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Absolute and relative dating of human remains in a Bahamian sinkhole (Great Cistern, Abaco)

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ABSTRACT

The Little Bahama Bank was likely the last island group colonized by the Lucayan natives in the tropical North Atlantic, but preserved Lucayan remains are rare from this region. Furthermore, the Lucayan diet included both marine and terrestrial contributions, which must be considered when calibrating conventional radiocarbon results from human remains into Common Era (CE) calendar years. Here we present a new discovery of Lucayan remains (proximal epiphysis of a right tibia) identified within a sinkhole on Great Abaco Island in the northern Bahamas, which was preserved in the extremely well-dated sedimentary infill (dated with 22 independent radiocarbon ages). The age of the human tibia was estimated through both the associated stratigraphy (relative age), and direct radiocarbon dating of the bone (absolute age). The direct age of the bone was calibrated by using a two-endmember mixing model to estimate the average proportion of marine versus terrestrial contributions to this individuals' diet using the $\delta^{13}C$ value of the bone collagen and applying a local ΔR value for regional aquatic settings. Absolute dating places the age of the remains from Great Cistern between 1255 and 1340 CE (2σ, probability: 0.89). Applying the same mixing model to the previously discovered remains from Sawmill Sink on Great Abaco Island indicates those remains are in fact 100 to 200 years younger than the previous estimate with internment likely occurring between 1110 and 1290 CE (2σ, probability: 0.95).

1. Introduction

At the onset of European colonization in the 15th Century Common Era (CE), the ethnic groups inhabiting the Caribbean were divided into several distinct spatial and cultural entities (Fitzpatrick and Keegan, 2007; Keegan and Hofman, 2016; Lalueza-Fox et al., 2003; Ross et al., 2020; Rouse, 1992; Schroeder et al., 2018). The windward Islands of the Lesser Antilles were populated primarily by the Carib, the Leeward Islands and Greater Antilles by the Arawak-Taino, with the Lucayans occupying the eponymous Lucayan archipelago from Turks and Caicos in the southeast to Grand Bahama island in the northwest. Multiple migratory pathways have been proposed for human dispersal throughout the Caribbean (Berman and Gnivecki, 1995; Fitzpatrick and Keegan, 2007; Mendisco et al., 2015; Napolitano et al., 2019; Rouse, 1986), but recent work by Ross et al. (2020) using craniofacial morphology concluded that colonization began first in Cuba around 5000 BCE by settlers emigrating from the Yucatan. This was followed in the 1st millennium BCE by the arrival of the Arawak-Taino in Puerto Rico and the Lesser Antilles from the north coast of South America. Carib expansion begins in 800 CE in Hispaniola and continues outward towards The Bahamas, giving subsequent rise to the indigenous Lucayan culture. The timing and sequence of Lucayan dispersal throughout The Bahamas remains uncertain.

The earliest known Lucayan settlements in The Bahamas are The Coralie Site on Grand Turk Island in Turks and Caicos (established circa. 705 ± 60 CE) (Keegan, 1997; Scudder, 2001) and the Three Dog Site on San Salvador in the central Bahamas (established between 800 and 900 CE) (Berman and Gnivecki, 1991). However, the dearth of human remains from Great Abaco Island and Grand Bahama Island promotes uncertainty regarding the arrival of Lucayans in the northern archipelago. The lack of early Lucayan remains on the Little Bahama Bank, along with recent work highlighting the lack of evidence for a

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Floridian-Bahamian migration route (Ross et al., 2020), and the temporal and northward Lucayan site progression pattern along the archipelago suggest that Great Abaco Island was one of the final islands to be colonized in the tropical North Atlantic Ocean. A wooden paddle indicative of Lucayan design found on the adjacent Moore's Island in 1912 (de Booy, 1915) provided a calibrated radiocarbon age of 1436 to 1500 CE (IntCal13, 2σ, probability: 0.91; Ostapkowicz et al., 2012). While artifacts such as this may provide evidence of a Lucayan presence at that time, our current knowledge for earlier pre-European occupation of the Little Bahama Bank follows from several lines of indirect evidence.

There are botanical indicators of landscape disturbance and potential indirect evidence of human predation occurring around 1000 CE. Increasing charcoal concentrations between 1000 and 1050 CE in lake sediment records from Abaco suggest landscape disturbance by Lucayans was initiated by this time (Slayton, 2010; Stork, 2006). Midden remains at Gilpin Point in southern Abaco contained green sea turtle *(Chelonia mydas)* remains, including a split shell. A split shell indicates human presence since no terrestrial predators on Abaco were capable of this action (Steadman et al., 2014). Radiocarbon-dated green turtle remains from Gilpin Point yielded a calibrated age (using Marine13, Reimer et al., 2013) of 910 to 1075 CE (2σ, probability: 1.0; Steadman et al., 2014). The extinction on Abaco of the native Albury's Tortoise (*Chelonoidis alburyorum*) and Cuban Crocodile (*Crocodylus rhombifer*) ~1000 years ago (Hastings et al., 2014) potentially indicates anthropogenic landscape alteration, since decreasing faunal diversity often follows human island colonization (Alcover et al., 1998; Crowley, 2010; Steadman et al., 2005; Stuart, 2015). However, crocodile and tortoise extirpation on Abaco may only correlate with human arrival, and other non-anthropogenic mechanism (e.g., changing precipitation patterns) cannot yet be discounted. The dearth of directly-dated Lucayan remains means that indirect evidence such as fire, extinction, and landscape change have thus far provided the best available constraints for the timing of Lucayan occupation of Abaco Island.

