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Correspondence and requests for materials should be addressed to D.J.K. (djk23@psu.edu)

Correlating the Ancient Maya and Modern European Calendars with High-Precision AMS ^{14}C Dating

Douglas J. Kennett[1], Irka Hajdas[2], Brendan J. Culleton[1], Soumaya Belmecheri[3], Simon Martin[4], Hector Neff[5], Jaime Awe[6], Heather V. Graham[7], Katherine H. Freeman[7], Lee Newsom[1], David L. Lentz[8], Flavio S. Anselmetti[9], Mark Robinson[10], Norbert Marwan[11], John Southon[12], David A. Hodell[13] & Gerald H. Haug[14]

[1]Department of Anthropology, The Pennsylvania State University, University Park, PA 16802, USA, [2]Laboratory of Ion Beam Physics, Swiss Federal Institute of Technology ETH, Schafmattstrasse 20, 8093 Zurich, Switzerland, [3]Department of Meteorology & Earth and Environmental Systems, The Pennsylvania State University, 319 C EES Building, University Park, PA 16802, USA, [4]University of Pennsylvania Museum, Philadelphia, PA 19104, USA, [5]Department of Anthropology, California State University Long Beach, Long Beach, CA 90840, USA, [6]Institute of Archaeology, Belmopan, Belize, [7]Department of Geosciences, The Pennsylvania State University, University Park, PA 16802, USA, [8]Department of Biological Sciences, University of Cincinnati, 614 Rieveschl, Cincinnati, OH 45221, USA, [9]University of Bern, Institute of Geological Sciences and Oeschger Centre for Climate Change Research, 3012 Bern, Switzerland, [10]Department of Geography & Anthropology, Louisiana State University, Baton Rouge, LA 70803, USA, [11]Potsdam Institute for Climate Impact Research, Post Office Box 60 12 03, 14412 Potsdam, Germany, [12]Earth System Science, University of California, Irvine, Irvine, CA 92697, USA, [13]Godwin Laboratory for Palaeoclimate Research, Department of Earth Sciences, University of Cambridge, Cambridge, UK, [14]Geological Institute, Swiss Federal Institute of Technology ETH, Sonneggstrasse 5, 8092 Zurich, Switzerland.

The reasons for the development and collapse of Maya civilization remain controversial and historical events carved on stone monuments throughout this region provide a remarkable source of data about the rise and fall of these complex polities. Use of these records depends on correlating the Maya and European calendars so that they can be compared with climate and environmental datasets. Correlation constants can vary up to 1000 years and remain controversial. We report a series of high-resolution AMS ^{14}C dates on a wooden lintel collected from the Classic Period city of Tikal bearing Maya calendar dates. The radiocarbon dates were calibrated using a Bayesian statistical model and indicate that the dates were carved on the lintel between AD 658-696. This strongly supports the Goodman-Martínez-Thompson (GMT) correlation and the hypothesis that climate change played an important role in the development and demise of this complex civilization.

Articulating the ancient Maya and modern European calendars depends on a correlation constant that has been debated for over a century[1–5]. Correlation is required because the Maya Long Count system fell into disuse before the arrival of the Spanish in the 16th century, leaving only a few clues to their correct alignment in early colonial chronicles and native documents[3,6]. Many solutions to the problem have been proposed, employing a variety of historical and astronomical data[7], with results separated in time by ~1000 years. The most widely accepted was first put forward by Joseph Goodman in 1905[1], which, after certain modifications, is known as the Goodman-Martínez-Thompson (GMT) correlation. In no small part the acceptance of the GMT correlation is based on a radiocarbon study that was carried out in the 1950s using gas counting of β particles from ^{14}C decay in two wooden lintels from the ancient Maya city of Tikal (Guatemala) that carry carved dates that can be fixed in the Long Count system[8]. The analytical error of these measurements and other uncertainties associated with this early radiocarbon study do not fully resolve the problem and support multiple correlations at the 95% confidence interval (Supplementary Fig. 1, 2). Here we report a series of high-resolution AMS ^{14}C dates from one of these wooden lintels (*Manilkara zapota;* commonly chico zapota or sapodilla) at Tikal (Lintel 3, Temple I; Fig. 1) with Maya calendar dates indicating that it was carved between AD 695 and 712 using the GMT correlation. These dates are wiggle-matched[9,10] to a mixed ^{14}C calibration curve (IntCal09[11], SHCal04[12]) using a Bayesian statistical model that includes tree growth rates estimated from changing calcium (Ca/C) concentrations that are linked to differential uptake seasonally[13]. The combination of high-resolution AMS ^{14}C dating and calibration using tree growth rates provides a more definitive test of the GMT correlation.

