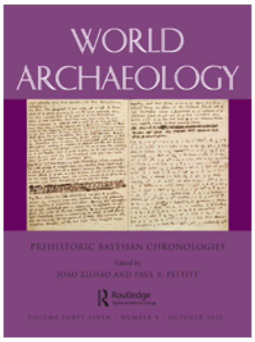

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Dating human dispersal in Remote Oceania: a Bayesian view from Hawai'i

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Dating human dispersal in Remote Oceania: a Bayesian view from Hawai'i

Thomas S. Dye

Abstract

Settlement date estimates for Hawai'i and New Zealand are derived using Bayesian calibration of radiocarbon dates on paleoenvironmental and archaeological samples to demonstrate that the Bayesian framework provides the tools needed to resolve the order of settlement events in Remote Oceania, as well as the time elapsed between them. It predicts that archaeologists will successfully refine the dating of human dispersal elsewhere in Remote Oceania when they work collaboratively to build chronological models within a Bayesian framework.

Keywords

Radiocarbon; Bayesian calibration; Pacific; Hawai'i; New Zealand.

Introduction

The voyages of discovery that populated the far-flung islands of Remote Oceania (Fig. 1) constitute one of mankind's great achievements. The magnitude of the enterprise, which saw humans with a technology based on stone tools migrate through a region that covers about one-third of the globe's surface, has fired the Western imagination at least since the voyages of Cook in the eighteenth century (Howard 1967). Using radiocarbon dating, augmented infrequently by U/Th (Burley, Weisler and Zhao 2012) and optically stimulated luminescence (Clark and Anderson 2009), archaeologists have established that human dispersal through the Pacific was episodic (Anderson et al. 2006) or 'pulse-like' (Rieth and Cochrane forthcoming), or, more colorfully, was accomplished in a series of 'explosive phases' (Bellwood 2013, 197), with initial pushes out of Island Southeast Asia into Western Micronesia perhaps as early as 1600 BC and by the Lapita peoples (Kirch 1997) of Near Oceania by about 1200 BC, expansion through central and eastern Micronesia about 200 BC and, finally, settlement of the far-flung islands of Eastern Polynesia about AD 1000 (Kirch

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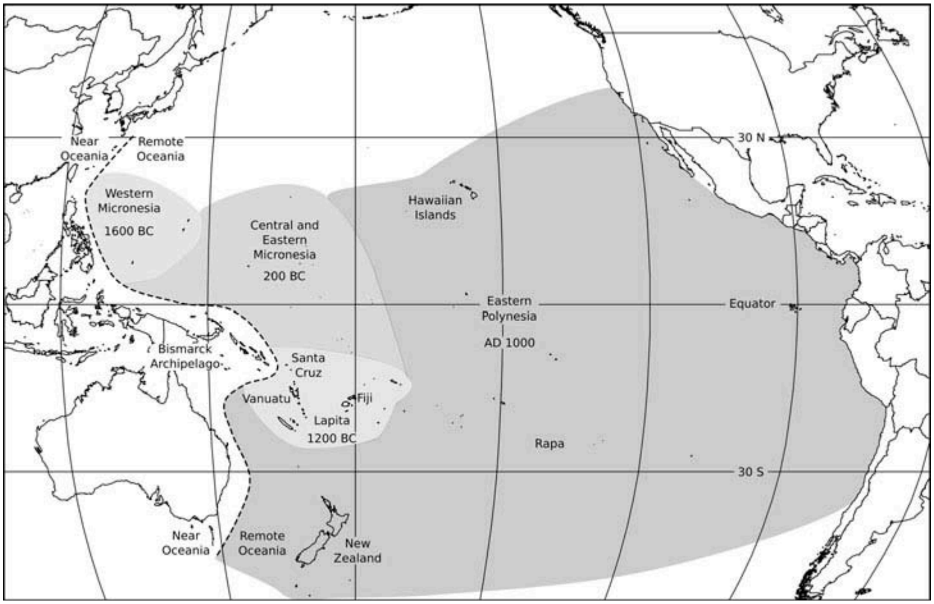

Figure 1 A model of human dispersal to the islands of Remote Oceania, showing the islands and island groups mentioned in the text.

2010). Although the dates of these 'explosive phases' are likely to change as more and better data are collected, the focus of current archaeological debate concerns the tempo of dispersal achieved during each phase. This article argues that a Bayesian framework is suited to this task.

