Monumental tombs within ancient civilizations worldwide hold precious clues for deciphering the architectural skill, acumen, and industry of prehistoric cultures. Most tombs were constructed from abiotic materials—stone, soil, and/or clay, predominately—and were built to permanently inter royalty or high-status individuals. On the island of Kosrae in the central Pacific, monumental tombs were constructed with scleractinian coral and were confined to the prehistoric island capital of Leluh, where they served as temporary mortuary processing points. Like other prehistoric tombs, the Leluh tombs were dated by association—from the remnants of the temporarily interred. We present new dates for three sacred tombs using high-precision U-Th dates from 24 corals collected directly from the structural materials. The results suggest that the tombs were built about 700 years ago during the 14th century, about three centuries earlier than previously reported. The new dates redefine the peak occupation of Leluh and place its ruling paramountcy at the leading edge of the developing trans-oceanic political hierarchies, as well as the social and economic systems that dominated the civilizations in this part of the world.

INTRODUCTION

Monumental tomb structures dating back to 3500 BC provide an archive of the architectural styles and cultural practices of ancient civilizations (1–3). Most ancient tombs were built to permanently inter royalty and were constructed of locally and/or regionally available abiotic resources, such as limestone, granite, and clay (2), and are dated by association (4, 5). On the central Pacific island of Kosrae (5°18’N, 162°58’E), however, there is a singular exception (Fig. 1). The ruins of the prehistoric capital city of Leluh (~AD 1250–1850) (6–9) contain several royal tombs, called saru, that are uniquely characterized by the use of biotic material (scleractinian coral) in their construction.

Kosrae is the easternmost island in Micronesia (Fig. 1B) and has been a key landmark for Pacific mariners over the centuries (10). Recognized as one of the ancient twin capitals of eastern Micronesia, Leluh supported a complex hierarchial society that developed over the six centuries preceding European contact in the mid-18th century. At its peak, Leluh covered an area of about 270,000 m² and was home to ~1500 people, including kings (Tokosras), chiefs, and commoners (8) (fig. S1). Today Leluh is listed on the National Register of Historic Places, USA, along with the ruins of Nan Madol (11), its twin on the neighboring island of Pohnpei. The shared history of these sister ancient capital cities is most apparent in their distinctive architecture—both are sprawling cities of man-made islets, canals, and walled compounds built of prismatic basalt in a header and stretcher style (7) (fig. S2). However, the use of coral in the structures on Leluh is a fundamental difference between these two ancient capitals.

Unlike other more well-known pyramidal mortuary chamber structures that culminate in an apex and are permanently sealed (1, 2), the pyramidal structures of Leluh were truncated, that is, a pyramidal frustum with a rectangular base, with a central crypt only accessible from above (Fig. 2). Leluh contains two royal burial complexes, Insriun and Insaru (8) (Fig. 1C). Insriun was destroyed by a typhoon early in the last century; however, the Insaru complex and three of its tombs or saru (Lurrin, Bat, and Inol-1) remain intact (8) (Fig. 2). Historical accounts suggest that the corpse of a Kosraean king, anointed with coconut oil and bound in mats and colored cordage, would have been interred in the saru for up to 3 months. A house was erected over the saru, and all the chiefs mourned and presented offerings to the deceased (12). After this time, the royal bones were exhumed, cleaned, re-bound, and secondarily buried in a deep hole on the nearby reef (8). Leluh’s truncated pyramidal tombs were, thus, temporary processing points that served a key function after the death of a high-status individual (13, 14).

Many aspects of precontact Leluh remain uncertain, including the chronology of tomb construction. It is speculated that the twin tombs of Lurrin and Bat are roughly 400 to 600 years old and Inol-1 is about 200 years old (6–8). The unique coral pyramidal tombs of Leluh present the opportunity to provide new dates for the age of construction on the basis of the biotic structural material. Hence, by using precise U-Th dating techniques, we determine the age of corals used in tomb construction to reevaluate the chronology of not only tomb construction but also the peak occupation of Leluh, and thus make inferences about the role that Leluh played in trans-oceanic political domination.