To date, the only directly-dated Lucayan remains on Abaco are the skeletal remains recovered from Sawmill Sink (Steadman et al., 2007). The conventional radiocarbon result on the human tibia from Sawmill Sink was originally calibrated to 900 to 920 CE or 950 to 1030 CE (2σ, Steadman et al., 2007) using the IntCal calibration curve available at that time (Reimer, 2004). By applying this calibration curve, one is assuming that the bone collagen tissue analyzed had incorporated carbon entirely sourced from the atmospheric radiocarbon pool (non-marine). However, $\delta\ ^{13}C$ and $\delta\ ^{15}N$ values extracted from the bone collagen of Lucayan skeletal remains indicates that the Lucayan diet included both terrestrial and marine organic carbon sources (Keegan and DeNiro, 1988; Stokes, 1998; Hastings et al., 2014). After considering the recent work done to reconstruct the Lucayan diet using well established stable isotopic approaches (Hastings et al., 2014), the previously reported calibrated age of the Sawmill remains is likely not accurate since it did not account for marine carbon in the Lucayan diet.

Here we present new evidence of Lucayan arrival in the northern Bahamas through the analysis of human skeletal remains recovered in a stratigraphic context and archived within a flooded dysoxic sinkhole (Great Cistern) on Abaco Island (Fig. 1). The high-quality stratigraphic record in Great Cistern allows for the mixed radiocarbon calibration of human bone into the Common Era to be independently validated against the well-preserved stratigraphy in which it was discovered.

2. Study site

Great Abaco Island is the largest landform among the Abaco Islands on the eastern margin of the Little Bahama Bank, which is the northernmost carbonate platform in the Lucayan archipelago (Fig. 1). The carbonate islands and platforms comprising the archipelago along the western tropical North Atlantic margin began forming in the late Jurassic, and this region has since weathered into a mature karst landscape (Mylroie et al., 1995a, 1995b; Mullins and Lynts, 1977; Mylroie and Carew, 1995). Sinkholes and blue holes are some of the most recognizable karst features throughout The Bahamas and are formed through subsurface dissolution of the antecedent carbonate. This dissolution initially forms caves which subsequently experience ceiling collapse becoming a notable depression on the subaerial landscape. After formation, the sediment and fossils that accumulate within sinkholes and blue holes preserve excellent records of past landscape and environmental change (van Hengstum et al., 2016, 2018; Steadman et al., 2007). When flooded by local groundwater, the often low dissolved oxygen and quiescent bottom water conditions promote exceptional preservation of any deposited sediment, pollen, charcoal, or faunal remains.

Great Cistern is a narrow (15 m diameter) terrestrial sinkhole located on the periphery of a shallow coastal embayment on the eastern shore of Great Abaco Island (26.57° N, 77.12° W; Fig. 1, S1). The depth of Great Cistern varies from 9 m to 11 m along a southwestern gradient with a tidal range of approximately 50 cm. Measurements of the water column structure reveal polyhaline and dysoxic conditions at the benthos (dissolved oxygen: 0.1 mg l^{-1}, salinity: 20 psu) and mesohaline oxygenated surface waters (surface dissolved oxygen: 6 mg l^{-1}, salinity: 10 psu).

3. Methods

3.1. Core collection, sedimentology and sediment age

Continuous sediment cores were collected from Great Cistern in 2014 (9.5 cm diameter push cores, C2) and in 2015 using a Rossfelder P3 submersible vibracoring machine (7.6 cm diameter vibracores, C7, C8; Fig. 2). It is likely that the entire unlithified sedimentary sequence in Great Cistern was sampled because an impenetrable substrate prevented vibracoring below a depth of 485 cm. Core C7 (total length 435 cm) sampled the complete Holocene sequence, though the upper 50 cm were not recovered. Core C8 sampled from the sediment water interface to a depth of 352 cm. C2 sampled to a depth of 250 cm below the sediment water interface, though the upper 14 cm were not captured due to over-penetration, yielding a recovered length of 236 cm. Cores were sectioned into 150 cm lengths for transport to the laboratory where they were subsequently split lengthwise, photographed, and X-radiographed (to image density variations).

Downcore textural variability was evaluated between cores with a Sieve-first Loss-on-Ignition procedure (van Hengstum et al., 2016, 2018), which is well suited to analyzing heterogeneous sedimentary successions from lake-like environments on carbonate landscapes (e.g., lakes, caves, and sinkholes). The cores were sampled at contiguous 1-cm intervals downcore, whereby 2.5 cm^3 sediment sub-samples were wet sieved over a 63-μm mesh, dried at 80 °C for 24 h, weighed, and ignited at 550 °C for 4.5 h to remove organic matter and concentrate the inorganic residue. Post-burn weights of the remaining mineral residue, expressed in mass per volume ($D_{>63\ \mu m}$ mg cm^{-3}), were then used to quantify the variability in coarse sediment down core.

