Vital evidence: Temporal shifts in the marine $^{14}$C reservoir around New Zealand (Aotearoa) over the last 750 years, and implications for Polynesian settlement

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ABSTRACT
Precise and accurate radiocarbon ($^{14}$C) chronologies are essential to achieve the tight chronological control needed for the ~750-year period since Polynesian settlement of New Zealand. Robust chronologies enable us to understand the drivers behind rapid archaeological and paleoenvironmental events, such as migration, colonisation(s), human impacts on the environment and climate (and vice versa), as well as changing material culture. For most of the Pacific sites, this goal has been elusive. While $^{14}$C datasets in this region typically consist of large numbers of marine and estuarine shell dates, this important set of chronological information is consistently ignored by those interpreting the timing of key events, ostensibly because of unknown regional $^{14}$C reservoir offsets, and/or errors introduced by upwelling, hardwater, intermixing of natural beach deposits and other environmental offsets. Many of these issues have been investigated over the last ten years at locations across the Pacific and can be mitigated, but we still lack a detailed regional calibration methodology for marine shell comparable to the highly precise Southern Hemisphere calibration curve. This gap has occurred because it has been assumed that a region-specific marine offset (ΔR), applied to the global marine calibration curve, will correct for regional and temporal variation respectively. In this paper, we present a temporal ΔR model for New Zealand based on paired estuarine/marine and terrestrial $^{14}$C dates from 52 archaeological contexts spanning the entire sequence since initial Polynesian settlement. Our dataset indicates that offsets equating to hundreds of years occur between the measured New Zealand data and the modelled global marine radiocarbon curve. These shifts are associated with climatic fluctuations during the late Holocene. Our application of a regional and temporal specific correction to archaeological shell dates will not only improve the accuracy of calibrated ages, but will also help improve the blurred chronology that has plagued archaeological theories about the colonization of New Zealand and other Pacific islands for decades.

KEYWORDS
Marine radiocarbon reservoir, Calibration curve, Polynesian settlement, Archaeology, Paleoenvironment

SIGNIFICANCE
Archaeological and paleoenvironmental chronologies related to the Polynesian settlement of New Zealand have predominantly relied on radiocarbon dates. Discrepancies between dates of marine and terrestrial materials have been hidden behind an imprecise calibration methodology for shells. Here we present, for the first time, evidence of temporal shifts in the marine radiocarbon reservoir which are associated with oceanographic fluctuation at the onset of the Little Ice Age ~AD 1350–1450 (650 -500 BP). These shifts reflect changes in ocean circulation that compliment information provided by terrestrial radiocarbon production. A combination of terrestrial and marine radiocarbon ages now promises more precise chronological control of archaeological sites than has hitherto been possible for Polynesian settlement of the South Pacific.

INTRODUCTION
The short prehistory of human occupation of New Zealand (NZ) has been vigorously debated for many decades. Recent research suggests that colonization started in the mid to late 13th century AD (Wilmshurst et al. 2008, 2010), but that sustained, widespread settlement was later (Jacomb et al. 2014, Holdaway et al. 2014), with an apparent strong archaeological (i.e. radiocarbon [$^{14}$C]) signal in the early 14th century thought to be evidence of a mass migration event (Walter et al. 2017). By the mid-15th century, moa (large flightless birds) had become extinct in the North Island with the last remnant populations soon dying out in the South Island (Holdaway and Jacomb 2000; Holdaway et al. 2014). During this time, settlement had expanded from sheltered coastal locations into inland regions and the extent and intensity of gardening increased (Barber 2004, Anderson 2016). By the end of the 15th century, fortified settlements (pā) began to be built across the landscape for reasons that are not yet clear (Schmidt 1996). These events most likely occurred at different rates in different places across NZ. Artefacts that document adaptation to new tasks, environments and materials often display regional variation, though many
forms eventually transformed into traditional Māori styles (Furey 2004, Walter et al. 2010). Despite thousands of published $^{14}$C dates, the middle, or transitional phase of Māori archaeology (~AD 1450 to AD 1650), has been described by Anderson (2016:2) as a “shadowland between highlights of Polynesian colonisation and classic Māori culture”. A lack of $^{14}$C precision over a “particularly wiggly portion of the radiocarbon calibration curve” commonly cited as the limiting factor (e.g., Walter et al. 2017:4).

Chronological control for NZ’s short prehistory has been plagued by uncertainty over the reliability of the different materials selected for $^{14}$C dating. Significant differences between charcoal, bone and marine shell were documented within a decade of the first reported $^{14}$C dates on a NZ archaeological site (Rafter et al. 1972). While bone and shell dates were initially considered to be more reliable than charcoal (Trotter and McCulloch 1984), the routine dating of ‘short-lived’ (single year) terrestrial materials provided a shorter chronology that was more reproducible (Anderson 1984, 1989). In his landmark study, Anderson (1991) excluded shell dates because of uncertainties associated with different taxa, estuarine contexts, dissolved ancient carbon (hardwater) and upwelling. The reliability of shell $^{14}$C dates was, however, backed up by research (e.g., Higham [1993], Schmidt [2000] and McKinnon [1999]) which attributed the majority of offset between terrestrial and marine $^{14}$C results to taphonomic factors such as post-depositional disturbance or inbuilt age in the associated wood charcoal. These projects secured the confidence of many archaeologists in the reliability of shell dates. Consequently, marine shell remains an important material for $^{14}$C dating in the Pacific because it is common in the archaeological sites and food taxa are easy to identify. In fact, recent counts (Nov 2019) indicate that 62% of the NZ archaeological materials dated at the Radiocarbon Dating laboratory, University of Waikato, are marine/estuarine shell. This equates to ~1800 shell dates for the NZ sequence.

However, in order to complement recent high-precision chronological terrestrial studies we need greater clarity about what $^{14}$C marine reservoir correction to use. The standard approach for the last ~30 years has used the modelled global surface marine curve (e.g., Marine13), determined from a box-diffusion model of global carbon exchange derived largely from $^{14}$C atmospheric data. This curve corrects for the approximate 400-year difference between terrestrial and marine $^{14}$C reservoirs. A local ‘reservoir offset’ (ΔR) is applied to the marine curve to account for regional variation (Stuiver, Pearson and Brazunas 1986). The ΔR for a specific location (‘s’) is calculated using the formula $R_{s}(t) - R_{g}(t) = \Delta R(s)$, where (AR(s)) is the difference between the global average ($R_{g}(t)$) and the actual $^{14}$C activity of the surface ocean at a particular location ($R_{s}(t)$; i.e., the archaeological marine date) at that particular time (based on the terrestrial $^{14}$C date or another independent means by which to determine age, such as U/Th dates). This methodology assumes that the calibration curve accounts for temporal variation.

Although some marine ΔR work has been carried out around the NZ coastline (e.g., McFadgen 1978, Rafter et al. 1972, McFadgen and Manning 1990, Higham and Hogg 1995, Petchey et al. 2008), it has predominantly been undertaken using “modern” (pre-AD 1950) shellfish of known collection date. Petchey et al. (2008) suggested some regional variation between the different outlying islands – Norfolk, Kermadec and Chatham Islands – because of the complex interplay of currents and water bodies (the Tasman Sea and the South Pacific Ocean). They settled on an average ΔR value of $-7 \pm 45$ $^{14}$C years for NZ as a whole, with little discernible variation around the main coastline, but identified a much higher and variable ΔR for the Chatham Islands caused by upwelling of $^{14}$C-depleted water along the Chatham Rise and Subtropical Front (which skirts the southeast coast of the South Island). The identification of temporal changes has been more difficult to evaluate because of low precision and numbers of archaeological $^{14}$C dates used, but the general consensus was that the regional ocean around NZ appears to have been stable over the recent past (McFadgen and Manning, 1990, Higham and Hogg 1995:415, Schmidt 2000).

