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BAYESIAN ANALYSIS OF HIGH-PRECISION AMS ^{14}C DATES FROM A PREHISTORIC MEXICAN SHELLMOUND

Douglas J Kennett[1,2] • Brendan J Culleton[1] • Barbara Voorhies[3] • John R Southon[4]

ABSTRACT. We establish a precision accelerator mass spectrometry (AMS) radiocarbon chronology for the Archaic period Tlacuachero shellmound (Chiapas, Mexico) within a Bayesian statistical framework. Carbonized twig samples were sequentially selected from well-defined stratigraphic contexts based on iterative improvements to a probabilistic chronological model. Analytical error for these measurements is ±15 to 20 ^{14}C yr. This greater precision and the absence of stratigraphic reversals eclipses previous ^{14}C work at the site. Based on this, we establish a chronological framework for a sequence of 3 clay floors dating to between 4930 and 4270 cal BP and determine that the bedded shell deposits that formed the mound accumulated rapidly during 2 episodes: a lower 2-m section below the floors that accumulated over a 0–150 cal yr period at 5050–4875 cal BP and, an upper 3.5-m section above the floors that accumulated over a 0–80 cal yr period at 4380–4230 cal BP.

INTRODUCTION

Several major methodological, conceptual, and procedural improvements for building precise archaeological site chronologies have coalesced during the last decade. A new generation of modified accelerator mass spectrometers enables the analysis of increasingly small samples with analytical error in the ±15 to 20 ^{14}C yr range when combined with low backgrounds on procedural blanks and appropriate primary and secondary standards (Beverly et al. 2010). Archaeologists are also paying greater attention to the collection of short-lived materials (e.g. carbonized seeds, twigs, and bone) to avoid the old-wood problem (Kennett et al. 2002) and to anchor their chronologies more effectively (Waters and Stafford 2007; Kennett et al. 2008). Bayesian statistical analysis provides a framework that reinforces the importance of stratigraphic context and the association of materials being ^{14}C dated (Buck and Millard 2004; Bayliss and Bronk Ramsey 2004; Bayliss et al. 2007). These improvements taken together challenge us to revisit established chronological sequences and the interpretations derived from them.

In this paper, we draw upon these advances to establish a new high-precision chronology for the Tlacuachero shellmound from the Pacific coast of southern Mexico. We start with an overview of these large shellmounds and our interpretations of them with respect to the subsistence and settlement strategies used by the people that occupied this coast during the Middle Holocene (7500–4000 cal BP). This will provide the reader with an appreciation for the significance of the more precise Tlacuachero chronology. We also hope to show how the Bayesian approach to chronology building assisted us with this analysis and will frame future work at other shellmounds.

ARCHAEOLOGICAL BACKGROUND

We establish a new AMS ^{14}C chronology for the site of Tlacuachero, one of 6 shellmounds known from the Pacific coast of Chiapas, Mexico (Figure 1). Five of these sites, including Tlacuachero, occur along the interior edge of the Acapetahua estuary and date within the Late Archaic period (~5500 to 3800 cal BP; Voorhies 1976, 2004). The remaining shellmound, Cerro de las Conchas, is positioned farther to the south on the interior edge of the El Hueyate swamp. This shellmound dates to the middle Archaic period (~7500 to 5500 cal BP; Clark 1986; Voorhies et al. 2002).

[1]Department of Anthropology, University of Oregon, Eugene, Oregon 97403, USA.
[2]Corresponding author. Email: dkennett@uoregon.edu.
[3]Department of Anthropology, University of California, Santa Barbara, California 93106, USA.
[4]Earth System Science Department, University of California-Irvine, Irvine, California 92612, USA.

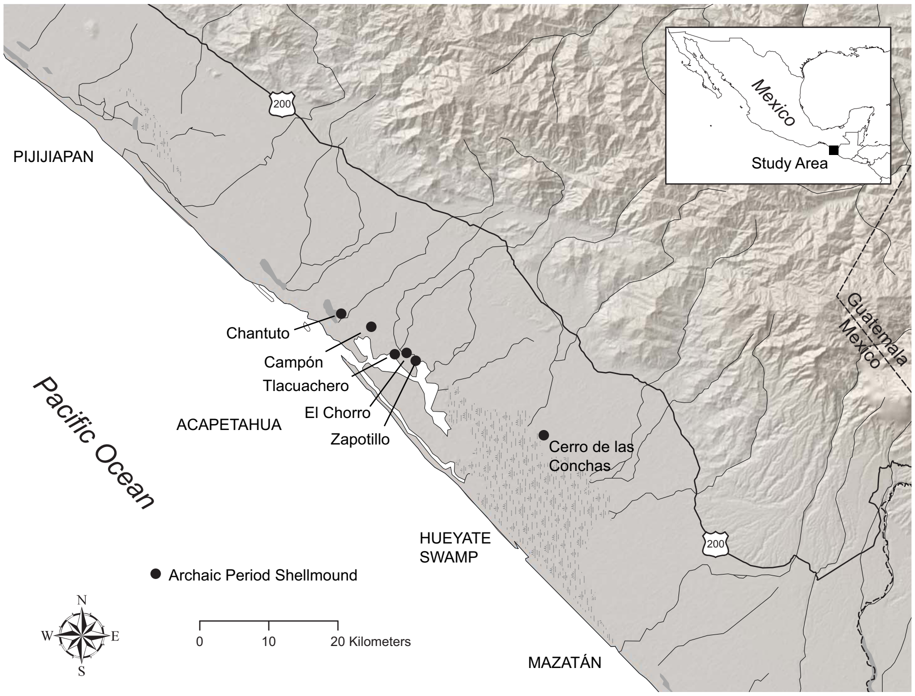

Figure 1 Locations of Archaic period sites along the Pacific coast of southern Mexico mentioned in text. Inset shows study area on the southern Pacific coast of Chiapas, Mexico.

