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From traces to trades: a late Roman bone workshop in Nora (CA, Italy)

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Abstract

In the framework of a Double Degree project shared between the University of Padua and the Université Bordeaux Montaigne, this dissertation surveys various kinds of surface modifications recognized on 12 worked bone fragments from the building near the east side of the Roman forum of Nora (CA, Italy). These 12 bone fragments are supposed to be representative of a manufacturing sequence recognized on an assemblage of 264 worked bone fragments found in a room of the building, a clear sign of the presence of a bone workshop during its late antique phases. The primary objective of this research is to reconstruct and define the manufacturing sequence along with the tools utilized, employing a multifaceted approach that encompasses bibliographic research, archaeological investigation, analytical techniques, and statistical analysis. The findings obtained from this comprehensive study are integrated to help to understand the socio-economic significance of the workshop within the broader context of the ancient city of Nora, enriching our understanding of its historical and economic role.

Nell'ambito di un progetto di Doppio Titolo tra l'Università di Padova e l'Université Bordeaux Montaigne, il presente elaborato esamina i vari tipi di modifiche riconosciute sulla superficie di 12 frammenti di ossi lavorati provenienti dall' edificio a est del foro romano di Nora (CA). Questi 12 frammenti di ossi dovrebbero essere rappresentativi di una sequenza di produzione riconosciuta in un insieme di 264 frammenti di ossi lavorati rinvenuti in una stanza dell'edificio, chiara evidenza della presenza di un laboratorio di lavorazione di ossi durante le sue fasi tardo-antiche. L'obiettivo principale di questa ricerca è ricostruire e definire la sequenza di produzione, insieme agli strumenti utilizzati, impiegando un approccio multidisciplinare che comprende la ricerca bibliografica, l'indagine archeologica, le tecniche analitiche e l'analisi statistica. I risultati ottenuti da questo studio contribuiscono a comprendere la rilevanza socio-economica della bottega dell'osso nel contesto più ampio dell'antica città di Nora, arricchendo la nostra comprensione del suo ruolo storico ed economico.

Dans le cadre d'un projet de Double Diplôme partagé entre l'Université de Padoue et l'Université Bordeaux Montaigne, cette recherche examine divers types de modifications de surface identifiées sur 12 fragments d'os travaillés provenant du bâtiment situé près de l'est du forum romain de Nora (CA, Italie). Ces 12 fragments d'os sont censés être représentatifs d'une séquence de fabrication identifiée dans un assemblage de 264 fragments d'os travaillés découverts dans une salle du

bâtiment, ce qui constitue une indication claire de la présence d'un atelier de travail de l'os lors durant les phases du Bas-Empire. L'objectif principal de cette recherche est de reconstituer et de définir la séquence de fabrication ainsi que les outils utilisés, en utilisant une approche multifacette qui englobe la recherche bibliographique, l'investigation archéologique, les techniques analytiques et l'analyse statistique. Les résultats obtenus de cette étude complète contribuent à comprendre la signification socio-économique de l'atelier dans le cadre plus large de la ville antique de Nora, enrichissant ainsi notre compréhension de son rôle historique et économique.

Introduction

It has been four years since the remarkable discovery of over 200 semi-worked bone fragments within room VII of the building near the eastern side of the Roman forum of Nora. This discovery marks a significant milestone in an ongoing research program initiated by the University of Padua in 2007. This comprehensive project commenced with the inaugural stratigraphic surveys in the south-eastern region of the Roman forum of Nora, located within the eastern sector of the ancient city. These initial surveys led to the identification of a remarkably well-preserved structure, colloquially referred to as the "building on the east side of the forum" based on its geographical location. Subsequent excavation campaigns have steadily expanded our understanding of this complex's architectural layout. During the 2019 excavation season, a substantial quantity of animal bones displaying distinct anthropic modifications of craftsmanship was unearthed within one of the rooms. These finds are situated beneath layers containing fragments of deteriorated plasters and are believed to be associated with artisanal activities, likely related to the processing of animal bone. Therefore, these semi-worked bones add an intriguing dimension to our comprehension of the late-phase utilization of the complex, offering valuable insights into the artisanal practices and activities of the era.

This discovery immediately piqued interest, as it holds the potential to provide insights into the methods, techniques, and even the gestures involved in crafting specific instruments that have been documented across the Mediterranean for centuries. Although this material has previously undergone thorough typological and archaeozoological examinations, the present analysis seeks to re-evaluate it from a functional, microscopic perspective. This involves the application and comparison of diverse imaging techniques. The ultimate goal is to reconstruct the operational chain, which involves not only deciphering the physical actions but also comprehending the tools employed in the process.

By scrutinizing the microscopic level and examining the work traces left on the bones, we aim to reconstruct the specific movements that produced these marks and to identify the precise tools that were used. While imaging can effectively assist in reconstructing the movements, a more specialized approach is essential for gaining insight into the nature of the tools utilized in this intricate process. This examination promises to provide a deeper understanding of the ancient techniques and craftsmanship involved.

PART I

Nora: archaeological context and materials

1. Nora and the building located near the East side of the Roman forum

1.1. Nora: a brief description of the archaeological site

1.1.1. Geography and geomorphology

Nora is an ancient city located on the southern coast of Sardinia Island (Italy), in the south-western limit of the Gulf of Cagliari. It occupies a sub-triangular shaped peninsula, constituted by a promontory, *Capo di Pula*, with two ends facing the sea, *Punta del Coltellazzo* to the east and *Punta 'e su Coloru* to the south, connected to the mainland by a narrow isthmus. From a geological point of view, the isthmus was a former tombolo connecting some volcanic islands not far from the coast. The subsequent cementification of the tombolo brought to the formation of the peninsula, characterized by two main lithotypes, because of the double sandy and volcanic origin: andesitic and arenite rocks, that can be both found as construction materials in the ancient city (Previato C. 2016). Throughout the ages, thanks to the constant link to the sea, the peninsula's morphology was affected by important marine processes: sea rising and coastal erosion reshaped the landscape continuously. As a consequence, the actual extension of the promontory is smaller than the ancient one and some archaeological findings are now eroded or submerged (Bonetto J. *et alii* 2022) (fig. 1).

The privileged location in the heart of the Mediterranean Sea, between Italy, Africa and Spain, made the city of Nora a centre of composite cultural dynamics, derived from the contact between different people over the centuries. Its bays could be used for centuries for stable or occasional anchoring of boats, as they guaranteed protection from weather and sea conditions in the different combinations of winds and currents.

1.1.2. History

The presence of neolithic (Luglié C. 2009, Mazzariol A. 2022) and Nuragic populations is attested from the end of the II millennium BC both in the promontory and in the near plain, between Nora and the modern village of Pula, where a nuraghe (*Sa Guardia Mongiasa*) was located. Some Nuragic ceramic remains were found at *Punta del Coltellazzo*, at the so-called Tanit Hill and other parts of the town, but they're not in their primary context. Therefore, it is difficult to give a precise frame of the Nuragic culture on the site and say whether there was still a Nuragic presence in the promontory when the Phoenician's frequentation started (Furlan G., Marinello A. 2022; Bonetto J., Furlan G., Marinello A. 2020).

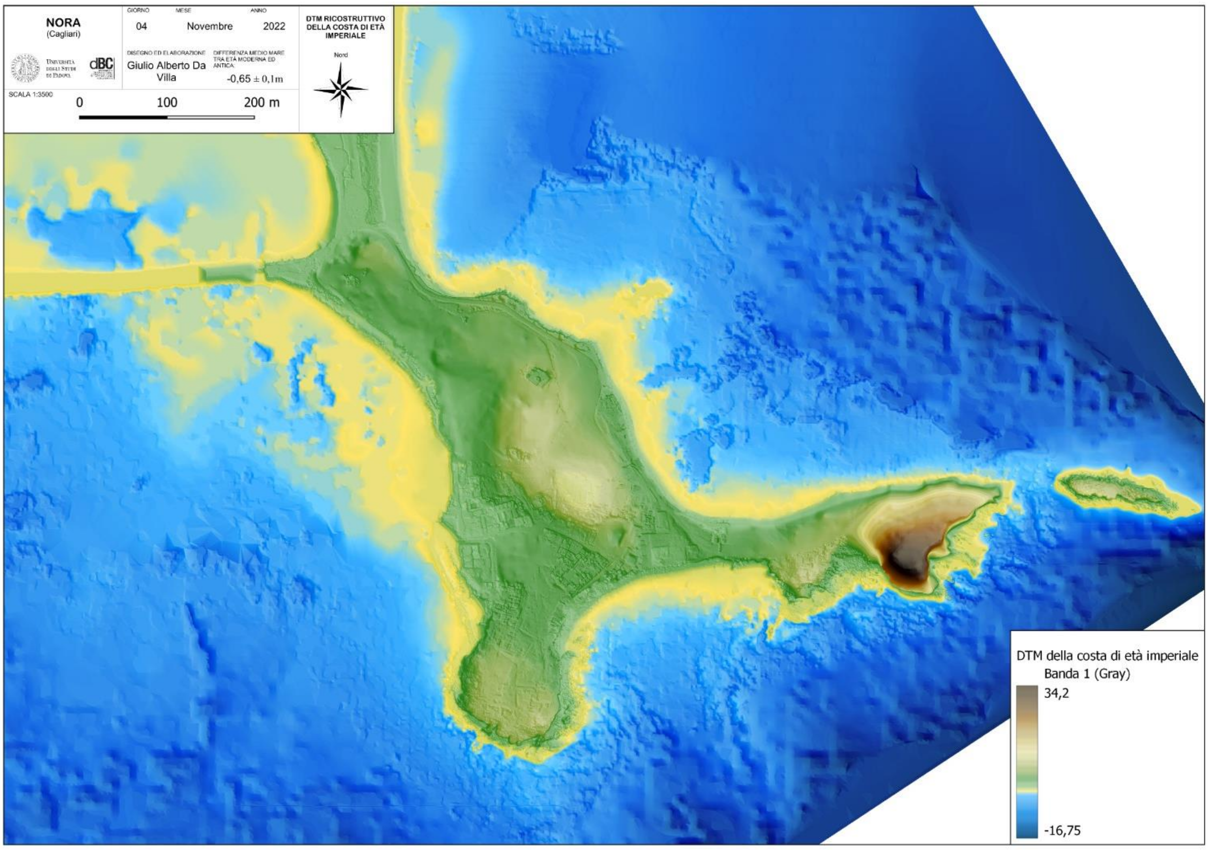


Fig. 1 – Digital representation of the peninsula in the Roman-Imperial age, the emerged land begins at -0.55m of the DTM (DA VILLA G.A. 2022).

Actually, a well-known literary and epigraphic tradition, together with a fair amount of pottery finds, testify the vitality of the centre between the VIII and VI centuries BC. The well-known stele of Nora, an inscription in Phoenician characters dated to the second half of the IX - first quarter of the VIII century BC, is the best-known document, as well as numerous ceramics, of the Phoenicians presence in Nora (BONETTO J., MARINELLO A., ZARA A. 2021). At that time, the site could be framed within an emporical-mercantile scenario, as a landing place for mainly Phoenician sailors (in contact with the indigenous Nuragic communities), whose settlements still appear simple and perishable (BONETTO J. 2013; BONETTO J. 2009): a small village, perhaps initially seasonal, that takes on larger dimensions from the VII century BC, acquiring also religious and funerary spaces (BONETTO J., MARINELLO A., ZARA A. 2021; BONETTO J. 2021a).

From the beginning of the V century BC Nora becomes a colony of Carthage. The peninsula starts showing an urban landscape with new masonry architectures (archaeological evidences were found in the area of the Roman forum) (BONETTO J. 2009) and the presence of farms in the surrounding area, signs of agricultural exploitation interests. Nevertheless, the Punic settlement reality is not completely clear concerning the building evidences, a part from a sort of "sacred belt" dotted with a series of religious complexes. In particular, to be mentioned are the temple on the eastern slopes of Tanit Hill, the sanctuary on the lower slopes of Coltellazzo Hill, and the sacred area at the southern promontory of *Punta 'e su coloru*.

The transition from a small trading post to an urban centre is also testified by the funerary context. The presence of a *tofet* sanctuary, together with rock-cut inhumation chamber necropoleis and their rich kits, both on the isthmus and near the north-eastern coast of the peninsula (in use from the V to the III century BC), give us the idea of a rich and more structured Nora, open also to international relationships (BONETTO J. 2021b).

Later, Romans inherit this colonial and urban layout: in 227 BC Rome creates the province of *Sardinia et Corsica*, including the city of Nora as an allied centre and trade pole with the peninsula.

During the early centuries of Roman control (III - I century BC), the administrative life goes along with the previous Punic one, as well as the Punic religious places, that are maintained, expanded and renovated. Signs of a progressive development of spaces regards not only the houses, more concentrated in the city central area, but also the crafting and commercial activities, that are shifted towards the sea, in accordance with a precise urbanistic plan (GHIOTTO A.R., ZARA A. 2020). These interventions are a consequence of the favourable economic situation experienced by Sardinia in the late Republican period, when the island started to join an international commercial network. Promoters of this urban renewal are the local elites, imitating the Italian elites' models, sometimes also entertaining client relationships with the most eminent elites of Rome: it's a proof of the progressive «Romanization» of the Punic society.

Then, the forum is built at the end of the I century BC, when the *municipium civium Romanorum* was established in Nora. It will be followed by the theatre, built shortly afterwards, before the end of the I century AD.

It is during the imperial age (II and III century AD) that the city grows and occupies the whole peninsula with infrastructures (paved streets, sewage systems, aqueduct), public buildings and private residences of great importance. Among the most important public interventions: the widening of the forum square, the last construction phase of the Roman Temple (BERTO S., ZARA A. 2016), the construction of three thermal buildings – connected to the construction of the aqueduct - and the paving of the streets, maintaining the urban plan of the Punic-Republican period. Different public structures are built *ex novo*, but at the same time a renovation and remaking of already existing structures is going on: it's the case of the building located near the East side of the forum (see paragraph 1.3).

Ordinary maintenance activities continue at the beginning of the late antiquity period, in order to keep the city efficiency high. The sacred spaces are renewed after Constantine and

Theodosius' laws: a Christian *Basilica* with a nave and two aisles is built in the western area of the peninsula, along the harbour road. This, together with the suburban location of the Saint Efisio's new worship centre, denotes a shifting of the Christian religious life towards the margins of the city centre, once constituted by the forum and its political-administrative function (BONETTO J., GHIOTTO A.R. 2013).

Between 459 and 466 AD the Vandals occupy the Sardinian territory. The city of Nora experiences a demographic and commercial reduction in a complex and dynamic period up to the Byzantine age, when it became a military fortress (*praesidium*) (*Cosmographia*, V, 26).

Due to increasingly frequent raids, the inhabitants moved progressively towards the inland until the complete abandonment of the site.

1.2. THE RESEARCH HISTORY

The ancient city of Nora remained buried until the XIX century. Until then, the area was used for agricultural purposes and only few of the main Roman monuments were known, such as the aqueduct's remains, the upper parts of the theatre's *cavea* and the so called *Terme a mare*. Also, rich entrepreneurs and landowners often collected art objects in an antiquarian perspective, without giving any precise description of the discovery contexts.

It was only at the end of the XIX century, when the Punic *tofet* was discovered, that the first archaeological operations began thanks to the work of F. Vivanet and F. Nissardi. Steles and urns from the *tofet*, as well as the materials from the eastern Punic necropoleis excavated in that period, were documented, partly reburied and partly brought to the Archaeological Museum of Cagliari. Today, some finds have been relocated and to the Museum "Giovanni Patroni" in the town of Pula (CA).

A decade later (1901), G. Patroni carried out both systematic field investigations and a study of the previous year's findings. His project had a more "scientific" and research aim, since he tried to take into account the history of the ancient city while studying the materials findings.

Later, a part from some local interventions of protection, not much was done in the archaeological site until 1952, that is the starting year of a great period of archaeological excavations, ended in 1960. The staging of a theatrical performance above the Roman forum ruins gave the possibility to explore for the first time the ancient square and the near theatre. G. Pesce was then coordinating the archaeological operations and, with his great direction, a varied group of workers highlighted over three hectares of urban centre from the Roman period. They worked on the main Roman imperial buildings with a non-stratigraphic method (in accordance with the contemporary archaeological trend), often stopping at the level of the mosaic's floors, but deepening on the private contexts to investigate the Punic settlement (BONETTO J., MAZZARIOL A., ZARA A. 2021). The excavation researches were noted daily and in the end a guide was published in 1957 (later republished in PESCE G. 1972). Unfortunately, a «scientific» edition of these excavations was never done, loosing for the most part of the findings the connection with the archaeological context. However, thanks to the work of Pesce and his team, the site of Nora became the first archaeological open-air museum in Sardinia.

Later, not such great excavations were done between the '60s and the '90s. Only in the last decade of the last century a new archaeological project, namely «Missione archeologica di Nora», has been set up by a collaboration between the *Soprintendenza Archeologica* of Cagliari and Oristano and the Universities of Pisa, Genoa, Padua and Viterbo, to which was added Venice, later replaced by Milan (TRONCHETTI C. 2018). Today, «Missione di Nora» includes the Universities of Cagliari, Genoa, Milan and Padua, always in collaboration with the *Soprintendenza*. The research activities started in 1990 and are still ongoing.

Fig. 2 - Ortophoto obtained by the photogrammetric survey made by C. Miele and A. Persichetti (Archetipo s.r.l.), elaborated by Giulio Alberto Da Villa (DA VILLA G.A. 2022).
The archaeological excavations today held by the University of Padua are highlighted by the red circles.
From left to right: the western Phoenician-Punic necropolis, the complex on the eastern slopes of Tanit Hill, the building located near the east side of the forum.

In particular, the University of Padua, leaded by F. Ghedini and J. Bonetto, during the last 30 years has carried on archaeological excavations in different areas of the ancient city, including the forum, the Roman temple, the sanctuary of Aesculapius, the western Phoenician-Punic necropolis, the building located near the east side of the forum and the complex on the eastern slopes of Tanit Hill (fig. 2). A complete overview of all the archaeological excavations can be found in the journal *Quaderni Norensi* (1-9) and in the monographic volumes of the *Scavi di Nora* series (I-X).

1.3. THE BUILDING LOCATED NEAR THE EAST SIDE OF THE ROMAN FORUM

In 2014 the University of Padua started the archaeological excavations of a Roman imperial building located near the eastern edge of the forum (fig. 2). It's an area never excavated by G. Pesce in the '50s, but instead touched by the construction of the so-called *Casa Sarda*, whose excavation works, together with marine erosion, have contributed to harmfully impact the northern part of the ancient building during the last century (fig. 3).

It was built during the Roman imperial period, undergoing various renovations throughout the centuries. Fourteen rooms and three trenches have been studied until now, disposed on different planimetric levels, covering an area of about 250 m^2 and facing the road, that from the forum headed to the eastern cape of the promontory (fig. 3).

The extraordinary state of conservation of the structures allowed to recognize the overall architecture: the ground floor was paved in cement or brick, while the walls were made of stone bases connected by means of a mortar binder, above which the upper part was made of pisé or adobe bricks, according to the local tradition. In most rooms, both the walls and the ceilings (externally covered by tiles and pantiles) were coated by painted plasters, that show the social prestige of the owner during the advanced Roman imperial period. More than 25.000 fragments of these plasters were found collapsed in the various rooms, but a remarkable work of study and reconstruction, still ongoing, is making clear their original appearance (fig. 4) (the last data about this important decorative wall apparatus can be found in STELLA MOSIMANN F. 2022; STELLA MOSIMANN F., SECCO M. c.s.). There are no doubts about the original development of the building on two floors, mainly because of the discovery of fragments of floor and walls in a state of collapse in the southern area of the building, where the bases of a pillar and a column, positioned in two different rooms, intended to support the attic (MARCHET B., ZARA A. 2022; GIATRELI A.M. 2020). Also, the water supply of the building was guaranteed by a well and a cistern, located below the floor levels of the ground floor.

A major renovation of the whole structure is well dated between 282 and 283 AD thanks to the discovery of a treasure of 49 bronze coins placed under the paving of a corridor, according to a Roman ritual tradition (ASOLATI M., BONETTO J., ZARA A. 2018). It's probably the beginning of one of the last living phases of the building, when the residential destination went alongside craft and production activities, undoubtedly attested in at least one room facing the street: the room VII (fig. 5).

Fig. 3 - Drone orthophoto of the building made at the end of the 2022 archaeological campaign (elaborated by Arturo Zara).

Fig. 4 - Reconstruction of the decorated room VIII (elaborated by University of Padua, Katatexilux project).

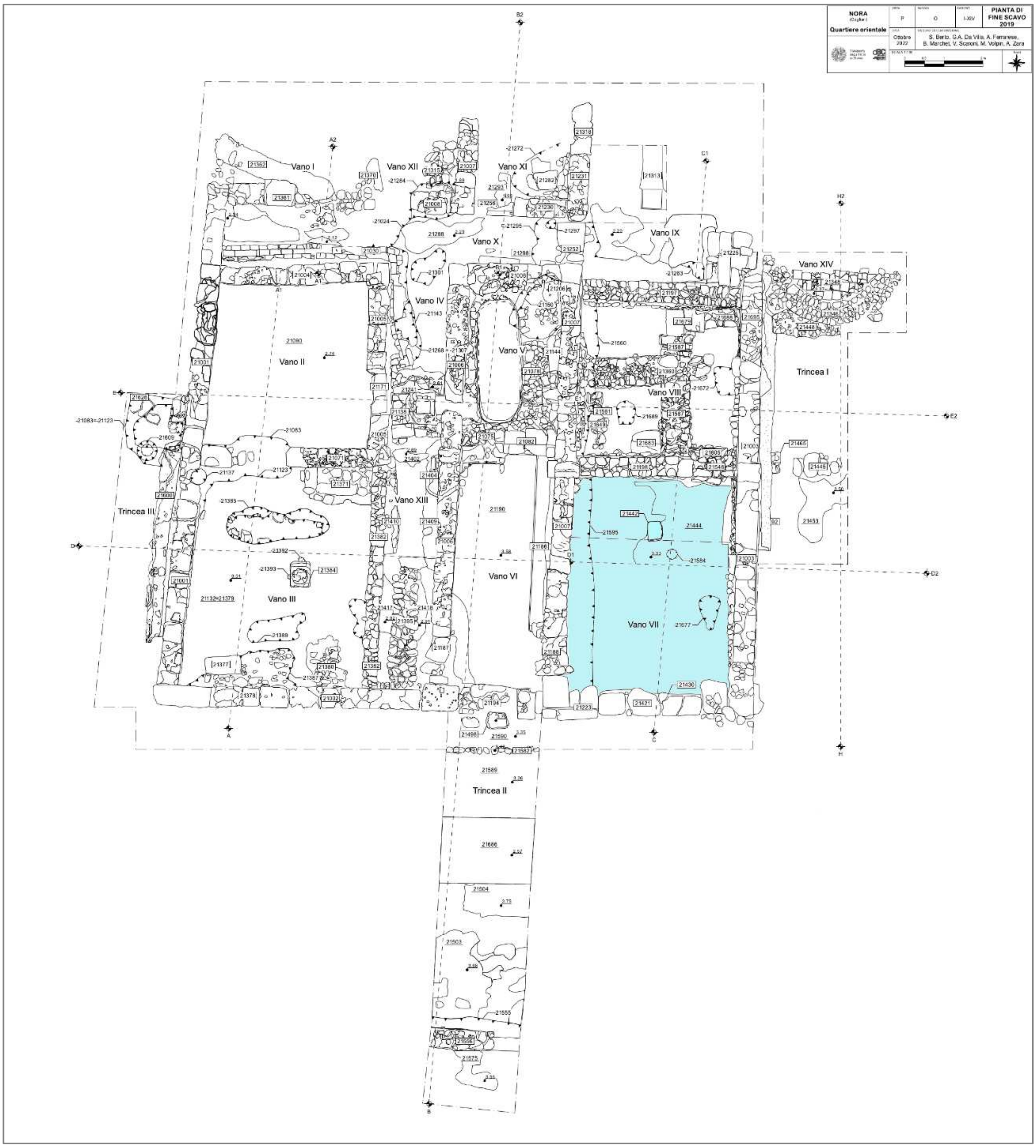


Fig. 5 – Plan of the building updated at the end of 2022 archaeological excavations (elaborated by S. Berto, G.A. Da Villa, A. Ferrarese, B. Marchet, M. Volpin, A. Zara).
In light blue is highlighted the room VII, where the bones studied in this dissertation were found.

1.4. ROOM VII: DISCOVERY CONTEXT AND LATE ANTIQUE STRATIGRAPHY

The room VII (5,55 x 4,20 m), located in the south-eastern part of the building (fig. 5), seems to be the main space of the building's last frequentation phases. The archaeological excavations and researches in this room started in 2019 and continued annually until 2022. As they are coming to an end, the image at least of the last frequentation period can be clearly depicted.

The room’s latest chronology is pretty well defined, thanks to the study of different numismatic finds (ASOLATI M. 2022), between the last decades of the III century and the first decades of the IV century AD. This dating aligns with the timeline of the ceramic discoveries, currently undergoing advanced studies (BARBISAN A. 2023), indicating a date no later than the early V century AD. It’s a brief period in which the room probably changed its function and became a bone working laboratory: right in the late archaeological layers more than 250 worked animal bones were found, showing different stages of a *chaîne opératoire* related to the production of pins or needles. The greatest amount of them comes from an accumulation layer (21427=21443) created above the last used pavement (probably 21551, preserved in an incomplete way only in the northern area of the room), but they were also found in the upper layers of abandonment and collapse of the room (21426=21433, 21413=21415), besides few bone fragments casually outside the door of the room, in the trench II (MARCHET B., ZARA A. 2022). Concerning their distribution, the north-western area of the room seems to have a particular importance, since the bones’ majority was attested in that zone towards the western wall (21007), whereas the rest was found dispersed in the eastern part, submerged inside the abandonment’s layers (fig. 6).

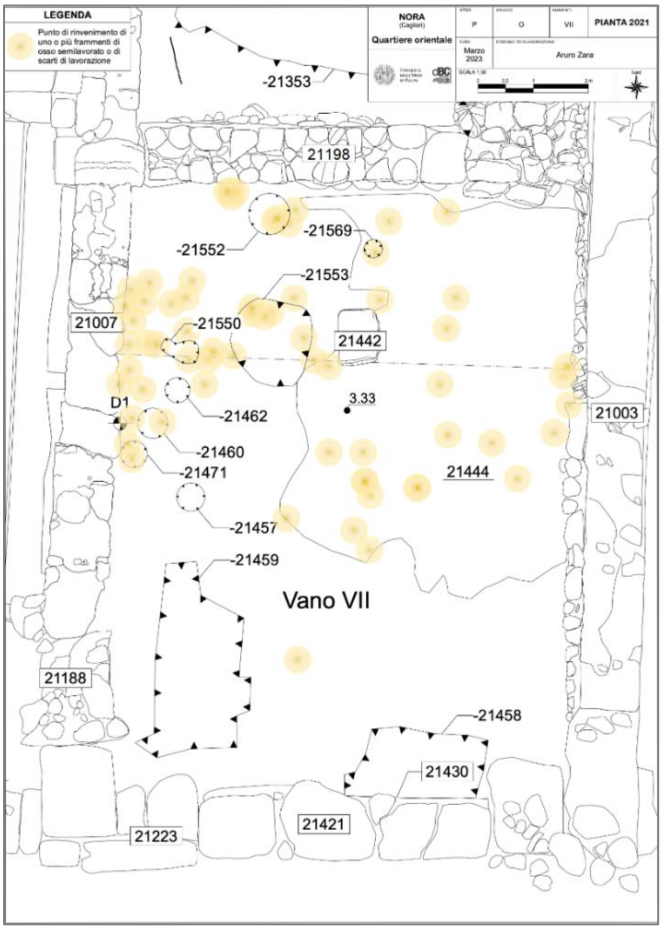


Fig. 6 - Plan of the discovery context of the bones' fragments in the room VII. In light yellow the precise discovery points can be seen (elaborated by Arturo Zara).

Other coeval layers give hints about the room's change of function. In particular, always in the north-western sector of the room, evident traces of rubefaction and abundant presence of ash and coals (21469, 21547) testify activities that involved the use of fire. Also, various holes (-21550, -21552, -21569, -21457, -21458, -21459, -21460, -21462, -21471) could have been made to host structures in perishable material, such as supports for tables or counters, perhaps used during the bones' artisanal activity (MARCHET B., ZARA A. 2022) (fig. 6).

Moreover, about 50 big *plaques* and fragments of the walls' painted plasters show superficial Latin numeral, alphabetic and figured graffiti. They were found concentrated in the north-western area of the room, but also in different locations of other three rooms of the building (room II, IV and VIII). Their epigraphic study is still ongoing (GHIOTTO A.R., MARCHET B., STELLA MOSIMANN F., ZARA A. 2022), but one inscription in particular needs to be mentioned here. It's the most complete and valuable one, marked in three matching plasters' fragments (fig. 7), originally part of the central area of one of the walls constituting the north-western corner of the room. The fragment bears two inscriptions, written by two different hands:

A)

[- - -]++ AN++[- - -].

B)

[- - - ?] mulomedic[us - - - ?]
[- - - ?] in macelo (!).

The first inscription (A) is too fragmentary, while the second (B) refers to a *mulomedicus*, one of the Latin names used to call the veterinarian, in particular the one who mainly deals with equids, known epigraphically in only five other Latin inscriptions. Also, in the second line the author quotes the *macellum* (reported with a single L instead of a double), that is the meat slaughterhouse and market in the late antique Roman city (the complete epigraphic analysis of this inscription can be found in BUONOPANE A., ZARA A. c.s.). Although the position of the *macellum* in Nora is not clearly identified, for sure it can be hypothesized the fact that the bone's craftsman who might create the graffiti could have taken right there the raw material useful for his activity.

To be mentioned are also the numeral inscriptions, engraved individually or separated into operations and counts, direct witnesses of the craft, buying and selling activities that took place in the building and in particular in the room VII during its late frequentation stages (GHIOTTO A.R., MARCHET B., STELLA MOSIMANN F., ZARA A. 2022).

Fig. 7 – Photo (on the left, elaborated by F. Stella Mosimann) and drawing (on the right, elaborated by A. Zara) of an inscription on three matching fragments of painted wall plaster. The text mentions a mulomedicus *and the* macellum.

As concerns the overall room architecture, a sandstone plinth (0.38 x 0.54 m) (21442) located towards the northern wall of the room (21198) must have supported a truss that made up the upper attic of the room. For sure this parallelepiped plinth was put down in that place after the creation of the room's floor, recognizable thanks to its mortar preparation (21444), today mainly present in the eastern portion of the room in a partial state of conservation (fig. 6) (Marchet, Zara 2022). On the southern limit of the room, a large andesite doorstep (about 2.6 m wide) suggests an opening to the outside of the building, where an urban road was identified (Andreatta, Zara 2022), probably for commercial or public use. Also, stone infillings of the doorsteps leading outside (21421) and to room VI (21188) can also be connected to episodes of re-functionalization and change of use of the room, before the abandonment and collapse of the building (Volpin M., Zara A. 2020).

To have a better view of all the characteristics descripted above, the building and the room VII can today also be seen in a 3D reconstruction (fig. 8), thanks to the work made in the last years by the newest e-archeo project (Bonetto J., Carlani R., Zara A. 2022).

Fig. 8 - Reconstruction of the internal and external view of the room VII (elaborated by University of Padua, Katatexilux Project).

2. A bone workshop in Nora: materials

2.1. Previous studies

A total of 264 worked bones have been collected from the late antique stratigraphy of the room VII (see paragraph 1.4). They've been found in two consequent years of archaeological excavations, 2019 and 2021, not considering the Covid-19's interruption in 2020.

During the previous years, just the ones found in 2019 (224 bones) were studied, according to a double line of research. On the one hand, in the framework of my bachelor's degree thesis, I have worked on the bones' cataloguing and typological classification, finding archaeological comparisons to better understand the bone processing methods, techniques and the theorical *chaîne opératoire* (Naso M. 2021). On the other hand, the archaeozoological and taphonomic bones' analyses were taken into consideration by E. Pontis in his final dissertation for the *Scuola di Specializzazione in Beni archeologici* of the University of Padua (Pontis E. 2022). He recognized the role of animals as a source of raw material in this late antique *atelier*, but also, he better defined the possible fabrication steps reading the manufacturing traces on the bones from a macroscopic point of view. A clear summary of our combined research can be read in Naso M., Pontis E. 2022.

These studies were updated to 2019's excavations of room VII, but forties bones found in 2021 weren't included in the research. To complete the archaeological record in this dissertation, the forties missing bones have been drawn, photographed, described and studied together with the others (Appendix A).

2.2. Archaeozoological information

The bones' description started with the fauna determination, that is always the first step when analysing a sample of faunal remains from an archaeological excavation (De Grossi Mazzorin J. 2008; Outram A.K. 2023).

Usually, it happens that objects identified as bone artifacts are categorized as small finds and directed to a bone tool specialist, while the remaining faunal assemblage is forwarded to a zooarchaeologist. However, it is possible that non-specialist excavators may have misclassified certain unmodified elements as tools due to their inherent shapes. Meanwhile, remnants and fragments from crafting processes could end up mixed within the general faunal collection. This is why, ideally, these materials should be examined collectively and approached in a comprehensive manner, always including the zooarchaeological point of view (SEETAH K., GRAVINA B. 2012; CHOYKE A.M., O'CONNOR S. 2013).

So, even though the high degree of fragmentation and the anthropic modifications often made the archaeozoological recognition difficult, or even impossible, the anatomical portion and species were determined for a good number of the Nora bones. In particular, the archaeozoological knowledge of these bones comes from the work of E. Pontis, who, in his final dissertation (see paragraph 2.1.), made an exhaustive archaeozoological study of the 224 bones found in 2019 (PONTIS E. 2022; NASO M., PONTIS E. 2022). Today, his percentages should be recalculated including the forties bones found during the archaeological excavations made in 2021 (Appendix A), although we can already say that the results don't seem to change dramatically (see paragraph 6.1.).

Most of the times the anatomical portion was defined referring only to the diaphyseal level. Both the proximal and distal epiphyses of the bones are in fact absent and all the bones are cut in the central portion of the diaphysis. Therefore, the portion of fusion and synostosis that would allow the evaluation of the degree of welding of the long bones is not appreciated.

In terms of taxonomic determination and reference species, part of the remains has been attributed to the domestic bovine (*Bos taurus)*, but the majority of the sample cannot be clearly classified. However, among the indeterminable bone remains at the species level, more than one half can be categorized within the large ungulate macro-group (UTG: *ungulati di grande taglia*): it can be said that a significant part of the record falls within this faunal grouping, as it is suggested from the robustness and cortical thickness of the bones.

Among the bones that could be identified by anatomical elements, the majority is attributed to the radial-ulnar district. In particular, these include fragments of fused radii and ulnae, as well as isolated fragments of radii and ulnae. A smaller percentage consists of tibiae, while femur remains are scarce (see paragraph 6.1. and fig. 9).

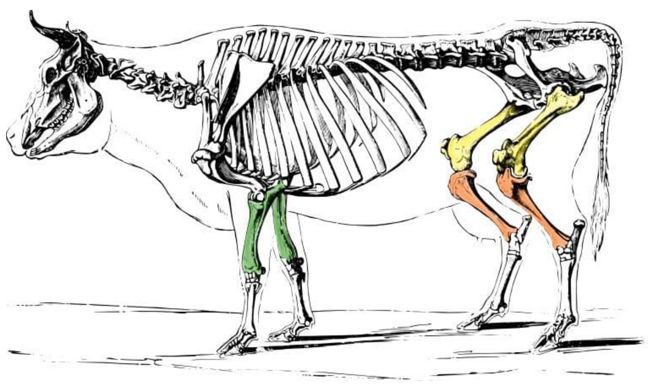


Fig. 9 - Highlighting of the identified anatomical elements: radius and ulna in green, femur in yellow and tibia in orange (PONTIS E. 2022).

From an archaeozoological point of view, it was possible to define the laterality of the fragments for a small part of the material, distinguishing between left and right bones thanks to the preservation of diagnostic elements, such as holes for nutrient vessels (*foramina*), roughness and morphological features. This is an information that can be useful in estimating the minimum number of individuals (NMI) (see paragraph 6.1.).

For some bones referring to the radio-ulnar district it was possible to note the synostosis between the two bones, resulting in a high degree of fusion, which can lead us to hypothesize the presence of adult individuals, an indication that would also be corroborated by the degree of compactness of the bones, which do not have the porosity typical of juvenile individuals.

It was not possible to identify the sex of the individuals, since the bones were too fragmented. Also, for none of the remains we arrived at a punctual understanding of the age at death, not preserving any of the diagnostic parameters suitable for this purpose (PONTIS E. 2022).

2.3. CLASSIFICATION AND DATABASE

From the beginning it was clear that the bones showed a coherent sequence of craftmanship and they represented an almost entire *chaîne opératoire*. For this reason, the first step of the study was to divide them into groups according to their macro-morphological characteristics, keeping an eye on the different working phases. Then, each of them was progressively labelled, measured, drawn and photographed, to create a comprehensible overall picture of the archaeological record (NASO M. 2021). All the data were later included in an implementable database started by the writer and completed by E. Pontis using Microsoft Access (NASO M. 2021; PONTIS E. 2022). Different interpretations were considered in the creation of the database, since the bones showed many potentialities: the information derived from the archaeological context; the faunal and archaeozoological data; the technological evidences and the macroscopic analyses of the working traces. In this way, a hierarchical order of description was followed, first reconstructing the materials biological value and then their potential as tools. Also, the database was conceived to be adjustable and modifiable according to what it is observed in the materials and to what it could be possibly found in future archaeological excavations. Below, in Table 1, the different entries of the database's table can be visualized in details. To name the different bones, the progressive ID number of the database is not taken into consideration, because it has been chosen to use the numbers given by the inventory system of the University of Padua (ADaM). In addition, since all the bones were fairly fractured, both in antiquity and later, the search for joinable fragments has made it possible to obtain more precise information about the number of remains (NR) present in the record, an essential basis for a correct interpretation of the material and of the context as a whole.

ID	Progressive number in the database
Site	Name of the archaeological site
Acronym	Acronym of the archaeological site
Area	General area of provenance of the material
Year	Excavation campaign's year
Room	Specific location of provenance of the material
US	*Unità stratigrafica*: archaeological layer where the bone was found
Chronology	Indication of the absolute chronology (if present)
Period	Relative chronology
N_Inv ADaM	Inventory number related to the inventory system of the University of Padua
N_Sabap	Inventory number related to the correspondent *Soprintendenza Archeologica*
Anatomical element	Radio-ulna; femur; tibia, etc...
Species	Specific or indeterminate *taxon.*
Portion	Medial; fragment; indeterminate.
Side	Right; left; indeterminate.
Other information	Anatomical description.
Shape	Rectangular; triangular; cylindrical; conical; cylindrical-conical.
Object	Support/matrix: base from which the working can start.
	Indeter: indeterminate object.
Artifact	*Baguette*: bone stick cut into regular shapes.
	Semi-worked: artifact with many working traces or that can be included in a specific typology.
	Fragment: broken *baguette.*
	Indeter: indeterminable artifact.
Tool	Pin: elongated object with a circular section; it may have a distinct head from the shank.
	Needle: pointed and elongated object with a circular section; it has a needle eye.
	Pin/needle: elongated object with a circular section.
	Awl: object with an elongated conical shape, pointed and with an expanded body.
	Case: container object.
Waste	Yes/no
Morpho-typological group	Group created from the morphological and typological analysis.
Functional group	Group created from the functional analysis, in order to reconstruct the process and the technological dynamics.
Traces	Yes/no
Traces' position	Marginal: along the margins.
	Local: in different points.
	Intrusive: they go beyond the margins.
	Covering: they affect the entire surface.
Traces' action	Sawing: clean cut, clearly visible traces of the saw.
	Abrasion: removal of surface material.
	Levigating: progressive notches for shaping.