This assumption of temporal stability in the marine reservoir offset is problematic. Recent $^{14}$C values of independently U/Th dated black coral $^{14}$C ages from Tasmania (Fig. 1a) (Komugabe-Dixon et al. 2016) indicate significant reservoir shifts. These shifts are also evident in archaeological ΔR from central South Pacific islands (Petchey 2019), and could potentially have major implications for archaeological chronologies that rely on marine and estuarine shell (Petchey and Kirch 2019), and it is likely that NZ waters are similarly affected, though this has not yet been quantified. In particular, the black coral data show a major positive ΔR shift, up to +150 $^{14}$C years, between ca. 400 - 200 years BP (AD 1550 - 1750) and a negative shift of up to -200 $^{14}$C years around 600 years BP (AD 1350). These ΔR offsets would introduce hundreds of years of error into shell $^{14}$C dates from NZ archaeological contexts, contributing to the blurring of calibrated shell results. A complex interplay of climate and oceanographic conditions are likely responsible for these shifts, which will almost certainly have had an impact on human adaptation to NZ, and may have in part been responsible for key economic changes evident in the material remains. Revisions to the global marine curve have been suggested which would incorporate regional calibration options – but these are based on refined climate models and not on measured data (Butzin et al. 2017) and still do not come close to the resolution of measured terrestrial curves such as SHCal13 (Hogg et al. 2013). Contained within the archaeological literature are a host of “paired” (i.e., from the same context) shell and charcoal $^{14}$C dates which can assist with this problem.

In this paper, we present a temporal ΔR model for NZ based on published archaeological paired estuarine/marine and terrestrial $^{14}$C dates spanning the entire sequence since initial Polynesian settlement. This
dataset is ten times larger than any previous assessment, and shows close agreement with black coral from Tasmania. Both datasets document significant changes in ΔR over the last 750 years which record changes in the ocean 14C reservoir associated with major climatic events.

RESULTS

We have identified 52 ΔR pairs calculated from marine/terrestrial samples recovered from contemporaneous deposits within 36 archaeological sites (Table S1). The majority of sites are located on the northwest coast of the North Island; the Coromandel and Auckland regions of NZ (Fig. 1b). There is an absence of material from the west coast of the South Island. Twelve contexts have a single terrestrial and single marine date, while twenty-five sites have a single terrestrial date for comparison with multiple marine dates. This limits assessment of deposit integrity, here determined by statistical agreement between terrestrial 14C dates. Thirteen sites contain multiple terrestrial and multiple marine dates - these provide the most robust evaluation and the ability to spot anomalies caused by taphonomic, environmental, taxa specific and/or laboratory variables (Table S2).

Black coral and archaeological ΔR values are shown in Fig. 2. Both sets of ΔR values follow the same trend, whereby the ΔR prior to 600 BP (AD 1350) is slightly negative, followed by an extreme negative shift around 600 BP and a subsequent gradual return to more positive values around 500 BP (AD 1450). This positive ΔR is very brief and quickly returns to moderately negative values which remains relatively stable over the next 150 years. Between 0 and 350 BP (AD 1600 and 1950), ΔR values are more positive. Using a combination of the black coral dataset, modern pre-AD 1950 shellfish, and the archaeological pairs, we recommend the following ΔR offsets between 0 and 750 cal BP:

1. Between 0 and 100 cal BP, we recommend the use of -7 ± 45 14C yrs derived from modern pre-AD 1950 shellfish (after Petchey et al. 2008).
2. Between 100 and 300 cal BP, we recommend the use of 46 ± 50 14C yrs – a combination of black coral and archaeological ΔR ($\chi^2_{27,0.00}=31.49<40.11$).
3. For the rest of the NZ sequence (i.e., 750-300 cal BP) we recommend using the archaeological ΔR given in Table 1 for each temporal block, i.e., 700-650 cal BP = -2 ± 42 14C yrs; 650-600 cal BP = -15 ± 24 14C yrs; 600-550 cal BP = -172 ± 92 14C yrs; 550-500 cal BP = 40 ± 39 14C yrs; 500-400 cal BP = -34 ± 65 14C yrs; 400-350 cal BP = -19 ± 40 14C yrs; and 350-300 cal BP = -26 ± 73 14C yrs.

Unfortunately, the black coral and archaeological datasets only hint at the complexity of the marine 14C environment. The U/Th dated black corals produce tightly controlled calendar ages, but there are relatively few values between 750 and 500 cal BP and none between 670 cal BP and 554. The terrestrial dates for each archaeological context have a wider spread in calendar age but enhance the extant coral data. They also provide
an insight into the potential additional variability, and may more closely represent the NZ situation than coral material from Tasmania. Additional research is required to map the temporal variability of this period.

**Fig. 2:** Temporal marine ΔR variation between 0 and 800 cal BP. Red diamonds = UTh/14C ages for Tasmania (Komugabe Dixson et al. 2016); error bars not shown. Black dots = median calibrated terrestrial age x ΔR value for each archaeological site (see Tables S1 and S2). Grey boxes = calibrated terrestrial age range for each site by ΔR error (given at 68.2% probability and calculated using http://calib.org/deltar/[Reimer and Reimer 2017]). Only archaeological sites with a median age >200 cal BP shown. Dashed lines show period of “Little Ice Age” transition (Goodwin et al. 2014). Age of the Kaharoa Tephra based on Hogg et al. (2002). Delta-R from Pleasant River Area D, Layer 4 is excluded (see Text S1).

Overall, these results indicate that structure is missing from the extant marine calibration curve. The most significant change occurs between 550 and 600 cal BP (AD 1350 and 1400). A major wiggle in the terrestrial calibration curve occurs at this time and the extreme negative ΔR reduces the difference between the terrestrial and marine curves to less than 100 years (see for example Fig. 3c). This has major implications for dating early context sites, potentially enabling greater refinement of site chronologies by contrasting calibrated results from terrestrial and marine dates. An example of this is given in Figure 3 where dates from Layer 9 of Cross Creek are calibrated using -7 ± 45 14C years (Fig. 3a), the average archaeological ΔR value for the period between 650 and 600 cal BP(Table S2, Fig. 3b), and a marine curve derived from the black coral data (Fig. 3c). These findings are of specific interest to a debate about the origins of a tephra sandwiched between layers 7 and 9. Furey et al. (2008) suggested this was the Kaharoa Tephra, an important chronostratigraphic marker, which has been precisely dated to 1314 ± 6 AD (1310-1320 AD 68% [Hogg et al., 2002]). Jacomb et al. (2014:29), however has described this association as “unconvincing” and considers the tephra to be redeposited. Rat gnawed seeds found within the Kaharoa Tephra at Te Rerenga in the Coromandel are a definitive indication that humans had made landfall in the North Island by this time (Wilmshurst and Higham 2004), so the inclusion of the ash between cultural layers cannot be dismissed outright. An analysis of radiocarbon dates from the site using the black coral ΔR values (Fig. 3c) results in an age for Layer 9 (AD 1241 - 1329 [95.4% prob.] that is equivalent to, and more likely older than the tephra (Text S1, S2). In the absence of a renewed dating program for Cross Creek, greater calendar age resolution for shell 14C dates through the development of a regionally specific marine calibration curve will be crucial to solving this and many other debates about the antiquity of many early sites (Text S1).
Fig. 3: Radiocarbon dates from Cross Creek Layer 9 grouped into a single phase. Red line represents the calendar age of the Kaharoa tephra (after Hogg et al. 2002). Dashed lines are the 68% prob. maximum age ranges of all three dates. A. Using the NZ regional marine ΔR of -7 ± 45 14C yrs (after Petchey et al. 2008). B. ΔR of -15 ± 24 14C years based on archaeological data collected in this paper. C. Age calibrated using the black coral dataset (“New Marine” calibration curve).