The shellmounds in the Acapetahua estuary range in size from 0.2 to 1.17 hectares. They are highly visible in aerial and satellite imagery due to their size and elevations ranging between 3 and 11 m above the current ground surface. All of these mounds extend well below the modern ground surface and are largely obscured by the accumulated sediments and mangrove forests of this coastal wetland environment. Dry land is limited in the littoral zone and these mounds form artificial islands that are still used today by the local inhabitants. Drucker (1948) initially located and described the Chantuto shellmound and this has become the namesake for these late Archaic period people (Chantuto People). It was Drucker's description of an aceramic (not ceramic-bearing) shellmound that initially attracted Voorhies (1976) to the region to explore early coastal sites. Her excavations and chronological work over the last 40 yr generally place the accumulation of these mounds between ~5500 and 3800 cal BP (Voorhies 2004). The dates on Tlacuachero itself range from 5500 to 4000 cal BP, but chronological work at the site was constrained by the large sample sizes required for conventional ^{14}C dating. There were also several major ^{14}C reversals in the sequence suggesting that the deepest deposits were the youngest, an unlikely scenario given the stratigraphic integrity of these deposits. In some instances, analytical error margins were also exceedingly high.

Voorhies and Kennett have argued that these shellmounds were not permanent settlements during the Archaic period (Voorhies 2004; Kennett et al. 2006) but staging areas for extracting resources from the adjacent estuarine environment. The mounds are predominantly composed of densely packed aceramic layers of marsh clam shells (*Polymesoda radiata*) with an overlying ceramic-bearing stratum of dark soil containing a mix of more recent cultural materials. The shell deposits are distinctively bedded with alternating layers of burned and unburned shells. Marsh clams in burned layers are more fragmented than in unburned layers and the overall pattern has been interpreted as periodic visitation to these localities. This is consistent with the overall lack of domestic features (e.g. housefloors, postmolds, formal hearths) and a low diversity of tools and faunal remains. Oxygen isotope seasonality studies suggest that shellfish during the earlier phases of occupation were collected throughout the year with an emphasis during dry season months and a shift at the very tail end of the Late Archaic towards largely wet season exploitation (Kennett and Voorhies 1996; Voorhies et al. 2002). Due to the limitations of previous ${}^{14}C$ work, the overall chronological picture at Tlacuachero and the other late Archaic period shellmounds in the Acapetahua region is that they accumulated gradually over a 1500-yr period.

BAYESIAN STATISTICAL APPROACH

Building Bayesian chronological models for archaeological sequences involves the use of prior knowledge about archaeological sites and regional cultural histories. Stratigraphic relationships between ${}^{14}C$ samples and the cultural deposits of interest provide the focus. The approach is well-established in Britain (Buck et al. 1991; Bayliss and Bronk Ramsey 2004; Bayliss et al. 2007) and has been used since the mid-1990s by English Heritage as a cost-effective way of building site chronologies. We use OxCal software (Bronk Ramsey 1995, 2001, 2005), which provides a pre-existing Bayesian environment to build and refine chronologies. Model building and testing is completed in an iterative fashion with new data informing and improving chronological models for individual sites.

Traditional statistical inference in ${}^{14}C$ dating relies strictly on probability distributions to determine the likelihood that 2 events or site occupations in the past were synchronous or sequential. A commonly applied test of contemporaneity between 2 or more ${}^{14}C$ dates is the method of Ward and Wilson (1978), which produces a test statistic with a chi-squared distribution based on the conventional ${}^{14}C$ ages weighted by their errors. This method is typically used to identify outliers, and is automatically used when combining ${}^{14}C$ ages in OxCal and CALIB (Bronk Ramsey 2005; Stuiver et al. 2010). A failed test (i.e. a high test statistic) indicates that the dates are unlikely to be contemporary, and therefore should not be combined through averaging. A subtle and often overlooked issue with the Ward and Wilson test is that a low test statistic does not mean that the dates are necessarily contemporary, merely that there is no evidence to the contrary. It is up to the researcher to decide based on the associations of the dated samples whether it makes sense to assume they are synchronous and therefore be averaged (e.g. multiple measurements on a single bone, a single hearth, or animal bones at a mass kill). Because of these sorts of prior assumptions and the contextual knowledge invoked, Buck et al. (1991) pointed out that the Ward and Wilson test is itself a Bayesian tool, though it is rarely couched in those terms.

A serious limitation of Ward and Wilson's method is that it compares only the conventional ${}^{14}C$ ages and their associated Gaussian error distributions, not the typically non-normally distributed calibrated age ranges. The vagaries of counting statistics in ${}^{14}C$ dating and fluctuations in the calibration curve can result in substantial overlap of probability distributions even if 2 events are known not to be contemporary based on the stratigraphic record. For example, during a prolonged ${}^{14}C$ plateau (e.g. the Younger Dryas) changing atmospheric ${}^{14}C$ concentrations can produce a series of conventional ${}^{14}C$ ages that appear to fall within a remarkably tight span, which a χ^2 test fails to discriminate between, and when calibrated overlap across several centuries. In this case, the dates themselves and standard parametric statistics can take the chronological interpretations no further in any productive direction. In contrast to classical statistics, Bayesian statistical analysis derives posterior information (*a posteriori*) by combining prior information (*a priori*), a likelihood function (a particular probability function) and the available data (Buck and Millard 2004:vii). In archaeological chronology building, a variety of non-quantitative contextual information (e.g. stratigraphic position, diagnostic artifact assemblages) can be integrated with probability distributions from ^{14}C dates (Bayliss and Bronk Ramsey 2004) to trim confidence intervals and refine the age of a sequence of depositional events.

Precise chronological models are dependent upon: 1) careful stratigraphic excavation and the exact recording of ^{14}C samples within the depositional sequence; 2) the selection of short-lived organisms for accelerator mass spectrometry (AMS) ^{14}C dating (e.g. carbonized seeds, twigs, marine shells, animal bones); 3) proper chemical protocols for processing samples; 4) an understanding of taphonomic processes affecting samples; and 5) the appropriate chronological model type and associated settings (sample sequences, phasing, etc.). Outdated ^{14}C dates with high error ranges from previous excavations may be used as an initial guide for model development when coupled with stratigraphic information, but the inescapable (if rarely acknowledged) reality is that large measurement errors not only reflect poor precision in the estimate of the ^{14}C content of the sample, but they undermine the *accuracy* of the age estimates by widening the possible range of actual calendar ages that could produce that measured age. Put another way, there are more calendar years that will produce a conventional ^{14}C age X when the instrument's precision is ±200 ^{14}C yr than when it is ±20 ^{14}C yr. The degree of precision and accuracy needed is largely dependent upon the research question being addressed and the temporal scale of the behaviors represented archaeologically. It is often necessary to start over with a clear idea of site stratigraphy, sample types, and locations, and the low analytical error afforded by new AMS ^{14}C technology. This was the case at Tlacuachero.

