A PALEOENVIRONMENTAL AND ARCHAEOLOGICAL MODEL-BASED AGE ESTIMATE FOR THE COLONIZATION OF HAWAI‘I

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Recent estimates of when Hawai'i was colonized by Polynesians display considerable variability, with dates ranging from about A.D. 800 to 1250. Using high resolution paleoenvironmental coring data and a carefully defined set of archaeological radiocarbon dates, a Bayesian model for initial settlement was constructed. The pollen and charcoal assemblages of the core record made it possible to identify and date the prehuman period and also the start of human settlement using a simple depositional model. The archaeological and paleoenvironmental estimates of the colonization date show a striking convergence, indicating that initial settlement occurred at A.D. 940–1130 at a 95 percent highest posterior density region (HPD), and most probably between A.D. 1000 to 1100, using a 67 percent HPD. This analysis highlights problems that may occur when paleoenvironmental core chronologies are based on bulk soil dates. Further research on the dating of the bones of Rattus exulans, *a Polynesian introduction, may refine the dating model, as would archaeological investigations focused on potential early site locations.*

Estimaciones recientes de cuando fue colonizado Hawai'i por los Polinesios muestran una gran variabilidad, con fechas superiores alrededor de 800 a 1250 d. C. Utilizando datos de núcleos paleoambientales de alta resolución y una cuidadosa definición de conjuntos de fechas arqueológicas de radiocarbono, se construyó un modelo Bayesian para el asentamiento inicial. La asociación de polen y de carbón de las muestras de núcleos hizo posible identificar y fechar el periodo pre-humano y el inicio del asentamiento humano utilizando un modelo de depósito simple. Las estimaciones arqueológicas y paleoambientales de la fecha de colonización muestran una sorprendente convergencia, indicando que el inicio del asentamiento ocurrió hacia 936–1133 d. C. en un 95 por ciento la región de mayor densidad posterior (HPD en inglés), y más probablemente entre 1000 a 1100 d. C., usando un 67 por ciento de HPD. Este análisis ilumina los problemas que pueden ocurrir cuando los fechamientos de núcleos paleoambientales se basan en las fechas del volumen de suelos. Además, investigaciones adicionales sobre la datación de huesos de Rattus exulans, *una introducción polinesia, puede refinar aún más el modelo de fechamiento, así mismo que los las investigaciones arqueológicas estén enfocadas en las posibles ubicaciones de sitios tempranos.*

Establishing a date for the initial settlement of Pacific islands has been a contentious issue among archaeologists almost since the advent of absolute dating methods (e.g., Anderson 1995). During the past roughly two decades archaeologists have made rather dramatic progress narrowing the dating disparities that plagued earlier researchers. This has been achieved by (1) redating sites that appeared to be early, which has almost always resulted in significantly younger ages (e.g., Anderson and Sinoto 2002; Anderson and Smith 1992; Dye and Pantaleo 2010; Kirch and McCoy 2007; Rolett and Conte 1995); (2) employing various forms of chronometric hygiene (Anderson 1991; Dye 2000; Spriggs and Anderson 1993) or date classification (Rieth et al. 2011; Wilmshurst et al. 2011a) to eliminate poorly provenienced samples, samples of low reliability, or those with an unknown ocean reservoir contribution; (3) great improvements in the technology of radiocarbon dating, particularly in the pretreatment of samples and the now common employment of the AMS technology, which has greatly reduced the standard error associated with date determinations; (4) use of short-lived plant taxa or plant parts to reduce the inbuilt age of samples (Dye 2000; McFadgen 1982); and (5) the application of Bayesian calibration (Denham et al.

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Table 1. Recent Hawai'i Colonization Age Estimates.

Colonization Estimate	Reference
A.D. 1214–1255 (Maui Island)	Duarte 2012
A.D. 780–1119	Dye 2011
Possibly A.D. 900–1000, probable A.D. 1000s, and colonization definite by A.D. 1200	Kirch 2011
A.D. 1220–1261 (Hawai'i Island)	Rieth et al. 2011
A.D. 1219–1266	Wilmshurst et al. 2011a

2012; Dye 2011; Dye and Pantaleo 2010; Petchey et al. 2011). We believe that most archaeologists would agree that research of the last two decades has established the broad outline of the timing of settlement throughout the Pacific, with the settlement of East Polynesia, of which Hawai'i is a part, occurring between about A.D. 900 and 1250 (Anderson and Sinoto 2002; Wilmshurst et al. 2011a). However, this is still a fairly broad range, which impedes our ability to identify the process or processes underlying such an extraordinary feat of finding and colonizing remote and isolated archipelagos and islands in the vast ocean of East Polynesia.