DISCUSSION
Komugabe-Dixson et al. (2016:977–978) attributed ΔR shifts along the Eastern Australian coastline to an increased influence of 14C-depleted water from equatorial waters, possibly caused by El Niño, Southern Oscillation (ENSO) variability. They attributed older waters (i.e., more positive ΔR values) around Tasmania to an increased influence of older sub-Antarctic waters, but did not discuss causes for the negative values observed in the black coral data that start around AD 1550 (400 BP). The extreme negative ΔR trend we have identified between 550 and 600 cal BP is an extension of this, and at its most negative broadly matches the date of transition from the Medieval Climate Anomaly (AD 700-1350; 1250-650 BP) to the Little Ice Age (AD 1350-1450; 650-500 BP) (Fig. 2). Using a range of proxy climate records from subtropical and extratropical sources, Goodwin et al. (2014:1212) argue that there is a “relatively abrupt shift” in mean climate state after AD 1300 resulting in winder, wetter and colder conditions across NZ (associated with a movement north of the westerly wind belt that circles Antarctica combined with El Niño conditions). Goodwin et al. (2014b:14719) suggest a brief period of finer weather 100 years later, which matches the positive ΔR in the archaeological data at the same time, rapidly followed by a return to wet, wild conditions. Moreover, according to Goodwin et al (2014b), El Niño-like conditions prevailed up to ~AD 1600 (350 BP). This observation is accompanied by more positive ΔR values. Komugabe-Dixson et al. (2016:978) suggest that weaker gyre circulation at this time may have resulted in a northward shift of cooler, older Sub-Antarctic waters from the Subtropical Front that skirts the southeastern coast of the South Island (Fig. 1). Unfortunately, the resolution of the archaeological data between AD 1950 and 1650 (0 and 300 BP) is limited because of the terrestrial calibration wiggles, and patterns cannot be fully assessed.

Conditions around NZ are the result of a complex interplay of many climate systems so this assessment of changing ΔR and climate patterns require further testing. Komugabe-Dixson et al. (2016, fig 4) recorded low marine 14C reservoir ages for black coral from the Norfolk Ridge between AD 1950 and 1700 (0-250 BP). A negative ΔR value (av. -49 ± 10 14C years) has also been recorded by Petchey et al. (2008) for shells from Norfolk Island, which they attributed to increased absorption of atmospheric CO2 in these waters due to increased biological activity at the intersection of warm tropical waters and the cool waters of the Tasman Sea. There is no evidence of lower ΔR values in the NZ archaeological data, but we have limited values from the far northern tip of the North Island where greater influence from the Tasman Sea is likely.

The short chronology for Polynesian settlement of NZ has proportionally magnified the many problems with interpreting dates of different materials, but significant improvements in 14C method and theory have reduced many of the issues that previously affected 14C chronologies. The improved precision now routinely reported with accelerator mass spectrometry 14C dates, combined with statistical techniques designed to work with prior information obtained from archaeological evidence (see Bayliss 2015), should have a major impact on our understanding of events, and a better understanding of the marine 14C reservoir will enable further improvements. In particular, it is evident that the marine 14C signal does not always match atmospheric 14C production due to the complex interrelationship of climatic and oceanic 14C, making the use of a marine calibration curve that has been modelled primarily on terrestrial data, problematic. However, this difference between the marine and terrestrial 14C reservoirs provides a means by which we can refine chronologies that have been limited by plateaus and wiggles in the terrestrial calibration curve. Until a more precise and accurate marine calibration curve is produced many researchers will continue to question the integrity of archaeological sites where shell and charcoal 14C dates do not agree within expected limits. In the meantime, the ΔR trends identified here will enable significant refinement to the chronology of Polynesian settlement and development of Māori culture.
MATERIALS AND METHODS
The marine reservoir age ‘R’ is the offset in 14C age between the atmosphere and the global ocean. Regional offsets from R are termed the ‘local marine reservoir age’, or ‘ΔR’ (Stuiver et al. 1986). Calibration of marine 14C dates involves application of a ΔR value to the marine calibration curve (Marine13; Reimer et al. 2013) to account for these regional offsets. A ΔR value can be calculated from “paired” (contemporaneous) terrestrial and marine samples excavated from archaeological sites. A regional reservoir offset can also be calculated from known-age marine carbonates collected prior to atmospheric bomb testing (e.g., Petchey et al. 2008), or from samples where independently measured calendar ages can be obtained, such as coral dated by both U/Th and 14C (e.g., Komugabe Dixson et al. 2016). No matter what materials are used to determine ΔR, they must comply with a set of prerequisites (see Petchey et al. 2009). For archaeological shell samples, the age is determined by dating short-lived (must be identified to species and/or element), ‘paired’ terrestrial materials from contemporaneous contexts.
A careful evaluation of each context and set of paired dates was made prior to inclusion in our temporal model of changing marine ΔR. During this evaluation of legacy data, we found numerous issues that warrant mention, as indicated below:

Calibration Issues: Any terrestrial sample with a calibrated age of less than 200 BP produces multiple calibrated ages because rapid fluctuations in 14C have resulted in ‘wiggles’ in the calibration curve. In these regions of less precise temporal control, it is near impossible to evaluate which of the multiple wiggles is the true as of the sample, and therefore the exact marine offset. We have therefore excluded any samples with a calibrated mean age of less than 200 BP.

Context Uncertainty: Typically, the most robust determinations come from well-defined features. We found the selection of charcoal and shell dates from single contexts to be rare, with the majority of dates being sourced from ‘midden’ layers. Radiocarbon dates from horticultural soils have not been included because they are typically mixed deposits (plaggen soils) (Gumbley et al. 2003). Where more than one terrestrial date was available from the same context, we used the Chi square test to assure the results were indistinguishable. This was only possible for thirteen contexts.

Differences between terrestrial and marine 14C dates have led to researchers searching for clues as to what caused these offsets. Anomalies have been attributed to hardwater (Anderson 1991), taxa variation (Higham 1993), upwelling (Anderson 1991), inbuilt age in charcoal (McKinnon 1999, Schmidt 2000) and the incorporation of natural shell or reuse of previous midden material (Schmidt 2000; Walter et al. 2010). However, the opposite has also occurred, where the integrity of the archaeological features has been questioned on the basis of widely varying 14C results, even when there is limited evidence of disturbance. Certainly, disturbance remains a very strong candidate for causing apparent ΔR variation with both positive and negative ΔR values possible. For this study, we have ignored any pre-conceived assumptions of site disturbance, upwelling, taxa variation and/or hardwater impact, unless there is additional independent evidence to back up these claims.

Material Suitability: The literature is full of recommendations regarding material suitability for 14C dating, and of the reliability of different pretreatment methodologies used. As the science progresses, many of these recommendations have been re-evaluated. With this in mind, we have carefully assessed preconceived ideas regarding different sample types and different pretreatments.

All charcoal dates included in this evaluation have been identified to species considered suitable for 14C dating. Unfortunately, it is rare for the publications to specifically state if the material has been positively identified as small diameter twigs, and there are very few dates on seeds. Anderson (1991) has speculated that even “short-lived” charcoal may have inbuilt age of 50-150 years, but this is difficult to evaluate on an individual basis. Inbuilt age will result in a reduction of the apparent age difference between the terrestrial and marine proxies and result in a more negative ΔR. Delamination of larger branches during combustion is also possible, and differences have been noticed between the ages of twigs from shrubby plants and those from larger trees (W. Gumbley, pers. comm., Nov 2019). We have excluded all dates on bark because the rate of shedding varies depending on taxa (Turner et al. 2010). We have also excluded dates on tree fern because they grow in a spiral pattern making it difficult to identify early or late growth (R. Wallace, pers. comm., Nov 2019).

Most shellfish precipitate their shells in equilibrium with the isotopic signature of dissolved inorganic carbon from the waters they live in (McConnaughey et al. 1997). Terrestrial organic material from rivers or rainwater runoff generally only have a small negative impact on the ΔR of filter-feeding estuarine bivalves because the uptake of this carbon is typically less than 10% of the 400-year difference between the marine and terrestrial 14C reservoirs (Petchey et al. 2018). Areas with calcareous rocks can, however, result in very positive ΔR values because the shellfish uptake the ancient bicarbonate ions that percolate through the substrate. But, this affect is highly localised and the presence of limestone does not guarantee a hardwater effect when dating suspension feeding bivalves (Petchey et al. 2018). Deposit-feeding and herbivorous shellfish can ingest both young and old (“stored”) carbon which may have a significant impact on results in areas with limestone or old sediment (Petchey et al. 2012). In the NZ context, Amphihola crenata is the best studied indication of the problems associated with deposit-feeders (Higham 1993:134-5; Anderson et al. 1996:65). These taxa are excluded from this evaluation. All other shellfish taxa were evaluated on a case by case basis. Although upwelling has been suggested for some anomalous shell ages, there is no definitive evidence of any influence on marine shell along the NZ coastline (Higham 1993:137-8; Chiswell and Schiel 2001).