PRECISION AMS ^{14}C DATING

The precise and accurate AMS ^{14}C dates presented in Tables 1–3 were dependent upon: 1) sample selection (short-lived material); 2) chemical preparation; and 3) upgrades to the Keck Carbon Cycle Accelerator Mass Spectrometer at the University of California (UC), Irvine. Carbonized twig samples (unidentified to species) were selected under a microscope and prepared for ^{14}C dating at the Archaeometry Facility at the University of Oregon (UO). After removing adhering sediment, samples were subjected to standard acid/base/acid (ABA) pretreatment consisting of repeated baths in 1N HCl and NaOH at 70 °C for 30 min on a heater block. The initial acid wash dissolved any carbonate contamination. Base washes extracted humic acids accumulated from soil organic matter, signaled by brown discoloration in the NaOH solution. Base washes were repeated until the solution remained clear, indicating that potential contaminants were absent. A final acid wash removed secondary carbonates formed during the base treatment. Samples were then returned to neutral pH with two 15-min baths in deionized water at 70 °C to remove chlorides, and dried on a heater block. Sample CO_2 was produced by combustion at 900 °C for 3 hr in evacuated sealed quartz tubes using a CuO oxygen source and Ag wire to remove sulfur and chlorine compounds. Primary (OX-1) and secondary (FIRI-D, FIRI-H) standards were selected to match the sample type and expected age and underwent the same chemical steps for quality assurance.

The CO_2 generated at the UO was reduced to graphite at 550 °C using a modified hydrogen reduction method onto a Fe catalyst (Alfa Aesar mesh –325 lots JO2M27 and L16P22; Santos et al. 2004, 2007), with reaction water drawn off with $Mg(ClO_4)_2$. The Fe catalyst used is baked monthly at 300 °C for 3 hr in air, and subsequently baked at 400 °C in H_2 for 45 min prior to analysis, to reduce modern carbon contamination. Solid graphite samples were pressed into Al targets and loaded on the target wheel with OX-1 (oxalic acid), other known-age standards, and wood blanks, for AMS analysis. AMS ^{14}C measurements were made on a modified National Electronics Corporation compact spectrometer with a 0.5MV accelerator (NEC 1.5SDH-1). The primary modifications impacting analytical measurement error are the use of a spherical ionizer ion source operating at high cathode voltage (9 kV) to generate intense C^- beams and injection beam line changes for better ion-optical matching to the accelerator. The injector modifications include the addition of a 2nd einzel lens plus an increased ion source voltage from 55.5 to 65.5 kV combined with a redesigned large-gap injector magnet (DF01319; Beverly et al. 2010). These alterations allow for analytical error in the 2–3‰ range for near-modern samples under currents of up to 225 µA of $^{12}C^-$, 40–50 µA higher than previously. For the current study, this translates to analytical error in the ±15 to 20 ^{14}C yr range for Middle Holocene samples. Precision decreases with sample age, with samples in the Late Pleistocene returning errors in the ±30 to 40 ^{14}C yr range. All ^{14}C ages were δ^{13}C-corrected directly via AMS for mass-dependent fractionation (Stuiver and Polach 1977) and calibrated with OxCal 3.10 (Bronk Ramsey 1995, 2001, 2005) using the IntCal09 Northern Hemisphere atmospheric curve (Reimer et al. 2009). Calibrated and modeled ranges are reported at the 2-σ level unless specified otherwise, and discontinuous ranges with gaps ≤30 cal yr are given as a whole span. It is worth noting with low measurement errors the difference between 1- and 2-σ ranges is often <50 cal yr during the period of interest. These data provide the raw material to build the precision chronological model described below.

ITERATIVE CHRONOLOGICAL MODELING

Redating the Tlacuachero mound was done iteratively in 3 stages, whereby we could initially characterize the broad outline of the entire sequence, and then begin to target specific archaeological features and periods of interest to refine our understanding of the tempo and mode of site use through the Archaic. This approach has the advantage of being relatively cost-efficient because we are not throwing money away on redundant dates, and it also leads to a more careful consideration of the site stratigraphy and formation processes because the stratigraphic arguments incorporated in the Bayesian model must be made explicit. For example, as will be described below, while trying to establish the age of one of the clay floors through multiple dates on charcoal embedded in that floor, we relied on the excavator's (Voorhies) knowledge of floor construction gained through both decades of excavation experience and familiarity with the ethnographic literature to decide *a priori* whether we should expect the charcoal to be old material incorporated into the construction medium, or whether this was material that was incorporated into the floor over decades or centuries of use as a living surface. In the former case, the dates would be considered a *terminus post quem* for floor construction; in the latter case, the dates would be considered an unordered group of dates modeled collectively as a *phase* that postdates floor construction and predates the subsequent deposition of shell above it. The dates themselves tell us next to nothing about which scenario is more likely to be correct, and either assumption can be modeled with OxCal, leading to different results. This example points to the most serious caveat to a Bayesian approach: the model is only as good as the priors, and ill-conceived assumptions can lead to erroneous results.

First Round

The portion of the shellmound available for sampling comprised a roughly 5-m-deep section of burned and unburned shell deposits, punctuated by 3 clay floors between ~4.2–4.5 m below datum (Figure 2). Establishing the date when these floors were constructed, and how long they may have been used as living or working surfaces before being buried by subsequent shell deposition were key goals for the revised dating program. There is no way to directly date the floors themselves, but within a Bayesian model implemented by OxCal we can produce reliable estimates of these events indirectly. We began with the assumption that all the deposits were in undisturbed stratigraphic order so that the series of dates could be placed in an ordered *sequence* by depth. We based this assumption on the fact that the horizontally bedded shell deposits are relatively undisturbed except in the uppermost deposits that were affected by later ceramic using peoples that used these locations (Voorhies 2004). The first 5 samples were selected to constrain the ages of the 3 floors: one below the deepest floor, Floor 3; one between Floors 2 and 3; two between Floors 1 and 2; and one from the surface of Floor 1 (Table 1).