The Long Count calendar is one of the defining features of Classic Maya civilization (AD 300–900, GMT correlation). These were not the first such dates in Mesoamerica and the system was likely adopted from adjacent regions where dates appear on stone monuments hundreds of years earlier (36 BCE, Chiapa de Corzo)[14]. The Classic Maya franchised the system and it proliferated to more than 40 different centers across the lowlands between AD 600–900[15–19]. These dates were used to anchor major historical events in time and the result is a remarkable chronicle of royal successions, rituals, victories and defeats in war, hierarchical relationships, and regal marriages[17]. These events are ordered in time by a count of individual days, the Long Count, but correlation is necessary to tie this rich record to the European calendar and to make comparisons with other sources of archaeological, environmental, or climatic data with chronologies based on ^{14}C and uranium-series dating[20–35].

The Long Count consists of a sequence of five time units: Bak'tun (144,000 days), K'atun (7,200 days), Tun (360 days), Winal (20 days), and K'in (1 day). The numbers 0–19 (represented by a bar [5], dot [1] system; with a zero symbol) were then used as multipliers for each unit so that the date 9 Bak'tuns, 13 K'atuns, 3 Tuns, 7 Winals, 18 Kins (noted as 9.13.3.7.18) is 1,390,838 days from a mythical starting point on August 11, 3114 BC using one variant of the GMT correlation. In this case a coefficient of 584283 days is added to the Long Count to obtain the equivalent day in the European calendar. This date was carved on Lintel 3, Temple 1 at Tikal (Fig. 2) and in the European Calendar is August 6, 695, the day that King Jasaw Chan K'awill I of Tikal defeated Yich'aak K'ahk' ('Claw of Fire'), a long-standing rival king of the powerful center of Calakmul located 90 km to the NW. Alternative correlation constants span nearly a millennium and range from 450,000 and 775,000 days and are based upon historical and astronomical data[7,36].

The GMT correlation hinges on historical texts that describe specific events (e.g. a massacre at Otzmal in the Yucatan) and the European year that they occurred (AD 1536) along with a date in a derivative Maya calendar that counts a series of K'atuns that reoccur every ~260 years (in this example 13 Ahau). Other historical and astronomical data is used to bolster the result[2–3] and in 1960 a University of Pennsylvania radiocarbon study of wooden lintel beams from Tikal bearing Maya dates was thought to provide independent verification[8]. Two lintels and multiple roof beams from Temple I and Temple IV were radiocarbon dated and compared to the expected European calendar dates using different correlation constants. The samples were large and taken from beam exteriors only. In addition, all of the ^{14}C dates from Temple I and IV have large analytical errors so that they show some overlap with the GMT along with several other correlation constants at the 95% confidence level when calibrated using the IntCal09 calibration curve (Supplementary Fig. 1, 2 & Tab. 1, 2)[11]. These alternative correlations (X and C) cannot be ruled out definitively. This is significant because even the archaeologists/epigraphers that championed the GMT correlation (Thompson 1935) never considered it to be infallible because the uncertainties in the historical and astronomical records left the possibility for other solutions. With only a few dissenting voices[4,37], the GMT correlation is widely accepted and used, but it must remain provisional without some form of independent corroboration.

Results

Here we build upon the University of Pennsylvania ^{14}C study and report a series of high-resolution AMS ^{14}C dates on one of the two