In this paper we focus on the dating of the Polynesian colonization of Hawai'i. Our point of departure concerns recent papers on this subject by Janet Wilmshurst and colleagues (2011a; see also Mulrooney et al. 2011 and Wilmshurst et al. 2011b);[1] Dye (2011); Kirch (2011); Rieth et al. (2011); and Duarte (2012) (Table 1). It is encouraging that the topic garnered four published papers, a published letter and reply debate, and a Master's thesis within two years, with researchers approaching the issue from three distinct perspectives. Using nearly identical methods, Wilmshurst et al. (2011a), Rieth et al. (2011), and Duarte (2012) classified large pools of archaeological radiocarbon dates based on their level of precision and accuracy and produced summed probability distributions using the most reliable dates. Their results are statistically indistinguishable, estimating colonization of Hawai'i by ca. A.D. 1220–1260. Dye (2011) created a model-based Bayesian calibration using dates from paleoenvironmental cores and from Polynesian-introduced flora and fauna to estimate colonization between A.D. 780–1119 (95 percent highest posterior density region [HPD], equivalent to two sigma). Kirch (2011) puts the issue into context by reviewing and summarizing the history of ideas relating to the timing of the colonization of Hawai'i. He then brings together the latest information, including the chronology of settlement for the Central East Polynesia region, paleoenvironmental proxy records from O'ahu and Kaua'i, dates obtained from bones of the Polynesian-introduced rat *Rattus exulans*, and the re-dating of the Bellows archaeological Site O18. He concludes (Kirch 2011:22) that colonization is "unlikely to have occurred before A.D. 1000," though he leaves open the possibility that it could have happened in the tenth century and that settlement was definitely established by A.D. 1200.

Though all of these approaches have converged upon a "short" (recent) chronology for Hawai'i in contrast to the "long" (early) chronology once favored by archaeologists (e.g., Graves and Addison 1995; Hunt and Holsen 1991; Kirch 1985), they nevertheless continue to represent a considerable range of possible settlement times, varying between about ca. 250–450 years.

We present the results of our model-based chronology building, which carries this research a bit further. Using a revised calibration chronology for the Ordy Pond paleoenvironmental sequence and an expansion of Dye's (2011) Bayesian colonization model, we address three components of the settlement debate. The first is to attempt to refine and narrow the A.D. 800–1250 time frame posited for initial settlement. Although some may feel that this is splitting hairs, considering the inherent statistical uncertainty of radiocarbon dates, a more finely calibrated date has implications for larger issues of Polynesian dispersals, including whether Hawai'i fits into a pattern of episodic Austronesian radiations throughout the Pacific, spurred by protracted ENSO events (Anderson et al. 2006), population growth models (Rieth and Athens 2013), and other issues. Secondly, we believe it is important to develop a statistical model for whatever date range or ranges we derive because it forces us to be more rigorous in specifying our assumptions and establishes the uncertainty of our estimates. Thirdly, we believe that by going through this process, we may be able to pinpoint some directions for future research on the issue of the initial colonization in Hawai'i.

Paleoenvironmental Studies

The paleoenvironmental data we utilize are from the coring investigations at Ordy Pond, a large water-filled limestone sinkhole in southwestern O'ahu (Athens 2009; Athens et al. 1999, 2002). Although many paleoenvironmental coring studies have been conducted on O'ahu and Kaua'i, and a few on the other larger islands, the Ordy Pond sinkhole has some almost unique characteristics that make it particularly suitable for obtaining high resolution chronological and environmental information. One of the most important of these is the integrity of its stratigraphic column, dating back almost 8,000 years (Uchikawa et al. 2008; Uchikawa et al. 2010). Also, because there are no drainages into the pond, the pollen record tends to emphasize the local vegetation surrounding the pond better than most other wetland locations. Lastly, the finely lamellar sediments (except for the upper part of the column) of alternating layers of authigenic carbonates and diatom tests (Uchikawa et al. 2008) and organic material (mostly detrital algal remains) suggest minimal to no bioturbation, which otherwise tends to muddle the discrete sampling intervals.

For this analysis, we are particularly interested in the proxies indicating human settlement on O'ahu and the date when they first begin to appear in the core record. The proxies consist of pollen from plants that were introduced to Hawai'i by Polynesians at the time of initial settlement or very close to the time of initial settlement.[2] The most important of these, because they produce abundant pollen and therefore tend to be easily visible in the core records, are coconut palms (*Cocos nucifera*) and candlenut (*Aleurites moluccana*, called *kukui* in Hawaiian), and there are a few others that appear fairly regularly. The microscopic charcoal particle record is also an important indicator of anthropogenic activities on O'ahu, since charcoal is entirely absent from the earlier prehuman sediments as documented by many coring studies. Thus, the possibility that the earliest charcoal might be the result of natural fires rather than human activities seems virtually nil.