The central datum of a dispersal model is the relationship between the settlement date estimates of two islands or island groups. Two fundamental questions about the relationship are of particular interest: (1) the *order* of settlement – which island or island group was settled before the other; and (2) the *elapsed time* between settlement of the first island or island group and the second. A Bayesian approach to these questions develops a chronological model (Buck, Cavanagh and Litton 1996) suited both to the question at hand and to the available data (e.g. Hamilton and Kenney 2015). A review of the history of settlement estimates in Hawai'i and New Zealand, two island groups that have been investigated intensively by Pacific archaeologists, indicates that the Bayesian model is well-behaved, in contrast to alternatives that tend to magnify discontinuities associated with a disparity (Dean 1978). In New Zealand, where a sustained attempt to control for disparity discontinuities and a concerted effort to collect suitable data forged a consensus estimate more than twenty years ago, application of the Bayesian model yields a settlement date estimate that closely matches the consensus. Comparison of the settlement date estimates for Hawai'i and New Zealand within a Bayesian framework yields a conclusive answer to the question of order and a useful estimate of the elapsed time between settlement events. The article concludes that debates over the tempo of dispersal can be resolved by archaeologists working collaboratively to develop chronological models within a Bayesian framework.

Discovery and settlement of Hawai'i

Estimates of the date Hawai'i was discovered and settled by Polynesians have varied considerably over the last century (Fig. 2). Prior to the radiocarbon revolution, tradition-based estimates of the settlement date varied by about 500 years, from AD 400–500 (Fornander 1916–19) to AD 900–1000 (Emory 1928). Subsequently, the trend over the first four decades of the radiocarbon era was towards increasingly older estimates, due primarily to the accumulating effect of dates on materials with in-built age (Rieth and Stephen Athens 2013). Another contributing factor was a move away from estimating the ages of early sites to investigations based on the age distribution of large radiocarbon date corpora that resulted in an estimate that Hawai'i was settled in the first century AD (Hunt and Holsen 1991).

The first challenge to this pattern of increasingly old settlement estimates was the application of 'chronometric hygiene' – a protocol for accepting or rejecting radiocarbon dates – that yielded an estimate of the settlement date as late as AD 1000 (Spriggs and Anderson 1993). This estimate initiated a period of almost twenty years during which archaeologists split into camps that favored either a 'long' or a 'short' chronology, despite the results of paleoenvironmental work that showed charcoal was absent through much of the Holocene and yielded radiocarbon dates that supported a 'short' chronology (Athens 1997; Athens et al. 2002). The split was not resolved until recently, when three papers (Wilmshurst et al. 2011; Kirch 2011; Dye 2011) independently estimated a chronology *shorter than* the 'short' chronology proposed by Spriggs and Anderson (1993). This new consensus was strengthened recently by a fourth settlement date estimate (Athens, Rieth and Dye 2014). Looking back on the first six decades of radiocarbon dating in Hawai'i from the vantage point of today's consensus, it is striking that most of the settlement date estimates proposed by archaeologists moved in the direction of

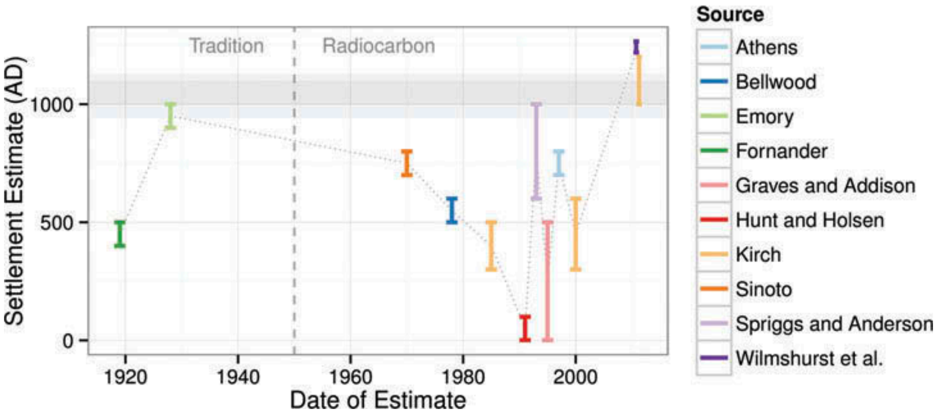

Figure 2 A history of settlement date estimates for Hawai'i. The dashed vertical line marks the invention of radiocarbon dating. The shaded band near the top shows the 68.2 per cent (dark) and 95 per cent (light) highest posterior density regions for a recent Bayesian estimate of the settlement date (see Fig. 4, *right*). *Sources*: Athens (1997), Bellwood (1979), Emory (1928), Fornander (1916–19), Graves and Addison (1995), Hunt and Holsen (1991), Kirch (1985, 2000, 2011), Sinoto (1970), Spriggs and Anderson (1993), Wilmshurst et al. (2011). Modified after https://commons.wikimedia.org/wiki/File:Settlement-estimates-hawaii.svg.

greater error and not towards the current consensus value. The *ad hoc* methods used to estimate the settlement date during this period behaved poorly in practice and proved incapable of leading archaeologists to an accurate estimate.