Sediment emplacement age and downcore age models were developed with terrestrial plant macrofossils (e.g., sticks and leaves) that were radiocarbon dated ($n = 22$, Table S1) at the National Ocean Sciences Accelerator Mass Spectrometry facility at the Woods Hole Oceanographic Institution. Terrestrial plant macrofossils only incorporate radiocarbon from the atmospheric carbon pool, and thus provide the best estimate for the maximum age of a given stratigraphic level in the sediment core. This approach also avoids problems of dating sediment using carbonate shell material (e.g., bivalves or gastropods, Hodell et al., 1991) or bulk organic matter produced by primary productivity (van Hengstum et al., 2018), both of which can be impacted by considerable hardwater effects from deriving carbon from the groundwater on a limestone landscape. Selected terrestrial plant macrofossils were first sieved over a 63 μm mesh to remove any adhering

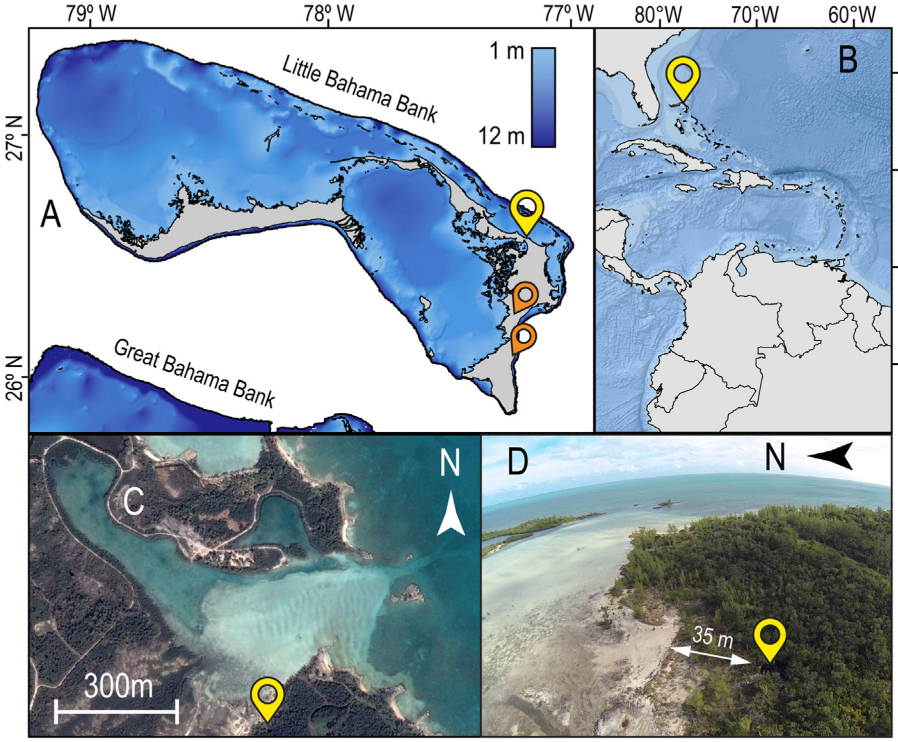

Fig. 1. A) Little Bahama Bank. Great Cistern sinkhole is shown in yellow (north). Sawmill Sink (central) and Gilpin Point (south) are shown in orange. B) Tropical Northwest Atlantic and Caribbean basin. Great Cistern sinkhole on Great Abaco Island marked in yellow. C & D) Great Cistern sinkhole is located < 40 m from the current shoreline on eastern Abaco Island.

sedimentary particles prior to dating. Conventional radiocarbon results on terrestrial plant macrofossils were calibrated into years before present using IntCal13 (Reimer et al., 2013), where present is considered 1950 Common Era. Final downcore age models for each core were derived using the Bacon v2.2 software package in the R computing environment which applies Bayesian statistical approaches to reconstruct sediment accumulation over time (Blaauw and Christen, 2011).

Following stratigraphic principles, clear stratigraphic contacts between prominent sedimentary beds, which could be confidently traced between all cores, were assumed to be contemporaneous and used as chronographic tie-points. (Fig. 2). Two tie-points were identified among C2, C7, and C8. The uppermost tie point (H1; Fig. 2) was derived from a radiocarbon date extracted from the base (onset) of the uppermost calcite raft horizon in C2 (114 cm core depth). The calibrated age of 1670 ± 25 yBP was then applied to the base of the corresponding calcite raft horizons in C7 (87 cm core depth) and C8 (139 cm). The lower tie point (H2; Fig. 2) came from the base of the thicker calcite unit in C2 (185 cm down core). The Bacon calculated median age of this interval (2530 yBP) was applied to the corresponding contact in C7 (153 cm) and C8 (209 cm). Applying the tie points from the better constrained C2 age model (11 radiocarbon dates) more accurately depicts sediment deposition between all three cores. Omitting the tie points produced stratigraphically incoherent age models from C7 and C8.