	Drilling: drilling of the surface.
	Polishing: polishing of the surface.
Traces' pattern	Transversal; longitudinal; both; with respect to the principal axis of the object.
Working phase	*Débitage; façonnage; polissage*
Description	Additional information
Measures (mm)	GL: greatest lenght; GB; greatest breadth; sB: smallest breadth.
To be photographed	Yes/no
Photographed	Yes/no
To be drawn	Yes/no
Drawn	Yes/no
For micro investigations	Yes/no
Notes	Any additional notes.
Attachment	Files attached.

Table 1 – Database's glossary created by E. Pontis (PONTIS E. 2022) divided in four parts: the bluish one includes the information about the archaeological context; the green one is the description of the archaeozoological analyses; the pinkish one is related to the macro-traceological analyses; the grey one concerns the more technical description.

The division into functional groups was found to be particularly important, since these bones are "objects in progress". In this sense, there are no finished artefacts, but a small part of the *corpus* seems to be at a rather advanced stage of manufacture. Most of the material falls into the category of supports, i.e., blocks of raw material from which the artefacts are manufactured.

Three are the studied functional groups (PONTIS E. 2022):

A. Starting supports: portions of the radius-ulna that preserve part of the ulna fused to the radius and on which one can recognise transverse and longitudinal sawing with respect to the axis of the bone. These finds are well recognisable from the point of view of the anatomical element, they inform us about the raw material from which they were made, but they cannot yet be defined as objects.

B. Supports cut into regular shapes: *baguettes* cut in rectangular or triangular shapes. In some cases, they provide information about the anatomical element. This group comprises most of the material.

C. Supports with several evident processing traces: artefacts that show more traces of workmanship, or possess characteristics typical of a certain class. These are semi-finished artefacts that do not provide reliable information on the anatomical element, as they are completely modified: the archaeozoological information is therefore obliterated by the processing stages.

In particular, the bones analysis reveals various stages of the production sequence, encompassing the initial roughing of the raw material (*débitage*) to create a support, followed by the shaping (*façonnage*) process that gradually moulds the object, concluding with the finishing (*polissage*) phase that aims to achieve smooth surfaces on the artifacts.

In addition, five techniques and actions related to the cutting of these bones have been hypothesized from the macroscopic reading of the cutting traces: sawing, abrasion, resizing, drilling and polishing (PONTIS E. 2022).

2.4. CHOICE OF REPRESENTATIVE BONES

The above-mentioned functional study (paragraph 2.3.) made on the Nora worked bones needed a multidisciplinary approach to be better defined, including microscopic and eventual experimental observations (for the description of the chosen analytical techniques see chapter 5). For this purpose, this thesis work started with the narrowing of the field of study into few representative bones, setting the significant specimens to be analysed.

In the first place I decided to select one (or more) bone for each stage of the observed manufacturing sequence (see paragraph 2.3.). Then, I took into account the following parameters:

- Presence of heterogeneous cutmarks;
- Specificities and interesting details (i.e., false cutting start, use-wear traces, etc.);
- Different conservation' states;
- Different sizes;
- Similarities with the other "non-selected" bones.

The choice wasn't easy, considering the heterogeneities present between the bones, the number of materials and the uniqueness of each cutmark. However, with the help of drawings (for a review of all the drawings see NASO M. 2021) and a good use of the stereomicroscope (see chapter 5) I was able to select 12 bones (fig. 10-19) out of 264, which are here described in Appendix B.

Fig. 10 – Sample 3335

Fig. 11 – Sample 3338

Fig. 12 – Sample 3351

Fig. 13 – Sample 3384

Fig. 14 – Sample 3391

Fig. 15 – Sample 3392

Fig. 16 – Sample 3416

Fig. 17 – Sample 3403

Fig. 18 – Sample 3460 (left) and 3316 (right)

Fig. 19 – Sample 3541 (left) and 3315 (right)

PART II

Methodologies

3. Bone as a raw material

Considerable attention should be given to the fact that bone industry depends first and foremost on the material itself, as ancient craftsmen determined their *modus operandi* according to the shape, the dimensions and the physical properties of the raw material. Unlike clay or metal, where you can add the mass you want to create a more significant object, with bone the craftsmen can only take advantage of the existing characteristics of unmodified raw materials (BÉAL J.C. 1983). These characteristics played a vital role in this craftsmanship and sometimes even influenced the forms created in other materials, lacking of this "primary controls" (MACGREGOR A. 1985). Throughout history, humans have used a composite array of hard materials derived from animals (fig. 20). These materials have been in use since prehistoric times (CHOYKE A.M., BARTOSIEWICZ L. 2001; LUIK H. *et alii* 2005; GATES ST-PIERRE C., WALKER R.B. 2007; LEGRAND-PINEAU A. *et alii* 2010; DE GROSSI MAZZORIN J. 2012; MA S., DOYON L. 2021), even long before the beginning of use of alphabet, and include, to name but a few, bones, deer antlers, tooth enamel, ivory, ostrich eggs, coral, and shells. However, the use of osseous tissues as raw materials for objects manufacture is not a uniform category. Examples such as antler, land-mammal bone, sea-mammal bone, and mammoth ivory, among others, differ in terms of their economic availability, workability, and reactions to use and wear (PÉTILLON J.M., 2008; MÜLLER K., REICHE I. 2011). It is even difficult to gather all of them together at a terminological level, and various terms have been adopted in an attempt to create a suitable word that includes all the hard animal substances used in the production of tools and implements. These terms are "osteodontokeratic materials" (DART R.A. 1957), "vertebrate hard tissues" (HALSTEAD L.B. 1974), or simply "skeletal materials" or "osseous tissues". Moreover, being products of animal origin, they are intrinsically tied to the cultural perception of the animal world by human groups, both in a general sense and concerning specific species (BINFORD L.R. 1981). Among all of the skeletal materials there aren't superior or inferior substitutes, but each material has distinct mechanical properties, which often makes it exceptionally well-suited for specific tasks. So that, when various of them were available, these distinctions played a role in guiding the preference for one over the other (ST. CLAIR A. 2003). In this way, bone awls and projectile points were often made from long bones, whose natural shape is fairly close to the shape of the desired end-product, or a condyle or articulation was employed as a butt or handle (fig. 21). Or, differently, cylindrical shells like *Dentalium* could be readily divided into beads, and various shell types frequently exhibit shapes that align well with intended artifact designs (BANNING E. B. 2020). The selection of a structurally less favourable skeletal material over another was driven only by contextual factors such as luxury and availability. The most common example is the use of ivory instead of bone and antler. If we compare the mechanical properties of bone, antler and ivory (CURREY J.D. 1970; MACGREGOR A. 1985; see paragraph 3.2), we will notice that both the bending strength and modulus of elasticity of ivory are inferior to those of bone and antler, making it a less desirable material for many classes of objects, such as combs and pins (ST. CLAIR A. 2003). Yet ivory was used for create admirable carved combs and pins, because it was its association with luxury and wealth that determined its choice (fig. 20, f).

Fig. 20 – Collection of various archaeological findings made of skeletal materials across different places and times. The measures are indicated here in the description. ***a)*** *The "Divje Babe flute", a perforated femur of a juvenile cave bear, 11,6 cm, Divje Babe (Slovenia), about 43,000 years ago (TURK M. et alii 2018);* ***b)*** *"Bison Licking Insect Bite" carved on reindeer antler, 10,5 cm, Dordogne (France), 20.000-12.000 BC;* ***c)*** *Mammoth in ivory contour carving, 6,9 cm, Pavlov I site, south Moravia (Czech Republic), about 27,000 - 25,000 years old (SVOBODA J. 2012);* ***d)*** *Ivory Venus of Brassempouy (France), 3.65 cm high, 2.2 cm deep, 1.9 cm wide, 25,000 years old;* ***e)*** *Wood and ivory figurine, Louvre Paris, 19,4 cm, New Kingdom, Dynasty XVIII, 1391-1353 BC;* ***f)*** *Ivory figurate pins from Greece, 13.9 and 13.3 cm, V century BC;* ***g)*** *Dice and bone tokens, Musée gallo-romain de Saint-Romain-en-Gal;* ***h)*** *Anglo-Saxon bone composite comb, 6.7 cm x 4.1 cm, IX-X century AD;* ***i)*** *Etruscan Situla of the Pania, elephant ivory pyxis found in the Tomb of the Pania, Chiusi (Italy), 22 cm high, end of the VII century BC;* ***j)*** *The Lewis chess pieces, walrus ivory and sperm whale tooth, height 60-100 mm, made in Trondheim (Norway), now at the National Museum of Scotland, Late XII – early XIII century AD;* ***k)*** *The Franks Casket, a small Anglo-Saxon whale's bone chest, 22.9 cm long x 19 cm wide x 10.9 cm high, early VIII century AD;* ***l)*** *Horn cases, Crypta Balbi, Rome (GIANNICHEDDA E., MANNONI T., RICCI M. 2001);* ***m)*** *Jane Austen's odontolite ring, Jane Austen House Museum, Georgian Era;* ***n)*** *Enthroned Virgin and Child in elephant ivory with traces of paint and gilding, 18.4 x 7.6 x 7.3 cm, The Metropolitan Museum of Art, made in Paris (France), ca. 1260–80.*

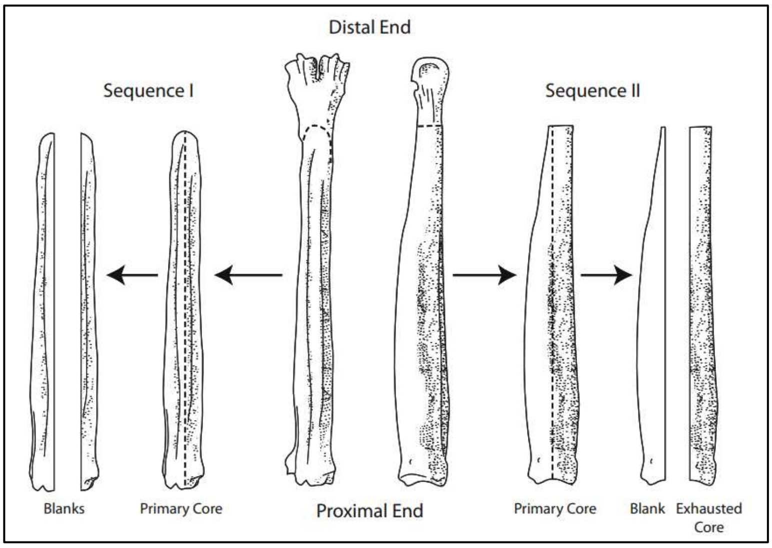


Fig. 21 – An example of primary reduction through longitudinal splitting, in which we observe the process applied to a caribou metatarsal. Initially, the metatarsal is split in the coronal plane behind the distal condyle. Subsequently, the posterior section is divided into medial and lateral halves, either along the left or right side of the sagittal plane (BANNING E. B. 2020, adapted from MORRISON D. 1986, p.110).

When it comes to Classic times, the material remains themselves tell us that their unique characteristics were deeply appreciated by the people who used them, thanks to personal observation and knowledge passed down through generations. At that time, craftsmen learned their trade through practical experience without much theoretical grounding in their training, developing a keen sense or "feel" for their materials based on their own experiences and the teachings of their masters. Although they may find it challenging to explain precisely why a particular raw material was well-suited for a specific purpose, their judgment undoubtedly remained valid and accurate. Unfortunately, our knowledge of skeletal materials utilized in the classic antiquity remains limited, and, since the use of such materials ceased long ago (at least in the European culture), there is a scarcity of written records pertaining to them (see paragraph 4.1.). Consequently, we can use scientifically-gathered data to conduct objective assessments to comprehend the attributes that led to the choice of specific materials for various purposes in ancient craft practices (MACGREGOR A. 1985). It is important to consider that the materials that we study were used in different contexts than their original evolutionary environment, reducing the importance of their original function and making the role of taphonomy much more important (see paragraph 3.3). Bones are remarkable living tissues, continuously adapting and growing alongside the animal's development, thanks to their widely recognized degree of plasticity. The concept of Wolff's law or "bone functional adaptation" (KIVELL T.L. 2016; AMSON E., BIBI F. 2021), proposed already in the late nineteenth century, perfectly explain the bones adaptations throughout an animal's life and it asserts that bone structure has the capacity to adjust and adapt in response to the mechanical forces experienced by skeletal elements throughout an individual's lifetime. This is one of the reasons why bones undergo different modifications and repairs *in vivo*, according to the animal's needs (physiological or pathological). For example, excessive workload may lead to the deposition of new bone at the point of stress, and in the event of a fracture, the tissue may repair itself; or, differently, changes due to physiological processes, such as pregnancy and breastfeeding, can lead to the reabsorption of mineral salts in bones (DE GROSSI MAZZORIN J. 2008). However, once the circle of life ceases, and the creature passes away, the bones enter a static state, pointing to the moment of death. Archaeologists encounter these lifeless skeletons during their work, and due to the prolonged period since death, these bones show distinct physical characteristics and chemical compositions compared to those of living bones. Anyways, the qualities that make these materials suitable for specific purposes are still closely related to their original skeletal function. This is why archaeologists can approach the most disparate texts and manuals about anatomy, histology and physiology of bones, applied or not to the world of the archaeological remains, to study their composition (even better, if there is the chance, addressing also a zooarchaeologist for all of the matters mentioned in this chapter). Just to mention a few among the most important of these manuals: RYDER M.L. 1969 is a handbook for beginners interested in the identification of domestic mammals' bones from archaeological sites; SCHMIT E. 1972 is one of the most famous manuals specifically dedicated to European vertebrates' anatomy; BARONE R. 1980 (and its recent edition of 2006) can be of particular importance for the anatomical identification of domestic animals; BROTHWELL D.R. 1981 gives archaeologists a knowledge about the proper excavation, preparation and analysis of skeletal remains (mainly humans, but it can be helpful also for the study of other mammals); DAVIS S.J.M. 1987 created a complete overview of the "archaeofaunal" remains' potentiality; as well as O'CONNOR T. 2000, DE GROSSI MAZZORIN J. 2008, BEISAW A.M. 2013 and many others. Anyhow, since we're talking of a material that it's being studied by a variety of disciplines, being the focus of plenty of contemporary researches, I preferred to combine the reading of these manuals with the most recent scientific articles to write this chapter.

Taking all of this in consideration, the understanding of the nature and characteristics of the raw material used is crucial to know what choices and logics were followed by ancient men. Hence, I provide in this chapter a concise examination of the structural and mechanical characteristics of bone, where the focus lies on comprehending the ratio behind the selection of this material and some specific parts of it over the others. Plus, the understanding of its properties and its taphonomy will help to read the ultimate results of this study.

3.1. BONE MORPHOLOGY: STRUCTURE AND PHYSICO-CHEMICAL COMPOSITION

Hard, rigid, yellowish-white, bones are the support for the vertebrates' body and they constitute their skeleton. They are surrounded by soft tissues (especially skin and muscles) and enables the animals to move, providing areas for muscle insertion. They protect vital organs like the brain, heart, and lungs, but also produce blood cells and release them into the circulatory system, to maintain a constant internal chemical composition of the body. Additionally, bones act as a reservoir of calcium and phosphorus salts, regulated by hormones, to keep their concentration in the body fluids and be readily available for the organism's needs (BARONE R. 2006). While fulfil all these functions, bones work inside a fascinating process of continuous development, where each element has a specific purpose. *Ossification* is the name that describe the process of transformation of non-bony tissue into bone tissue and it is the result of different complex phenomena (DESCHLER-ERB S. 1998; BREELAND G., SINKLER M.A., MENEZES R.G. 2023). These processes happen in an intricate architecture, that can be read according to different scales and hierarchical levels of organization (RHO J.-Y., KHUN-SPEARING L., ZIOUPOS P. 1997; WEINER S., WAGNER H.D. 1998, BUSS D.J. *et alii* 2021; HAMANDI F., GOSWAMI T. 2022). Indeed, a combination of techniques with different resolution is required to reveal the material structures and properties at the many different length scales (RHO J.-Y., KHUN-SPEARING L., ZIOUPOS P. 1997; DESCHLER-ERB S. 1998).

3.1.1. MAJOR COMPONENTS

The basic composition of bones revolves around the dynamic interaction between organic and inorganic elements, creating an optimal balance of strength, flexibility, and resilience. Specifically, in the sub-nanostructure (RHO J.-Y., KHUN-SPEARING L., ZIOUPOS P. 1997), the combination of a mineral phase (70%), represented by carbonated hydroxyapatite (HAC) crystals, and an organic phase (30%), represented by collagen (CO) molecules, non-collagenous proteins, bone cells, and water with different percentages (HAMANDI F., GOSWAMI T. 2022), yields an exceptionally robust and durable framework (see paragraph 3.2.), intricately linked within a structured three-dimensional arrangement.

In detail, three are the primary constituents:

1. Collagen is the basic building block. It is a fibrous protein also found in skin, tendons, and various soft tissues, as it is one of the main components of extracellular matrix in the animals' body. Actually, there are 29 known types of collagen, among which type I collagen, the one we find in bones, is the most widely investigated (MA C. *et alii* 2021). Within the animal body, this collagen typically adopts a fibrous structure, and the

disposition of collagen fibres varies across different tissues, aiming to fulfil the different mechanical requirements of the body and create a suitable cellular environment (SHOULDERS M.D., RAINES R.T. 2009). Type I collagen stands out due to its fibrous nature, composed of three polypeptide chains (one α2-chain and two α1-chains), each consisting of approximately 1000 amino acids, mainly glycine (GLY), proline (PLY), and hydroxyproline (HYP). These chains are coiled together in a triple helix, forming a cylindrical molecule with an average diameter of around 1.5 nm and lengths reaching 300 nm. The triple-helical molecules are staggered by about 68 nm, creating a spatial separation of approximately 35 nm along the longitudinal axis (WEINER S., WAGNER H.D. 1998). This intricate fibril configuration results in a lack of radial symmetry within the internal structure, manifesting distinct characteristics in all three orthogonal directions. These fibrils congregate to shape arrays of aligned structures, collectively constituting larger entities referred to as fibres. Notably, the arrangement of fibrils within a fibre may vary from one tissue to another, thereby influencing the material's mechanical attributes (ORGEL J.P.R.O *et alii* 2006; HAMANDI F., GOSWAMI T. 2022).

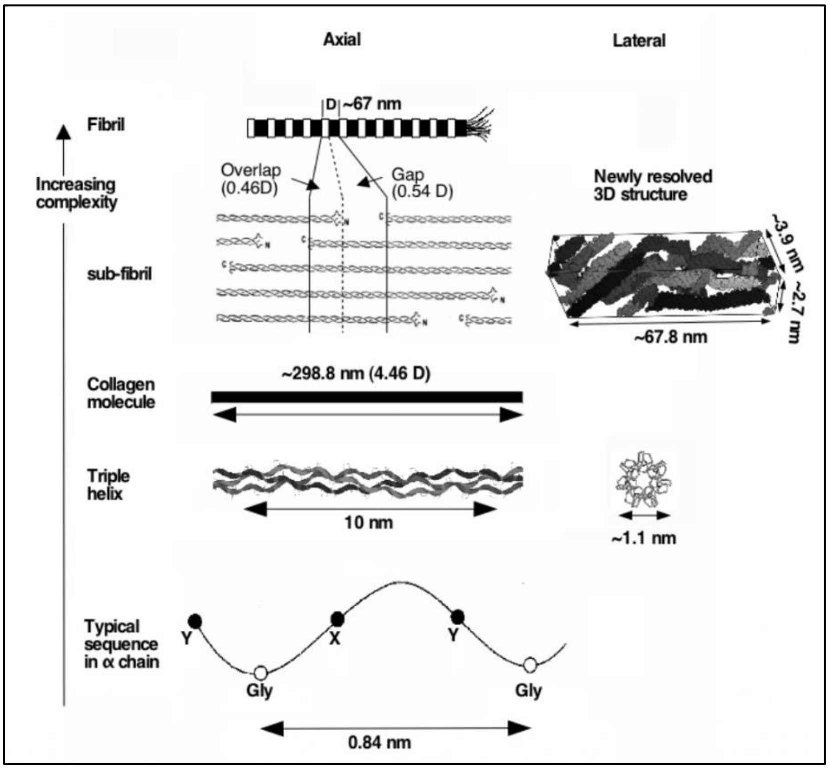
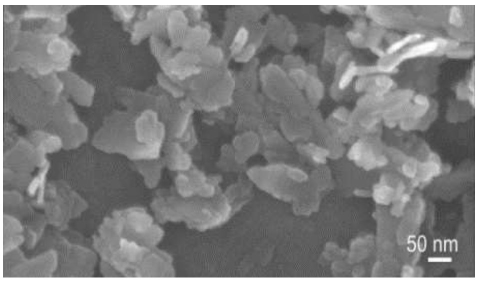


Fig. 22 – Summary of the general organization of type I collagen (ORGEL J.P.R.O et alii 2006).

2. The apatite mineral is the second key constituent (PASTERIS, J.D., WOPENKA B., VALSAMI-JONES E. 2008). It is a complex calcium phosphate that is the basic mineral component of a number of composite biomineralizations: mammal bones and teeth

(including enamel and dentin), ivory, brachiopod's shells, and several pathological human and animal mineralizations (calculi, stones). It is a carbonate-substituted form of geologic hydroxylapatite [$Ca_5(PO_4)_3OH$] containing traces of F, Na, Mg, Zn and Sr (PASERO M. *et alii* 2010; KENDALL C. *et alii* 2018). Variations in composition arise due to the structural replacement of phosphate groups with [CO_3] groups, as well as extensive substitutions of monovalent anions. Table 2 shows a compilation of the most prevalent phosphate-based mineral species sharing the apatite-type structure (ARTIOLI G. 2010). Although the fundamental building block of mammalian bones and teeth is carbonated hydroxylapatite (or dahllite), the Table 2 underscores the potential for significant crystallochemical substitutions. The carbonated hydroxylapatite is characterized by plate-shaped crystals of slight thickness (1.5–4 nm, as shown in Fig. 23). The small size of these crystals, along with substitutions and surface adsorbed ions in the non-apatitic hydrated layer covering the core, leads to disordered crystallinity and greater solubility compared to geologic apatites. The *in vivo* chemical composition and crystal structure of bioapatite are controlled by metabolic processes in order to fulfil specific functions, as well as to regulate physical properties, such as solubility, thermal stability and crystal size. These influencing factors can be collagen properties, non-collagenous proteins, diet, disease, cell viability, and bone turnover (KENDALL C. *et alii* 2018). Among the measurable properties of bioapatite, crystallinity is an extremely meaningful indicator of bone preservation, in the case of fossil bones and of integrity, in the case of fresh bones (DAL SASSO G. *et alii* 2018)



Mineral	Composition	Notes
Hydroxylapatite	$Ca_5(PO_4)_3OH$	
Fluorapatite	$Ca_5(PO_4)_3F$	
Chlorapatite	$Ca_5(PO_4)_3Cl$	
Dahllite	$Ca_5(PO_4,CO_3)_3OH$	Carbonate-hydroxylapatite (also called collophane). Basic constituents of human bones and teeth
Francolite	$Ca_5(PO_4,CO_3)_3F$	Carbonate-fluorapatite (also called collophane, dehrnite, or lewistonite)
Alforsite	$Ba_5(PO_4)_3Cl$	
Pyromorphite	$Pb_5(PO_4)_3Cl$	
Strontium-apatite	$Sr_5(PO_4)_3OH$	
Fermorite	$Ca_5(PO_4,AsO_4)_3OH$	
Belovite	$(SrNa,La,Ce)_5(PO_4)_3OH$	

Fig. 23 (left) - Scanning electron microscope image of plate-shaped crystals of bone carbonate hydroxyapatite (REZNIKOV N., SHAHAR R., WEINER S. 2014). Table 2 (right) - The most common chemical end-members and solid solutions of the apatite group mineral (ARTIOLI G. 2010).

3. Water, the third major element, is closely intertwined with these components, and it resides within the fibril structure, within gaps, and among the triple-helical

molecules. Additionally, it occupies spaces between fibrils and fibers. It has long been known that the mechanical properties of bone are strongly dependent on its hydration state (NYMAN J.S. *et alii* 2006).

Therefore, within the composite structure of bone, collagen acts as a framework, whereas bioapatite crystals serve as reinforcement between the collagen helices. The final outcome of the combination of the three major elements, plus other non-collagenous organic proteins, is the mineralized collagen fibril (MCF), composed of layers of plate-shaped crystals that extend across the fibril's cross-section, having that this arrangement strongly depends on the internal organization of the collagen triple helices (ORGEL J.P.R.O, PERSIKOV A.V., ANTIPOVA O. 2014). As a result, the fibril lacks radial symmetry and instead boasts an orthotropic, fundamentally crystalline arrangement (REZNIKOV N., SHAHAR R., WEINER S. 2014) (fig. 22). Proportions vary according to the different bone tissue, and they can significantly differ across different members of the skeletal materials family. In particular, the arrangement of these foundational elements into more complex structures varies, serving as the distinguishing factor among different entities within the bone family of biological materials (WEINER S., WAGNER H.D. 1998).

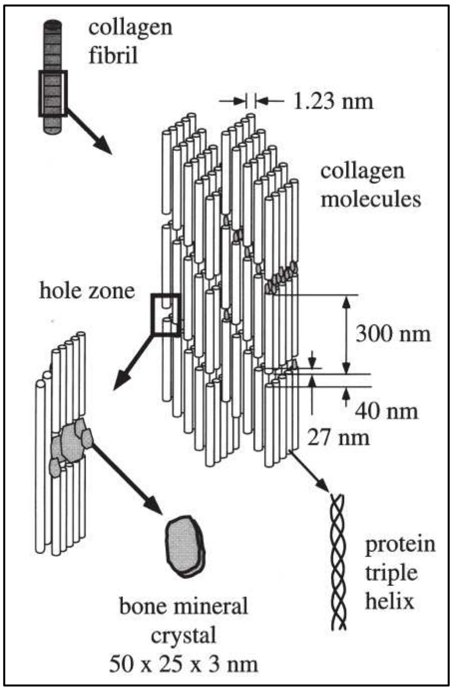


Fig. 24 - A schematic diagram illustrating the assembly of collagen fibrils and fibers and bone mineral crystals (RHO J.-Y., KHUN-SPEARING L., ZIOUPOS P. 1997).

3.1.2. BONE TISSUE ORGANIZATION

The different MCFs, in turn, are bundled into larger organized fibrils, which are grouped into even larger mineralized fibres. They are organized in various forms and patterns (unidirectional, fanning, etc.), where there is a distinction between an “ordered material” and a “disordered material” (fig. 25). MCFs are found in different proportions and arrays in these materials. The disordered material can be found as thin layers between the aligned collagen fibril arrays, but can also be found as relatively extensive layers (REZNIKOV N., SHAHAR R., WEINER S. 2014). Therefore, it is not only a space-filler between the ordered arrays, but it houses the whole lacuno-canalicular network of bone and thus may play an important role in mechano-sensing and mineral homeostasis (REZNIKOV N. *et alii* 2015).

Among these mineralized collagen matrix arrangements, the bone cells (osteocytes) are organized. Specifically, there are three categories of bone cells:

- Osteoblasts, the bone forming cells, responsible for generating bone tissue and secreting the bone matrix. Once fully enveloped and confined by this matrix, their synthesis ceases, transforming them into osteocytes.
- Osteocytes, the primary constituents of mature bone tissue.
- Osteoclasts, sizable cells tasked with the breakdown of bone tissue via the process of bone resorption.

The osteocytes that originate from osteoblasts are located in cavities known as osteoplasts or bone lacunae. Osteocytes have thin cytoplasmic extensions that extend through the intercellular substance and communicate with each other through canaliculi (KERSCHNITZKI M. *et alii* 2011) (fig. 25). The continuous remodelling of bone is traditionally attributed to activity of both osteoclasts, the bone resorbing cells and osteoblasts, the bone forming cells (PALUMBO C., FERRETTI M. 2021).

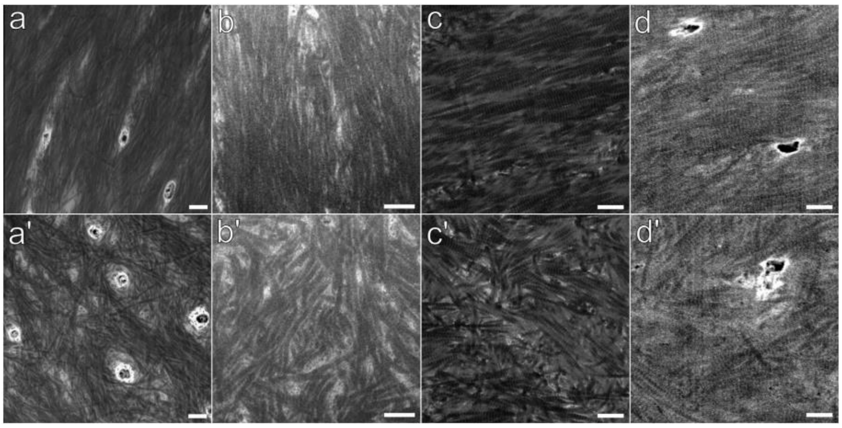


Fig. 25 - Selected images in 'serial surface view" (SSV) (a method that exploits the capability of the focused ion beam (FIB) scanning electron microscope (SEM) to sequentially cut thin (ca. 10 nm) slices off an embedded block and image the block face) of ordered and disordered materials in lamellar bone. Scale bars: 1 micron. Four pairs of images were taken from rat circumferential lamellar bone (a, a'), human cortical osteonal (b, b') and circumferential lamellar bone (c, c'), and human trabecular lamellar bone (d, d'). Each pair was selected from one continuous SSV volume and the two images in each pair are separated by 0.5–1.0 microns (REZNIKOV N., SHAHAR R., WEINER S. 2014). Osteocytes are also visible, especially in a, a' and d,d', and they are the semi-circular bright cells intricated between the fibres.

At this level we can definitely talk about tissues, as products of cellular activities, and in particular about lamellar and woven bones, the two most common structural materials in bones. The woven bone is composed of mineralized collagen fibril bundles that have little or no preferred orientation in three dimensions. By contrast, the collagen fibrils in lamellar bone (the most common structural element in mammalian bone) are grouped in finer bundles of about 3-7 microns of diameter and are arranged in distinct layers or lamellae. Each lamella contains both the ordered material and the disordered material with its embedded canaliculi (REZNIKOV N., SHAHAR R., WEINER S. 2014) (fig. 26). Depending upon when and where the bone forms, the lamellae adopt several different structural motifs in addition to the circumferential lamellar motif. In some cases, these lamellae of mineralized collagen fibres wrap in concentric layers (3–8 lamellae) around a central canal, twisting (BUSS D.J. *et alii* 2021) to form what is known as an osteon. The osteon looks like a cylinder about 200–250 mm in diameter running roughly parallel to the long axis of the bone (RHO J.-Y., KHUN-SPEARING L., ZIOUPOS P. 1997). Osteons are commonly categorized as primary or secondary osteons, with the latter also known as Haversian systems. Primary osteons differ from the secondary ones mainly because they do not have a cement line, that is the outer layer of the secondary osteon. Secondary osteons result from bone remodelling and are prevalent in mature skeletons, particularly of large animals. The secondary osteons, or Haversian systems, are cylindrical structures about 100–200 microns in diameter with a central canal of some 30–40 microns diameter (REZNIKOV N., SHAHAR R., WEINER S. 2014). In the past, Haversian canals (longitudinal) and Volkmann's canals (transverse) were treated as separate entities. Yet, advanced micro-computerized tomographic reconstructions revealed their strict association, highlighting that they constitute a unified system (COOPER D.M.L. *et alii* 2003). Finally, this system of osteons forms the so-called Haversian bone tissue, which it's found, in different manners, in two of the most commonly found types of bone tissue in adult mammals, classified according to their size and density:

- Cortical bone, also referred to as compact or dense bone, presents as a solid, unbroken structure characterized by minuscule pores. This tissue possesses great mechanical strength (FUCHS R.K., WARDEN S.J., TURNER C.H. 2009), with its Haversian systems exhibiting a consistent, cylindrical arrangement that runs parallel to one another. Each of these osteons encompasses a slender central canal known as the Havers' canal, housing a small quantity of specialized connective tissue (referred to as Haversian bone marrow) and being traversed by extremely delicate blood vessels and nerves. Encircling the central canal, the concentric arrangement of bony lamellae can be observed (fig. 27). The bone cells, or osteocytes, primarily align themselves between the lamellae in distinct concentric rows. In the central segment of elongated bones, the orientation of osteons mirrors the bone's major axis, aligning precisely with the direction in which compressive and tensile forces are applied to the bone (see paragraph 3.2.).
- Cancellous (also known as spongy or trabecular) bone, which gets its name from its porous and honeycomb-like appearance, and it is composed of short, dilated, and irregular osteons (REZNIKOV N. *et alii* 2015). The Haversian canals are represented by labyrinthine or honeycomb-shaped cavities that communicate with each other. The bone lamellae surrounding these cavities join with others to form trabeculae (fig. 26), oriented to maximize the mechanical efficiency of the bone (BARONE R. 2006).

It is the combination of compact and spongy material in a bone that allows maximum strength and at the same time minimum weight (DE GROSSI MAZZORIN J. 2008), forming a perfectly composed organ. The fig. 26 shows the bone's hierarchical structure just described in details.

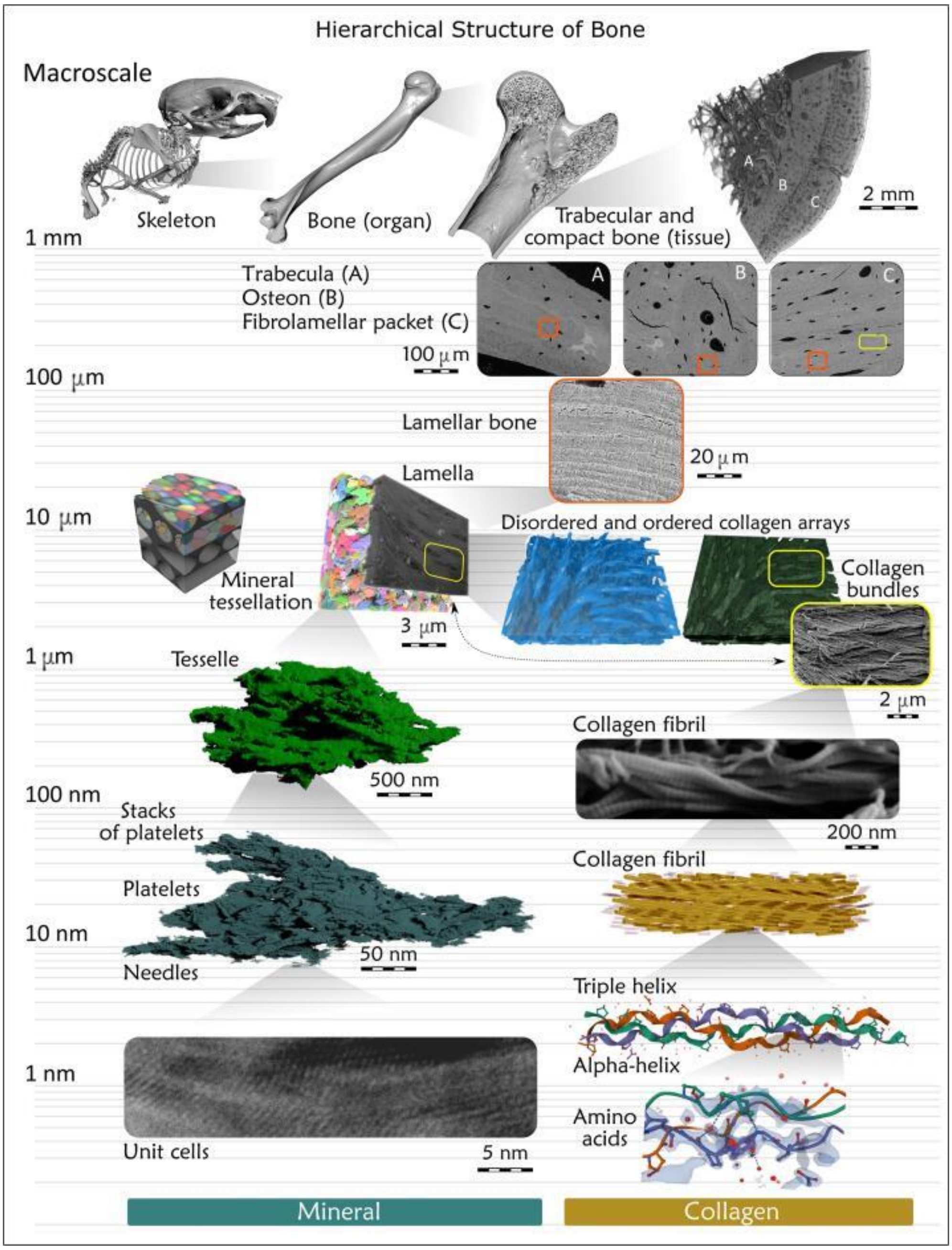


Fig. 26 - Contemporary understanding of the hierarchical structure of bone. The levels were intentionally not numbered, because the cascade of hierarchical levels splits at the micrometer level for organic and inorganic matter, and because same-level mineral and collagen units have different shapes and even scale (for example, the tesselles, and the collagen fibrils, which are both level 9), and also for visual flow and continuity. According to the recent inventory, there are approximately twelve levels: 1) skeletons, made of 2) bones, made of 3) cortical and trabecular tissue, made of 4) cortical osteons, fibrolamellar bone packets, and trabecular lamellar packets, all of which contain 5) lamellar bone, made of 6) lamellae, made of 7) ordered collagen motifs that form 8) bundles, surrounded by the disordered collagen motif. The bundles are made of 9) collagen fibrils, made of 10) triple helices, made of 11) alpha-helices, made of 12) amino acids. The mineral organization in 3D shows its own hierarchical organization starting at level 8) of mineralized collagen bundles, that contain 9) tessellated prolate ellipsoids of mineral, made of 10) mineral platelets, made of 11) laterally merging acicular crystals, made of 12) unit cells (BUSS D.J., KRÖGER R., MCKEE M.D., REZNIKOV N. 2021).

The topographical distribution of compact and spongy bone is well defined within the different bones that make up the skeleton. Actually, bones are divided, according to their shape and the ratio of width to thickness, into flat bones (skull, scapula, pelvis and ribs), long bones (most of the limb bones, such as the femur and humerus), short bones (the vertebrae and the carpal and tarsal bones) (DE GROSSI MAZZORIN J. 2008) and irregular bones (such as plate scapula) (fig. 36). The cortical bone is primarily found along the medial part (diaphysis) of long bones (fig. 27), the petrous pyramid (at the base of the skull) and the mandible, and as a thin outer cover at the ends of long and flat bones; whereas the cancellous bone is found at the jointed ends (epiphysis) of long bones, as flat plates in the cranium, sternum, and ilium, and underlying tendon attachments (KENDALL C. *et alii* 2018). Generally, the long bones provide structural support for the motor system and support body movement, whereas the flat, short, and irregular bones can fill and protect the body (such as the skull) and help the body complete life activities more flexibly and efficiently (such as sesamoid bone). Considering long bones in particular (the most used in Roman bone craftsmanship, see paragraph 4.3.1.), these have a cylindrical appearance, and have the mechanical function of bearing the weight of the body. They are anatomically divided into three parts: a medial part or diaphysis, the ends (proximal and distal epiphyses), and a connecting part between the epiphysis and diaphysis, called the metaphysis (fig. 27). Each of these parts possesses a distinct composition of bone tissue. The diaphysis, where the cortical bone is particularly prominent, forms a hollow cylindrical structure enveloped by robust walls composed of compact bone tissue (forming the cortex), encompassing a central canal housing the bone marrow (FUCHS R.K., WARDEN S.J., TURNER C.H. 2009). It reaches its maximum thickness around the midpoint and gradually tapers as it extends towards the ends, where it becomes notably thin and dense over the articulating surfaces of the joints. On the contrary, the epiphyses are comprised of spongy bone tissue, encased at its edges by a layer of cartilage known as articular cartilage (see paragraph 3.1.3., BARONE R. 2006). The gaps between the trabeculae within the spongy tissue connect directly with the central medullary cavity of the diaphysis, housing marrow and, in mature bones, adipose tissue. Bridging the diaphysis and the epiphysis is the metaphysis, characterized by a columnar arrangement of spongy tissue, establishing a connection between these two main segments.

