those from Layers III and IV and, when bounded by the results for Layers IV and III, sit over the ~AD 1600 rise in the calibration curve (i.e., an age inversion), anchoring the Layer II deposit to this wiggle. This new chronology (excluding WkA-55276) places the start of occupation of the site at AD 1410 – 1440 (68.3% prob.; AD 1370 – 1450 at 95.4% prob.) and suggests the site was occupied for between 160 and 220 years (68.3%; 60 – 260 years at 95.4% prob.) ending AD 1590 – 1630 (68.3% prob.; AD 1490 –1660 at 95.4% prob.) (Table 4).

This, at first glance, does not appear to be an improvement on the previous Bayesian evaluation by Higham *et al.* (2004; AD 1420 – 1670 [95% prob.]). However, higher-precision AMS dates now allow us to statistically evaluate the possibility of distinct periods of activity at the site using the OxCal difference command to test whether the sand lenses separating the layers represent significant time intervals. The calculated difference between the end of Layer IV and the start of Layer III (i.e., the upper sand) is between -2 and 35 years (at 68.3% probability; unrounded). Here, a distribution that includes zero supports continuous deposition (i.e., Layer III may have started 2 years before Layer IV ended). In contrast, the difference between the end of Layer Va and the start of Layer IV (the lower sand) ranges from 3 to 56 years; by excluding 0, a hiatus is suggested. These findings are at the limits of our model precision and, in the context of New Zealand archaeology, a difference of between 3 and 56 years is still low-resolution, but the most logical conclusion given the calibration curve wiggles is that the midden deposit of Layer IV occurred decades after the initial activity at the site and that Layers IV – II were deposited closer in time.

One consequence of a ^{14}C plateau is that any early dates that do not intersect with the plateau will preferentially anchor the chronology at the earlier end of the calibration curve when sequence models are constructed (Figures 10 and 11). Previously, lower-precision legacy dates from Layer Va tied the chronology to the beginning of the plateau and pulled later dates from Layer II towards the earlier section of the calibration curve (Figure 10b). New high-precision dates also support pre-plateau activity, but there is now evidence that Layer II dates to AD 1600 (see discussion above). By removing the Layer Va dates, we can override the strong preference the model has for the steep calibration slope of the earlier time period, and the model now supports the deposition of midden Layers IV – II between AD 1490 and 1630 (68.3% prob.) with a span of 0 – 90 years (68.3%).

