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A model-based age estimate for Polynesian colonization of Hawai‘i

THOMAS S. DYE

Abstract

A model-based Bayesian calibration using ^{14}C data from paleoenvironmental cores and materials introduced to the islands by Polynesian colonists estimates that the islands were likely colonized sometime late in the first millennium AD. Two calibrations, one using ^{14}C dates on floral materials and the other using ^{14}C dates on floral and faunal materials, indicate that archaeological materials yield relatively imprecise estimates of the colonization event with 95% highest posterior density regions 3–5 centuries long. Materials introduced to the islands by Polynesians date to two periods, one that coincides with the colonization event, and another some 3–6 centuries later. A disparity between colonization and the first reliably dated archaeological evidence of human activity is identified and estimated to be 1–4 centuries long.

In the sixty years since an unexpectedly old age estimate was returned by the first ^{14}C date from Hawai‘i (Libby 1951), archaeologists have used ^{14}C dating evidence to estimate when Polynesians first colonized the islands. Initially, the ^{14}C method was seen as a precise scientific replacement for the settlement dates derived from traditional histories, which relied on genealogical information and estimates of the average length of a generation to calculate when Polynesians colonized the islands. Somewhat surprisingly, the use of ^{14}C dating evidence has failed to yield a precise estimate. In fact, over time, it has produced a wider range of settlement estimates than genealogical dating with all its vagaries. Published estimates based on ^{14}C data now range from the beginning of the common era (Hunt and Holsen 1991) to the thirteenth century AD (Wilmshurst *et al*. 2011a). Much of this variability is due to Hawaiian archaeologists' uncritical use of the ^{14}C method, in particular the on-going failure to control for the effects of old wood (Dye 2000; Dye and Pantaleo 2010). Another important source of variability is the ad hoc methods used to interpret ^{14}C dates when estimating the colonization event. A model-based Bayesian approach is proposed here as a solution to this persistent problem.

Brief review of ad hoc age estimates for Polynesian colonization

Archaeologists have developed three different approaches to estimating when Polynesians colonized Hawai‘i. These include a search for early sites, evaluations of lists of ^{14}C dates compiled from site excavation reports, and evaluations of ^{14}C dates from paleoenvironmental investigations. All of these approaches have been implemented in an ad hoc way, without benefit of an explicit chronological model.

Early ^{14}C-based estimates of Polynesian colonization of Hawai‘i were framed in the context of arguments for the ages of purportedly early sites. Arguments for an early establishment of three coastal sites were made, including Pu‘u Ali‘i, Site H1 (Emory and Sinoto 1969); Bellows, Site O18 (Pearson *et al*. 1971); and the Halawa Valley Dune, Site MO-A1-3 (Kirch and Kelly 1975), which was interpreted as somewhat later than the other two. At each of the three sites artifactual or structural evidence was found that differed from expectations based on the known ethnographic and museum records and which was interpreted as indicating some antiquity for the site: at Pu‘u Ali‘i this was a multi-faceted sequence of change in various types of fishing gear (Emory *et al*. 1968); at Bellows an artefact assemblage with an unusual shell coconut grater, pearl shell fishhooks, and adzes with trapezoidal and triangular cross sections (Pearson *et al*. 1971); and at Halawa Valley, a buried round-ended house, untanged and ground adzes, and various early fishhook types (Kirch and Kelly 1975).

The early age estimate for each of these sites was subsequently challenged. Dye (1992) showed that the argument for an early date at H1 was based on outliers among the dated samples and used an analysis of cumulative probability curves to argue for a much later fifteenth century date for establishment of the site. The O18 site was re-dated twice. The first attempt yielded somewhat equivocal results, which were interpreted as indicating a later establishment of the site in the eighth century AD (Tuggle and Spriggs 2001). The second attempt yielded a stratigraphically consistent set of results that compare favorably with other well-dated sites nearby and indicate that the site was established in AD 1040–1219, some nine centuries later than the earliest estimate of its age (Dye and Pantaleo 2010). Six new AMS dates from contexts near the base of the Halawa Dune site clearly indicate that the original basis for early settlement there was an outlier, probably due to the old wood effect. The site is now believed to have been established in the fifteenth century AD (Kirch and McCoy 2007).

This situation led in the 1990s to development of an approach to estimating the date of Polynesian colonization that doesn't rely on identifying an early site. In this approach, a corpus of ^{14}C dates is assembled, the dates are calibrated, and the early tail of the temporal distribution of the calibrated ages is used to estimate the age of colonization. This is the approach used by Hunt and Holsen

T.S. Dye & Colleagues, Archaeologists, Inc., 735 Bishop St., Suite 315, Honolulu, HI 96813 and University of Hawai`i. tsd@tsdye.com

(1991) and Graves and Addison (1995) to argue that Hawai‘i was discovered by Polynesians in the first to fifth centuries AD. At the time, this early colonization date appeared to be supported by the colonization sequence in the Eastern Polynesian homeland of Hawai‘i, but subsequent ^{14}C dating of purportedly early sites there that controlled for the effects of old wood (Anderson and Sinoto 2002; Rolett and Conte 1995; Wilmshurst *et al*. 2008) has shown that the colonization sequence as it was understood in the early 1990s was several centuries too early. As a result, the estimated colonization ages for Hawai‘i based on corpora of ^{14}C dates were recognized as implausibly early. In response to this situation, Wilmshurst, Hunt, Lipo, and Anderson (2011a) have developed a set of criteria for accepting or rejecting individual ^{14}C dates, an approach known in the Pacific as ‘chronometric hygiene’ (Spriggs and Anderson 1993), and have applied this to the problem of estimating the colonization dates of island groups in East Polynesia, including Hawai‘i. Using a substantially reduced corpus of ^{14}C dates, this approach yields an estimate that Polynesian colonization of Hawai‘i took place in AD 1219–1266.