3.2. Radiocarbon dating and calibration of the Lucayan bone fragment

The human bone identified during the initial inspection and description of C2, is the proximal epiphysis of a right tibia (mass: 14.9 g, Fig. 3). Following careful extraction from the sediment matrix, the bone was rinsed in fresh water to remove adhering sedimentary particles, and then placed in a freshwater bath to flush any salts from the materials. The bone was then scanned and imaged with a handheld Arctec Spider with the resultant image processed in Arctec Studio 13 to create a digital 3D model for archival and analysis. Finally, the bone was sent to Beta Analytic (Miami, Florida) where 50% of the epiphysis was used for direct radiocarbon dating of the bone collagen by accelerator mass spectrometry and δ ^{13}C and δ ^{15}N values were measured by isotope ratio mass spectrometry.

A challenge that emerges in calibrating conventional radiocarbon results from the remains of terrestrial omnivores and carnivores in coastal settings is correctly estimating the dietary contributions of marine versus terrestrial organic carbon since marine carbon is subject to reservoir effects not applicable in terrestrial environments (Broecker and Olson, 1961; Bronk Ramsey, 2008; Stuiver and Suess, 1966). Ingested carbon is incorporated into an organism's bone collagen and populations with a mixed terrestrial and marine diet will contain carbon from both sources (Chisholm et al., 1982; Hastings et al., 2014). Radiocarbon from the marine carbon pool enters the food web at a delayed rate compared to terrestrial sources meaning that substantial radioactive decay may have already occurred prior to organic incorporation (Broecker and Olson, 1961). Still further, a globally applicable marine reservoir correction of 400 years is not regionally consistent. Deviations from this global average (ΔR values) can be measured and included during calibration of materials that incorporate marine-derived carbon. Previous work in the shallow inshore waters of the northern Bahamas determined a regionally appropriate ΔR value of −55 ± 10 (Broecker and Olson, 1961).

The application of a mixed calibration curve is required to accurately calibrate the conventional radiocarbon age reported from organisms with a mixed diet. The proportionality of the calibration curves used is dependent upon the proportion of marine versus terrestrial sourced carbon in the bone collagen. Underestimating the marine component of a sample will produce radiocarbon calibration results older than the actual age of the sample, while overestimating the marine contribution shifts calibrated results too young. Determining this ratio typically involves analysis of local subsistence patterns and is often challenging in archaeological contexts. However, the ratios of stable isotopic carbon ($^{13}C_{org}/^{12}C_{org}$, expressed as δ ^{13}C) and nitrogen ($^{15}N_{org}/^{14}N_{org}$, expressed as δ ^{15}N) preserved in bone collagen often reflect dietary sources (Chisholm et al., 1982; Stokes, 1998; Keegan and DeNiro, 1988; Hastings et al., 2014). Analysis of these values by Hastings et al., (2014), Stokes (1998), and Keegan and DeNiro (1988)