Today, disagreements among settlement date estimates are narrower than previously, and the basis for the disagreements can be specified. The disagreement between the estimate by Wilmshurst et al. (2011) and the Bayesian estimates of Dye (2011) and Athens, Rieth and Dye (2014) can be attributed to difficulties in estimating the settlement date with a disparity (Dean 1978). The archaeologist dating with a disparity (Fig. 3 left), in which the reference event is younger than the target event, must guard against the possibility that composition and association errors yield an estimate of the dated event that is older than the target event, which would confound their expected temporal relationship. Chronometric hygiene deals with this situation by applying a protocol designed to eliminate dates with the potential to confound the expected temporal relationship. A weakness of chronometric hygiene is that it is not possible to know in advance whether a dated event is older or younger than a target event, leaving the archaeologist to decide whether to accept or reject a date on the basis of indirect criteria more or less plausibly related to chronology. In the case of Wilmshurst et al. (2011) the criteria employed appear to have been too strict, resulting in an estimate of the settlement date that is too young. The archaeologist has different concerns when dating with a disjunction, where the dated event is older than the target event (Fig. 3 right). One advantage of dating with a disjunction is that when discontinuities are large, either because suitable short-lived materials were not recovered or because materials from the reference event could not be confidently distinguished from possibly residual materials with in-built age, the temporal relationship between the dated event and the target event is not altered; the dated event is simply older than the target event and estimates it imprecisely.

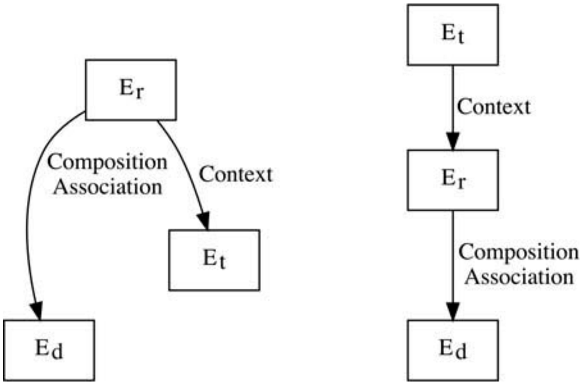

Figure 3 Directed graph representation of discontinuities in archaeological dating identified by Dean (1978): *left*, dating with a disparity, in which the reference event is younger than the target event; *right*, dating with a disjunction, in which the reference event is older than the target event. The arrows point from a younger event to an older event. Labels on the arrows indicate potential sources of discontinuity. E*t* = target event, 'the event to which the date is to be applied' (Dean 1978, 228), E*r* = reference event, 'the potentially dated event that is most closely related to the phenomenon to which the date is to be applied' (Dean 1978, 228), and E_d = dated event, 'the event that is actually dated' (Dean 1978, 226).

A Bayesian solution to the problem of estimating the settlement date of Hawai'i does away with the need to choose between a disparity and a disjunction. It establishes two abutting phases, a pre-settlement phase, whose start and end dates can be represented as $_{\alpha}pre$ and β_{pre}, respectively, and a post-settlement phase, whose start and end dates can be represented as α_{post} and β_{post}, respectively (Dye 2011). In outline, the chronological model is $\alpha_{pre}>\beta_{pre}=\alpha_{post}>\beta_{post}$, where > means 'is older than' and = indicates that the phases are abutting, i.e. that the pre-settlement phase ended when the islands were discovered by Polynesians and the post-settlement phase began.

Following the work of Athens and his colleagues (Athens 1997; Athens et al. 2002), Dye (2011) argued that pre-settlement deposits could be identified by the absence of charcoal particles in cores collected on the older, northern islands of the archipelago where volcanism, the only plausible natural source of forest fires, has long been dormant. At Ordy Pond on the old northern island of O'ahu, where the paleoenvironmental record was especially well preserved, charcoal first appeared as tiny particles immediately before pollen from Polynesian introduced plants (Athens 1997; Athens et al. 2002). This was interpreted as convincing proof that the charcoal was anthropogenic, and it raised confidence that charcoal-free sediments were reliable indicators of pre-settlement deposition. Dye (2011) argued further that dates on plants and animals introduced to the islands by Polynesians, including the human commensal Polynesian rat, sweet potato, breadfruit, candlenut, bottle gourd and ti plant can be confidently associated with the post-settlement phase because the probability that archaeologists recovered and dated materials brought from the homeland by the Polynesian discoverers is negligible. Bayesian calibration of one pre-colonization phase radiocarbon date on a seed and six post-colonization phase radiocarbon dates on Polynesian introductions yielded a settlement date estimate with a 95 per cent highest posterior density region of AD 780–1119 (Fig. 4, left).