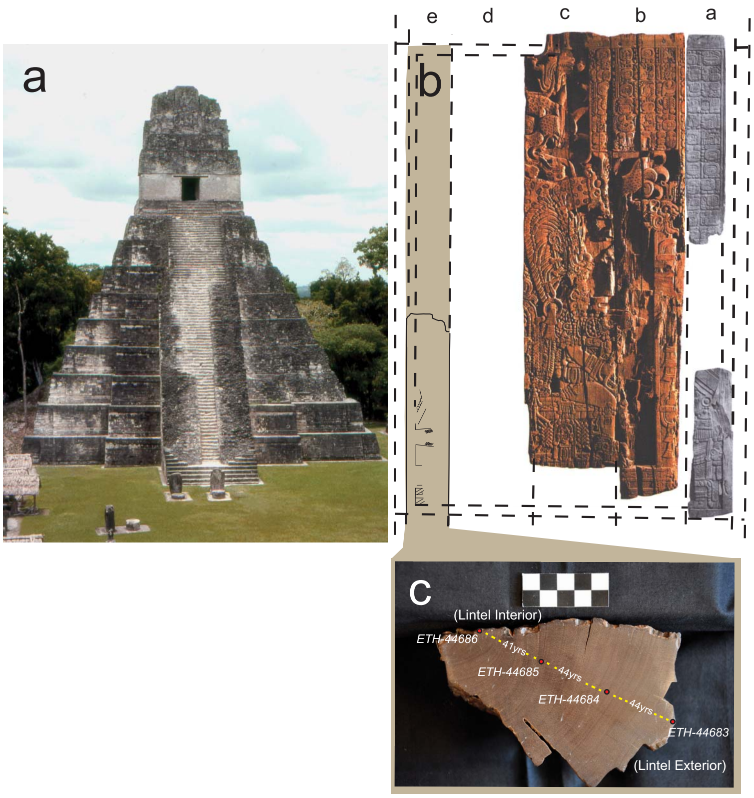

Figure 1 | Temple I (a, Photo: D. Webster) and Lintel 3 (b, Photo: Courtesy Museum der Kulturen Basel and UPenn Museum) at Tikal. This is what remains of the carved panels from Lintel 3 (b) memorializing Jasaw Chan K'awiil and his victory over Yich'aak K'ahk' of Calakmul. The carved lintel beams in color are at the Museum der Kulturen Basel (Switzerland) and the black and white panels are at the British Museum. (c) Cross section of lintel beam e showing sequential ^{14}C sampling locations through the trees growth. The number of years between AMS ^{14}C samples was determined using seasonal Ca/C cycles measured via LA-ICP-MS (Fig. 2, Supplementary Fig. 6).