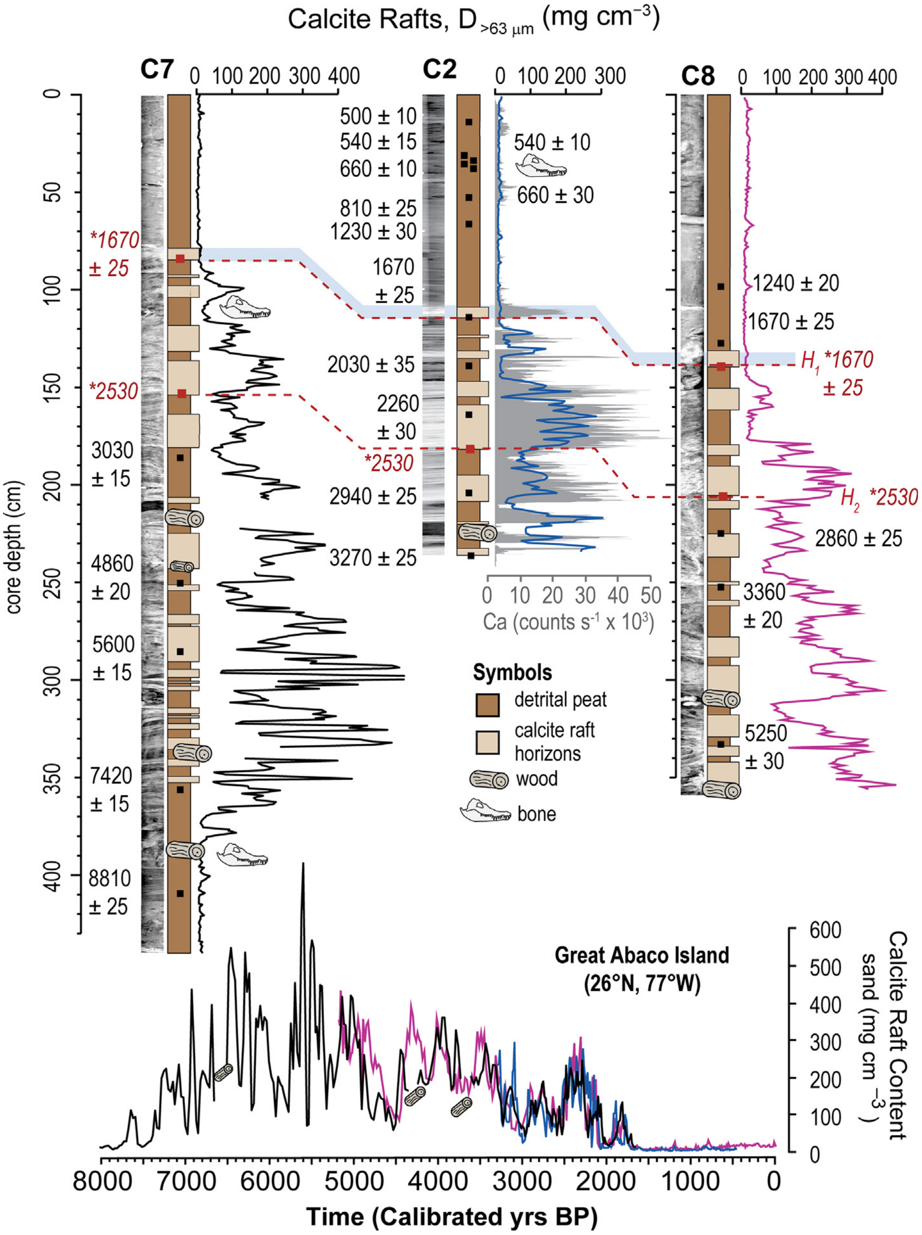

Fig. 2. (Top) Downcore stratigraphic variability, including lithologic changes, coarse-grained particle content. Only the highest probability 1σ calibration result is shown for the radiocarbon dates, depicted in years before present (1950). Red dates indicate stratigraphic tie points (H1 and H2) used to correlate coarse beds clearly represented in all three cores. XRF calcium counts for C2 shown in grey. (Bottom) Coarse data for all three cores plotted against the Bayesian age/depth results.

concluded that the Lucayan diet included both marine and terrestrial sources of carbon. $\delta^{15}N$ values indicated that terrestrial plants constituted only a small part of this mixed diet, and $\delta^{13}C$ was determined as more useful for diagnosing the relative contributions of each carbon source within an individual (Keegan and DeNiro, 1988). In the recent work of Hastings et al. (2014), enriched $\delta^{15}N$ and $\delta^{13}C$ values on bone collagen collectively indicate a mixture of marine and terrestrial contributions to the Lucayan diet. This mixed diet is consistent with archaeological excavations that routinely find terrestrial and marine food sources in Lucayan occupation sites (Berman and Pearsall, 2000; Keegan, 1986).

The $\delta^{13}C$ value of bone collagen is routinely provided by radiocarbon analytical facilities and is expressed against international standards in the standard delta ($\delta^{13}C$) notation per mil (‰). The $\delta^{13}C$ value can then be used to estimate the relative proportion of marine versus terrestrial dietary contributions. For Lucayan remains, the relative proportions of marine versus terrestrial organic carbon can then be estimated using a simple, yet applicable, two-endmember isotopic mass balance for carbon: $\delta X = F_m \times \delta X_m + F_t \times \delta X_t$; where F_t and F_m represent the fractional component of terrestrial and marine carbon respectively and $1 = F_t + F_m$ (van Hengstum et al., 2011). A value of –23‰ was used as the terrestrial end member (δX_t) in the isotopic mass balance as reported from Hastings et al. (2014) for Abaco, which is slightly more enriched than the –25‰ result from Keegan and DeNiro's (1988) archipelago-wide analysis. The marine end member (δX_m) used was –11‰, which is similar to the dietary analysis work of Keegan and DeNiro (1988) who determined that a $\delta^{13}C$ value of –11‰ was appropriate for a diet wholly reliant on marine carbon (± 1‰ to account for fractionation between flesh and bone collagen). One must consider that CAM and C_4 plants (such as maize) can increase the $\delta^{13}C$ value of a consumer's bone collagen, in turn leading to a false positive of a marine-rich diet in archaeological material. However, the $\delta^{15}N$ value of bone collagen can be used as a secondary test to confirm that marine resources were consumed by the individual in question, and guide

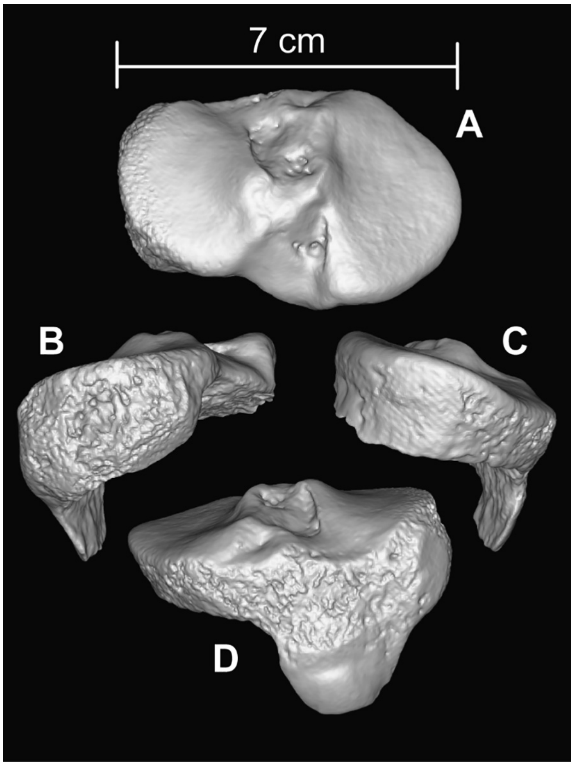

Fig. 3. 3D scan of the proximal epiphysis of a right tibia recovered from Great Cistern Sinkhole. A) Proximal upper view. B) Left lateral view. C) Right lateral view. D) Anterior view.

radiocarbon calibration.

