New insights into the formation process and chronology of the *Sambaqui* Morro do Ouro, Joinville, Santa Catarina, Brazil

Novas perspectivas sobre o processo de formação e cronologia do sambaqui Morro do Ouro, Joinville, Santa Catarina, Brasil

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Abstract: *Sambaquis* are unique cultural heritage assets in Brazil, encapsulating Indigenous cultures and ecological knowledge that thrived for nearly 7,000 years in some of the world's most diverse biomes. Despite decades of scientific research, uncertainties remain regarding their origins and evolving nature and their role in major socio-economic and demographic shifts linked to food production systems in the Americas. Additionally, gaps persist in our understanding of how anthropogenic factors, such as urbanization and commercial exploitation, have volumetrically impacted *sambaqui* sites since colonial times. To address these issues, an archaeological excavation was conducted at the *Sambaqui* Morro do Ouro in Babitonga Bay (Santa Catarina State) during July and August 2019, supported by the National Geographic Society (Explorer Grant). The primary goal was to improve our understanding of the site's formation processes, chronology, plant and faunal remains, and associated artefacts. This article outlines the excavation and sampling strategies employed, presents radiocarbon dates of the areas investigated in 2019, and discusses key aspects of the site's formation processes.

Keywords: Babitonga Bay. *Sambaqui* Morro do Ouro. Sedimentary record. Chronology. Bayesian age-depth model.

Resumo: Os sambaquis são patrimônios culturais únicos no Brasil. Eles comunicam culturas indígenas e conhecimentos ecológicos que floresceram por quase 7.000 anos em alguns dos biomas mais diversos do mundo. Apesar de décadas de pesquisas científicas, ainda existem incertezas em relação às suas origens e ao seu papel nas mudanças socioeconômicas e demográficas ligadas aos sistemas de produção de alimentos nas Américas. Também persistem lacunas de conhecimento sobre a extensão em que os sambaquis foram afetados volumetricamente por fatores antropogênicos (urbanização, exploração comercial) desde o período colonial. Para abordar algumas dessas questões, foi realizada uma escavação arqueológica no Sambaqui Morro do Ouro, na baía Babitonga (estado de Santa Catarina), em julho e agosto de 2019, financiada pela National Geographic Society (Explorer Grant). O objetivo principal foi aprimorar o entendimento dos processos de formação do sítio, sua cronologia, os vestígios de plantas e animais, além dos artefatos associados. Este artigo descreve as estratégias de escavação e amostragem empregadas, apresenta as datas de radiocarbono das áreas investigadas em 2019 e discute aspectos-chave dos processos de formação do sítio.

Palavras-chave: Baía Babitonga. Sambaqui Morro do Ouro. Registro sedimentar. Cronologia. Modelo bayesiano de idade-profundidade.

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INTRODUCTION

Coastal shellmounds in Brazil, known as *sambaquis*, are some of the most prominent and recognizable archaeological sites along eastern South America. Created by diverse Indigenous communities between 7000 and 1000 calibrated years before present (cal BP), these mounds serve as a testament to the socio-ecological diversity of fishing cultures that thrived in various ecosystems all along the Atlantic coast of Brazil (Toso et al., 2021; Gaspar, 1998; DeBlasis et al., 1998, 2021). The sites offer invaluable insights into ancient fishing and horticultural practices, landscape management, human demography, diet, health, and genetic stock that have few parallels in lowland South America (DeBlasis et al., 2021; Villagran, 2014; Colonese et al., 2014; Ferraz et al., 2023; Scheel-Ybert & Boyadjian, 2020; Souza et al., 2024; Majander et al., 2024). *Sambaquis* function as time capsules, preserving records of past animal and plant diversity, revealing complex interactions between humans and nature that we are only beginning to fully understand (Fossile et al., 2019, 2020, 2023a, 2023b, 2023c, 2024; Mendes & Rodrigues, 2024; Klokler, 2017).

Although research on *sambaqui* sites started decades ago, significant uncertainties persist regarding their origins and evolving nature. For many sites, the chronology is poorly resolved, and their stratigraphic records are generally not well understood. Previous studies on a handful of sites have uncovered a great diversity of site formation processes, highlighting the need for further research (Villagran, 2014, 2019; Villagran et al., 2010, 2011a; Scheel-Ybert et al., 2020; Giannini et al., 2010; Fish et al., 2000).

For many of the *sambaquis*, little is known about the extent to which historical human activities, such as rural and urban expansions, have altered original site numbers, distribution, content, and configurations through time. Given their high visibility and proximity to many early European colonisation sites, *sambaquis* have been heavily exploited since colonial times for their economic potential (e.g., shell extraction for lime production, embankments – Gaspar, 1998; Calazans, 2017), and threats to these sites still persist nowadays (DeBlasis & Gaspar, 2009). This is particularly evident in *sambaquis* within the metropolitan area of Joinville and other urban and rural contexts of Babitonga Bay, in Santa Catarina State. The *Sambaqui* of Morro do Ouro (Figure 1A), for instance, has been directly impacted by Joinville's urban expansion in the 20th century, initially being exploited as paving material for industrial areas, and later by three extensive archaeological excavations (Beck, 2007; Goulart, 1980; Tiburtius, 1996). The site is now located in an urban park with a busy road on one side and an industrial sector on the other, meaning it is exposed to high vehicle traffic, visitors and urban pollution, the impacts of all of which on the site are poorly known. In such cases, effective monitoring programs require comprehensive data that extends beyond visual site inspection. Assessing changes in site volume through time, for instance, can be a cost-effective approach for tracking the impacts of multiple stressors on *sambaquis*. Fortunately, Babitonga Bay is one of the regions where historical records exist about the number of *sambaqui* sites, their locations and physical conditions (area and volume) before and after the implementation of the Federal Law No. 3,924, of July 26, 1961, which protects Archaeological and Prehistoric Monuments (Tiburtius, 1996; Rohr, 1984; Oliveira, 2000), making this an ideal study region for assessing the extent *sambaqui* sites have changed in relation to the urban development of the last decades.

The *Sambaqui* of Morro do Ouro is also currently in the spotlight for debates surrounding the antiquity and models of plant cultivation in the Atlantic Forest coast of Brazil (Wesolowski & Neves, 2002; Wesolowski et al., 2010; Pezo-Lanfranco et al., 2018). Radiocarbon dates from a few human burials have placed its chronology between 4824-4527 and 4510-4101 cal BP (Wesolowski, 2000; Wesolowski et al., 2010; Pezo-Lanfranco et al., 2018). Analyses of plant remains from dental calculus suggest a

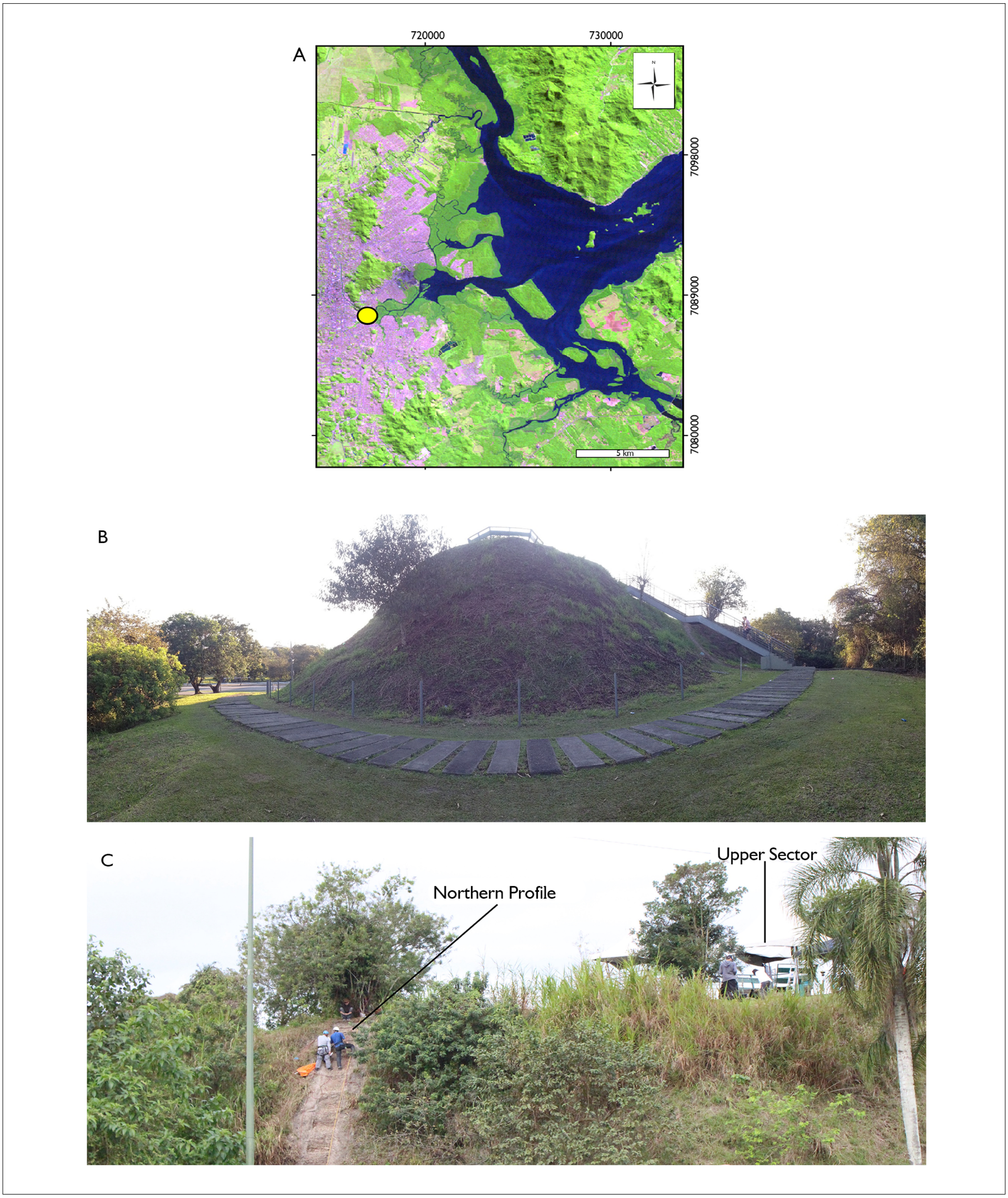

Figure 1. A) Location of Morro do Ouro in Joinville (Santa Catarina); B) view of the site before the excavation in 2019, and C) the 2019 excavation sectors: the Northern Profile and the Upper Sector. Map: Terrametrics (2023) (A). Photos: author (2019) (B and C).

number of taxa may have been gathered and cultivated, including sweet potato, yam, and Araceae (Wesolowski et al., 2010), while oral pathologies revealed levels of dental caries comparable to agriculturalists, and stable isotope analyses showed high consumption of plant carbohydrates by some human individuals (Pezo-Lanfranco et al., 2018).