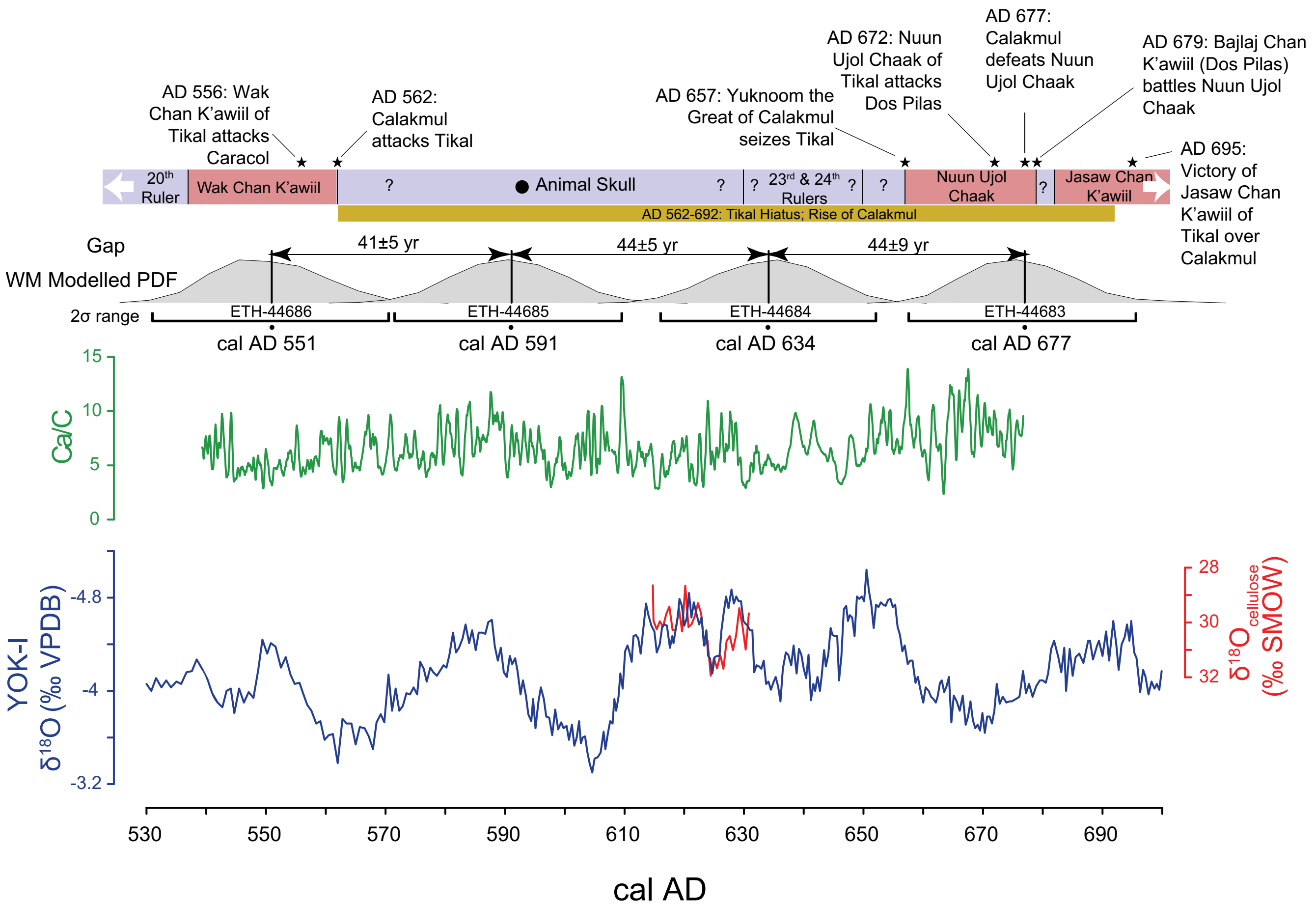

Figure 2 | Tikal lintel Ca/C data (Green) shown relative to a stalagmite $\delta^{18}O$ regional rainfall record from Yok Balum cave in southern Belize (Blue)[16]. Spectral analysis of the Ca/C record indicates annual growth rates between 0.94 and 1.43 mm per year (see Supplementary Fig. 6). Incremental $\delta^{18}O$ measurements of wood cellulose (red) from the Tikal lintel between AD 615 and 631 are shown relative to the rainfall record from southern Belize. Radiocarbon date distributions (2σ ranges, gray) are shown along with the number of years between these dates estimated from spectral analysis of the Ca/C data (see supporting documentation for details). The upper panel shows a series of historical events recorded in the region prior to the dedication of Temple 1, Lintel 3[17] that occurred during the growth of the *M. zapota* tree (beam e).

lintels originally investigated (Lintel 3 from Temple I [Beam e], Fig. 1, Supplementary Tab. 3) that bears a series of dates indicating it was cut, carved and dedicated sometime between AD 695 and 712 (using the GMT correlation). This is one of four wooden lintels in the Maya region, all from Tikal, with calendar dates coherent enough to be compared against a ^{14}C chronology[8] and the only sample currently available for study. The cellular structure of the wood confirms that the sample is *M. zapota* (Sapotaceae; Fig. S3).

Several observations indicate that this lintel beam was cut and carved within a short interval of time and that only small amounts of exterior wood was removed when it was carved. *M. zapota* can live for several hundred years[38], but trees of this age and size (30–40 m tall, 1.5 m in diameter[39]) were rarely, if ever, used for structural beams by the Maya[29]. Smaller trees of a consistent size were usually selected and logs were squared off to minimize work effort. This is because the wood is extremely hard and difficult to carve and this is especially the case with the stone-age technology available at the time. The beam we sampled is consistent with this observation and we estimate, based on tree growth rates (see below), that ~10–15 years of growth was removed during the carving process. Dry *M. zapota* wood is also extremely hard and even more difficult to carve, so it is unlikely that the beam was cut and stored for years prior to carving. Roof beams were sometimes recycled or replaced, but this does not appear to be the case with Lintel 3 at Tikal[8]. The sampled exterior of the lintel beam is therefore estimated to be 10–15 years short of the true cut date.

