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RESEARCH

Ancient Skeletons *In Situ*: Evaluating Bone Diagenesis at an Open-Air Archaeological Site and Community Museum in Central Thailand

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Abstract
Archaeological human skeletal remains are displayed in many museums across Thailand, under glass in exhibit halls, and as part of open-air displays where skeletons are partially excavated but remain *in situ.* This form of outdoor exhibit is a notable component of public archaeology initiatives and local educational outreach, but the potential long-term implications for bone preservation have raised concerns. This study investigated patterns of diagenesis at the Ban Pong Manao Archaeological Site and Community Museum in Lopburi Province, central Thailand, where some ancient skeletons are curated indoors in the on-site antiquities archive, and others are displayed outdoors in covered open-air excavation units. We applied a biogeochemical approach to investigate diagenesis, using methods from stable isotope analysis and Fourier-transformed infrared spectroscopy to assess post-excavation taphonomic processes. Results from this study revealed no statistically significant differences in values for bone collagen or bioapatite preservation indices between *in situ* and curated skeletons. However, we observed lower collagen yields and higher bioapatite carbonate yields among *in situ* skeletons that suggested processes of diagenesis may be accelerated by partial exposure in open-air display contexts. After roughly 20 years, differences between post-excavation contexts are not yet substantial but over time may increase if current taphonomic trajectories are maintained. We consider the implications and limitations of these results and examine partial excavation and exposure as simultaneously deleterious and additive in the context of cultural heritage management in Thailand.

Keywords Southeast Asia · Public archaeology · Heritage management · Stable isotope analysis · Fourier-transformed infrared spectroscopy · แหล่งโบราณคดีบ้านโป่งมะนาว

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Introduction

Thailand is home to approximately 1600 museums, reflecting a variety of forms of material culture. Most are historical and archaeological museums, including 120 dedicated specifically to archaeology ("Thai Museums Database", 2024). Alongside large national museums, local archaeological and site museums play an important role in cultural heritage preservation and management and have been recognized for their successful integration of community-based archaeology and mutually beneficial engagement (Glover, 2015; Marwick et al. 2013; Shoocongdej, 2011, 2023). Archaeological human skeletons are prominently featured in many museums, where they are displayed under glass as part of exhibits, and/or in open-air contexts, partially excavated, but not exhumed (Fig. 1). The first open-air site museum was established at the Ban Chiang National Museum in Udon Thani Province, northeast Thailand, after King Bhumibol Adulyadej visited the site in 1972 (Fine Arts Department, 2015). In addition to creating traditional museum exhibits, the Fine Arts Department preserved burials *in situ*, displaying human skeletal remains and the artifacts with which they were interred (Tourism Authority of Thailand, 2024). Thereafter, numerous open-air site museums have been developed across the country, demonstrating the significant role that

Fig. 1 Skeletons *in situ* at Ban Pong Manao Archaeological Site and Community Museum

human skeletal remains can play in public outreach, education, and research and humanizing archaeological peoples by providing insights into ancient lives and lifeways (Pureepatpong, 2000). Although some open-air site museums show replicas of human skeletal remains, most display real human bones, raising practical challenges, ethical concerns, and questions about the long-term effects of *in situ* exposure on bone preservation (Case et al. 2023; Halcrow et al. 2019).

Under Thailand's Article 4 of the Act on Monuments, Antiques, Objects of Art, and National Museums (1961, amended 1992), human skeletons from archaeological sites are considered antiquities, undifferentiated from artifacts, ecofacts, and other forms of ancient movable material culture (Halcrow et al. 2011, 625). Cultural heritage legislation has focused on preventing the loss of culturally significant antiques and deterring their illegal trade (Lertcharnrit, 2020). Local and site museums have contributed to these aims by raising awareness of the long-term value of archaeological research and preservation, in part by creating lasting local opportunities that are unparalleled by short-term gains made through illegal looting activities (Glover, 2015, 245). The resulting benefits of community engagement are particularly consequential for archaeological human skeletons, as ancient cemeteries are not specifically regulated (Lertcharnrit, 2020), and looters frequently target burials to retrieve grave goods of black market interest or those with perceived spiritual significance (Halcrow et al. 2011; Lertrit, 1996).

A growing body of scholarship has addressed ethical considerations for conducting bioarchaeological research in Thailand (i.e., Halcrow et al. 2011, 2019; Lertcharnrit, 2020; Pureepatpong, 2000). Based on contemporary Buddhist practices and beliefs, many Thai people regard ancient human skeletal remains as distant ancestors, but the physical body and spirit are disaggregated (Halcrow et al. 2019), and human bones are not considered inherently sacred (Halcrow et al. 2011). Even so, ceremonies that make merit to the spirits or ancestors are typically performed before archaeological excavations commence (Halcrow et al. 2011, 2019). Research involving ancient human skeletal remains is generally accepted (Halcrow et al. 2011, 2019), although perspectives vary (see, for example, Artayok, 2000).

Some concerns have been raised, however, regarding the preservation of skeletons *in situ* at open-air site museums, where partial exposure is *seemingly* at odds with concepts of bioarchaeological preservation ethics (Walker, 2008). At a macroscopic scale, morphological features and articular surfaces routinely observed to estimate sex and age oftentimes are not visible, and entire portions of the skeleton are rendered completely unobservable in such contexts (posterior aspects, for instance, in the case of individuals buried in extended supine inhumations). These limitations contribute to broader issues of data comparability, especially for paleopathological assessments, as *in situ* preservation may impact observations and reported frequencies of skeletal and dental pathologies (Case et al. 2023, 90). Open-air site museums also expose bone to ambient temperatures and humidity, which can accelerate fragmentation and decrease skeletal completeness (Halcrow et al. 2011, 2019; Pureepatpong, 2000). Together, these detriments to data collection and bone preservation create analytical and comparative issues that limit future research (Halcrow et al. 2019, 472).