Recently, this model was augmented to produce a more precise estimate of the settlement date. Athens, Rieth and Dye (2014) argued that pre-settlement phase deposits on the geologically younger islands with active volcanism could be identified by a pollen spectrum that included native taxa that had elsewhere been shown to decline precipitously following human settlement. This resulted in the addition of a single date for the pre-settlement phase. In addition, the criteria for recognizing post-settlement dates were relaxed to include short-lived plant taxa

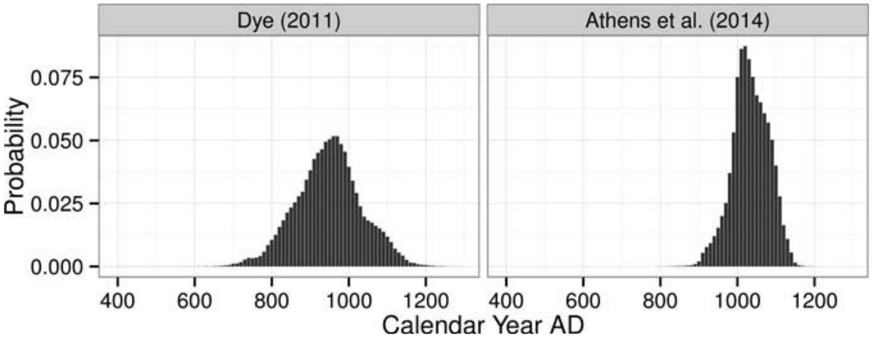

Figure 4 Bayesian settlement date estimates for Hawai'i: *left*, the 95 per cent highest posterior density region is AD 780–1119; *right*, the 95 per cent highest posterior density region is AD 940–1129.
Sources: Dye (2011, fig. 1); Athens, Rieth and Dye (2014, fig. 3).

and parts recovered from confidently identified fire-pit features. In all, twenty-seven dates for the post-settlement phase were added. Bayesian calibration yielded a settlement date estimate with a 95 per cent highest posterior density region of AD 940–1129 (Fig. 4, right), a gain in precision of 150 years, mostly at the early end of the estimate.

These results demonstrate that the Bayesian model is well-behaved; increasing the number of valid observations increases the precision of the settlement date estimate.

Discovery and settlement of New Zealand

The history of archaeological estimates of the New Zealand settlement date differs from that of Hawai'i, in part because of differences in the archaeological records of the two island groups. Unlike Hawai'i, where settlement-era sites are difficult to identify and have yet to yield a diagnostic artifact assemblage (Bayman and Dye 2013, 34–5), the earliest sites in New Zealand are highly visible and yield distinctive artifacts. They typically include remains of extinct fauna endemic to New Zealand, especially the eleven species of *moa* bird, which, simulations and direct evidence indicate, were driven to extinction within a century of human settlement (Holdaway and Jacomb 2000; Holdaway et al. 2014). Early New Zealand sites also yield a suite of artifacts directly comparable to artifacts found in the East Polynesian homeland and unlike the artifacts produced by contact-era Maori (Davidson 1984, 1994). This so-called Archaic assemblage, which appears to have developed in Eastern Polynesia, has not been identified in Hawai'i (Kirch 1986, 20–1). The differences are also due to the contributions of paleoenvironmental investigations in New Zealand, which have collected and analyzed abundant data related to the settlement date question. A third contributing factor is that radiocarbon dating laboratories have been operating in New Zealand for many years and the collaboration of archaeologists with radiocarbon scientists has yielded benefits.

Prior to the radiocarbon revolution, S. Percy Smith synthesized regional Maori traditions and brought them into line with nineteenth-century discoveries of a Moa Hunter culture antecedent to the traditional Maori (Simmons 1969). Smith's synthesis posited three migrations to New Zealand, the earliest of which, associated with Kupe, was dated genealogically to the early to mid-tenth century AD (Fig. 5). This version of the settlement chronology was popularized in several influential books (e.g. Buck 1925) and taught to New Zealand schoolchildren.

An attempt to interpret the earliest radiocarbon dates for New Zealand pushed back the estimate of the settlement date to AD 750–850 (Groube 1968, 145), but over the next decade and a half, as archaeologists gained some appreciation for the likely effects of old wood and recognized some of the uncertainties of the radiocarbon method, the consensus estimate broadened to include the traditional settlement date estimate within its range.