3.1.3. CONNECTED TISSUES

There are other tissues connected with the main bone tissue that need to be mentioned. To start, inside many of the bone’s cavities (the central marrow cavity, Haversian canals, and the areolae of the spongy bone tissue) there is the bone marrow (fig. 27), a highly vascularized connective tissue, that is more abundant in the spongy bone tissue compared to compact bone, as there are more active exchanges with the blood in this region (NOMBELA-ARRIETA C., MANZ M.G. 2017; WEI Q., FRENETTE P.S. 2018). Specifically, there are distinct *foramina* (specific holes) designated for nerves and nourishing blood vessels to pass through. These openings also serve the purpose of connecting with the blood-producing red marrow present within the flat bones like the skull, sternum, ribs, and in the spongy ends of long bones. In contrast, the medullary cavity within the long bone diaphysis of mammals is primarily filled with yellow marrow, which consists mainly of fat (MACGREGOR A. 1985). In their outermost level, bones are covered (except for the joint surfaces and muscle and tendon insertions) by a fibrous membrane: the periosteum (fig. 27). This membrane is composed of dense connective tissue with fibres mainly crossing bone in a longitudinal direction. In addition to its normal osteogenic functions during growth, the periosteum may be stimulated to produce new bone in order to repair damage, or in response to demands from the muscles or tendons for more secure anchorages (DESCHLER-ERB S. 1998).

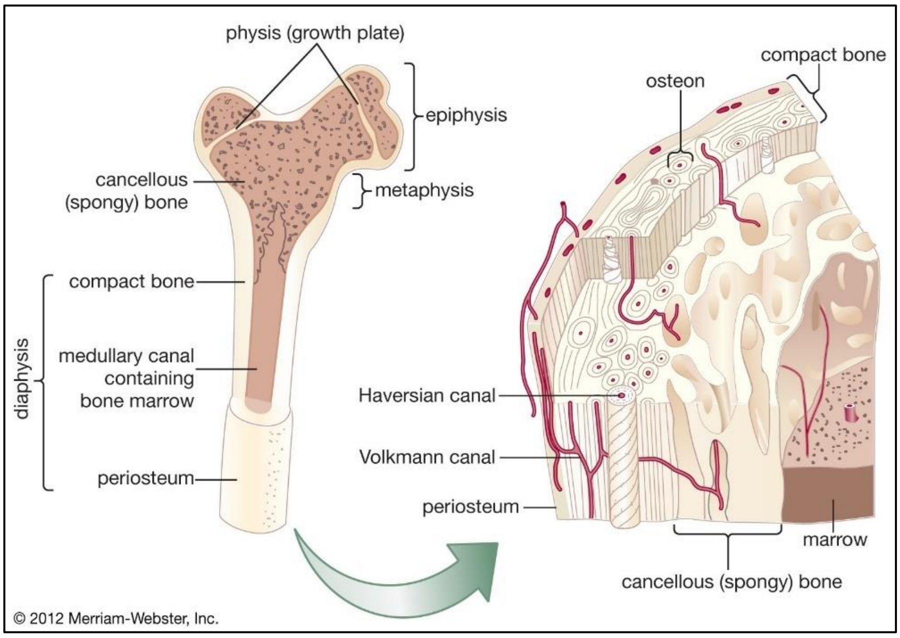


Fig. 27 - Internal structure of a long bone, with a magnified cross section of the interior (https://www.britannica.com/animal/mammal/Skeleton#/media/1/360838/66017).

Also, the true environment of development of many bones is the cartilage tissue. Indeed, bone formation often begins with a preliminary cartilaginous structure, serving as a fundamental template for subsequent bone tissue development (MACKIE E.J. *et alii* 2008). This cartilage framework gradually undergoes replacement by bone, except for specific regions of cartilage that are intentionally left unossified, either temporarily or permanently. These regions give rise to conjugate cartilage and articular cartilage, which are not supplementary or external elements of bone, but intrinsic components (BYERS P.D., BROWN R.A. 2006). The cartilaginous tissue is composed of a flexible matrix rich in chondrocyte cells and collagen fibres. Without blood vessels, it depends on the diffusion of nutrients. Cartilages are usually enveloped by a thin layer of connective tissue called the perichondrium, except for the articular cartilages that overlay joint surfaces and integrate with bone, showcasing a sleek and glossy appearance (BARONE R. 2006). Last but not least, as already said, bones have also an important hemopoietic function, and their blood vessels and nerves are numerous. So, I will just mention here the different types of arteries:

a) The main one is the nutrient artery (also called diaphyseal), which penetrates through a specific hole called the nutrient *foramen*, and it's present in each skeletal segment, except in short bones. It follows a characteristic oblique path through the nutrient canal, reaching the marrow cavity in long bones or the centre of the spongy tissue in other types of bones. It branches finely to supply blood to the marrow and spongy tissue, anastomosing with other bone arteries and forming a continuous vascular network. The finer branches reach the canals of compact bone.
b) Smaller arteries, called epiphyseal arteries, penetrate the ends of long bones or the periphery of other bones. They branch into the spongy tissue and contribute to the vascular network described above.
c) Periosteal arteries, very thin and numerous, penetrate the periosteum, forming a network. Their branches enter the bone through small third-order holes to reach the deep vascular network, which sends capillaries into the Haversian canals.

Veins generally run alongside arteries, creating a more intricate internal network. While true lymphatic vessels are not found within bone tissue, but perivascular sheaths exist, potentially serving similar roles. Nerves mainly accompany arteries, with fewer present in compact bone than in spongy bone. Notably, the periosteum, unlike bone tissue, does contain true lymphatic vessels and it is abundantly supplied with nerves, enhancing its sensitivity relative to other bone components (BARONE R. 2006).

Of course, there is significant diversity among the bones of various species and understanding their distinctive characteristics holds immense value in the examination of bone artifacts. Even in cases where the overall shape of the bone is not informative, a skilled observer can discern subtle hints that might enable the recognition of the bone's composition or even the specific species involved (MACGREGOR A. 1985) (fig. 28).

Fig. 28 - Foramina *preserved in a bone* applique *carved as a theatrical mask, III-IV century AD, Museo Egizio, Turin (GHIRINGHELLO C., TRAPANI M. 2019)*

3.2. MECHANICAL PROPERTIES

From the previously provided histological explanations (see paragraph 3.1.), it becomes evident that it is the exceptional coordination of each component (organic and inorganic) that make skeletal tissues such remarkable structural substances. Bone material can actually be considered an uneven and anisotropic composite, since its components have completely different properties (MACGREGOR A. 1985; WEINER S., WAGNER H.D. 1998). Composites are actually materials that are composed of two or more different components, and they are commonly used in engineering and industry where the combination of the two (or more) materials creates a composite with properties that are superior to those of the individual components. So, despite its organic nature, bone can frequently be analysed using principles similar to those applied to human-engineered materials, exhibiting, however, greater variability in measured characteristics, depending on the age, the gender, the location in the body, the temperature, the mineral content, the amount of water presents and the eventual diseases (SKEDROS J.G. *et alii* 2006; MORGAN E.F., UNNIKRISNAN G.U., HUSSEIN A.I. 2018). Also, studies can be made across the different levels of skeletal materials (see paragraph 3.1.), because distinct microstructural elements, such as individual fibrils or lamellae, have dissimilar behaviour compared to bone at the larger tissue or organ level (PAHR D.H., REISINGER A.G. 2020).

Most researches on bone mechanics have been carried out for biomedical, rather than archaeological purposes. Archaeologists with an interest in bone artefacts usually take advance of these researches and use the methods proper of other disciplines to demonstrate the conditioning factors which determined the choice of some skeletal materials in preference to others (MACGREGOR A. 1985; SCHEINSOHN V., FERRETTI J.L. 1995, MARGARIS A.V. 2009; PFEIFER S.J. *et alii* 2019). Generally, bones are tough and resistant to fracture, providing a significant contrast, for example, to lithic media, that tend to be brittle (BRADFIELD J. 2015). As a result, osseous materials offer a more complex framework than stones for examining how raw material properties influence technological organization (MARGARIS A.V. 2009). In addition, their anisotropic structure means that their mechanical properties must be considered in two orthogonal directions: longitudinal, that is the usual direction of loading (i.e. parallel to osteon alignment); and transverse (i.e. at right-angles to the long axis of the bone). Not considering the actual geometry can lead to significant inaccuracies in modulus calculations (MORGAN E.F., UNNIKRISNAN G.U., HUSSEIN A.I. 2018), especially considering the anisotropic nature of bone materials and the potential slight variations in stress intensity across the bone. In fact, the benefit of this configuration lies in the ability to attain higher unit strengths in directions that typically experience maximum loads compared to what could be achieved with an equivalent volume of isotropic material. For instance, woven bone, with its less aligned structure, might possess a lower ultimate strength than laminar bone but will exhibit more consistent performance when faced with stresses from multiple directions. This characteristic makes woven bone appropriate for developing bones where the direction of maximum stresses can alter during growth (MACGREGOR A. 1985).

So, the bone strength is affected not only by its composition but also by bone mass, geometry, and microstructure (MORGAN E.F., UNNIKRISNAN G.U., HUSSEIN A.I. 2018). Plus, long bones in particular (WEINER S., WAGNER H.D. 1998) experience bending moments during typical loading and this generates both tensile and compressive stresses in various sections of the bone. The response of biological tissues to mechanical loads is usually described as the relationship between the size-independent measures of mechanical stress and strain (PAHR D.H., REISINGER A.G. 2020). The stress exerted on a solid represents the outcome of the applied load or force divided by the cross-sectional area of the material. This means that at any given point within the material, stress = load/area. This equation holds true for both compressive and tensile stress. Strain is instead an expression of the proportion by which a material is extended (or compressed) under stress, represented by the formula: strain = increase in length/original length. So, for a certain strain stimulus that is imposed, the material is reacting with stress response and vice versa. This response is intrinsic to the material and generally depends on the magnitude, the rate, the direction, the duration, and the number of repetitions of the imposed stimulus (PAHR D.H., REISINGER A.G. 2020). Usually, the relationship between stress and strain for any given material can be expressed in the form of a graph (fig. 29).

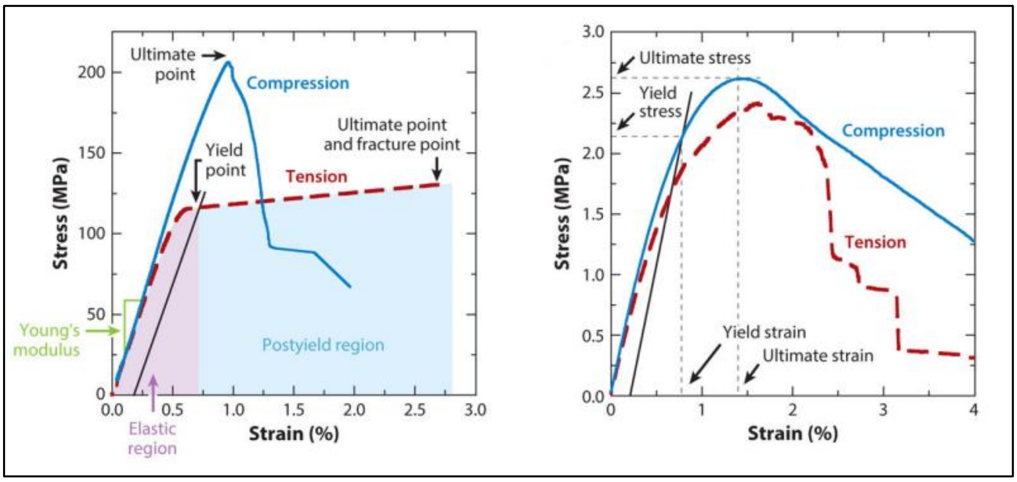


Fig. 29 - Stress–strain curves for (left) cortical bone tested along the longitudinal direction and (right) trabecular bone tested along the principal direction. The panels show monotonic tests in tension and compression annotated with some basic material properties (modified from MORGAN E.F., UNNIKRISNAN G.U., HUSSEIN A.I. 2018). Monotonic (or quasi-static loading) is a single load to failure test and measures the mechanical response of bone during elastic deformation and failure. It is the simplest and commonly used approach for determining the mechanical properties of bone.

When the increase in stress within certain limits produces a proportional increase in strain, the ratio of stress to strain, as expressed by the slope of the straight line (fig. 29), is a constant, known as the elastic Young's modulus or Young's modulus of elasticity (E). Hence, elastic modulus = stress/strain. Young modulus is effectively a measure of stiffness (not the same of strength): the less the deformation for a given load, the stiffer the material (MACGREGOR A. 1985).

Moreover, another valuable indicator of material properties is the bending strength, that possesses the benefit of relatively straightforward establishment and the level of precision required in creating test samples is notably lower for the bending test (BAILEY S., VAHISHTH D. 2018). However, due to the more intricate forces at play compared to a simple tensile or compressive test, the outcome cannot be considered equivalent to the ultimate stress and it is termed as the modulus of rupture (MACGREGOR A. 1985).

To sum up, the mechanical properties of osseous raw materials are usually determined by two variables: stiffness (Young's modulus of elasticity) and longitudinal bending strength. So, researches can measure these values to have an idea of the reasons why ancient people chose bone instead of other osseous (or not) materials to produce specific tools. For example, according to this connection between functional-gestural tool class and selected raw material, PFEIFER S.J., WILD M. 2016 analysed the mechanical properties of well-preserved osseous assemblages from north-western Central Europe to understand the continuity/discontinuity in the general choice of raw materials for certain tool types in the Pleistocene/Holocene transition. Despite certain method-related variations, their findings led to the conclusion that, in that period, striking tools (that have to withstand impacts) were exclusively produced from antler, with antler being also the primary material for barbed tools (which served as hunting tools whose function was to remain inside the hit prey or to hook to it), while bone was favoured for perforating tools. Antler is quite easy to deform as shown by a rather low modulus of elasticity, whereas mammal bone is substantially stiffer, which contributes to this preference. So, instead of migrating reindeer herds, more sedentary taxa provided antler and bone, and hunter-gatherers were able to adapt to the non-availability of previously favoured raw materials (PFEIFER S.J., WILD M. 2016).

We can state that one important variable in determining the mechanical properties of archaeological osseous materials is their dry or wet state (Table 3). Additionally, the distinctions in bending strength identified between the longitudinal and transverse axes hold greater practical significance. We can have an example of this in the composite comb assembly method, for which, in most cases, the antler surface was aligned horizontally for side plates and vertically for tooth plates (fig. 20, h). This is because the dry material is stiffer in the long axis than across the grain. Furthermore, the preference for antler over bone is attributed to its significantly superior ability to absorb sudden shocks and impact loads (an ability that originally comes from their resistance to the impact loads to which they are subjected during combat). This quality proves especially valuable for the teeth of combs as they endure the strain of navigating through tangled hair (MACGREGOR A. 1985).

	species	element	status	Modulus of elasticity [GPa]	Bending strength [MPa]	Reference
antler	*A. alces*	beam	?	11.8	-	Blob and Snelgrove, 2006
	C. canadensis	beam	dry	7.6 ± 0.3	197.3 ± 24.0	Chen et al., 2009
	C. canadensis	beam	hydrated	7.0 ± 0.3	145.1 ± 9.0	Chen et al., 2009
	C. elaphus	beam	dry	7.4	179.4	Currey, 1979
	C. elaphus	beam	dry	13.6	342.8	MacGregor and Currey, 1983
	C. elaphus	beam	hydrated	7.2	158	Currey, 1990
	C. elaphus	beam	?	10	250	Currey, 1999
	C. elaphus	beam	?	5.3	81.9	Landete-Castillejos et al., 2007
	C. elaphus	beam	dry	7.5	115.4	Chen et al., 2008
	C. elaphus	beam	dry	17.5 ± 0.5	352.2 ± 8.8	Currey et al., 2009
	R. tarandus	beam	hydrated	6.4	-	Currey, 1988
	R. tarandus	beam	hydrated	8.1	95	Currey, 1990
	R. tarandus	beam	hydrated	5.8 ± 0.4	-	Shah et al., 2008
	R. tarandus	beam	hydrated	6.0 ± 1.0	130 ± 20.0	Margaris, 2009
	R. tarandus groenlandicus	beam	dry	5.0 ± 1.0	336.6 ± 43.0	Krey, 2013
mammal bones	*Bos sp.*	femur	hydrated	26.1	238	Reilly and Burstein, 1975
	Bos sp.	femur	hydrated	13.5	-	Currey, 1979
	Bos sp.	femur	hydrated	26.1	148	Currey, 1990
	Bos sp.	femur	hydrated	22.4	263	Currey, 2009
	C. capreolus	femur	hydrated	18.4	150	Currey, 1990
	C. elaphus	femur	hydrated	15	250	Margaris, 2009
	D. dama	radius	hydrated	25.5	213	Currey, 1990
	Eq. caballus	femur	hydrated	21.2	-	Currey, 1988
	Eq. caballus	femur	hydrated	24.5	152	Currey, 1990
	H. sapiens	femur	hydrated	16.7	166	Currey, 2002
bird bones	*A. patagonicus*	ulna	?	22.9	193	Currey, 1999
	G. antigone	tibiotarsus	?	23.5	254	Currey, 1999
	Phoenicopterus sp.	tibiotarsus	?	28.2	212	Currey, 1999

Table 3 - Published experimental data for antler and long bone of different species using standard bending tests. Unknown parameters: " ? "(PFEIFER S.J., WILD M. 2016).

These findings have significant importance in enhancing our understanding of these materials. Ultimately, they shed light on the ratio behind specific manufacturing decisions made by the Nora artisan(s) studied in this dissertation (refer to chapter 6). These artisans possessed an 'intuitive' understanding of the material's capabilities and limitations, acquired through close observation of its behaviour in both routine and exceptional situations. Such intuition could be the result of a lifetime dedicated to keen observation, with the eventual cumulative wisdom passed down through preceding generations.

3.3. AFTER DEATH: TAPHONOMY

When the animals' life ends, the taphonomic history of its bones starts. This history is about the processes that generate, modify and destroy faunal remains during the post-mortem, pre- and post-burial. Taphonomic actions change the physical characteristics and distribution of animal carcasses and tissues, and the taphonomic effect is a trace of such a process (LYMAN R.L. 1994). The term taphonomy literally means "laws of burial" (from the Greek terms *taphos*, meaning tomb, and *nomos*, meaning law) and was first coined in 1940 by the Russian palaeontologist Efremov, who defined it as the study of the transformation of animal remains from the biosphere (the living world) into the lithosphere (the mineral world). Within zooarchaeology, the term is frequently understood more broadly than that to encompass the full range of processes that can happen to a bone from the death of an animal to its archaeological recovery and analysis. Some things that happen to bones during that sequence are important evidence of human activity, whilst other processes are natural causes of damage and diagenesis that can destroy, obscure, mimic, or otherwise confuse such evidence (OUTRAM A.K. 2023). The interaction between bone material and its burial environment changes according to different factors, such as the environment's pH level, chemical composition, temperature or humidity (LYMAN R.L. 1994). Then, all the post-mortem physico-chemical mechanisms that modify the structure of bone led to various levels of modifications, including for example changes in porosity, crystallinity or trace element content. Analytical methodologies can characterise the changes induced by diagenesis at each scale of the bone material. In recent years, a lot of methodologies have been developed for this necessity to establish the state of conservation of the archaeological bone material (REICHE I. *et alii* 2007; MÜLLER K., REICHE I. 2011; FONTAN E., REICHE I. 2011). The modifications on osteological material produced by actions of an anthropic nature can be: 1) actions aimed at recovering and consuming parts of alimentary interest (e.g., bone marrow extraction); 2) actions aimed at recovering and modifying bone supports for the production of artefacts (CILLI C., MALERBA G., GIACOBINI G. 2000). Within the particular framework of the archaeozoological record under consideration in this dissertation, the potential of the taphonomic science finds expression through the broader characterization of intentional human actions directed at procuring and altering durable animal materials for the creation of artifacts. This specific taphonomic effect aligns with the category of mechanical modification (LYMAN R.L. 1994) and, in particular, with bone surface modifications made by humans (FISHER J.W. JR. 1995; BRADFIELD J.

2015; FERNÁNDEZ-JALVO Y., ANDREWS P. 2016). Table 4 shows a series of human and nonhuman marks that can modify the archaeological bones, connected to their possible agents. The types of modification are the first evidence observed when paleontological or archaeological collections are made, but there are many processes producing similar types of modification (Table 4). For instance, groove or striation on a bone are forms of modification. However, this particular mark can arise from different sources such as carnivores gnawing, human butchery, damage from trampling, etching from roots, insect activity, bacterial or fungal action, or gnawing by rodents (FERNÁNDEZ-JALVO Y., ANDREWS P. 2016).

Modification	Agent 1	Agent 2	Agent 3	Agent 4	Agent 5
Abrasion	Sediment + water	Wind	Bioturbation	Trampling	Carnivores
Breakage	Humans	Carnivores	Sediment pressure	Trampling	Bioturbation
Cave corrosion	High humidity				
Chop marks	Human	Falling blocks			
Corrosion	Humic acids	Organic acids	Dense low plant cover	Cave humidity	Moss and lichen
Cracking	Weathering	Digestion	Organic acids	Humic acids	Plant roots
Curved ends	Human	Falling blocks			
Deformation/bending	Human	Sediment pressure			
Digestion	Carnivores	Birds	Crocodiles		
Disarticulation	Carnivores	Humans	Trampling	Bioturbation	Weathering
Discoloration: black	Burning	Manganese	Carbon stain	Fungi	
Discoloration: brown	Burning	Humic acids			
Discoloration: light	Burning	Gley soils	Leaching		
Discoloration: red	Burning	Oxydized soil			
Double arch punctures	Human molars				
Enamel loss	Digestion	Corrosion			
Gouges	Carnivores	Birds			
Linear mark U-shape	Carnivore chewing	Pland roots	Insects	Beak marks	Herbivore and rodent gnawing
Linear mark V-shape	Human cut marks	Trampling	Bone tool preparation		
Multiple scrapes	Humans	Trampling	Gnawing		
Notches	Human percussion marks	Carnivores			
Peeling	Human				
Pits	Carnivore	Birds	Insects	Trampling	Plant roots
Polishing	Wind + sand	Water + gravels	Licking	Digestion	
Punctures	Carnivore	Birds	Insects	Plants	Humans
Rounding	Sediment + water	Wind	Digestion	Carnivores	Trampling
Solution marks	Diatoms	Lichen	Algae		
Splitting	Weathering	Digestion			

Table 4 – Taphonomic modifications and the processes and agents by which they are produced (FERNÁNDEZ-JALVO Y., ANDREWS P. 2016)

The discernible marks on the Nora worked bones, observable both on a macroscopic and microscopic scale, are described in details in paragraph 6.2., with the main aim to reconstruct one or more theoretical sequences of operations to produce the bones assemblage object of this study, taking in consideration also all the nonhuman processes that affected the bones surfaces. In this sense, I used a technical approach (LEGRAND A., SIDÉRA I. 2007; KHAN B., PICOD C. 2018; BOISVERT M.-È. 2018), identifying the techniques, the cutting procedures and methods of this specific bone manufacturing. It is an approach usually used with prehistoric artefacts (i.e., ALLARD

M. *et alii* 1997), because of their strong morphological and technical homogeneity, that can answer questions about cultural practices, innovation, relationships between different traditions and transfers from one culture to another. In our case, it is used in a different scenario, where Roman artisans followed an almost "industrial" methodology in cutting bones. Thus, reading the cutmarks on Roman worked bones can be useful to understand the category of instruments that were used and the processes that were implied in the manufacturing (OUTRAM A.K. 2023).

4. Bone as an object: fabrication techniques in Roman times

An artefact's value is a consequence of the makers' ability to interact with their materials. Intertwined factors, which include the perceptions of viewers and users at all levels, the artisans' place of work and the tradition in which they learned their craft are always reflected in the techniques and methods used in the manufacturing (ASHBY S. P. 2011; HOCHSCHEID H., RUSSELL B. 2021). In the context of Classical cultures, it is recognized that the proliferation of bones objects was affirmed thanks to urban development. The city's growth generated groups of various professionals and the distribution of their production to potential clientele. Also, this population regrouping imposed a daily supply of food products, including meat in particular. Hence the presence of butchers, if not a slaughterhouse, as an essential profession for the installation of a bone worker who himself would provide material for other professionals (cutler, carpenter, etc.) (BARBIER M. 2016). This specialised and "sustainable" craftsmanship (SAUTOT M.C. 1978), which involved a good prior knowledge of the source material (as I have already underlined at the beginning of chapter 3), is testified mainly by the fact that today we have plenty of material remains that show really specialized productions for different purposes, that involved a wide range of skills in their production (an example in PICOD C., RODET-BELARBI, CHÂTELET M. 2019). Evidence of certain tools like lathes or fine saws used for cutting comb teeth suggests the ownership of specialized toolkits, irrespective of the skill displayed in using them. On the other hand, some items can be recognized as entirely professional solely based on their quality of craftsmanship or possibly because they used costly raw materials (as it is more common for ivory). Some objects were made for trade, but others were simply crafted as needed, due to their basic and practical nature. For instance, intricate bone pins would have had some value in trade, but few would pay for a crude dress pin made from a pig's fibula when pork was readily available to everyone (MACGREGOR A. 1985). It is to be said, however, that the working of bones very often seems to be regarded as a secondary production cycle. This is due to a problem of perishability of the material and a relative great number of non-perishable materials alternatives, rather than to its actual marginal importance. Also, this is reflected on the fact that for long time bone tools seldom received the attention they deserved from archaeologists, who considered them as less attractive or informative than other material classes (GATES ST-PIERRE C., WALKER R.B. 2007).

It is impossible here to talk in detail about the history of studies on the remains of the bone working in Roman times. I can just mention the fact that it is more or less from the '60 of the last century that new contributions and studies dedicated specifically to this argument started to appear. Initially, they were still linked to an initial intent of typological classification of bone and ivory objects, but, progressively, major attention was given to the production process, analysing in detail the different stages of workmanship on the basis of recognisable remains (among the most important: SCHMID E. 1968; SAUTOT M.C. 1978; BÉAL J.C. 1983; MACGREGOR A. 1985). Since then, numerous studies have followed, examining important batches of material, from archaeological excavations or in collections, providing interpretations for the remains of the workmanship, with great attention paid to the recognition of the raw material used, clearly distinguishing bone from ivory and cervid antler, where possible also by means of laboratory analyses (an example is the work of DESCHLER-ERB S. 1998 for the *Augusta Raurica* site) or, not less important, using an experimental approach (BARBIER M. 2016; MÜLLER H., DESCHLER-ERB S. 2021). Today worked bone studies are on the rise. It is perfectly understood how the reconstruction of the bone working *chaîne opératoire* (ROUX V. 2020; SCHLANGER N. 2005) can lead to the understanding of its dynamic processes, appreciating alongside tools, raw materials, energy and various physical or environmental possibilities. Researchers developed various methodologies and approaches to study these objects: it is clear that these materials are a great source of knowledge, which can provide information about the diet, economy, social life, or craftsmanship (BACKWELL L.R., D'ERRICO F. 2001; MÜLLER H., DESCHLER-ERB S. 2021). To gain a better insight into this "industry", the best method seems to be the study of concentrations of manufacturing waste or items discarded during production due to breakage or other reasons. Since the ancient city of Nora gives us a perfect example of these remains, in this chapter I want to analyse the ancient bone craft production, especially during Roman and late antique periods, from the perspective of the labour, energy, and skills behind it to show that making has a value and that such value is key to objects' use and meaning.

4.1. LITERARY, EPIGRAPHIC AND ARCHAEOLOGICAL EVIDENCES

Even if bone can be a better carving medium over other categories of osseous materials under certain conditions (see paragraph 3.2.) and its craft seems to be very prolific in the Roman times, both Greek and Roman literature rarely mentions it. From these texts, we know that the bone items in use at that time were merely "utilitarian", like pins or implements, fruit knives, grafting tools, medicament containers, and flutes (Pliny, *Nat. Hist*. XI, 87, 215; XVII, 24, 109; Vergil, *Georgics* II, 193; Propertius, *Elegiae* IV, 6, 8; Philostratus, *Life of Apollonius* V, 21; Columella, *De re rustica* XII, 14, 1 and 47, 4; cited by ST. CLAIR A. 2003). The tone of the only authors who talks about bone objects seems to be pretty negative. Pliny the Elder (I century AD) suggests that bone was also employed for more elevated purposes like adorning furniture, although this was considered a last resort: "[R]ecently owing to our poverty even the bones have begun to be cut into layers in as much as an ample supply of tusks is now rarely obtained except from India, all the rest of the world having succumbed to luxury" (*[Q]uamquam nuper ossa etiam in laminas secari coepere paenuria, etenim rara amplitudo iam dentium praeterquam ex India reperitur, cetera in nostro orbe cessere luxuriae*; *Nat. Hist.* VIII, 4, 7, trans H. Rackham; cited by ST. CLAIR A. 2003). Juvenal, writing in the second century AD, further expands the repertory: "So destitute am I of ivory that neither my dice nor my counters are made of it: even my knife handles are bone" (*[A]deo nulla uncia nobis est eboris, nec tessellae nec calculus ex hac materia, quin ipsa manubria cultellorum ossea*, *Satires* XI, 131-134, trans. G.G. Ramsey; cited by ST. CLAIR A. 2003). There is even less information available regarding the craftspeople. It is important to remember that in the Roman world, any craft or manufacturing activity is forbidden to the gentleman, and the craftsman seems to be relegated to the status of a “second-class” citizen. According to Cicero, “the artisan's workshop is not at all compatible with the condition of a free man” and “all artisans practise a low trade” (*De Officiis*, XLII, 150). For Seneca, the craftsman's tasks are “vile” and “vulgar”: “they have nothing to do with the true qualities of man” (MOREL J.-P. 2002).

That said, the specific bone working is documented in very few inscriptions. An example is given by an inscription on a fragmentary tile, dated at the end of III century or the beginning of the IV century AD, found at the Roman fort of Halmyris (Romania). It is an *epistula commendaticia* sent on behalf of *Valerius Valerinus Constans* of *Legio I Iovia,* to his comrade *Hermes,* recommending him a certain *Secundus*. On the obverse, probably the same personage, urges *Valeria* of *Diocletianus* “the one who process the bone objects to give something to the one who is perforating the bones” (RAFAILĂ-STAN S., NUȚU G. 2017). There has been some discussion about its ambiguous meaning, but this is for sure a proof of two bone workers (of both sexes) in the same workshop connected to a military context. We understand that Valeria probably was a simple worker, preparing the raw material and probably being involved in early stages of the processing, like cutting, boiling, etc., and another unnamed figure, a skilled piercer, likely handled final bone product creation (RAFAILĂ-STAN S., NUȚU G. 2017). Apart from this exceptional case, the *eborarii* (the ivory workers), whose work can be easily combined with that of the bone processing, are best known. In Rome in particular, which was the main terminal of the ivory trade routes, the term *eborarius/eburarius* occurs in a number of funerary epigraphs, where the *eborarii* are also qualified as *liberti* (BIANCHI C. 2019). We know a total of thirteen *eborarii* who have left epigraphic evidence of themselves, plus, the collective reality of a professional *collegium* (DI GIACOMO G.

2021). Therefore, it was suggested that also bone workers were included in this term, at least in Rome (OBMANN J. 1997). However, the role of these professionals is not very clear, as the term indicates both the craftsman in charge of working or the owner or master expert of a workshop dedicated to the production of ivory objects, or, according to other interpretations, the trader who traded in raw materials and artefacts on a large scale. Plus, there are more specific terms that relate to specific professional titles:

- The *faber eborarius* (CIL VI, 33423) or *eboris faber*, that is more precisely the craftsman dedicated to the working of ivory (Horace, *Epistulae* II, 1, 96: [...] *marmoris aut eboris fabros aut aeris amavit* [...]);
- The *politor*, namely the material polisher, that could be indicative of a division of labour within the same workshop or between different workshops;
- The *eborarius negotiator*, the ivory trader, which is not clear if it was about the trade of raw materials or finished products or both (BIANCHI C. 2019). An example is given by the figure of *M. Consius Cerdo*, on whose altar of the Augustan age appears an elephant carrying baskets with ivory tusks (CIL VI, 16077, from the *Via Appia*). It was together with at least other three *liberti*, *Antiochus* (AE 1990, 76) and *Dionysius* (CIL VI, 37793), belonging to the same gentilitian family, that he was probably implied, between the end of the Roman Republic and the beginning of the imperial age, in the trade and the working of ivory in the city of Rome (NONNIS D. 2007; DI GIACOMO G. 2021).

Moreover, an interesting epigraph, that was found on a marble slab in Trastevere (Rome), contains the *lex collegi* (CIL VI, 33885), that refers to a part of the statute of a *Collegium of negotiatores eborarii and citriarii*, datable to the Hadrianic age (fig. 30). It is about a prescription, which emphasises the exclusive nature of this association, in which only the members who practised the *ars citriaria* or the *ars eboraria* were admitted. The two arts were actually closely interdependent because they were vertically integrated in the same production and commercial chain of the luxury industry: the *citriarii* produced tables, beds and other furniture carved in *citrum* (Plin. nat. 13, 95), the precious wood of tuja imported from Mauretania, while the *eborarii* completed and finished these furnishings with the creation of legs, feet or slats, which were then applied to the body of the artefacts (BIANCHI C. 2019; DI GIACOMO G. 2021). Furthermore, it is topographically interesting how in Rome among the epigraphs relating to *eborarii*, some were found in the area between *Porta Salaria* and *Porta Pinciana*, while in other two instances (CIL VI, 7655; 9645) the term *eborarius* is combined with the term *ab Hercule primigenio* or *primogenio* (NONNIS D. 2007; PANELLA C. 2015; DI GIACOMO G. 2021). It is possible that this implies a connection between the worker and a cult, in which the functional aspect was probably important

(WOJCIECHOWSKI P. 2013), but it is equally likely that the statue or building mentioned was simply a convenient topographical marker, indicating the location of the craftsperson or workshop, approximately located outside the Servian Wall, along the *Via Salaria* (DUMSER E.A. 2020).

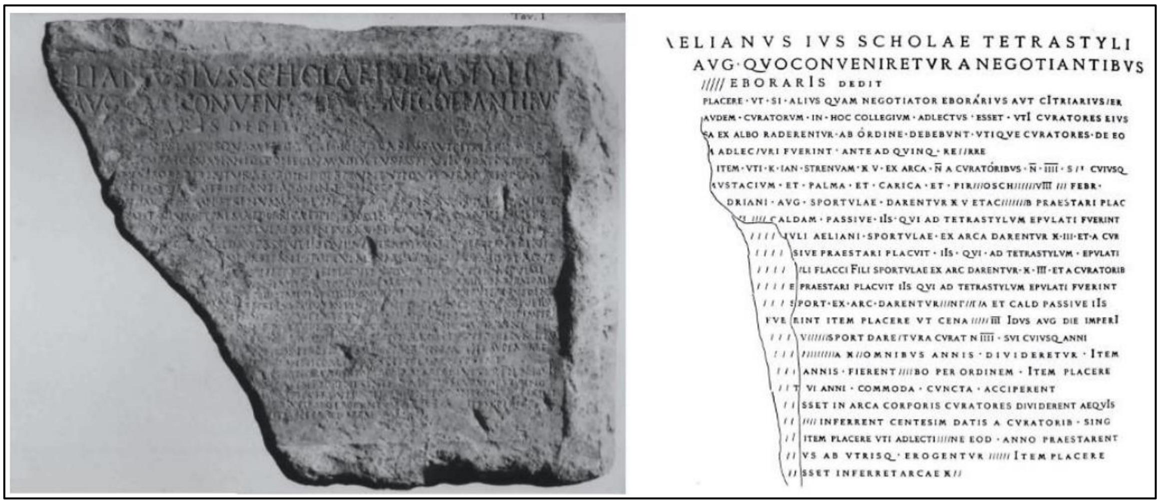


Fig. 30 - Epigraph with the statute of the collegium *of* negotiatores eborarii *and* citriarii *found in Rome (CIL VI, 33885, cited by* BIANCHI *C. 2019).*

It is also interesting to notice that even if the individuals mentioned in these inscriptions are male, it would not be surprising if craftspeople were of both sexes, as we have previously seen for Valeria in Halmyris, given that bone working could also be practiced as a household skill. Actually, also Pliny (*Nat. Hist.* XXXV, 40, 147-148) mentions a woman, Iaia of Cyzicus, who engraved images on ivory in addition to working as a painter in Rome (ST. CLAIR A. 2003). We cannot be sure, however, that these *eborarii* also worked "normal" bone or just ivory and if this professional term covered all bone working activities (LANG F. 2011). Nevertheless, there is evidence (see paragraph 4.2.) that in cases of artisanal production, in the same area, bone, a much cheaper and widely available material, could also be worked together with ivory, which could be used for the same types of objects, such as beds, pyxis, pins.

As concerns the artisans' activities and specific techniques of bone working, only Plutarch, I-II century AD, briefly mentions the use of ashes and vinegar to aid in wire sawing bone, but he doesn't provide specific details about the method, such as whether these materials were used separately or mixed, or any specific soaking times (*ὡς γὰρ ἡ κρόκη τὸ ὀστέον πρίει τέφρᾳ καὶ ὄξει διάβροχον γενόμενον, καὶ τὸν ἐλέφαντα τῷ ζύθει μαλ ακὸν γενόμενον καὶ χαλῶντα κάμπτουσι καὶ διασχηματίζουσιν, ἄλλως δ' οὐ δύνανται [...]; An vitiositas ad infelicitatem sufficia*, 4, ed. Loeb, trans. W.C. Helmbold, London, 1954, pp. 499-500, cited by BÉAL J.C. 1983). More detailed information is provided by a number of treatises dating back to the Middle Ages and dedicated to the different sectors of artistic production, which however must obviously be considered with caution due to the risk of the interference of data dating back to the time of their compilation. Heraclius (VIII century AD) in his treatise *De coloribus et artibus Romanorum*, chapter *Quo modo dirigitur et ornatur ebut* (III, 19) (GARZYA ROMANO C. 1996) mentions some methods of workability and decoration of ivory, but particular mention should be made of the treatise attributed to Theophilus (XII century AD), *De diversis artibus*, in particular the chapters *De sculptura ossis* about the bone carving and *De rubricando osse* (III, 93-94) concerning the red staining of bones (DODWELL C.R. 1961). Also, according to BARBIER M. 2016, we can find some incorrect information in an illustration of Diderot et D'Alembert's *Encyclopédie* (fig. 31). In the picture we can see a worker (a) in the background, preparing rods for turning rosary beads, whereas the one in the front (b) is removing the muscular residues.