A revised age depth model of the Ordy Pond core was performed using the *clam* software package, version 2.1. As discussed by Blaauw (2010:516), *clam* "attempts to provide an easy, automated, transparent, documented and adaptable environment for producing age-models from radiocarbon sequences." It allows the researcher to easily consider different age-depth model choices and to input such constraints as "presence or absence of a hiatus, reservoir effect, outliers, or anchor points." For our purposes, an important feature of *clam* is that it can produce confidence intervals for undated sampling levels (or intervals) derived from the calibrated radiocarbon ages at other points in the core sequence.

A linear interpolation dating model was selected because it involves only the assumption of a regular progression of age with depth between dating samples, which seems appropriate for a sinkhole near sea level (there are not likely to be depositional hiatuses given that the top of the sediment column is well below sea level). Although the available dates suggest relatively minor fluctuations in depositional accumulation for the prehistoric time period represented by the core (Athens et al. 1999:71), more complex models are not needed to accommodate these. Finally, the limited number of radiocarbon dates (3) and the single pollen age estimate for the timing of the advent of historic pollen do not lend themselves to the use of more complex age models (e.g., cubic spline).

In order to highlight the selection of the Ordy Pond paleoenvironmental record for modeling initial settlement, we provide comparative data from the Weli Pond core (Athens and Ward 2000), one of our best records after Ordy Pond for dating the Polynesian colonization of O'ahu. The problem is that, while the pollen and charcoal records that document initial colonization in Weli Pond fully duplicate the Ordy Pond findings, the chronology between these records is not synchronized, with Weli Pond being earlier. As will be shown, the bulk soil radiocarbon determinations obtained from Weli Pond are likely the source of the dating discrepancy.

Archaeological Data

A conservative subset of archaeological radiocarbon dates was selected for our Bayesian model. These determinations were derived from (1) charred wood and nutshells of Polynesian-introduced taxa; (2) bones of the Polynesian-introduced rat *R. exulans*, in which the dates have

Table 2. Paleoenvironmental and Archaeological Radiocarbon Age Estimates Included in the Bayesian Colonization Model.