In this study, we assessed patterns of bone diagenesis at the Ban Pong Manao Archaeological Site and Community Museum in Lopburi Province, central Thailand. Some human skeletons are curated in the on-site antiquities archive, in plastic bags and boxes in a non-climate-controlled building, and other individuals are displayed *in situ*, as part of the open-air site components of the museum (Fig. 2). We used a suite of biogeochemical methods frequently applied in bioarchaeological applications of stable isotope analysis to assess potential differences in preservation between skeletons from both post-excavation contexts at the site. After nearly two decades of exposure to ambient conditions in a tropical climate, we did not detect statistically significant differences in preservation between *in situ* and curated skeletal remains. However, there are subtle differences in collagen and carbonate content that suggest different diagenetic trajectories between curation groups. We address these results in light of public archaeology, with consideration of exposure in open-air contexts as simultaneously deleterious and additive to cultural heritage management initiatives.

Background

Ban Pong Manao Archaeological Site and Community Museum

The archaeological site of Ban Pong Manao (PMN) is located in the eastern margins of central Thailand, Huai Khun Ram Subdistrict, Phatthana Nikhom District, Lopburi Province (Fig. 3). The contemporary village of Pong Manao was established in 1957 by people from a diverse array of ethnicities, including Thai Yuan, Lao Phuan, and Lao Ngaew people, among others. Today, most villagers are engaged in sugar cane, maize, cassava, and dairy farming ("Ban Pong Manao, Lopburi Province" 2024). The archaeological site is situated within the undulating terrain of the Pasak River Basin in a landscape that was predominated by subtropical rainforest prior to contemporary agricultural practices (Ciarla, 2005).

Fig. 2 The on-site antiquities archive (*left*) and one of the open-air excavation units at the Ban Pong Manao Archaeological Site and Community Museum (*right*)

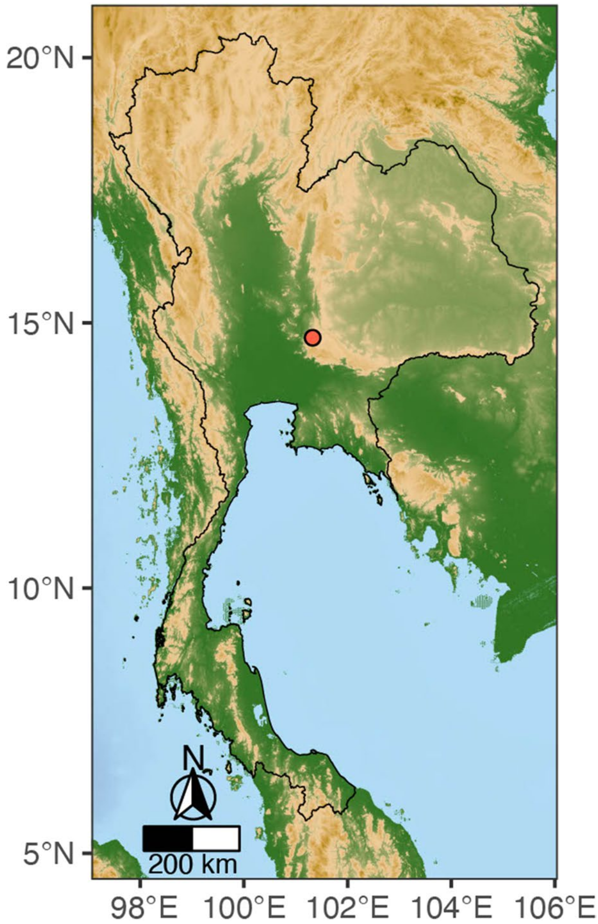

Fig. 3 Map of Thailand showing the location of Ban Pong Manao Archaeological Site and Community Museum

PMN was first documented in 2000, after extensive looting damaged and disturbed as many as one hundred burials located on the grounds of the village temple, Wat Pong Manao (Lerdpipatworakul, 2009). Local people later attempted to enlarge the looted portion of the site, and sought the expertise of faculty from the Department of Archaeology at Silpakorn University. Together, their main goal became to develop the archaeological site into a tourist attraction by creating an education center and on-site museum. The first scientific excavations at PMN were undertaken in 2001 as part of the summer field school of the Department of Archaeology, Silpakorn University, led by Surapol Natapintu, Professor of Archaeology at Silpakorn University, and a number of subsequent excavations were carried out (Natapintu, 2005).

In the years since initial documentation, Thai and foreign archaeologists have conducted excavations at PMN, collaborating with local and national agencies, and leading teams of students and local villagers. Excavations have revealed a settlement of approximately 6 hectares with an inner cemetery distinct from outer habitation zones (Lerdpipatworakul, 2009). Burials from the central part of the cemetery date to the Iron Age (Natapintu, 2004), and the site has been described as quintessential of the Iron Age 2 period (c. 200 BCE–CE 200) in central Thailand's eastern margins (Rispoli, 2022, 587). Burials excavated from PMN document an organized cemetery with east–west oriented extended supine inhumations that represent interments from multiple generations of past inhabitants. Though *in situ* preservation prevents comprehensive skeletal analyses and, to some extent, limits data comparability between sites (Case et al. 2023), bioarchaeological analyses at PMN have revealed low prevalence rates for a variety of skeletal and dental paleopathological conditions, consistent with results from other sites in central and northeast Thailand (Lerdpipatworakul, 2009; Liu, 2012). The wide variety of grave goods found in association with burials at PMN, which include ceramics, metal implements, glass and stone beads, metal jewelry, and other forms of personal adornment, provided new insights into a community with both highly localized craft traditions and connections to vast networks of inter-regional trade (Chuenkaek, 2003; Natapintu, 2004, 2007, 2015; Rispoli, 2022). Archaeological materials from PMN have been the subject of extensive research by archaeologists and numerous Thai and foreign graduate students, and the resulting information produced is often incorporated into museum displays and site signage.