RESULTS

To estimate the construction ages, 47 coral samples were collected from three saru—Lurrin, Bat, and Inol-1 (Fig. 3, fig. S2, and table S1). In addition, living corals were collected as control samples. High-precision U-Th dating techniques (15–17) were used on the 24 corals that passed the screening tests for secondary calcite. The determined ages of coral deaths varied from 702.4 ± 6.5 to 1094.8 ± 5.4 years for Inol-1, from 691.1 ± 4.8 to 5717 ± 23 years for twin tomb 1—Lurrin, and 625.6 ± 6.5 to 1036.8 ± 6.6 years for twin tomb 2—Bat (table S2). The wide age intervals of hundreds to thousands of years indicate that a mixture of live and fossil coral was used to line the crypts (Fig. 4), infill walls, and...
as facades. The determined minimum coral dates represent the possible oldest ages of saru construction as follows: Inol-1 AD 1310.7 ± 6.5, twin tomb 1—Lūrūn AD 1322.0 ± 4.8, and twin tomb 2—Bat AD 1387.5 ± 6.5 (table S3).

The surveys along the facades of the three saru indicate that eight types (genera) of coral were used as tomb fascia (Acropora, Favia, Favites, Goniopora, Hydnophora, Platygyra, Pocillopora, and Porites; table S3). Observations within the crypts of the pyramidal tombs show that only two types of coral (Porites and Platygyra) were used in the crypts. The largest number of coral colonies (but lowest diversity of coral types) was documented on the façade transects of twin tomb 2—Bat, which according to our coral dates was the last of the three saru examined to be built. Whereas a larger diversity of coral types was used as fascia on the older saru, that is, on Inol-1 and twin tomb 1—Lūrūn, where a smaller quantity of colonies were counted (table S3).

To determine if the corals used in saru construction are a random subset of those corals available on the reef, we compared the diversity of corals used in construction with the proportional composition of the surrounding shallow reef community. On the contemporary reef, a total of 10,887 colonies were identified on 66 belt transects pertaining to 154 species of hard coral from 49 genera. Overall, the taxonomic composition of corals used in the tomb construction was not a proportional subset of the shallow (3 to 5 m) water live coral community on the surrounding reef ($x^2 = 2487$, df = 38, $P < 0.0001$). Even when the analysis was restricted to the 17 most common coral genera (each comprising more than 1% of the shallow water live coral community), the composition of corals documented in saru fascia did not reflect the surrounding live coral community ($x^2 = 2674$, df = 16, $P < 0.0001$).

The contemporary coral reef community was dominated by the genus Porites, followed (in decreasing order) by Acropora, Galaxea, Heliopora, Platygyra, and Leptoria (fig. S3). These corals were used to construct the saru of Leluh (fig. S3); however, there were 37 genera present on the reef that were not recorded in the saru (fig. S4). These include Diploastrea, Plerogyra, Pocillopora, Seriatopora, Turbinaria, Montipora, Pavona, Gardinoseris, Fungia, and Astreopora.

**DISCUSSION**

The chronology of saru construction is still subject to speculation (6–8). All three saru examined here were excavated in 1910 (18). At that time, the tombs of Lūrūn and Bat were empty. These tombs were believed to be used as temporary processing sites. However, skeletal remains of a 50-year-old man and a dog and shell artifacts were found in Inol-1.
Radiocarbon dating of the bones indicated that *Inol-1* was in use in more recent times, from AD 1824 to 1850 (6). Although no direct determined dates were obtained for the twin tombs—*Lūrūn* and *Bat*, an associated construction date sometime around AD 1600–1650 has been proposed on the basis of their centralized location and construction style (8). The determined coral U-Th dates we present indicate that all three tomb structures are far older, constructed during the 14th century. *Lūrūn* was built around AD 1322.0 (±4.8), followed about 65 years later in AD 1387.5 (±6.5) by *Bat*. *Inol-1* is the oldest of the three, dated to AD 1310.7 (±6.5) (table S3).

While the *Inol-1* radiocarbon dates suggest that this *saru* was in use in the mid-1800s (6), this does not preclude it having an earlier date of origin. Oral traditions suggest that *saru* were reused (19); however, no evidence has been provided in support of this premise. We consider tomb reuse as plausible on the basis of the historical records that (i) the tombs were temporary processing points, and (ii) it is likely that a number of kings or paramount chiefs ruled *Leleu* over the centuries of occupation (20). Furthermore, the relatively small amount of space available on the island would have made it impractical for every member of royalty to have been allocated a dedicated *saru*.

Today, the relict pyramidal tombs of *Leleu* stand over 2 m high and over 16 m wide at their respective bases (Fig. 2). It has been estimated that in total, more than 12,000 individual coral colonies would have been used to construct the three *saru* of *Insaru* (21). Corals were also used to build other parts of the city, such as the 3-m-high seawall, canals, paths, terraces, and floors of at least 20 other private, feast, and special compounds (8). Hence, the local coral resources are likely to have been depleted. Whereas the basalt megaliths used in construction could have been quarried from a site in Utwe (about 15 km from *Leleu*) and transported to *Leleu* via rafts (7), there is no evidence that corals were quarried from fossil deposits. Rather, a Kosraean legend tells that coral was taken from the shallow reef around *Leleu* and that the people “formed a long chain across the reef and passed pieces of coral from hand to hand” (12). Although it is likely that some fossil coral fragments used in *saru* construction were collected from the high-tide mark, the presence of whole coral colonies with fine-scale structures intact and a lack of surface abrasion (21) indicates that some corals were collected alive and were used in construction shortly after they were collected.