A third response to the lack of early dated sites was to look outside of archaeological sites for information that might be used to infer when colonization took place. Prominent examples of this approach include Burney *et al*. (2001) and Athens *et al*. (2002). This approach yielded especially useful results on the ‘Ewa Plain of O‘ahu Island, where paleoenvironmental coring in Ordy Pond revealed a stratigraphic sequence of thin layers, each of which represents a short interval of time, and excavations in limestone sinkholes yielded apparently old materials introduced to the islands by Polynesians. Dates on materials from the pre-colonization and post-colonization periods were interpreted as supporting a settlement range of AD 700–800 (Athens *et al*. 2002: 57, n. 1). The model-based approach outlined below builds on this approach to propose a solution to the problem of when Hawai‘i was colonized by Polynesians.

Advantages of a model-based approach

The theory and practice of Bayesian calibration for the archaeologist have been fully explicated by Buck, Cavanagh, and Litton (1996) and the interested reader is enthusiastically referred to that volume for an in-depth treatment of the topic. In what follows the Bayesian approach to calibration is summarized to draw out the contrast with ad hoc approaches in general, and the approach used most recently by Wilmshurst *et al*. (2011a) in particular.

The archaeologist carrying out a Bayesian calibration has two tasks: build a model that specifies the temporal relations among the events of interest and incorporates any prior information on their ages, and identify and collect dating information that fits into the model. The calibration itself, carried out in software such as BCal (Buck *et al*. 1999) or OxCal (Ramsey 1995), uses the model to constrain the values assigned to the calibrated ages of the samples during a probabilistic resampling process that is designed to converge on the result that would be obtained through direct analysis by a skilled statistician.

It is important to note that the Bayesian calibration doesn’t test the model in any meaningful sense. Rather, Bayesian calibration takes the model as a given set of facts and reports back the best estimates of model parameters – the ages of archaeological events of interest – in the light of the data collected for the model. Bayesian model-building isn’t an exercise in speculation or imagination so much as it is an assessment of what is known about a set of archaeological events and their relations to one another. Typically, this assessment is based on excavation data where apt field procedures ensure that archaeological events are identified and the laws of stratification (Harris 1989), conscientiously applied, provide the basis for ordering them temporally. The model need not have its basis in a stratigraphic sequence, however, and all that is required is a clear statement about the archaeological events of interest and their temporal relations to one another. When dating information is properly fit into a reasonable model, the Bayesian calibration will yield archaeologically interpretable results. This is a strong claim. It can be made because the modeling process explicitly specifies the relationship at the heart of any successful dating project – the relationship between the dated event and the archaeological event of interest.

This model building step is ignored in the ad hoc interpretations, which don’t specify the relationship of dated events to the colonization event. This can be clearly seen in the recent article by Wilmshurst, *et al*.

> Our main objective is to establish the most accurate age, or ages, for initial colonization in East Polynesia. To accomplish this, it is necessary to be conservative in evaluating the usefulness of data. That is, to accept only those dates that (i) are clearly and directly linked to cultural activity, (ii) have the fewest intrinsic sources of potential error (e.g. from inbuilt age, dietary, or postdepositional contamination by old carbon), and (iii) are capable of providing a calibration that is close to the ‘true’ age of the actual target event (i.e. human activity). (Wilmshurst *et al*. 2011a)

Here, the dates are carefully chosen from a pool of potential dates to ensure that they are reliably associated with ‘cultural activity’ (or ‘human activity’), but without regard to how these activities are related to the colonization event.

Instead of modelling the relationship between the dated events and Polynesian colonization, an assumption is made that the early tail of the empirical calibrated age distribution of a selected sample of age determinations equates to the colonization event. Wilmshurst *et al*. (2011a) investigate this tail closely and propose two methods related conceptually to the *floruit* (Ottoway 1973) to estimate the age of the earliest human activity represented in the corpus of ^{14}C dates. With the sample of ^{14}C dates selected from Hawai‘i, this method yields a range of AD 1219–1266. But the method does nothing to ensure that the human activity represented by the sample has any association with the colonization event. A moment's reflection is enough to convince oneself that there are very many samples that could be drawn from a population of ^{14}C dates for which the early tail of the empirical calibrated age distribution will not equate to the colonization event. How can one distinguish which samples do and which don't? Wilmshurst *et al*. (2011a) note that their estimates for New Zealand and Rapa Nui coincide with colonization estimates derived by other means, but these coincidences carry no information about the association between dated events and colonization at the other island groups. The ad hoc interpretive schemes have no answer for the fundamental question of association. The results of their analyses require a leap of faith that the early tail of an empirical calibrated date distribution is associated with the colonization event. The leap of faith required by this ad hoc inferential procedure contrasts strongly with a Bayesian calibration, which explicitly models the relationship between dated and target events, and which yields a probability distribution for the colonization event based on a well-defined and thoroughly tested statistical method (Buck *et al*. 1996).