Public engagement was prioritized from the beginning of archaeological investigations at PMN. As Natapintu (2005, 109) explained, "the target was to create not only a tourist attraction as such, but rather a self-sustained study center, managed by local villagers, with the aim to disseminate the knowledge of the archaeology and history of the site area among local schoolchildren and students." What started as a small showcase of archaeological artifacts, photographs, and descriptions over time expanded into a sizable site museum with multiple exhibit halls, an on-site antiquities archive, and multiple covered open-air excavation units visited by thousands of people each year (Natapintu, 2005, 111). Local staff welcome visitors on weekdays, and members of the volunteer youth guide club lead tours on the weekends, practicing communication skills in Thai and English (Natapintu, 2005; Pongprairat, 2020). The Ban Pong Manao Archaeological Site and Community Museum has been recognized as "one of the most successful community archaeology projects in Thailand" (Shoocongdej, 2011, 100), bridging archaeological research with local education, tangible community benefits, and overall improvements to quality of life among contemporary local people.

Natapintu, who directed excavations and helped to establish the Ban Pong Manao Archaeological Site and Community Museum, noted how attitudes toward archaeological heritage changed among local villagers: "conservation, which is normally viewed only as a means for protection, can also be considered as a means for progress and development" (Natapintu, 2005, 110). Within a decade of PMN's initial excavations, ancient human skeletons had become strongly associated with archaeology and cultural heritage among local people. When Lertcharnrit and Niyomsap (2008) interviewed villagers from Ban Pong Manao and asked what they thought of when they heard the word, "archaeology," 41% ($n=85/207$) of responses mentioned some form of human skeletal remains. Contemporary people living in and around Ban Pong Manao experienced some tangible benefits from archaeological tourism, especially during the Community Museum's early years in operation. Sub-district and provincial government administrations invested in the improvement, maintenance, and management of the museum, along with public infrastructure. Narrow dirt roads were replaced with wider asphalt roads to promote tourist access to the site, which also improved the safety and accessibility for local people. New markets emerged for local vendors, from food to the revival of handweaving traditions for the sale of baskets and other handicrafts as souvenirs (Glover, 2015; Natapintu, 2005). Overall, public archaeology initiatives at PMN provided some economic benefits to local people and a sense of collective appreciation for cultural heritage in the village (Natapintu, 2005). Between 2000 and 2005, over 40,000 people visited PMN (Natapintu, 2005), but, in some respects, the "fame faded quickly" (Booneiam et al. 2019, 97). Despite high rates of local participation, Ban Pong Manao's distance from major cities, coupled with the lack of public transportation to the village, has limited its reach as a site of cultural heritage tourism. Nearly 20 years after its initial excavation, visitor demographics have shifted, and the economic benefits have slowed. Today, most people who tour the Ban Pong Manao Archaeological Site and Community Museum are students on school or university field trips, and community members have advocated for increased financial support to achieve more broadly sustainable tourism (Booneiam et al. 2019).

Bioarchaeological Applications of Stable Isotope Analysis

Bone diagenesis has been a topic of intensive study in archaeology, bioarchaeology, and related disciplines, in part because of the proliferation of research using stable isotope analysis and other archaeometric techniques in recent decades. Briefly, bioarchaeological applications of stable isotope analysis traditionally focused on reconstructing aspects of diet, ecology, and migration histories among past peoples by analyzing the organic (collagen and other proteins) and/or inorganic (bioapatite) fractions of bones and teeth (Ambrose & Krigbaum, 2003; Britton, 2017; Katzenberg, 2008). Carbon isotope ratios reliably differentiate between the consumption of C_3 plants like rice, wheat, and most terrestrial plants from C_4 plants like millet, maize, and sorghum (Lee-Thorp et al. 1989; van der Merwe, 1982) and can help to elucidate paleoecological conditions, like aridity and forest density (Kohn, 2010; van der Merwe and Medina 1991).

The stable carbon isotope composition preserved in the organic and inorganic fractions of bone reflect slightly different aspects of diet and behavior. Carbon isotope ratios from collagen preferentially reflect the composition of consumed proteins, while those preserved in bioapatite better reflect the whole diet (proteins, carbohydrates, and lipids) (Ambrose & Norr, 1993). Nitrogen isotope ratios recorded in bone collagen are used to estimate consumer trophic positions (Ambrose, 1991; Hedges & Reynard, 2007; Schoeninger, 1985) and can be assessed alongside carbon isotope ratios to distinguish between marine and terrestrial diets (Kellner & Schoeninger, 2007; Schoeninger & DeNiro, 1984; Schwarcz & Schoeninger, 2012). Oxygen isotope ratios from phosphate and structural carbonates in bone bioapatite reflect the composition of imbibed waters (Bryant et al. 1996; Chenery et al. 2012;

Kohn et al. 1996), which in turn are influenced by a number of environmental factors (for review, see Knudson, 2009) and can be used as an indicator of paleoclimate conditions and, in some contexts, as a line of evidence regarding migration (Gregoricka, 2021; Knudson & Price, 2007; Pederzani & Britton, 2019). However, a critical aspect of applying stable isotope analysis is ensuring that tissues analyzed preserve the biological signals of interest and have not been altered by taphonomic processes.

Bone Diagenesis and Stable Isotope Analysis

The utility of stable isotope analysis in paleodietary and paleoenvironmental studies is predicated upon the preservation of biological tissues and, more specifically, the retention of *in vivo* isotope ratios, which may be altered by processes of diagenesis. On archaeological timescales, the preservation of bone and its constituent collagen and bioapatite components are influenced by a combination of factors in the burial environment, including soil pH, humic content, and hydrology, microbial activity (bioerosion), and climate conditions, like seasonal variation in temperature and precipitation (for a more comprehensive review, see Kendall et al. 2018).