Bone dating has a long and troubled history in the dating of archaeological contexts (Bayliss and Marshall 2019). Problems related to bone pretreatment and diet variability make this material incredibly complex to interpret. For this reason, the following constraints have been applied:  
1. All ‘collagen’ dates are excluded (see Petchey [1998] for definition of collagen used). Samples pretreated to gelatin or ultrafiltered gelatin are accepted (cf., Petchey 1999; Bayliss and Marshall 2019:14) except where the laboratory has identified an inhouse laboratory problem (e.g., Bronk Ramsey et al. 2004).
2. Tripeptide dates on fish bone (Petchey 1998) are excluded because subsequent research at the Oxford Radiocarbon laboratory indicated column bleed could result in older carbon being introduced (pers comm Tom Higham, 31 Oct 2019).
3. Rattus etuans 14C dates are excluded. In the mid 1990’s there was considerable debate over laboratory errors resulting in anomalous dates (Anderson 2000). These errors are likely to reflect the limitations of accelerator mass spectrometry 14C dating at a time when these extremely tiny samples pushed the limits of the technique. Stringent quality control procedures now used by many laboratories limit a repeat of this episode.
4. We have included bird bone dates from terrestrial or marine environments, but birds that inhabit freshwater lakes and rivers are excluded due to dietary complexity (Higham et al. 2005:371).

AR Calculation: AR values for both 14C and U/Th dated pairs (Table S1) have been calculated using the online tool found at http://calib.org/deltar(Reimer and Reimer 2017), which first calibrates the terrestrial 14C age with the appropriate calibration curve and then reverse-calibrates discrete points of the resulting probability density function with the marine calibration curve (Marine13; Reimer et al. 2013). We have used the Southern Hemisphere calibration curve (SHCal13; Hogg et al. 2013) for terrestrial samples. Calendar ages derived from U/Th measurements from Komugabe-Dixson et al. (2016) are similarly reverse-calibrated using the marine calibration curve.
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Vital evidence: A temporal shift in the marine \(^{14}C\) reservoir around New Zealand (Aotearoa) over the last 750 years, and implications for Polynesian settlement

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Supporting Information Appendix (SI Appendix)

1. Evaluation of archaeological sites by 50 and 100 year blocks

<table>
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<tr>
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<tr>
<td>Sites dating to between 300 and 400 cal BP (AD 1300 - 1200)</td>
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3. Figures

- S1: Sites <200 BP (cal 100-300 BP)
- S2: Cross Creek Figure

4. OxCal code for Cross Creek

5. Supporting references

1. Evaluation of archaeological sites by 50 and 100 year blocks

Sites dating to between 100 and 300 cal BP (AD 1850 - AD 1650)

Ten archaeological ΔR pairs have mean calibrated ages dating between 100 and 300 BP. These include; Waioneke, Aotea Harbour Site 210, Hurumoimoi, two Puriri-91 sites (885 and 340), Stingray Pa, Aotea Island Site 171A and Site 171B, and Aotea Island Site 16C (Figure 1, Table S1). The age of each context is difficult to assess here because of multiple wiggles in the terrestrial calibration curve at this time. Only two contexts, both with mean calibrated ages greater than 200 BP, are included in Figure 2; Aotea Site 16C (ΔR = 140 ± 50 \(^{14}C\) yrs) and Site 171B (ΔR = 29 ± 39 \(^{14}C\) yrs). The large offset between charcoal and shell dates from Site 16C was thought to be the result of post-depositional disturbance (Schmidt 2000:136), but the ΔR value is similar to black coral data between 200 and 300 cal BP.

The calibrated distributions for most paired shell and charcoal dates overlap when an average ΔR of 46 ± 49 \(^{14}C\) yrs, derived from the black coral (Table S2), is used to calibrate shell dates from these young contexts (Figure S1). Material from Ponui Site 95, Layer B, is the only exception. Schmidt (2000:138) suggested that this midden site which was composed entirely of one shellfish species (Austrovenus sp.) was unusual for Ponui Island. Anomalous, old dates from the lower Layer D at the same site (Table S1) are clear evidence of intermixing with secondary beach deposits.

Sites dating to between 300 and 400 cal BP (AD 1650 - AD 1550)

Delta-R (ΔR) values from ten different contexts have been identified with mean calibrated \(^{14}C\) ages between 300 and 400 BP; Cryers Road, Aotea Harbour Site 111, Kokohuia Layers 2 and 3, Sawpit Point Layer 1B, Taputapueta middens E2 and F, Ligar Bay Driveway, Ponui Island Site 333 (Layer B), and Tata Beach Layer 3 (Figure 1, Table S1). Between 300 and 350 cal BP the average ΔR value is -26 ± 73 \(^{14}C\) years, and -19 ± 40 \(^{14}C\) yrs between 350 and 400 cal BP (excludes Ponui Island Site 333, Layer B as discussed below). Between 300 and 350 cal BP the black coral data has an average ΔR value of 21 ± 104 \(^{14}C\) yrs with considerable variability (Table S2). Little change is observed between 350 and 400 cal BP with an average ΔR of -11 ± 35 \(^{14}C\) yrs.

The ΔR value for Ponui Island Site 333 (Layer B) is a major outlier from the other contexts, returning a ΔR of -204 ± 41 \(^{14}C\) yrs. Schmidt (2000:134) could not find any specific cause for this apparent offset. There is a single black coral value at 345 cal BP with a ΔR of -134 ± 40 \(^{14}C\) yrs which may hint at a short-lived event.
influencing the regional $\Delta R$ – akin to wiggles in the terrestrial calibration curve – but this needs to be investigated further.

### Sites dating to between 400 and 500 cal BP (AD 1550 - AD 1450)

Eleven separate contexts have been identified with suitable marine and terrestrial pairs in this period; Tumbledown Bay Layer 3, Sawpit Point Layer 1C, Torpedo Bay Layer 3, Omaha 042, Ponui Island Site 27 (Layer D) and Site 333 (Layer D), Ligar Bay middens 1 and 2a, Kokohua Layers 4 and 5, and Pleasant River Area 3/7 (Table S1). Between 400 and 500 cal BP the average $\Delta R$ value for the archaeological dataset is -34 ± 65 $^{14}$C yrs. The black coral displays greater variability, with an average $\Delta R$ of -4 ± 97 $^{14}$C yrs and -56 ± 53 $^{14}$C yrs between 400-450 cal BP and 450-500 cal BP respectively.

Two sites hint at increased $\Delta R$ variability across this period. More negative $\Delta R$ values are indicated in shell from Tumbledown Bay (-130 ± 50 $^{14}$C yrs) and Omaha 042 (-159 ± 65 $^{14}$C yrs). Calibrated terrestrial results for both of these sites overlap, at 68.2% probability, a single black coral $\Delta R$ value of -134 ± 40 $^{14}$C yrs dated to 345 BP. Unfortunately, there is limited published information for the paired dates from Omaha 042, but they were specifically selected to test the difference between terrestrial and marine reservoirs (Bickler et al. 2003:50-51).

Archaeological deposits at Tumbledown Bay are specifically interesting because they cover a period of major economic change of moa being readily available in Layer 3 (16th century AD) to local moa extinction in Layer 2 (mid 15th century AD). Artefacts also have similarities to both earlier and later types, with clear precursors to some later styles, but a conspicuous absence of many early styles (Allingham 1988:2; Challis 1995:62). Unfortunately, precise temporal control of the archaeological deposit is affected by a large wiggle in the terrestrial calibration curve resulting in multiple intercepts for terrestrial dates. On the basis of the present limited dating of each site it is therefore possible that both Tumbledown Bay, Layer 3 and Omaha 042 could belong to the next $\Delta R$ phase discussed below (500-600 cal BP). The return to more positive values, evident in both the archaeological and black coral data by 450 cal BP, confirms that this negative trend is likely to be of short duration.