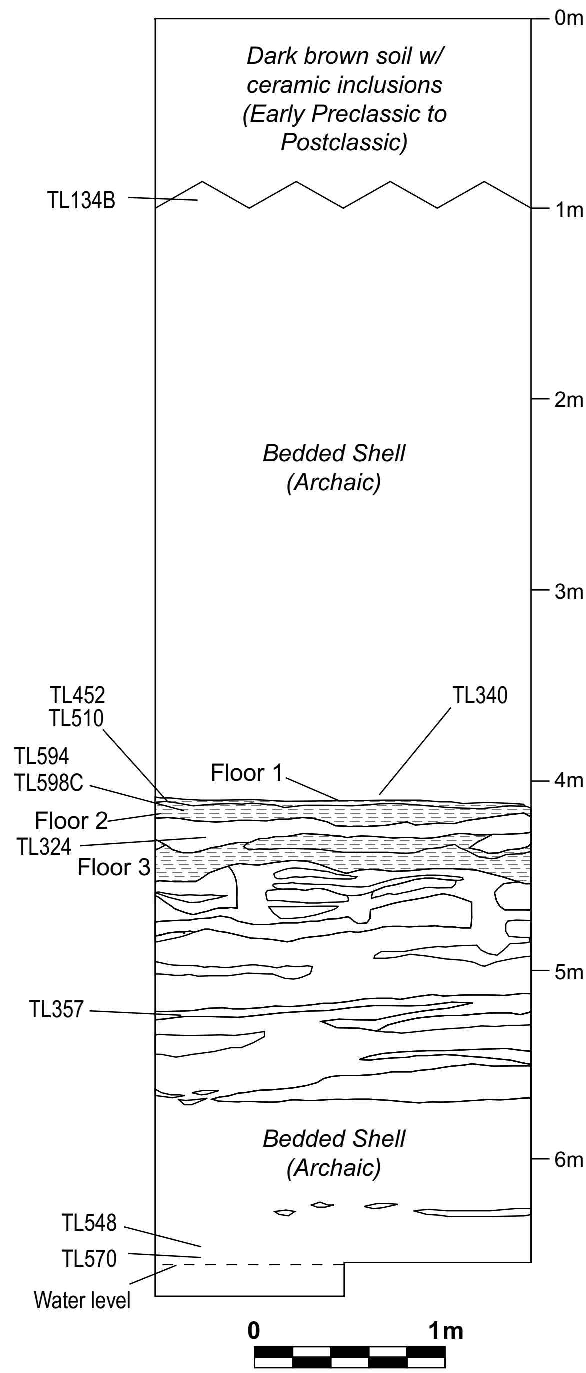

Figure 2 Profile drawing of Tlacuachero showing the stratigraphy of interest and the locations of all samples analyzed in this study. The drawing is a compilation based on several excavation units at the site. The lower portion of the profile (4–7 m) is based on unit N1W1, which was placed in a larger unit that exposed the upper surface of Floor 1. N1W1 penetrated the deposits from the level of floor construction to just below the water table. For this reason, the upper deposits are not present in the same profile and are idealized in this drawing based on the exposures in the larger excavation unit. The microstratigraphy in the bedded shell above and below the floor construction levels is not shown in the drawing. It consists of alternating layers of burned shell gravel and whole unburned marsh clam shells (*Polymesoda radiata*).

Table 1 AMS ^{14}C dates from 1st round of modeling (all samples are carbonized twigs).

UCIAMS #	Sample code	Context	^{14}C age	2 σ cal BP	Modeled 2 σ cal BP
68829	TL340	N2E1, Floor 1, from burned area	3875 ± 15	4410–4240	4360–4180
		Floor 1 Construction (Boundary)			*4390–4240*
68831	TL452	S1E1, below Floor 1, Stratum C, SubFloor 1	3900 ± 15	4420–4250	4410–4290
68832	TL510	N1W2, Floor 1 and subfloor	3890 ± 15	4420–4250	4420–4310
		Floor 2 Construction (Boundary)			*4850–4300*
68828	TL324	N1W1, between Floors 2 & 3	4260 ± 15	4855–4825	4855–4825
		Floor 3 Construction (Boundary)			*5030–4830*
68830	TL357	N1W1, Stratum C, from burned area below floors	4380 ± 15	5030–4860	5040–4870

In a conventional chronology, the considerable overlap in the calibrated dates above and below Floor 2, respectively, would be intractable and depending on one's inclinations could be interpreted as a series of events spanning a vague period represented by the 2-σ calibrated ranges. Alternately, following what has become a common practice in archaeology, we could take the 3 dates above Floor 2 and apply Ward and Wilson's (1978) chi-squared test to them, and finding that they pass the test at the 0.05 level ($t = 1.407$; $df = 2$; $\chi^2 = 5.991$), we could average them to 3888 ± 7 BP and say that the deposits above Floor 2 date to somewhere between 4420–4250 cal BP (2 σ). This again would mean accepting *a priori* that we dated a single event 3 times; that is, that the deposition of the shell above Floor 2, the construction of Floor 1, and then activities on Floor 1 all occurred simultaneously, or nearly so. There may be circumstances where such a scenario might seem plausible to an excavator, but given our assumptions about the deposition of the shellmound, these are more reasonably viewed as a sequence of discrete events, following one after another. In this framework, the posterior distributions for the 5 AMS dates are slightly trimmed compared to the standard calibrations (particularly those above Floor 2; Figure 3), and construction episodes of the 3 clay floors were estimated despite not being directly dated. OxCal generates an agreement index (*A*) for individual calibrations and for the entire model, which is a statistical measure of the correspondence between the prior and posterior distributions; values below a critical value ($A'c$) of 60% indicate that the stratigraphic assumptions of the model may be in error and need to be reassessed. The agreement indices for all the dates were well above the critical value and the overall agreement was $A = 95.2\%$, indicating strong agreement within the model. It is important to note that this value doesn't mean that our stratigraphic assumptions *are correct*, it merely means that based on the data at hand we have no reason to suspect they are incorrect. The most striking aspect of this sequence is the absence of the reversals that had plagued previous chronologies for Tlacuachero (e.g. Voorhies 1976, 2004; Kennett and Voorhies 1996) and suggested the potential for mixing and reworking within the shellmound. Though not definitive (being wary of a circular argument), the first round of 5 dates suggested that Tlacuachero retains reasonable stratigraphic integrity, and that previous reversals may have arisen from the mixed samples of bulk charcoal required for conventional ^{14}C dating.

Second Round

Having sketched a general outline of the sequence of clay floor construction, we focused the second round of dates on constraining the end of shell deposition at the top of the mound, roughly 3 m above Floor 1, and understanding the span of time during which Floor 2 was constructed. The possible range for the construction of Floor 2 was poorly constrained by a sample (TL324) initially thought to be between Floors 2 and 3, and the 2 samples in sequence (TL510 and TL452) below Floor 1 (Table 2). Two charred twig samples were selected (TL594 and TL598) from the matrix of Floor 2.