The evidence that there is no significant association between the corals used to build the tomb facades and the proportional abundance of corals on the reef suggests that corals were preferentially selected for *saru* construction. The motivation for choice of coral may be due to their size and shape and how this relates to ease of extraction and transport or may serve particular construction purposes (for example, fascia), or it may relate to cultural preferences (22). Clearly, the possibilities proposed here should be considered with caution because the composition of reefs today would be different from the composition some 700 years ago.

Nevertheless, to extract and translocate the amount of coral used to build the *saru*, as well as the structures and walls throughout *Leleu*, would have required a highly structured social order that could organize and demand significant labor and logistical support from the population. By the beginning of the 19th century, an already distressed Kosraean population dwindled, as a consequence of a devastating typhoon followed by the arrival of foreign ships, pirates, European whalers and traders, missionaries, and castaways (10). The Kosraean populace could no longer keep up with the continuing demands for the construction and maintenance work on *Leleu*, and the ancient city fell into disrepair.
The bones excavated from Inol-1 (18) may in fact represent the last person interred in a royal saru on Leluh. The fact that the burial cycle was not completed, that is, the bones were not deposited in the hole on the reef, may indicate that widespread changes were already under way in mid-19th century Kosraean culture. Contact with Europeans began in 1824 with the arrival of Duperrey’s expedition on board the La Coquille (23) and intensified from the 1830s to 1860s. The rapid population decline due to the introduction of diseases brought by the western arrivals, coupled with the introduction of Christianity, led to a decline of the ancient feudal system and traditional cultural practices. After 1830, the saru were no longer used; the last Tokosru, Awane Lepalik I and Awane Oa, were not buried in saru, and the very last Tokosru of Leluh, Awane Salik II, was forced to abdicate in 1874 and was buried in a Christian graveyard (8).

The sacred semi-pyramidal tombs of Leluh provide a substantive example of the way ancient cultures used local products and altered their immediate environment in the process. The use of colonial as construction material distinguishes the ancient monumental tombs of Leluh and has helped establish a new chronology indicating an earlier construction date that began in the 14th century, far earlier than previously understood. The U-Th dating techniques applied directly to architectural materials can significantly alter existing archaeological interpretations of these ancient, though remote, civilizations. For the monumental site of Leluh, the coral dates have redefined the timing of its peak occupation and elevated the position of its ruling kings in the struggle with Nan Madol for control over the trans-oceanic political hierarchies, as well as the social and economic systems that dominated the civilizations in this part of the world.

**Site description**

The ancient capital of Leluh is located on the small island of Leluh on the eastern side of the volcanic island of Kosrae in Micronesia, NW Pacific Ocean. Kosrae is a relatively young volcanic island (1 to 3 million years) with a land mass of 109.6 km² and a maximum elevation of 629 m. It has a high average rainfall (250 to 450 mm per month), particularly from December to June, during which there is an average of 22 days of rainfall per month (www.worldweatheronline.com). The ancient capital of Leluh occurs within a large shallow harbor fed by the Tafeyot River, which empties into the head of the bay. Fringing reefs surround the island of Kosrae and vary in width from <100 m on southern to eastern shores to 1.6 km on western exposures. There is also an extensive mangrove system, and some reefs extend into the mangroves.

**Pyramid and reef coral surveys**

To determine if corals used in saru construction were selected, the diversity of corals used in construction was compared with the proportional composition of the surrounding shallow reef community. Three random belt transects (5 m long, 0.5 m wide) along the facades of each of the three truncated pyramidal tombs were compared to three random belt transects (50 m long, 2 m wide) at 22 sites around the island of Kosrae (Fig. 1). Every coral visible on the surface layer of the truncated pyramid tombs was counted and identified to genus level. Three coral samples were collected from each transect, and additional coral samples were collected from inside the wall of the crypt and a 50-cm-deep hole dug into the corner of each truncated pyramid. Three additional samples were collected alive from the reef. Overall, 48 coral samples of 13 genera were collected (table S1).