Fig. 31 – Bone working from the Encyclopédie by Diderot et D'Alembert (cited by BARBIER M. 2016).

Experimentation has however revealed the impracticality of performing series of cuts, as the man in the background is doing, by using indirect percussion on a horizontally positioned diaphysis, especially when the bone still retains its epiphyses. On the other hand, longitudinal splitting with the diaphysis vertically oriented on a block (man b) can be realized. The only problem is that in this way you will obtain fragmented and largely unusable pieces with a substantial material loss (BARBIER M. 2016).

Because of this scarcity of written information about the specific bone working, pretty unusual for the Classical times, we must rely on the archaeological remains to reconstruct how this type of production took place. This manufacturing is represented by the discovery of more or less substantial scraps of raw material (usually the ends of long bones and parts of their diaphyses), residues of processing, which may show traces of roughing and shaping of the artefacts, and finished objects showing advanced stages of working on their surface (RODET-BELARBI I. 2018). Among these materials, distinctions can be made between the raw material reserves set aside for future processing, the sketched objects that help us to read the various phases of the production process, the scraps due to errors or breakages, and finally the leftovers of unused material (BIANCHI C. 2019). In the Mediterranean areas, these findings are widely documented in many centres throughout the course of the Roman era, and in particular during the Imperial age (BIANCHI C. 2019). From the late I and early II century AD onwards, production centres emerge in almost every Roman province. Archaeologists must therefore recognise that the craftsman, with his products and services, occupies a place in the Roman world that he might not have suspected if he had confined himself to reading ancient authors, leafing through the corpus of Latin inscriptions, or to most museums.

4.2. BONE WORKSHOPS AND CRAFTSPEOPLE

The discovery of working waste or unfinished artefacts can suggest the presence of a *in situ* or close-by workshop for crafting this material. Most of the time we do not have information about their architectural structure, because we find materials remains as dumps or secondary deposits (MORONI M.T. 2008; CHOYKE A.M. 2012). However, the studied archaeological contexts show that the processing of bones could be done almost anywhere, both *intra* and *extra muros* (RODET-BELARBI I., LEMOINE Y. 2010; BELDIMAN C. *et alii* 2014; KOVAČ M. 2016), since it did not require complex structures, but only a few working tools, easily transportable, and possibly water to soften and mould the work material (PANELLA C. 2015). One main suggestion is that bone working was usually associated with other crafts (OBMANN J. 1997; KHAN B. 2014). According to LANG F. 2011, this is the reason why written sources about this craft are almost lacking. Thus, we should not consider bone working as a proper profession, because it is more likely that a craftsman or a workshop was working different raw materials than different workmen specialized in certain raw materials were collaborating with each other. Anyhow, it's reasonable to hypothesize that this type of craftsmanship could rely on other types of working processes, which used more complex structures, possibly exploiting their equipment (see the case of the *Collegium of negotiatores eborarii and citriarii* in the previous paragraph). For example, in various places, such as Colchester (England) (CRUMMY N. 1981), Gloucester (England) (CRUMMY N. 2001), Limoges (France) (VALLET C. 1994), Amiens (France) (THUET A. 2008), waste pieces have been found probably intended as applied ornament on wooden furniture. Also very interesting is the case of Autun-*Augustodunum*, where a building known as the "Maison aux Artisans" was used during the I century AD for working together bronze, horn and bone (fig. 32) (RODET-BELARBI I., CHARDRON-PICAULT 2005). The combined work of bones and metals was found in many other places, such as the late antique city of Agrigento (Italy) (PARELLO M.C. 2018), the sanctuary of Gué-de-Sciaux (France) during the late I and early II century AD (BERTRAND I., SALIN M. 2010) or in *Iuvanum*/Salzburg (Austria), where bone working was connected with iron working and it probably existed a workshop of smiths, where also the bone handles of knives were produced (LANG F. 2008).

In the city of Rome, in the famous big dump in the exedra of the *Crypta Balbi* (GIANNICHEDDA E., MANNONI T., RICCI M. 2001; VENDITTELLI L., RICCI M. 2015), datable to the

VI-VII century AD, it has also been suggested that some of the iron tools found, such as burins, could be used precisely for processing bones, which artefacts and waste remains have been found in the same context (fig. 33). We can also think about different organisational forms, from a network of collaborations between neighbouring specialised workshops to a cooperation between different craft skills within single large workshops (PANELLA C. 2015). Not to forget the fact that the iron saw blades' precision was crucial for the bone working, favouring precision and speed of cutting for industrial productions that heavily relied on the ability to replicate actions consistently and swiftly (BARBIER M. 2016).

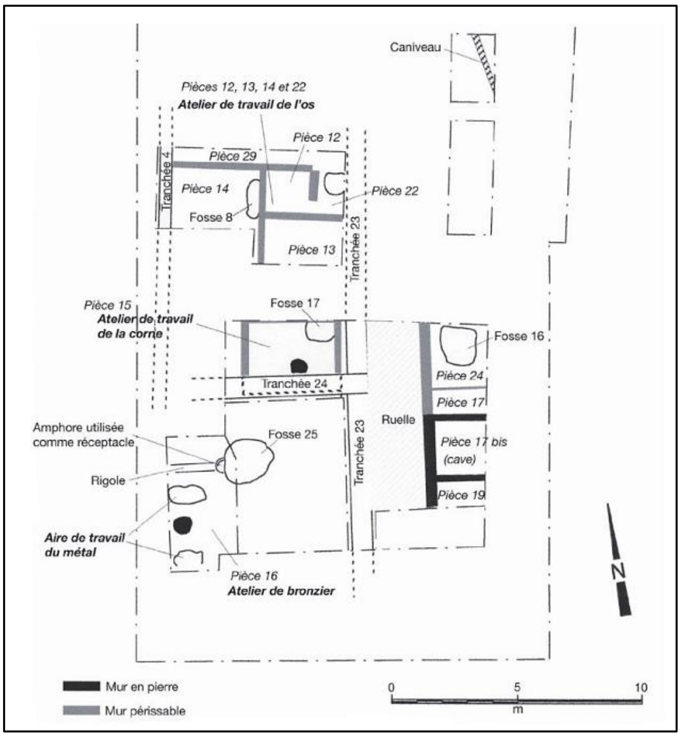


*Fig. 32 - Plan of the bone and horn workshops in the "Maison aux Artisans" in Autun-*Augustodunum *(RODET-BELARBI I., CHARDRON-PICAULT 2005).*

Fig. 33 - Smoothed bone and horn plates with saw marks and various metal elements in bronze and iron from the Crypta Balbi atelier *in Rome (GIANNICHEDDA E., MANNONI T., RICCI M. 2001).*

In the big cities it seems that bone working could be found even in central areas, where, as I already said, the proximity and possible collaboration with other crafts has been frequently attested. Rome gives the perfect example of this central organization (BIANCHI C. 2019), that is also found, for example, in Alexandria, the other centre of production of bone and, especially, ivory objects that spread throughout the Hellenistic world. Here we can see how the workshops were arranged in series along a north-south road axis, where, thanks to their proximity to important public monuments, they enjoyed advantageous trading opportunities (RODZIEWICZ E. 2016). Consequently, from the evidence emerging in the two most illustrious centres, Rome and Alexandria, we can confirm that the bone craft wasn't for sure a secondary craft, neither in terms of the location of the facilities nor the quantity and quality of the objects produced (BERTRAND I. 2008).

Still, evidences of the rooms where this activity was carried out are very rare. This lack of evidence cannot only be due to the randomness of the archaeological discoveries, but must be attributed to the very characteristics of these workshops, which could be installed in very simple environments, unlike other craft productions such as glass and metals that required much more complex installations (e.g. melting furnaces), which left more evident and lasting traces. BIANCHI C. 2019 made two main considerations about these places:

1. These artisans needed open spaces for the storage and preliminary treatment of bones, i.e., the bones from the slaughter areas. This type of structure helped to avoid odours and hygiene problems for civil society.
2. Bone working could occur within rudimentary architectural settings, including compact rooms with only few floors, probably even in semi-open areas with canopies. It might have been necessary to have tanks for boiling or simple preliminary washing of the bones.

They were therefore 'light', ductile and easily transferable working systems, also due to the simplicity of the tools used, with which high production levels were achieved thanks to the skill of the craftsmen (BIANCHI C. 2019).

Other evidences go towards a potential alternative framework for the bone-processing activity, different from the "stable" workshop organization model. These include self-production and seasonal or part time nature of the craft (OBMANN J. 1997; FROSDICK R. 2008; JUNG P. 2013). Some artisans were undoubtedly specialists and this can be confirmed when we encounter for example accumulations of bone blanks, partially shaped items and completed objects in the same context. They could be either professionally engaged in their work, or fulfil the needs of a largely rural population with a small stock-in-trade and manufacture on demand (MACGREGOR A. 1985). An example of great specialization can be already seen in the Classical Greece, V century BC, with the case of Pheidias and his significant sculptural work. The excavation of Pheidias' workshop at Olympia, where the magnificent chryselephantine statue of Zeus was created, significantly enhanced the understanding of both the statue's form and the creative process (MALLWITZ A., SCHIERING W. 1964; LAPATIN K. 2001). This discovery yielded valuable insights into the materials and techniques employed in crafting the statue, as well as the physical environment in which Pheidias meticulously worked on the image, as described by Pausanias (*Description of Greece*, V, 15, 1). The building, sharing the same alignment and dimensions as the temple's cella (32.18 x 14.5 meters), likely served as the location for at least assembling the statue. It contained two metalworking forges and a large bronze cauldron used as a water container, functioning partly as a foundry (MALLWITZ A., SCHIERING W. 1964). Work on the statue extended beyond this building, possibly in nearby or temporary open structures. Discoveries outside its walls included ivory and bone-carving debris, tools, terra-cotta molds for shaping glass drapery, glasswork fragments, various materials like rock crystal, quartz, obsidian, ebony, and amber, bronze remnants, iron, lead, chalk, pumice, gypsum, and scrap metal. The bone-carving debris comprised discarded metapodial articular ends (fig. 34), mostly from cattle but occasionally from sheep and goats, sawn bone sections, and partially worked scapulae (shoulder blades). Blanks included preliminary bone shafts and roughly shaped bone sections. Additionally, there was evidence of lathing debris. The site yielded finished bone tools with one spatulate and one pointed end, varying in size, with smaller examples also found in bronze. These seem to be styles used for writing and smoothing wax tablets, but they were likely tools for engraving and smoothing. Several complete bone leaves and a partial fragment, featuring ornamental palmette designs, suggest that bone was also employed for decorative purposes, potentially on the figure's throne. Additional bone mounts, such as disks and partially preserved turned cylinders, are also associated with furniture (ST. CLAIR A. 2003).

Fig. 34 – Phidias' ergasterion *bone remains at the Archaeological Museum of Olympia (photos by J. Bonetto).*

Besides these civilian activities, there seems to have been a degree of production both for and by the military (see the example of the inscription from the fort of Halmyris in the previous paragraph). An example is given by the Roman fort of Iža-Leányvár (Hungary) (HRNČIARIK E. 2017), where 254 artefacts made from bone and antler has been attested. Among these, there are objects that were part of the Roman military equipment, such as sword hilts, scabbard chapes and pieces of bone inlay of a composite bow, as well as parts of soldiers' clothing represented by bone rings and fittings from a military belt (*cingulum*). The fort could be supplied by both artisans *in situ* manufacturing simple tools and Pannonian workshops, such as the ones in the nearby *Brigetio* area (HRNČIARIK E. 2017). In this sense, NUȚU G., STANC S.M., STAN A. 2014 made an interesting analysis of the workshops from the Lower Danube, where most of them were discovered along the *limes* in military milieus. Whereas in the north-western provinces, an extensive armorers' workshop was found at Caerleon, Gwent (BOON G.C. 1972), where it is attested the production of bone scabbard chapes and splints for composite bows. Objects like sword hilts might have been crafted in comparable situations, for example at Augst in Switzerland, where SCHMID E. 1968 observed that long-bone shafts were consistently used to make handles, alongside other non-service materials like hinges and pins.

We can understand how this craft was organized in different manners according to the different places' traditions, which vary greatly between the eastern parts of the Roman empire's territory and the western and northern ones. However, the social order's disruption accompanying the decline of the Roman rule would have undoubtedly deprived most settled craftsmen of their regular customer base. It is possible that during this period, the bone industry, which persisted for centuries afterward, was predominantly sustained by traveling or itinerant craftsmen, as it is testified in England by CRUMMY N. 2001.

4.3. FABRICATION TECHNIQUES AND INSTRUMENTS

As I wrote in paragraph 4.1., the consultation of written sources for the description of trades close to bone making, in order to check whether certain techniques had persisted, is not the most beneficial. Nevertheless, several observations can be made in order to better understand Roman bone artefacts' manufacture, for example, studying semi-finished products and factory waste, observing their working traces, adding collaborations between researchers and professional bone artisans (BÉAL J.C. 1983; MACGREGOR A. 1985; DESCHLER-ERB S. 1998; BARBIER M. 2016).

As concerns the instruments used by the craftspeople, they are only partly suggested by the traces left on the finished objects. In other words, they're virtually unknown a part from rare examples (MÜLLER H., DESCHLER-ERB S. 2021). They are not found in excavations, perhaps linked to bone remains in a workshop setting, either because archaeologists may not recognize their true function or because certain metal fragments are not correctly identified as working tools. Experimentation has revealed that these instruments are generally small and delicate, and therefore, lacking the original wooden handle and potentially distorted by oxidation, might be incorrectly categorized as scrap metal (BARBIER M. 2016). Alternatively, they might have been utilized for working different materials, not just bones, or it is also possible that the craftspeople may have been part-time or migrant artisans who carried their tools with them, leaving only the partially finished products and waste behind (MÜLLER H., DESCHLER-ERB S. 2021). In the next sub-paragraphs, I will try to describe the range of the hypothesized craftsmen's tool kit and the principal methods they employed in working raw materials, following the overall *chaîne opératoire.*

4.3.1. RAW MATERIAL SELECTION

The first step of the *chaîne operatoire* relates to the choice of which animals and specific skeletal elements use for crafting bone tools. This choice seems to have been shaped by a dynamic interplay of various factors, that would have included the availability of certain bones, the suitability of the shape of the skeletal element, its fracturing properties and the cultural beliefs regarding the qualities associated with certain bones and animal species. The ready accessibility of bones in most of the Roman Empire territories likely played a significant role in promoting its use, as there would have rarely been a scarcity of raw materials to meet the requirements of both professionals and casual users. According to various archaeozoological studies, these bones come almost exclusively from large domestic herbivores, most often adults, as they are the largest and widest animals available in large numbers, being bred for their meat, their draught power or their ability to travel long distances. These species, which almost constantly had to bear considerable weight, either their own or that of loads imposed on them, developed thick, robust bones. For sure, beef (*Bos taurus*) was the animal of reference for bone craftsmen throughout the Roman Empire and beyond (DESCHLER-ERB S. 1998; DE CUPERE B. 2001; DE GROSSI MAZZORIN J. 2012). Various other species served as sources of raw material, albeit in smaller quantities and with variations depending on the region. For example, DESCHLER-ERB S. 2010 noted that in the Gallo-Roman territories craftsmen preferred to work with equine bones, despite the difficulties of supply and their rather inferior quality compared with that of beef. Even in Rome the use of horses' bones has been documented by GIANNICHEDDA E., MANNONI T., RICCI M. 2001; CHOYKE A.M. 2012; DE GROSSI MAZZORIN J., MINNITI C. 2012. In Pergamon (Turkey), for instance, horses constituted one-third of the bones discovered in the processed materials. DESCHLER-ERB S. 2010 and DE GROSSI MAZZORIN

J. 2012 highlight the fact that their long bones, prized for their thickness and shape, were especially valuable for crafting, though obtaining them from slaughterhouses might not have been straightforward due to the limited use of these animals for food. Antler, from red deer (*Cervus elaphus*) or roe deer (*Capreolus capreolus*) was another popular raw material, preferred because of its flexible structure, especially in certain provinces rich in forests (VASS L. 2010; RAFAILĂ-STAN S., NUȚU G. 2017). Even camelid bones were utilized, as evidenced by the findings in the excavations at ez-Zantur in Petra, Jordan. It also seems that not only were long camelid bones fashioned, primarily to create rings, but also the shoulder blades were repurposed as shovel heads (STUDER J., SCHNEIDER A. 2008; KHAN B. 2014). Another example is given by the bone *atelier* found in Petra, in the Qasr al-Bint *temenos*, where to produce rings and pins even bones from the Camelidae family were used (KHAN B. 2014). However, other animals used could be pigs (*Sus domesticus*), sheep (*Ovis aries*), goats (*Capra hircus*) and even chickens (*Gallus gallus*) (DE GROSSI MAZZORIN J. 2012; STUDER J. 2013), but their use was done to a much lesser extent (due to their bones smaller dimensions and, consequently, exploiting possibilities), so they don't correspond to the Roman production's generalities. Local butchering and food processing traditions for sure narrowed which bones remained available for working. In the cities, there probably was a close circuit of relationships between the carvers' workshops and the slaughterhouses, where other craftsmen such as leather tanners and glue manufacturers were also supplied (DE GROSSI MAZZORIN J. 2012). This is confirmed by the absence of skeletal elements other than long bones or already sawn bone pegs in the artisanal deposits, sign of a predetermined acquisition of raw material. Epiphyses with discarded technical marks found in fairly large quantities in the deposits indicate a fairly large supply. A relatively organised system must therefore have been put in place to collect the raw material from the butcher or abattoir so that the craftsmen could be supplied, probably on an almost continuous basis. In the case of horn and, above all, ivory, which were available in much smaller quantities, it is plausible that they sourced their supplies on an order-by-order basis, due to the preciousness of these materials and their much more limited accessibility. An interesting place where easily raw materials were found could be also the sanctuary, where it is possible that the meat of animals slaughtered on site during sacrifices was partly sold or exhibited in the sacred buildings. We can imagine artisans being regular visitors and, in addition to performing religious acts, some of them collected raw materials there. This has been hypothesized for example in the sanctuary of Gué-de-Sciaux (France) during its late I and early II century AD (BERTRAND I., SALIN M. 2010), but we should consider that bones were often burnt with the meat in the shrines.

However, it's important to remember that bone isn't a uniform material, as discussed in chapter 3, and its utilization was a selective and purposeful process. Even if there was a thriving bone-working industry nearby, it's likely that most bones were judged as unsuitable by craftsmen and disregarded. They chose the raw materials they handled with great care, searching for a certain format for a standardised production: each workshop seems to have made only a small number of types of objects, between four and five different ones (DE GROSSI MAZZORIN J. 2012). Actually, the big size of long bones was no longer an obstacle for crafting even small elongated items (punches, pins, needles, etc.) because these objects could now, with the use of precise iron blades, be directly fashioned from the bone itself, allowing for mass production and wider availability. While in the past it wasn't so easy, as these tools, for example, were extracted by grooving with a flint chisel or they were fitted on fractured diaphysis (BARBIER M. 2016).

During Roman times, long bones (see paragraph 3.1.2.), in particular, metacarpals and metatarsals (fig. 36) were the most commonly used, having little flesh and marrow and being destroyed to a lesser extent by butchers (LIGNEREUX Y., PETERS J. 1996; DE GROSSI MAZZORIN J. 2012). On the contrary, there is evidence to suggest that craftspeople made minimal use of elongated, flat, and short bones due to their composition and limited versatility. These bones were mainly employed for specialized purposes, often justified by their ideal shape, such as the creation of items like fish hooks, which could be crafted from the scapular spine. Alternatively, these bones were occasionally used for crafting low-quality objects. Among these three morphological types, ribs (elongated bones) and scapulae (flat bones) are the segments most frequently employed, for example for the creation of slabs for lining purposes (BARBIER M. 2016; BIANCHI C. 2019). The use of certain type of bones instead of others indicate that the artisans were familiar with the material and its properties, choosing the best material for specific productions. BARBIER M. 2016 made a clear description of the exploitable areas of the different types of bones, which I will not report here completely, but rather focus on the radio and ulna segment, since it is the most testified bone in the Nora workshop (see paragraph 6.1.). With an average length of 11/12 cm, the radius shaft offers versatility due to its relatively regular shape, offering various crafting possibilities. Its oval cross-section with slightly concave and convex faces allow for efficient cutting with minimal waste. According to BARBIER M. 2016, the most favourable crafting area accounts for only about a

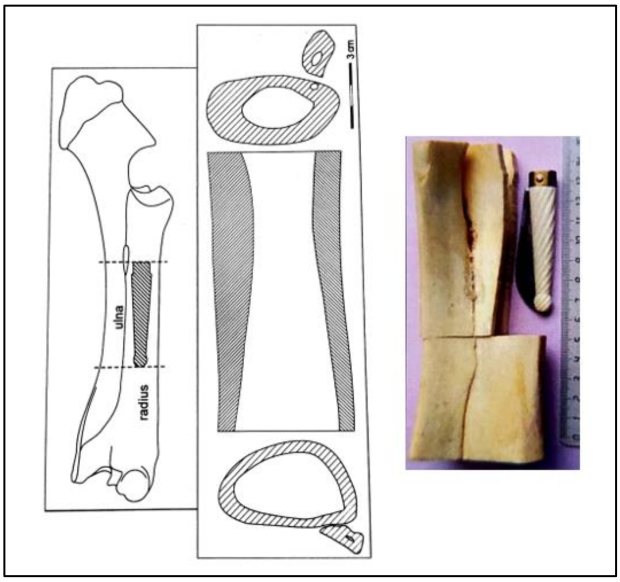


Fig. 35 - Possible utilisation of bovine's radius and ulna for the production of spiral knife handle (modified from BARBIER M. 2016).

quarter of its length (fig. 35 and 36). The thicker proximal end (8 to 10 mm) provides opportunities for creating plates used in crafting pyxis lids, tokens, spindles, or spoons. Additionally, this side face can be turned into rods for crafting elongated objects such as pins, needles, and punches (we will see that this is our case). The medial and lateral edges are also thick, with the latter being even thicker (ranging from 15 to 20 mm arcuate proximally to 7 to 9 mm distally). These areas can be used for crafting small handles, dice, turned pin nipples, and certain types of belt buckles. The artisan however should be choosing between sawing a plate (from the lateral face) or sawing a rod (from the caudal edge), as one action may negate the other. Regarding the ulna, it's considered a "secondary" segment, and its usability depends on the animal conformation. The ulna's small diameter and pronounced curvature limit its use, with only a few centimetres available for crafting specific items (see an ulna awl in GIANNICHEDDA E., MANNONI T., RICCI M. 2001).

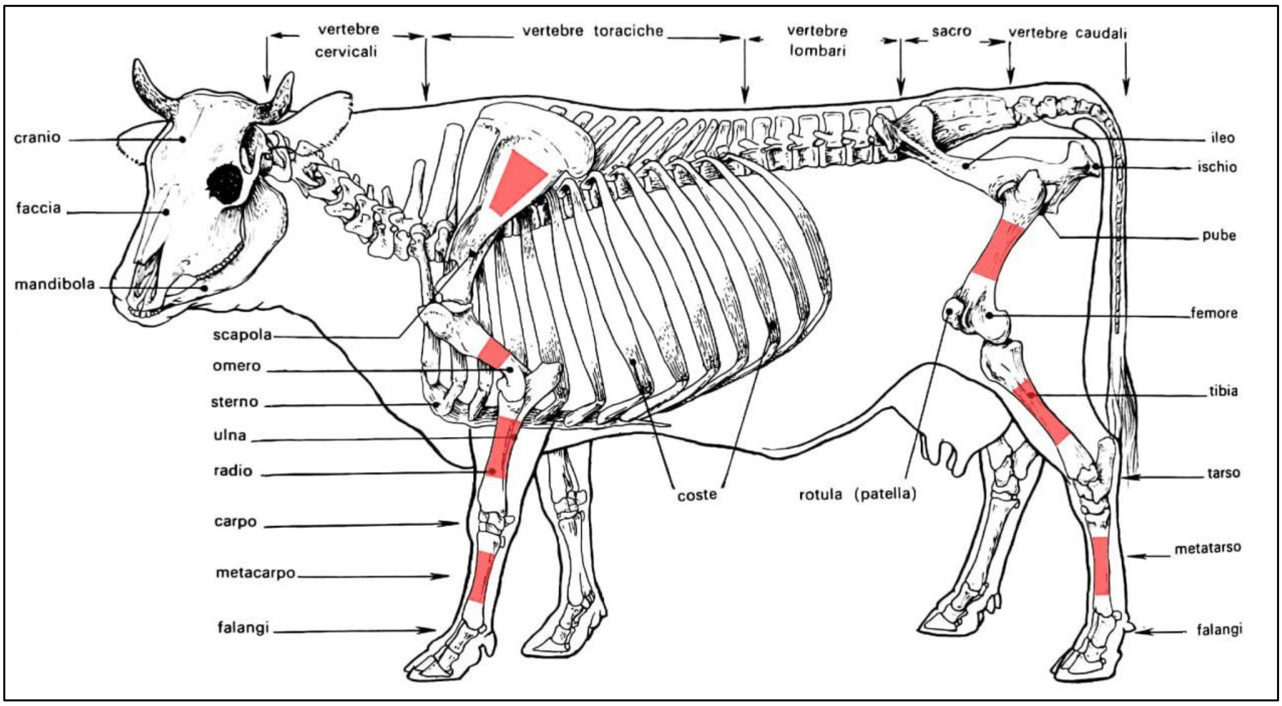


Fig. 36 – Names of the different cow skeleton parts, with the highlighting in red of the portions that could actually be exploited by the bone artisans (modified from BARONE R. 2006).

4.3.2. SOFTENING AND MOULDING

Softening process could be applied on bones to modify the shape of an artifact or the raw material and then return it to its original hardness. Also, it was a process employed to make the material easier to cut, aiding in the shaping or decorating process (MACGREGOR A. 1985). Indeed, after slaughter, it was necessary to clean the bones of any remaining tendons and meat residues, along with removing the periosteum sheath. These procedures were likely complex and time-consuming. To clean the bones, artisans might have been buried them in sand to allow parasites to naturally clean them, and heat was used to accelerate the aging process and whiten the bones. Then, to remove the periosteum membrane (fig. 27), it's possible that the bones were soaked or boiled for an extended period. Modern bone carvers, for example in Sântionlunca, Romania, https://www.youtube.com/watch?v=4pe7szDEuf0), usually make lye from ash and then boil bones with that, so that it perfectly deodorizes them. GHIRINGHELLO C., TRAPANI M. 2019 tried an experimental test to understand better these preliminary processes. Firstly, they boiled the bones for several hours and then, when they've cooled down enough to be seized with hand, removed mechanically the membranes with small blades. After, the bones were soaked in cold water for 48 hours to soften the raw material so it could be processed more easily and be more flexible (MACGREGOR A. 1985). Alternatively, the bone could be immersed in natural acidic solutions, as present-day exponents of Russian folk art do, using vinegar (acetic acid) in solution (MACGREGOR A. 1985). This method, however, must have been a much riskier method, as it could alter the chemical and physical composition of the bone, being irreversible.

4.3.3. CUTTING AND SPLITTING

Once the artisan cleaned and preliminary prepared the bones, the cutting took place. Saws were certainly among the most important implements used for this purpose, both for cross and longitudinal cutting, at different intensities. As I previously mentioned, saws finding in context referable to the manufacture of bone are almost lacking. Anyhow, many Roman metal tools are known (GAITZSCH W. 1980) and we can hypothesize that they would have been similar to the ones related to bone working. For example, two saw fragments were discovered in Anglo-Saxon contexts, one in Thetford, Norfolk, and the other in Icklingham, Suffolk (fig. 37). The Icklingham blade is single-edged and attached to a rigid backing of folded sheet metal, featuring relatively fine teeth averaging about 4.6 teeth per cm over 13 cm. The Thetford blade, although incomplete, has teeth on both sides, with frequencies of around 3.7 and 6.1 teeth per cm, respectively (WILSON D.M. 1981; MACGREGOR A. 1985). These are measures that can be compared with the distinct marks that saws leave on worked bones, that are usually one of the only traces of their use. These marks consist of distinct angled striations on the material, usually with a W-shaped cross-section (SYMES S.A. *et alii*), with bundles of these marks intersecting. The sawing process involves a sequence: starting with an upward angle, the saw blade tilts, becomes more pronounced at the end, and then lowers its contact point for cleaner sawing. Craftsmen could encounter difficulties at the beginning and end of the process, leading to shallow grooves when the saw slipped on the smooth bone surface (fig. 37). In some cases, fine sawing grooves develop on an oblique plane or raised area, possibly due to retouching or pressure applied during detachment, indicating adjustments in the tool's angle near the end of the work. Artisans typically turn the bone 180 degrees after sawing one side, resulting in parallel sawing axes (BÉAL J.C. 1983). Both BÉAL J.C. 1983 and BARBIER M. 2016 note that there are no traces of wire sawing, perhaps accompanied by an abrasive, as mentioned by Plutarch (see paragraph 4.1.), despite the fact that he was contemporary with some of the material in their hands, although this technique was used in the early centuries of our era. Furthermore, it's possible that the author is passing on information from others or simply restating a well-known idea from literature.

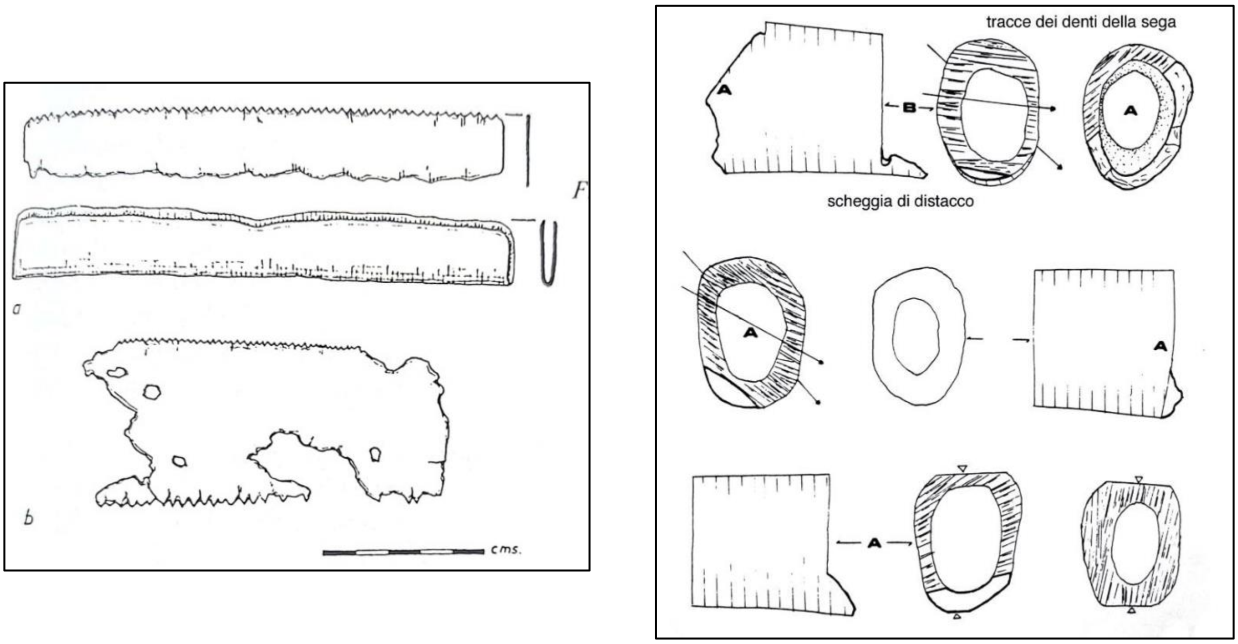


Fig. 37 – On the left, drawings of two saws' fragments from (a) Mitchell's Hill, Icklingham, Suffolk and (b) Thetford (WILSON D.M. 1981). On the right, transverse cut of a long bone with visible grooves left by the saw teeth and the detachment splinter (BIANCHI C. 2019, modified from BÉAL J.C. 1983).

It appears that the matrices initially underwent rough sawing, primarily to remove unusable epiphyses. This is why we do find a lot of epiphyses remains on bone workshops excavations (see fig. 34 on the right) or butchery spaces, depending on where this cutting took place. It is probable that some of the raw material was stored for an extended period at the butcher's and the bone worker's, who did not exclusively use fresh bones, eliminating the need for preservation methods (BÉAL J.C. 1983). After removing the epiphyses, these long bones seem to have provided only a third of apparently usable material (fig. 35), limiting the exploitation to small-scale samples (BARBIER M. 2016). The marrow removal was then performed. According to BARBIER M. 2016's experiments, after the long bone cutting, a pinkish-white marrow was expelled. Over time, this marrow in the medullary cavity, spongy tissue, and osteone ducts liquefied, turning yellowish. Sunlight exposure sped up this process, making the bone somewhat translucent, especially at the ends. The obtained cut matrices were subsequently reworked and cut to the desired size. Not only saw was used for these processes, but also knives, chisels, planes and lathes (MÜLLER H., DESCHLER-ERB S. 2021). The traces that these instruments leave on bones have been observed by

MACGREGOR A. 1985, DESCHLER-ERB S. 1998, BARBIER M. 2016 and many others. However, BARBIER M. 2016 has proven that the only way to cut *baguettes* from the diaphysis is by sawing (fig. 38), as it is suggested by the saw striations recognized on many samples. As for the chisel, although it produces a flat cut and transverse stops, its action causes tears that can harm the shaping or the final appearance of the object. Although used, this tool, whose action is limited in length, cannot correspond to the one that produces the large removals that can be seen on some blanks. Plus, removals were conducted from the central region towards the ends, according to an approach that aligns with the technical and anatomical logic, as it corresponds to the growth pattern of long bones. Consequently, when shaping with a metal blade, it's advisable to work the material along these axes (BARBIER M. 2016). We should consider that for the cutting different clamping methods must have been used (fig. 38). Moreover, when removing material with a certain width, it's possible to notice a slight concavity caused by the curvature of the cutting edge of the plane.

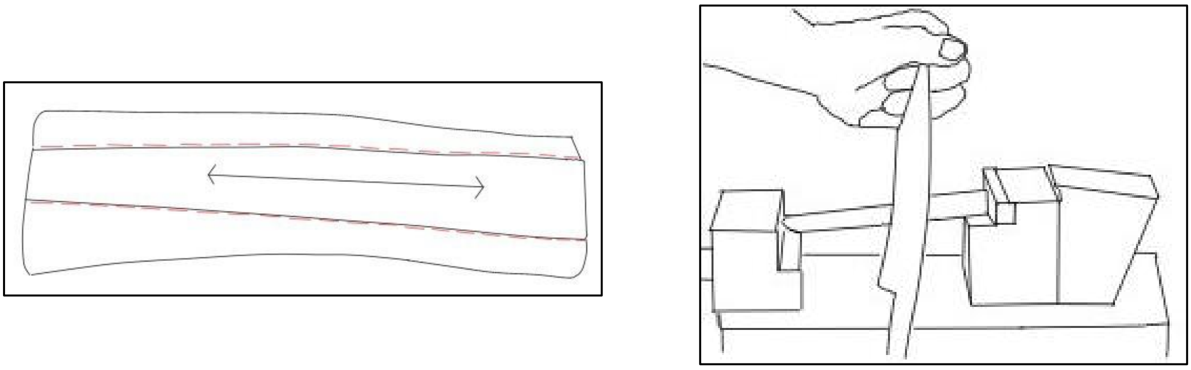


*Fig. 38 – On the left, longitudinal sawing of a long bone diaphysis to obtain a rod (*baguette*). On the right, clamping system to achieve large removals from a bone* baguette*, to quickly rectify the its ends by adjusting them to the thickness of the central zone. This adjustment is of real importance, as the pointing that will be carried out at the ends will depend on turning in line with the axis (drawings by M. Naso, modified from BARBIER M. 2016).*

4.3.4. SMOOTHING AND POLISHING

The marrow impregnation mentioned above (paragraph 4.3.3.) was advantageous for the creation of objects like pins, needles, and punches, which may have been shaped in a greasy matrix or greased through use, whereas it posed challenges especially with fine files. These files, used to smooth the material after the cutting, tended to get clogged with a mix of grease and bone powder, reducing their effectiveness and requiring frequent cleaning to remove the stubborn residue (BARBIER M. 2016). It is to underlined the fact that these archaeological tools can exhibit distinct characteristics compared to modern tools. For instance, Roman files (fig. 39) had different cross-sections like square, half-round, or round, and they primarily featured single cuts (GAITZSCH W. 1980), whereas modern files often have double cuts. Thus, to perform a perfect experimental bone manufacture replica it should be better to consider these differences, of course keeping in mind that it is a time and cost consuming process (MÜLLER H., DESCHLER-ERB S. 2021). Bone objects often display transverse parallel lines, suggesting that some smoothing was accomplished using a knife blade held crosswise and pulled along the surface, creating distinctive "chatter marks". In the absence of suitable tools, various mineral and organic substances were likely used for smoothing and polishing. Possibilities include fragments of pumice (as it is suggested in Mart, *Epigr.*, I, 117, 16) collected from shorelines, a form of sandpaper made from leather with fine sea sand, rottenstone (a decomposed siliceous limestone), crushed chalk, powdered charcoal, ashes of bones or antlers, and shave-grass. Pumice stones have been found in Rome, related to a bone workshop dump of the II century AD discovered in via G. Sacchi, and they've been interpreted as abrasive for bones manufacture (MORONI M.T. 2008). Additionally, coarse fish skin may have been employed for smoothing bone, a practice observed in the Roman period for ivory. Modern horn workers use a range of polishing media, including swansdown, to achieve a high degree of polish, often obscuring traces of coarser smoothing stages (MACGREGOR A. 1985). The same materials could be used to polish bones as a last step of the manufacture. Polishing, similar to abrasion, involves a rubbing action, either in a circular or back-and-forth motion. This technique not only holds aesthetic significance, but also serves a functional purpose by enhancing the penetrating ability of sharp objects due to their perfectly smooth surfaces and strengthening the object by compacting the material (PROVENZANO N. 1997).

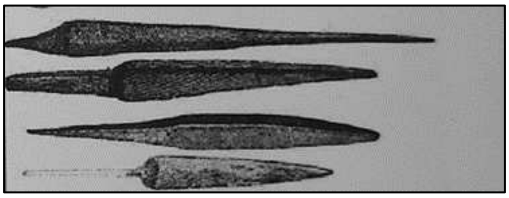


Fig. 39 – Files from the site G-R du Châtelet, Gourzon (France) (BARBIER M. 2016).

4.3.5. TURNING

Once the bone rods were sawed and finely cut, they could either be shaped with the only use of other type of blades or dressed with longitudinal facets to be mounted in a lathe and turned. No depictions of bone workers' lathe exist to aid the understanding of its operation, and written sources only provide unclear descriptions (DESCHLER-ERB S. 1998). The absence of identifiable parts in excavations led to the conclusion that it must have been based on wood (BARBIER M. 2016), used by one person, requiring little space and being easily transportable. Again, these characteristics can suggest the fact that bone and wood workers could collaborate or that a bone worker could create his tools by himself (see paragraph 4.2.). Indeed, FELLMANN R. 1991 notes that wood and bone turning machines were probably the same. However, it can be assumed that these turning tools were of different types, because different forms of blanks required individual clamping and operating devices (DESCHLER-ERB S. 1998). Multiple lathes from Roman times have been reconstructed and used. Lathes driven by a fiddle bow have been reconstructed in experimental settings by various researchers and can be found for example in PICOD C. 2004, JUNG P. 2013, and BARBIER M. 2016 (fig. 40). While most of these reconstructions employ a fiddle bow drive, it's worth noting that alternative systems could also be considered, as suggested by BÖCKING H., GÉROLD J.-C., PETROVSZKY R. 2004. The lathe's operations are indirectly suggested by the finished objects (easily recognisable by their round and symmetrical shape), by the expanded rods and the turning waste, offering insights into technical phases, tool characteristics, and their angles of attack. Valuable information comes from rough drafts, some of which have pointed tips ready for transformation, as well as waste pieces with conical points at one end and diminishing profiles at the other, reflecting the removal of a turned object (fig. 41) (BARBIER M. 2016).