### Sites dating to between 500 and 600 cal BP (AD 1450 - AD 1350)

Between 500 and 550 cal BP the trend towards a more negative $\Delta R$ value continues in the black coral data (average $\Delta R$ = -61 ± 96 $^{14}$C yrs), with an occasional outlier. This trend is not immediately obvious in the archaeological values, which instead show a brief increase in $\Delta R$ around 500 cal BP (Figure 2). Archaeological sites that have a mean calibrated age later than 550 BP include; Watsons Beach Area A, Pleasant River Area 1 (Layer 2), Tapatapuatea Area 4 (Layer Di), and Rotokura Layer 4 (Table S1). These four contexts combine to give a positive $\Delta R$ value (40 ± 39 $^{14}$C yrs; Table S2).

Seven contexts fall in the period between 550 and 600 cal BP; Pleasant River Area 7 (Layer 2a), Pleasant River Area D (layers 3 and 4), Ponui Site 14 (Layer D), Houlhora, Cooks Cove (Layer 5b), and Watsons Beach Area B (Figure 1, Table S1). Two additional sites with mean calibrated ages just after 600 cal BP have been included in this period; Aotea Harbour sites 218 and 433. Ponui Island site 95 Layer D is excluded because of the inclusion of beach ridge material, as discussed above. Of the remaining seven sites, Pleasant River Area D (Layer 3), Pleasant River Area 7 (Layer 2a), both Aotea Harbour sites, Pouni Island Site 14 (Layer D), and Cooks Cove Layer 5b have very negative $\Delta R$ values (-236 ± 55, -153 ± 92, -84 ± 26, -129 ± 121, -162 ± 45, -331 ± 56, and -287 ± 41 $^{14}$C yrs respectively). Values from Layer 4 at Pleasant River Area D are excluded due to complications discussed below. A more negative $\Delta R$ value is also evident in the black coral dataset at this time (-198 ± 50 $^{14}$C yrs at 554 cal BP [AD 1396]). There are no black coral values for the previous ~120 years when the average $\Delta R$ value was -42 ± 44 $^{14}$C yrs.

Variability in shell $^{14}$C dates from Pleasant River, in particular Area D, has been widely discussed (see Anderson 1991:782) and $\Delta R$ research undertaken in Area D was specifically intended to investigate young shell $^{14}$C results. Based on agreement between moa eggshell and charcoal $^{14}$C dates Higham (1993:152) interpreted Layer 4 as a single undisturbed chronostratigraphic unit, while the highly variable shell dates were considered to be the result of differential impact of environmental carbon on each shell taxa. Subsequent excavation, dating and interpretation of the Pleasant River site has not helped clarify this issue. Smith (1997:45) described a new suite of charcoal and shell $^{14}$C dates which fell into three temporal groups; 14th, and 14th to early 15th, and late 15th - 16th centuries AD, but the ages were not always in stratigraphic agreement within the same excavation unit and layer. Based on the new chronological assessment of Areas 1-7 at Pleasant River, Smith (1997:48) concluded that the earlier Area D excavation represented a mixing of material from separate occupations along the eroding river edge of the site. Subsequent dating of four marine dates (Thysites atun [snapper] gelatin and Austrovenus stutchburyi) from Area 7, Layer 2a gave consistent results, but also indicated a significant marine offset (average $\Delta R$ of -236 ± 55 $^{14}$C yrs) comparable to the Area D, Layer 3 $\Delta R$ value of -153 ± 92 $^{14}$C yrs. Our findings suggest that the variability in the shell dates from Pleasant River may partly have been caused rapid change in the marine $\Delta R$ over a relatively short period of time (probably less than 50 years) just before 600 cal BP. We have not included the $\Delta R$ for Pleasant River Layer 4 in Figure 2, or in the statistical evaluation (Table S2), because there is considerable
variation in the marine values which skew the average value (two Paphies australis, an Austrovenus stutchburyi and a Cookiea sulcata date; the conventional 14C ages of which range from 740±45 14C yrs to 1120±45 14C yrs resulting in ΔR values between 119±61 and -261±61 14C yrs (see Table S1). It seems unlikely that a rapid change in marine reservoir offset could be responsible for this observed degree of offset within a single layer, and that Smith’s conclusion of mixing is correct, but the possibility is worth further investigation.

The chronologies of other sites in this time range have also been interpreted as problematic. Cooks Cove has a paired shell and ultrafiltered moa bone gelatin date from Layer 5b which only just overlaps at "2 sigma" (Walter et al. 2010:16). However, the negative ΔR value (-162±45 14C yrs; Table S1) supports an age for this lowest deposit at the time of the extreme negative ΔR (Figure 2). Aotea Harbour sites 433 and 218 were specifically sampled for ΔR research. McKinnon (1999:85, 87) considered ΔR values from both sites to be abnormal, and probably the result of inbuilt age in the charcoal, but the extreme negative values obtained also fit with observations from other sites at this time.

**Sites dating to between 600 and 650 cal BP (AD 1350 - AD 1300)**

Many of the contexts that date around this period could be placed in either this, or the earlier 550-600 cal BP time frame. We have assumed the majority in this section date prior to the major offset in ΔR, identified between 550 and 600 cal BP, based on a combination of terrestrial calibrated age range and a more positive ΔR offset evident from the marine dates. Taputapuata Area 6 (ΔR = -44 ± 42 14C yrs), Shag River Mouth Dune Layer 4 (ΔR = -24 ± 58), Layer 7 (ΔR = -2 ± 52 14C yrs) and Layer 11 (ΔR = -60 ± 64 14C yrs), Cabana Lodge (ΔR = -4 ± 40 14C yrs), Wairau Bar midden (ΔR = 77 ± 37 14C yrs), Watsons Beach Layer 2 (2 ± 33 14C yrs) and Cross Creek (ΔR = -5 ± 60 14C yrs) all date within this period (Table S1). These sites show relatively little variation in ΔR with an average value of -15 ± 24 14C yrs (excludes Wairau Bar, see discussion below). There are no black coral values in this period for comparison.

Shag River Mouth is one of the most extensively dated archaeological sites in NZ (Higham 1993, Anderson et al. 1996, Petchey 1997, Higham et al. 2005). The site is thought to have been occupied for between 20 and 50 years in the 14th century AD. This conclusion was based on a combination of shell dates (n=15) with a calibrated age of AD 1329-1373 (68% prob.), charcoal (n=14; AD 1330-1346 and AD 1393-1409) and eggshell dates (n=3; AD 1335-1336 and AD 1405-1433) (Anderson et al. 1996:67). Following the initial dating of the site, a number of dates were obtained on various bird taxa (and Rattus exulans, which are not reported here) (Higham et al. 2005). The list in Table S1 includes terrestrial and marine animal bones from this study. However, the Chi square statistic for the terrestrial dates (charcoal, moa bone gelatin and pigeon ultrafiltered gelatin) is variable ($\chi^2_{0.05} = 10.74$-$9.49$; Table S1). Higham et al. (2005:371) noted a significant difference between dates on gelatin and ultrafiltered gelatin measured on the same pigeon bone (OxA-13239). They concluded the ultrafiltrated bone gelatin date, while younger, was more reliable, but the presence of small amounts of older contamination is not indicated in tests undertaken comparing gelatin and ultrafiltered gelatin baramaca bones (Wk-5345a and Wk-5345b). Because of these uncertainties we have excluded the OxA dates from further analysis.