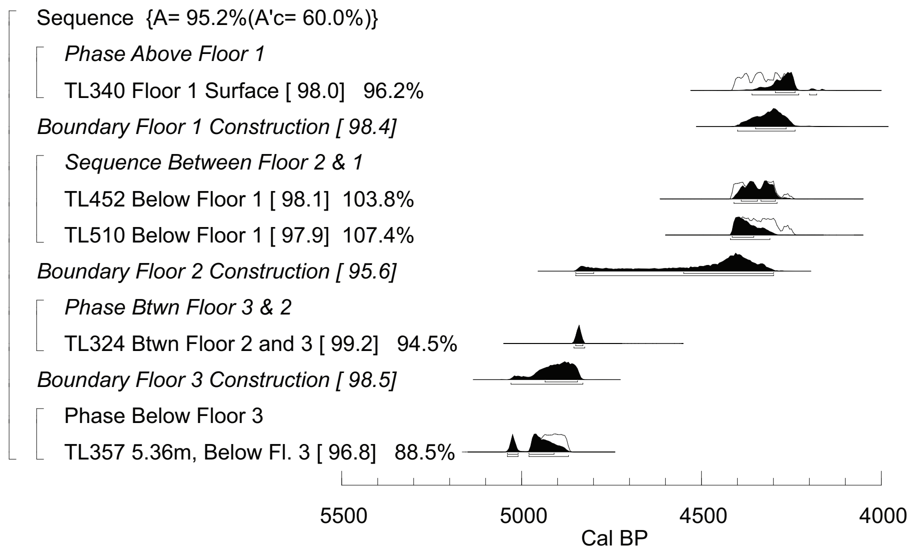

Figure 3 First round modeling results showing probability distributions of modeled dates from Tlacuachero. Prior distributions (routine calibration) are shown in outline and posterior distributions (modeled) are solid. The stratigraphic position of each sample dated is shown in Figure 2 and Table 1 provides sample details. Square brackets indicate the structure of the stratigraphic model. The agreement indices (*A*) for individual calibrations and for the entire model are statistical measures of the correspondence between the prior and posterior distributions. Values below a critical value (*A'c*) of 60% indicate that the stratigraphic assumptions of the model may be in error and need to be reassessed.

A single charcoal sample TL134B was also selected from the highest elevation of the bedded shells in the mound at 1.0 m below the surface. In the process of identifying appropriate samples to address our stratigraphic questions, we learned from one of the field technicians that sample TL324 was actually from a combustion feature interpreted to be a small campfire within what had been generally designated Floor 2. The model was revised in light of this information to accommodate the sequential construction of a Lower Floor 2 (a *boundary*), the use of Lower Floor 2 (the camp fire, sample TL324), and the construction of an Upper Floor 2 (also a *boundary*). The 2 charcoal samples from within Upper Floor 2 (TL594 and TL598C) were interpreted as material that had been incorporated into the floor after its construction rather than, e.g. as older charcoal incidentally included in the clays from which the floor was built. Not being vertically stratified, the 2 dates could not be placed in an ordered sequence, so they were modeled as a unordered *phase* bounded by 2 undated events: the construction of Upper Floor 2; and the beginning of shell deposition after it was abandoned as a working surface. Sample TL134B was treated as a *terminus ante quem* for the entire sequence.

The 3 additional dates and revisions to the model parameters relating to Floor 2 produced a few key insights. First, the overall agreement index for the model A = 80.0% remained above the critical value, indicating that the revised model could accommodate the additional data comfortably, and still no reversals were identified (Figure 4). The additional stratigraphic details regarding sample TL324 and its relationship with Lower and Upper Floor 2 both helped to constrain the series of events represented in the lower section of the sequence. Floor 3 construction was estimated to have occurred at 5030–4850 cal BP, and the construction of Lower Floor 2 was placed between 4960–4830 cal BP. Because it falls in a particularly favorable (i.e. steep) part of the calibration curve, placing the campfire date (TL324) in this revised sequence between the construction of Lower and Upper Floor 2 did not result in a tighter calibrated span than the previous iteration, 4855–4825 cal

Table 2 AMS ^{14}C dates from 2nd round of modeling (all samples are carbonized twigs).

UCIAMS #	Sample code	Context	^{14}C age	2 σ cal BP	Modeled 2 σ cal BP
72130	TL134B	N0E3, Highest elevation of bedded shells	3905 ± 20	4420–4250	4350–4230
		Difference			*–5–80 yr*
68829	TL340	N2E1, Floor 1, from burned area	3875 ± 15	4410–4240	4380–4250
		Floor 1 Construction (Boundary)			*4410–4270*
		Interval			*–5–65 yr*
68831	TL452	S1E1, below Floor 1, Stratum C, SubFloor 1	3900 ± 15	4420–4250	4410–4300
		Interval			*–5–65 yr*
68832	TL510	N1W2, Floor 1 and subfloor	3890 ± 15	4410–4250	4420–4320
		Interval			*–10–130 yr*
		Start Deposition above Upper Floor 2 (Boundary)			*4520–4320*
72132	TL598C	N1W2, #2, within Upper Floor 2	4040 ± 20	4570–4430	4580–4430
72131	TL594	S2W1, #3, within Upper Floor 2	4160 ± 20	4830–4610	4820–4780
		Upper Floor 2 Construction (Boundary)			*4860–4650*
68828	TL324	N1W1, Campfire on Lower Floor 2	4260 ± 15	4855–4825	4855–4825
		Lower Floor 2 Construction (Boundary)			*4960–4830*
		Floor 3 Construction (Boundary)			*5030–4850*
68830	TL357	N1W1, Stratum C, from burned area below floors	4380 ± 15	5030–4860	5040–4880
68831	TL452	S1E1, below Floor 1, Stratum C, SubFloor 1	3900 ± 15	4420–4250	4410–4300
		Interval			*–5–65 yr*