4. Stratigraphy in Great Cistern

The recovered sedimentary infill in Great Cistern is generally characterized by identifiable terrestrial plant fragments from the surrounding landscapes (e.g., twigs, leaves), interspaced by intervals with increased deposition of coarse-grained calcite in discrete horizons. Further examination of coarse-grained horizons under a stereomicroscope determined that all coarse sediment was a unique calcite morphology known as calcite rafts. Calcite rafts form from the off-gassing of CO_2 from groundwater supersaturated with calcium carbonate, whereby a calcite crystal forms at the air-water interface with a distinctive morphology: a planar surface above with euhedral crystal growth below. When the force of gravity exceeds the buoyant force on the mineral, the calcite raft sinks and forms part of the sediment record (Taylor and Chafetz, 2004). These rafts are often present in the sediment deposited in limestone caves flooded by freshwater (Kovacs et al., 2017, 2018; Fornós et al., 2009; van Hengstum et al., 2011). Despite the proximity to the shoreline (< 40 m), the sediment record is devoid of sedimentary evidence that marine overwash processes (i.e., hurricanes) transported marine sediment into Great Cistern. For example, the adjacent subtidal lagoon contains abundant marine gastropods, bivalves, and benthic foraminifera, which were never observed in the cores from Great Cistern. These observations suggest that the organic and calcite particles present in the stratigraphic record were deposited *in situ*, and not transported from elsewhere by natural processes.

Sedimentation in Great Cistern likely initiated in 7300 BCE as Holocene sea-level rise forced the upward migration of the coastal aquifer and began flooding the sinkhole. C7 is the only core to capture the complete early and mid-Holocene sequence and records the sedimentary infill of the hole at a rate of 1 cm every 25.5 years (or 25.5 yrs/cm) between 7300 and 1000 BCE (Fig. S2). The sedimentation rate increased over the last three millennia to a rate of 13.8 yrs/cm. C8 records sedimentary infill at a similar rate of 13.0 yrs/cm over the last 3000 years but differs from C7 with a rate of 18.7 yrs/cm prior to 1000 BCE. C2 encompasses the last 3200 years at a consistent rate of 12.7 yrs/cm. Bayesian age/depth analysis shows that sedimentation is consistent, within uncertainties, over the past 3000 years. The rate of sediment infill observed in all cores indicates that Great Cistern contains a record of past environmental and landscape change resolvable at multidecadal scales.

Numerous faunal remains associated with the known local reptile community were also identified in all cores. Only the human tibia was directly dated, but ages for all other faunal remains can be stratigraphically inferred based on the established sedimentation rates in the cores. Most animal bones were recovered from the lower intervals of C7, and presumably belong to the native anole and rodents that likely occupied the marshy environment created during initial sinkhole flooding between 7300 and 6000 BCE. Distinct among the anole and rodent remains was an assemblage of small ribs and vertebrae identified as belonging to a Bahamian Boa. The depositional age of the boa falls between 6710 and 6000 BCE (2σ, probability: 1.0). The remains were dispersed around a large piece of charred wood suggesting that the snake entered the hole when an overhanging tree burned and collapsed, carrying the animal with it. The fragments of a juvenile crocodile skull were located higher in the stratigraphic record, likely deposited between 170 BCE and 100 CE (2σ, probability: 1.0). Though extinct today, these dates are consistent with the presence of the species on Abaco (Hastings et al., 2014; Steadman et al., 2007). In the upper intervals of the cores, the most abundant faunal remains belonged to small native fish.

A human right proximal tibial epiphysis was recovered in C2 between 38 and 35 cm core depth. The epiphysis is intact on all sides with no indication of fracture. Union between the tibial epiphysis and the diaphysis typically begins in adolescence (females: age 13, males: age 15.5, as per Cunningham et al. (2016). The lack of evidence for fusion with the diaphysis suggests that the individual was adolescent at time of death. The detrital peat matrix surrounding the epiphysis contained no evidence of disturbance or any anomalous deposition (i.e., storm induced transport). From the stratigraphic age (1240 to 1380 CE, 2 σ, probability: 1.0) the human bone pre-dates European contact in the 15th Century, indicating an indigenous provenance associated with the Lucayan culture.