The much earlier settlement date estimate proposed by Sutton (1987) was based primarily on a review of palynological and geomorphological evidence and characterized by a willingness to interpret changes in the paleoenvironmental record as anthropogenic rather than natural. The response was 'immediate and vigorous' (Sutton 1994a, 9), and it raised serious objections to Sutton's analysis and interpretation. Subsequent support for an early settlement date estimate among archaeologists was rare (e.g. Bulmer 1989, 700–1). A decade later, when dates on bones of the human commensal Polynesian rat yielded unexpectedly early results (Holdaway 1996), later shown to be erroneous (Wilmshurst et al. 2008), they were interpreted as implying 'an

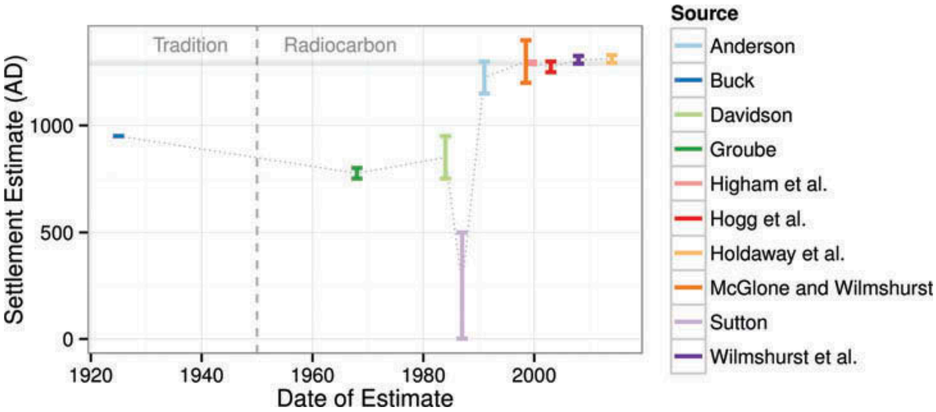

Figure 5 A history of settlement date estimates for New Zealand. The dashed vertical line marks the invention of radiocarbon dating. The shaded band near the top shows the 68.2 per cent (dark) and 95 per cent (light) highest posterior density regions for a Bayesian estimate of the settlement date (see Fig. 6). *Sources*: Buck (1925), Groube (1968), Davidson (1984), Sutton (1987), Anderson (1991), McGlone and Wilmshurst (1999). Higham, Anderson and Jacomb (1999), Hogg et al. (2003), Wilmshurst et al. (2008), Holdaway et al. (2014).

early, transient, human contact with New Zealand more than 1,000 years before settlement' (Holdaway 1996, 225) and not as evidence for settlement *per se*.

Opposition to Sutton's proposal appears to have galvanized New Zealand archaeologists in the effort to minimize discontinuities associated with a disparity. Anderson (1991) applied chronometric hygiene to the existing corpus of relevant archaeological dates, yielding an estimate that ranged to the early fourteenth century and effectively established the modern consensus. This was followed by the discovery that *moa* eggshell, which preserves well in archaeological sites and lacks in-built age, could be made to yield reliable age determinations (Higham 1994). *Moa* eggshells previously collected from an archaeological site with a rich assemblage of Archaic artifacts at Wairau Bar yielded dates that were interpreted as indicating the site was inhabited in AD 1288–1300 (Higham, Anderson and Jacomb 1999). The dating of the Wairau Bar site was subsequently confirmed by dates on nine *moa* eggshells collected from a large oven pit at the site (Jacomb et al. 2014, 29). Most recently, Holdaway et al. (2014) reported ninety-six dates on archaeological *moa* eggshell from seven sites, including Wairau Bar, on the east coast of the South Island, and used ninety-three of them to estimate a 95 per cent highest posterior density region of AD 1294–1330 for the onset of Polynesian interaction with *moa*. The posterior probability distribution for the start date of human interaction with *moa* is constrained at its early end by the date of the Kaharoa tephra with the argument that there is no definitive proof of human presence prior to deposition of the tephra, which covered 30,000km^2 of the northern and eastern North Island over a brief period in AD 1314±6 according to a wiggle-match date on wood encased by the tephra deposit (Hogg et al. 2003). This argument has two potential flaws. First, the Kaharoa tephra covers a large area and it is not possible to look under it all for evidence of prior human activity. Absence of evidence is not evidence of absence. Second, the Kaharoa tephra deposit, large as it is, covers only a portion of the North Island. An argument that insists on direct stratigraphic evidence of pre-Kaharoa tephra human activity potentially ignores pertinent evidence elsewhere in New Zealand. The Kaharoa tephra is precisely dated, but there appears to be no intrinsic connection between its eruption and Polynesian settlement of New Zealand. The two events just happen to be pene-contemporaneous.

Hand in hand with this archaeological progress, environmental scientists collected abundant data on the timing of anthropogenic change. An analysis of pollen and charcoal evidence from peat bogs, swamps, estuaries and lakes concluded that the first evidence for the environmental effects of human settlement dated to AD 1200–1400 (McGlone and Wilmshurst 1999). Although the Kaharoa tephra has not been found overlying an archaeological site, indicators of human settlement are reported in paleoenvironmental cores immediately beneath the tephra (Lowe et al. 2000) and seeds gnawed by the human commensal Polynesian rat have been found encased in it (Wilmshurst and Higham 2004). Rat-gnawed seeds and rat bones have both been dated extensively (Wilmshurst and Higham 2004; Wilmshurst et al. 2008); materials associated with rats are argued to be a good proxy for first settlement because the animals reproduce quickly and spread widely, and both seeds and bones are relatively easy to find and can be dated confidently (e.g. Wilmshurst and Higham 2004, 801–2).