The community composition of the modern coral community was quantified on three random belt transects (50 m long, 2 m wide) at 22 sites around the island of Kosrae. Each coral observed within the belt was identified to species and counted. A χ² test for association was used to determine if the composition of corals used in the tombs is the same as the proportional composition of corals on the modern fringing reef (figs. S3 and S4).

**U-Th dating**

A chipped subsample, 3 to 10 mm³, was carefully cut from the outermost 2nd to 4th annual band for the selected 24 corals with aragonitic composition and nondetectable postdepositional calcite (<3%) confirmed by x-ray diffractometry. The subsample was gently crushed into 0.5- to 1-mm³ segments and physically cleaned with ultrasonic methods (15). About 100 to 200 mg were used for U-Th chemistry (24). A triple-spike, 234U/238U, 231U/235U, 232U/238U, isotope dilution method was used to correct mass bias and determine U-Th isotopic contents (15). Isotopic compositions and concentrations were determined on a multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS), Thermo Neptune, with single secondary electron multiplier protocols in the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University (17). U-Th measurement results are summarized in table S2. Criteria of 146 ± 8 for initial δ²³⁵U (25, 26) and U contents of 1.9 to 4.0 parts per million (ppm) (25–27) were applied to evaluate reliable dates of pristine corals. One coral, Insaru-13, with abnormal high U content of 6.57 ppm, did not pass the criteria. We estimated the site-specific nonradiogenic ²³⁰Th/²³²Th ratio and its variability (16, 28) by dating a living coral head, Pocillopora verrucosa, collected on 11 February 2012. Using an atomic ratio of 4 ppm, inferred from diverse sites in the Pacific and Indian Oceans with a 100% variability (16), we determined the U-Th ages of three replicates as AD 2012.4 ± 1.1, 2012.3 ± 1.2, and 2012.2 ± 1.1 (table S2), matching the collection date. The ratio and uncertainty were used to correct for the contribution of nonradiogenic ²³⁰Th to the U-Th age. Coral death dates were calculated by subtracting 3 (±1) years from the corrected U-Th age.
RESEARCH ARTICLE

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/1/2/e1400060/DC1

Fig. S1. Prismatic basalt walls.
Fig. S2. Selection of samples collected from the coral tombs.
Fig. S3. Proportional composition of the contemporary coral reef community.
Fig. S4. Taxonomic composition of corals used to build the pyramid tomb facades versus the modern reef.
Table S1. Coral samples collected from the Insaru compound.
Table S2. Uranium and thorium isotopic compositions and U-Th dates for Insaru coral samples by MC-ICPMS, Thermo Electron Neptune.
Table S3. The quantity and type of corals used to construct the Leluh pyramids.

REFERENCES AND NOTES

9. The orthography of compound names, tombs, titles follow that of Cordy (1993) with the following exceptions. We spell the name of the ancient city Leluh (spelt Lelu by Cordy). We spell the sacred compound Insaru (spelt Insu by Cordy). We have made these changes following advice from Berlin Sigrah of the Kosrae State Historic Preservation Office.
20. Tokosras genealogies prior to AD 1800 have not been recorded; however, from 1800 to 1850, ten Tokosras reigned over Leluh for 1 to 10 years each (ref. 8).

Acknowledgments: We thank P. Sigrah for participation in the fieldwork and many useful discussions about Kosraen oral history. Permission to conduct research was granted by Berlin Sigrah Kosrae State Historic Preservation Office. Thanks also to R. Cordy without whose detailed investigations of Leluh, the interpretations made in this study would not have been possible.

Funding: This project was supported by the Australian Museum Foundation, Kosrae Safety and Conservation Organization, and Kosrae Village. U-Th dating was supported by Taiwan ROC MOST and NTU grants (101-2116-M-002-009, 102-3113-P-002-011, 103-2119-M-002-022, and 101R4000). Z.T.R. was funded in the final write-up stage of this project by Woodside Energy.

Author contributions: Z.T.R. and J.-P.A.H. conceived the project. Z.T.R. secured fieldwork funding. C.-C.S. directed and funded the high-precision dating. X.J. and C.-C.W. performed the x-ray diffractometry and U-Th isotope analysis and dating. Z.R. conducted coral surveys and collected the coral specimens with assistance from J.-P.A.H. Z.T.R. prepared the draft, and C.-C.S. and F.B. contributed to the writing of the manuscript. Competing interests: The authors declare that they have no competing financial interests.

Submitted 28 October 2014
Accepted 8 February 2015
Published 13 March 2015
10.1126/sciadv.1400060


New precise dates for the ancient and sacred coral pyramidal tombs of Leluuh (Kosrae, Micronesia)
Sci Adv 2015, 1:
doi: 10.1126/sciadv.1400060

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