Lab No.	Sample Material	Provenience	Conventional C14 Age (B.P.)	Period	Reference	Island	Comment
Beta-83313	Seed	Ordy Pond	1120 ± 60	Pre-colonization	Athens et al. 1999	O‘ahu	Prehuman colonization deposit
Wk-15982	Fibrous plant material, (mostly palm roots?)	Kaloko Pond	993 ± 45	Pre-colonization	Athens et al. 2007	Hawai‘i	Prehuman colonization deposit
Beta-20852b	*Aleurites moluccana*	Bellows	1330 ± 230	Post-colonization	Tuggle and Spriggs 2001	O‘ahu	Polynesian introduction
Wk-19312	*Aleurites moluccana*	Pololū	568 ± 38	Post-colonization	Field and Graves 2008	Hawai‘i	Polynesian introduction
Wk-19313	*Aleurites moluccana*	Pololū	463 ± 31	Post-colonization	Field and Graves 2008	Hawai‘i	Polynesian introduction
Beta-135125	*Aleurites moluccana*	Ka‘ohe	440 ± 40	Post-colonization	Williams 2002	Hawai‘i	Polynesian introduction
Beta-42172	*Aleurites moluccana*	Makawao	865 ± 80	Post-colonization	Kennedy 1991	Maui	Polynesian introduction
Beta-310824	*Aleurites moluccana*	Nu‘u	430 ± 30	Post-colonization	Rieth et al. 2013	Maui	Polynesian introduction
Beta-343212	*Aleurites moluccana*	Kailua	690 ± 30	Post-colonization	Unreported (Athens)	O‘ahu	Polynesian introduction
Beta-5613	*Aleurites moluccana*	Anahulu	600 ± 110	Post-colonization	Kirch 1992	O‘ahu	Polynesian introduction
NOSAMS-0809-26	*Artocarpus altilis*	Halawa	690 ± 35	Post-colonization	McCoy et al. 2010:377	Hawai‘i	Polynesian introduction
Beta-339778	bark (charred)	Hearth; Ka‘aphu	570 ± 30	Post-colonization	Rieth and Tomonari-Tuggle 2013	Maui	Combustion feature
Beta-208143	cf. *Ipomoea batatas*	Kahua 1	580 ± 40	Post-colonization	Ladefoged et al. 2005	Hawai‘i	Polynesian introduction
Beta-101871	cf. *Osteomeles anthyllidifolia*	Probable hearth; Bellows	720 ± 40	Post-colonization	Addison 2001	O‘ahu	Combustion feature
Beta-101872	cf. *Osteomeles anthyllidifolia*	Probable hearth; Bellows	670 ± 40	Post-colonization	Addison 2001	O‘ahu	Combustion feature
Beta-260904	*Chamaesyce* sp.	Hearth; Bellows	580 ± 40	Post-colonization	Dye and Dye 2009	O‘ahu	Combustion feature
Beta-138980	*Chenopodium oahuense*	Hearth; Bellows	440 ± 40	Post-colonization	Desilets 2000	O‘ahu	Combustion feature
Beta-150615	*Cocos nucifera*	Kipahulu	730 ± 50	Post-colonization	Dye et al. 2002	Maui	Polynesian introduction
Beta-233042	*Cordyline fruticosa*	Halawa	440 ± 40	Post-colonization	McCoy and Graves 2010	Hawai‘i	Polynesian introduction
Beta-150620	*Cordyline fruticosa*	Kipahulu	420 ± 50	Post-colonization	Dye et al. 2002	Maui	Polynesian introduction
Beta-251247	*Cordyline fruticosa*	Bellows	450 ± 40	Post-colonization	Lebo et al. 2009	O‘ahu	Polynesian introduction
Wk-19311	fern caudex	Hearth; Pololū	781 ± 38	Post-colonization	Field and Graves 2008	Hawai‘i	Combustion feature
Wk-19310	fern caudex	Hearth; Pololū	696 ± 35	Post-colonization	Field and Graves 2008	Hawai‘i	Combustion feature
Beta-135126	*Lagenaria siceraria*	Ka‘ohe	640 ± 40	Post-colonization	Williams 2002	Hawai‘i	Polynesian introduction
Beta-260905	*Sida fallax*	Hearth; Bellows	400 ± 40	Post-colonization	Dye and Dye 2009	O‘ahu	Combustion feature
Beta-45363	*Syzgium malaccense*	Luluku	1060 ± 80	Post-colonization	Leidemann et al. 2003	O‘ahu	Polynesian introduction
Beta-28136	*Tetraplasandra* sp.	Hearth; Kualoa	840 ± 40	Post-colonization	Carson and Athens 2007	O‘ahu	Combustion feature
Beta-28135	*Tetraplasandra* sp.	Hearth; Kualoa	650 ± 40	Post-colonization	Carson and Athens 2007	O‘ahu	Combustion feature
CAMS-25560	*Rattus exulans*	‘Ewa	1030 ± 60	Post-colonization	Athens et al. 1999:247	O‘ahu	Polynesian introduction
CAMS-26396	*Rattus exulans*	‘Ewa	990 ± 50	Post-colonization	Athens et al. 1999:247	O‘ahu	Polynesian introduction
CAMS-25561	*Rattus exulans*	‘Ewa	680 ± 50	Post-colonization	Athens et al. 1999:247	O‘ahu	Polynesian introduction
SR-5081	*Rattus exulans*	‘Ewa	460 ± 50	Post-colonization	McDermott et al. 2000	O‘ahu	Polynesian introduction
SR-5085	*Rattus exulans*	‘Ewa	650 ± 50	Post-colonization	McDermott et al. 2000	O‘ahu	Polynesian introduction
SR-5080	*Rattus exulans*	‘Ewa	740 ± 50	Post-colonization	McDermott et al. 2000	O‘ahu	Polynesian introduction
SR-5082	*Rattus exulans*	‘Ewa	990 ± 130	Post-colonization	McDermott et al. 2000	O‘ahu	Polynesian introduction

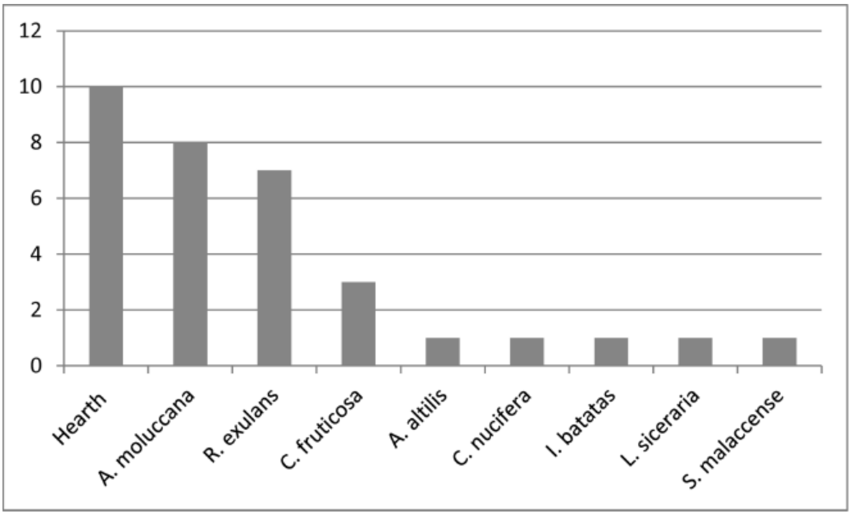

Figure 1. Count of radiocarbon dates by origin or type, including hearth features, rat bones, and various Polynesian-introduced plant taxa. These include *A. moluccana* (candlenut, kukui), *R. exulans* (Pacific rat), *C. fruticosa* (ti, kī), *A. altilis* (breadfruit, ʻulu), *C. nucifera* (coconut, niu), I. batatas (sweet potato, ʻuala), *L. siceraria* (bottle gourd, ipu), and *S. malaccense* (mountain apple, ʻōhiʻa ʻai).