The lack of highly resolved and chronologically constrained sedimentary records, however, prevents a full understanding of the nature of plant exploitation and its socio-ecological context at Morro do Ouro, and more broadly in Babitonga Bay. In order to address some of these gaps, an archaeological excavation was conducted at Morro do Ouro from July 18 to August 13, 2019. Here, we provide information on the excavation methods, the sedimentary record, and new radiocarbon dates, along with a Bayesian age-depth model for a large sedimentary sector of Morro do Ouro. This work was aimed at generating fundamental stratigraphic and chronological information to elucidate the nature of human-environmental interactions in Babitonga Bay during the Middle and Late Holocene, and the extent the site has changed over the last decades.

SITE LOCATION AND PREVIOUS EXCAVATIONS

Morro do Ouro is located in the urban area of Joinville, adjacent to the Cachoeira River (Figure 1A), and its geological and environmental settings have been described in detail in previous publications (Beck et al., 1969; Beck, 2007). Prior to 2019, the site had undergone a few assessments on its heritage value (Castro Faria, 1959; Tiburtius & Bigarella, 1960) and three systematic archaeological excavations: one by Tiburtius between 1952 and 1960 (Tiburtius, 1996), during which the site's deposit was being used for paving a nearby industrial area; a second in 1968 by Beck (Beck et al., 1969; Beck, 1972, 2007); and a third conducted by Goulart in 1979 and 1980 during the construction of the adjacent bridge '*Ponte do Trabalhador*' (Goulart, 1980).

With the excavations conducted during the dismantling of the site for paving material (1952 to 1960), Tiburtius (1996) brought to light distinctive archaeological deposits. An uppermost deposit (2 m thick) consisting mostly of large oysters (Ostreidae), an intermediate deposit (8 m thick) dominated by cockles (*Anomalocardia flexuosa*), and a lowermost deposit primarily composed of '*bacucu*' (mussel, possibly *Mytella guyanensis*), which was interspersed between seven small layers. Throughout the stratigraphy, Tiburtius (1996) recovered 26 human individuals, stone and bone artefacts (including zooliths associated with human burials), rock dyes (possibly ochre) and faunal remains (mollusks, fish, and some mammals and birds), among other features.

In 1968, Beck and colleagues conducted fieldwork at the site and estimated that only one-quarter of its total volume had survived the industrial exploitation (Beck et al., 1969). They identified three distinct stratigraphic units with considerable differences in composition and matrix. The lowermost deposit contained evidence of hearths and floors indicating that the site may have been initially used for residential purposes. Throughout the stratigraphy, they retrieved marine and terrestrial faunal remains, stone tools, and shell artefacts. Ten human burials were also recovered in the uppermost part of the site.

Later, excavations by Goulart between 1979 and 1980 documented a range of stone and bone tools linked to plant gathering, hunting, and fishing, such as points, blades, net sinkers, etc., as well as charcoal and charred palm seeds (possibly *Arecastrum romanzoffianum*), and a large number of faunal remains, including approximately 5,000 otoliths, mammal and bird bones, and shells. They documented 48 hearths, some with associated faunal remains indicating they may have been used for processing food. Furthermore, their excavation documented 89 human individuals, including single and double burials, some of which contained grave goods. Radiocarbon dating was later performed on a few individuals, obtaining uncalibrated ages of 4030 ± 40 BP (MO28), 3870 ± 40 BP (MO80), and 4300 ± 50 BP (MO31) (Wesolowski, 2000; Wesolowski et al., 2010).

Having already endured years of alteration, Tiburtius estimated the site's area to be around 140 m x 70 m, and 7 m high, in 1952-1960 (Tiburtius, 1996). Rohr (1984) reported an estimated size for the site of 100 m x 100 m, and 10 m high, and in Oliveira (2000), it was estimated to be 95 m x 60 m, and 13 m high. In 2019, the visible surface of the site (elevated portion) measured approximately 73 m long (NNW-SSE) x 62 m wide (WE), and 16 m high (Figure 1B), representing an estimated volume of 17,465.90 m^3 (based on SIMgeo, Prefeitura Municipal de Joinville, 2025). These latest figures reveal an alarming decline in the site's volume compared to Tiburtius's early record. Assuming the site had the shape of a spheroidal cap when Tiburtius first reported the size, its volume can be calculated using the equation below:

$$Vm3 = \pi h/6(3ab+h2)$$

Where Vm^3 is the volume in cubic meters, h is the height of the cap (from the base of the cap to the top of the dome), a and b represent the semi-major and the semi-minor axes of the horizontal base respectively, and π (pi) is a mathematical constant that represents the ratio of a circle's circumference to its diameter (3.14159). This results in an estimated volume of 27,118.75 m^3 for 1952-1960. By comparing with historical information, the data from 2019 revealed a staggering loss of approximately 35.6% of the site's volume over the last 70 years.

These figures provide valuable insights for archaeologists, cultural heritage managers, communities, and decision-makers, a prominent one being that, due to their large size, the volume of *sambaquis* should be periodically monitored as an additional conservation indicator. This approach should be extended to all *sambaquis* in Babitonga Bay and beyond, particularly those in urban areas, and implemented by local authorities in collaboration with stakeholders, including communities, professionals, and managers (UNESCO, 2011). Moreover, both current and future archaeological interventions must prioritize minimal invasiveness to ensure the preservation of these sites for future generations. The 2019 excavation of Morro do Ouro carefully considered the ethical implications of large-scale interventions, opting for a small, precise excavation that minimized destruction while effectively recovering sedimentary, botanical, faunal, and artefactual data.

METHODOLOGY

FIELDWORK AND RECOVERY METHODOLOGY

Excavation and assessment of the stratigraphic record of Morro do Ouro was performed over three weeks, between the 18th of July and the 13th of August 2019, following authorisation by the National Historic and Artistic Heritage Institute (IPHAN) (01510.000196/2019-63) (IPHAN, 2019). The Museu Arqueológico de Sambaqui de Joinville (MASJ) provided institutional endorsement and the entire excavated collection is under its custody. The work focused on two distinct areas: the Upper Sector (excavation) and the Northern Profile (assessment of the stratigraphic record) (Figure 1C).

UPPER SECTOR

The Upper Sector was located in the topmost part of the archaeological site, adjacent (west) to a modern stationary cement platform (Figure 2A). The excavation aimed at I) establishing the nature and the age of the uppermost stratigraphic record and II) maximising the recovery of archaeological materials including artefacts and faunal, plant, and human remains, by implementing horizontal sampling strategies. Particular attention was devoted to avoiding areas that may have been affected by previous archaeological activities (Beck, 2007; Beck et al., 1969; Goulart, 1980; Tiburtius, 1996) and modern infrastructure. Before and during the excavation, historical sources (excavation and planning reports, satellite images, photographs, and early documents) were routinely consulted to ensure the chosen area had not been significantly altered by recent activities.

A 16 m^2 excavation area was established (4 x 4 m), with 1 m^2 grids in alphanumeric order (west-east: F, G, H, I; south-north: 20, 21, 22, 23), divided into four clockwise quadrants of 50 cm^2 (I, II, III, IV in brackets) (Figure 2B). A single reference point was used to derive the altitude of the excavation area, both in the Upper Sector and the Northern Profile. Reference number 1 (RN1, at 18.70 m above sea level) was the reference for altitude (Z) against which the archaeological deposits, materials and features were vertically positioned. The surface before the excavation had a 0.17% slope SE-NW (70 cm).