Tropical climates are known to affect the preservation of bone and its constituent collagen and bioapatite (Pestle & Colvard, 2012). Despite the close structural relationship between collagen and bioapatite, the preservation of collagen does not necessarily indicate the preservation of bioapatite, and vice versa; as such, diagenesis for both the organic and inorganic fractions of archaeological bone should be assessed independently to ensure that isotope ratios actually reflect *in vivo* values (Beasley et al. 2024). Importantly, a substantial corpus of literature has established quantitative thresholds to assess the integrity of archaeological collagen and bioapatite (Ambrose, 1990; DeNiro, 1985; Dobberstein et al. 2009; Driessens & Verbeeck, 1990; Guiry & Szpak, 2021; van Klinken & Hedges, 1995), as interpretations of stable isotope ratios from diagenetically altered samples can lead to erroneous interpretations of diet, ecology, and migration in the past (DeNiro, 1985; Nelson et al. 1986).

Materials and Methods

This study was part of an investigation of human mobility and dietary practices in Metal Age central Thailand (Palefsky, 2023). We analyzed bone fragment samples from a total of 33 individuals with associated identification numbers and well-documented provenience at PMN. Fragments were selected opportunistically rather than consistently from the same element to limit the impact of destructive analyses on complete skeletal elements. Among them, 21 samples (~64%) were from individuals curated in the antiquities archive, while 12 (~36%) were from skeletons that have remained *in situ*. With permission from the National Research Council of Thailand and Thai Fine Arts Department, we prepared bone fragment samples for stable isotope analysis and Fourier-transformed infrared spectroscopy (FTIR).

Collagen was isolated by demineralizing approximately 300 mg of homogenized cortical bone in a 0.5 M solution of ethylenediaminetetraacetic acid (EDTA) following methods developed by Tuross et al. (1988). This approach allowed us to maximize yields by slowly and gently isolating collagen while also removing humic acids. Samples were demineralized over a period of approximately four weeks, with EDTA decanted and refilled after 2 weeks. Once samples were fully demineralized, EDTA was removed with a series of ten deionized water rinses with sonication and extended 24-h soaks after the first, fifth, and final rinses. Collagen samples were then freeze dried and weighed into tin capsules for analysis.

Bone bioapatite carbonate was prepared following procedures modified from Koch et al. (1997). Approximately 10 mg of homogenized cortical bone was treated with 3% sodium hypochlorite (NaOCl) to remove organics over a period of 48 h, with NaOCl decanted and refilled after the first 24 h had passed. Samples were rinsed to neutrality with a series of three deionized water rinses and then treated with 1 mL 0.1 M acetic acid (CH_3COOH) for 4 h to remove diagenetic carbonates. Samples were again rinsed to neutrality with a series of three deionized water rinses and then dried in a lab oven at 50 °C for 24 h.

Collagen $\delta^{13}C$ and $\delta^{15}N$ values were measured simultaneously using a Costech 4010 Elemental Analyzer coupled with a Delta V Plus Continuous Flow Isotope Ratio Mass Spectrometer housed in the Stable Isotope Ecosystems Laboratory (SIELO) of the University of California, Merced. Stable isotope composition was corrected for drift using reference materials USGS 41a and Costech acetanilide and then normalized to the international V-PDB and V-AIR scales for organic carbon and nitrogen, respectively, using USGS 40 reference materials. Replicability for standards was ≤ 0.1‰ for both $\delta^{13}C$ and $\delta^{15}N$ values (USGS 40, $n=8$; USGS 41a, $n=11$; Costech acetanilide, $n=11$).

Bone carbonate $\delta^{13}C$ and $\delta^{18}O$ values were measured simultaneously using a Thermo-Finnigan Gasbench II coupled with a Delta V Plus Continuous Flow Isotope Ratio Mass Spectrometer, also housed in the SIELO. The analytical drift was monitored using NBS 18 and CM reference materials and normalized to the international V-PDB scale using NBS 18, a Carrara Marble (CM), and USGS 44 reference materials. Replicability for $\delta^{13}C$ measurements was 0.1‰ for CM ($n=13$), 0.2‰ NIST 120C ($n=15$), <0.1‰ for NBS 18 ($n=13$), and 0.1‰ for USGS 44 ($n=14$). Replicability for $\delta^{18}O$ measurements was 0.3‰ for CM ($n=13$), 0.2‰ NIST 120C ($n=15$), 0.2‰ for NBS 18 ($n=13$), and 0.1‰ for USGS 44 ($n=14$).

Standard quality control metrics for collagen were assessed, including collagen yield (Ambrose, 1990), carbon and nitrogen content (Ambrose, 1990), and atomic C:N (Guiry & Szpak, 2021). We also assessed bioapatite carbonate content using regression of sample-gas peak area versus carbonate content using several calcium carbonate reference materials (CM, NBS 18, USGS 44). Following established thresholds, we identified well-preserved samples as those with collagen yield ≥ 0.5 wt%, collagen wt% C >13.0 wt%, wt% N >4.8 wt%, and atomic C:N between 3.1 and 3.6, and bioapatite carbonate content between 3 and 13 wt% (Ambrose, 1990; DeNiro, 1985; Dobberstein et al. 2009; Driessens & Verbeeck, 1990; Guiry & Szpak, 2021; van Klinken & Hedges 1995).

Fourier-Transform Infrared Spectroscopy (FTIR)

Attenuated Total Reflectance Fourier-Transform Infrared Spectroscopy (ATR-FTIR) is a minimally destructive method to semi-quantitatively determine the molecular structure of a material. ATR-FTIR irradiates a material with different wavelengths of infrared light. Because different molecular bonds preferentially absorb or transmit different infrared wavelengths, ATR-FTIR produces a characteristic spectrum with peaks ascribed to chemical functional groups (Stuart, 2004). Samples were not chemically treated or otherwise altered prior to any FTIR analysis. We analyzed ~ 1 mg of powdered bone from our samples using a Bruker Vertex 70 Far-Infrared FTIR housed in the Nuclear Magnetic Resonance Facility at the University of California, Merced. The spectra were collected from 400 to 4000 cm^{-1} over 32 scans at a spectral resolution of 4 cm^{-1}.