been obtained from properly pretreated/processed collagen samples (Rieth and Athens 2013); and (3) charred wood/plant material from short-lived plant taxa/parts obtained from archaeological combustion features (Table 2). This selection of radiocarbon dates is conservative in that the presence of these plants, animals, and archaeological features is wholly dependent on people and thus must belong to the post-colonization period. Contemporaneous, or older, dates obtained from identified short-lived native plant taxa/parts collected from non-feature archaeological midden or cultural deposits were avoided because the sample association with an archaeological event was ambiguous, and for Maui and Hawaiʻi Island, there is a possibility that the charcoal could be from natural fires predating humans. With regards to the Polynesian-introduced plants, the in-built age of these samples (e.g., *A. molluccana*, *C. nucifera*, *Syzgium malaccense*, and others) is of no concern, because the target event of interest is not the specific archaeological feature or cultural deposit, but rather the timing of human colonization, which cannot postdate the growth of the plant.

Thirty-three archaeological dates are used in our Bayesian model; 16 are from Polynesian-introduced plants, seven are from *R. exulans* bones, and 10 are from short-lived plant materials from archaeological combustion features (Figure 1). Six of these dates were included in Dye's (2011) initial presentation of the Bayesian model. Geographically, 19 of the dates are from Oʻahu, nine are from Hawaiʻi Island, and five are from Maui (Figure 2).

Statistical Modeling

The Bayesian model was calibrated using the BCal software (Buck et al. 1999) and the IntCal09 Northern Hemisphere curve (Reimer et al. 2009). As described by Dye (2011:132), "A Bayesian model to estimate the Polynesian colonization of Hawaii 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." An advantage of Bayesian models for archaeology and paleoenvironmental studies derives from the incorporation of prior knowledge into the statistical calculations, thereby "bookending" or limiting probability distributions. The application of Bayesian statistics to archaeological chronologies is fully described by Buck et al. (1996).

The Hawaiʻi colonization model can be expressed as:

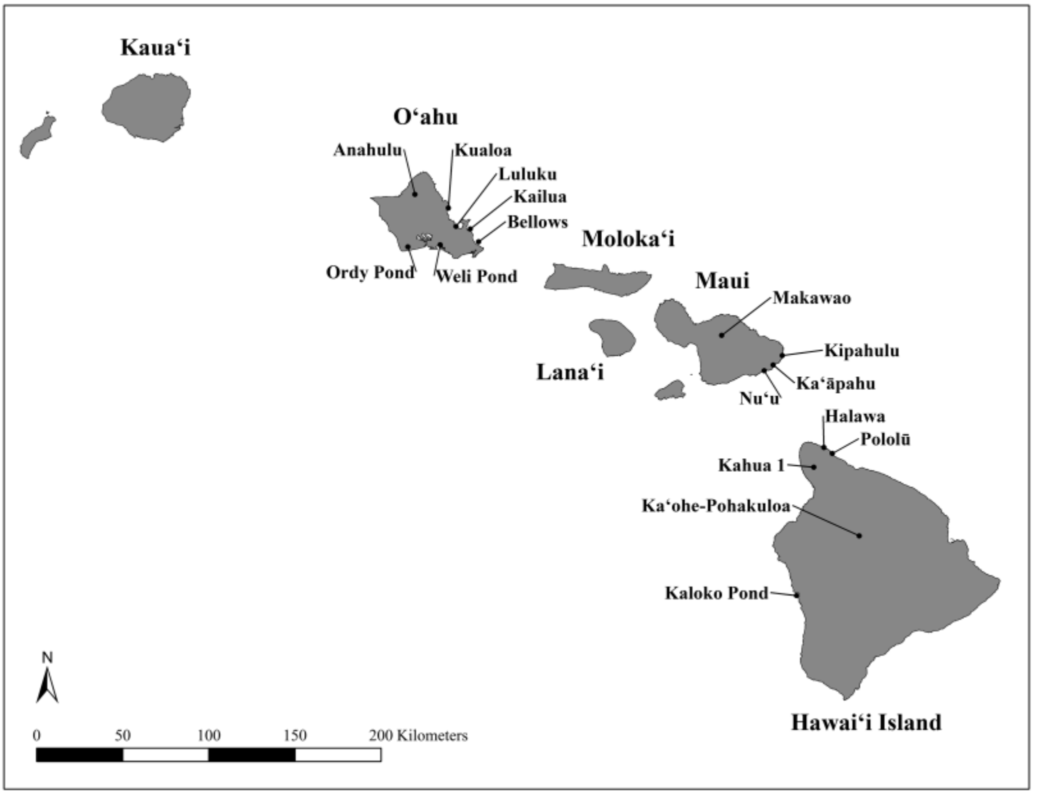

Figure 2. Hawaiian archipelago displaying the locations from which pre- and post-colonization radiocarbon dates were obtained for the Bayesian model and also the paleoenvironmental coring locations.