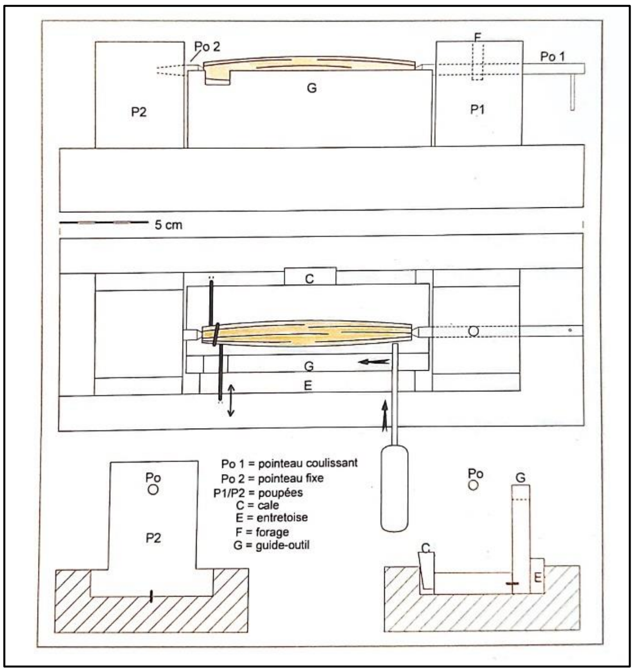


Fig. 40 – One of the lathe reconstructions made by BARBIER M. 2016.

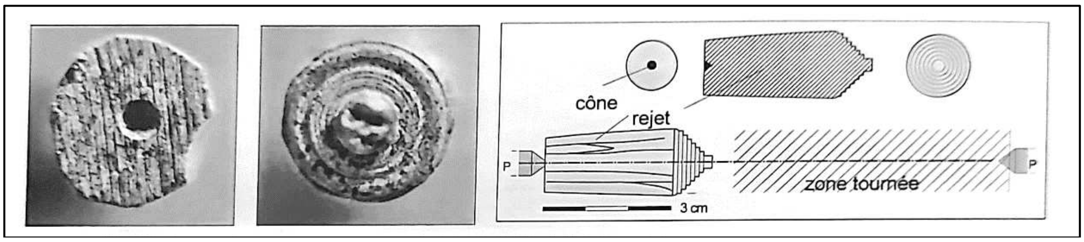


Fig.41 – Characteristics traces left by the turning (BARBIER M. 2016).

4.3.6. DRILLING

Drilling occupies an intermediate position between the filed and carved artefacts on the one hand and the turned artefacts on the other, as the drilled holes are mostly found in the former group, but were drilled by means of a violin bow. The holes can be roughly divided into two groups:

smaller, round holes with a diameter less than about 5 mm are found in items like handle knives and sewing needles, with variations in the shape of the eye for needles; larger holes, with a diameter greater than 5 mm, are found in knife handles, spindles, sword parts, and furniture, and they are consistently circular as they were drilled vertically (DESCHLER-ERB S. 1998). Drilling could be done according to different methods:

a) Carving with a chisel;
b) Use of a simple drill (a cylindrical stick with a point rubbed with the hands to give rotary motion);
c) Use of a violin bow drill, pulling a spur or a cord wrapped around a pointed spindle back and forth.

Different types of points allowed the creation of decorative motifs. For example, the so-called 'cube eye', an engraving characterised by a central point and one or more concentric circles, was obtained through the use of three-pointed cutters (fig. 42). The work was then regularised by smoothing processes (DE GROSSI MAZZORIN J. 2012).

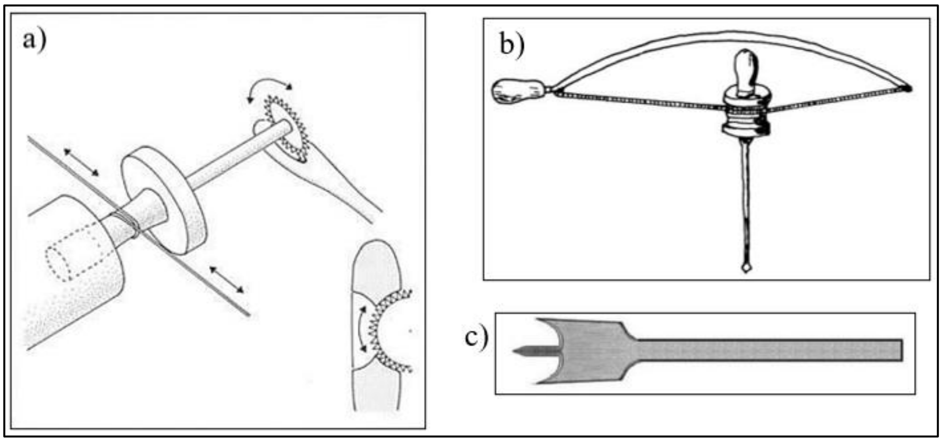


Fig. 42 – a) drilling of a slotted needle hole (DESCHLER-ERB S. 1998); b) bow drill (BIANCHI C. 2019) and c) tool tip used to create the "dice eye" (DE GROSSI MAZZORIN J. 2012).

4.3.7. DECORATING AND COLOURING

Ornaments can be found on various artifacts made through filing, carving, and turning processes. Linear decorations, whether carved or notched, were likely created using a knife, and they show a degree of precision linked only to freehand execution. Turned objects, on the other hand, didn't require additional tools for ornamentation. For notched decorations, a turning chisel with a narrow tip was used (DESCHLER-ERB S. 1998). To enhance the appearance of these objects, colour was occasionally applied. Colouring was achieved in various ways and it seems that green and red colouring were notably favoured among the other colours (fig. 20, f-g and 44) (MACGREGOR A. 1985). Recent bone finds coloured in green from the city of Reims (France) have been analysed through IR spectroscopy, XRD and TEM observations. It was found that the starting materials, consisting of fresh ox bones, were boiled in a copper vessel containing an acidic brine (FERRAND J. *et alii* 2014). Another interesting study carried on by WINNICKA K. *et alii* 2020 on some Early Bronze Age pins has been using ED-XRF, SEM-EDS and micro-Raman for the determination of the origin of the green colouration, but in this case the colouring seems to be not clearly intentional. Additionally, dark colour (fig. 44 on the right) can be caused by the laying conditions in the finding context (natural processes within soil), but we cannot exclude the presence of a treatment carried out by immersion in herbal teas rich in tannins or in a brine with mineral pigments (GHIRINGHELLO C., TRAPANI M. 2019). In some cases, colour was used as inlaid pigment to highlight incised decoration, such as on Roman bone carvings from Egypt (fig. 43) (RODZIEWICZ E. 2016). For example, four coloured bone plaquettes now preserved at the Museo Egizio of Turin (Italy), found in Ashmunein (Egypt), belong to a very specific category of engraved *appliques*: they are cut in *intaglio* and combined with coloured fillings made of resin and wax. The image and the details were etched with thin tips, while the surface that had to be filled with coloured resin was carved with a slightly rounded chisel: in these plaques traces of red and green resin are still visible (GHIRINGHELLO C., TRAPANI M. 2019). The technique suggests a connection with the medieval jewellery technique of *cloisonné*. Additionally, gold leaf was applied to sheathe the shanks of some Roman bone pins, similar to its use on carved ivory objects. Various historical methods for dyeing and colouring skeletal materials were documented, including the use of vinegar, copper fillings, verdigris, and organic dyes like madder (MACGREGOR A. 1985).

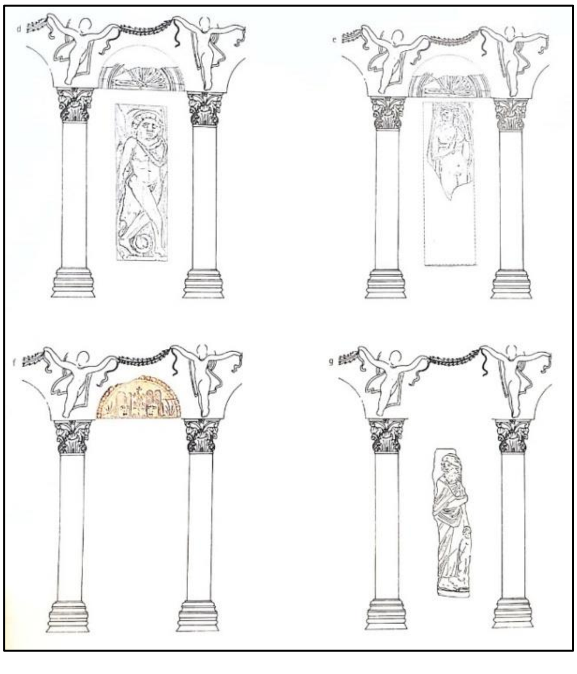


Fig. 43 – On the left a semicircular bone coloured appliqué representing theatrical masks from National Museum of Warsaw. One the right, theorical reconstructions of the wooden door of the armarium *with the bone panels excavated in Alexandria or attributed to Alexandrian* ateliers, *such as the highlighted appliqué (RODZIEWICZ E. 2016).*

Fig. 44 – On the left, green and red coloured bone pins from the Whitaker Museum, Mozia (Italy). On the right, Gallo-Roman pins from the Musée d'Aquitaine, Bordeaux (France) (photos by M. Naso).

4.3.8. PRODUCTS: ARTEFACTS TYPOLOGIES

It seems impossible here to start talking about all the different products that have been found all around the Roman provinces, as we have understood that each production and choice in this manufacture is peculiar in its own way. The knowledge and selection of the specific type of bones and the adopted techniques and instruments are all related to the creation of specific objects. Among the most produced objects there are spoons, combs, pins, writing implements, spindles, and sword hilts (see paragraph 4.1. and Table 5) (MACGREGOR A. 1985; DESCHLER-ERB S. 1998; JUNG P. 2013). From a typological point of view, considering this class of materials diachronically, it seems possible to recognise a progressive standardisation of types. In the pre-protohistoric periods, there is a different variety of types attested, compared to those normally found in Classical or later contexts. This is linked to a purely utilitarian reason, and should be seen in the context of the advent of metallurgy (CRISTIANI E., ALHAIQUE F. 2005), which inevitably extends to the production to other materials as well. To separate out all those objects that were imported and those that were made in the various Roman empire provinces would be difficult, if not impossible. Styles changed slowly and were often empire-wide, or at the very least, spread over a large number of neighbouring provinces (CRUMMY N. 1981). An interesting topic is for example the study of the bone artefacts trends, such as it is in the case of the fashion for, and imitation of, the Hellenistic models in Roman art and artefacts (ST. CLAIR A. 2003). Also, some studies have been done concerning the choice of particular shapes, that changed throughout time, as it is for example for the typical asymmetry of the Roman dice (EERKENS J.W., DE VOOGT A. 2022). Different books were written about bone artefacts typologies in specific contexts or regions (BÉAL J.C. 1983; MACGREGOR A. 1985;

BIANCHI C. 1995; BERTRAND I. 2007; DESCHLER-ERB S., GOSTENČNIK K. 2008; HRNČIARIK E. 2017 and many others). I will just insert here a useful review of the main typologies of bone Roman objects (Table 5), while in paragraph 6.2.4. I will talk specifically about what are the possible objects produced in the building near the east side of the forum of Nora.

OBJETS ALLONGÉS, CREUX *À section circulaire* *- Pommeaux d'épées* *- Fusée d'épée et de poignard* *- Manches de grands couteaux* *- Manches de petits couteaux, creux* *- Manches perforés* *- Boîtes à section circulaire ou ovale* *- Etuis à section circulaire* *- Bobines* *- Tubes moulurés* *- Eléments cylindriques* *- Eléments de charnière (creux)* ***OBJETS CREUX*** *- Dés creux* *- Manches de petits couteaux* *- Fourreaux d'épées miniatures*	***OBJETS ALLONGÉS PLEINS*** *À section circulaire* *- Eléments de charnière* *- Poincons* *- Manches pleins* *- Baguettes moulurées* *- Quenouilles* *- Fuseaux* *- Aiguilles* *- Epingles sans décor* *- Epingles à décor figuré* *- Spatules* *- Strigiles* *- Cuillères à parfum* *- Cuillères (cochleria et ligulae)* *- Agrafes* *- Amulettes phalliques* *- Eléments terminaux de charnière* *- Pieds de coffret* *- Jouets* *- Eléments cylindriques pleins*
OBJETS PLEINS *- Dés* *- Serrures* *- Pied pliant* *- Plaques de manches de couteaux à riveter* *- Moulures et placages, section rectangulaire* *- Couvercles* *- Lames ou peignes de tisserand* *- Plaques diverses* *- Manches de couteaux pliants* *- Boucles de ceintures* *- Broches* *- Boîtes à sceau* *- Peignes à cheveux* *- Tablettes* *- Dominos* *- Spatules* *- Lissoirs*	***OBJETS CIRCULAIRES APLATIS*** *- Eléments de couvercle (couronne moulurée)* *- Anneaux* *- Bracelets* *- Bagues* *- Eléments annulaires* *- Jetons* *- Pions de jeux* *- Tessères* *- Fusaioles* *- Gardes d'épées ou de couteaux* *- Placages* *- Médaillons en bois de cerf* *- Eléments circulaires*

Table 5 – Main typologies of Roman bone artefacts, not exhaustive (BARBIER M. 2016, from BÉAL J.C. 1983).

5. Methodologies and instrumentations

5.1. METHODOLOGICAL ISSUES

We start from the fundamental premise that the correct identification of bone surface modifications is the first step in understanding the processes by which they are formed and the agents behind the processes (FERNÁNDEZ-JALVO Y., ANDREWS P. 2016).

An adequate methodology has been followed to read and distinguish microscopically the marks that the ancient artisan(s) and the later taphonomic agents left on the Nora worked bones. Precisely, two research lines have been developed:

1. The study of the working cutmarks, related to the definition of the manufacturing sequence and the reconstruction of the instruments used in the Nora bones workshop.
2. The examination of the bone surface modifications that came from nonhuman processes, in particular some traces of colour found in little quantities on the bones, in order to clarify what type of taphonomic interventions modified these bones either before or after their burial.

The two researches were carried out at the same time and the used analytical instruments were, at least initially, the same (stereomicroscope and ESEM). Also, the work was divided between three laboratories, connected with the two universities involved in the Double Degree program I took part in: Geosciences and Cultural Heritage Department laboratories at the University of Padua and Archéosciences Bordeaux laboratory at the University of Bordeaux Montaigne.

I started with the creation of the specific overview of the manufacturing cutmarks, drawing and writing notes about the bones parts to be investigated. Then, I confirmed (or disproved) the chosen characteristics of each bone through stereomicroscopic observations, later implemented by the use of ESEM. The produced images were thus compared with bibliographic examples of cuttings and taphonomic alterations of bones. Then, I completed the bones description using the confocal microscope, which enables the measuring of the cutmarks' cross-sections. It was important to keep always in mind the different magnifications references, not losing sight of the original entire shape of the studied bone and the overall arrangement of the cuts. It is actually known that the most effective interpretation results are achieved when high-power and low-power magnification are combined (BRADFIELD 2015).

The samples didn't request any preliminary preparation, since all the chosen analytical instruments are non-destructive, but one main issue to take in consideration was the orientation and positioning of the bones. If under the stereomicroscope the bone can be easily rotated and moved, the ESEM requires the stability of the analysed material inside the vacuum chamber. This can be a bit problematic when one bone presents different cuts, each of them to be analysed. Also, the length of the samples (a mean of 10 cm) didn't allow the study of the transversal cuts. This is why I focused my researches on the longitudinal ones.

Manufacturing cutmarks were not the only modifications present on the Nora worked bones: various taphonomic alterations are visible in their surfaces, probably related to processes and agents acting in the different stratigraphical units. For the chemical identification of these alterations, I used SEM-EDS, VIS-NIR hyperspectral imaging, together with Raman and p-XRF spectrometries. For none of these techniques the bones were sampled.

5.2. STEREOMICROSCOPY

Stereomicroscope is a useful tool for initial microscopic observations and surface analysis. It relies on the binocular vision provided by the eye pieces (having two optical paths under a convergence angle, similar to the human binocular vision) for the possibility of analysis of details and texture or topography of the surface of the sample. The implementation of the binocular vision provides an accurate perception of dimensions of the analysed object by including the possibility of depth perception. This allows the visual examination of the sample and the recognition of the surface's clues.

What is really useful for this research, in addition to the increasing magnification of the optical microscope, is the presence of the tiltable mirror base for both brightfield, darkfield and oblique light illumination. These illumination methods can provide improved image contrast, and this results particularly useful in the case of cutmarks on the bones' surfaces, rich of topographical irregularities, and, in particular, of abraded surfaces.

For this thesis project, two models of stereoscopic microscopes were used: Zeiss Stemi 305EDU (Università degli Studi di Padova) and Leica M125 optical microscopes (Université Bordeaux Montaigne) (fig. 45). The first one has optics that allow a maximum magnification of 40x in a range of 8-40x, thanks to the 5: 1 zoom with 5 stops, at 0.8x, 1x, 2x, 3x and 4x; while the Leica one has a range of magnification that goes from 8x to 100x, with a 12.5:1 zoom. Both the stereomicroscopes have incorporated a software that allows the automated acquisition of images with a high-resolution. In the case of Zeiss Stemi 305EDU, images were captured using the Wi-Fi camera and documented using Labscope, an imaging app; whereas with Leica M125, photographs were taken using a CCD camera coupled to Leica Application Suite software.

Fig. 45 – Zeiss Stemi 305EDU stereomicroscope at the Geosciences Department of the University of Padua (left) and Leica M125 stereomicroscope at Archéosciences Bordeaux laboratory (right).

Moreover, to avoid the problem of the shallowing of the depth of field and the reduction of amount of light that reaches the specimen with high magnifications, I used Hugin stacking program. It allows to stack a series of images taken at the same point with progressive focus, so that the signal-to-noise ratio (S/N) increases and the image results focused (fig. 46).

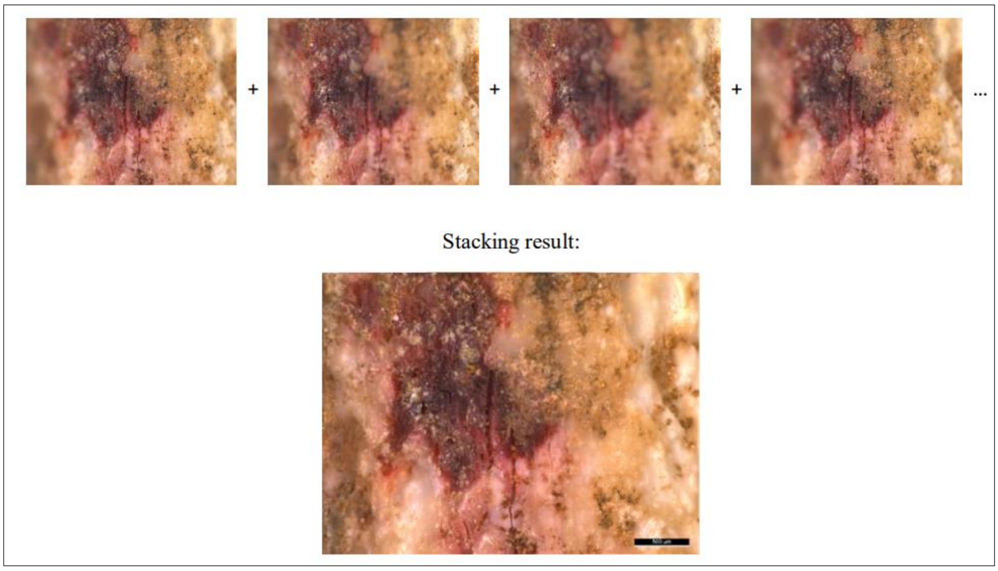


Fig. 46 – Sample 3315. Example of stacked images with Hugin to obtain a clear overview of the selected area. By optically sectioning the specimen, the in-focus information at the specimen's surface can be acquired over a range of images, which can then be processed to generate a single in-focus image.

Considering that each bone presents different cutmarks, the first thing I did was describing these cutmarks according to some parameters. The stereoscopic images resulted to be fundamental in the description of:

- Position of the cutmarks with respect to the main axis the object: transversal/longitudinal/oblique
- Quantity: single/multiple

- Arrangement: parallel/overlapping
- Width: narrow (<<100 μm), broad (=and > 100 μm);
- Morphology: straight/curved/sinuous
- Presence/absence of internal micro-linear marks.

I decided to use a description based on *type of modification* rather than the *agent* of modification, because types of modification are the first evidence observed when archaeological collections are made, and there are many processes producing similar types of modification.

The collected information was used to be compared to similar cutting images and speculate about the class of instruments that might have produced these traces. It is in fact not unusual that quantitative data from various studies can be directly compared, and the analyses can be reproduced as long as the same equipment is used.

5.3. SCANNING ELECTRON MICROSCOPY (SEM)

The most interesting areas of the selected bones required a more advanced equipment to accurately differentiate and identify certain modifications and the agents responsible for them. They were examined by scanning electron microscopy (SEM), that can be used at higher magnifications and with better resolution than light microscopes, and also has greater depth of field (BOREL A. *et alii* 2014; SHAH F.A., RUSCSÁK K., PALMQUIST A. 2019). Generally speaking, the scanning electron microscope uses the recording of backscattered electrons and secondary electrons emitted by the sample, after being impacted by an electron beam, to form a detailed and high magnification image of the sample's surface. The basic concept is that electrons have much shorter wavelengths than light, enabling better resolution (DUNLAP M., ADASKAVEG J.E. 1997; ARTIOLI G. 2010).

The used electron microscope (one of the two SEMs present at the Archéosciences Bordeaux laboratory) is the model JEOL IT500HR. It is an environmental scanning electron microscope which can examine the insulated materials without the need for conductive coatings to be applied. These coatings are typically necessary to prevent electron absorption by the specimen, which could hinder observation and potentially cause harmful effects. Environmental SEM operates instead in a series of vacuum gradients that absorb some of the electrons and allow the examination of specimens without a metallic covering. This is the reason why the bones could be examined without any particular sampling preparation, in low-vacuum mode and at a pressure of 30 Pa. Moreover, the working distance was 10 mm, the acceleration voltage was 20 keV, and the detectors featured three imaging modes: composition, topographic, and shadow, which is a combination of composition and topographic (fig. 47). This could help to visualize much more clearly the parts of the bones that are only the result of taphonomic alteration, not related to the bones working before their burial.

Then, chemical compositions were measured using the energy dispersive X-Ray spectrometer (EDS) with two Oxford UltimMax 100 detectors coupled to the electron microscope, operating at 20 kV primary beam voltage and a net acquisition time of 30 s. The EDS spectra were processed using Oxford Instruments Aztec software. The data was normalised and expressed as a percentage by mass.

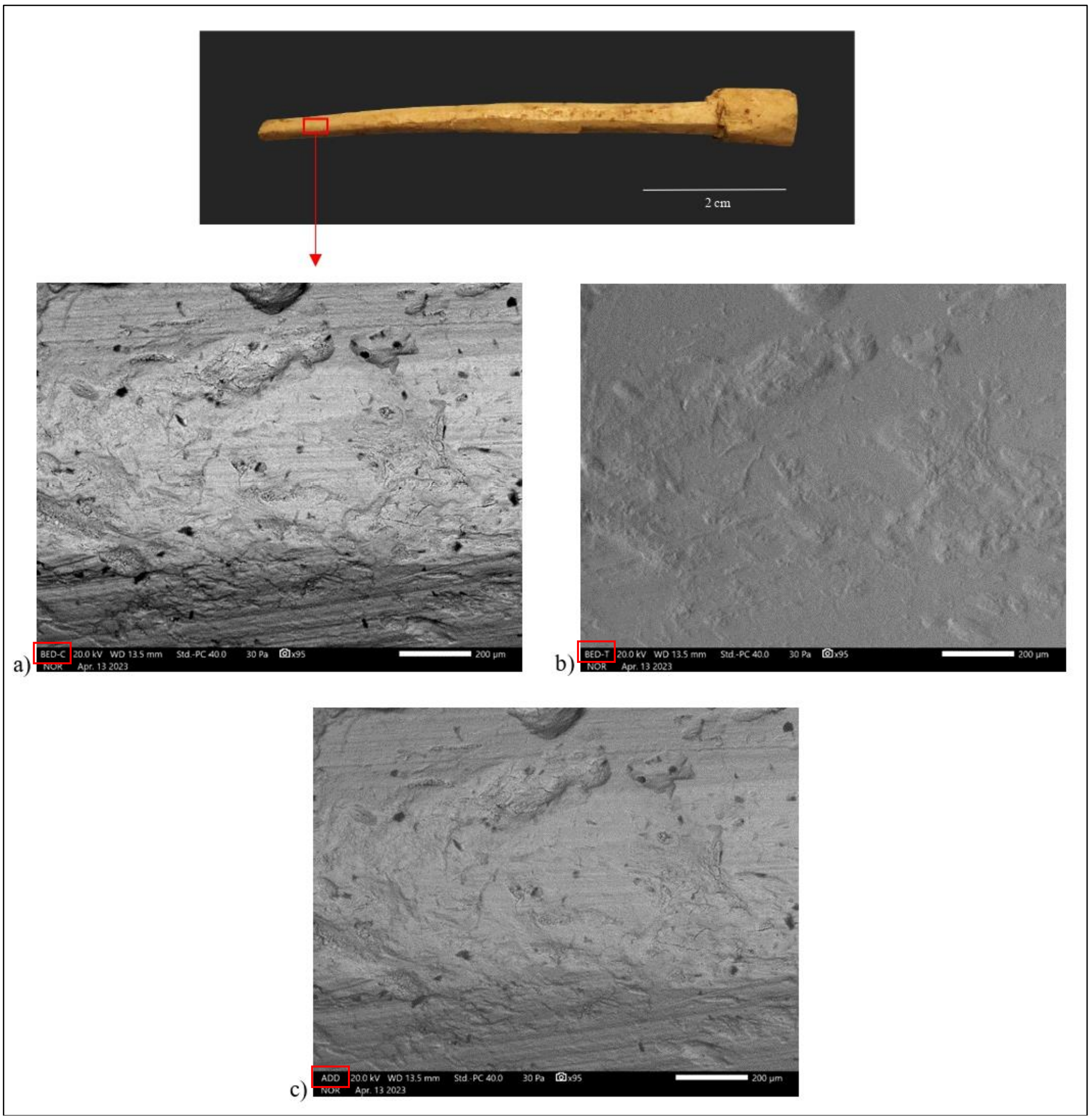


Fig. 47 – Example of a portion of the sample 3541 seen by SEM in a) composition mode (C), b) topographic mode (T), c) addition of composition and topographic modes (ADD). The composition and topographic modalities provide the relative atomic density and the topographical information of the selected area. In a) and c) the elements with a high atomic number appear lighter in the resulting images, while elements having a low atomic number are darker.

5.4. LASER SCANNING CONFOCAL MICROSCOPY (LSCM)

To conclude the cutmarks description and quantification, I used the Olympus LEXT OLS 4000 confocal microscope present at the Geoscience Department laboratory in the Università degli Studi di Padova (fig. 48).

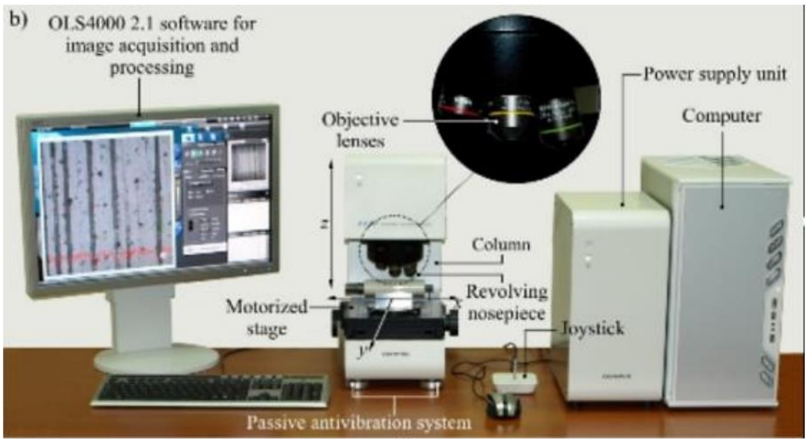


Fig. 48 - Olympus LEXT OLS 4000 confocal microscope (Università degli Studi di Padova) (left) and the overall instrumentation (right).

LSCM offers significant advantages compared to scanning electron microscope. Unlike SEM that relies on electron emissions, the confocal microscope utilizes optical energy emitted by lasers. It gets its name from its distinctive light path configuration, because it uses two pinholes positioned equidistantly from the specimen to create a shared focal plane for both the illumination and detection light paths. The resulting images can penetrate several microns beneath the sample's surface, rather than being limited to the outer layer. If secondary electron (SE) images are beneficial for examining manufacturing evidence in specific regions, they are not suitable for comprehensive 3D mapping of the entire object. Additionally, SE images do not offer a way to correlate the morphology of the material with its actual physical properties such as colour, opacity, transparency, or the presence of inclusions, as LSCM images do.

Laser microscope is particularly suitable for bone cutmarks' measurements (DUCHES R. *et alii* 2020), since it can measure the surface roughness of micro geometries at high resolution due to its minute laser spot diameter. Beside the fact that it is a non-contact instrument and it can perform accurate surface roughness measurement regardless of surface texture conditions (fig. 49).

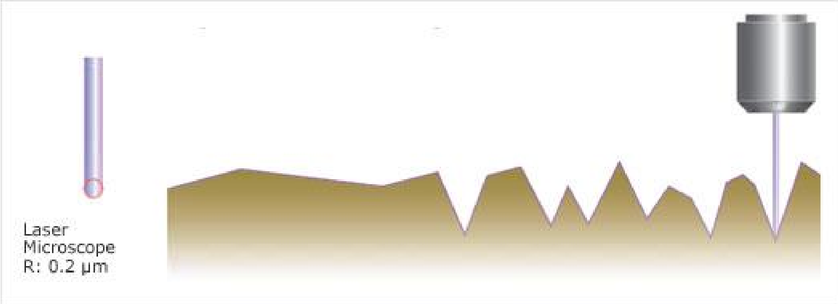


Fig. 49 – Representation of micro roughness measurements with laser scanning confocal microscope (https://www.olympus-ims.com/it/metrology/ols4000/).

5.5. HYPERSPECTRAL IMAGING AND SPECTROMETRY (VIS-NIR HSI)

The utilization of various techniques was crucial for extracting concealed information from the studied bones assemblage. First of all, a compact ultraportable HSI camera (Specim IQ hyperspectral camera, Archéosciences Bordeaux laboratory, fig. 50) has been used to obtain the reflectance spectra of some evident small spots of red colour recognized on the surfaces of five of the twelve selected bones. Specifically, bones 3335, 3384, 3403, 3541, 3315 showed several of these red spots located in random positions all over their surfaces (see paragraph 6.1.3.).

The basic principle of this camera is that each pixel of the produced images corresponds to a reflectance spectrum of the reflected light that has interacted with the object. For each wavelength of the visible and near infrared light there are corresponding intensities. So, if there is a lot of light reflection there will be a lot of intensity in the reflectance spectrum, whereas if there is a lot of absorbance, therefore little reflection, the intensity will be low. The obtained reflectance spectra allow to recognise in most cases the presence of a pigment through comparison of specific spectra databases.

It is a non-invasive, therefore non-destructive, portable technique. It's not necessary to take anything out from the samples, but it's important to create a specific lighting-controlled environment while taking the pictures: Specim IQ camera can actually operate under controlled lighting conditions with halogen lamps or in full sunlight. Calibration is performed against a Spectralon tile positioned near the target during image acquisition. Then, the IQ camera software allows the recording of white reference data in one image, which can be used for subsequent acquisitions. The imaging process involves capturing images using a CMOS sensor that covers a wavelength range from 350 to 1000 nm. The spectral resolution is 7 nm, and the spatial resolution is 512 x 512 pixels per image (each pixel: 17x17 microns squared). After processing the monochromatic images of the datacube, a final hyperspectral image is reconstructed, with each pixel containing the reflectance spectrum corresponding to the specific point on the object (SCIUTO C., CANTINI F., CHAPOULIE R., COU C., DE LA CODRE H. *et alii* 2022). I used Resonon's hyperspectral data acquisition and analysis software, coupled with Omnic software, to open and study the obtained spectra.

5.6. RAMAN SPECTROMETRY

Another technique used to clarify the reasons behind the "coloured" bones was Raman spectrometry. In a similar manner to LSCM, Raman spectrometry is based on laser energy. Briefly, it can be said that it is a non-invasive technique developed on the inelastic scattering of light principle, that provides a fast chemical analysis, usable also with organic materials. The inelastic exchange of energy through Raman scattering, which occurs between the incident laser beam and vibrating atomic groups, offers a valuable means to investigate the vibrational states of molecules. Each molecule or atomic group possesses unique vibrational properties influenced by factors such as atom composition, inter-atomic chemical bonds, and dynamic group characteristics (such as rotations). Consequently, experimental measurements of these vibrational states produce distinct spectra in the infrared region, enabling the identification of specific compounds (ARTIOLI G. 2010).

Analyses were performed in Archéosciences Bordeaux laboratory with a Renishaw RM 2000 Raman spectrometer equipped with a CCD detector and coupled to a confocal Leica DM LM microscope (fig. 50). Two significative samples were chosen (3315 and 3451) and analysed under three different laser wavelengths (785 nm, 633 nm and 532 nm), eventually changing the power and the time of the laser to have better results. Finally, the experimental data were treated to have a curve from the coefficients of the Raman shift and then compare it with the known red pigments (hematite) and apatite Raman curves.

Fig. 50 – Ultraportable Specim IQ hyperspectral camera (left) and the overall Raman spectrometry equipment (right) from Archéosciences Bordeaux laboratory.

5.7. PORTABLE X-RAYS FLUORESCENCE SPECTROMETRY (p-XRF)

The study was completed with the use of a portable X-Rays Fluorescence spectrometer. This instrument helped the elemental characterization of three bones (3384, 3403, 3315) that couldn't be properly analysed with SEM-EDS.

The essential principle of XRF technique is the expulsion of core electrons from atoms using high-energy primary X-rays. The resulting ionized atoms then relax to the ground state by undergoing a series of electron jumps into lower orbitals to fill the vacancies. During this process, fluorescence photons are emitted in the X-ray region, reflecting the quantum structure of the atom. These emitted fluorescence photons, known as secondary X-rays, constitute the "characteristic" spectrum of the atom. They can be readily utilized to identify and measure the chemical elements present in the samples. The calculated X-ray emission lines for every element in the periodic table are crucial for accurately interpreting all measured spectra. These calculated emission lines serve as an important reference for identifying and analysing the X-ray spectra obtained from various samples.

The portable XRF version of the instrument offers convenience, simplicity, and non-invasiveness. The instrument model used for this thesis work was the portable Olympus Vanta VCR-CCX-G2 analyser. The detector is large Silicium SDD 13 mm2 with a resolution of <140 eV fwhm on Ka of Mn. The spot is 10mm or 3mm in diameter with an integrated camera (variable collimator). The data calibration was made with the "GeoChem" program. The GeoChem mode uses a calibration called "Fundamental Parameters", with 2 beams (40 kV and 10 kV). The beams are automatically sequenced, and the total analysis time is 30 seconds. Each analysed point gives a spectrum, which I finally studied through Pymca software (SOLE V.A., PAPILLON E., COTTE M., WALTER PH., SUSINI J. 2007).

PART III

Final considerations

6. Results and discussion

In this chapter I will show and discuss the results obtained during the microscopic and chemical analyses made on the 12 worked bones selected from the Nora assemblage (see paragraph 2.4. and Appendix B). In particular, the final aim was to reconstruct the logic behind the artisan’s choices in this specific manufacturing sequence (*chaîne opératoire*) through the traces left of these bones. Doing so, it was possible to identify a minimum amount of equipment that was used by the artisan(s) and appreciate all the work done on these artefacts. As I already stressed in chapter 5, due to the uniqueness of the finds, preference has been given to non-destructive and non-invasive procedures.

6.1. Conservation state of the bones

6.1.1. Macroscopic observations

The Nora's worked bones, when examined without magnification, appear remarkably well-preserved and distinctly defined. They exhibit a commendable level of structural integrity, making them easy to handle. Nevertheless, some signs of alteration are present, including missing parts, a dull surface, fissures, as well as remnants of polychromy (fig. 10-19 and 46). Variations in the state of preservation are evident within the corpus. Among them, objects 3335 and 3451 stand out as exceptionally well-preserved, while object 3315 exhibits the most significant signs of alteration. Furthermore, even within individual pieces, differences in surface condition can be observed. For instance, sample 3351, formerly broken, displays a notably different surface on its two divided parts. This is due to differences in depositional microenvironments within the levels of the site, and when the fragments can be refitted it suggests that the two fragments were not adjacent during diagenesis.

6.1.2. Microscopic observations

It was essential to take a closer look at the artefacts’ surfaces. As a result, imaging techniques were employed at various levels of magnification (see chapter 5). The stereomicroscope and the scanning electron microscopy (SEM) were used as complementary methods, to facilitate a systematic analysis of the surfaces. At the micro- and nano- scale, samples show a relatively advanced state of deterioration due to probable post-depositional alterations. The bones appear to be very fragmented and brittle, partly losing their cohesion. Sediments cover most part of all the samples in different quantities and typical traces of root marks are present in all of them (fig. 51-52).

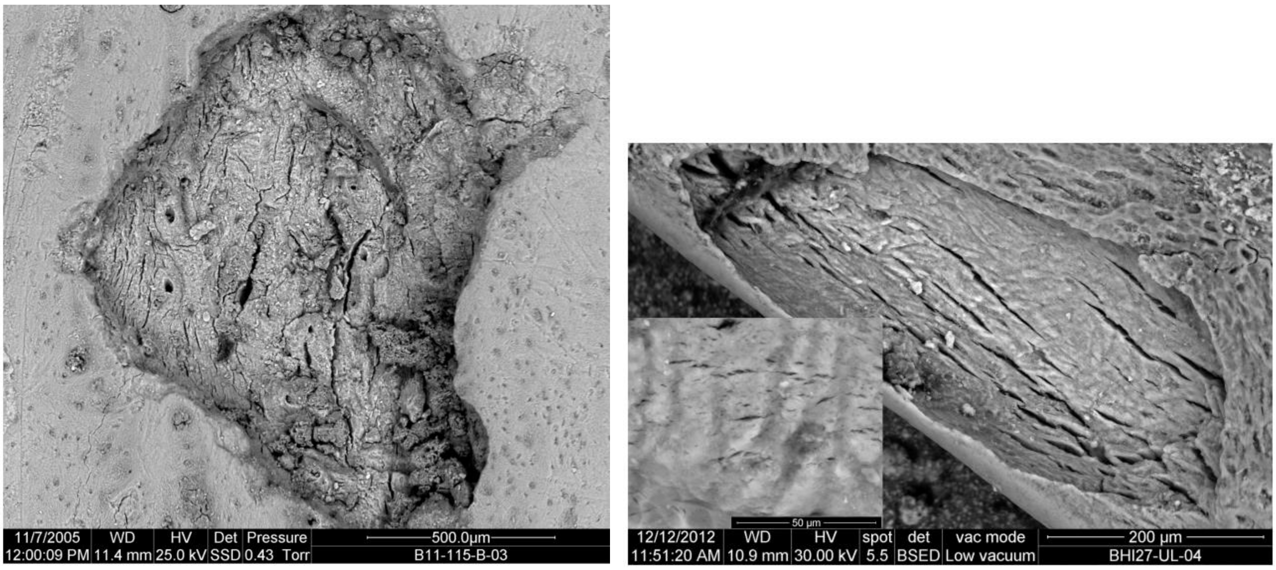


Fig. 51 – On the left, SEM microphotograph of a fossil specimen from Gorham's Cave (Gibraltar) showing a roots mark. The puncture root mark has cracking in the interior. Roots may have a sinuous trajectory or penetrate into the bone. The type of plant that makes perforations in contrast to branched or sinuous trajectory is unknown. It is possible that perforations may be formed by different parts of the root. Further investigations are needed to establish these differences and identify the types of plant that form root marks. On the right, SEM microphotograph of linear marks on a modern bone from experimental burials. The grooves follow a characteristic pattern of linear marks at the interior of a hole apparently also made by insects (FERNÁNDEZ-JALVO Y., ANDREWS P. 2016).