Once distinctive archaeological layers were identified (mainly based on sedimentary matrix), the excavation of these layers proceeded through a series of

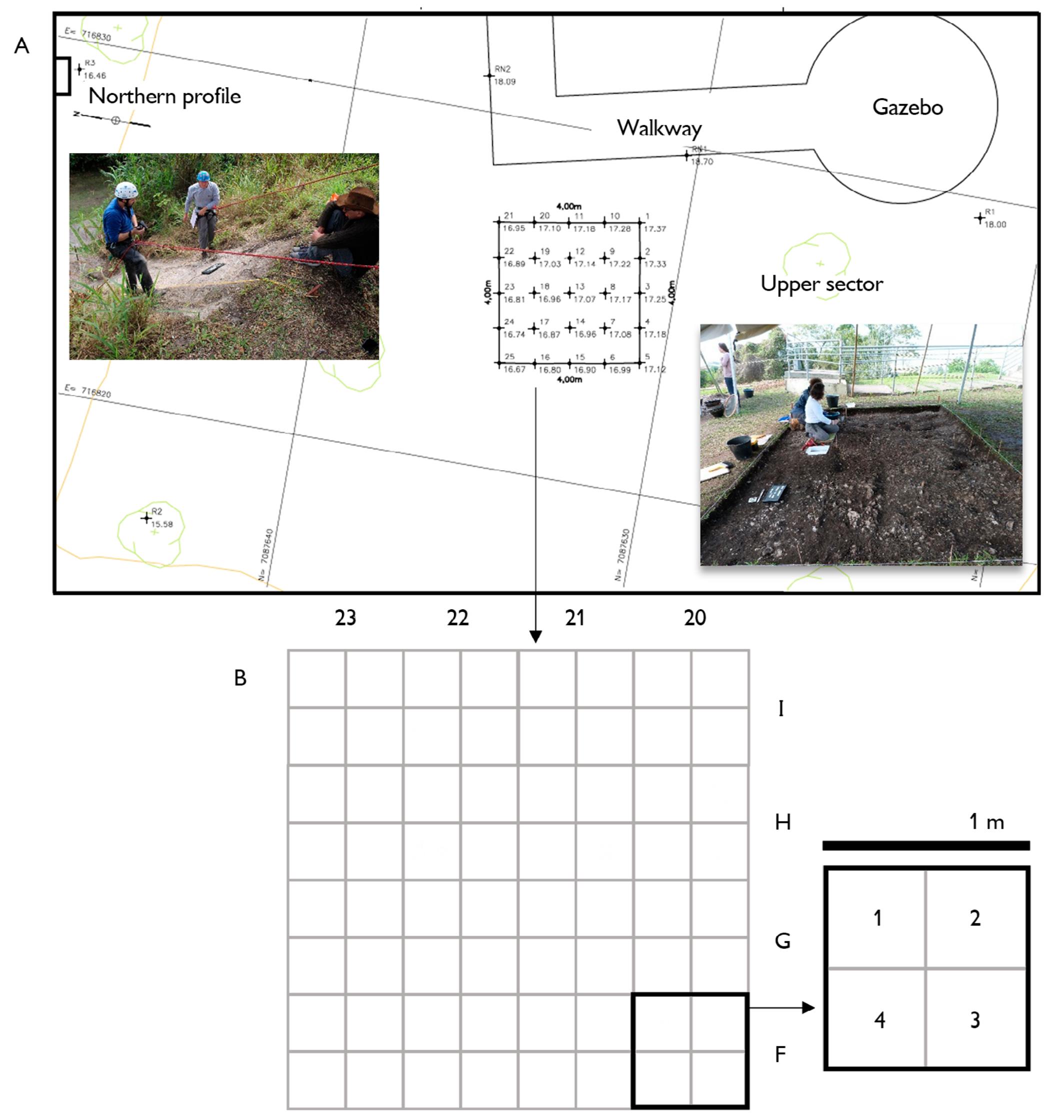

Figure 2. A) Position of the excavated areas of the Upper Sector and Northern Profile; B) detail of the 1 m^2 excavation grids in alphanumeric order (W-E: F, G, H, I; S-N: 20, 21, 22, 23), divided into four quadrants of 50 cm^2 (I, II, III, IV). Photos and maps: author (2019).

subdivisions, or '*décapage*' (also known as 'spit' – Royer, 2014), varying between 2 to 5 cm. Whenever possible the *décapages* were guided by the horizontal and vertical distribution of visible 'markers' that helped to identify what could have been 'discrete' occupation surfaces (Dibble et al., 1997; Barba Pingarrón, 2014). These markers were, for example, the base of large pebbles and rocks, and distinct concentrations of shells and bone remains. This approach allows for recording subtle changes in the distribution of archaeological materials within large stratigraphic deposits (thus reducing the "palimpsest effect" – Royer, 2014), and for high resolution processes within auxiliary temporal approaches, such as Harris matrix (Harris, 1975).

All altitudes in the archaeological layers as well as their *décapage* were taken as '*teto*' (upper) and '*base*' (lower) highs, in the format '*teto/base*,' in relation to RN1 for each 1 m^2. By extension, the *base* of a given archaeological layer or *décapage* represents the *teto* of its underneath layer or *décapage*. Various features were documented during the excavation of the Upper Sector, and several were tentatively interpreted as structures (on the basis of morphology, soil matrices, or content). As research advances on the recovered material from some of these features, their origin and function may be clarified (e.g. hearths/cooking facilities, pits).

Excavated sediments were collected in buckets of 12 L, with every single bucket of sediment receiving an identifier (X, Y, Z, operator, layer ID) and the volume (litres) recorded. This information constitutes the minimum sample ID of all materials recovered at Morro do Ouro. Stone and bone artefacts, faunal and botanical remains were recovered using distinct sampling protocols (Colonese, 2025) and their analyses are in progress.

MICROSTRATIGRAPHY

Undisturbed blocks of sediment (n = 6) were sampled for micromorphological analysis (Figure 3). Five blocks were collected from the Upper Sector, and one from the Northern Profile. Some of the blocks were large enough to capture the contact between stratigraphic layers and structures. In those cases, two thin sections were produced from the same block to capture all the stratigraphic differences in the sample beyond the size of the thin sections (e.g. samples MO-19-1 and MO-19-4). Samples were analysed in plane polarised light (PPL) and cross-polarized light (XPL) with a Leica 2700P microscope and a Leica S9i stereomicroscope at the Laboratory of Microarchaeology of the Museu de Arqueologia e Etnologia (Universidade de São Paulo, Brazil).

RADIOCARBON DATING

Samples of plant charcoal (n = 18) and one fragment of human bone were analysed by Accelerator Mass Spectrometry (AMS) at the National Center of Accelerators (CNA) (Spain) and at the Centro di Fisica Applicata, Datazione e Diagnostica (CEDAD) (Università di Lecce, Italy). Radiocarbon dates from charcoal were calibrated using the 100% atmospheric calibration curve for the southern hemisphere, SHCal20 (Hogg et al., 2020). In order to factor the usually high contribution of marine carbon to bone collagen of individuals in this region, the radiocarbon date of the human bone collagen was modelled using a mixed curve (SHCal20 and Local Marine curve). For this we adopted an estimated average local marine radiocarbon reservoir correction value (ΔR) of -126 ± 29, generated from eight reference points between latitudes 32.00 °S and 23.73 °S (Angulo et al., 2005; Alves et al., 2015; De Masi, 1999) according to the Marine Reservoir Correction database (Marine20 Database, n. d.). For the human sample we considered the average relative contribution of marine carbon to collagen (52 ± 9%) as proposed by Toso et al. (2021) (Table 1).

In addition, a Bayesian age-depth model was performed on radiocarbon dates from the Northern Profile using the P_Sequence model in Oxcal v4.4 (Ramsey, 1995). This approach essentially determines the optimal alignment of radiocarbon ages (representing events) on the radiocarbon calibration curve by considering variations in sedimentation accumulation rates between events. Details of the model parameters, inputs and assumptions can be found in (Ramsey, 2008; Ramsey & Lee, 2013). In short, uncalibrated ^{14}C age (n = 12) were calibrated in the modelling process using the calibration curve for the southern hemisphere, SHCal20.

We failed to obtain a ^{14}C age for the topmost part of the Northern Profile. As an alternative, we used the oldest ^{14}C date from the Upper Sector (CNA 5548.1.1, 3740 ± 30 uncal BP) to define the Boundary Top of the Northern Profile. In addition, the model was set up to exclude a visible outlier in layer 24 (CNA 5558.1.1), which represented an intrusion of charcoal from the upper deposits. The P_sequence model assumes that

Figure 3. A) Location of sample MO-19-5 in the lower part of the Northern profile; B) detail of sample MO-19-5 after plastering; C) view of sample MO-19-6 in the north profile of the Upper Sector; D) detail of sediments in sample MO-19-6. Photos: author (2019).

Table 1. Radiocarbon dates from the Upper Sector and Northern Profile. Calibrated radiocarbon dates from plant charcoals were not modelled. Modelled calibrated ages only applied to the human bone (LTL22537). Calibration outputs were rounded to 50 years.

Area	Layer (features)	Depth (cm)	Lab code	Material	^{14}C yr BP uncal	^{14}C yr cal BP (2σ)	Median cal BP
Upper Sector	2A-B (filling of structure 1)	3	LTL20159A	Plant charcoal	89 ± 40	0-250	100
Upper Sector	2A-B (G2-IV)	24	LTL20158A	Plant charcoal	239 ± 40	100-300	200
Upper Sector	3A (I21-II)	10	LTL20160A	Plant charcoal	3610 ± 45	3750-4000	3850
Upper Sector	3A (H20-III)	16	LTL22537	Human bone	3831 ± 40	3950-3700	3850
Upper Sector	3A (filling of structure 3)	11	LTL20161A	Plant charcoal	3578 ± 40	3700-3900	3850
Upper Sector	3A (filling of structure 3)	23	CNA 5547.1.1	Plant charcoal	3650 ± 30	3850-4000	3900
Upper Sector	3C (filling of structure 8)	39	CNA 5548.1.1	Plant charcoal	3740 ± 30	3950-4150	4050
Northern Profile	Layer 3	90	CNA 5549.1.1	Plant charcoal	4000 ± 35	4300-4550	4450
Northern Profile	Layer 5	150	CNA 5550.1.1	Plant charcoal	4040 ± 35	4400-4550	4500
Northern Profile	Layer 8	282	CNA 5551.1.1	Plant charcoal	4130 ± 35	4500-4800	4600
Northern Profile	Layer 14	380	CNA 5553-1-1	Plant charcoal	4120 ± 35	4400-4800	4600
Northern Profile	Layer 17	495	CNA 5554.1.1	Plant charcoal	4140 ± 25	4500-4800	4600
Northern Profile	Layer 19	595	CNA 5555.1.1	Plant charcoal	4120 ± 25	4450-4800	4600
Northern Profile	Layer 21	690	CNA 5556.1.1	Plant charcoal	4190 ± 25	4600-4850	4700
Northern Profile	Layer 24	750	CNA 5558.1.1	Plant charcoal	3680 ± 25	3850-4100	3950
Northern Profile	Layer 24	780	CNA 5557.1.1	Plant charcoal	4210 ± 25	4600-4850	4700
Northern Profile	Layer 26	890	CNA 5559.1.1	Plant charcoal	4210 ± 25	4600-4850	4700
Northern Profile	Layer 27	950	CNA 5560.1.1	Plant charcoal	4290 ± 25	4700-4900	4850
Northern Profile	Layer 28	995	CNA 5561.1.1	Plant charcoal	4230 ± 25	4650-4850	4750