A Bayesian estimate of Polynesian colonization

A Bayesian model to estimate the Polynesian colonization of Hawai'i can be simple. It establishes two periods, one for the period before the islands were colonized by Polynesians and one for the period after the colonization event. If the beginning and end of the pre-colonization period are represented by α_{pre} and β_{pre}, respectively, and the beginning and end of the post-colonization period likewise represented by α_{post} and β_{post}, then the model can be summarized as follows:

$$\infty = \alpha_{pre} > \beta_{pre} = \alpha_{post} > \beta_{post} = 0 \quad (1)$$

where > means, 'is older than' and numbers express years before present. The parameters of interest in this model are β_{pre} and α_{post}, which the model indicates are equal; the colonization event simultaneously ended the pre-colonization period and began the post-colonization period. The other two parameters are known. The main Hawaiian Islands are geologically young, 0.4–5 mya, but much older than the effective range of the ^{14}C method. The age of α_{pre} is essentially infinite. Likewise, β_{post}, the end of the post-colonization period, is 0 BP, which by convention in ^{14}C dating is AD 1950 (Stuiver and Polach 1977).

^{14}C dating material from pre-colonization period deposits is rarely, if ever, collected during archaeological excavations. In part, this is due the nature of the 'sterile', which in many cases is a mineral subsoil that lacks macroscopic organic inclusions. In other situations, such as calcareous beach sand deposits, there is abundant organic material but it is not possible to relate its age to the overlying cultural deposit or to the colonization event. In caves or sinkholes, where natural deposition processes laid down organic materials before the onset of cultural deposition, it is sometimes possible to distinguish pre-colonization deposits from natural post-colonization deposits based on changes in floral and faunal materials and the absence of introduced taxa in lower levels of the excavations (Burney *et al*. 2001). Mixing of deposits is a pervasive problem in many sinkholes, however (Athens *et al*. 2002). In contrast, paleoenvironmental coring on the older, northern islands of O'ahu and Kaua'i has consistently revealed a pattern of sediments with charcoal overlying sediments that lack charcoal. The charcoal in these cores has been attributed to human activities because, it is argued, the two causes of natural fires – volcanism and lightning strikes – were either absent or extremely rare on the northern islands. Organic material from the charcoal-free lower layers of several paleoenvironmental cores has been dated, with results that are older than the oldest dated materials from archaeological deposits. Paleoenvironmental coring investigations on O'ahu Island at Ordy Pond yielded a finely divided stratigraphic profile with organic material from a charcoal-free stratum near the boundary marking the onset of charcoal deposition (Athens *et al*. 1999). The date on an unidentified seed, Beta-83313, is the youngest ^{14}C date from a pre-colonization period deposit (Table 1).

^{14}C dates from the post-colonization period are all on materials believed to have been introduced to the islands by Polynesians (Table 1). The ^{14}C dates chosen for analysis are the oldest known for each of the dated materials. These include a bone of the Polynesian rat, *Rattus exulans*; a nutshell of the *kukui* tree, *Aleurites moluccana*; a charred fragment of a tentatively identified sweet potato tuber, *Ipomoea batatas*; wood charcoal identified as breadfruit,

Lab. No.	CRA	θ	Material	Source
Pre-colonization				
Beta-83313	1120 ± 60	1	seed	(Athens *et al*. 1999: 66)
Post-colonization				
Beta-208143	580 ± 40	2	*cf. Ipomoea batatas*	(Ladefoged *et al*. 2005: 362)
NOSAMS-0809-26	690 ± 35	3	*Artocarpus altilis*	(McCoy *et al*. 2010: 377)
Beta-20852b	1330 ± 230	4	*Aleurites moluccana*	(Tuggle and Spriggs 2001)
Beta-135126	640 ± 40	5	*Lagenaria siceraria*	(Williams 2002)
Beta-233042	440 ± 40	6	*Cordyline fruticosa*	(McCoy and Graves 2010)
CAMS-25560	1030 ± 60	7	*Rattus exulans*	(Athens *et al*. 1999: 247)

Table 1: ^{14}C dates for the pre- and post-colonization periods.

Artocarpus altilis; a piece of gourd, *Lagenaria siceraria*; and wood charcoal identified as *kī*, *Cordyline fruticosa*. Barring the rather unlikely possibility that one or more of these dated materials was brought to Hawai'i from the homeland by the first colonists, they cannot be older than the colonization event because they were unknown in Hawai'i during the pre-colonization period. They can be confidently assigned to the post-colonization period regardless of the archaeological contexts from which they derived.