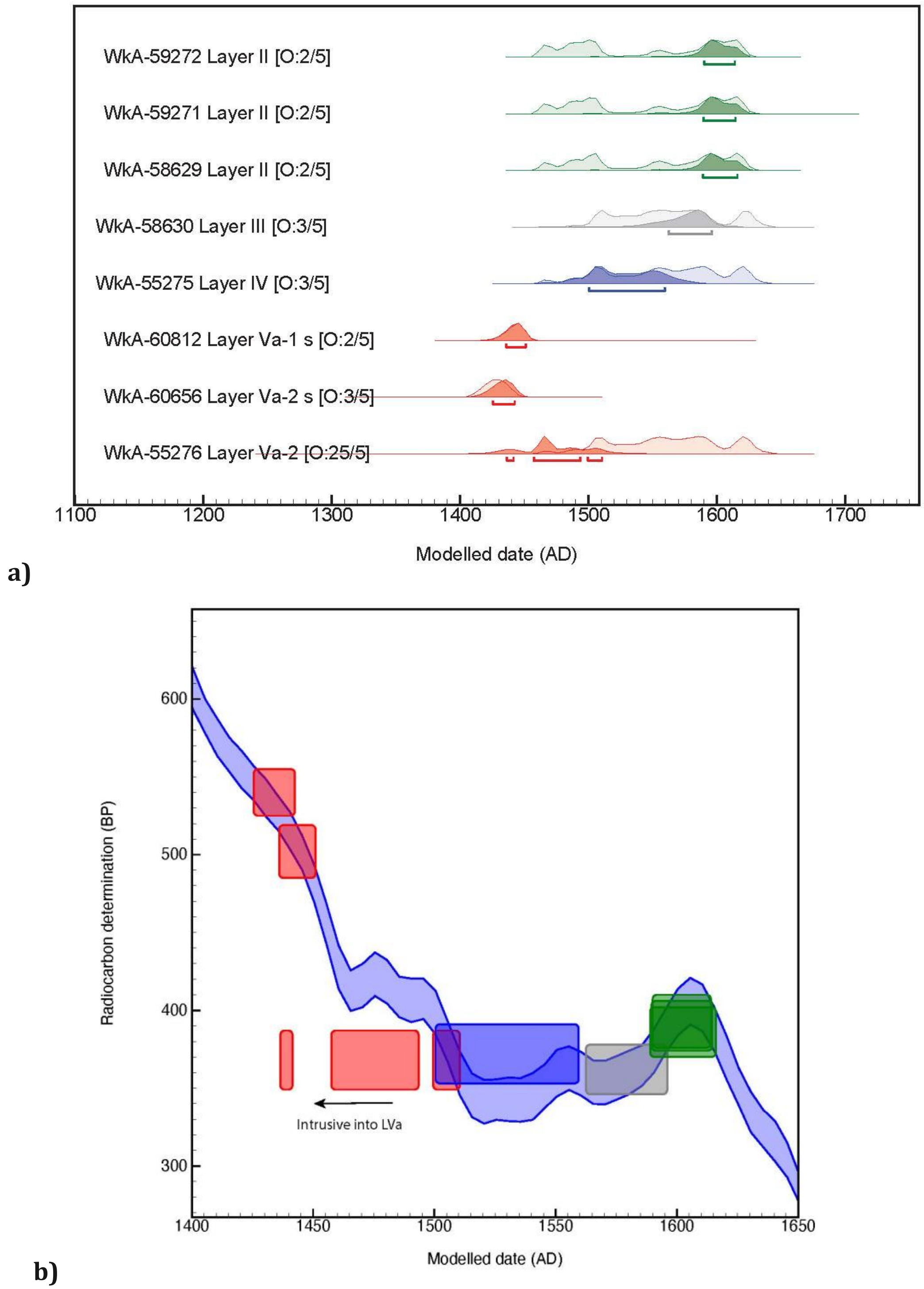


Figure 11: (a) Bayesian analysis of radiocarbon dates from the lower midden. Darker distributions represent ages after applying model constraints. The notation [e.g. O:2/5] indicates a 2% posterior probability of being an outlier in the model. Values >5 may be problematic (Bronk-Ramsey 2009b). (b) Schematic showing new dates plotted against the calibration curve (68.3% probability). Red = Layer V and Va (oldest), Blue = Layer IV, Grey = Layer III, Green = Layer II (youngest).

Table 4. Modelled Chronology: Kokohuia, Area 3

Stratigraphic Level	Modelled Start Date (68% Prob.)	Modelled End Date (68% Prob.)	Archaeological Content
Site Occupation	AD 1410 – 1440	AD 1590 – 1630	Kokohuia occupation
Span Kokohuia	160 – 220 years		
Layer Va	AD 1410 – 1440	AD 1430 – 1460	Unidentified early activity represented by seeds/fire scoops
Interval Layer IV/V	0 – 60 years		
Layer IV	AD 1450 – 1520	AD 1500 – 1570	Shell and fishbone midden
Interval Layer III/IV	0 – 40 years		
Layer III	AD 1530 – 1590	AD 1570 – 1610	Shell and fishbone midden
Layer II	AD 1570 – 1610	AD 1590 – 1630	Shell and fishbone midden
Span midden (Layers IV -II)	0 – 90 years		