A Bayesian chronological model similar to the one developed for Hawai'i, which distinguishes pre-settlement and post-settlement phases, can be applied to the New Zealand situation if criteria for distinguishing pre-settlement from post-settlement deposits can be developed. The criteria used to identify pre-settlement phase deposits in Hawaiian paleoenvironmental cores do not work in New Zealand, where pre-settlement fires were widespread and the marked vegetation changes brought on by Polynesian settlement of Hawai'i are not found (McGlone and Wilmshurst 1999). A potential criterion for identifying pre-settlement deposits in New Zealand builds on the argument that rat-gnawed seeds are a sensitive indicator of Polynesian settlement. If this is so, then seed caches without evidence of rat gnawing probably represent deposits that were not active into the post-settlement phase and the seeds within them must date to the pre-settlement phase. Post-settlement phase dates on *moa* eggshell, Polynesian rat bones and rat-gnawed seeds are abundant, as discussed above.

The chronological model can be expressed algebraically as $\alpha_{pre}>\Theta_{pre}>\beta_{pre} = \alpha_{post}>\Theta_{post}>\beta_{post}$, where Θ_{pre} is the set of dated events $\theta_1 \ldots \theta_9$ from the pre-settlement phase, represented by the intact and bird-cracked seed cases from caches at Long Beach, Dunedin and Waitoetoe, Taranaki (Wilmshurst et al. 2008, table S2); and Θ_{post} is the set of dated events $\theta_{10} \ldots \theta_{108}$ from the post-settlement phase, comprising eleven *moa* eggshells from Wairau Bar (Higham, Anderson and Jacomb 1999), nine *moa* eggshells from an oven pit at Wairau Bar (Jacomb et al. 2014), forty-eight rat-gnawed seed cases (Wilmshurst and Higham 2004; Wilmshurst et al. 2008) and thirty Polynesian rat bones (Wilmshurst et al. 2008).

Bayesian calibration yields a 95 per cent highest posterior density (HPD) region of AD 1270–1309 (Fig. 6), which fits well with the current consensus estimate of the settlement date. The 95 per cent HPD, which spans just four decades, overlaps the range of every settlement date estimate since Anderson (1991).

As Denham, Ramsey and Specht (2012) point out, one advantage of estimating settlement dates in a Bayesian framework is that the estimates can then be compared directly. It is possible to answer the fundamental question of which island group was settled before the other with a probability that expresses the confidence that the answer is true, given the model and the data. In this case, the probability Hawai'i was settled before New Zealand is greater than 0.99, a virtual

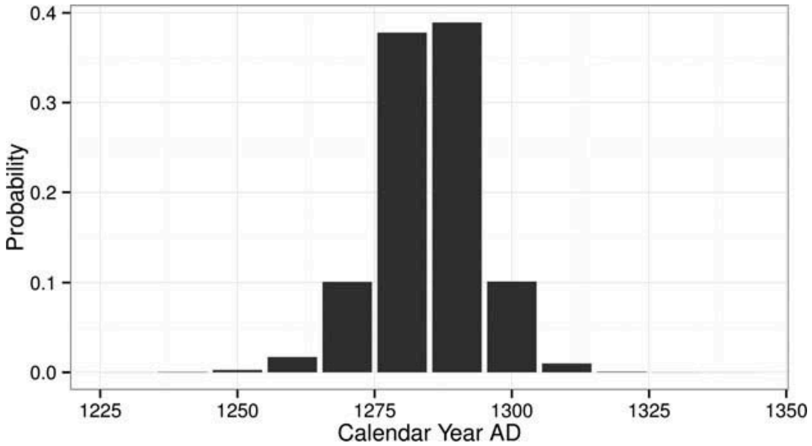

Figure 6 A Bayesian settlement date estimate for New Zealand. The 95 per cent highest posterior density region is AD 1270–1309.

certainty. A Bayesian answer to the second fundamental question, how many years elapsed between the settlement of Hawai'i and New Zealand, takes the form of a posterior probability distribution with a modal value of 170 years and a 95 per cent HPD of 90–259 years (Fig. 7).

Bayesian settlement date estimates in Remote Oceania

Other Bayesian settlement date estimates for islands and island groups in Remote Oceania use chronological models based on disparities.