5. Age of skeletal remains in Abaco

5.1. Great Cistern

The results of the stratigraphic arguments (relative) from the well-preserved stratigraphy in Great Cistern provide the depositional age of the Lucayan bone, and direct AMS (absolute) dating of the tibia yields the likely date of the individual's death. The results of both methods converge between the late 13th and early 14th century CE. As previously introduced above, a 100% terrestrial carbon calibration (IntCal13, 2σ age range of 1030 to 1170 CE, 0.98 probability, Fig. 4A), or 100% marine carbon calibration (Marine13, 2σ age range of 1320 to 1440 CE 1.0 probability, Fig. 4B) would both be incorrect for Lucayan remains based on their subsistence patterns. However, these results do provide the endmembers that constrain a time interval spanning the correct age (Fig. 4C, E, F). Using two-endmember mixing with the laboratory reported $\delta\,^{13}C$ value of –14.9‰ (Table S1) for the bone collagen, we can estimate that 67.5% of the individual's diet came from marine organic carbon. The reported $\delta\,^{15}N$ value on the bone collagen of 12.0‰ further indicates inclusion of marine resources into the individual's diet, and thus supports the use of a mixed radiocarbon calibration curve.

Assuming 67.5% of the individual's diet was based on marine contributions, the bone had a calibrated 2σ date range of 1255 to 1340 CE (probability: 0.89, Fig. 4C) with a weighted median age of 1295 CE.

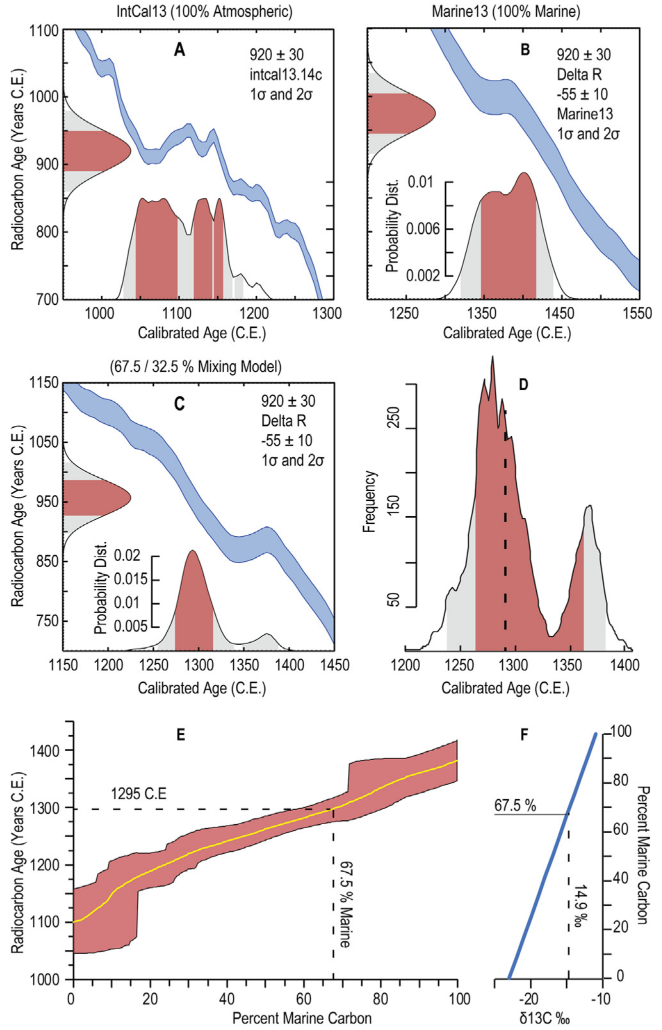

Fig. 4. A) 1σ (red) and 2σ (grey) radiocarbon calibration results for the Great Cistern tibia representing a 100% atmospheric carbon source using the IntCal13 calibration curve. B) 1σ (red) and 2σ (grey) calibration results for the Great Cistern tibia using the Marine13 calibration curve representing a 100% marine carbon source and ΔR value of − 55 ± 10 years. Probability distribution scale is the same between A and B. C) 1σ (red) and 2σ (grey) calibration results for the Great Cistern tibia using the mixed (67.5% marine, 32.5% atmospheric carbon) calibration curve and ΔR value of − 55 ± 10 years. D) 1σ (red) and 2σ (grey) age probability of the sediment depth where the bone was recovered (C2, 38 cm down core). The weighted median sedimentary age of 1290 CE is marked with the dashed line. E) The calibrated age of the Cistern tibia at 1% intervals from 0% to 100% marine carbon source. The 1σ uncertainty envelope is shown in red. The yellow line indicates the weighted mean age at each % interval. The dashed line denotes the mixed model calibrated weighted median age of 1295 CE and corresponding percent marine carbon. F) Two-end member linear stable carbon isotopic mixing model developed to calibrate the Great Cistern tibia. The laboratory derived δ^{13}C of 14.9‰ is marked by the dashed line.

Alternatively, the 2σ age range for the stratigraphic level (52 cm below the sediment water interface) is 1240 to 1380 CE (probability: 1.0) with a weighted median age of 1290 CE (Fig. 4D). The results of these separate methods are exceedingly similar. The uncertainty range provided by the sedimentary age model is wider than that for the bone because of increased uncertainty in the IntCal13 calibration curve between 1000 and 1200 CE (Reimer et al., 2013). However, the agreement between the results provides validation for each technique while also indicating that deposition of the remains and death of the individual occurred contemporaneously (within 2σ uncertainties).