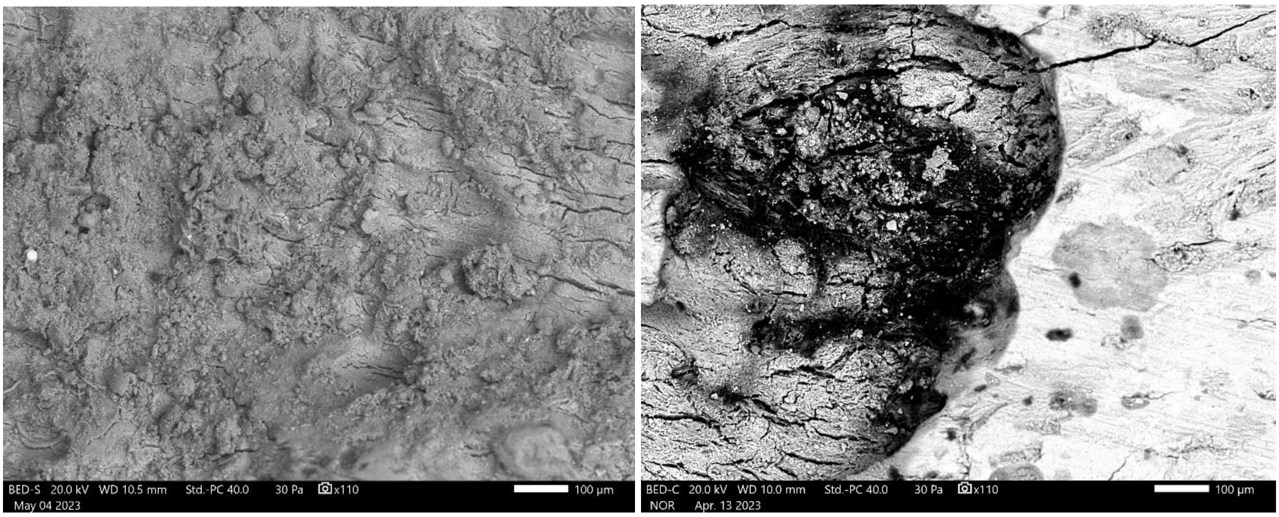


Fig. 52 – ESEM microphotographs of sample 3392 (left) and sample 3541 (right) showing typical roots fractures and marks, enriched by organics and sediments.

6.1.3. RED SPOTS

Already visible with naked eye, some red spots on the surfaces of 5 of the 12 selected bones captured our attention and, in the subsequent analytical stage, spectroscopic methods were employed to analyse what initially seemed to be organic residues and red pigmentation (fig. 46 and 53), to understand their composition and provenance. These spots are not homogenously distributed (actually they seem pretty casual) and have a colouration ranging from light to dark red. The main part of the bones still present their natural colour, so that it was already possible to say that the colouring agent didn't penetrate deeper than the top layer of the bones. The initial hypothesis was related to the probable contamination of these bones by the red ochre pigments present in the walls plasters of the room VII (STELLA MOSIMANN F., SECCO M. c.s.), buried together with the bones, in the same layers. It is actually well testified to the possibility of deterioration of coloured objects on proximal bones found in the same burial environment (WINNICKA K. *et alii* 2020). Therefore, we expected to see the typical curves and peaks of the red ochre (iron oxide) composition analysing them with SEM-EDS, hyperspectral imaging, Raman and p-XRF techniques.

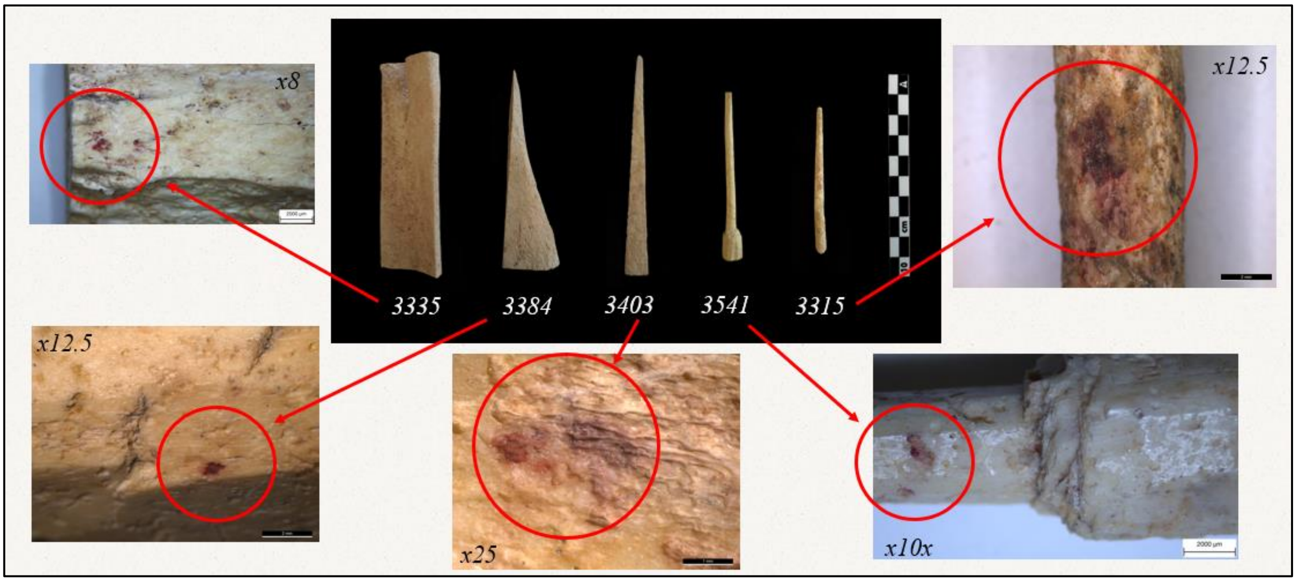


Fig. 53 – 5 bones (of the selected 12) show red spots, here showed through stereoscopic observations.

Actually, various factors can affect the colour of bones. Organic acids in soil typically cause brown staining, while oxygenated soils rich in iron can lead to a reddish hue. So that the distinctive reddish-brown coloration is a reliable indicator of oxygenation and biological activity in the soil at the time of burial. Fungal attack may darken bones, while exposure to water can lighten them or promote manganese dioxide crystal growth, turning them black. Manganese deposition is associated with wet, mildly alkaline, and oxidizing environments with bacterial involvement. Manganese dioxide is insoluble and forms crusts in caves. Soil burial can either lighten bones (poor drainage soils) or darken them (organic-rich soils). Cooking or burning bones alters their colour, including black deposits due to carbon deposition. Root growth on bones can also change their colour, lightening or darkening depending on the marks left by roots (FERNÁNDEZ-JALVO Y., ANDREWS P. 2016).

6.1.3.1. SEM-EDS

From the SEM-EDS chemical analyses, the composition of the reddish parts didn't seem to differ much from the bone composition. To perform these analyses, I selected just three samples out of five because of their surfaces' irregularities, which make it difficult to keep the instrument on focus while analysing them. So, I measured the quantities of the elements present in the red spots of the samples 3315, 3541 and 3384 (fig. 54-55), even detecting more than one chemical spectra (3315_1, 3315_2, 3315_3, etc.) (tables 6). Then, I did the same for the bone matrix areas near the detected red spots (table 7). Finally, I calculated the total average quantities of the elements in all the three samples red spots and bone matrixes (fig. 56). The data are all expressed in mass percentage of oxides, as it is usually expressed in the related literature.

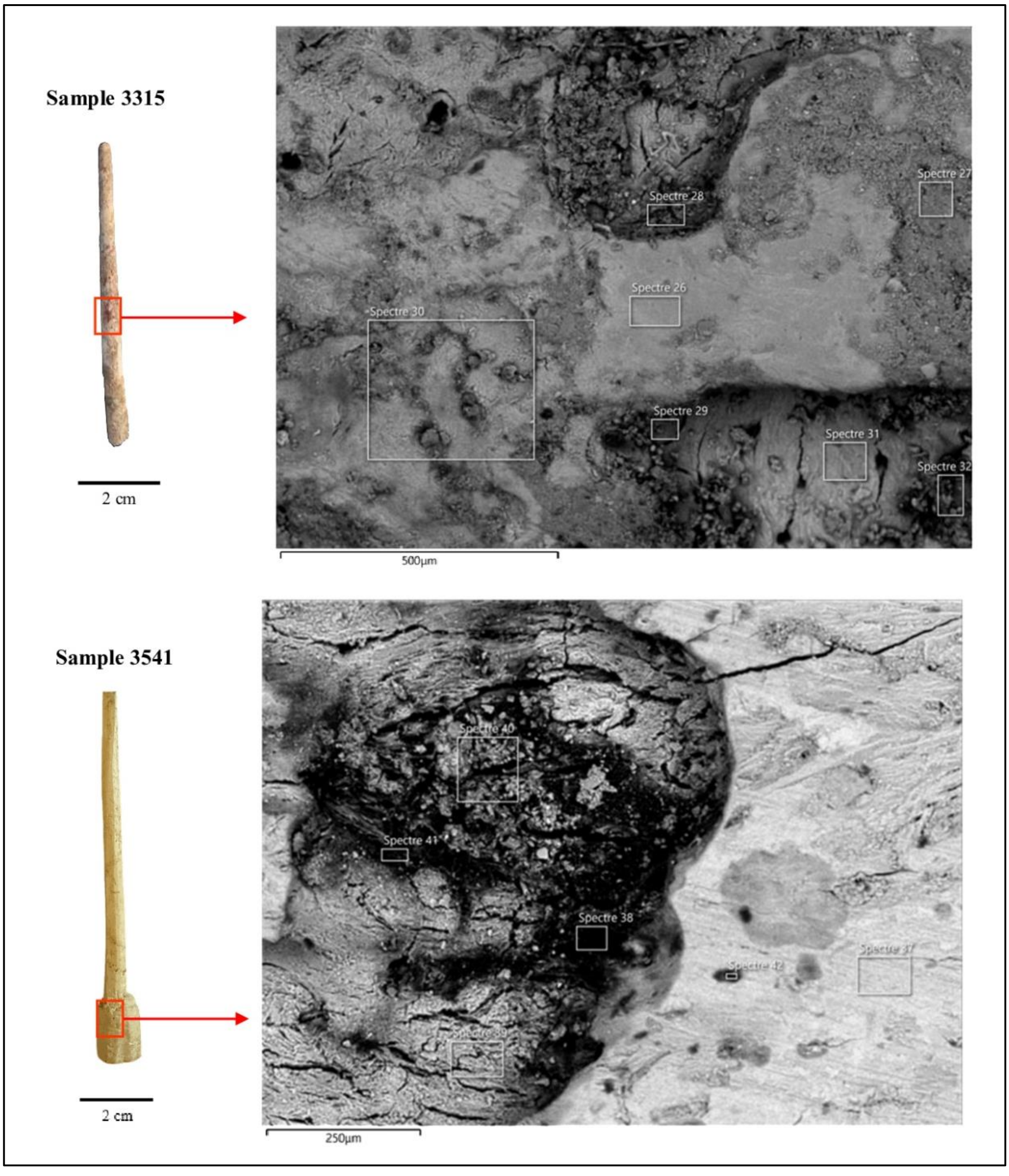


Fig. 54 –SEM-EDS detected spectra of samples 3315 and 3541.

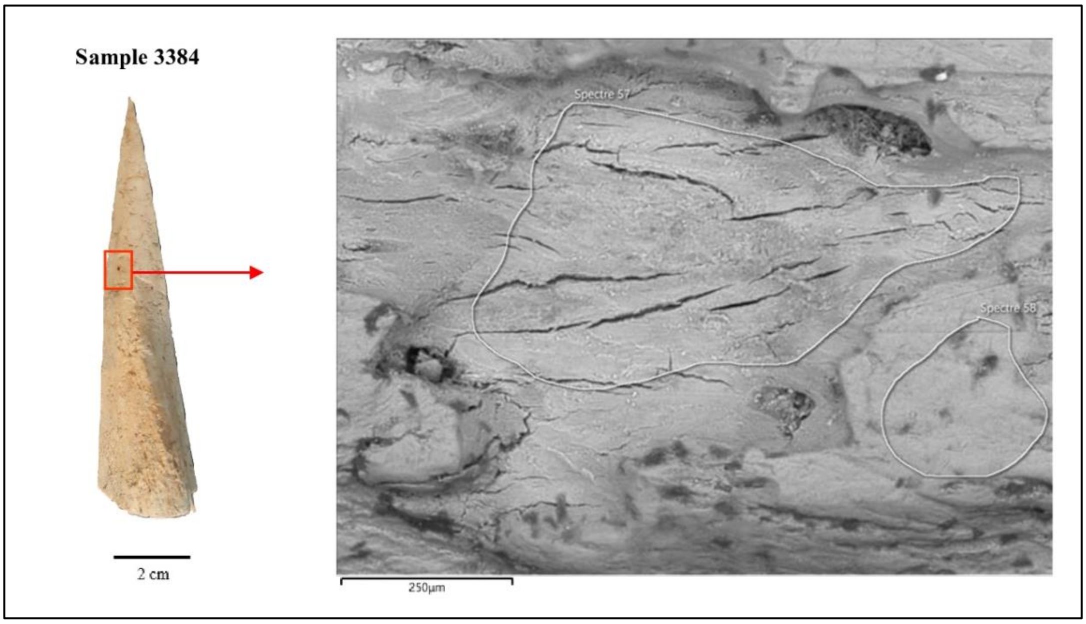


Fig. 55 - SEM-EDS detected spectra of sample 3384.

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_3	SO_2	K_2O	CaO	TiO_2	Fe_2O_3
3315_1	0.68	2.07	14.64	35.2	13.77	1.12	2.26	23.64	0.36	6.15
3315_2	1.08	1.05	4.13	11.38	31.68	1.43	0.47	47.06	0.18	1.46
3315_3	1.11	0.65	1.69	2.93	36.6	1.03	0.14	54.41	0	0.52
3315_4	1.06	1.79	14.31	32.1	15.39	2.75	1.93	24.98	0.43	5.07
3541_1	1.62	1.98	5.48	10.64	26.15	6.39	0.75	43.77	0	1.68
3541_2	1.03	1.57	11.85	31.2	15.04	1.37	2.11	31	0.31	4.12
3541_3	0.85	1.81	8.7	22.66	21.94	3.5	1.07	35.39	0	3.34
3384_1	1.11	0.62	0.39	0.67	36.88	0.72	0	59.37	0	0.15
Average	**1.07**	**1.44**	**7.65**	**18.35**	**24.68**	**2.29**	**1.09**	**39.95**	**0.16**	**2.81**

*Table 6 – **Red spots** elements quantities (in mass percentage of oxide) from different spectra detected on three samples: 3315, 3541 and 3384.*

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_3	SO_2	K_2O	CaO	TiO_2	Fe_2O_3
3315_1	1.03	0.72	1.28	2.28	37.44	0.80	0.15	55.34	0.00	0.48
3315_2	0.61	1.83	18.30	54.71	2.11	0.33	3.28	10.62	0.94	7.09
3315_3	0.85	0.99	5.21	11.02	29.56	1.05	0.68	48.47	0.18	1.91
3541_1	1.20	0.72	0.68	1.12	37.67	0.74	0.00	57.42	0.00	0.22
3541_2	0.76	0.71	1.91	3.59	33.52	1.08	0.17	56.73	0.00	0.76
3541_3	1.32	0.84	0.69	1.19	38.58	1.57	0.20	55.14	0.00	0.24
3384_1	1.62	0.81	0.56	1.05	37.30	0.93	0.27	56.99	0.00	0.22
Average	**1.06**	**0.95**	**4.09**	**10.71**	**30.88**	**0.93**	**0.68**	**48.67**	**0.16**	**1.56**

*Table 7 – **Bone matrix** elements quantities (in mass percentage of oxide) from different spectra detected on three samples: 3315, 3541 and 3384.*

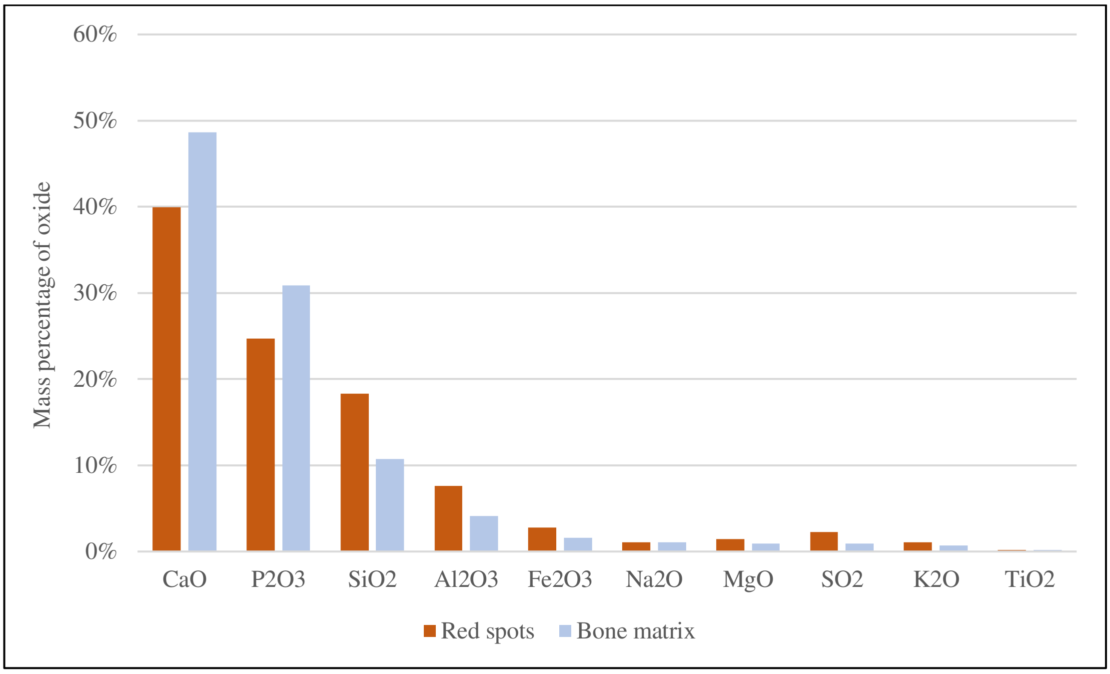


Fig. 56 – Calculated average of the chemical elements detected with SEM-EDS analyses on the red spots and the bone matrix. They present the same elements in similar quantities.

From fig. 56 it's evident that the chemical elements detected from the red spots and from the bone matrixes are the same with pretty much similar quantities. Noticeable is a high amount of calcium (Ca) and phosphorous (P), the two main components of bones, with the addition of aluminium (Al), silicium (Si) and sulphur (S) concentrations, detected in different quantities, related to a probable contamination from the archaeological sediment. Moreover, in some of these red spots little presence of iron (Fe) was detected. It seems however too small to suggest clearly the presence of iron oxides pigments referable to the red colour of the spots. It is possible that this iron can be also related to sediment contaminations.

6.1.3.2. p-XRF

The p-XRF analyses were performed on the samples 3315, 3384 and 3403. Two of these three samples (3315 and 3384) have been already analysed with the SEM-EDS. With the p-XRF technique we wanted to see if this time the results could be better. Both the red spots and the bone matrixes (fig. 57-59) compositions were analysed to be compared.

The portable XRF instrument was clearly very easy to handle in comparison to the SEM, which needed time to prepare its vacuum chamber and position the detectors to the right place. Both of them, however, presented some problems related to the irregularity of the samples' surfaces, as I said in the previous paragraph. This is why sample 3335 couldn't be analysed neither with SEM nor with p-XRF: its shape and dimensions were non-uniform and too big (see Appendix B, sample 3335).

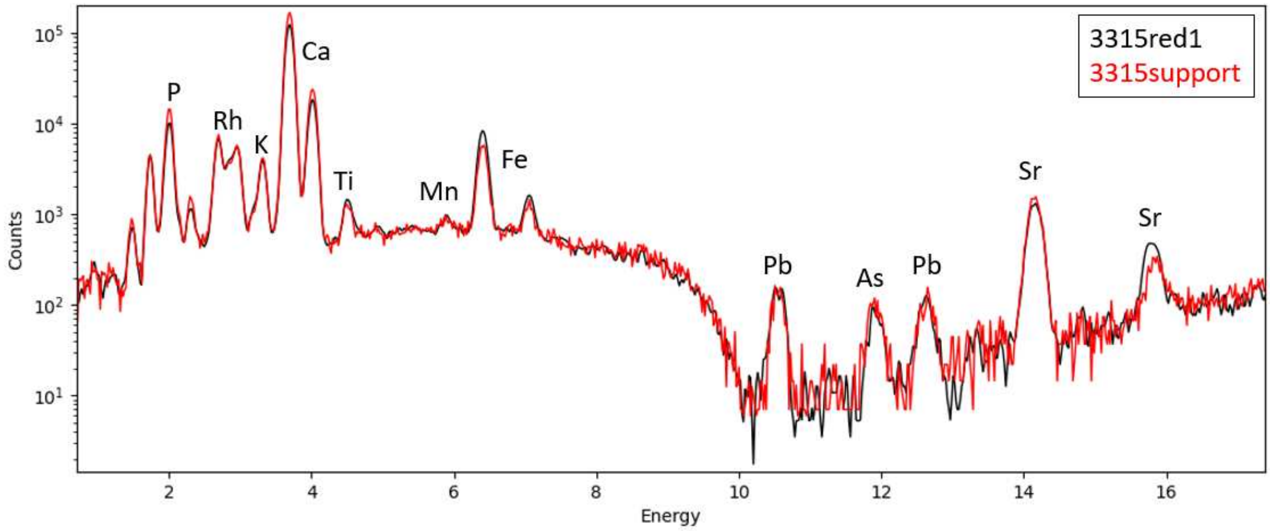


Fig. 57 – p-XRF spectra from one red spot and the near bone matrix analysed in the sample 3315.

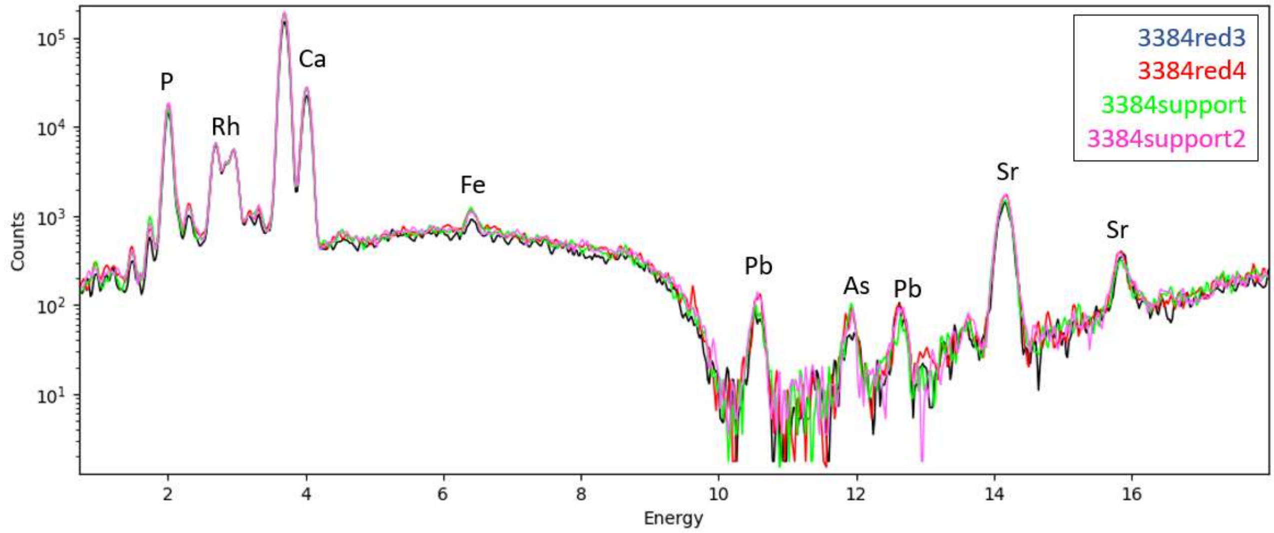


Fig. 58 - p-XRF spectra from two red spot and the near bone matrixes analysed in the sample 3384.

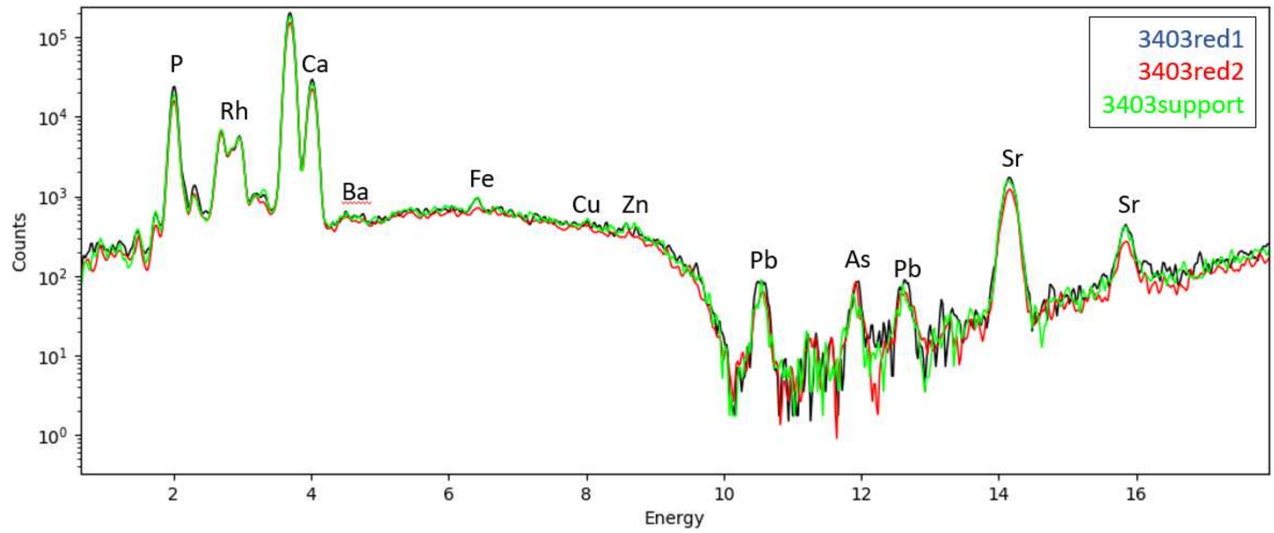


Fig. 59 - p-XRF spectra from two red spots and the near bone matrix analysed in the sample 3403.

Even in the p-XRF spectra, as it was for the SEM-EDS, the composition of the red spots is not different from the general composition of the bone (fig. 57-59). Indeed, phosphorus (P) and calcium (Ca) peaks (the ones referring to the bone composition) are clear in the spectra. There is a little peak of iron (Fe), as it resulted from the SEM-EDS spectra, while the peak of rhodium (Rh) is linked to the p-XRF instrument. More interesting and unexpected are the peaks of lead (Pb), arsenic (As) and strontium (Sn). These elements can perhaps suggest the use of a red lead (Pb_3O_4) or an arsenate (like realgar, As_4S_4) as a red pigment, rather than a red ochre, as it was the initial hypothesis, or, it could be used even a mixture of them.

6.1.3.3. Raman spectroscopy

The Raman spectroscopy analyses didn't give good results, as the background fluorescence complicated the identification of the baseline of each peak. Only two samples were analysed in this case: 3315 and 3451. They were selected for their little dimensions and regular shapes, as it was for the SEM-EDS and p-XRF analyses. Three different laser wavelengths (532, 633 and 785 nm) were used in three red spots of sample 3315 and one laser wavelength (633 nm) was used for one red spot from the sample 3541 (fig. 60-61, table 8).

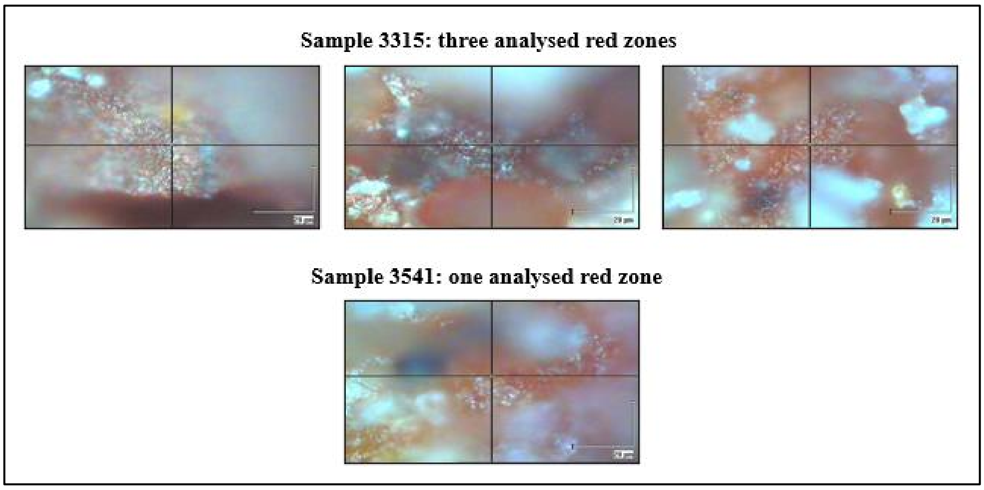


*Fig. 60 – **Red spots** analysed by the Raman spectrometer: three red spots from sample 3315 (above) and one red spot from sample 3451 (below).*

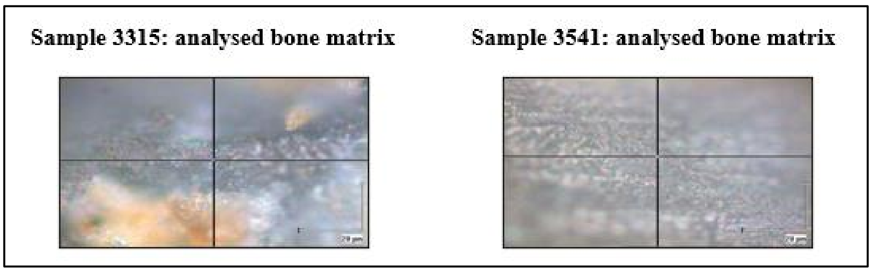


*Fig. 61 – **Bone matrixes** analysed by the Raman spectrometer: one zone from sample 3315 and one from 3541.*

Nora 3315 - 1 - Red zone 532nm x50 Pw10% t5x12s
Nora 3315 - 2 - Bone support 532nm x50 Pw50% t5x30s
Nora 3315 - 3 - Darker red zone 532nm x50 Pw10% t5x40s
Nora 3315 - 4 - Red dot 532nm x50 Pw25% t5x30s
Nora 3315 - 5 - Red zone close to #1 785nm x50 Pw50% t2x10s
Nora 3315 - 6 - Red zone exactly #1 785nm x50 Pw50% t2x10s
Nora 3315 - 7 - Darker red zone exactly #3 785nm x50 Pw25% t2x10s
Nora 3315 - 8 - Red dot exactly #4 785nm x50 Pw50% t2x10s (100-1600cm-1)
Nora 3315 - 9 - Red dot exactly #4 785nm x50 Pw50% t2x50s (15000-3500cm-1)
Nora 3315 - 10 - Red zone close to #1 633nm Pw25% x50 t5x10s
Nora 3315 - 11 - Darker red zone exactly #3 633nm x50 Pw25% t5x10s
Nora 3315 - 12 - Red dot exactly #4 633nm x50 Pw25% t5x10s
Nora 3541 - 1 - Red zone 633nm x50 Pw25% t3x10s
Nora 3541 - 2 - Black grain 633nm x50 Pw25% t5x10s
Nora 3541 - 3 - White bone 633nm x50 Pw25% t2x10s
Nora 3541 - 4 - Bone middle of body 633nm x50 Pw25% t5x20s

Table 8 – Raman conditions for each detected zone. The laser wavelengths are highlighted.

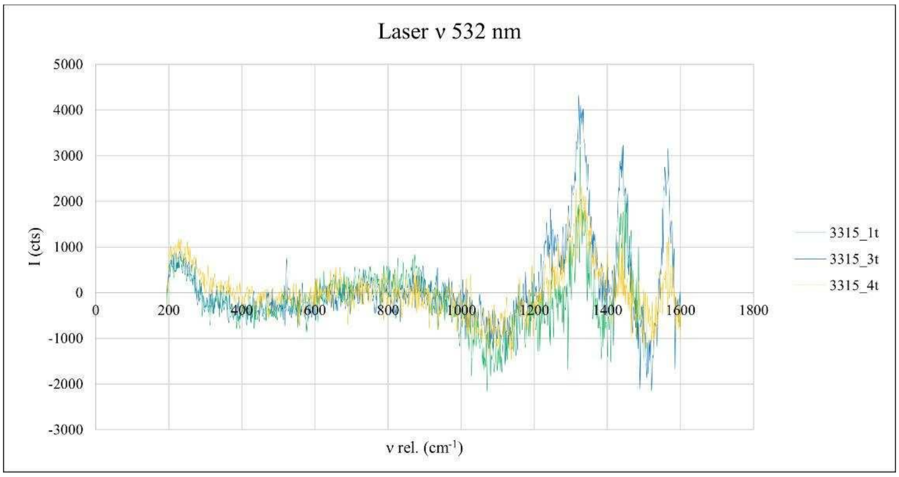


Fig. 62 – No results from the Raman analyses made on the three red spots from sample 3315 with 532 nm of laser wavelength.

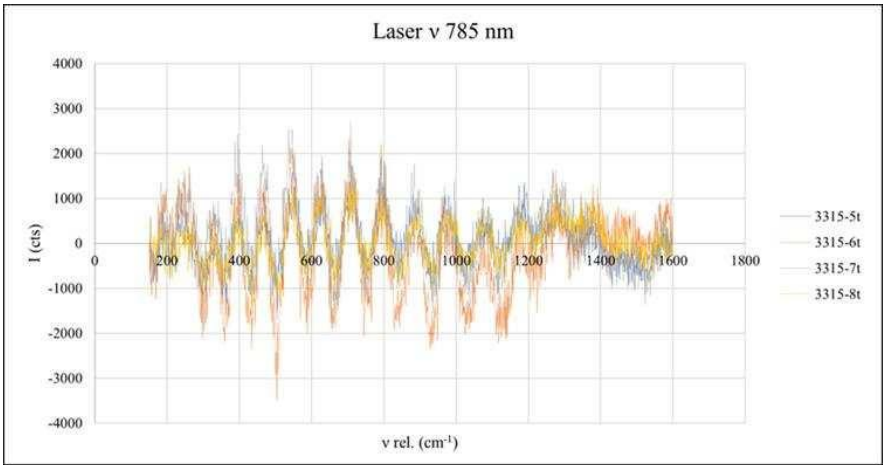


Fig. 63 – No results from the Raman analyses made on the three red spots from sample 3315 with 785 nm of laser wavelength.

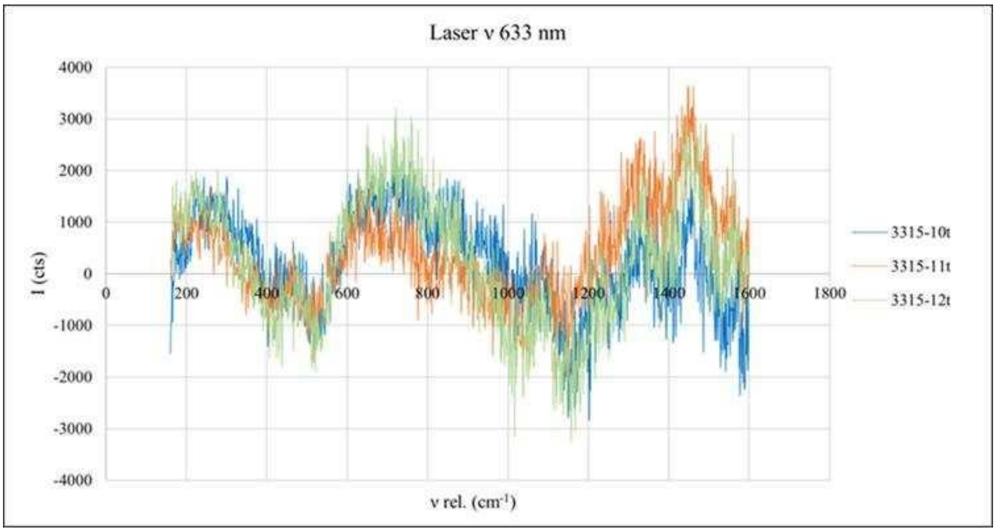


Fig. 64 – No results from the Raman analyses made on the three red spots from sample 3315 with 632 nm of laser wavelength.

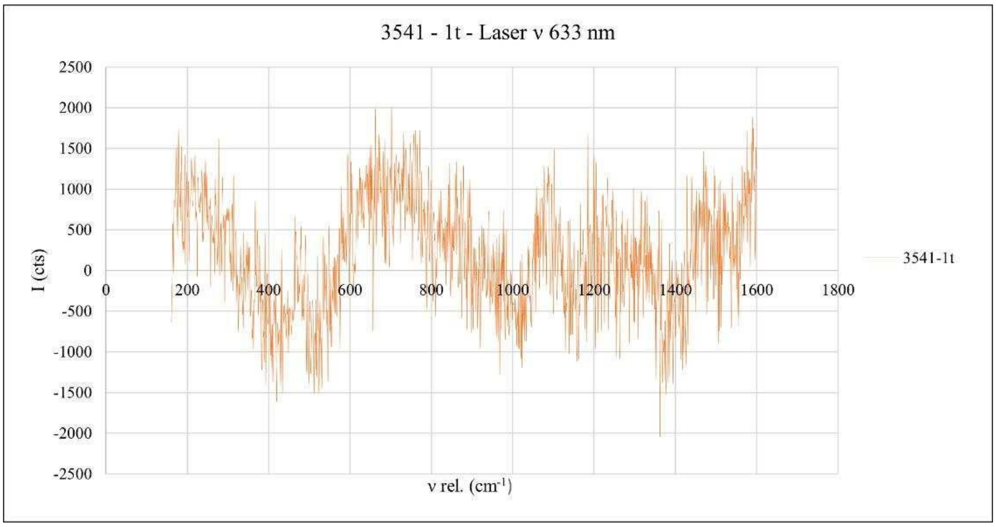


Fig. 65 – No results from the Raman analyses made on the three red spots from sample 3541 with 632 nm of laser wavelength.