Green, Jones and Sheppard (2008) established a two-phase sequence for the SE-SZ-8 Lapita site on Nendö Island in the Santa Cruz Group. The chronological phases were based on the

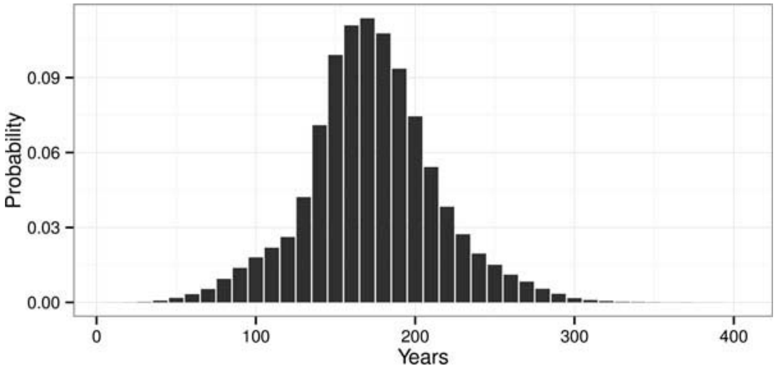

Figure 7 A Bayesian estimate of the time interval between Polynesian settlement of Hawai'i and of New Zealand. The 95 per cent highest posterior density region is 90–259 years. The 68.2 per cent highest posterior density region is 140–209 years.

cultural stratigraphy of the site, with the earlier phase corresponding to the Layer 2 Lapita deposit and the later phase to the modern garden soil of Layer 1. No dates were obtained from pre-settlement Layer 3 deposits. Based on four marine shell dates from Layer 2 and a single date on wood charcoal from Layer 1, Bayesian calibration estimated the onset of cultural activity at 1700–1050 BC. The wide range of this estimate is due to the few dates from Layer 2 and the lack of dates from Layer 3, which might serve to constrain the early tail of the estimate.

Denham, Ramsey and Specht (2012) used a Bayesian framework to compare and contrast two chronometric hygiene protocols applied to data on the settlement of Mussau Island and the rest of the Bismarck Archipelago in Near Oceania and the subsequent dispersal of humans from the Bismarck Archipelago to the island groups of Vanuatu and Fiji in Remote Oceania. The chronological model established a single phase for each island or island group with no constraints among the phases. The 95 per cent HPD of the estimated settlement date for Vanuatu was 1484–1076 BC and for Fiji 1344–1024 BC. Depending upon which chronometric hygiene protocol was used, the estimate of time elapsed between settlement of the Bismarck Archipelago and human dispersal into Remote Oceania varied between 99–478 years and 36–375 years. These variable and imprecise results are inherent in the attempt to estimate the settlement date with a disparity. In addition, they highlight the central role of the subjectively chosen rejection protocol in chronometric hygiene.

Discovery and excavation of a remarkable settlement-era burial ground at the Teouma site on Efate Island in Vanuatu yielded dates on human bone, which eliminates potential context and association problems, but the need to estimate the relative proportions of the diet provided by terrestrial foods, which take up carbon from the atmospheric reservoir and marine foods, which take up carbon from the older, marine reservoir, complicates the analysis (Petchey et al. 2014). Based on measures of δ^{13}C and δ^{15}N in the human bone and comparison with published values for various Pacific Island food sources, two potential diets were hypothesized that differed in the contribution of marine foods. The dietary effects on bone dates from four burials were compared with ^{14}C dates on associated marine shell artifacts, leading to the preference for a correction routine based on the hypothesized diet with a greater contribution of marine foods. The dates on human bone and marine shell artifacts were calibrated using a single-phase model with trapezoidal priors for the phase boundaries, and compared to dates on materials from contemporary deposits adjacent to the cemetery, yielding a 68.2 per cent HPD estimate of 990–930 BC for the onset of regular cemetery use. This complex model yields precise results compared to other analyses that also lack information from a pre-settlement phase.

Excavation of the Bourewa site in Fiji yielded a problematic suite of radiocarbon dates that suffers from problems of context, association and sample composition (Nunn and Petchey 2013, 27–30). Based on expectations about the age of the site, ten out of sixty-eight dates were rejected as either unexpectedly old or too young given the archaeological context from which they were collected. Approximately 20 per cent of the dated marine shell samples are on ‘medium to low-reliability species for radiocarbon dating’ (29); these samples are included in the calibration because their radiocarbon ages conformed to expectations. Twelve dated charcoal samples included in the calibration could be identified only as angiosperm wood, so it was not possible to determine whether or not they might incorporate in-built age. Rather than reject age determinations on unidentified wood charcoal, as is often the case in applications of chronometric hygiene, a decision was made ‘to weight samples according to how likely they are to be correct based on assumptions outlined within set parameters and rely on a model-averaging approach' (27). The 95 per cent HPD for the initial occupation of the Bourewa site yielded by the calibration is 917–822 BC, which is two to four centuries younger than the estimate of the settlement date for Fiji calibrated by Denham, Ramsey and Specht (2012), also based on dates from the Bourewa site and about three times as precise.