The Wairau Bar midden is dated by twelve moa eggshell samples from an oven considered to represent a single cooking and discard event. The four paired shell dates come from the “Layer 4 midden” and “main occupation” layers from earlier excavations, and consequently are not well-provenance ΔR pairs. Our inclusion of these separate contexts in Table S1 assumes deposition close in time, as suggested by Walter et al. (2017:8) who interpreted the site¹ as a large village that was occupied for decades around AD 1320–1350 (68% prob.) based on eggshell dates from a single oven (Jacomb et al. 2014) and limited stratigraphic complexity across the site. Assuming this interpretation is correct, our ΔR results suggest a return to a much more positive and ΔR value (77 ± 37 14C yrs) by this time. Alternatively, the shell ages may date from midden deposits that are slightly older than the single use oven, which would give a positive ΔR value. Delta-R values from other sites in this time period, while not statistically different to the ΔR from Wairau Bar, are more negative (Table S1, Fig. 2) and may indicate a problem with the assumption that the site was occupied for such a short duration. Unfortunately, there are no black coral ΔR values around 600 cal BP for comparison. Because of uncertainties over contemporaneity between the oven and midden deposits, we have removed Wairau Bar from the temporal average (Table S2). Multiple moa eggshell dates and four ultrafiltered moa collagen results from Wairau Bar have also been published (Holdaway et al. 2014, supplementary), but specific context information for each date is not given, so these dates are not included here.

**Sites older than 650 cal BP (older than AD 1300)**

Shell samples from Fyffes site return a ΔR of -2 ± 42 14C yrs (Table S1 and Table 2). This matches the single black coral ΔR value at this time (-3 ± 36 14C years). The calibrated ages of charcoal and shell samples from this

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¹ The burial ground is considered to date to a similar age (Higham et al. 1999), but the dating of grave goods (moa eggs) is problematic due to the likelihood of interment of heirloom items.
site suggest an early to mid 13th century AD occupation. A number of theories have been published to explain 14C ages that are considered to be too old for orthodox opinions of first settlement. McFadgen (1987) concluded that both natural and cultural materials had become mixed during the formation of a beach ridge. He further suggested the site represented a transient settlement most likely dated to 500 cal BP. This was not endorsed by Anderson (1989:126) who suggested a more permanent settlement was likely based on the extent of the archaeological site and proximity to a nearby Archaic cemetery. Instead, Anderson (1991:777) concluded that local upwelling and/or ancient carbon derived from nearby limestone outcrops, might account for the old shell dates, while the charcoal was excluded (because it was a single charcoal date with the possibility of inbuilt age (ibid:782; the charcoal was identified to Leptospermum sp. and Coprosma sp. both of which could theoretically have 100 years inbuilt age (McFadgen, Knox and Cole, 1994)). Higham (1993:137-8), using modern shellfish, tested the possibility of upwelled or limestone derived ancient 14C affecting the shell ages, but found no evidence of a significant offset. He suggested seasonal variation in upwelled water along the Subtropical Front (Fig. 1) could account for the ages. Intra-shell radiocarbon studies of marine molluscs from California (Culleton et al., 2006; Fergusson et al. 2013, Holmaquist et al. 2015) have demonstrated that this is possible. Studies along the NZ coastline, however, indicate that here a long and sustained period of upwelling is required to show up in near-shore animals (Chiswell and Schiel 2001). Moa eggshell dates from Fyffes are also reported by Holdaway et al. (2014, supplementary). These range from 592 ± 17 14C yrs to 683 ± 15 14C yrs, with one outlier of 1082 ± 15 14C yrs, which suggests mixing of subfossil material into the archaeological deposit. Unfortunately, no information on sample provenance is published for these eggshell dates. Ultimately, the exact age of Fyffes site remains problematic, but the calibrated age ranges for dates in Table S1 (1075-1266 AD [875-684 cal BP] at 68% prob.; 1190-1372 AD [760-579 cal BP] at 68% prob.) overlap with orthodox opinions of early settlement and cannot presently be excluded on the basis of parameters used in this study. Combined the shell and charcoal dates support an early age for the site.
### Sites dating to between 100 and 300 cal BP (AD 1850 - 1650)

<table>
<thead>
<tr>
<th>Site</th>
<th>Context</th>
<th>Detail</th>
<th>Material</th>
<th>Terrestrial statistics (median age (68% prob. range)</th>
<th>ΔR 14C yrs (68% prob.)</th>
<th>ΔR statistics</th>
<th>Reference/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astor Harbour (South Head) NZAA = R15/210</td>
<td>Meadow</td>
<td>Wk-6647; 19238</td>
<td>Charcoal identified</td>
<td>-200 BP</td>
<td>-</td>
<td>-</td>
<td>McKinnon (1999:88)</td>
</tr>
<tr>
<td>Harbouroast NZAA = T12/347</td>
<td>Hangs, Layer 3</td>
<td>Wk-2853; 10567</td>
<td>Charcoal identified</td>
<td>-200 BP</td>
<td>-</td>
<td>-</td>
<td>Doedens (1993)</td>
</tr>
<tr>
<td>Parrot Site 91 NZAA = T12/340</td>
<td>Area II, Phase B, midden</td>
<td>Wk-2841; 14641</td>
<td>Charcoal identified</td>
<td>-200 BP</td>
<td>-</td>
<td>-</td>
<td>Bedford and Allen (1993:131)</td>
</tr>
<tr>
<td>Parrot Site 91 NZAA = T12/885</td>
<td>Assemblage 23b</td>
<td>Tran-2842; 19749</td>
<td>Charcoal identified</td>
<td>-200 BP</td>
<td>-</td>
<td>-</td>
<td>Bedford and Allen (1993:131)</td>
</tr>
<tr>
<td>Pitt Island Site 95</td>
<td>Pit A</td>
<td>Wk-3599; 19939</td>
<td>Charcoal identified</td>
<td>-200 BP</td>
<td>-</td>
<td>-</td>
<td>Furry et al. (2017)</td>
</tr>
<tr>
<td>Astor Island 171</td>
<td>Layer 2</td>
<td>Wk-3463; 19887</td>
<td>Charcoal identified</td>
<td>-200 BP</td>
<td>-</td>
<td>-</td>
<td>Schmidt (2000:136) suggested possible mixing with natural deposits</td>
</tr>
<tr>
<td>Astor Island 173</td>
<td>Layer 2</td>
<td>Wk-3461; 19885</td>
<td>Charcoal identified</td>
<td>-200 BP</td>
<td>-</td>
<td>-</td>
<td>Schmidt (2000:136) suggested disturbed by ploughing and horizon building activities</td>
</tr>
<tr>
<td>Astor Island 173</td>
<td>Layer 2</td>
<td>Wk-3467; 22239</td>
<td>Charcoal identified</td>
<td>195 cal BP</td>
<td>3416; 5537</td>
<td>2666</td>
<td>Schmidt (2000:124)</td>
</tr>
<tr>
<td>Astor Island 173</td>
<td>Layer 2</td>
<td>Wk-3468; 21738</td>
<td>Charcoal identified</td>
<td>192 cal BP</td>
<td>110±52; 196±54</td>
<td>140±38; 5.99</td>
<td>Schmidt (2000:136) suggested post-depositional disturbance</td>
</tr>
<tr>
<td>Cryers Head NZAA = R111519</td>
<td>Area 41: Base of shell deposit</td>
<td>Wk-1126; 30656</td>
<td>Charcoal identified</td>
<td>327 cal BP</td>
<td>292±442BP; -26±7</td>
<td>-</td>
<td>Fredericksen and Vasse (1988)</td>
</tr>
<tr>
<td>Astor Harbour (South Head) NZAA = R15/111</td>
<td>Meadow</td>
<td>Wk-6660; 32196</td>
<td>Charcoal identified</td>
<td>367 cal BP</td>
<td>-24±88; 58±88</td>
<td>17±63</td>
<td>McKinnon (1999:89)</td>
</tr>
<tr>
<td>Kohuita NZAA = X06/317</td>
<td>Layer 2</td>
<td>Wk-3695; 33084</td>
<td>Charcoal identified</td>
<td>188 cal BP</td>
<td>51±452BP; 2.29±9.49</td>
<td>-</td>
<td>Schmidt (2000:117)</td>
</tr>
<tr>
<td>Pumice point NZAA = N26/214</td>
<td>Layer 3B</td>
<td>Wk-4028; 34649</td>
<td>Charcoal identified</td>
<td>189 cal BP</td>
<td>315±445BP; 5±64</td>
<td>6±2</td>
<td>Schmidt (2000:133)</td>
</tr>
<tr>
<td>Etapopatapua NZAA = T11/914</td>
<td>Meadow 1</td>
<td>Wk-41321; 35840</td>
<td>Charcoal identified</td>
<td>192 cal BP</td>
<td>324±41BP</td>
<td>30±44</td>
<td>Hoffmann (2014:39)</td>
</tr>
<tr>
<td>Etapopatapua NZAA = T11/914</td>
<td>Meadow 2</td>
<td>Wk-41321; 37820</td>
<td>Charcoal identified</td>
<td>187 cal BP</td>
<td>328±455BP</td>
<td>1±52</td>
<td>Hoffmann (2014:39)</td>
</tr>
<tr>
<td>Lagar Bay Driveway</td>
<td>Layer 4</td>
<td>Wk-3553; 38759</td>
<td>Charcoal identified</td>
<td>186 cal BP</td>
<td>525±485BP</td>
<td>17±5</td>
<td>Schmidt (2000:133)</td>
</tr>
<tr>
<td>Pumice Island</td>
<td>Layer B</td>
<td>Wk-3582; 39142</td>
<td>Charcoal identified</td>
<td>197 cal BP</td>
<td>527±487BP</td>
<td>4±2</td>
<td>Schmidt (2000:134) suggested charcoal infralimb age, misidentification or long storage.</td>
</tr>
<tr>
<td>Kohuita NZAA = O06/317</td>
<td>Layer 3</td>
<td>Wk-3707; 40749</td>
<td>Charcoal identified</td>
<td>385 cal BP</td>
<td>325±451BP; 1.3±5.99</td>
<td>-76±64; 28±64</td>
<td>Schmidt (2000:117)</td>
</tr>
</tbody>
</table>
### Sites dating to between 500 and 500 cal BP (AD 1550 - 1450)