sedimentary depositions are not uniform, but fluctuate throughout the stratigraphy. In the model, the K parameter defines the number of accumulation events per unit depth. The unit depth in our model is metre (m), and because K can vary (due to sediment composition, granularity, etc), we adopted the 'variable K' option, which is expressed in terms of *log10(k/k0)* (Ramsey & Lee, 2013). We used a default nominal value for K of 100 (100 cm^{-1}), and a number of interpolations per unit of 50 (50 cm^{-1}), meaning that model outputs were generated for every 2 cm. Finally, a threshold of 60% (agreement index, A_{model}) was used to assess the agreement between the calibrated (likelihoods, unmodelled) and modelled dates (probability distributions – Ramsey, 1995, 2009) (Colonese, 2025).

IDENTIFICATION OF HUMAN REMAINS BY COLLAGEN PEPTIDE MASS FINGERPRINTING

During excavation, a few highly fragmented bones were recovered and tentatively identified as human (n = 8). In order to confirm their identification, samples were transported to the palaeoproteomic lab of the Institute of Environmental Science and Technology (ICTA-UAB, Universitat Autònoma de Barcelona, Spain) for collagen peptide analysis, also known as ZooMS (Buckley et al., 2009, 2014; McGrath et al., 2019). Briefly, subsamples of 10-30 mg of bone were demineralised in hydrochloric acid (HCl, 0.6 M) at 4 °C, then rinsed with ammonium bicarbonate (NH_4HCO_3, 50 mM, pH 8) and gelatinised for 1 hour at 65 °C. The samples were then digested with 0.4 μg of trypsin at 37 °C overnight, then acidified to 0.1% trifluoroacetic acid (TFA) to stop the trypsin, and purified using C18 resin ZipTip pipette tips (EMD Millipore). 1 μl of sample was combined with 1 μl of matrix solution (α-cyano-hydroxycinnamic acid) and run in triplicate along with calibration standards on a Bruker ultraflex III MALDI TOF/TOF mass spectrometer at the LP-CSIC (Universitat Autònoma de Barcelona). Spectra were analysed using mMass software (Strohalm et al., 2008) and species were determined based on a database of known peptide markers (Buckley et al., 2009, 2014; Kirby et al., 2013; Welker et al., 2015). Of the eight potential human bones, ZooMS analysis confirmed that only two fragments were in fact human. The remaining bones were identified as tapir (n = 2), peccary (n = 1), and 3 unknown mammals (species not currently in the reference database).

NORTHERN PROFILE

The Northern Profile was located 13 m north of the Upper Sector, on a partially exposed profile of approximately 10 m height (Figure 2A). The profile was sampled in order to obtain a long-term chronological and stratigraphic record of Morro do Ouro in this remaining area of the site. Surface sediments and vegetation were manually removed on a 10 m x 1m vertical grid. Sediments (2 L) were systematically sampled for faunal, botanical and environmental DNA (eDNA) analyses, and charcoal remains were collected for radiocarbon dating. Microstratigraphy and phytolith analyses were performed on a deposit rich in organic matter at the bottom of the sequence.

RESULTS AND DISCUSSION

STRATIGRAPHY, BIOLOGICAL REMAINS, ARTEFACTS AND INTERPRETATION OF THE UPPER SECTOR

A detailed stratigraphic analysis was only performed on the Upper Sector. Visual inspection during excavation enabled the identification of discrete superimposed facies of archaeological deposits (layers), characterised by distinctive colour, matrix and material composition. The Upper Sector was excavated to a maximum depth of 43.8 cm and generated approximately 4700 L of sediment.

Layer 1: 12 m^2 excavation (F, G, H, I; 20, 21, 22). Characteristics: Topmost superficial deposit, consisting of modern soil (dark organic-rich soil), with grass and modern artefacts (glass, plastic, cigarettes, etc.). Started from 1.33 to 1.90 m in relation to RN1, and ranged from 2 to 7 cm thick. Layer 1 was not sieved and was removed by hoe.

Layer 2: 12 m^2 excavation (F, G, H, I; 20, 21, 22). Initially divided in two sublayers (layers 2A and layer 2B) due to a visible increase of archaeological materials with depth (shells, bones, etc). The layer 2A and layer 2B were later merged as a single layer 2A-B.

Layer 2A-B: Characteristics: 5YR (3/2) very fine, dark reddish brown (Munsell colour chart), with patched residues of modern soil (layer 1). Started from 1.39 to 1.96 m in relation to RN1, and ranged from 1 to 12 cm thick. Overall interpretation: mix of contemporary and disturbed (reworked) *Sambaqui* deposits by modern/historical activities.

Composition and spatial distribution: the archaeological deposit was visibly dominated by faunal remains, with abundant shells of *A. flexuosa* and Ostreidae (e.g. *Ostrea* sp. e *Crassostrea* sp.). Several shells of *A. flexuosa* and Ostreidae were closed, but most were open as single shells. Some exceptionally large shells of Ostreidae were found (*ca*. 20 cm length), as also documented by Tiburtius in 1952 (Tiburtius, 1996). In terms of abundance, shells were followed by bones (mainly fish, and to a much lesser extent terrestrial mammals), dispersed charcoal (including combusted palm fruit seeds), pebbles, and intrusive modern materials (plastic, glass). Microstratigraphy analysis (sample MO-19-1) on the south profile of square G20 (Figures 4A-4B) revealed a deposit with higher porosity than the underlying shell deposit (layer 3), with a dark brown micromass made of organic matter and clay. It contained shell fragments, together with quartz grains and bone fragments, all with random distribution.

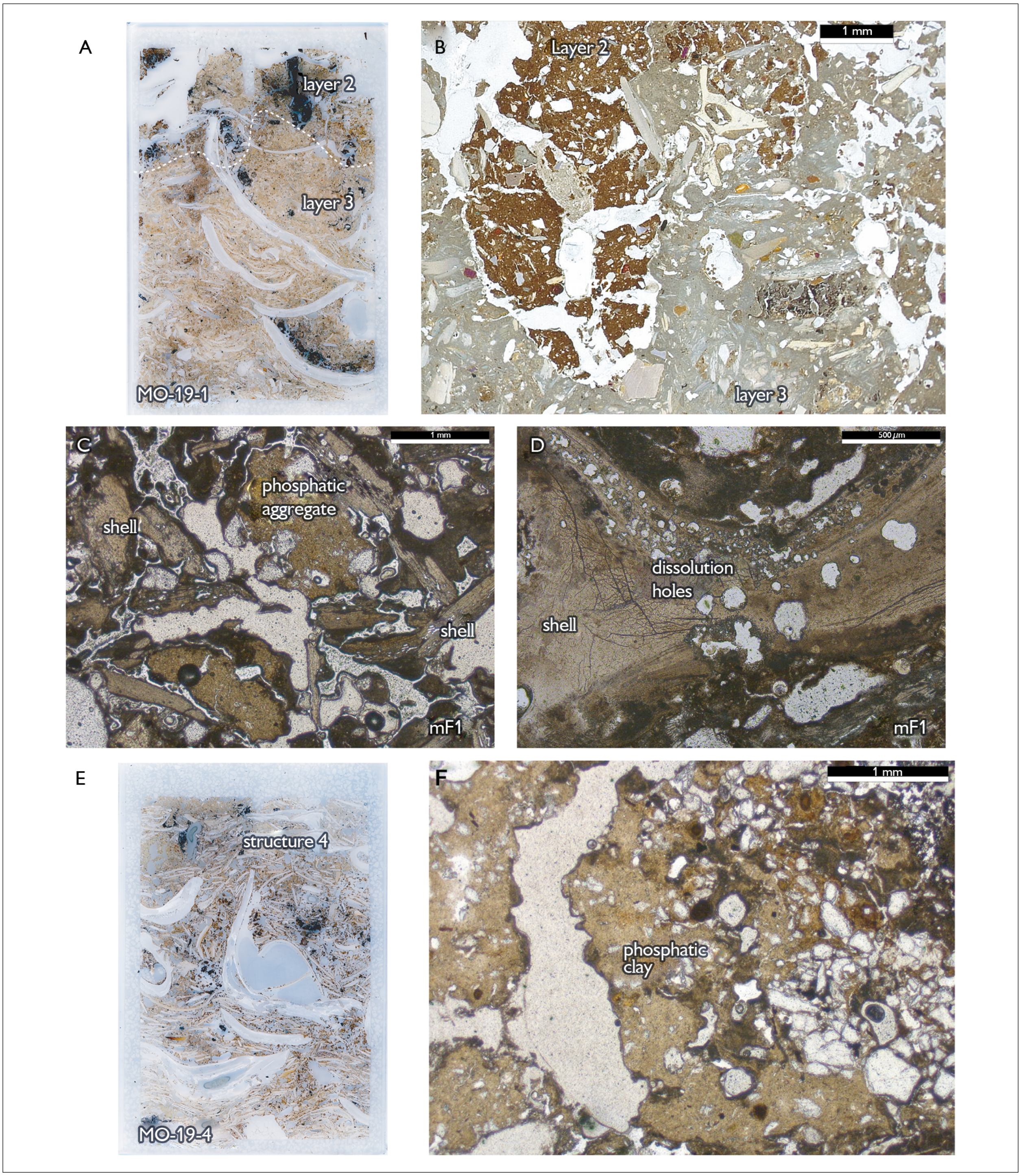

Figure 4. Photomicrographs of selected sedimentary thin sections from Morro do Ouro: A) scanned thin section of sample MO-19-1 with identification of archaeological layers 2A-B and 3; B) contact between layers 2A-B and 3 with organomineral clay and carbonic micromass, respectively (PPL); C) shell fragments and phosphatic aggregates in layer 3 (PPL); D) shell fragment with dissolution holes in layer 3 (PPL); E) scanned thin section of sample MO-19-4, capturing structure 4; F) detail of phosphatic clay with quartz found exclusively in structure 4 (PPL).