5.2. Implications

While the new Kokohuia chronology still falls within the broader parameters of the 15th to mid-17th century AD chronology of Higham *et al.* (2004) and Schmidt (1996a), we argue that the deposition of the shell midden, represented by Layers IV – II, began no earlier than the late 15th century AD and was deposited over a period of less than 90 years. While almost certainly longer than the actual period of midden dumping, this aligns better with the available archaeological evidence reported by Leach et al. (1997) that suggested little change in fish catches between the layers. Similarly, the fishhook assemblage is dominated by shell 2-piece hooks (Layer II [n=1], Layer III [n=2], Layer IV [n=18] and Layer Va [n=9]), most of which were found during sieving or subsequent midden analysis. There is one one-piece hook, one trolling lure shank fashioned from pāua, and a fragment from a bone lure (possibly whale), but overall, there is no stylistic change in hook shank line lashings through the layers, suggesting little time depth to the deposits. Moreover, our new midden chronology fits more closely with other sites in Northland/Coromandel where two-piece shell hooks are not common in the earliest contexts (e.g., Houhora [Furey 2002], Hot Water Beach [Leahy 1974], Cross Creek [Sewell 1984], Cabana Lodge [Gumbley 2014]) or in controlled excavations further afield (e.g., Long Bay had shell hooks from layers dating mid-AD 1400s onwards [Campbell *et al.* 2019]).

There is, however, evidence of activity approximately 60 years earlier than the main midden deposition, represented by charred seeds at the base of Layer Va. Unfortunately, no features were directly dated, though a series of overlapping fires of limited distribution were noted in Layer Va (Taylor 1993:16). Given that all dates come from broad layers, sometimes split into 5cm spits, earlier and later material is almost certainly mixed in the lower deposits. This early activity is the likely source of a Duff-type 2A style adze, as mentioned by Taylor (1993, 24), found in Layer "V", Square D10E (note that there are no figures to support the adze identification, and it is possible that the adzes were refurbished and reused [cf. Turner 2000]). Small fragments of moa bone from the lower levels of the midden may also originate from this time, but there is no clear evidence of the fragments being used in tool manufacture or having been a constituent of the diet. These finds would be consistent with an early 15th-century date for Layer Va.

We were lucky with Kokohuia. Many archaeological midden sites are interpreted as short, one-phase deposits with no discernible vertical stratigraphy, hiatuses, or noticeable changes in material culture, and interpretation often relies on regional scale observations and site function. Such sites are difficult to date reliably when they intersect a calibration plateau. Solutions have been found by anchoring the model's start or end date to a steep section of the calibration curve. Manning *et al.* (2020), for instance, wiggle-matched longer-lived timber from a single-phase Late Woodland Northeast site to a steep section of the calibration curve. Where such materials are unavailable, ethnohistoric and archaeological evidence on the duration of site use can constrain the model (cf. Manning *et al.* 2020). Such techniques hold promise for New Zealand archaeology but require prior understanding of these methodologies during excavation and sampling accordingly for radiocarbon analysis.

6. Discussion

This study serves as a proof of concept that East Polynesian settlement and Transitional periods of New Zealand's prehistory possess significant temporal structure that can add to our understanding of past lives. It is widely accepted that Bayesian sequence analysis can produce accurate, testable chronologies, often to within the span of a human lifetime (cf., Bayliss 2009, 141-142) and even the AD 1480–1640 calibration plateau, while still a formidable obstacle, is not insurmountable (Manning *et al.* 2020; Meadows *et al.*2020). Our results indicate that this goal is achievable for archaeological sites in our region.

However, the application of these methodologies has been inconsistent. There are only a handful of New Zealand archaeological sites with rigorous Bayesian chronologies, and more often than not, the number of radiocarbon dates per site is too few to help resolve some of the most pressing questions about early Māori economic shifts (see Bickler and Petchey [2024]), settlement patterns, or adaptation to environmental changes (Bunbury *et al.* 2022, Tomlinson *et al.* 2024). Moreover, basic principles of dating and calibration are misunderstood, oversimplified (e.g., top-and-tailing whereby only the youngest and oldest deposits are dated), or stratigraphic changes are insufficiently dated. The taphonomy of many coastal sites – often characterised by deflated or mixed deposits in dunes and high-tide zones – is partly responsible for this issue, with researchers assuming that ^{14}C cannot achieve resolution within 100 years and therefore justifying minimal dating. However, at both sites reported here, the middens were more complex than originally thought, and were revisited many times over many years, even decades.