5.2. *Sawmill Sink*

The only other dated Lucayan skeletal remains from Great Abaco Island is the tibia from an adolescent discovered in Sawmill Sink. The Sawmill remains had a conventional radiocarbon age of 1040 ± 40 years before present and a δ^{13}C value of –14.7‰ (Steadman et al., 2007). This δ^{13}C value indicates that the individual from Sawmill also likely had a diet composed of both terrestrial and marine organic carbon (Keegan and Deniro, 1988; Hastings et al., 2014). Similar to the individual in Great Cistern, either a wholly terrestrial or marine radiocarbon calibration would be inappropriate since the reported δ^{13}C value falls between the endmembers reported by Hastings et al. (2014) and Keegan and Deniro (1988). The Great Cistern radiocarbon calibration benefited from the high-quality stratigraphy and recent advancements in dietary analysis by Hastings et al. (2014), and the new radiocarbon calibration curves (IntCal13 and Marine13; Reimer et al., 2013) which were unavailable when the Sawmill remains were discovered and reported (Steadman et al., 2007). By applying the same two-endmember carbon isotopic mixing model used in Great Cistern, we estimate that the Sawmill individual's diet consisted of 69% marine resources. After applying the same ΔR value of –55 ± 10 for the Bahamian coastal waters (Broecker and Olson, 1961), the individual interred in Sawmill Sink has a revised 2σ calibrated age range of 1110 to 1290 CE (probability: 0.94) with a median result of 1210 CE. This new result is ~100 to 200 years younger than previously reported (Steadman et al., 2007).

6. Discussion & conclusion

6.1. *Implications for human arrival and diet in the northern Bahamas*

Indirect evidence for human activity suggests that Lucayans had arrived on Abaco Island by ~1000 CE. This is indicated by the increase in disturbance taxa and charcoal identified though palynological analysis (Slayton, 2010), the finds at the Gilpin Point midden in south Abaco (Steadman et al., 2014), and the rapid extirpation of the Albury tortoise and Cuban crocodile from the island at that time (Hastings et al., 2014; Steadman et al., 2007). However, without direct evidence of human colonization, this 1000 CE date cannot be corroborated. The remains from Great Cistern and Sawmill Sink provide direct evidence of human presence on Great Abaco Island by the 13th Century CE. The 200-year interval separating the direct and indirect evidence does not imply any contradiction in establishing a human presence on the island, though it does mean that the earlier arrival estimate continues to remain unverified.

Identifying the probable period of death of the individuals recovered from Great Cistern and Sawmill Sink depended upon the recent advancements in stable isotope dietary reconstructions (Hastings et al., 2014). δ^{13}C value from the bone collagen of both individuals indicated a diet with a dominant reliance on marine sources (67.5% for Great Cistern and 69% for Sawmill Sink). This is consistent with both archaeological evidence of fishing and shellfish consumption (Berman and Pearsall, 2000; Keegan and DeNiro, 1988), and the stable isotope dietary reconstructions (Hastings et al., 2014; Keegan and DeNiro, 1988).

Identifying the date of inhumation in Great Cistern relied on the stratigraphic (relative) age of the sedimentary infill. We have increased confidence that Great Cistern represents a primary internment site (Duday et al., 2014) given that the sedimentary age and the direct age of the bone so tightly align. However, the possibility of secondary interment remains viable given the age uncertainties and the lack of other recovered bones or cultural artifacts.

6.2. *Does Great Cistern represent another sinkhole burial?*

The practice of interring human remains in caves and sinkholes is not uncommon among the Lucayan and Taíno traditions (Keegan, 1997; Schaffer et al., 2012). Across the Lucayan archipelago there have been 16 identified human burial sites within submerged caves (Pateman, 2007). While the recovery of one tibia fragment does not constitute satisfactory archaeological evidence of Lucayan mortuary practices, it remains possible that the Great Cistern remains are part of a larger grave site, especially when considering the Lucayan predilection for sinkhole internment. However, we cannot discount the possibility that the individual or remains entered the hole accidently or from other post-mortem transport. While motives for the selection of Great Cistern as a burial site may never be resolved, the limited size of the hole and the dearth of substantial fish remains in the sediment cores suggest that Great Cistern would not have been used as a direct source of food. Additionally, at the time of internment, long-term shoreline encroachment to Great Cistern from relative sea-level rise during the late Holocene had already caused back-stepping of the local meteoric lens (i.e., freshwater resources) toward the interior of the island (van Hengstum et al., 2018, 2020; Khan et al., 2017). This would have ensured that the water in Great Cistern would have no longer been potable by the time of inhumation. While the remains from Great Cistern and Sawmill Sink do not resolve the uncertainty surrounding Lucayan arrival on Abaco, the similarity in age between the Great Cistern and Sawmill Sink bones potentially indicate a period of increased blue hole interment on the island once occupation had been established.

CRediT authorship contribution statement

Richard M. Sullivan: Writing - original draft, Investigation, Formal analysis. **Peter J. Hengstum:** Formal analysis, Funding acquisition, Project administration, Supervision, Writing - review & editing. **Jeffrey P. Donnelly:** Formal analysis, Funding acquisition, Resources. **Tyler S. Winkler:** Investigation. **Samuel E. Mark:** Formal analysis. **Nancy A. Albury:** Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2020.102441.

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