Analyses of mtDNA indicate that the bones of commensal animals can be used to trace human migration patterns in the Pacific (Matisoo-Smith *et al*. 1998; Matisoo-Smith 1994). Because rats multiply rapidly once introduced to an island they provide a visible archaeological signal of colonization. Archaeologists have demonstrated that ^{14}C dates on rat bones can serve as an effective proxy for the age of the colonization event (Wilmshurst *et al*. 2008). In Hawai'i, rats introduced by the first Polynesian colonists are believed responsible for many of the environmental changes that characterize the early post-colonization period (Athens *et al*. 2002). There are several old rat bone dates from sinkholes on the 'Ewa Plain. The oldest of these, CAMS-25560, was collected from Site 5108-F1 (Athens *et al*. 2002: 72), and was pre-treated prior to dating using the XAD resin processing protocol (Stafford *et al*. 1991). Apparently, there was no control for the possible effects of dietary uptake of carbon depleted in ^{14}C, as would be the case if there were a marine component to the rat diet (Beavan and Sparks 1998). Although Wilmshurst *et al*. (2008: 7678) found no evidence for a marine component in the diet of 30 rat bones analyzed from New Zealand, Richards *et al*. (2009) detected a marine influence on the diet of rats at the Hanamiai site. The possibility that such an effect is present in the dated bones from the 'Ewa Plain can't be discounted. Thus, the ^{14}C age estimate for CAMS-25560, along with the other ^{14}C age estimates on rat bone, might be older than their true ages. If present, however, the disjunctions are not great enough to yield implausibly old age estimates; all of the ^{14}C age estimates on rat bone are likely younger than the oldest dated *kukui* nutshell.

Nutshells of the *kukui* tree, *Aleurites moluccana*, are a common component of archaeological sites, typically as readily identifiable charred fragments. Introduced to the islands by Polynesian colonists, the tree is now 'a conspicuous component of mesic valley vegetation, 0–700 m, on all of the main islands except Kaho'olawe' (Wagner, *et al*. 1990: 598). Its presence in small hanging valleys of cliff faces, where the nuts could not have dispersed naturally, suggests that the nuts were 'sown' during traditional Hawaiian times (Ziegler 2002: 330). Most of the ^{14}C dates on *kukui* nutshell are relatively recent, but one, Beta-20852b, from Layer II of the Bellows Dune Site O18 (Dye and Pantaleo 2010; Tuggle and Spriggs 2001), is the oldest dated Polynesian introduction. It was recovered from the upper cultural layer of the site and was 700–800 years old when it was deposited (Dye and Pantaleo 2010).

The sweet potato was introduced to Polynesia from America (Yen 1974) probably in the eleventh to twelfth centuries AD (Green 2005). It was likely a secondary introduction to Hawai'i (Hommon 1976). Material identified as carbonized sweet potato tuber is occasionally recovered from archaeological sites in Hawai'i. Two pieces have been dated (Ladefoged *et al*. 2005). The dated sample used in this analysis, Beta-208143, the older of the two, was collected from a trench near the seaward edge of the Leeward Kohala Field System in the land of Kahua-1. The sample was tentatively identified as sweet potato due to its small size and lack of diagnostic characters.

According to Hawaiian tradition, breadfruit was also a secondary introduction to the islands after the fourteenth century AD (Handy and Handy 1972: 149–155). The Hawaiian breadfruit, like other breadfruit cultivars in eastern Polynesia, is seedless and is propagated vegetatively (Zerega *et al*. 2004). It has not become naturalized in Hawai'i (Wagner *et al*. 1990: 14). It was planted in groves in the Kona Field System (Allen 2004: 215), but elsewhere plantings tended to be solitary. Breadfruit is not short-lived, so it is rarely dated in archaeological situations where the dated event must be closely associated with the target event. The sample included in this analysis, NOSAMS-0809-26, was collected from an irrigated pondfield sediment of Layer V at Site 26086 in Halawa Ahupua'a, North Kohala (McCoy *et al*. 2010). In this context the sample probably represents secondary deposition of older material brought into the pondfield with irrigation water (Allen 1992). It is thus somewhat problematic for dating the use of the pondfield sediment in Layer V, but the identification as *A. altilis* ensures that it belongs to the post-colonization period and is thus useful for the analysis at hand.

The bottle gourd, *Lagenaria siceraria*, appears to have been introduced to Eastern Polynesia from South America along with the sweet potato in the eleventh or twelfth century AD (Green 2000). It would thus likely have been a secondary introduction to Hawai'i. Uncharred pieces of the gourd are sometimes recovered from dry contexts with good preservation. The sample, Beta-135126, consisted of uncharred gourd fragments recovered from the floor of cave Site 50–10–31–21286 at Pohakuloa (Williams 2002: Fig. 10a), a high altitude desert used traditionally by bird hunters (Athens *et al*.1991). Site 21286 had a sparse deposit; the only material collected appears to have been the gourd fragments.

The *kī*, *Cordyline terminalis*, is a shrub that was transported widely in prehistory (Wagner *et al*.1990: 1348). The green-leaved variety transported to Eastern Polynesia and Hawai'i by Polynesians is sterile, perhaps a result of cultural selection in Western Polynesia for 'improved portability, rhizome flavor or texture, increased ecological tolerance or size, or other characteristics that sterility could potentially confer' (Hinkle 2007: 834). The leaves are sometimes recovered from pit ovens and the charred wood is occasionally identified in the charcoal from fires. The sample used in this analysis, Beta-233041, was recovered from an abandoned taro pondfield in lower Halawa, North Kohala (McCoy and Graves 2010: 101).