We calculated four proposed FTIR indices, commonly used to assess diagenetic processes in archaeological and fossil bone, including carbonate content (Sponheimer & Lee-Thorp, 1999), organic content (Lebon et al. 2016; Roche et al. 2010), and the degree of bioapatite recrystallization (Sponheimer & Lee-Thorp, 1999; Weiner & Bar-Yosef, 1990). Briefly, the A-carbonate-on-Phosphate-Index (API; [B_{1545}/B_{605}]) and B-carbonate-on-Phosphate-Index (BPI; [B_{1415}/B_{605}]) track structural A-type and B-type carbonate in bioapatite (Elliott, 2002). Loss of structural carbonate can indicate diagenetic uptake of other elements (e.g., fluorine) and may indicate alteration to primary stable isotope compositions (Roche et al. 2010). The Phosphate Crystallinity Index (PCI), [$B_{605} + B_{565}$ /V_{590}], is related to apatite crystallinity where higher values indicate more recrystallization and organized crystals, potentially resulting from prolonged exposure or heat-induced recrystallization (e.g., deliberate burning or wildfires (Thompson et al. 2013). Finally, we calculated the Water-Amide-on-Phosphate-Index (WAMPI), [B_{1650}/B_{605}], as a proxy for organic collagen content (Roche et al. 2010). This index is essentially identical to the Amide-I-to-Phosphate ratio used by Lebon et al. (2016) but is also used as an indicator of collagen quality (Trayler et al. 2023). Elevated WAMPI values should indicate greater organic content. Prior to index calculation, each spectrum was background-corrected over several background points and smoothed using a weighted moving average with a Gaussian kernel (sd = 1 cm^{-1}) prior to index calculation. Since absorbance band positions are approximate, we located the local minima or maxima as appropriate for each sample prior to index calculation. All FTIR data processing and index calculations used custom R scripts following the methods of Trayler et al. (2023).

We assessed the normality of each index value for both post-excavation context groups using normal quantile plots, density plots, and Shapiro–Wilk tests ($\alpha = 0.05$). Given the small sample size and non-normal distributions observed, we then used Mann–Whitney U tests ($\alpha = 0.05$) to compare preservation indices by post-excavation context group.

Results

Results for indices of preservation assessed in this study are reported in Table 1. No significant differences were observed between *in situ* and antiquities archive skeletons for any preservation index (Table 2). Collagen yields, carbon and nitrogen contents, and atomic C:N ratios all fell within the expected range for taphonomically unaltered bone collagen, as did bioapatite carbonate contents (3–13%) (Driessens & Verbeeck, 1990). On average, bone samples from *in situ* skeletons yielded 0.9 wt% less collagen, and surviving collagen retained 0.5 wt% less carbon and 0.2 wt% less nitrogen. Mean bone bioapatite carbonate content was 0.4 wt% higher for the *in situ* group compared to the group curated in the antiquities archive.

Samples from each individual showed the expected spectrum for collagen-bioapatite mixtures, with prominent peaks for carbonate (880, 1415, 1545 cm^{-1}), phosphate (565 cm^{-1}, 605 cm^{-1}, 1020 cm^{-1}), and organic amide (amide III = 1230 cm^{-1}, amide II = 1545 cm^{-1}, amide I = 1650 cm^{-1}) functional groups. WAMPI values are significantly correlated with collagen yield for both preservation groups ($r^2 = 0.7$, $p = 1 \times 10^{-9}$), and BPI values were weakly correlated with bioapatite carbonate contents ($r^2 = 0.17$, $p = 0.01$). There were no statistically significant differences between any of the FTIR indices by preservation group.

Discussion

Collagen and Bioapatite Preservation

Across all nine indices considered in this study, no statistically significant differences were identified between skeletons *in situ* and skeletons housed in the antiquities archive at the Ban Pong Manao Archaeological Site and Community Museum (Table 2). The results demonstrate that all bone collagen and bioapatite samples analyzed are considered taphonomically unaltered, retaining *in vivo* isotope ratios useful for paleodietary reconstruction, regardless of their post-excavation context group.

Skeletons from PMN analyzed in this study yielded collagen in quantities similar to those reported at other archaeological sites in Mainland Southeast Asia (C. A. King, 2006; C. A. King & Norr, 2006; C. L. King et al. 2013) and elsewhere in tropical and subtropical areas (Pestle & Colvard, 2012); however, it is notable that all bone fragments yielded diagenetically unaltered collagen. For context, only ~67% of human bone samples from Tha Kae ($n = 8/12$), 55% from Phu Noi ($n = 11/20$), and 24% from Ban Mai Chaimongkol ($n = 6/25$) prepared using identical methods yielded collagen suitably preserved for stable isotope analysis (Palefsky, 2023), which are also more consistent with recovery rates reported elsewhere in the tropics (Pestle & Colvard, 2012). Previous research attributed the high degree of skeletal preservation at PMN to the site's elevation in the undulating terrain and the sandy, well-drained, basic soil conditions in which the

Table 1 Results from all preservation indices considered in this study reported by individual