All the analysed red zones didn't give results, but just high fluorescence problems (fig. 62-65). So, we couldn't confirm the possible presence of hematite, red lead or realgar, according to the hypotheses made through the other instruments' results. We therefore tried to see if it was a problem related to the instrument, and we measured the hematite pigment from a sample from the prehistoric site of Abri-Pataud (France) (fig. 66). This gave actually good results, showing the typical peaks of hematite. Thus, it was concluded that it was a problem probably linked to the extensive alterations on the bones' surfaces, along with the few treatments they had received throughout the years after the excavations (as it is a suggested common problem for bones analysed through Raman spectroscopy by UNAL M. *et alii* 2021). Actually, this is a problem concerning not only the red zones, but also the bone matrixes (fig. 67).

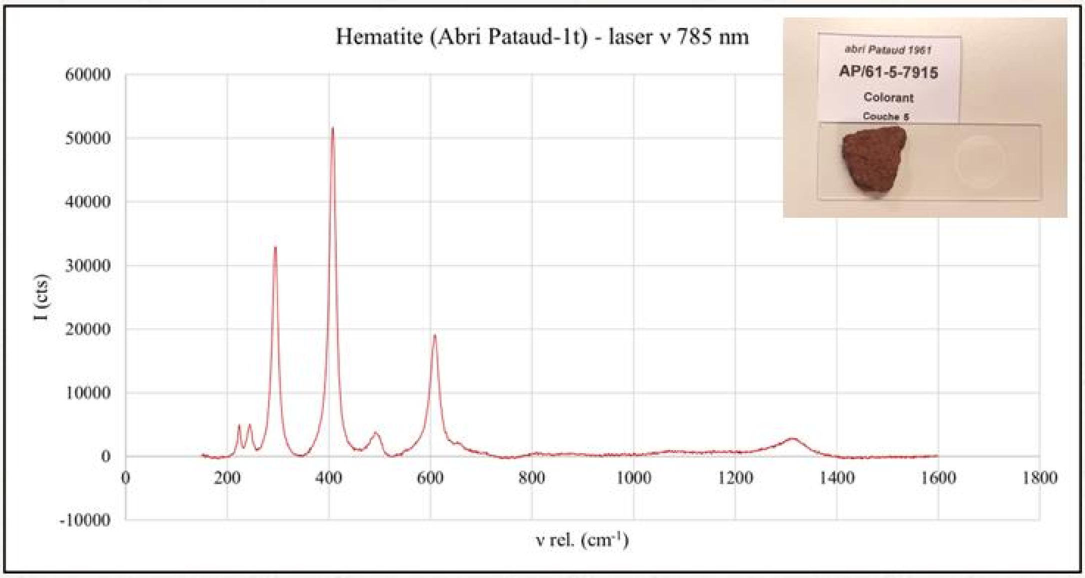


Fig. 66 - Raman spectrum of an example hematite pigment detected from a sample from Abri-Pataud site (France). The results show no fluorescence, therefore the lack of signals from the bones red zones is not related to instruments' problems.

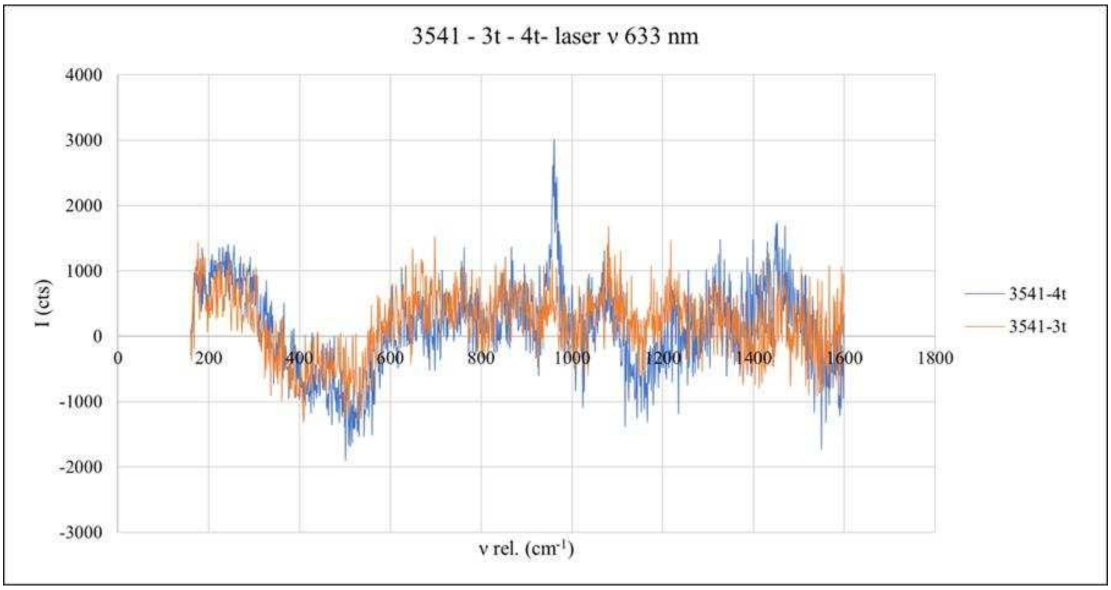


Fig. 67 – Raman spectrum of the bone matrix of sample 3541. The signal is in general very noisy, even if the characteristic apatite peak is a bit visible at 965 cm^{-1}.

6.1.3.4. VIS-NIR HSI

The last analyses were performed on all the five samples (fig. 53) with the hyperspectral camera. From the obtained spectra, it's clear that the curve has a sigmoid shape with a calculated main point of inflexion at 600 nm (fig. 66).

To confirm the hypothesized contamination of the bones by dissolution of hematite, red lead or realgar red pigments, I compared their HSI spectra with the ones I obtained from the red spots on the bones. It is known that the typical absorption bands of hematite are positioned at 580 and 875 nm, the main band of red lead is at 565 nm and the one of realgar is at 530 m (fig. 69-70) (ACETO M. *et alii* 2014), but none of these correspond to the obtained spectra (fig. 68).

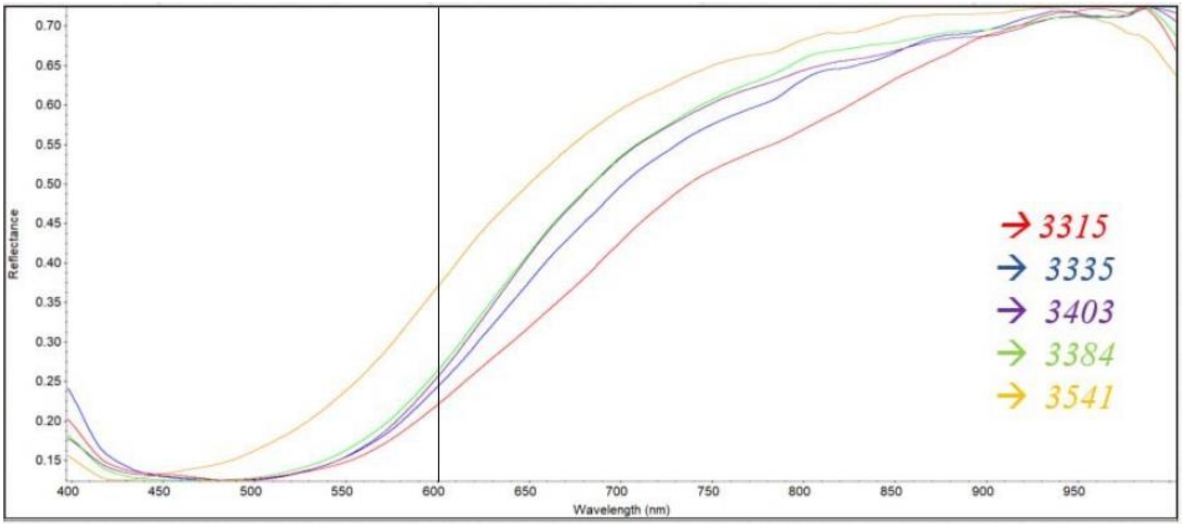


Fig. 68 – Representative hyperspectral imaging spectra of the red spots of five bones (3315, 3335, 3404, 3384, 3541). It is evident a point of inflexion at 600 nm (black line).

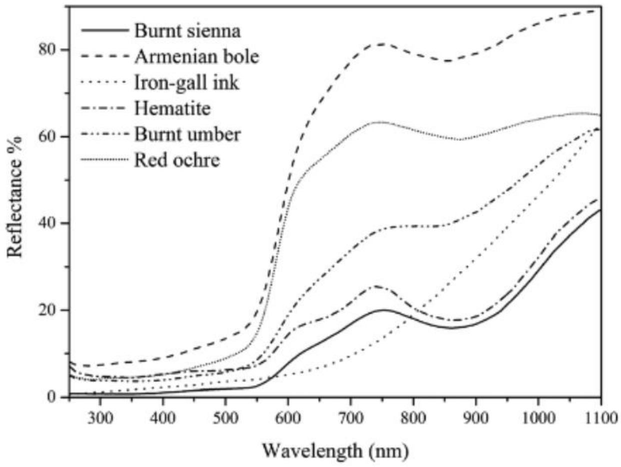


Fig. 69 – Spectra of red and brown iron-based colourants (ACETO M. et alii 2014).

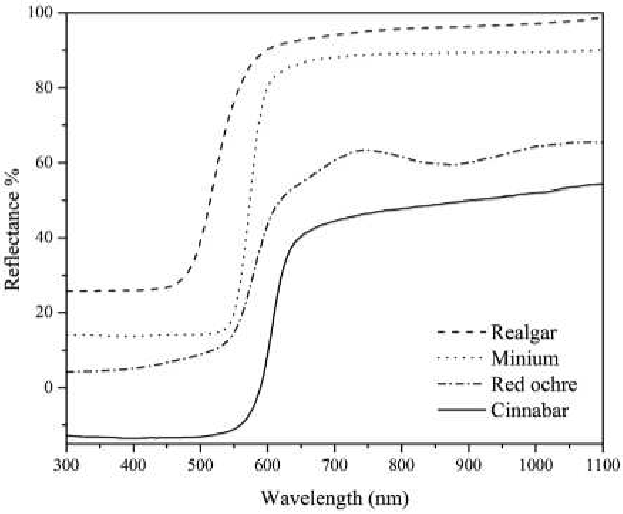


Fig. 70 – Spectra of red and orange pigments (ACETO M. et alii 2014).

Another hypothesis could be the possible presence of blood traces producing these reddish coloured spots on the bone surfaces. Given that I had no readable results by the Raman spectra and that with the SEM-EDS and p-XRF I had basically the same results of the bone matrixes (a part from Pb and As), I used the HSI spectrum reference in particular to confirm this latter hypothesis. According to CADD S. *et alii* 2018, the blood reflectance spectrum in the visible region is dominated by the presence of haemoglobin, which spectrum contains a strong narrow absorption at 415 nm, called the Soret or γ band, with two weaker and broader absorptions between 500 and 600 nm, known as the β and α bands (fig. 71). They're actually well-defined peaks, therefore, neither this time corresponding to our spectra (fig. 68).

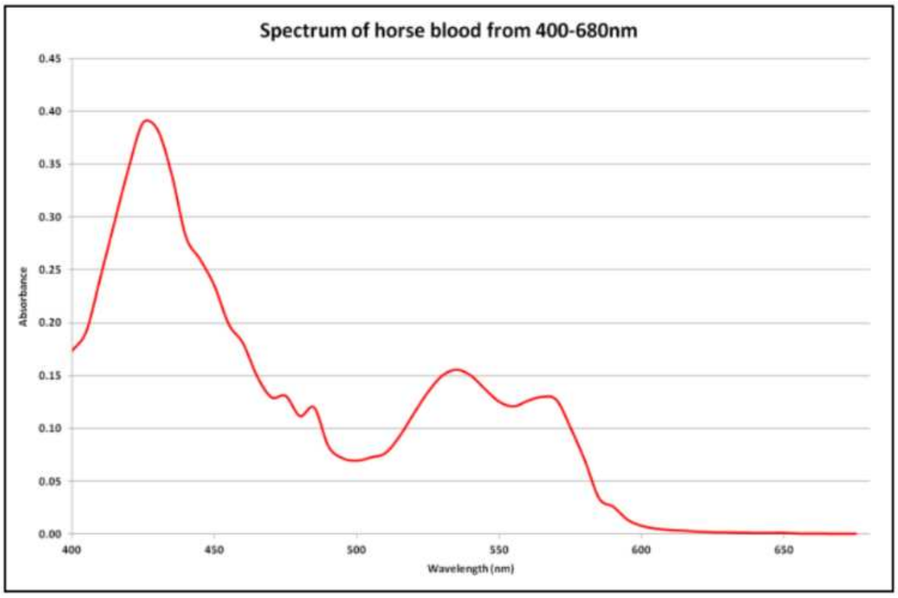


Fig. 71 – Spectrum of blood from 400-680 nm (CADD S. et alii 2018).

Therefore, we could perhaps think for example about a shifted red lead (600 nm instead of the 565 of the reference red lead), or the use of a mixture of hematite, red lead or realgar red pigments. Since the presence of Pb and As detected with the p-XRF cannot be ignored, more analyses are needed to rule out that these elements are related to the dissolution of the red pigments of the building coloured plasters on the worked bones. Thus, p-XRF is the best way to detect these elements and it could be used to recognize Pb and As on some plasters samples from the room VII of the building near the east side of the Roman forum of Nora. Actually, it is already known the use of different red pigments on the walls of the Nora houses (GALLUZZI F. 2014), so it wouldn't be unexpected to have similar results.

6.2. Reconstruction of the manufacturing sequence

6.2.1. Material selection: archaeozoological statistics recalculation

In paragraph 2.2. I already discussed the Nora bones' taxonomic determination and reference species. Therefore, here I will just provide a recalculation of the Nora worked bones' percentages to include the 40 bones remaining unstudied in the last two years. This part didn't require any type of equipment, since it was possible to determine the species and the relative side of the bones just through macroscopic observations. Also, during this calculation, I obviously needed to take into account all the 264 Nora's worked bones.

We start from the fact that today the total number of the faunal remains that show anthropic modifications aimed to obtain bone supports or artefacts is for sure 264. It is a number that doesn't include the faunal remains that don't exhibit any anthropic mechanical modifications, such as a fragment of a small ungulate rib, a fragment of an ostrich egg, a fragment of a long bone diaphysis pertaining to avifauna, or others bones found in the same room of the building, that clearly cannot be considered part of the manufacturing sequence. Of these 264, the majority (67,4%) is indeterminable at the anatomical element level, indicating the high degree of selection of the material. Of the bones that could be determined by anatomical element, the majority (77,9%) were confirmed to be bones pertaining to the radio-ulnar region (fig. 9). Specifically, 25 of the remains refer to fragments of radii whose diaphysis is still fused to the ulna; plus 20 fragments of radii only and 22 portions of ulnae only. Thus, there are 8 femurs and 12 tibiae (fig. 67).

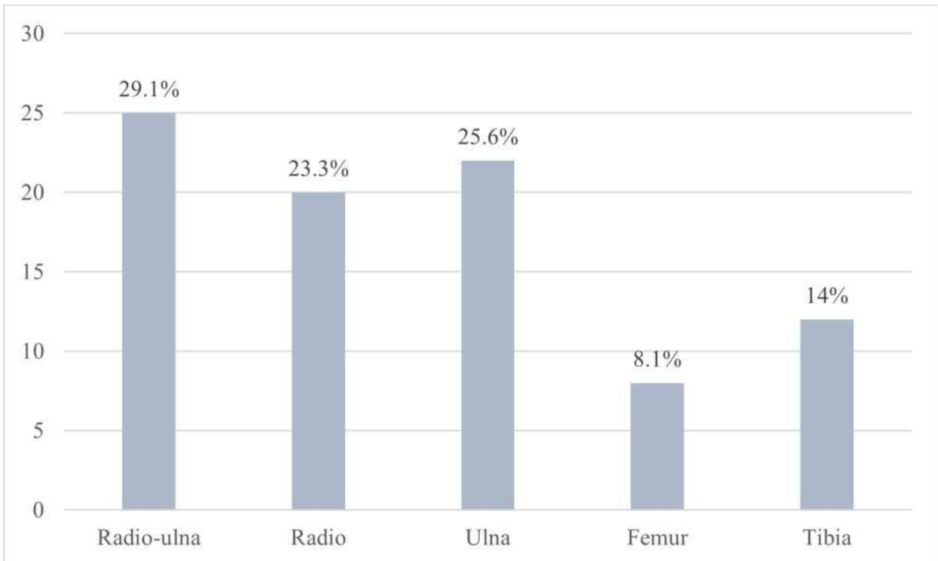


Fig. 67 – Anatomical elements statistics representation (modified from PONTIS E. 2022).

For 26.5% of the sample, corresponding to 70 bones, it was possible to distinguish between left and right bones, thanks to the preservation of diagnostic elements such as holes for nutrient vessels (*foramina*), roughness and morphological features. In general, we note that of the remains that provide us with laterality 38 are left and 32 right (Table 9, fig. 68-72).

SIDE	LEFT		RIGHT	
ANATOMICAL ELEMENT	NR	NR%	NR	NR%
Radio-ulna	15	39.5	10	31.3
Radio	8	21.1	3	9.4
Ulna	12	31.6	9	28.1
Femur	2	5.3	5	15.6
Tibia	1	2.6	5	15.6
Tot.	38	54.3	32	45.7

Table 9 – Anatomical elements divided by side, number of remains (NR) and percentage values (modified from PONTIS E. 2022).

Fig. 68 – The 25 fragments of radii whose diaphysis is still fused to the ulna, divided by side: left side in blue, right side in red.

Fig. 69 – The 20 fragments of radii only, divided by side: left side in blue, right side in red, undetermined side in green.

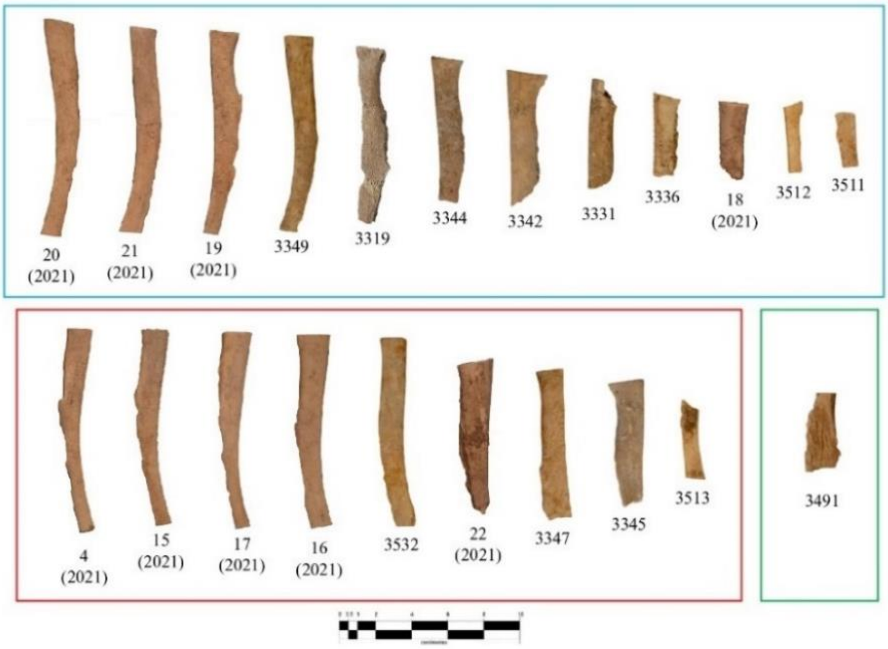


Fig. 70 – The 22 fragments of ulnae only, divided by side: left side in blue, right side in red, undetermined side in green.

Fig. 71 – The 8 fragments of femurs, divided by side: left side in blue, right side in red, undetermined side in green.

Fig. 72 – The 12 fragments of tibiae, divided by side: left side in blue, right side in red, undetermined side in green.

The count of the minimum number of individuals that were used in this craftsmanship can be inferred from the anatomical element that appears most frequently. There are 15 left and 10 right radii-ulnae. Following the approach initially employed by WHITE T.E. 1953 (DE GROSSI MAZZORIN J. 2008), we should consider the most abundant lateralized component. It's evident that within the radii-ulna, a minimum count of 15 individuals can be established. Additionally, it's reasonable to include the count of fragments specifically from the left radii. During the analysis phase, the lateralization of these fragments linked to this anatomical element were determined based on the *foramina* connected to impressions and attachment roughness to the ulnae. This determination excludes their inclusion in the previously calculated radii-ulnae, as they pertain to the same diagnostic segment. Instead, the accurate quantitative assessment of the ulnae remains uncertain, making it difficult to entirely dismiss their potential association with radii.

Concerning the remaining anatomical components, it's worth mentioning that the right side demonstrates the highest frequency for both the femur and the tibia. The collection of 5 fragments from the right femur should be attributed to distinct individuals, given that identical diagnostic segments are conserved across all these fragments. Similarly, this applies to the set of 5 tibia fragments. Nonetheless, due to the extent of selectiveness in the material, which prevents the confirmation of additional diagnostic factors like sex and ontogenetic age, it remains a possibility that the collection of 5 femur and 5 tibia fragments may not correspond to the identical 25 individuals mirrored by the left bones within the radio-ulnar region.

Consequently, the ascertained minimum count of individuals contributing to the faunal assemblage totals now 23 oxen.

6.2.2. CUTTING: MICROSCOPIC OBSERVATIONS

Apart from the macroscopic archaeozoological work, my dissertation focused on the microscopic reading of the cutmarks present on the bones' surfaces (in particular, of the selected 12 bones). Two were the aims: the understanding of the techniques used in this bones manufacturing, and, secondly what instruments were used by the artisan(s). I started reading the cutmarks through stereomicroscopic observations. The process involved the specific description of all the types of marks I saw on the bones with a consequent classification (Appendix B). Therefore, I chose the most interesting and useful parts to be visualized and measured through the SEM microphotographs and, last but not least, I used the confocal microscope for making measures. Once that the techniques of bone manufacturing were understood and all the bones, together with the specific twelve selected bones, were generally classified in the crafting sequence, I could work on the specific identification of the classes of instruments, thanks to few particular marks present on three bones.

As concerns the cutting techniques identified in this specific *chaîne opératoire,* I was able to recognize only sawing marks. If the cutmarks appeared different macroscopically, when I started to see in detail the traces with the stereomicroscope and the ESEM, I understood that they all present the same striations type. It is the action and the power used by the artisan that make them look different (fig. 75). It was essential to understand firstly, how the instruments are designed and, secondly, how cutting movement took place. Without knowledge of the principles of cutting action of saws or knives and of the response of bone to this reciprocating and continuous motion, the data from these measurements may misrepresent the facts. Actually, saws are defined as blades with teeth. When analysing saw features, one must consider the way in which the teeth are "set." The set produces distinctive marks in the cut surface. For example, if teeth are bent (set) right and left, the teeth carve out a wider kerf (the actual saw trough) than the blade width. This design allows a blade to deeply penetrate a hard material without binding. Other design features usually revolve around the teeth, particularly with regard to shape and size. Today, we can distinguish for example the "rip cut" saws, that have teeth not angled or filed, forming a flat chiseled face, designed to tear along the grain, acting like a miniature chisel; and the "cross cut" saws, teeth filed to an angle, with a design that allows each tooth to act like a small knife and slice through the wood. As concerns the teeth, there is a distinction for example among the "alternating" teeth, in which adjacent teeth are bent in an opposite direction, and the "wavy" teeth, that are laterally bent in groups (fig. 74). In the case of crosscut saws, their consecutive teeth are sharpened at opposing angles, typically around 70 degrees. This sharpening process results in teeth that end in a pointed shape, resembling a set of finely honed blades that slice through materials, akin to a sequence of knives, rather than chipping away at them. On the other hand, traditional rip saws lack sharpened teeth and, as a result, produce a flat-bottomed groove when cutting (saw 4 in fig. 74).

A common misconception is that saws and knives are similar in appearance. Knives can be differentiated from other blades in that knives are tools with a thin blade that sometimes terminate in a point. Knives also commonly have blade bevel (blade tapering) and always have at least one area of edge bevel (sharpened edge) on the blade. To distinguish knives from saws it is useful to look at their cross section. Knives leave a typical V-shaped cross section, saws have usually a U- or W- shaped cross section (SYMES S.A. *et alii* 2010).

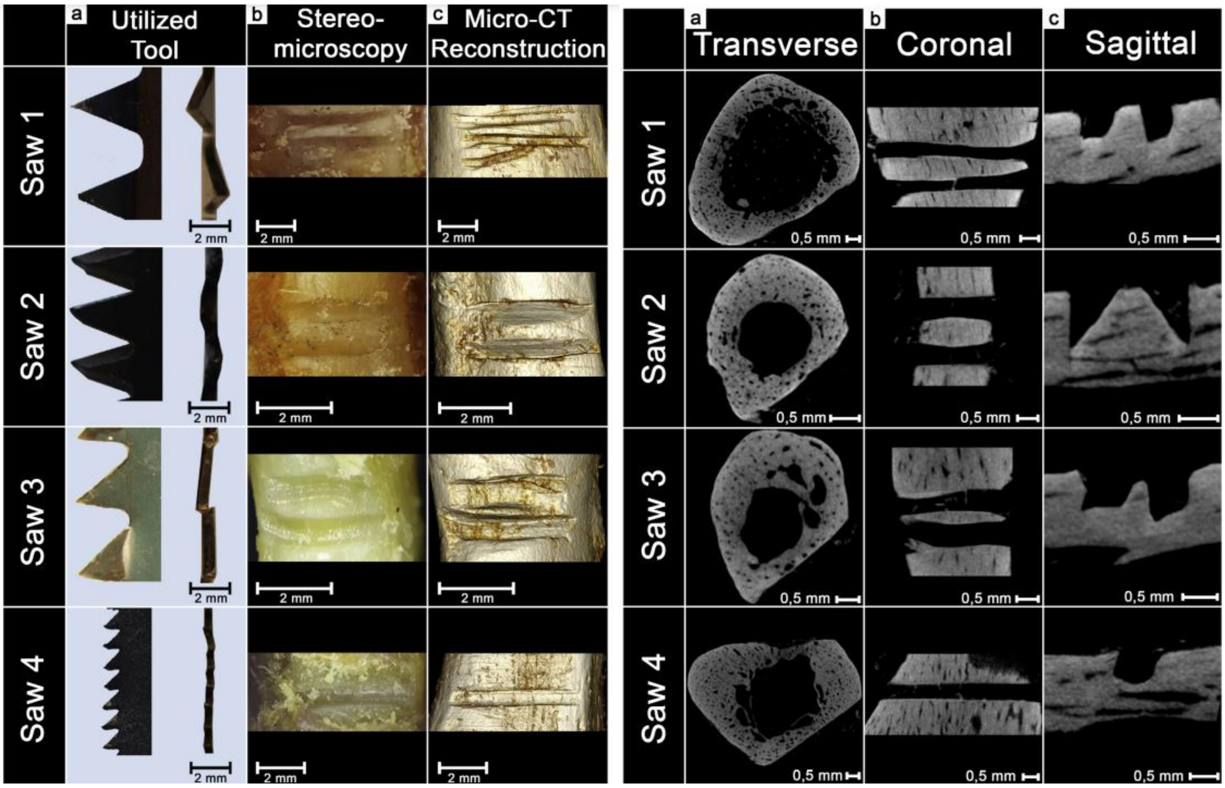


Fig. 74 – From the left to the right, visual comparisons of the saws used in an experiment in a frontal and a lateral view; pictures of false starts obtained by stereomicroscopy; 3D reconstructions obtained by micro-CT. Saw n. 1: 5 teeth per inch (TPI) rip cut saw with alternating set; Saw n. 2: 8 TPI crosscut saw with alternating set; Saw n. 3: 10 TPI rip cut saw with alternating set; Saw n. 4: 24 TPI rip cut saw with wavy set. On the right, multiplanar reconstructions (MPR) obtained by micro-CT, showing the morphological features of the false starts in each Cartesian plane: transverse (a), coronal (b) and sagittal (PELLETTI G. et alii *2017).*

As concerns the cutting action, the sawing recognized on the studied twelve bones is a general pushing and pulling action. The critical phases are the initial and final stages. It is actually possible that in these instances craftsmen misused their tools on the bone's surface. The blade would slip, causing cuts beyond or beneath the intended location, resulting in shallow grooves that mostly disappear as the work continues. At the beginning of the sawing process, the worked area exhibits extremely fine and closely spaced striations, often with the sawing direction changing frequently. Similarly, at the end of the sawing operation, when the craftsman aims for a clean cut, we observe a similar pattern. In a few cases, whether due to retouching the work or exerting more pressure on the section to be detached, the fine sawing grooves develop on a slightly inclined plane or a slightly raised area (in forensic science this is called "break-away spur") (fig. 75 and for a general view of the bones that have them see Appendix B). This suggests that when nearing the end of their work, the craftsman intentionally increased the angle of their tool.

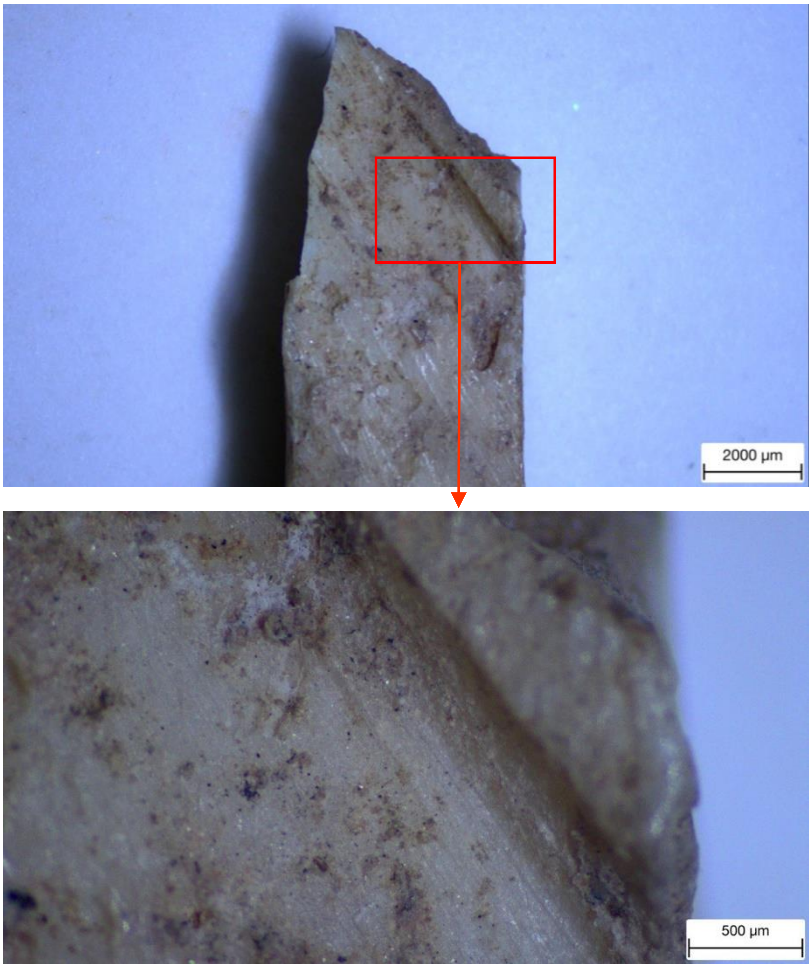


Fig. 75 – Stereomicroscope images (x8 and x40 magnification) of sample 3416. Break-away spur produced at the end of the sawing movement.

The four saws' types shown in fig. 74 are distinguishable only through single cutmarks on bones, while in the most part of the twelve samples the marks are multiple and show different patterns according to the movement, the power or the inclination of the instrument used to cut them. So, the overall patterns observed on the cut surfaces of bone were of little use, because the saw teeth change or wear when cutting hard material, due to a continuous push and pull motion (fig. 76). Few measures could actually recognize the difference between force and saw design. In particular, only the ones took in single cuts, made by error by the artisan(s), which in Appendix B I defined as "false starts" of cuttings. It's therefore important to understand this distinction between single and multiple marks, respectively corresponding to the distinction between instruments false starts of cutting and continuous/consecutive cutting actions. This is why the instruments recognition wasn't easy and straightforward, and the ESEM images didn't result as accurate as the confocal microscope to measure these few significant cutmarks.

I measured the width and depth of the single cutmarks (where it was possible, see fig. 77) and then, the cuts' data collected were applied to saw blade and tooth characteristics of size, set and shape. This information was used to hypothesize the saw class or type. To have a clear image of the entire set of instruments that could be utilized by artisans I used manuals, for instance GAITZSCH W. 1980, and comparisons with the known archaeological findings (for example the saws in fig. 37).

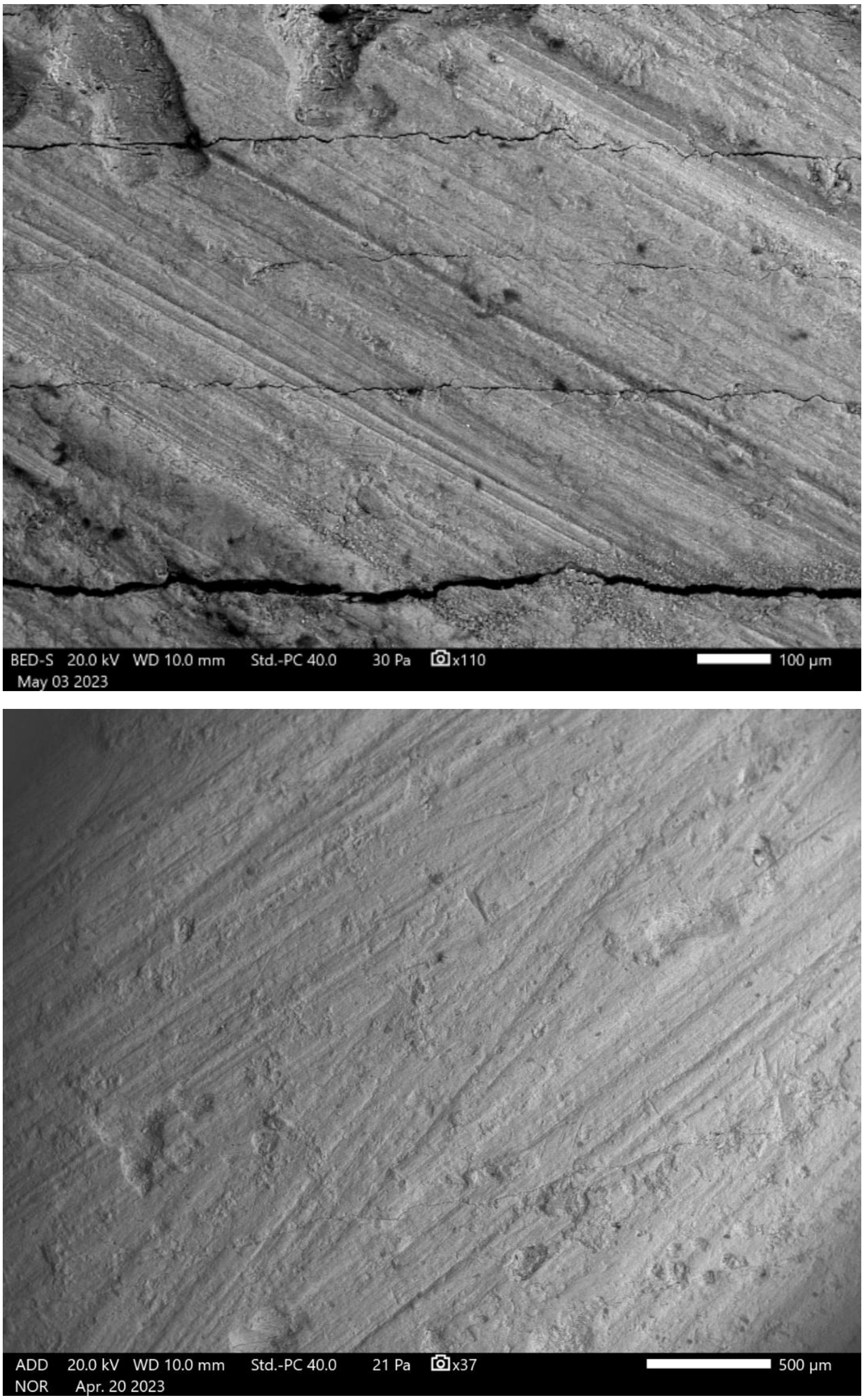


Fig. 76 – ESEM microphotographs of samples 3460 (above) and 3338 (below). An ordered striations pattern is visible in the image above, while in the second image the striation pattern is irregular and continuously changing. This is due to the sawing movements, inclinations and power that the artisan put in the cutting action, but the created striations, thus the used instrument, is the same.

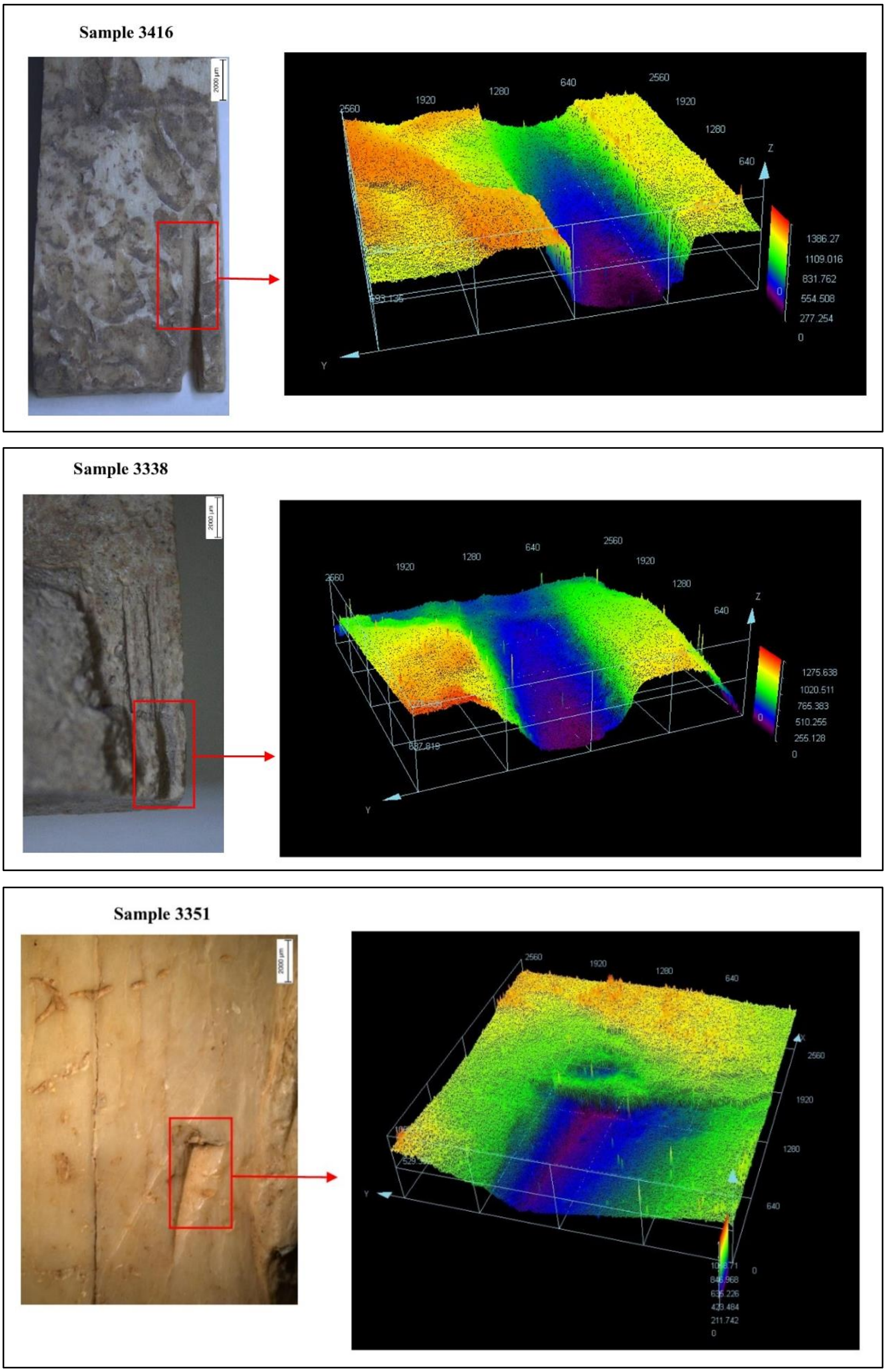


Fig. 77 – Confocal microscope images of sample 3416, 3338 and 3351 showing the single marks that could be measured to make hypothesis about the size of the instruments used.