Given the possibility that the rat bone dates from the ‘Ewa Plain are too old due to the uncontrolled effects of a marine component in the diet, the model was first calibrated without them, the post-colonization period represented by dates on introduced flora. This model can then be expressed as in (2). The model and data were calibrated with the BCal software package (Buck *et al*. 1999). The posterior probability of the colonization event, α_{post}, has a 95% highest posterior density (HPD) region of AD 810–1289 and a mode at AD 980 (Fig. 1, left).

$$\infty = \alpha_{pre} > \theta_1 > \beta_{pre} = \alpha_{post} > \theta_{2-6} > \beta_{post} = 0 \quad (2)$$

The estimate yielded by the model of (2) is relatively imprecise; the oldest date, Beta-20852b on *kukui* nutshell, has a standard deviation of 230 ^{14}C years and the next oldest date, NOSAMS-0809-26 on breadfruit charcoal, is several hundred years younger. The floral evidence for the early end of the post-colonization period is, thus, relatively weak and the calibration produces a posterior probability for α_{post} that is skewed to the right.

If the age of the earliest rat bone from the ‘Ewa Plain is accepted, then the model can be expressed as (3). The addition of the earliest rat bone date, CAMS-25560, fills a gap between the early date on *kukui* nutshell and the next-oldest date on breadfruit. When (3) is calibrated with BCal the posterior probability of α_{post} has a 95% HPD region of AD 780–1119 with a mode at AD 960 (Fig. 1, right).

$$\infty = \alpha_{pre} > \theta_1 > \beta_{pre} = \alpha_{post} > \theta_{2-7} > \beta_{post} = 0 \quad (3)$$

Detailed comparison of ad-hoc and model-based approaches

The ad hoc estimate of AD 1219–1266 (Wilmshurst *et al*. 2011a) appears almost certainly to be too late. The probability that AD 1219 is later than the colonization event estimated by (2) is 0.89, and for the estimate yielded by (3) it is greater than 0.99. One reason for this disparity is the ad hoc method used by Wilmshurst *et al*. (2011a), which doesn’t specify the relationships between the dated events and Polynesian colonization of Hawai‘i. Another reason is the decision to exclude from analysis ^{14}C dates whose standard error is greater than ten percent of the conventional radiocarbon age. One casualty of this decision is the date on *kukui* nutshell, Beta-20852b, which is perhaps the oldest dated material introduced by Polynesians known from Hawai‘i. The ad hoc method cannot sensibly interpret the large standard deviation of this age determination, 230 ^{14}C years, and the long early tail it would create for the probability distributions. This, however, is a failing of the ad hoc method and not of the age determination, which carries information about when Polynesians colonized Hawai‘i. It is useful, in this light, to compare how this age determination is incorporated into the Bayesian analysis.

The first thing to note is that the ^{14}C age of the *kukui* nutshell is older than the dated seed from the pre-colonization period deposit in Ordy Pond. Because (2) and (3) both specify that the pre-colonization period is older than and abuts the post-colonization period, the Bayesian calibration will not consider a scenario in which the true age of the *kukui* nutshell is older than the true age of the seed from Ordy pond. The practical effect of this constraint is that the posterior probability for θ_1 will shift to the left and that for θ_4 will shift to the right. This is illustrated in Figure 2, which shows the results of an unconstrained calibration of the two ^{14}C dates in the top two panels, and the Bayesian calibration of (2) in the bottom two panels. As can be seen in the figure, the posterior probabilities of θ_1 are similar to one another. In contrast, the posterior probability of θ_4 changes dramatically. The primary mode of AD 860 in the unconstrained calibration shifts almost three centuries to AD 1150 in the Bayesian calibration. The 95% HPD region of the unconstrained calibration is AD 380–1159; the long left tail of this distribution is anathema to the ad hoc interpretation. The 95% HPD region of θ_4 in the Bayesian calibration is AD 850–1619, a shift of some five centuries. The relatively minor changes in the posterior probability of θ_1 compared to those of θ_4 are related directly to the standard errors of the age estimates. The standard error of Beta-83313 is 60 ^{14}C years, about a quarter of the standard