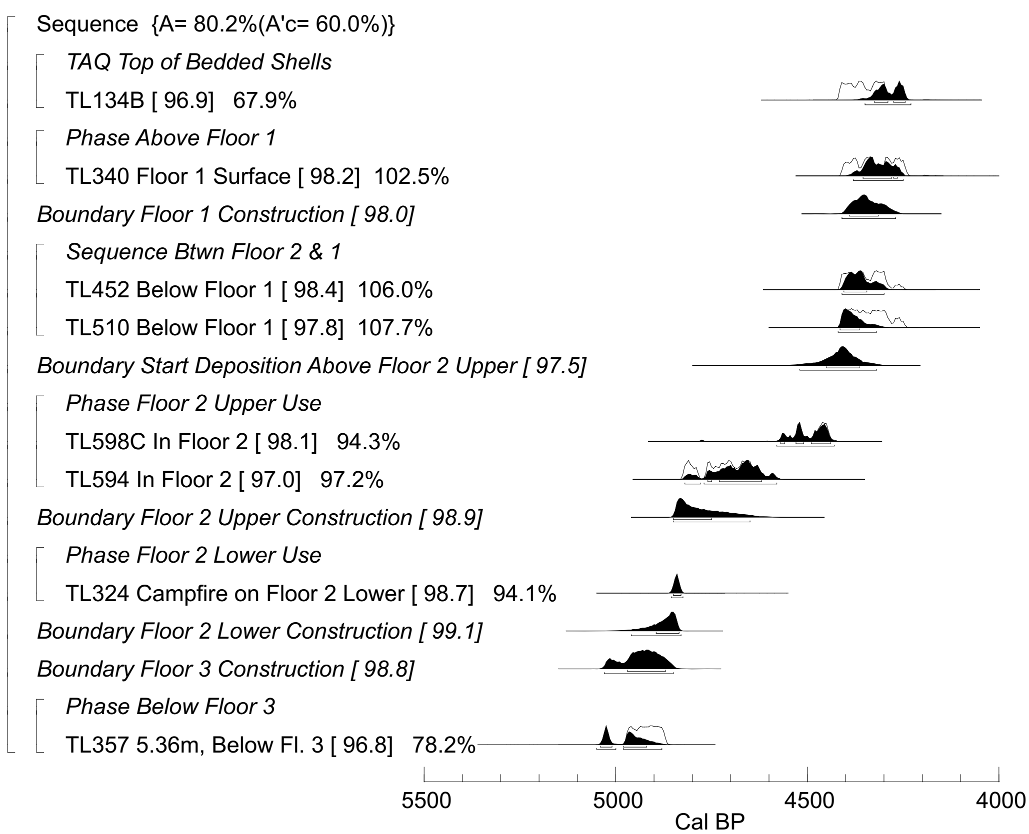

Figure 4 Second round modeling results showing probability distributions of modeled dates from Tlacuachero. See Table 2 for details and the caption in Figure 3 for additional information about how the figure is organized.

BP. Construction of Upper Floor 2 was estimated at 4860–4650 cal BP. The 2 dates on charcoal within the Upper Floor 2 matrix (TL594 and TL598C) spanned a surprisingly long range, suggesting that the surface had remained unburied for sometime, essentially representing a break in shell deposition that is unique in the sequence. Using the OxCal query *Span*, this phase is estimated to be between 50–350 cal yr long. It occurred between the construction of Upper Floor 2 (4860–4650 cal BP) and the resumption of shell deposition (4520–4320 cal BP).

Floor 1 was constructed between 4410–4270 cal BP estimated as the ending boundary of a sequence starting with shell deposition above Upper Floor 2 (another boundary, 4520–4320 cal BP) and including the 2 dates TL510 and TL452. Using the *Interval* function suggests periods of –10–130 cal yr between the lower boundary and TL510, and –5–65 cal yr between TL510, TL452, and the upper boundary (see Table 2). The sample dating the highest elevation of the bedded shells in the mound (TL134B) is of nearly identical age to the 3 dates above Upper Floor 2 (TL340, TL452, and TL510). The timespan represented by the deposits is estimated by the *difference* between TL340 and TL134B, indicating that roughly 3.5 m of shell accumulated fairly rapidly above Floor 1 (0–80 cal yr with a weighted mean of 30 cal yr). We estimate the uppermost bedded shell deposits were laid down between 4350–4230 cal BP, a date that represents the last well-preserved deposits associated with shellfishing at this locale, keeping in mind that later activities at the site have removed some of the upper most parts of the shellmound.

Table 3 AMS ^{14}C dates from 3rd round of modeling (all samples are carbonized twigs).

UCIAMS #	Sample code	Context	^{14}C age	2 σ cal BP	Modeled 2 σ cal BP
72130	TL134B	N0E3, Highest elevation of bedded shells	3905 ± 20	4420–4250	4350–4230
		Difference			*–5–80 yr*
68829	TL340	N2E1, Floor 1, from burned area	3875 ± 15	4410–4240	4380–4250
		Floor 1 Construction (Boundary)			*4400–4270*
		Interval			*–5–65 yr*
68831	TL452	S1E1, below Floor 1, Stratum C, SubFloor 1	3900 ± 15	4420–4250	4410–4300
		Interval			*–5–65 yr*
68832	TL510	N1W2, Floor 1 and subfloor	3890 ± 15	4420–4250	4420–4320
		Interval			*–10–130 yr*
		Start Deposition above Upper Floor 2 (Boundary)			*4520–4320*
72132	TL598C	N1W2, #2, within Upper Floor 2	4040 ± 20	4570–4430	4580–4430
72131	TL594	S2W1, #3, within Upper Floor 2	4160 ± 20	4830–4610	4820–4580
		Upper Floor 2 Construction (Boundary)			*4860–4650*
68828	TL324	N1W1, Campfire on Lower Floor 2	4260 ± 15	4855–4825	4860–4825
		Lower Floor 2 Construction (Boundary)			*4920–4830*
		Floor 3 Construction (Boundary)			*4960–4840*
68830	TL357	N1W1,Stratum C, from burned area below floors	4380 ± 15	5030–4860	4975–4875
76143	TL 548	N1W1, Stratum C, Deepest shell deposits	4380 ± 20	5040–4860	5040–4890
76144	TL 570	N1W1, Stratum C, Deepest shell deposits	4405 ± 20	5050–4870	5220–5200, 5050–4920
		Span Below Floor 3			*0–150 yr*

Third Round

After the second round of AMS ^{14}C dates and revisions to the model structure, the potential for clarifying the major features of the sequence had been exhausted, with the exception of the deepest sections of the shellmound that had been excavated. Samples roughly 1.3 m below TL357 in Stratum C were pulled from the deepest accessible deposits (TL548 and TL570, respectively). These were ~6.5 m below the surface and just above the current water table (sea level). These 2 dates were added in sequence to the lower part of the model without altering the rest of the model structure from the previous iteration (Table 3, above).