$$\alpha_{pre} > \beta_{pre} = \alpha_{post} > \beta_{post} = 0$$

where α_{pre} and β_{pre} represent the beginning and end of the pre-colonization period, while α_{post} and β_{post} signify the beginning and end of the post-colonization period; ">" means "older than." Again from Dye (2011:132), "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." While our present model treats the settlement of the Hawaiian archipelago as a unitary phenomenon, we leave open the possibility that future high resolution data might disclose a sequence of initial settlement for the different islands (or even of district/regional settlement within the individual islands).

The pre-colonization period includes two radiocarbon determinations (Table 2). One of these, used in Dye's (2011) earlier model, is from a seed obtained from Ordy Pond at the 668 cmbs interval, which is well below the earliest signs of human activities in this record (which definitely begins at the 630–632 cmbs interval, though, less conclusively, may be as early as the 643–644.5 cmbs interval [see Athens et al. 1999:176]). The other pre-colonization date was obtained from fibrous plant material, mostly endemic palm (*Pritchardia* sp.) roots, collected from the base of a paleoenvironmental core at Kaloko Pond, Pu‘uhonua o Hōnaunau National Historical Park (Athens et al. 2007). The pollen record for this level of the core indicates an entirely pristine lowland native forest in this area, which other paleoenvironmental research has shown to antedate the arrival of humans (Athens 1997; Athens et al. 2002). Ideally, dates included in the pre-colonization group relate to deposits immediately predating paleoenvironmental evidence for human activity because such dates yield more precise estimates of the colonization event.

Results

Paleoenvironmental Data

The Ordy Pond pollen diagram (Athens 2009; Athens et al. 1999, 2002) is quite interesting because even a glance shows there are substantial changes occurring at what is clearly the prehistoric/prehuman interface of the record. The first appearance of charcoal particles occurs in the 630–632 cmbs interval, along with a "possible" coconut pollen grain, and there are also several major vegetation shifts.[3] At the next higher study interval at 618–619.5 cmbs, we see not only a major increase in charcoal particles, but also the definite presence of coconut, and there are major changes in the frequency of other plant taxa as well. In fact, a transformation of the landscape had occurred in a matter of scarcely 100 years, and perhaps in much less time (Athens 2009:1495; Athens et al. 2002:63). Extensive archaeological investigations on the ʻEwa Plain where Ordy Pond is located show that very few, if any, people were occupying this arid landscape at this early period for another 100 to 200 years (Athens et al. 2002) and that it is not until after about A.D. 1250 that the charcoal particle record suggests local settlement (the density and size of charcoal particles substantially increase at this time, suggesting a more local origin, and hence proximal settlement and agriculture [Athens et al. 1999:83–85; Clark 1988; Patterson et al. 1987]). Presumably this was because the aridity of the ʻEwa Plain would have been unfavorable for habitation and agriculture compared to many other areas on Oʻahu.

Thus, at Ordy Pond, we regard the critical study interval for Hawaiian colonization as the 630–632 cmbs interval. To date this interval, we utilized a linear interpolation model based on three AMS radiocarbon determinations on two seeds and one piece of wood (the uppermost ^{14}C sample), which were almost evenly spaced in the stratigraphic column. We also estimated a date of 120 B.P. (A.D. 1830) for the upper part of the core when historic pollen first began to appear in the record; Western contact and influence had become pervasive in the islands by this date. Obviously our task would be much easier if we could directly radiocarbon date the two intervals of interest, but unfortunately plant material for dating in this core was limited to just the three dated samples in the entire column (the algal mat lenses were inappropriate for dating [Athens et al. 1999:63–65]). Thus, it was necessary to interpolate dates for the pollen and charcoal particle sampling intervals. The *clam* statistical program provided an interpolated age estimate at a 95 percent confidence interval for the 630–632 cmbs interval of A.D. 936–1133 (Table 3). By way of comparison, an estimate is also provided for the next higher interval at 618–619.5 cmbs. An external comparison is also provided by two intervals from a core obtained from Weli Pond along the south coast of Oʻahu (Figure 2). The deepest Weli Pond interval having charcoal particles along with a single grain of *kukui* pollen is at 560–563 cmbs, and the next highest interval at 545–548 cmbs displays substantial vegetation changes, three Polynesian plant introductions (*kukui*, *C. nucifera*, and *Cordyline fruticosa*), and also a quantum increase in charcoal particles.