Individual	Post-excavation context	Skeletal element	Collagen yield (wt%)	Collagen carbon content (wt%)	Collagen nitrogen content (wt%)	Collagen atomic C:N (mol/mol)	Bioapatite CO_3 content (wt%)	WAMPI (unitless)	PCI (unitless)	API (unitless)	BPI (unitless)
PMN-SQ1-B1-2001	Antiquities archive	Tibia	9.3	42.0	15.2	3.2	6.8	0.7	3.8	0.6	0.9
PMN-SQ1-B2-2001	Antiquities archive	Ulna	1.0	44.2	14.4	3.6	5.4	0.2	5.1	0.3	1.0
PMN-SQ1-B3-2001	Antiquities archive	Radius	6.5	43.6	15.8	3.2	6.7	0.3	3.3	0.4	1.0
PMN-SQ1-B5-2001	Antiquities archive	Tibia	7.1	43.1	15.7	3.2	6.9	0.4	3.4	0.4	1.1
PMN-SQ1-B7-2001	Antiquities archive	Radius	5.8	42.4	15.4	3.2	7.3	0.4	3.3	0.4	0.9
PMN-SQ1-B8-2001	Antiquities archive	Ulna	1.9	45.6	16.2	3.3	6.2	0.3	3.8	0.3	0.9
PMN-SQ1-B9-2001	Antiquities archive	Tibia	6.2	43.4	15.7	3.2	6.9	0.3	3.3	0.3	1.0
PMN-SQ1-B10-2001	Antiquities archive	Ulna	3.4	42.4	15.2	3.3	8.8	0.3	3.5	0.3	1.2
PMN-SQ1-B11-2002	Antiquities archive	Fibula	5.5	42.8	15.4	3.2	7.2	0.4	3.3	0.4	1.2
PMN-SQ1-B15-2001	Antiquities archive	Femur	4.1	42.1	15.2	3.2	6.5	0.3	3.7	0.4	1.0
PMN-SQ3-B2	Antiquities archive	Radius	4.0	45.3	16.3	3.2	6.1	0.3	3.5	0.3	0.8
PMN-SQ3-B4	Antiquities archive	Femur	0.6	44.4	15.7	3.3	6.4	0.2	5.0	0.3	1.0
PMN-SQ3-B9-2002	Antiquities archive	Fibula	3.5	42.2	15.1	3.3	5.2	0.3	3.6	0.3	0.9

Table 1 (continued)

Individual	Post-excavation context	Skeletal element	Collagen yield (wt%)	Collagen carbon content (wt%)	Collagen nitrogen content (wt%)	Collagen atomic C:N (mol/mol)	Bioapatite CO_3 content (wt%)	WAMPI (unitless)	PCI (unitless)	API (unitless)	BPI (unitless)
PMN-SQ3-B10-2003	Antiquities archive	Fibula	2.8	46.3	16.4	3.3	6.6	0.3	3.6	0.3	0.9
PMN-SQ3-B11-2002	Antiquities archive	Radius	4.2	44.2	16.0	3.2	6.4	0.3	3.5	0.4	1.0
PMN-SQ4-B3-2003	Antiquities archive	Fibula	7.8	46.8	17.0	3.2	7.5	0.5	3.0	0.5	1.2
PMN-SQ18-B1	Antiquities archive	Femur	6.2	43.8	16.0	3.2	4.9	0.4	3.7	0.5	0.9
PMN-SQ18-B2	Antiquities archive	Femur	3.6	45.0	16.3	3.2	5.7	0.3	3.6	0.3	0.9
PMN-SQ18-B4	Antiquities archive	Fibula	5.1	45.7	16.4	3.3	5.3	0.3	3.8	0.3	0.8
PMN-SQ18-B6-2007	Antiquities archive	Femur	4.5	42.6	15.3	3.2	8.9	0.3	4.7	0.3	0.9
PMN-SQ18-B7-2007	Antiquities archive	Femur	4.7	44.0	16.0	3.2	5.9	0.3	3.5	0.3	0.8
PMN-SQ1-B1-2007	*In situ*	Radius	2.7	42.6	15.5	3.2	7.9	0.3	3.4	0.4	0.9
PMN-SQ1-B16	*In situ*	Ulna	5.2	42.0	15.2	3.2	7.4	0.3	3.4	0.4	1.2
PMN-SQ2-B4	*In situ*	Fibula	2.5	45.3	16.3	3.2	6.0	0.3	3.7	0.3	0.9
PMN-SQ3-B3-2003	*In situ*	Fibula	6.4	44.3	16.0	3.2	6.2	0.3	3.4	0.4	1.1

Table 1 (continued)

Individual	Post-excavation context	Skeletal element	Collagen yield (wt%)	Collagen carbon content (wt%)	Collagen nitrogen content (wt%)	Collagen atomic C:N (mol/mol)	Bioapatite CO_3 content (wt%)	WAMPI (unitless)	PCI (unitless)	API (unitless)	BPI (unitless)
PMN-SQ3-B11-2014	*In situ*	Humerus	3.1	42.4	15.2	3.3	7.2	0.3	3.4	0.3	1.1
PMN-SQ3-B12	*In situ*	Rib	3.6	37.3	13.6	3.2	6.1	0.3	3.6	0.4	0.9
PMN-SQ3-B13	*In situ*	Radius	3.4	45.2	16.4	3.2	5.9	0.3	3.4	0.3	1.0
PMN-SQ3-B6A-2003	*In situ*	Femur	6.8	43.2	15.5	3.3	6.5	0.4	3.6	0.4	1.2
PMN-SQ4-B7	*In situ*	Clavicle	4.9	45.2	16.0	3.3	7.8	0.3	3.5	0.4	1.1
PMN-SQ4-B5-2007	*In situ*	Femur	2.4	43.3	15.6	3.2	6.6	0.2	3.8	0.3	1.0
PMN-SQ4-B6	*In situ*	Humerus	2.5	45.7	16.0	3.3	9.0	0.3	3.8	0.4	1.0
PMN-SQ4-B32	*In situ*	Humerus	1.9	44.8	15.9	3.3	6.8	0.3	3.6	0.3	1.0

Table 2 Mean and one standard deviation for all preservation indicators by location. Preservation indices were compared by post-excavation context group using Mann–Whitney *U* tests ($\alpha = 0.05$)