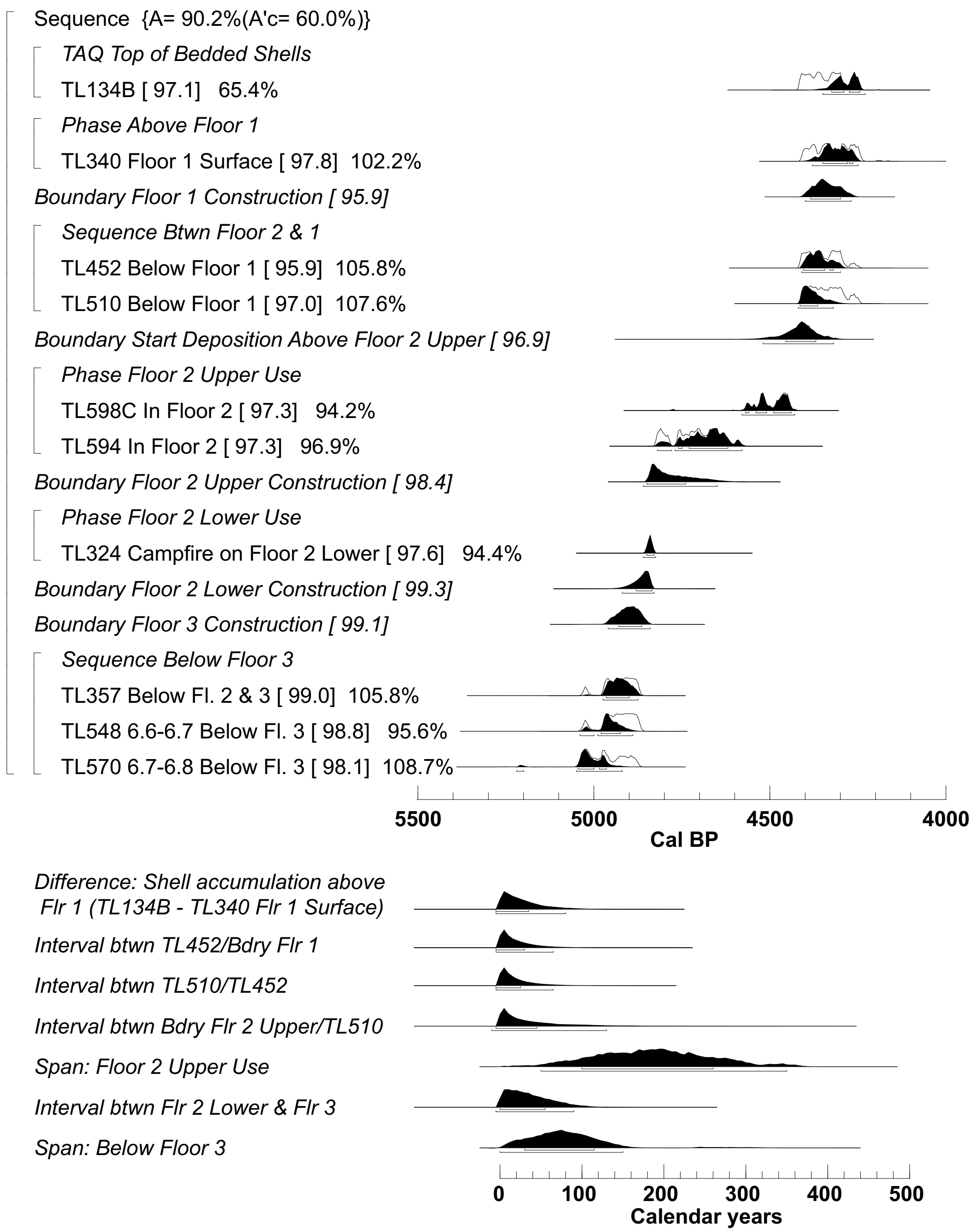

Figure 5 Third round modeling results showing probability distributions of modeled dates and calculated intervals between events from Tlacuachero. See Table 3 for details and the caption in Figure 3 for additional information about how the figure is organized.

The 2 additional dates fall closely before the previous date below Floor 3 (TL357) and the overall model agreement remains high (A = 90.2%), indicating good conformity between the data and the model structure (Figure 5). Constrained within the sequence, the deepest accessible sample in the shellmound sequence (TL570) dates to 5220–5200 (2.0%) and 5050–4920 (93.4%) cal BP, and the overlying TL548 sample dates to 5040–4890 cal BP. Adding these 2 dates within roughly the same timeframe had the effect of further compressing all of the age estimates below the campfire on Lower Floor 2 (TL324). In this iteration, TL357 is estimated at 4975–4875 cal BP (revised from 5040–4880 cal BP), the construction of Floor 3 at 4960–4840 cal BP (revised from 5030–4850 cal BP), and the construction of Lower Floor 2 at 4920–4830 cal BP (revised from 4960–4830 cal BP). Applying the *Span* query to the sequence of dates below Floor 3, we can estimate the 2.0 m of shell deposits between the water table and Floor 3 accumulated between 0–150 cal yr, with a weighted mean span of 80 cal yr.

SUMMARY AND IMPLICATIONS

The Bayesian statistical framework provided us with an iterative statistical environment to select carbonized twigs from well-defined stratigraphic units at the site of Tlacuachero. The modified Keck Carbon Cycle Accelerator Mass Spectrometer at UC Irvine allowed for analytical precision of between ±15 to 20 yr. The first set of ^{14}C results established a framework for subsequent rounds of sample selection and chronological simulation. Each new set of dates altered the model and work continued with diminishing returns until a point when the likelihood of chronological improvement was close to nil. Therefore, the model allowed for strategic and guided sampling to constrain the ages of culturally significant events and phases.

One of our primary objectives was establishing a chronology for the clay floor sequence. The lowest floor (Floor 3) dates to 4930–4865 cal BP. We also determined that the 2-m bedded clam deposit between the watertable and Floor 3 accumulated rapidly between 0–150 cal yr (mean is 80 cal yr). The bedded shell deposits above Upper Floor 1 also accumulated rapidly over a 0–80 cal yr period (mean 30 cal yr), after a hiatus in shell deposition potentially spanning 50–360 cal yr. Bedded shell deposits continue below the watertable to an unknown depth, but the observation that a majority of the visible component of the shellmound accumulated rapidly in 2 episodes was unexpected and inconsistent with our previous notion of more gradual accumulation over ~1500 cal yr (Figure 6).