As may be seen in Table 3, the two cores provide conflicting dating results, with the Weli Pond record indicating colonization at A.D. 703–966 and Ordy Pond at A.D. 936–1133, with the latter only minimally overlapping the date range of Weli Pond at two standard deviations. We have greater confidence in the Ordy Pond dates because they were obtained from macro-plant remains that must derive from the immediate environs of Ordy Pond, while the Weli Pond dates derive from bulk sediment. The problem is that the bulk sediment apparently incorporated older carbon material deposited from erosion of the interior slopes through colluvial and fluvial action (see Anderson 1994 for a discussion of the problem of bulk soil radiocarbon dates in pollen cores from Mangaia, Cook Islands). That this is probably the case is suggested by the date for the latest clearly prehuman vegetation at Ordy Pond, which is A.D. 829–1065 (Table 3).[4] In our view, it is not realistic for dates of major vegetation changes of the landscape to differ at locations on leeward Oʻahu separated by only 17 km with no significant geographical barriers or differences in the paleo-vegetation communities. Thus, we feel confident that the Weli Pond dates are too early due to the incorporation of older carbon in the bulk soil radiocarbon samples.

Archaeological Bayesian Model

The results of the Bayesian calibration of radiocarbon dates obtained from archaeological fea-

Table 3. Interpolated Age Estimates from *Clam* Statistical Program, Ordy Pond and Weli Pond (95 Percent Confidence Interval).

Location	Depth (cmbs)	Calibrated 2-sigma Date Range (yrs. B.P.)	Calibrated 2-sigma Date Range (yrs. A.D.)	2-sigma Age Spread (yrs.)	Significance
Ordy Pond	618–619.5	774–957	993–1176	183	Substantial native vegetation changes, abundant charcoal, and Polynesian-introduction
Ordy Pond	630–632	817–1014	936–1133	197	Substantial native vegetation changes, first charcoal, and possible Polynesian-introduction
Ordy Pond	651–653	885–1121	829–1065	235	Unchanged native forest, no charcoal, no Polynesian-introductions
Weli Pond	545–548	926–1162	788–1024	236	Substantial native vegetation changes, abundant charcoal and Polynesian-introductions
Weli Pond	560–563	984–1247	703–966	263	Minor native vegetation changes, first charcoal, and Polynesian-introduction

tures, Polynesian-introduced plant taxa, and bones of Polynesian-introduced rats yield an estimate of the colonization date, given the data and model parameters. This date converges with the interpolated estimate obtained from Ordy Pond. The 95 percent HPD for an iteration of the model using the dates from only Polynesian-introduced flora and archaeological combustion features is A.D. 1000–1210 (Figure 3). Adding the *R. exulans* bones to the model produces a 95 percent HPD of A.D. 940–1129, 60–70 years older than the model that excludes the rat bone dates.

Conclusions

Within the last few years, renewed inquiry into the timing of Polynesian colonization of Hawai‘i has resulted in estimates ranging from ~A.D. 800 to 1250. Our reanalysis of the Ordy Pond paleoenvironmental record using *clam* software and an expansion of Dye's (2011) model-based Bayesian calibration converge on the 95 percent HPD range of A.D. 940–1129 as the best estimate of the colonization event.

If a 67 percent HPD is used, the Polynesian colonization of Hawai‘i would most probably have occurred between about A.D. 1000 and 1100. Scarcely 50 years later in the Ordy Pond record, by A.D. 993–1176, population expansion on O‘ahu is evident in substantially increased charcoal counts and major pollen changes at Ordy Pond. This expansion is mirrored in the archaeological data in the form of radiocarbon dated Polynesian plant introductions and combustion features (Table 2).

With respect to the rat bone dates, admittedly there are unresolved questions regarding the po-

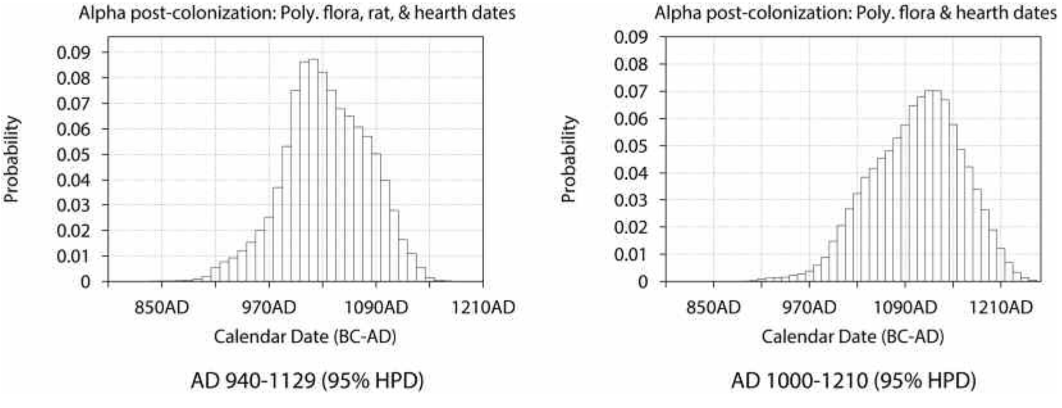

Figure 3. 95 percent HPD for two iterations of the Bayesian model, excluding (right) and including (left) Polynesian rat bone dates.