Four samples were taken starting near the lintel beam exterior, representing our best estimate of the cut and carving date, and moving inward (Fig. 1c). To improve the precision of the calibrated radiocarbon dates we wiggle-matched the series using the V-Sequence model in OxCal 4.1[40,41] estimating the time span in years that separates them in the lintel beam using dendrochronological methods. *M. zapota* trees have indistinct annual growth rings so we measured changing calcium concentrations (Ca) continuously through the lintel beam using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS; Fig. 3, Supplementary Fig. S6). Ca cycles are known to be seasonal in other tropical tree species[13] and spectral analyses of these data suggest growth rates between 0.94 and 1.43 mm per yr (Supplementary Fig. 6).

To confirm growth rates and the Ca-based age model (±5 yrs) in the prehistoric lintel we measured the concentration of bomb ^{14}C in the outer wood of a modern *M. zapota* tree and calibrated these results against the Northern Hemisphere Zone 3 atmospheric bomb curve (Supplementary Fig. 4)[42]. We hypothesize that Ca cycles are driven by seasonal changes in rainfall and these patterns accord well with instrumental data for the region (Supplementary Fig. 4)[13]. Average growth rates based on spectral analysis of the Ca data in both the lintel beam and modern tree range between 0.55 and 1.0 mm/yr and conform well with estimates based on a previous study of growth rates relative to known ages of chicle tap scars[38].

Based on the spectral work on the lintel beam we modelled the true gap between the AMS ^{14}C dates to be (from interior to exterior): 41 ±

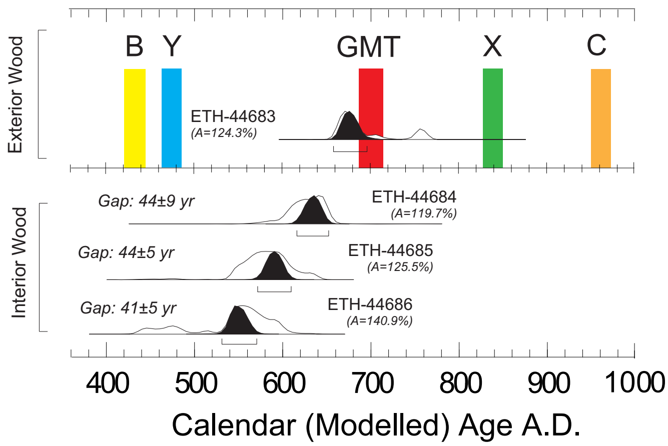

Figure 3 | Posterior probability distributions of ^{14}C dates from Beam e, Lintel 3 (Temple I). These distributions show the relative probability of each calibrated ^{14}C date taken through the incremental growth of the beam, calibrated against a mix of northern and southern hemisphere ^{14}C curves in OxCal 4.1. Two distributions are shown for each ^{14}C date. The outline shows the unmodeled calibrated date (prior) and the solid distribution is the wiggle-matched posterior distribution that accounts for the estimated timespan between each date. Agreement indices (A) above 60% indicate good fit between the model and the dates. The upper panel shows the probability distribution (ETH-44683) representing the age that the lintel beam was cut and carved (AD 650-685) and this is compared to age ranges derived from five correlation constants. These data are strongly supportive of the GMT correlation.

5 yr; 44 ± 5 yr; and 44 ± 9 yr (Fig. 2; Supplementary Table 6). Inferring variation in the position of the Intertropical Convergence Zone (ITCZ) estimated from a stalagmite δ^{18}O rainfall record[16,43] and incremental δ^{18}O measurements of wood α-cellulose from the lintel itself (Fig. 2, Supplementary Fig. 5, 7), the radiocarbon dates were then wiggle-matched[10,40] to a mixed model of the northern and southern ^{14}C calibration curves (IntCal09, 33% and SHCal04, 67%)[11,12] in OxCal 4.1. Sensitivity analysis of multiple gap spacing models indicates that increasing the gap errors has little effect on the age estimate for the exterior wood sample, and only diverges noticeably if the unrealistic condition of 100% southern hemisphere atmosphere is assumed. The calibrated ranges of these AMS ^{14}C dates overlap only with the GMT at the 95% confidence level and provide strong evidence for this correlation. This remains the case when ~10–15 years is added to compensate for the exterior wood lost during carving (1.5 cm).