Kennett et al. (2012) used radiocarbon dating as a survey technique to yield a chronological framework for landscape use on Rapa Island. Archaeological contexts were categorized as Initial Colonization, Coastal Expansion, Initial Fortification, First Fortification Expansion and Final Fortification Expansion. OxCal software (Bronk Ramsey 2001) was used to implement an island-wide chronological model with overlapping phases. Using seven radiocarbon dates from the basal deposit of a coastal rock-shelter, Bayesian calibration estimated the start date of the Initial Colonization phase at AD 800–1300 (Kennett et al. 2012, 197). The wide range of the estimate is due to the small number of dates assigned to the Initial Colonization phase and the fact that the chronological model lacks a constraint on the lower boundary of the phase.

Discussion

The precision of a settlement date estimate yielded by a Bayesian framework can be calculated because the estimate is reported as a posterior probability distribution. The difference in precision of the Hawai'i settlement date estimate, which has a 95 per cent HPD of 190 years, and the New Zealand estimate, which has a 95 per cent HPD of forty years, indicates the need for additional pre-settlement and post-settlement phase data from Hawai'i. Renewed analysis of the Ordy Pond sequence that leverages technological advances that make it possible to date pollen (Piperno et al. 2007) has the potential to yield dates on pre-settlement phase material that immediately precedes the introduction of charcoal to sediments. The utility of introduced Polynesian rat bone as a post-settlement phase dating material is apparent in the experiments carried out so far (Dye 2011; Athens, Rieth and Dye 2014), and Hawaiian archaeologists might follow the productive lead of their New Zealand colleagues to expand the inventory of Polynesian rat-bone dates.

Estimating the tempo of human dispersal through Remote Oceania using the two-phase Bayesian model described here raises at least two practical problems. First, the model requires dating of pre-settlement contexts, which archaeologists in Remote Oceania rarely attempt. As the examples of Hawai'i and New Zealand show, how best to identify and date pre-settlement contexts varies from one place to another, a circumstance that highlights the potentially important role of regional paleoenvironmental specialists. Second is that the comparison of settlement date estimates at the heart of a dispersal model requires that Bayesian calibration results for individual islands and island groups be distributed in a way that makes it possible for other investigators to evaluate them fully and perhaps incorporate them into their own work. Here, archaeologists find themselves in the position of investigators in other fields, where an increasingly important aspect of statistical practice is the dissemination of statistical methodology, data analyses and statistical arguments. While statistical practice has evolved to encompass more computation and larger and more complex datasets and models, the primary vehicle for delivery has remained the static, printed page (Gentleman and Temple Lang 2007, 4–5).

One solution to this general problem is a digital compendium that includes the information and instructions needed to reproduce a published analysis and can be conveniently distributed over the Internet (Gentleman and Temple Lang 2007). Open access to Bayesian calibration compendia would awaken the prospect of progress, where the community of archaeological and paleoenvironmental researchers works to achieve the common goal of creating a detailed record of human dispersal in Remote Oceania.

Conclusion

Bayesian calibration provides tools that archaeologists can use to establish the tempo of human dispersal in Remote Oceania and move beyond the characterization that it occurred in a series of 'explosive phases'. One key to the Bayesian project is to build models that control for discontinuities associated with a disparity. In Hawai'i, where archaeologists failed for many years to control for the in-built ages of dating materials, settlement date estimates were typically *less* accurate than their predecessors, and it was only through applications of chronometric hygiene and investigation of the paleoenvironmental record that progress was made towards an accurate settlement date estimate. Although chronometric hygiene played a beneficial role in Hawai'i, its application there betrays one of its weaknesses, which is that one cannot know whether the rejection protocol is too strict or too lax. A two-phase Bayesian model yields more desirable behavior; additional observations increase the precision of the settlement date estimate.

The history of New Zealand settlement date estimates contrasts strongly with Hawai'i. Archaeologists and environmental scientists in New Zealand have processed more than 100 high-quality dates from the post-settlement phase and this effort has yielded a consensus estimate that has been relatively stable for more than two decades. Application of a two-phase Bayesian model to a large collection of well-controlled archaeological and paleoenvironmental dates from New Zealand yields an estimate of the settlement date that fits well with the modern consensus.

Two Bayesian tools are especially useful for dispersal studies. One calculates the probability that one colonization event occurred before another, and the other estimates the elapsed time between colonization events. Their application to the settlement date estimates from Hawai'i and New Zealand indicates that prehistorians can (1) be certain that New Zealand was settled after Hawai'i, and (2) begin to theorize about the causes and consequences of a 140–209-year lag between settlement events (Fig. 7).

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Disclosure statement

No potential conflict of interest was reported by the author.

Supplemental data

The underlying research materials for this article can be accessed by sending an email message to c.e.buck@sheffield.ac.uk with the subject line Dye WA Supplement. An account will be set up on the BCal server, as necessary, and the projects will be copied to a subdirectory of the account named WA Supplement.

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