Preservation indicator	*In situ* ($n = 12$)	Antiquities archive ($n = 21$)	*W* value	*p* value
Collagen yield (wt%)	3.8 ± 1.6	4.7 ± 2.2	89.5	0.78
Collagen carbon Content (wt%)	43.4 ± 2.3	43.9 ± 1.4	122	0.9
Collagen nitrogen Content (wt%)	15.6 ± 0.7	15.8 ± 0.6	118	0.78
Collagen atomic C:N (mol/mol)	3.2 ± 0.04	3.3 ± 0.08	134	0.78
Bioapatite CO_3 content (wt%)	7.0 ± 1.0	6.6 ± 1.0	153	0.33
WAMPI (unitless)	0.30 ± 0.05	0.33 ± 0.10	115	0.7
PCI (unitless)	3.56 ± 0.17	3.70 ± 0.57	119	0.81
API (unitless)	0.34 ± 0.04	0.36 ± 0.09	131	0.87
BPI (unitless)	1.03 ± 0.12	0.95 ± 0.11	175	0.07

No significant differences were observed between *in situ* and antiquities archive skeletons for any preservation index

dead were interred (Lerdpipatworakul, 2009; Liu, 2012). This comports with studies of diagenesis of archaeological bone samples from northeast Thailand, where soil composition and groundwater flow were found to be the most prominent influences on patterns of diagenesis (King et al. 2011). Additionally, temporal factors may play a role in the consistently well-preserved collagen from individuals at PMN, as time is one of the strongest predictors of collagen preservation in tropical regions (Pestle & Colvard, 2012), and several of the aforementioned sites in central Thailand include one or more mortuary phases that pre-date burials from PMN altogether.

Despite the preservation of taphonomically unaltered bone collagen and bioapatite at PMN regardless of post-excavation context, it is important to note that bone samples from *in situ* skeleton, on average, had lower collagen yields and higher bioapatite carbonate content compared to samples from curated skeletons (Fig. 4). The *in situ* skeletons also exhibit lower average collagen carbon and nitrogen contents, but this difference is accounted for by a single *in situ* individual (PMN-SQ3-B12) whose collagen carbon and nitrogen content values are both considered outliers. Together, the results suggest that the post-excavation taphonomic trajectories of *in situ* skeletons may differ from those of skeletons curated in the antiquities archive, but not in a statistically meaningful way. These observations represent logical outcomes considering the skeletons' shared antiquity, issues of fragmentation at open-air site museums, and sustained exposure in a tropical climate with highly seasonal patterns of rainfall. Other factors may also contribute to these observations, including the fact that the antiquities archive is not climate controlled, exposing curated remains to temperatures and ambient humidity beyond those considered desirable for curation (Wills et al. 2014, 64). Furthermore, some skeletons curated in the antiquities archive may have previously been display *in situ* for some time prior to their complete exhumation.

Partial excavation of human skeletal remains at PMN creates a liminal long-term context between interment and exhumation in conditions known to impede the biochemical survival of bone collagen and bioapatite (Pestle & Colvard, 2012). Open-air site museums raise concerns about the context's deleterious effects on skeletal

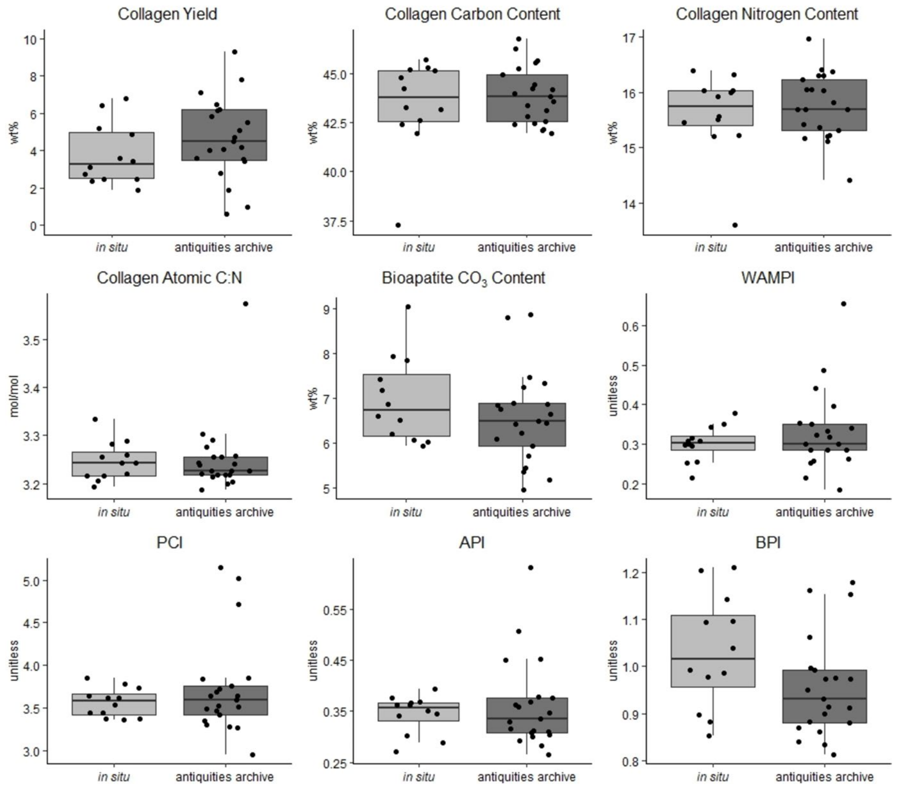

Fig. 4 Across all preservation indices analyzed in this study, differences between *in situ* ($n = 12$) and antiquities archive ($n = 21$) skeletons were not statistically significant. Even so, *in situ* skeletons tend to exhibit lower collagen yields and higher bioapatite carbonate contents, suggesting differences in ongoing taphonomic trajectories between post-excavation context groups

completeness, as bones left *in situ* are observed to crack in the humid conditions of Southeast Asia (Halcrow et al. 2011, 2019; Pureepatpong, 2000). Bone surfaces with cracks lose collagen more readily than those without cracks (Boaks et al. 2014; Trueman et al. 2004), in part because exogenous materials can be introduced through cracks, altering the mineral structure of bone, and further exacerbating collagen loss (Smith et al. 2007). As bones crack into multiple fragments, some are inevitably displaced during site maintenance, when volunteers clean open-air portions of the museum using brushes, brooms, and dustpans. Loose, displaced, or otherwise dislodged fragments are visible in aggregated piles near some of the open-air excavation units (Fig. 5).