Shells showed signs of heating and dissolution. Overall the blocky and granular microstructures of layer 2A-B are typical of soil development.

Shells and pebbles were dispersed in horizontal and vertical positions, and several appeared to have been reworked in the stratigraphy. In some areas, such as in G20 (III), shells of Ostreidae were visibly more concentrated, and apparently reworked. These concentrations coincided with visible patches of dark deposits, which were soft and rich in organic matter (similar to layer 1), and visibly distinct from the surrounding archaeological deposit. The excavation revealed that these dark deposits filled several circular and semicircular cuts (n = 18) in layer 2A-B. The cuts were relatively deep (some >30-40 cm deep), variable in diameter (from *ca*. 10 to 40 cm), with 90° to 45° inclination, and intercepted the deposit below (layer 3). Together they formed clusters (evident in layer 3) suggesting they may have been anthropogenic pits, possibly remnants of recent structures or natural bioturbations (from animals or plants) (Figures 5A-5B). Samples of sediments were collected from the pits for botanical analysis and radiocarbon dating. One charcoal sample from the dark deposits filling Pit 1 provided a conventional radiocarbon age of 89 ± 40 BP, revealing this was a modern feature. This was also corroborated by the radiocarbon dating of a charcoal sample from the deposit of layer 2A-B, which provided a conventional age of 239 ± 40 BP. Polished stone artefacts were found in layers 2A-B and 3A (see below), resembling some artefacts reported by Tiburtius (1996) in his early intervention in Morro do Ouro (Figures 6 and 7). A perforated shark tooth was also found in layer 2A-B. Layer 2A-B can be therefore interpreted as a *Sambaqui* deposit heavily altered by soil formation and recent activities.

Layer 3: 12 m^2 excavation (F, G, H, I; 20, 21, 22). Divided into three sublayers (layers 3A, B and C).

Layer 3A: Characteristics: 10YR (6/3) fine to very fine, pale brown (Munsell colour chart). Started from 1.48 to 1.97 m in relation to RN1, and ranged from 5 to 19 cm thick. Visibly less disturbed deposits compared to layer 2A-B, locally intercepted by historical pits. Relatively abundant in entire shells; relatively poor in charcoal (based on *in situ* visual inspection). Overall interpretation: *Sambaqui* deposits with evidence of occupation surface and possible structures.

Composition and spatial distribution: as for layer 2A-B, layer 3A was also visibly dominated by faunal remains, with abundant shells of *A. flexuosa* and Ostreidae. Several shells of *A. flexuosa* and Ostreidae were also closed, but most of the shells were open with detached parts. Bones were abundant, mainly fish, some of large size. We documented dispersed charcoal (including combusted palm fruit seeds, but no evidence for a structural hearth), pebbles and less intrusive modern materials (glass remains in the *décapage* 1 of layer 3A).

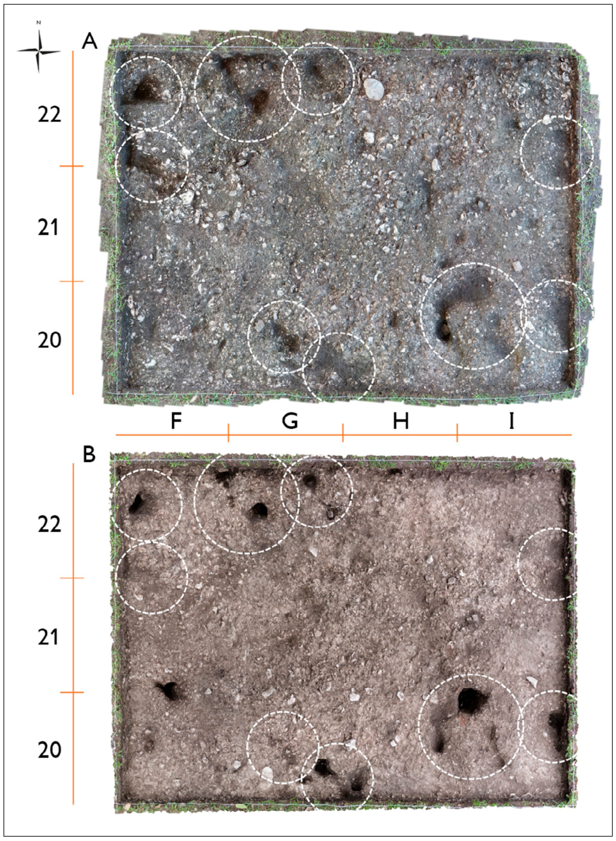

Figure 5. A) Layer 2A-B (base) and B) layer 3A (base décapage 1). The dotted circles show the position of some modern/historical pits identified in layer 2A-B, that partially cut layer 3A. Photos: author (2019).

Most of the entire shells and pebbles exposed by *décapage* 2 and 3 of layer 3A were laid down horizontally, suggesting the presence of occupation surfaces. *Décapage* 2 and 3 exposed several (n = 9) pits (ca. 20 cm diameter) in F20-21, G20, H20-21 and I22 (Figure 8A). These pits had their origin (cuts) in the layer 3A (meaning they were not visible in the layer 2A-B), suggesting they were part of a structure (or multiple structures) in a discrete occupation surface (flooring). It is worth noting that similar features were documented by Goulart when excavating the site in 1979 and 1980 (Goulart, 1980). Microstratigraphic analysis from layer 3A (sample MO-19-1, in G20) uncovered a massive microstructure with low porosity, bioturbations and voids produced by soil fauna. It contained more shell fragments than the above layer 2A-B, both with random and horizontal distribution (Figure 4C). Shells with horizontal distribution showed signs of in-situ breakage (e.g. interconnected fragments), which has been attributed to trampling (Balbo et al., 2010; Villagran et al., 2011b; Villagran, 2019). Shells also had signs of intense dissolution, including numerous dissolution holes that were also visible in the few bone fragments (Figure 4D). Together, in-situ breakage, highly dissolved and fragmented shells might be evidence of trampling (Schiffer, 1983) and long-term exposure of shells to atmospheric conditions, which corroborates the hypothesis that layer 3A was an occupation surface, affected by weathering and soil development. The coarse fraction of the deposit also includes quartz grains, bone fragments (with signs of heating), and phosphatic aggregates possibly from bone and/or animal tissue degradation (Figure 4C). The micromass was greyish light brown, and crystallitic, made of calcium carbonate with organic matter domains. Significantly, *décapage* 2 uncovered one fragment of human

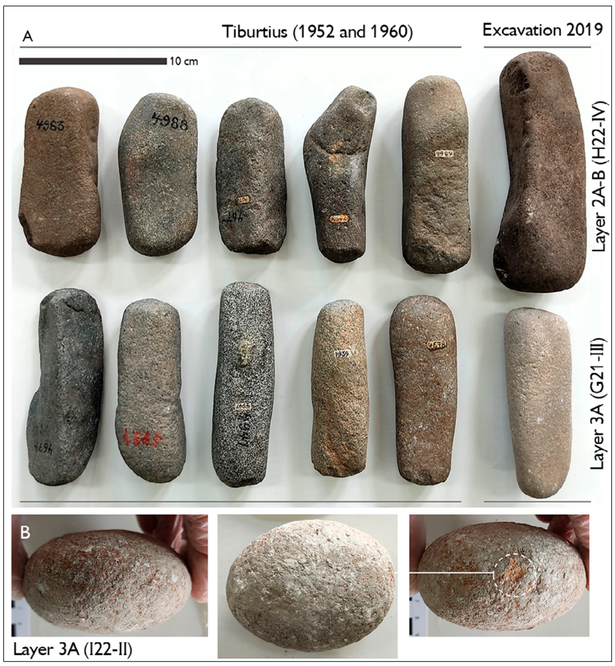

Figure 6. A) Polished stone artefacts found in layer 2A-B and layer 3A, comparable with some stone artefacts reported by Tiburtius (1996) from Morro do Ouro; B) pebble from layer 3A with visible marks possibly originating from percussion or grinding. Photos: author (2019).

Figure 7. Polished stone artefact found in layer 2-B. Photos: author (2019).

bone in H20-III (confirmed by ZooMS), which was directly radiocarbon dated to 3831 ± 40 (Table 1) and a pebble with visible marks possibly originating from percussion or grinding (Figure 6) (Adams, 2014).