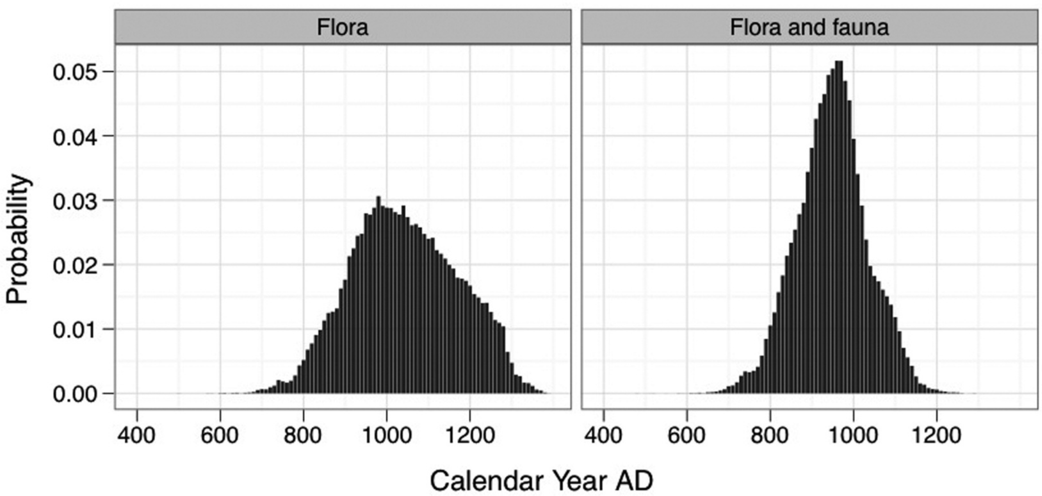

Figure 1: Posterior probability for Polynesian colonization of Hawai‘i: left, estimate based on (2), with a 95% highest posterior density region of AD 810–1289; right, posterior probability for Polynesian colonization of Hawai‘i based on (3), with a 95% highest posterior density region of AD 780–1119.

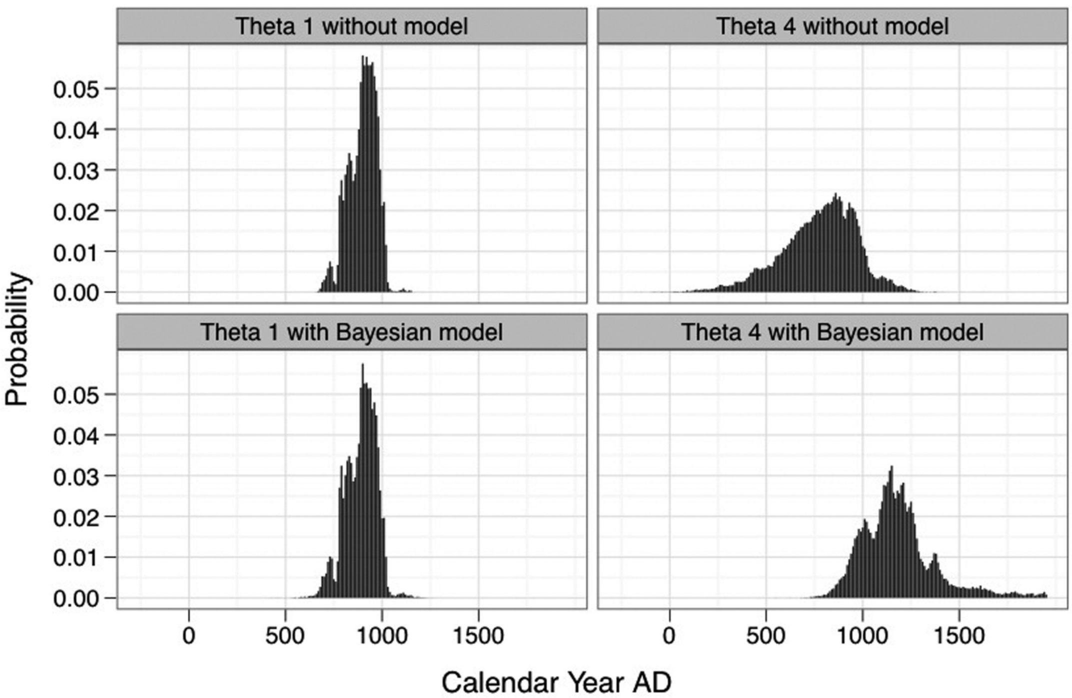

Figure 2: Stratigraphically inverted ^{14}C dates: top, calibration without a Bayesian model; bottom, calibration with the Bayesian model of (2).

error of the age determination for Beta-20852b. The Bayesian calibration exploits the lack of confidence in the age determination of Beta-20852b to produce results that are archaeologically interpretable.

Other results of the model-based calibration

The chronological models developed in (2) and (3) using the BCal software package make it possible to estimate the elapsed time between the colonization event and the archaeological evidence for the introduction of the dated plants and animals that were used as evidence of the post-colonization period. Table 2 shows the 67% HPD region for estimates of the hiatus between colonization and the introduction of plants and animals based on (3). The introduced materials fall into two general categories. The early introductions *R. exulans* and *A. moluccana* arrived either with the first colonists or soon after the initial colonization event. In contrast, based on present evidence, *I. batatas*, *A. altilis*, *L. siceraria*, and *C. fruticosa* all arrived later, some three to six centuries after the colonization event.

Taxon	Hiatus (years)
Ipomoea batatas	330–499
Artocarpus altilis	280–459
Aleurites moluccana	10–169
Lagenaria siceraria	300–489
Cordyline fruticosa	430–619
Rattus exulans	10–139

Table 2: Archaeological evidence for introduced plants and animals.