Central Thailand's tropical climate also presents significant challenges in protecting *in situ* skeletons from exposure to water during flood events. Classified as a tropical savannah (Beck et al. 2023), conditions oscillate between frequent drought and high rainfall, with most precipitation falling between May and October each year (Mudar, 1995). Interactions between bone and water are known to hasten diagenesis (Smith, 2002), especially when seasonal fluctuations in water percolation are high (Turner-Walker, 2011). It can be particularly difficult to protect open-air sites from the damaging effects of floods,

Fig. 5 Shelves near one of the open-air excavation units at Ban Pong Manao holding offerings of fruit and incense on the top shelf and aggregated bone fragments and ceramic sherds on the bottom shelf

which have been known to inundate excavated areas and, in some cases, rebury human skeletons in thick deposits of newly introduced alluvial sediments (Case et al. 2023, 95).

Cultural Heritage Management Considerations at Open-Air Archaeological Sites

Bioarchaeological research tends to situate taphonomy as a distortive and reductive process, limiting the amount and types of information that can be known about past people. Although open-air site museums have helped to raise awareness about archaeological heritage and have created new opportunities through cultural heritage tourism, they can also expose human skeletal remains to agents that may hasten their deterioration. Even so, it is important to contextualize these observations alongside local conceptions of value and materiality. The values that local people ascribe to archaeological resources are oftentimes markedly different from those conceptualized in (bio)archaeological discourse that is primarily Western centered. While practitioners tend to emphasize gains in informational and economic value, local people also consider the spiritual and/or symbolic value of archaeological resources (Lertcharnrit, 2010).

Conservation is deeply rooted in the history and practice of archaeology in Thailand (Glover, 1993; Peleggi, 2004, 2016; Shoocongdej, 2007, 2017). At the same time, there exists a contradiction between preservation and impermanence, a principle of Buddhist philosophy that characterizes all living beings, concepts, objects, and phenomena as constantly in flux and ultimately temporary. Decay is understood as a natural part of the life cycle; nothing persists in perpetuity, and resisting impermanence is futile and leads to sorrow and suffering (Khanjanusthiti, 1996, 172). These tensions have been explored in depth regarding the restoration of Buddhist monuments and temples in Southeast Asia (Byrne, 1995; Karlström, 2005, 2013; Khanjanusthiti, 1996, 2004; Peleggi, 2016) and more broadly in literature focused on cultural heritage management in Thailand (Lertcharnrit, 2010, 2017, 2020; Lertcharnrit & Niyomsap, 2020; Lertcharnrit & Watanasawad, 2023; Lertrit, 1996; Peleggi, 1996, 2016; Shoocongdej,

Fig. 6 Garlands placed on a sign that says "cradle of Ban Pong Manao prehistoric civilization" near the expanded looter's pit, one of several open-air units at the site where skeletons remain *in situ*

2011). Similar considerations of materiality, preservation, and impermanence may be particularly relevant because, like the Ban Pong Manao Archaeological Site and Community Museum, many open-air archaeological site museums in Thailand are located on the grounds of village temples (Fig. 6).

As Lertrit (1996, 284) reminds us, "heritage is with us, is lively, and is not dead and cold," and this is certainly the case for the unique contexts created by open-air site museums. Cultural heritage practitioners in Thailand have emphasized the importance of involving local people in archaeological investigations and related community decision-making processes, especially because the people who live in close proximity to sites are considered their best protectors (Lertcharnrit, 2020; Lertrit, 1996). Doing so also requires a contextualized understanding of conservation norms and expectations among local communities and stakeholders. As such, we do not advocate for the exhumation and curation of skeletons at open-air site museums solely to improve their long-term preservation for scientific analyses, nor do we promote eschewing preservation altogether in response to local outreach objectives or the concept of impermanence. Instead, we have provided information that can inform ongoing conversations about preservation concerns at open-air sites, bringing ontological distinctions to light and highlighting the complexities of public archaeology and archaeological research in Thailand.

Conclusion

This study investigated patterns of diagenesis among human skeletal remains from the Ban Pong Manao Archaeological Site and Community Museum in Lopburi Province, central Thailand. In order to better understand how open-air displays may affect long-term bone preservation, we used indices from stable isotope analysis and Fourier-transformed infrared spectroscopy to investigate differences in diagenesis between skeletons *in situ* and skeletons curated at the on-site antiquities archive. No statistically significant differences in bone collagen or bone bioapatite preservation metrics were observed between post-excavation context groups. However, *in situ* remains exhibited lower collagen yields and higher bioapatite carbonate contents, suggestive of differences in ongoing taphonomic trajectories between *in situ* and antiquities archive groups. More broadly, we situate the effects of open-air display alongside the benefits that cultural heritage tourism can have within local communities, and the broader role that open-air site museums play in raising awareness for the importance of archaeological heritage. Results from this study reveal aspects of preservation invisible to the naked eye with the ultimate goal of providing information that can inform ongoing conversations among local communities, stakeholders, archaeologists, and other cultural heritage practitioners.

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Author Contribution GP and TL conceptualized this project. TL and SLK facilitated and supervised the completion of the research. GP and LEL prepared samples and collected data. GP led manuscript writing. RBT and LEL also contributed written sections to the manuscript. GP and RBT created graphs and figures. GP and RBT analyzed data. TL and SLK provided critical feedback and edits.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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