#### Tumblemown Bay

| Layer 3 | NZ-7656; 411B47 | Wk-7099; 70650; Wk-7164; 75400 | Charcoal: identified | Paphies australis | 432 cal BP | (330-449 BP) | *T*°C = 18.43 | -11.8 ± 7.4 | -160 ± 96 | -1.13 (50) | 3.84 | GSD = 16 | Anderson (1999:128); Allingham (1988) |

#### Sampson Bay

| Layer 1.4 | Wk-4022; 114A45 | Wk-4031; 89014 | Paphies australis | Charcoal: identified | 415 cal BP | (330-449 BP) | *T*°C = 0.44 | -20 ± 65 | -22 ± 71 | -2.13 (40) | 3.84 | GSD = 26 | Schmidt (2002:148); Barber (1994) |

#### Tindale Bay


#### Omaha Bay

| Layer 2 | Wk-1229; 871G32 | Wk-1425; 662A25 | Paphies australis | Charcoal: identified | 432 cal BP | (330-449 BP) | *T*°C = 18.43 | -159 ± 65 | - | - | - | - | - | - | - |

#### Porotip Island

| Layer D | Wk-3586; 411G39 | Charcoal: identified | 459 cal BP | (330-449 BP) | *T*°C = 0.44 | -54 ± 54 | 91 ± 52 | 73 ± 38 | 3.84 | GSD = 26 | Schmidt (2002:127, 135) |

#### Tiger Bay

| Layer 4 | Wk-3539; 442G38 | Wk-3545; 879G39 | Paphies australis | Charcoal: identified | 461 cal BP | (330-449 BP) | *T*°C = 0.44 | 257 ± 56 | -34 ± 56 | 14 ± 78 | 0.29 | 3.84 | GSD = 27 | Schmidt (2001:131) |

#### Kohukina


#### Porotip Island

| Layer D | Wk-3596; 468G43 | Wk-3597; 744A00 | Paphies australis | Charcoal: identified | 483 cal BP | (453-519 BP) | *T*°C = 0.44 | -126 ± 58 | -50 ± 58 | -88 ± 42 | 3.84 | GSD = 54 | Schmidt (2001:129) |

#### Kohukina

| Layer 5 | Wk-3718; 386G41 | Wk-3719; 443G42 | Paphies australis | Charcoal: identified | 499 cal BP | (472-511 BP) | *T*°C = 0.44 | -92 ± 25 | 9 ± 25 | 3.84 | GSD = 52 | Schmidt (2001:129) |

#### Pleasant River, Area 1

| Layer 1 | NZ-2802; 498G62 | Wk-3851; 811G00 | Paphies australis | Charcoal: identified | 497 cal BP | (453-581 BP) | *T*°C = 0.44 | -16 ± 69 | -140 ± 66 | -81 ± 48 | 3.84 | GSD = 26 | Smith (1997:47, 45-48) |

### Sites dating to between 500 and 600 cal BP (AD 1450 - 1350)

#### Wattona Beach, Area I

| Layer 2 | Wk-1296; 474G12 | Wk-1302; 101H16 | Mass eggshell | Charcoal: identified | 506 cal BP | (475-512 BP) | *T*°C = 0.44 | 111 ± 51 | 82 ± 52 | 97 ± 37 | 3.84 | GSD = 21 | Kerk (2001:32); Jacobson and Dynomy (2002:54) |

#### Pleasant River, Area 1

| Layer 2 & 3 | NZ-794; 957G61 | Wk-2730; 970G30 | Paphies australis | Charcoal: identified | 506 cal BP | (466-551 BP) | *T*°C = 0.44 | 63 ± 76 | 2 ± 72 | 43 ± 41 | 3.84 | GSD = 59 | Smith (1998:76); Higham (1999) |

#### Tapotapatau

| Area 4 | Wk-4212; 596G20 | Wk-4116; 526D21 | Paphies australis | Charcoal: identified | 511 cal BP | (501-520 BP) | *T*°C = 0.44 | 20 ± 26 | - | - | - | - | Hofmann (2014:30) |

#### Rotorua

<p>| Layer 3 | NZ-1105; 586G67 | Wk-5482; 529G57 | Charcoal: not identified | 534 cal BP | (519-580BP) | <em>T</em>°C = 0.44 | - | - | - | - | - | Feathery (1998:145) | Note: Layer 3 was sterile clay, therefore association with L4 most likely. Unidentified charcoal sample (NZ-1105) has been included in this report. |</p>
<table>
<thead>
<tr>
<th>Sites dating to between 600 and 650 cal BP (AD 1350 - 1300)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shag River Mouth</strong></td>
</tr>
<tr>
<td>Area C, Dunns</td>
</tr>
<tr>
<td>NZA # = 43/2</td>
</tr>
<tr>
<td>Imperial # = S15/5</td>
</tr>
<tr>
<td>Layer 4</td>
</tr>
<tr>
<td>NZA-2415; 631261</td>
</tr>
<tr>
<td>WK-2617; 112045</td>
</tr>
<tr>
<td>Charcoal: identified</td>
</tr>
<tr>
<td>Austrovenus stutchburyi</td>
</tr>
<tr>
<td><em>Paphies australis</em></td>
</tr>
<tr>
<td><em>Charcoal</em>: identified</td>
</tr>
<tr>
<td>Austrovenus stutchburyi</td>
</tr>
<tr>
<td><em>Paphies australis</em></td>
</tr>
<tr>
<td>1091 cal BP</td>
</tr>
<tr>
<td><em>T</em>&lt;sub&gt;95&lt;/sub&gt;=0.05</td>
</tr>
<tr>
<td>3.84</td>
</tr>
<tr>
<td>±82 ± 70</td>
</tr>
<tr>
<td>±91 ± 56</td>
</tr>
<tr>
<td>±72 ± 56</td>
</tr>
<tr>
<td>Schmidt (2000:127)</td>
</tr>
</tbody>
</table>

**Notes:** NZA-2415 and NZ-2607 taken from later with possibility of retrofishing.
Brackets = 

Information on each site location can be found at http://www.archsite.org.nz

Imperial # =

Taputapuata
T11/914 = NZAA

Area 6 Layer P

Charcoal: Identified
Perna canaliculus

602 cal BP
(562-646 BP)