Décapage 3 exposed a patch of clay with relatively defined boundaries, containing fine, yellowish and highly fragmented aragonitic shells in H and I 21-22 (I-IV). This patch was identified as structure 3 (Figure 8B). Microstratigraphic analysis of structure 3 (MO-19-2 and MO-19-3, south profile, H22) evidenced a microstructure with low porosity, and voids produced by soil fauna, with dissolved shell fragments in horizontal and random distributions. Quartz grains, fine charcoal fragments and yellowish phosphate aggregates were dispersed in a greyish light brown micromass made of calcium carbonate, clay and organic matter. The nature of structure 3 is unclear, but the underlying processes that produced it had altered the shells in a way that had not been observed in the deposits above. Shells were also more fragmented in *décapage* 3 and 4 compared to the superimposed deposits, which reinforce the view that the area had been affected by intense trampling (Schiffer, 1983). Some burnt shells were found in the structure 3 but microstratigraphic analysis did not provide evidence for protracted fire in the deposit.

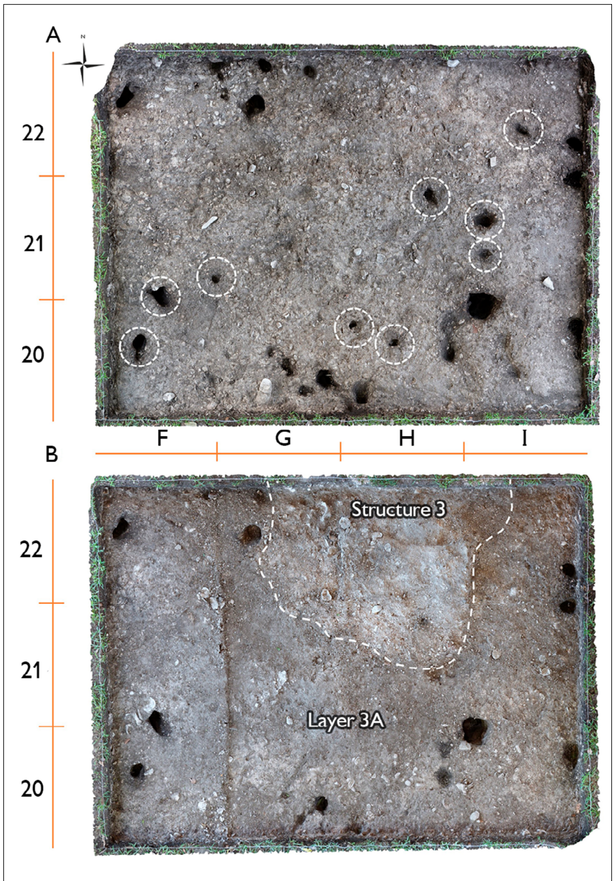

Figure 8. A) Layer 3A (base décapage 2). The dotted circles show the position of pits opened in layer 3A; B) layer 3A (base décapage 4) with the partial extension of structure 3 (dotted contour line). Photos: author (2019).

Structure 3 contained three fragments of polished, flat stone artefacts made with a soft rock (mineral identification in progress). Two fragments were found in H22 and could be refitted, measuring 10 cm long. Another fragmented artefact (4 cm) was found in G22. Both artefacts had a concave surface on one side, and the refitted artefact contained traces of a red residue (possibly ochre – Tiburtius & Leprevost, 1952) with possible finger marks, which is an exceptional finding in *Sambaqui* archaeology (Figures 9A-9B). A few stone flakes (mineral identification in progress), which could also be refitted, were found in H and I 21-22, and one polished stone was found in horizontal position in G21 and I22 (Figure 6A). Polished stone artefacts may have been used for pounding or grinding plant, animal and mineral substances. *Décapage* 3 also recovered two fragments of a bone artefact (bi-point) that could be refitted in I20.

One charcoal sample from layer 3A (I21-II) provided a conventional radiocarbon date of 3610 ± 45 BP, while two charcoal samples from structure 3 were dated to 3578 ± 40 and 3650 ± 30 BP, showing great chronological coherence. The radiocarbon dates from structure 3 and the surrounding layer 3A are also broadly consistent with the radiocarbon date from the human bone found in H20-III (3831 ± 40). Overall the chronological consistency of these dates, the sedimentary features, and the presence and distribution of the archaeological materials indicates that layer 3A was an occupation surface.

Layer 3B: characteristics: deposit underneath structure 3; 10YR (6/3) fine to very fine, pale brown (Munsell colour chart). Excavation restricted to 6 m^2 due to time constraints (H-I, 22-20). Started from 1.58 to 2.08 m in relation to RN1, and ranged from 7 to 17 cm thick. Overall interpretation: *Sambaqui* deposits with possible evidence for an occupation surface.

Composition and spatial distribution: layer 3B was visibly dominated by faunal remains, with a large abundance of shells (*A. flexuosa* and Ostreidae), fish bones, dispersed charcoal and pebbles. *Décapage* 1 in H-I 20-21 exposed patches similar in composition, texture and colour to structure 3 (identified as structures 4 and 5).

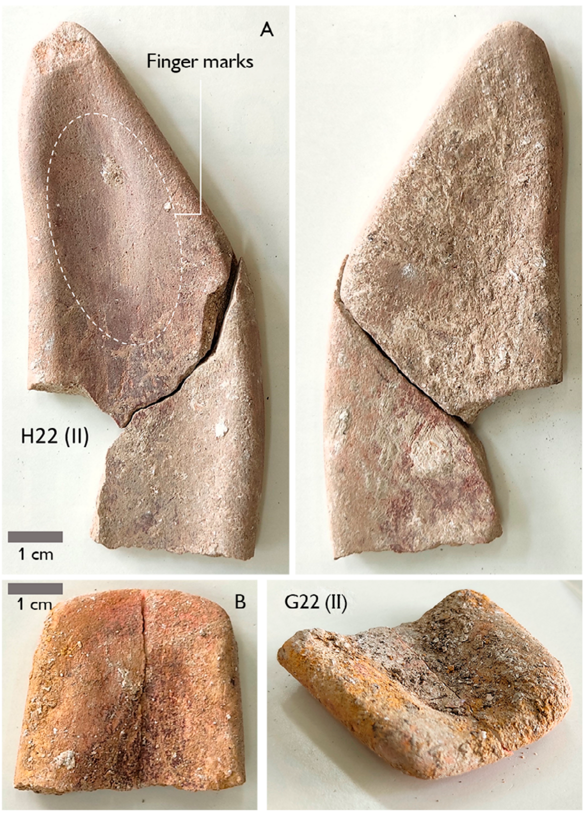

Figure 9. A) Flat and polished fragments of a stone artefact with a concave surface on one side found in structure 3 (layer 3A, H22), showing possible finger marks with red residues. The fragments could be refitted; B) similar flat stone fragment from structure 3 (layer 3A, G22). Photos: author (2019).

Structure 4 was partially covered by the clayish deposit at the base of structure 3, thus it possibly referred to a distinct feature predating structure 3. Because some of the shells in structure 4 appear to have been degraded (exfoliation/calcination) and charcoals were visibly more abundant, it is possible that some of the material in structure 4 had been exposed to heat. Microstratigraphic analysis of structure 4 (MO-19-4, I20) showed a mix of dark brown clay with organic matter, areas of carbonate precipitation from shell dissolution, and yellowish phosphatic domains (Figure 4E). It had a spongy and chamber microstructure, with low porosity, and contained shell fragments in similar frequency as the surrounding layer 3B, with signs of intense dissolution and random distribution. Quartz grains, bone fragments with signs of heating, rounded clay aggregates and charcoal fragments appear in-between shells. The phosphatic micromass (Figure 4F) contains pedofeatures not described in other samples, such as iron oxide hypocoatings, indicating water passage and mite excrements. It also contains glassy slag from grass ashes. Together, this evidence suggests some combustion in place. *Décapage* 2 exposed a concentration of charcoal in H20 (IV), which we identified as structure 6, one bone artefact (bi-point) and one perforated shell of Ostreidae.

Layer 3C: characteristics: deposit underneath structure 6; 10YR (6/3) fine to very fine, pale brown (Munsell colour chart). Excavation restricted to 6 m^2 due to time constraints (H-I, 22-20). Started from 1.65 to 2.03 m in relation to RN1, and ranged from 1 to 8.8 cm thick. Overall interpretation: *Sambaqui* deposits with evidence of occupation surface.

Concentrations of charcoal and calcined stones and shells in H-I 22-21 and I20 were interpreted as evidence for two distinct structures (structures 7 and 8, Figure 10). As for structures 4 and 5, the lack of stratigraphic connections between these features led us to consider them as distinct structures, however they may have been produced by the same activity. We interpreted these structures as hearths (or cooking facilities) or areas where combusted materials were dumped. The radiocarbon date of a charred palm fruit from structure 8 provided a conventional age of 3740 ± 30 BP.

Overall our results indicate that layer 2A-B represents soil formation on shellmound sediments, while deposits in layers 3A to 3C are typical of *sambaquis*, with reworked shells (burnt and unburnt) and other debris (bones, heated bones, charcoal) (Villagran, 2014; Villagran et al., 2018). Intense dissolution of shells in layer 2A-B and layers 3A to 3C has not been described before in other shellmounds of the south and southeast coast of Brazil. Layers 3A to 3C seem to be the topmost, preserved deposit of the site, but it has gone through intense decalcification, compaction (e.g. trampling), and bioturbation. Quartz grains that appear mixed with shell fragments, bones and charcoal in the shellmound sediments from layers 2A-B and layers 3A to 3C are not aeolian, but brought by incidental human transport, possibly from the shell beds where the clams and oysters were harvested. This is also broadly supported by the recovery of several oyster shells attached to stones in the deposits.