Discussion

Bayesian statistical modeling of the data provides an age estimate of cal AD 658–696 (2σ) for the cutting and carving of Lintel 3 from Temple I. The carving on the lintel depicts King Jasaw Chan K'awiil (Ruler A) and the adjacent text describes his defeat of King Yich'aak K'ahk' ('Claw of Fire'; Martin and Grube 2000; see above for Long Count) from Calakmul. Based on the historical text and some specific stylistic elements on the lintel it was carved sometime between AD 695–712 in the European calendar using the GMT correlation[8]. This is ~20–30 years later than the central tendency in the ^{14}C distribution but represents the only correlation accommodated within the 95% confidence interval. Adding 10–15 yrs to compensate for the removal of exterior wood during carving puts this date even closer to the expected range. These data thus strongly support the GMT correlation and there is no overlap with other correlation constants so that we can rule these out definitively (Fig. 3).

Thus, our high-precision radiocarbon-based chronology strongly supports the GMT family of correlations. We can now argue with greater certainty that Jasaw Chan K'awiil's accession to Tikal's throne occurred in AD 682 and that his decisive victory over Calakmul occurred in AD 695 (Fig. 2). The *M. zapota* tree that was cut and carved to commemorate this victory grew in the vicinity of Tikal during the reigns of five of his predecessors, including his father Nuun Ujol Chaak[17]. Jasaw Chan K'awiil's defeat of Calakmul followed a series of great wars between Tikal, Calakmul, and Dos Pilas between AD 657 and 677 that resulted in the defeat of Nuun Ujol Chaak (Fig. 2). These events and those recorded at cities throughout the Maya lowlands can now be harmonized with greater assurance to other environmental, climatic, and archaeological datasets from this and adjacent regions and suggest that climate change played an important role in the development and demise of this complex civilization[16,20–35].

Methods

Wooden lintel samples from Tikal (Guatemala) were treated by soxhlet with hexane, acetone, and ethanol for 1 hour to remove fat, oil, waxes and resins. This was followed by a series of Acid-Alkali-Acid (0.5 M HCL, 0.1 M NaOH) to remove carbonates and humic acids[44]. Cellulose was separated by adding bleach (5% $NaClO_2$, 4% HCL at 75°C, 2 hrs)[45]. Dried cellulose samples were graphitized and analyzed via Accelerator Mass Spectrometry (AMS; ETH Zurich)[46] along with a set of standards and blanks. We identified the rise and fall of atmospheric bomb carbon (to constrain *M. zapota* growth rates) with a series of wood samples extracted from a modern tree within the ancient Maya center of Caracol (Belize). Samples were prepared with standards and blanks using standard Acid-Base-Acid methods and analyzed at the University of California Irvine KCCAMS facility using comparable techniques[47]. Calcium (Ca) and strontium (Sr) profiles were obtained using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (Thermo X-Series II Quadrupole ICP-MS; New Wave UP-213 laser ablation system; Penn State Earth and Environmental Systems Institute). Ablation was continuous through the trees incremental growth (30 micron spot size). Ca and Sr were determined in modern *M. zapota* at CSU Long Beach (Time of Flight ICP-MS; 213 laser ablation system, Spot size = 40 microns; laser speed = 50 microns/second) using the same approach. Spectral analysis was used to determine the annual growth rates of *M. zapota*. Oxygen isotopes in α-cellulose were analyzed using stable isotope mass spectrometry (University of Utah SIRFER Facility; TC/EA; Thermo Finnigan Delta Plus XL) using appropriate standards. Additional methodological detail is provided in the on-line supplement.

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Author contributions

D.J.K., I.H., F.S.A., D.A.H., G.H.H. conceived and designed the experiments. D.J.K., J.A., S.B., M.R. collected the samples. L.N. and D.L.L. performed the wood identification. I.H., J.S. determined the age of the samples via AMS ^{14}C. B.J.C. calibrated and modeled the ^{14}C dates. H.N. did the elemental analysis via ICP-MS, H.G., K.A.F., S.B. did the α-cellulose extractions for stable isotope work, B.J.C., S.B., D.J.K. analyzed the Ca and Sr data, $\delta^{18}O$ data, N.M. performed the spectral analysis, J.S. reanalyzed the UPenn ^{14}C data, S.M. did the historical analyses. D.J.K. drafted the manuscript with input from all co-authors.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

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