±
33
60

T11/914 = NZAA

Waimauku, Area B
T11/914 = 845/10
Imperial # = S172.55

Layer 2

Moa eggshell

639 cal BP
(543-634 BP)

±
33
60

Waimauku, Area C, Dome
NZAA # = 945/2
Imperial # = S155.5

Layer 3

Charcoal: Identified
Halosia tui

603 cal BP
(550-640 BP)

±
60
64

Shag River Mouth
Area C, Dome
NZAA # = 945/2
Imperial # = S155.5

Layer 11

Charcoal: Identified
Pipturus auratus (ultrafiltrated gelatin)

685 cal BP
(605-627 BP)

±
38
45

Wairau Bar
T11/914 = P28/21

Area 4, Unit J, Oven Pa 1

Main occupation w/ Layer 4 midden

Charcoal: Identified

Nestor meridionalis (ultrafiltrated gelatin)

655 cal BP
(574-676 BP)

±
79
97

Cross Creek
T10/399 NZAA
Imperial # = N49/260

Layer 9

Charcoal: Identified

Turbo austrepera

722 cal BP
(674-757)

±
12
24

Fyffe (Arenui Point)
T11/914 = O51/30
Imperial # = S49/48

Occupation n deposit, Sq 9-10

NZ-2716; 840/69
NZ-2718; 1181/29
NZ-2719; 1743/13

Charcoal: Identified

Eudyptula minor

722 cal BP
(674-757)

±
12
24

Trotter (1980)

Sites older than 650 cal BP (older than AD 1300)

- ±

Hoffmann (2014:30)

Kemp (2010:82); Jacobs and Sharrock (2002:54)

Anderson et al. (1996:68-69)

Anderson et al. (1996:68-69)

Gambley et al. (2014:45)

Jacomb et al. (2014); Higham et al. (1999)

Ngay et al. (2008)

Furey et al. (2008)

Furey et al. (2008)

Jacomb et al. (2014); Higham et al. (1999)

Anderson et al. (1996:68-69)

Furey et al. (2008)

*Information on each site location can be found at http://www.archsite.org.nz

** All dates have been calibrated using OxCal v.4.3.2.

Dates initially reported as "modern" following the recommendations of Suwier and Polach (1977) for reporting radiocarbon ages less than 200 BP.

All Waikato University dates (Wk-) have been checked against laboratory files. In some cases, radiocarbon ages were originally reported rounded to the nearest 10 years following the recommendations of Suwier and Polach (1977). Where possible, this has been removed and dates may therefore differ from published reports.

Brackets = dates removed from δR average (see §1 text for discussion).
Table S2. Change ΔR value over time as determined by black coral (Tasmania) and New Zealand archaeological pairs.

<table>
<thead>
<tr>
<th>Cal BP (AD)</th>
<th>Black Coral Dataset</th>
<th>NZ Archaeological Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. Mean and error</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-50*</td>
<td>8  29±10</td>
<td>$\chi^2_{\text{obs}}=17.88&lt;14.07; \text{GSD}=47$</td>
</tr>
<tr>
<td>(AD 1950-1900)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50-100</td>
<td>3  45±15</td>
<td>$\chi^2_{\text{obs}}=7.3&lt;5.99; \text{GSD}=12$</td>
</tr>
<tr>
<td>(AD 1890-1850)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100-150</td>
<td>7  22±15</td>
<td>$\chi^2_{\text{obs}}=9.88&lt;12.59; \text{GSD}=60$</td>
</tr>
<tr>
<td>(AD 1800-1750)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150-200</td>
<td>4  22±18</td>
<td>$\chi^2_{\text{obs}}=4.23&lt;12.59; \text{GSD}=45$</td>
</tr>
<tr>
<td>(AD 1750-1700)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200-250</td>
<td>7  22±18</td>
<td>$\chi^2_{\text{obs}}=4.23&lt;12.59; \text{GSD}=45$</td>
</tr>
<tr>
<td>(AD 1800-1750)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250-300</td>
<td>4  21±21</td>
<td>$\chi^2_{\text{obs}}=20.60&lt;7.81; \text{GSD}=104$</td>
</tr>
<tr>
<td>(AD 1750-1700)</td>
<td></td>
<td></td>
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<tr>
<td>300-350</td>
<td>3  -11±24</td>
<td>$\chi^2_{\text{obs}}=1.34&lt;5.99; \text{GSD}=35$</td>
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<tr>
<td>(AD 1650-1600)</td>
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<tr>
<td>350-400</td>
<td>3  -4±20</td>
<td>$\chi^2_{\text{obs}}=19.96&lt;5.99; \text{GSD}=97$</td>
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<tr>
<td>(AD 1600-1550)</td>
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<td></td>
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<tr>
<td>400-450</td>
<td>9  -36±18</td>
<td>$\chi^2_{\text{obs}}=7.6&lt;15.51; \text{GSD}=53$</td>
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<tr>
<td>(AD 1550-1500)</td>
<td></td>
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<tr>
<td>450-500</td>
<td>4  -81±28</td>
<td>$\chi^2_{\text{obs}}=10.9&lt;7.81; \text{GSD}=96$</td>
</tr>
<tr>
<td>(AD 1500-1450)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500-550</td>
<td>1  -198±50</td>
<td>-</td>
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<tr>
<td>(AD 1450-1400)</td>
<td></td>
<td></td>
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<tr>
<td>550-600</td>
<td>-  -</td>
<td>-</td>
</tr>
<tr>
<td>(AD 1400-1350)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>600-650</td>
<td>-  -</td>
<td>-</td>
</tr>
<tr>
<td>(AD 1350-1300)</td>
<td></td>
<td></td>
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<tr>
<td>650-700</td>
<td>3  -42±25</td>
<td>$\chi^2_{\text{obs}}=0.01&lt;5.99; \text{GSD}=44$</td>
</tr>
<tr>
<td>(AD 1300-1250)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700-750</td>
<td>1  -3±36</td>
<td>-</td>
</tr>
<tr>
<td>(AD 1250-1200)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Grey boxes indicate 50-year blocks where there is rapid change and significant ΔR instability.
† Average value excludes AR from Wairau Bar, Ponui Island Site 333 (Layer B), Ponui Island Site 95 (Layer D) and Pleasant River Area D (Layer 4) (see S1 text for discussion).
**Figure S1:** Sites dating to <300 cal BP. Calibrated using a ΔR of 46±50 yr 14C years (a combination of black coral and archaeological ΔR values).
Fig. S2: Calibrated results for Cross Creek, Layer 9 using the black coral ΔR of -42 ± 25 14C yrs for the period between 600 and 700 cal BP (OxCal code given in S4 text). The position of the Kaharoa Tephra has been “questioned”. P= probability that this determination occupies that position. Note: the lowest probability is obtained if the tephra deposition is placed prior to Layer 9.

4. OxCal code for Cross Creek fig. S2

```
Plot()
{
  Curve("Marine13","Marine13.14c");
  Sequence("Start layer 9")
  {
    Boundary("Layer 9 start");
    Phase("Layer 9")
    {
      Delta_R("LocalMarine",-42,25);
      R_Date("Snapper", 1007, 34);
      R_Date("Snapper2", 1092, 34);
      Curve("SHCal13","SHCal13.14c");
      R_Date("Kaka bird bone", 744, 33);
    }
    Boundary("Layer 9 end");
    C_Date("Kaharoa Tephra", 1314, 12)
    {
      Outlier("sc");
    }
    Boundary("Layer 7 start");
    Curve("Marine13","Marine13.14c");
    Delta_R("LocalMarine",-42,25);
    R_Date("P. subtriangulata", 1035, 28);
    Boundary("Layer 7 end");
  }
};
```
5. References


L. Furey, F. Petchey, B. Sewell, R. Green, New observations on the stratigraphy and radiocarbon dates at the Cross Creek site, Opito, Coromandel Peninsula. Archaeology in New Zealand 51:1, 46-64 (2008).


C. Jacomb, R. Darmody, Interim report on Excavations at Watson's Beach (H45/10); an early coastal Otago archaeological site. Archaeology in New Zealand 45:1, 47-58 (2002).