The models of (2) and (3) can be extended to measure the hiatus between the colonization event and other archaeological events of interest. One example is the hypothesis formulated some years ago by Graves and Addison (1995) that there was likely to be a disparity between the Polynesian discovery of Hawai‘i and the earliest evidence of colonization recovered by archaeologists. Using the model-based Bayesian calibration, a practical test of the hypotheis with current data compares the Bayesian colonization date estimate with the likely age of the earliest materials in the ^{14}C dates assembled by Wilmshurst *et al*. (2011a). These dates were selected as indicators of human activity and arguably represent the full temporal range of activities reliably collected by archaeologists.

The disparity between the earliest reliable indicator of human activity and the Polynesian colonization event can be estimated by adding a third period to either (2) or (3) and populating it with one or more ^{14}C age determinations. In this case, the model (3) was augmented by (4). Wk-19310 is the oldest ^{14}C age determination in the most reliable class established by the chronometric hygiene procedure (Wilmshurst *et al*. 2011a: Table S1) (see Table 3). It is a piece of carbonized fern caudex collected from excavations at Site 4916 in a sand dune near the mouth of Pololu Valley, Kohala, Hawai‘i Island (Field and Graves 2008).

$$\beta_{pre} > \alpha_{activity} > \theta_8 > \beta_{activity} \qquad (4)$$

The results of calibration with BCal (Buck *et al*. 1999) indicate that, based on the model and data of (3) and (4), the 67% HPD region for the disparity between the colonization event and the first archaeological evidence of human activity is 110–369 years; the 95% HPD region is 10–459 years (Fig. 3, *left*).

Lab. No.	CRA	θ	Material
Human activity			
Wk-19310	696 ± 35	8	cf. fern caudex
O18, Layer III			
Beta-231220	870 ± 40	9	*Dodonaea viscosa*
Beta-231222	490 ± 40	10	*Canthium odorata*
Beta-248818	820 ± 40	11	Pearl shell
Beta-248819	840 ± 40	12	Pearl shell
Beta-248820	790 ± 40	13	Pearl shell

Table 3: ^{14}C dates for human activity and Layer III at O18. Sources: Wk-19310, Field and Graves 2008; others Dye and Pantaleo 2010.

Perhaps the most practical uses of (2) and (3) will be to supply an early bound for Bayesian calibrations of cultural activity, especially at potentially early sites. The Bellows Dune site was recently re-dated by Dye and Pantaleo (2010), who modeled the colonization event as a normal curve centered at AD 800 and with a standard deviation of 50 years. It is interesting to ask whether the colonization age estimate has an effect on the estimated age for establishment of O18, and to estimate the hiatus between the colonization event and establishment of the site. This can be accomplished by augmenting either (2) or (3) with (5), which defines a new period with an early boundary, α_{o18}, and a late boundary, β_{o18}, and populating it with the ^{14}C age determinations on short-lived materials from Layer III of the site (Table 3). Using (3) and calibrating with BCal yields a 67% HPD estimate for site establishment of AD 1050–1209. The slight differences between this estimate and the estimate published by Dye and Pantaleo (2010) are due to the stochastic nature of the calibration process; the estimate of site establishment was not changed by the new estimate of the colonization event. An estimate of the hiatus between the colonization event and establishment of O18 is 50–249 years, using the 67% HPD (Fig. 3, *right*).

$$\beta_{pre} > \alpha_{o18} > \theta_{9...13} > \beta_{o18} \quad (5)$$

Discussion

The estimates of Polynesian colonization produced by the Bayesian calibration are based on dated materials from the pre-colonization and post-colonization periods. Dated materials from the pre-colonization period recovered by paleoenvironmental investigations yield a terminus post quem for the colonization event. ^{14}C dates on materials absent during the pre-colonization period and introduced to Hawai‘i by Polynesian colonists are unambiguously assigned to the post-colonization period. They yield a terminus ante quem for the colonization event. The Bayesian calibration, guided by an explicit model that relates the dated events to the archaeological events of interest, yields a probability distribution that indicates not only when Hawai‘i was colonized by Polynesians, but also the level of confidence that one might reasonably have in the estimate.

Two calibrations, one with a potentially problematic date on an old introduced rat bone from the ‘Ewa Plain and the other with ^{14}C dates on introduced flora, were run. The calibration without the rat bone date yields a conservative estimate of the uncertainty in the analysis, with a 95% HPD region that spans almost five centuries. The additional information from the potentially problematic old rat bone reduces the uncertainty of the estimate to slightly more than three centuries. As can be seen by comparing the shapes of the distributions in Figure 1, the difference is primarily at the late end of the estimate. Adding the rat bone date yields a probability distribution that is nearly symmetrical around its mode, without the skewing apparent in the posterior probability of the estimate based solely on floral remains. Note that the early end of the distribution changes very little with the addition of the rat bone date and that the two estimates have very similar modes in the late tenth century AD. The reduction in uncertainty brought about by the addition of the rat bone date, without much change in the central tendency of the distribution, should hold more generally with the addition of new ^{14}C dating information.