Structures 3 and 4 had similar composition, but differed slightly from the surrounding deposits as they did not contain bones, and were notably richer in phosphatic clay. Specifically, structure 4 exhibited traits of rapid water runoff with iron precipitation and contained glassy slag from grass ashes. This evidence suggests structure 4 was the remains of a combustion event. Overall, the structures identified in layers 3A to 3C (structure 3 to 8) resemble features documented in 1968 by Beck et al. (1969; Beck, 2007) and in 1979 by Goulart (Goulart, 1980). Beck et al. (1969), identified three distinct structures: "patches of red dyes" (possibly ochre – Tiburtius & Leprevost, 1952), hearths and floors, characterised by high concentrations of shell, clay and charcoal remains, and in some cases stones.

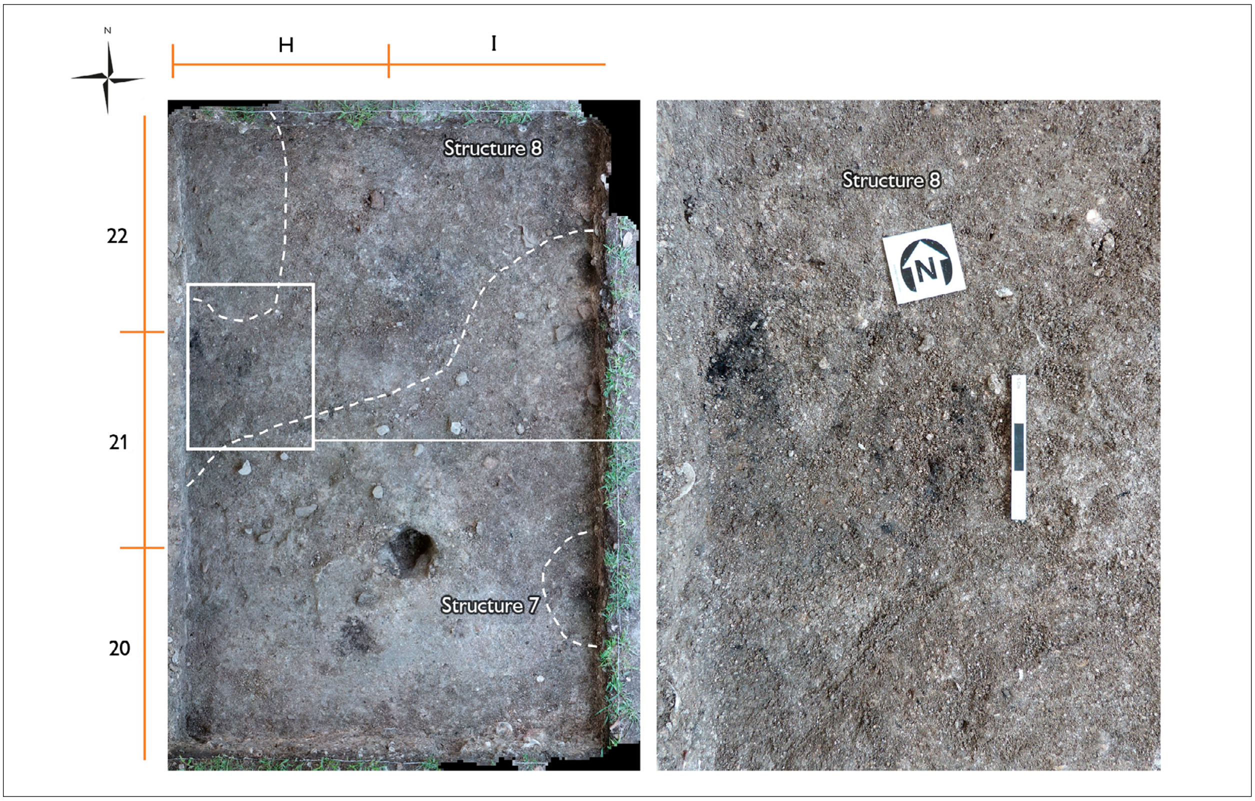

Figure 10. Structures 7 and 8 in layer 3C, with details of structure 8 showing concentration of plant charcoals. Photos: author (2019).

Later on, Goulart documented a total of 11 structures ranging from 15 to 6 cm thick, generally consisting of discrete patches of highly fragmented, compacted and calcined marine shell and fish remains, possibly produced by trampling and exposure to fire. These also contained variable amounts of stone and stone artefacts (some burnt), clay deposits, ash and charcoal remains, along with human burials and hearths. A common aspect of many of these structures was the compactness of shell remains and clay that may point to some degree of trampling. Moreover, Goulart identified at the bottom of Block II (*décapage* 11) several pits which were then interpreted as postholes. The pits and structures documented in 2019 adds to the previous evidence pointing to a complex depositional history at Morro do Ouro.

NORTHERN PROFILE

The cleaning of the Northern Profile exposed 28 discrete archaeological layers along its 920 cm depth, characterised by differences in colour, matrix and faunal composition (Figures 11A-11B). Five distinct deposits could be visibly documented:

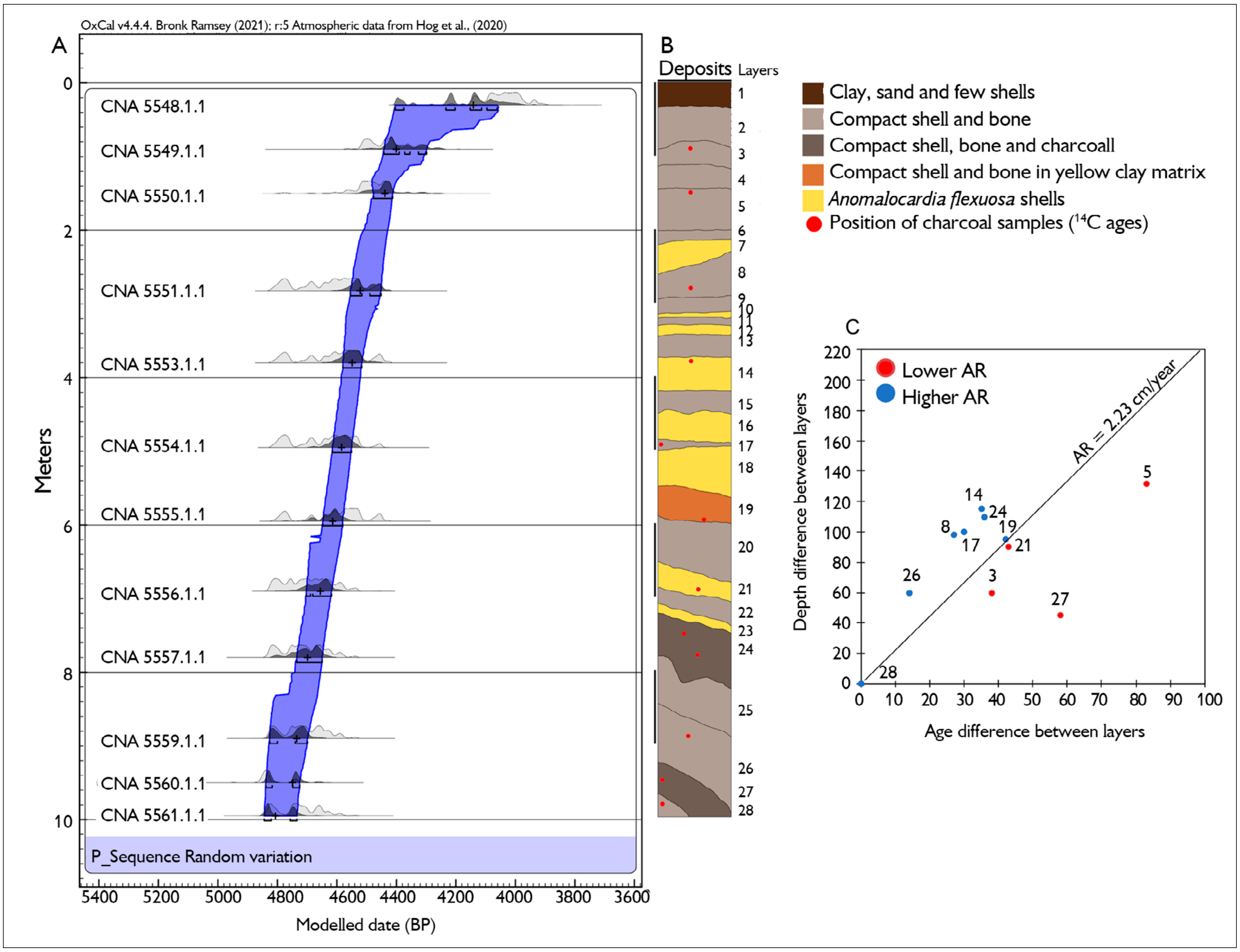

Figure 11. A) Bayesian age-depth model of the Northern Profile along with B) a schematic sketch of the stratigraphic features and the position of the charcoal samples radiocarbon dated; C) a plot indicating layers with higher (blue) and lower (red) accumulations rates (AR) in relation to the overall accumulation rate of 2.23 cm/year (regression line). The estimates were obtained by calculating the differences in age (median modelled BP) and depth (cm) between layers, from the bottom to the top of the stratigraphy.