tential for a marine dietary component for the rats (Commendador et al. 2012; Richards et al. 2009), or the possibility of their intake and metabolism of ^{14}C-depleted carbon in their food as a result of the ʻEwa Plain's limestone substrate.[5] However, at face value, the Bayesian model and Ordy Pond age interpolation suggest settlement must have occurred, with a 95 percent probability, between A.D. 940 and 1130.

As Dye (2011:137) predicted, the addition of more data has improved the precision of the age estimate for colonization. Our results offer analytical support for Kirch's (2011:22) preference for a colonization date after A.D. 1000. We can now also see that Wilmshurst et al. (2011a), Rieth et al. (2011), and Duarte's (2012) calculations document the secure establishment of colonizing populations in Hawaiʻi, approximately 10–280 years after initial colonization.

As a practical matter, this research has provided insight into an apparent dating inconsistency between the Ordy Pond and Weli Pond cores. Consideration of the latest date for intact native vegetation in the Ordy Pond core, at A.D. 829–1065 (Table 3), suggests that the earlier dates of the Weli Pond core must be due to the incorporation of older carbon in the bulk soil dating samples of this core. For much paleoenvironmental research, such bulk soil dates on wetland/lake soils (where not contaminated by ^{14}C-depleted carbon from groundwater or limestone sources) probably have sufficient precision. The problem, however, is that the level of required precision clearly varies situationally. Thus, while the variation between the Weli Pond and the Ordy Pond dates might be regarded as relatively minor for some research problems, it is too large if we are attempting to narrow the timing of Polynesian colonization in Hawaiʻi.

Our results highlight two future research directions. One is that a systematic, geographically-informed research program should be initiated to select and test potential early settlement locales. No such program has been undertaken in Hawaiʻi, and the current sample and distribution of known early archaeological deposits has largely been a product of chance investigations. Currently, the deposits at Bellows and Kualoa, on Oʻahu, and Pololū, on Hawaiʻi Island, are reliably dated to this initial colonization period, but there must be others. Second, further research on the dating of *R. exulans* bones is required to determine whether the dietary habits of *R. exulans* need to be accounted for in radiocarbon calibrations, and also to refine the date when rats were introduced to Hawaiʻi and to evaluate the model for exponential growth of rat populations following introduction by colonizing Polynesians (Athens 2009; Athens et al. 2002).

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Notes

1. Mulrooney et al. (2011) critiqued several of Wilmshurst et al.'s (2011a) date classification criteria, noting that they are "overly strict and exclude accurate estimators of early cultural activity" (Mulrooney et al. 2011:E192). They reanalyzed Wilmshurst et al.'s data sets using a different set of criteria, resulting in estimates of A.D. 1184, 1230, and 1268 for colonization of Hawaii (the range of ages is based on the application of different criteria). In their reply to Mulrooney et al. (2011), Wilmshurst et al. (2011b) point out, among other issues, that Mulrooney et al.'s reanalysis only increases the age of colonization estimates proportional to the increased statistical error and uncertainty of the dates introduced by their relaxed selection criteria.

2. The Polynesian introduction of numerous plant taxa to Hawai'i has been discussed by botanists (e.g., Nagata 1985; Wagner et al. 1990). Confirmation of botanical assessments for the introduction of many agricultural and non-agricultural taxa has been confirmed palynologically in numerous wetland cores in which the pollen of these taxa (e.g., coconut and *kukui*) is coincident with, or follows, the expected initial arrival of Polynesians but is absent from earlier core intervals (Athens 1997:267–269). Some taxa, however, have been difficult to identify palynologically due to rarity or non-diagnostic characteristics. There have been a few modifications of several of the botanical assessments.

3. Note that substantial changes in the pollen frequency of several plant taxa begin in the earlier interval at 643–644.5 cmbs. While these earlier changes may be part of the same process, human activities cannot be unambiguously associated with them.

4. The latest clearly prehuman vegetation for the Pu'uhonua core on Hawai'i Island is slightly later at A.D. 972–1160, which entirely falls after the Weli Pond date, though it is within the earlier half of the Ordy Pond range. Whether this means that Hawai'i Island was settled slightly later than O'ahu, or only that the Pu'uhonua area did not begin to manifest the effects of Polynesian settlement until slightly later due to the much larger size of this island, is unclear.

5. While representing a different environmental and edaphic context, Wilmshurst et al. (2008:7678) did not observe marine reservoir offsets in their stable isotope measurements on a large suite of dated rat bones in New Zealand.

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