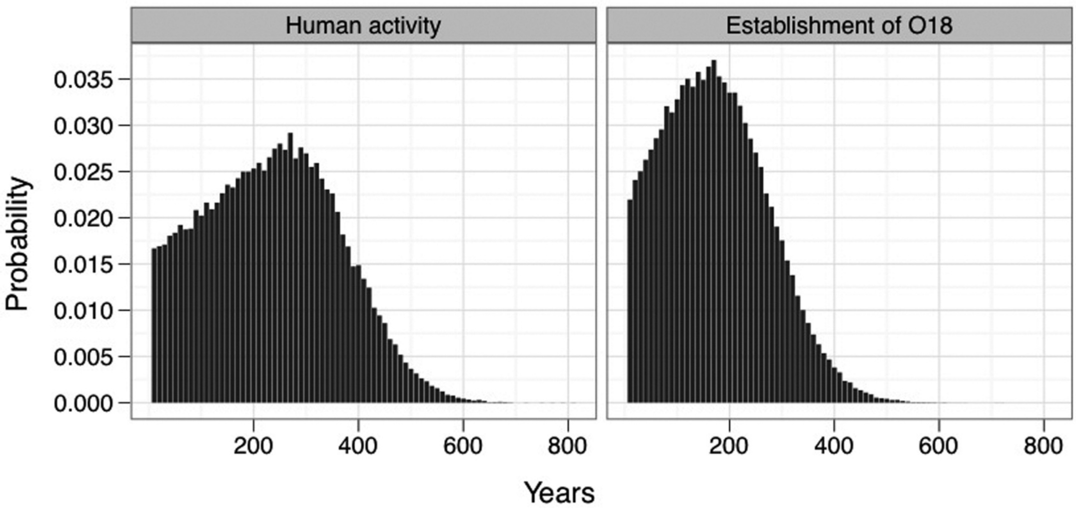

Figure 3: Hiatuses between colonization, based on (3), and other events of interest: left, human activity, 67% HPD 110–369 years; right, establishment of O18, 67% HPD 50–249 years.

Instead of the wide swings in the estimates yielded historically by ad hoc procedures, a model-based approach should yield increasingly precise estimates of the colonization event around a stable centre as new data become available.

An advantage of model-based calibration over ad hoc interpretation of ^{14}C dating results is that relations between parameters of the model are specified and can be interrogated directly. Comparing the earliest dated evidence for a variety of Polynesian-introduced materials supports traditional historical accounts of post-colonization introduction of various cultivated plants (Handy and Handy 1972: 150–151, 189). The *kukui* tree and the Polynesian rat appear to have been introduced at the time of colonization or very soon thereafter. The other introduced plants – sweet potato, gourd, breadfruit, and *kī* – were, on present evidence, introduced some three to six centuries later. These results offer some support for Green's hypothesis that sweet potato and gourd were introduced to and spread throughout eastern Polynesia together (Green 2000). They might have arrived in Hawai'i at about the same time as breadfruit and *kī*.

These results are heavily dependent on the few introduced materials that have been dated; larger samples of dated Polynesian introductions might well yield older dates. Archaeologists should select sweet potato, gourd, *kī* or other short-lived introduced material for dating whenever possible. It would also be worthwhile to date additional Polynesian rat bones, taking care to control for the possible influence of a marine component in the diet. It is potentially significant that rat bones from the lowest levels of the sinkholes, which might be expected to yield the oldest dates, have not been dated.

A decade ago, Tuggle and Spriggs (2001) observed that archaeologists working in Hawai'i were not able to identify an example of a colonization period site, and thus that there was a disparity between the colonization event and the earliest reliably dated evidence of cultural activity. A few years earlier, Graves and Addison (1995) argued that evidence for the colonization period was likely to be difficult to find, so that archaeologists should expect a disparity of this type. Recently, the presence of a disparity has been disputed by archaeologists who believe there is none. Wilmshurst *et al*. (2011a) assert, without offering any counter argument, that the argument for such a disparity is 'no longer reasonable.' However, a comparison of the colonization age estimate with the oldest material in their list of purportedly reliable dates for human activity in Hawai'i indicates a disparity of one to four centuries. To the extent that the dates assembled by Wilmshurst *et al*. (2011a) actually reflect the temporal range of confidently identified human activity in Hawai'i (Mulrooney *et al*. 2011; Wilmshurst *et al*. 2011b), these results offer support for the hypothesis that archaeologists in Hawai'i have not managed to identify and reliably date cultural deposits associated with the initial voyaging period of Polynesian colonization. Kirch (2010, in press) has taken a different tack. Based on an ad hoc estimate of the colonization event, he suggests that archaeologists have found a colonization-era deposit, Layer III of the Bellows Dune site, O18. On present evidence, the O18 site was established about a century before the earliest evidence reported by Wilmshurst *et al*. (2011a), but it post-dates the colonization event by about 200 years. Colonization period sites in Hawai'i should yield distinctive faunal assemblages, rich in the remains of animals unable to sustain formerly large populations in the face of human pressure, as elsewhere in Polynesia. Such sites appear to have escaped discovery in Hawai'i (Dye and Steadman 1990).

The four Bayesian calibration projects reported here are publicly available. Access to the projects can be gained by sending an email message to c.e.buck@sheffield.ac.uk with the subject line Dye Hawaii Colonization. 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 Dye Hawaii Colonization. Detailed instructions can be found at http://www.tsdye.com/research/hawaii_colonization.html.

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