The surface of the upper most floor (Floor 1) has served as a datum for a series of major changes at the site and was previously dated to ~5500 cal BP (Kennett and Voorhies 1996:696). We now assign a date to Floor 1 of 4400–4270 cal BP, a more precise age that fits well within the overall chronological model for the site. The changes evident above this floor include a shift in the seasonality of marsh clam harvesting from dry to wet season exploitation, culminating in the upper most intact deposits showing only wet season exploitation (Kennett and Voorhies 1996). This shift is coincident with the appearance of maize phytoliths in these deposits along with evidence for forest clearance (Jones and Voorhies 2004). These data are consistent with new paleoecological (phytoliths, pollen, and charcoal) evidence from a nearby sediment core indicating significant land clearance and the cultivation of maize in the vicinity after 4400 cal BP (Kennett et al. 2010). Slash-and-burn farming was practiced on this coastal plain as early as 6500 cal BP, but an increasing commitment to maize-based food production is in evidence starting after 4400 cal BP (Neff et al. 2006; Kennett et al. 2010). Bayesian chronological simulations coupled with precision AMS ^{14}C dating indicate that these slash-and-burn farmers were also intensively harvesting marsh clams throughout this interval.

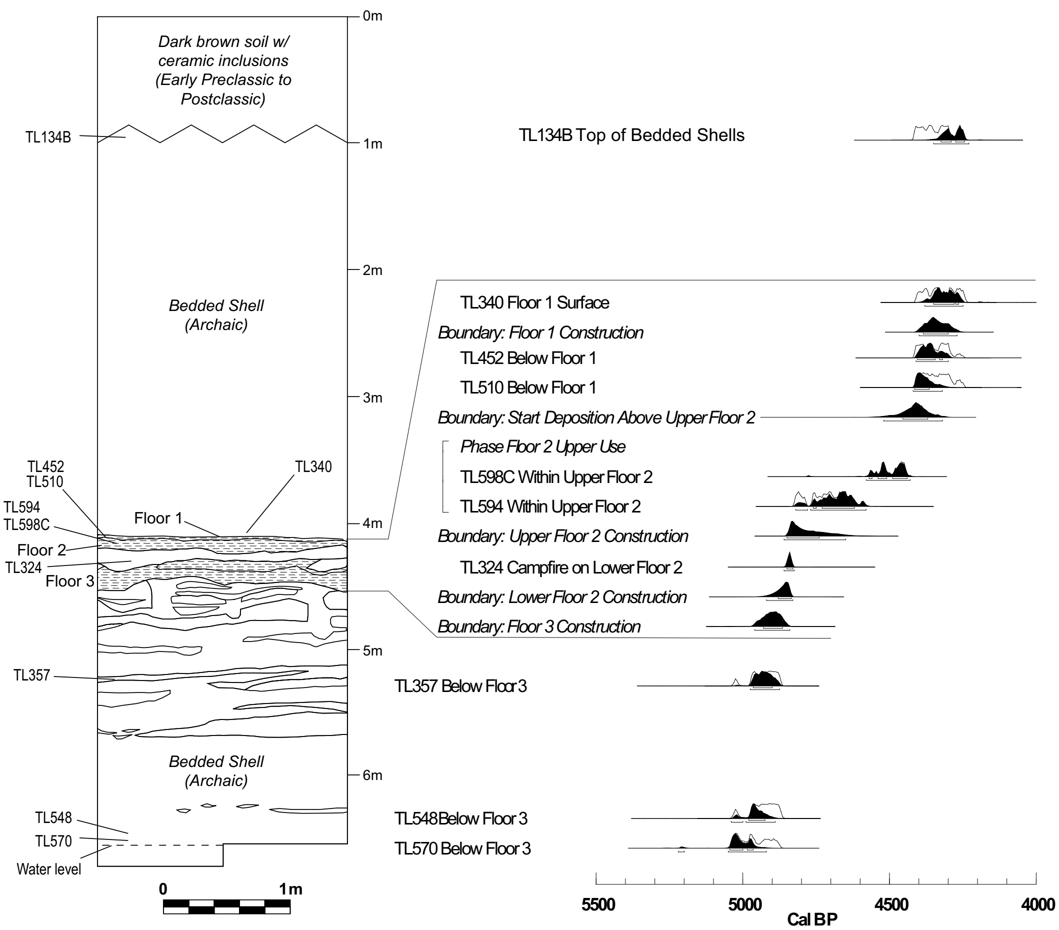

Figure 6 Final OxCal modeling results scaled to the stratigraphic section at Tlacuachero. The locations for all samples analyzed are plotted on the stratigraphic section and keyed to the probability distributions to the right of the profile.

CONCLUSIONS

Building sound chronologies is central to archaeological research. Interpretations of all other data sets (faunal, floral, artifacts, etc.) are dependent upon our ability to sequence events and characterize variability through time and across space. Testing alternative behavioral models and understanding cultural processes demand a firm chronological framework.

Libby's ^{14}C revolution of the 1950s allowed for spatiotemporal comparisons of archaeological deposits that stimulated archaeologists to ask new questions about the past. The development and improvement of calibration in the 1970s and the small sample capabilities of AMS ^{14}C in the 1990s had similar effects. Now the combination of Bayesian statistical analysis and high-resolution AMS ^{14}C dating of short-lived materials challenge archaeologists to revisit concepts like "contemporaneity" and dispense with outdated cultural chronologies and associated inferences. The iterative Bayesian chronological framework here provides a way of doing this in the most cost-effective way possible, and the approach is viable as long as reasonable turnaround times can be realized.

We have used this approach to establish a new chronology for the site of Tlacuachero, a large shellmound site located on the Pacific coast of southwestern Mexico. Prior work at this site suggested that the bedded shell deposits accumulated between ~5500 and 4000 cal BP (Blake et al. 1995; Voorhies 2004), but ^{14}C age reversals and large error margins prohibited a finer-grained chronology. We had assumed that this large shellmound accumulated gradually over a ~1500-yr period. Our new data indicate that the visible mound formed in 2 short bursts: one spanning a period 0–150 cal yr at (most probably) 5050–4875 cal BP; and the other spanning 0–80 cal yr at 4380–4230 cal BP. This observation is consistent with intensive shellfish harvesting during these 2 intervals. With this knowledge and the iterative Bayesian approach, we plan on improving the chronologies of the other 5 shellmounds in the region.

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