1. Deposits rich in clay and sand, containing few shells, are located in the uppermost part of the sequence (layer 1).
2. Deposits rich in fragmented shells and some bones, relatively compact, and seemingly lamellar in deposition (shells in a horizontal position). These deposits occurred throughout the sequence (layers 2-6, 8, 9, 11, 13, 15, 17, 20, 22, 25, 26, 28) and alternated with deposits composed almost entirely of the shells of *A. flexuosa*.
3. Deposits representing accumulations of shells of *A. flexuosa*, which occurred primarily in the middle of the sequence (layers 7, 10, 12, 14, 16, 18, 21, 23).
4. Deposits with shells, few bones, and rich in charcoal remains, generally well compacted (layers 24, 27). Microstratigraphic details were obtained for layer 24 (MO-19-5). In particular, two microfacies were identified: one typical of shellmound sediments, with loose shell fragments in a light brown carbonatic micromass; and another made of dense aggregates of organic matter and clay with shells. The overall shell content is lower than described for layers 2A-B and 3A-C, and the porosity is higher. Large shell fragments appear perpendicular to the surface, while smaller fragments have a random distribution. All shell fragments were heated but better preserved than the shells in layers 2A-B, 3A-C, and in structures 3 and 4. The coarse fraction also contained quartz grains, bone fragments with signs of heating and dissolution, and charcoal fragments.
5. Deposits with shells, few bones, and rich in charcoal remains with a yellow clay matrix (layer 19).

Of particular interest is the consistent alternation of deposits abundant in fragmented shells and bones with deposits primarily composed of shells of *A. flexuosa*. Similar stratigraphic successions alternating thick layers of closed packed shells, and centimetric dark sediments with bones (sometimes burnt) and shells have been described for other shellmounds in the states of Santa Catarina and Rio de Janeiro (Rohr, 1984; Afonso & De Blasis, 1994; Giannini et al., 2010; Klokler, 2014; Villagran, 2014; Villagran et al., 2015). Understanding the nature of this accumulation pattern requires determining the timing of these events and assessing whether the accumulation occurred continuously or was marked by alternating periods of high and low intensity, potentially related to cycles of occupation and abandonment of the site (Stein et al., 2003; Jerardino, 1995).

BAYESIAN AGE-DEPTH MODEL OF THE NORTHERN PROFILE

The Bayesian age-depth model estimated an accumulated duration of 665 years, calculated from the difference between the modelled median ages (68.3% probability) of the Boundary Top (4142 cal BP) and Boundary Bottom (4807 cal BP) of the Northern Profile (920 cm). This accumulation duration represents an overall accumulation rate of 1.38 cm/year. The overall good agreement between the model (prior) and the observational data (likelihood) (A_{model} = 84.4%) indicate that in general the outputs were robust. The only exception refers to the ^{14}C date of the Upper Sector used to define the Boundary Top. The age was significantly younger than the most recent ^{14}C dates from the sequence, resulting in a poor model performance for this specific part of the sequence (A = 54.9%). By removing this outlier, the model offered a likely accumulation duration of the Northern Sector of 406 years (905 cm), and a more robust overall accumulation rate of 2.23 cm/year (Colonese, 2025).

The vertical position of the median modelled calibrated ^{14}C ages (68.3% probability) suggests that the accumulation rate of 2.23 cm/year was not constant, but varied throughout the stratigraphy, as is typically documented in large shellmound sites (Stein et al., 2003). Lower accumulation rates were observed at the bottom and at the top of the sequence, while higher accumulation rates were estimated for the middle of the sequence (Figure 11C). Specifically, at the bottom of the sequence, 45 cm of deposits between the ^{14}C ages of layers 28 to 27 were formed in approximately

58 years (0.77 cm/year). If we assume an average human generation time of 26.9 years (Wang et al., 2023), it would have taken around four human generations (108 years) to elevate the site just 100 cm above the surrounding ground, between layers 28 and 24. At the top of the sequence, 132 cm of deposits between the ^{14}C ages of layers 8 and 3 accumulated in approximately 83 years (1.59 cm/year). By contrast, higher accumulation rates were observed between the ^{14}C ages of layers 27 and 26, where 60 cm of deposits accumulated in only 14 years (4.28 cm/year), representing the fastest accumulation event in the entire sequence. Other high accumulation events were observed between layers 26 and 24 (3.05 cm/year) and layers 19 and 8 (3.40 cm/year), in areas with conspicuous depositions of *A. flexuosa* shells.

It is unclear which taphonomic processes may have altered the physical and chemical aspects of the deposits in the Northern Profile, and the extent these may have affected our estimates. Compact deposits of *A. flexuosa* shells may be more susceptible to erosion, vertical and horizontal movements than sediment-based deposits. Furthermore, with nearly 35% of Morro do Ouro lost in the last 70 years, there is uncertainty regarding whether our results accurately represent the formation history of the entire site or a more localised process. Previous studies at the site documented the alternation of shell- and sediment-rich deposits similar to those observed in 2019 (Beck et al., 1969; Tiburtius, 1996; Goulart, 1980). Beck et al. (1969) documented contrasting depositional patterns throughout more than 8 m of archaeological deposits at Survey 1. They retrieved several human burials in the uppermost part of the site, extending down to a depth of 3.15 m. Beneath this, they identified approximately 2 m of layers with scarce archaeological material, followed by nearly 4 m of what they described as residential floors (*fundos de cabana*) – compacted deposits likely resulting from intensive occupation. On the other hand, Goulart who excavated large areas of Morro do Ouro reported the presence of very compacted deposits surrounded by concentrations of *Anomalocardia* shells (e.g. Goulart's structure I in Block II), suggesting that distinctive depositional patterns were formed simultaneously due to localised activities (Goulart, 1980). In addition, Goulart recovered 89 human individuals, distributed in four stratigraphic packages (0.10-0.65 m, 1.05-1.50 m, 4.90-5.55 m, 6.20-6.50 m – Wesolowski, 2000), but their distributions do not show any particular correlation with the stratigraphic features and the chronology obtained here. Spatial variability in Morro do Ouro's formation process is also visible at the stratigraphic records of the south and north faces of the site reported by Tiburtius (1996), suggesting that certain areas experienced more or less intensive use over time.

While it remains complex to integrate our results with previous studies due to spatial and vertical variability in site formation processes, two significant conclusions can be drawn from the stratigraphic and chronological assessment presented here. First, the depositional history of Morro do Ouro was made of alternating periods of fast and slow depositional events over approximately 25 generations of human activity. Combining our data with previous results suggests that the use of the site has changed over time and across distinct areas. However, it remains unclear whether these changes reflect variations in population size, shifts in site function, cycles of occupation and abandonment, or a combination of these factors. Second, the creation of a monumental mound was a gradual and likely evolving process, where the significance of its size and physical presence on the landscape became apparent only after multiple generations.

CONCLUDING REMARKS

In this study, we present new insights into the sedimentary and chronological record of Morro do Ouro, a *sambaqui* site located in Babitonga Bay, Santa Catarina. Key results from our study include:

1. Morro do Ouro has lost a significant fraction of its historical volume, and archaeological interventions must seek to maximise information while minimising physical alterations of the site. Due to their large

size, the volume of *sambaquis* should be periodically monitored as an additional conservation indicator, particularly in urban areas.

2. The uppermost part of the site (Upper Sector) has preserved its stratigraphic deposits remarkably well, which are associated with its Late Holocene occupation. These deposits are found beneath approximately 20 cm of soil formation and disturbed archaeological layers. Recent historical activities have disrupted the site by disturbing some localised archaeological deposits. However, these disturbances can be identified and isolated thanks to the presence of stratigraphic markers and radiocarbon dating.
3. Archaeological features (structures, pits), faunal and plant remains, stone and bone artefacts were found throughout the stratigraphy of the Upper Sector, often associated with evidence of trampling. Their spatial distribution suggests the presence of several distinct occupation surfaces created over a span of approximately 200 years. Archaeological materials and features (e.g. structure 3) observed in layer 3A, in particular, reflect approximately 50 years of site occupation, which can be translated in two human generations.
4. Several stone tools from the Upper Sector could have been used for grinding plant material, such as palm fruits, which were visibly abundant. Fish bones and shells of marine-brackish species were the most abundant faunal remains in the Upper Sector. No human burials were found, and only a few fragmented human remains were recovered in the Upper Sector. Their fragmented nature remains a matter of debate (ritual, taphonomic).
5. The site formation history derived from the exposed deposits in the Northern Profile indicates complex and variable deposition patterns, marked by slow and fast depositional events. The distinct layers of shells of *A. flexuosa* may indicate intentions of raising the site faster than the ordinary sedimentary accumulation rate. This could be taken as evidence of higher levels of human activities in this area of the site between 4656 (layer 21) and 4522 (layer 8) cal BP (134 years), representing approximately five human generations. Historical reconstructions relying on biological and artefact evidence from complex sedimentary records, such as the *Sambaqui* Morro do Ouro and others in the region, can only achieve robustness when high-resolution depositional rates are known and integrated into interpretative models.
6. The final monumental stage of the *Sambaqui* Morro do Ouro was achieved only after more than 600 years and 25 human generations. Internal changes during *sambaqui* formation hold the key to understanding their origin, changing nature, regional diversity and commonalities.

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AUTHORS' CONTRIBUTION
A. C. Colonese contributed to conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing (original draft, review and editing); K. M. McGrath contributed to conceptualization, funding acquisition, investigation, methodology, writing (original draft, review and editing); T. Fossile contributed to conceptualization, data curation, investigation; A. Toso contributed to conceptualization, investigation, writing (review and editing); D. R. Bandeira contributed to conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, writing (original draft, review and editing); T. A. K. Silveira Montes contributed to methodology; X. S. Villagran contributed to conceptualization, data curation, formal analysis, investigation, methodology, writing (original draft, review and editing); J. Iriarte contributed to investigation, methodology, writing (original draft, review and editing); J. Ferreira contributed to conceptualization, investigation, methodology, writing (original draft); J. C. Sá contributed to investigation, methodology, writing (original draft, review and editing); F. M. Borba contributed to conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, writing (original draft, review and editing); M. C. Alves contributed to investigation, methodology; and R. M. Veiga contributed to funding acquisition, project administration.

RESEARCH DATA
The data have been deposited in the Zenodo repository and can be accessed in Colonese (2025).

PREPRINT
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PEER REVIEW
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