While the cost of radiocarbon dating relative to archaeological research funding is often considered prohibitive, producing low-precision chronologies has been much more costly in the long run. As Anderson (2022) notes, there may be no alternative but to re-sample legacy sites to uncover the temporal complexity required to engage with traditional Māori oral histories. Moreover, our unusually brief prehistory of 500 years is unforgiving and demands best practices when using ^{14}C (cf. Baylis *et al.* 2015). The chronologies of SM/C:Dune and Area 3 at Kokohuia used 12 and 8 dates, respectively, a number elevated because of missing records and limited available samples from secure contexts.

The impact of the calibration curve on date interpretation has broader theoretical implications than just low-precision site chronologies; it has also shaped our understanding of cultural change. Samples dating to the end of the early East Polynesian settlement period intersect the calibration curve at points of rapid ^{14}C change (~AD 1450), creating a false hard boundary between the early and subsequent "Transitional" periods. Conversely, slightly earlier, the dates intersect multiple sections of the curve, where unordered radiocarbon ages can point to several different calendar years. It comes as no surprise, therefore, that activity prior to AD 1450 has been lumped into a broad 14th-century settlement phase. After AD 1450, calibrated ^{14}C dates intersect the AD 1480 – 1640 plateau, obscuring any transition to Classic Māori. Archaeologists have bridged this gap by relying on artefacts considered transitional in style, a methodology that Manning (2020, 1787) critiqued as "untestable stepwise logic transfer", where interpretation can be skewed by the retention of artefacts and economic practices. Moreover, as indicated at SM/C:Dune, cultural and economic changes were already underway before AD 1450, as people adapted to the challenges they faced, making some orthodox ideas about artefact and economic change problematic. Clearly, without more detailed chronological modelling, we are missing the temporal complexity that would enable greater engagement with traditional histories and environmental records.

The problem is not solely the responsibility of archaeologists; it also requires advances in calibration science. Recent developments in Southern Hemisphere terrestrial calibration have identified minor variations that could affect interpretations of events dating to the beginning of the AD 1480 – 1640 plateau (see Hogg *et al.* 2019, Boswijk *et al.* 2025). However, just as importantly, we must develop our understanding of the marine ^{14}C reservoir. Over time, researchers have shifted toward a preference for charcoal over shell (e.g., Anderson 1991, 777; Leach *et al.* 2022, 12, 24), which is unfortunate given that errors in shell dates are typically smaller than those from non-twig, shorter-lived charcoals. However, marine calibration research is decades behind research into the terrestrial atmosphere. This limits our ability to conduct high-resolution analyses of coastal sites or to evaluate economic changes involving marine animals or animals that incorporate carbon from both land and ocean. The regional marine reservoir is the subject of ongoing research by the authors, and reliable terrestrial chronologies, as developed here, are essential for comparison with and improvement of the marine ^{14}C record (Petchey and Schmid 2020).

This paper marks a significant step toward a high-definition archaeology of Aotearoa, New Zealand. It proves that the transition from East Polynesian to Classic Māori culture was a dynamic period of adaptation that can be tracked if – and only if – we apply the rigorous Bayesian methodologies required to navigate the atmospheric ^{14}C wiggles and plateaus of the past.

Supplementary Materials

The supporting information can be downloaded at https://doi.org/10.70460/jpa.v16i1.412

S1: Observations about legacy dates from SM/C:Dune and Kokohuia, Area 3 midden.

S2: Model OxCal codes for SM/C:Dune and Kokohuia, Area 3.

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Data Availability Statement

All calibrations and Bayesian analyses were undertaken with OxCal v.4.4 using the SHCal20 dataset; Available online: https://c14.arch.ox.ac.uk/oxcal/OxCal.html.

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Conflicts of Interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Author Contributions

Conceptualisation, F.P., A.A., L.F., G.O. and S.B.; methodology, F.P.; excavation and sample curation, A.A., M.S., P.S.; formal analysis, F.P., R.W.; writing—original draft preparation, F.P.; writing—review and editing, F.P., A.A., L.F., G.O., R,W. and S.B. All authors have read and agreed to the published version of the manuscript.

AI Disclosure Statement

During the preparation of this work, the author(s) used Google Gemini (Gemini 3 Flash variant) in order to create the 3D shaded relief map (Figure 2) and colourise Figures 5 and 8. Gemini also evaluated the possible Inbuilt age contribution for taxa if not a twig (see Supplementary Table 3). After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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