Sample	Width max (µm)	Depth max (µm)
3416	742.5	980.9
3416	755	909.2
3416	785	818.1
3338	800	336.7
3338	757.5	302.55
3338	732	188.55
3351	580	292.56
3351	567	144.25
3351	647	223.05
Average	**707.3**	**466.2**

Table 10 – Measures of width and depth of the single cuts measured in samples 3416, 3338 and 3351. More than one measure was taken for each cut.

From these results, we can see how the single cuts from samples 3416 and 3338 could be actually used as proofs of the instruments used. Instead, the single cut measured in sample 3351 is not as easy to read. As shown in the table, the average maximum width of these three measured cuts is 707.3 µm, while the average depth is varying a lot between the three, having the minimum results from the sample 3351. This is due to the intensity that was used to infer the cut.

However, because at least the single cuts in samples 3416 and 3338 show a U-shaped cross-section and similar measurements, we can definitely talk about saws, and specifically rip cut saw with wavy set (see saw 4 in fig. 74). It's very difficult to arrive at the specific type of saw used, as it is even possible that the artisan used more than one type in his work. From the known literature and comparisons, it can be just hypothesized that saw like the ones in fig. 79 was used.

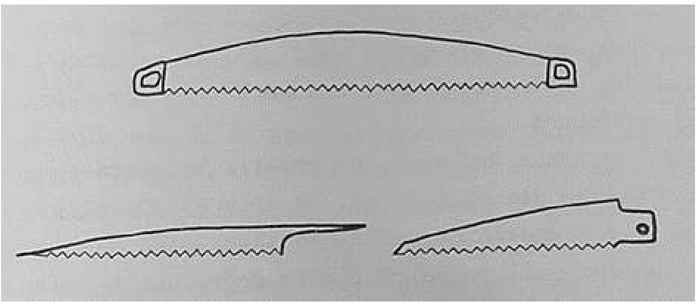


Fig. 79 – Blade-saws: bandsaw (above) and jigsaws (below) (GAITZSCH W. 1980).

6.2.3. SMOOTHING: MICROSCOPIC OBSERVATIONS

Clear smoothing traces were visible on sample 3541 and 3460. This time, the striations were clearly finer and slightly sinuous (fig. 80-82), having a pattern clearly different than the sawing marks.

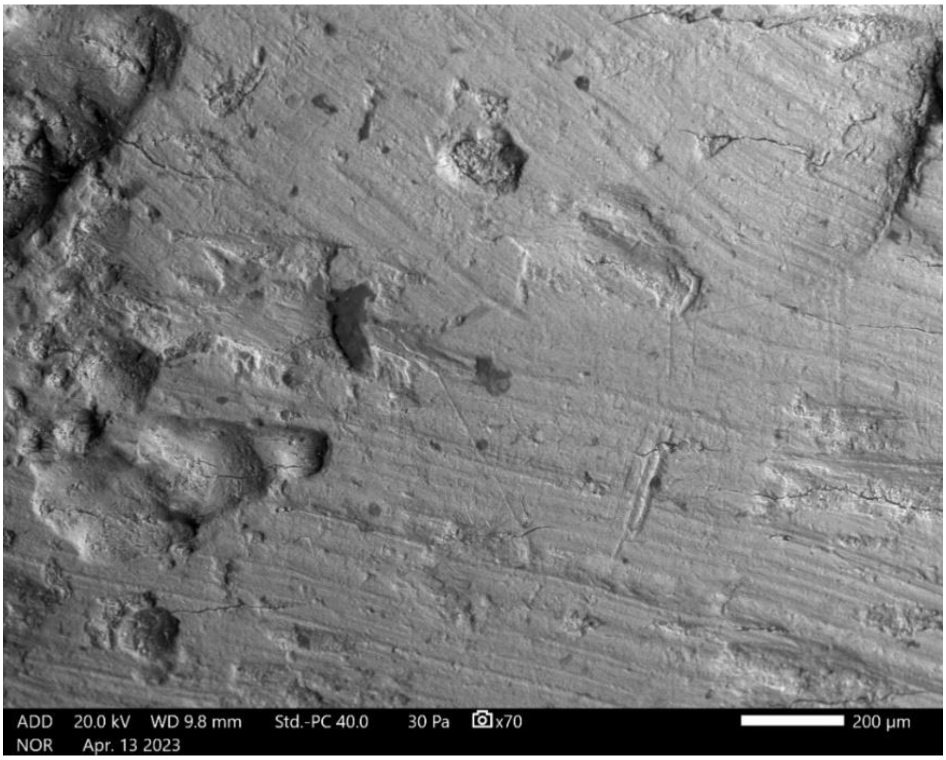


Fig. 80 - ESEM microphotograph of smoothing striations from the sample 3541.

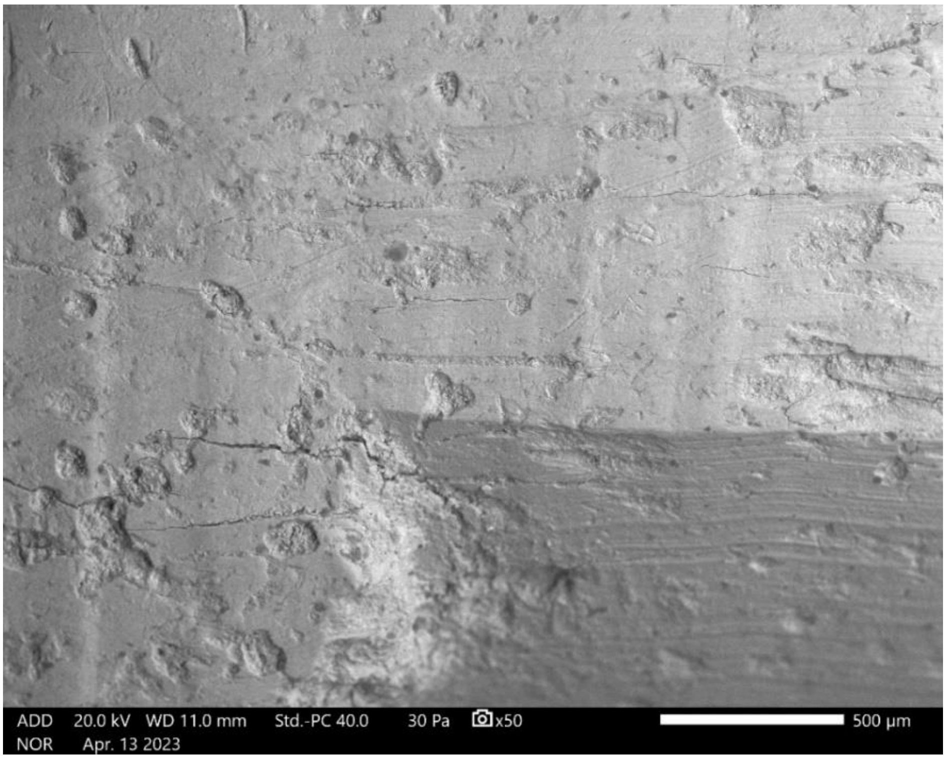


Fig. 81 – ESEM microphotograph of smoothing striations from the sample 3541.

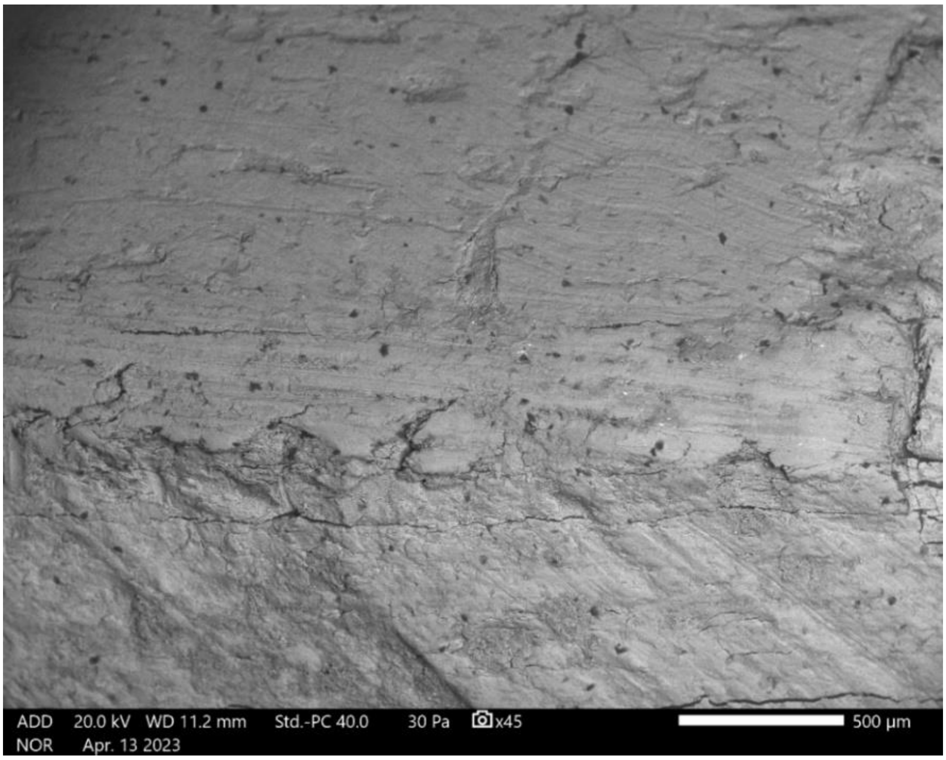


Fig. 82 – ESEM microphotograph of sample 3460 which show a clear distinction between the smoothing marks (above) and the sawing marks (below). In between an angle smoothing proof.

These images allow comparisons with existing studies on bone abrasion (ORŁOWSKA J., CWIEK M., OSIPOWICZ G. 2022; FERNÁNDEZ-JALVO Y., ANDREWS P. 2016). Abrasion, which involves the smoothing and polishing of bones, varies depending on their condition, whether they are fresh, dry, weathered, or fossilized. Weathered bones are more susceptible to abrasion, and different types of sediment, such as gravel, coarse sand, fine sand, clay, and silt, can influence the extent of abrasion. However, in this case, the observed regular striations suggest the possible use of tools like files or knives, as these are the only instruments capable of producing such distinct marks. The evidence does not support the idea of polishing on these twelve bones. Given the delicate nature of the polishing process and the considerable alteration of the bones, it is challenging to define this type of action definitively.

6.2.4. DRILLING AND TURNING

Among all the 264 worked bones from the building near the east side of the forum, there are just two pieces of evidence of the drilling action: the needle 3316 and the hinge 40 (fig. 83-84). They also represent the unique examples of needle and hinge typologies within this specific collection. Just the needle 3316 has been observed through the stereomicroscope. From this observation, I could notice a really smoothed internal surface of the needle eye, without any kind of cutmarks (fig. 83). This might imply that the object was nearing completion, approaching the final stages of its production. Even in this case, the bad state of conservation of the object couldn't allow us to confirm this hypothesis.

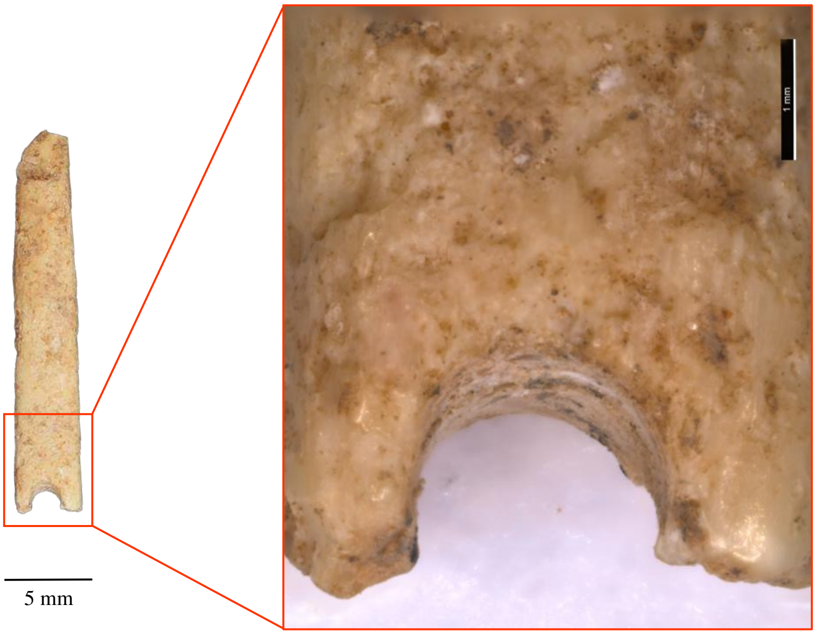


Fig. 83 - Needle 3316, the only evidence of drilling process among the 264 worked bones from the building near the east side of the forum of Nora.

The second perforated object is the hinge 40, evidence also of the turning technique. It is thus clear its importance to confirm the use of a lathe by the bone artisan(s) in the late antique city of Nora. In particular, circular cutmarks are visible all around its central hole even by the naked eye (fig. 84). Unfortunately, this object couldn't be microscopically observed.

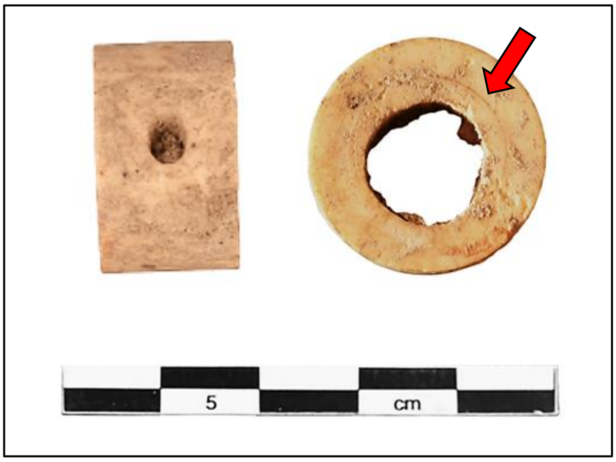


Fig. 84 – Hinge 40 (2021), evidence of the turning process: there are circular marks running overall the bone section (highlighted by the red arrow).

It is clear that these working phases are related to the production of specific items. So, considering that the needle and the hinge are just two of their kind within the assemblage, we can hypothesize that this wasn't the main work that the artisan(s) could have done at the building near the east side of the forum of Nora. He/She/They would rather have preferred working on pins or *stili,* so basically thin elongated and pointed rods (fig. 85; see Appendix A for a complete overview of the findings), tools which manufacture didn't require complex clamping techniques or lathes, but just a good precision of cutting.

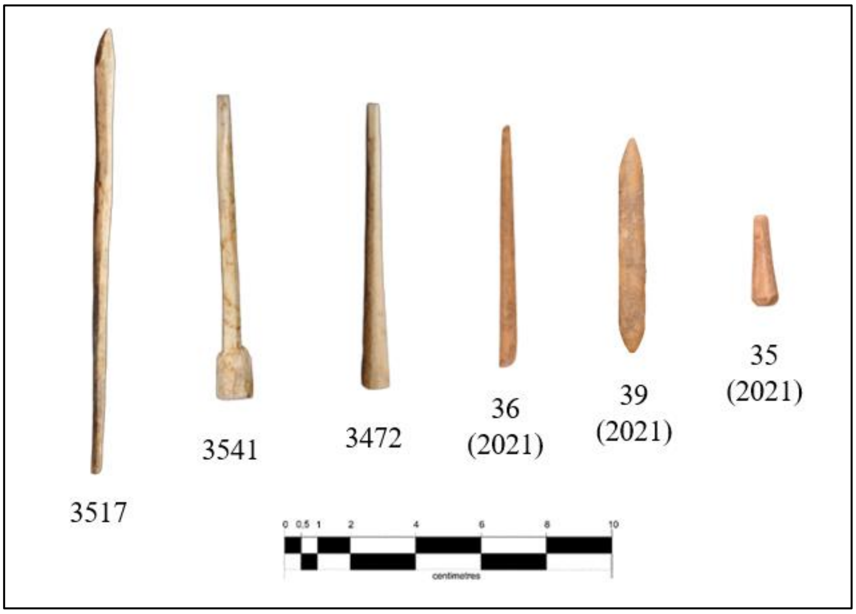


Fig. 85 – Most represented artefacts' typologies from the building near the east side of the Roman forum of Nora, room VII. Although they're not finished, these on-working bones are really close to common Imperial non-decorated pins (3517, 3541, 3472, 36, 35) and stili *(39) typologies.*

6.2.5. USE-WEAR

Even if the studied bones from the building near the east side of the Roman forum are not finished objects (therefore never been used), meaning that they've been found still on an on-going working process, the sample 3403 gives some hint about the possible use of its tip (fig. 86). When observed with the naked eye and at 10x magnification, the *baguette*'s tip exhibits different smoothing traces compared to the regular ones created by a metal blade (fig. 86). These traces are longitudinal, quite long and parallel to the long axis of the *baguette*. At 95x magnification, the tip's examination shows an irregular topography, due to the variety in dimension and direction of the depressions, striations, micro-pits and craters. These irregularities are typical characteristics of the use's abrasion (LEGRAND A., SIDÉRA I. 2007). It's interesting to note that these traces are located on the active end of the *baguette*, on its tip, not a casual position for the use of a pointed object.

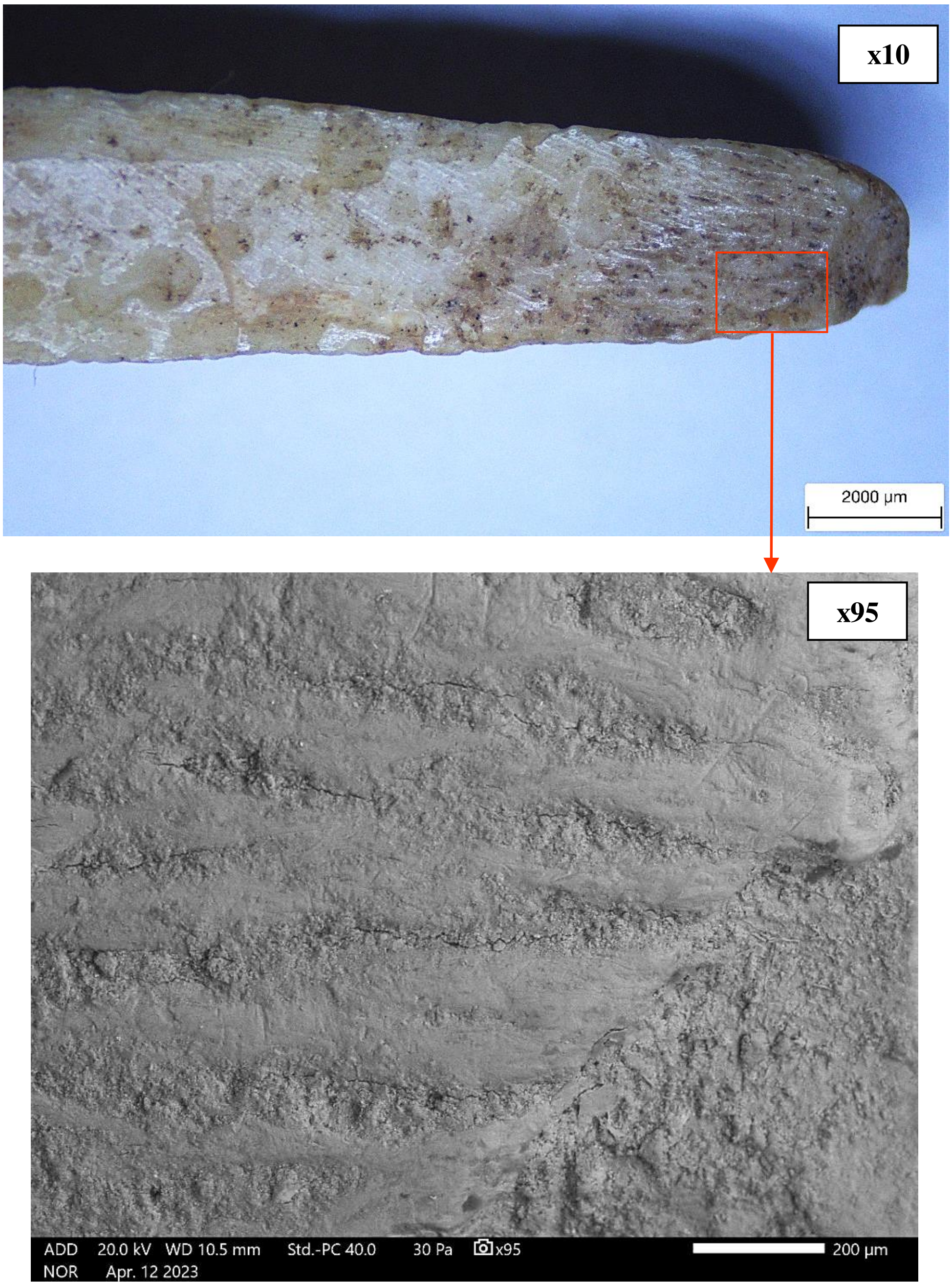


Fig. 86 – Stereomicroscope and ESEM images of 3403 sample tip showing traces of use-wear.

7. Conclusions and future perspectives

In the framework of the late antique city of Nora, from the last decades of the III century AD to no later than the beginning of the V century AD, the building near the east side of the Roman forum witnesses an artisanal everyday life moment of work, testified by 264 bones fragments of an ongoing craftsmanship, identified within the layers of collapse of the room VII.

Thanks to this interdisciplinary research, I confirmed the importance of the room VII' specialized bones working sequence, where oxen's long bones were utilized by an artisan (or more than one) to create little pointed artefacts. Specifically, the conducted detailed microscopic examinations and related studies on 12 chosen representative bone samples allowed me to read and classify the different working cutmarks on the bones' surfaces, using and compare different methodologies. The stereomicroscope and the confocal microscope appeared to be most useful instruments to use in the classification and measuring of the bones cutmarks. The samples could be moved and seen at different magnifications through the stereomicroscope and the confocal microscope was particularly useful to visualize and measure the cutmarks cross-sections. While, the observations conducted using the ESEM yielded similar findings and considerations as those obtained with the other instruments, reinforcing the consistency of the results across the other methods. Ultimately, through the meticulous examination and interpretation of cut marks, I successfully pieced together the theoretical *chaîne(s) opératoire(s)* responsible for the creation of these bone fragments. This comprehensive analysis illuminated the intricate processes and techniques employed in their production.

In particular, starting from the raw materials supply, the procurement of the bones must have taken place plausibly within the city butchers, where the artisan(s) chose mostly the oxen' radius and ulna diaphysis for his manufacturing. From the place of slaughter, the bones had to pass to a place (which is not necessarily the same) where they were completely stripped and decanted to be worked by the craftsman. This place, known from other archaeological sites, has not been found in Nora; it could be outside our workshop, as well as elsewhere. Here, the bones' epiphyses were cut and the diaphysis were preliminary prepared, being sought in water and treated in different ways to remove any remaining tendons and meat residues, along with the periosteum sheath. Once they were ready, the cut and clean bones were brought to the building near the east side of the forum, where the artisan(s) started his manufacturing inside the room VII, that could be the working environment where to progressively shape the prepared bones. Removed the bones' internal marrow, the first instrument that was used was the saw, probably a rip cut band- or jigsaw with wavy set. Both cross and longitudinal cutting are testified. In particular, from the radius diaphysis were extracted rectangular and triangular *baguettes* through longitudinal cuttings. Then, they were smoothed with the use of some files and cut again. The obtained *baguettes* could take two different paths: being cut and smoothed progressively with saw and files until the creation of non-decorated pins or *stili*, or they could have been perforated and turned with the use of a lathe to obtain more defined artefacts, such as needles and hinges. Since no finished objects have been found in the room VII excavations, these working remains cannot lead us towards a specific production with certainty. The artefacts could then have been sold elsewhere in or outside the city.

Many variables have been taken in consideration by the artisan(s), who seemed to have worked in a really specialized manner. In particular, there is a clear preference for only ox bones and only specific types of bones (the radius and ulna), with a discard of the ulna out of the fused radius, then there is the creation mostly of specific elongated shaped (usually the metacarpus and metatarsus are the bones most used to produce objects like pins or needles), even apparently limiting the use of the lathe. However, to confirm all the hypotheses made until now, the only thing that should be done is an experimental work. This approach allows to gain a practical understanding of how this process could have realistically unfolded, providing a deeper insight into the ancient practices and techniques employed. With the microscopic images of the work traces on these bones in hand, a direct comparison with experimental data is essential to rigorously assess the studied working techniques and the types of tools involved. This practical experimentation will provide valuable insight into the accuracy of the analytical findings. Also, it's essential to note that due to the limited representation of the 12 selected bones, the broader archaeological assemblage warrants further scrutiny. Still, it’s a good work to start reasoning about the precise techniques and objects that were used at that time in the Nora’s building.

Given the great homogeneity of the bone blanks, with partially shaped items and completed objects in the same context, we can hypothesize that we are in the presence of a single specialist, working in room of a former prestigious Roman house, not connected to other factories, but simply reutilizing the old house structures, using perishable tables, clamping machines and few easy-transportable instruments: saws, files, knives and also a lathe. The artisan was probably involved in the creation of the walls graffiti plasters found in a state of collapse in the room VII. The graffiti numerical counts may correspond to orders or commissions, for the production of a certain number of artefacts, to be subsequently distributed in the city, and perhaps even outside Nora. Even the city veterinarian is mentioned in an inscription and was somehow involved in the bones manufacturing. Actually, we cannot exclude the fact that the artisan himself was the veterinarian, considering his good knowledge of animals and their bones. He would for sure have known that the radius and ulna had great properties to produce little elongated objects, like pins, needles, *stili* or even his vet surgical probes. Otherwise, he could just be a client asking for specific products. Also, some of these bones baguettes or objects could have been used to write and draw on the painted plasters of the room VII, as it can be suggested by the use-wear present on the tip of the sample 3403.

The depicted bones manufacturing system needs however to be connected to the late antique socio-economic life of the city. For example, it is known that this artisan wasn't the only one: another bone craftsmanship has been already identified in some rooms of the so-called House of the tetrastyle atrium, in the Nora's western quarter (PESCE G. 1972). Also, from an inventory drawn up in the '50s of the last century, we know about the discovery of more than 800 bone objects in Nora, including fragments and intact objects, out of a total of approximately 3400 inventoried materials, to which we can add all the archaeological discoveries from the most recent excavations. This is why, among the possible study developments, it could be useful to conduct a comparative morphometric analysis with the finished specimens of pins found in Nora, already published and, as far as possible, of a chronology compatible with that of the semi-finished products found, in order to be able to trace an "*intra moenia*" commercial flow from the workshop of the building located on the east side the forum to other places in the late antique city.

Last but not least, as concerns the parallel chemical analyses made on the red spots noticed on the bones' surfaces, they allowed us to confirm the hypothesis about the dissolution of the painted plasters red colour on the bones. Among the four performed analyses (SEM-EDS, p-XRF, Raman spectrometry and the HIS), the p-XRF instrument gave the most interesting results, detecting heavy elements like lead (Pb) and arsenic (As), besides from the iron (Fe). These elements can perhaps suggest the use of a red lead (Pb_3O_4) or an arsenate (like realgar, As_4S_4) as a red pigment, rather than a red ochre, as it was the initial hypothesis. Otherwise, a mixture of these pigments could be used. More analyses are needed to rule out that these elements are related to the dissolution of the red pigments of the building-coloured plasters on the worked bones. Thus, it could be useful to use p-XRF to recognize Pb and As on some plasters samples from the room VII.

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Appendix A

40 fragments of semi-worked bones from the archaeological excavation of 2021 in the room VII of the building near the east side of the Roman forum of Nora

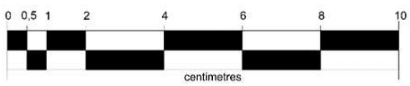
1 (US 21433 = 21426)

2 (US 21433 = 21426)

3 (US 21433 = 21426)

4 (US 21433 = 21426)

5 (US 21433 = 21426)



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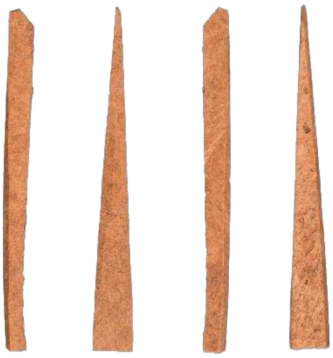

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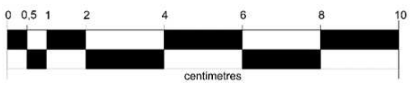
11 (US 21433 = 21426)



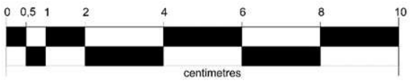
12 (US 21443 = 21427)

13 (US 21443 = 21427)

14 (US 21443 = 21427)

15 (US 21443 = 21427)

16 (US 21443 = 21427)



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18 (US 21443 = 21427)

19 (US 21443 = 21427)

20 (US 21443 = 21427)

21 (US 21443 = 21427)

22 (US 21443 = 21427)

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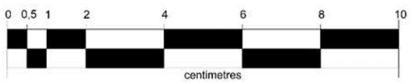
25 (US 21443 = 21427)



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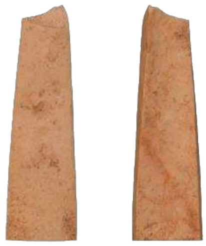

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28 (US 21443 = 21427)

29 (US 21443 = 21427)

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31 (US 21443 = 21427)

32 (US 21443 = 21427)

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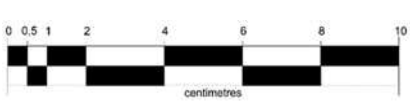
34 (US 21443 = 21427)



35 (US 21443 = 21427)

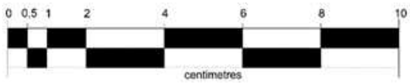
36 (US 21443 = 21427)

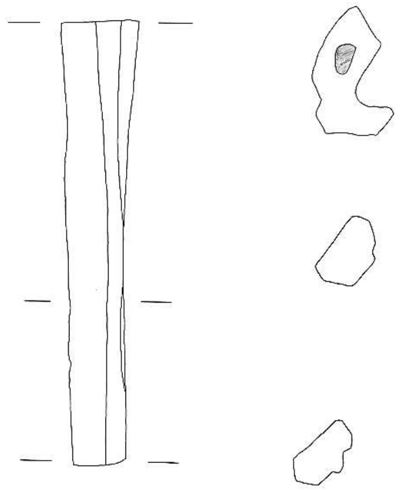
37 (US 21443 = 21427)

38 (US 21443 = 21427)

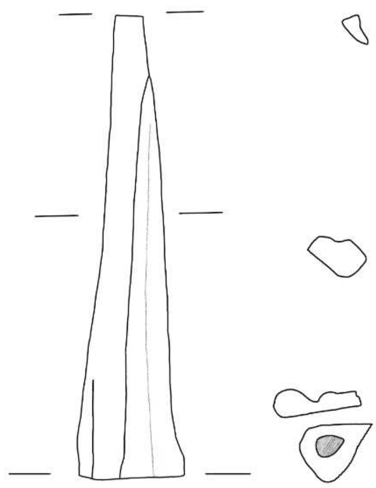
39 (US 21443 = 21427)

40 (US 21443 = 21427)





2 (US 21433 = 21426)



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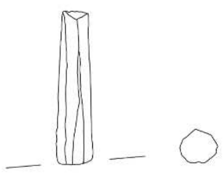

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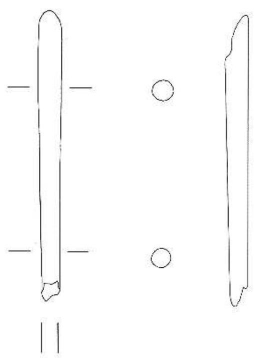

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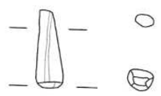

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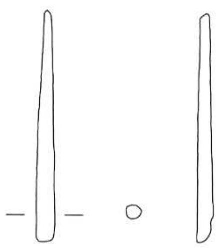
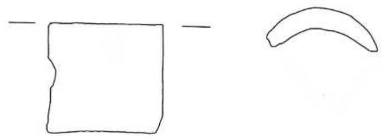


36 (US 21443 = 21427)



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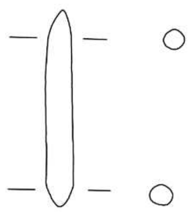

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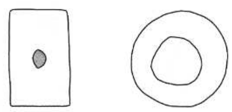
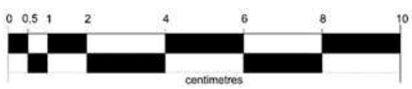


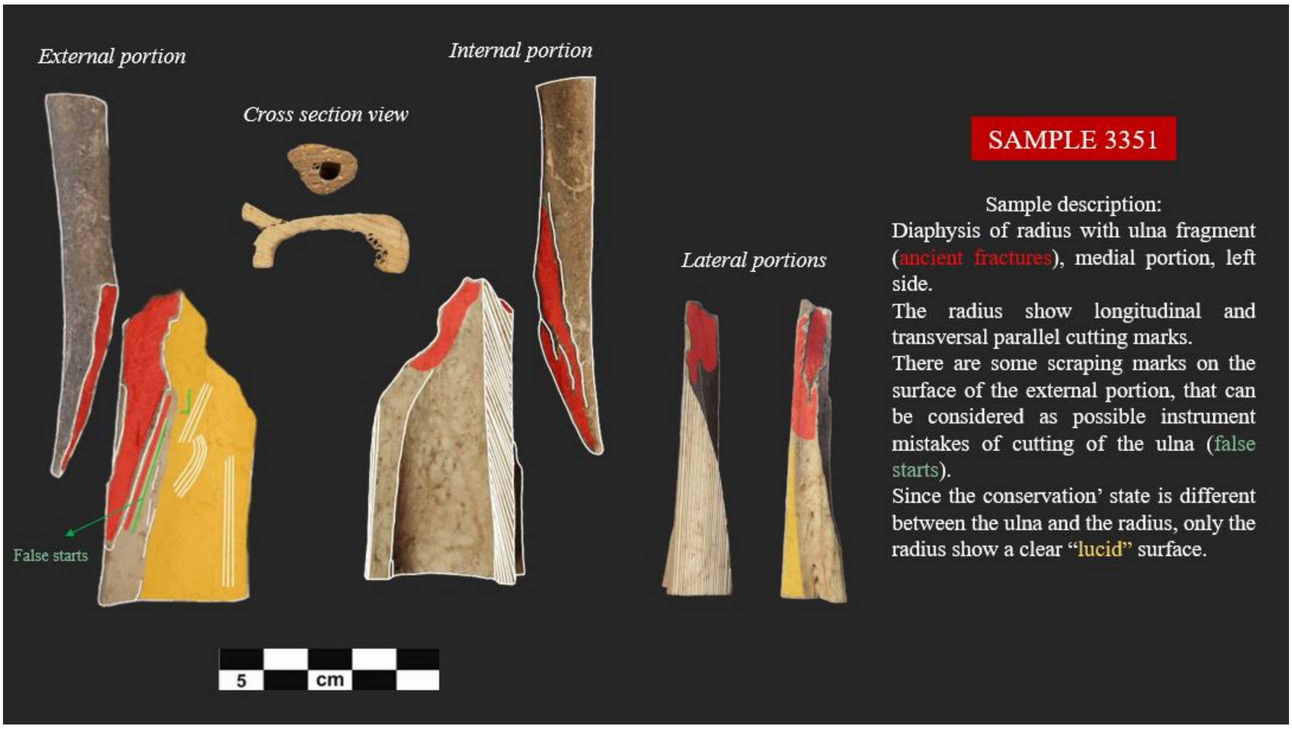
40 (US 21443 = 21427)



Appendix B

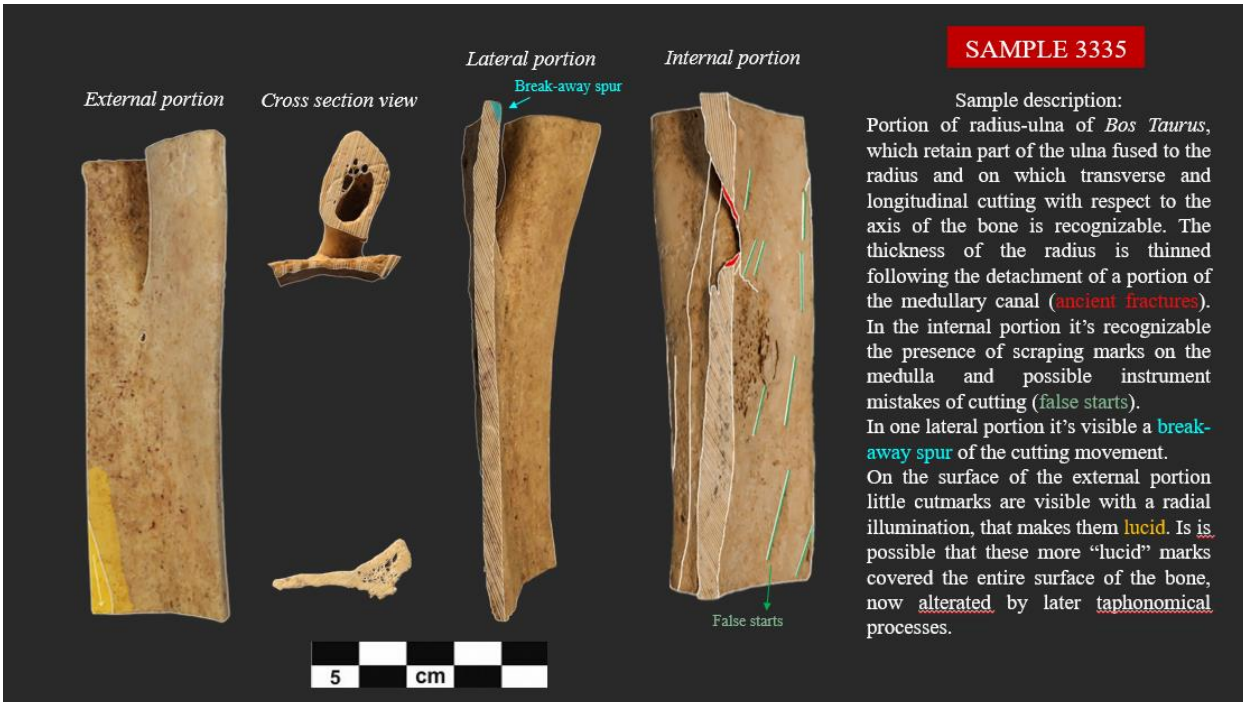
12 selected representative bones' descriptions and drawings

N_Inv ADaM 3351



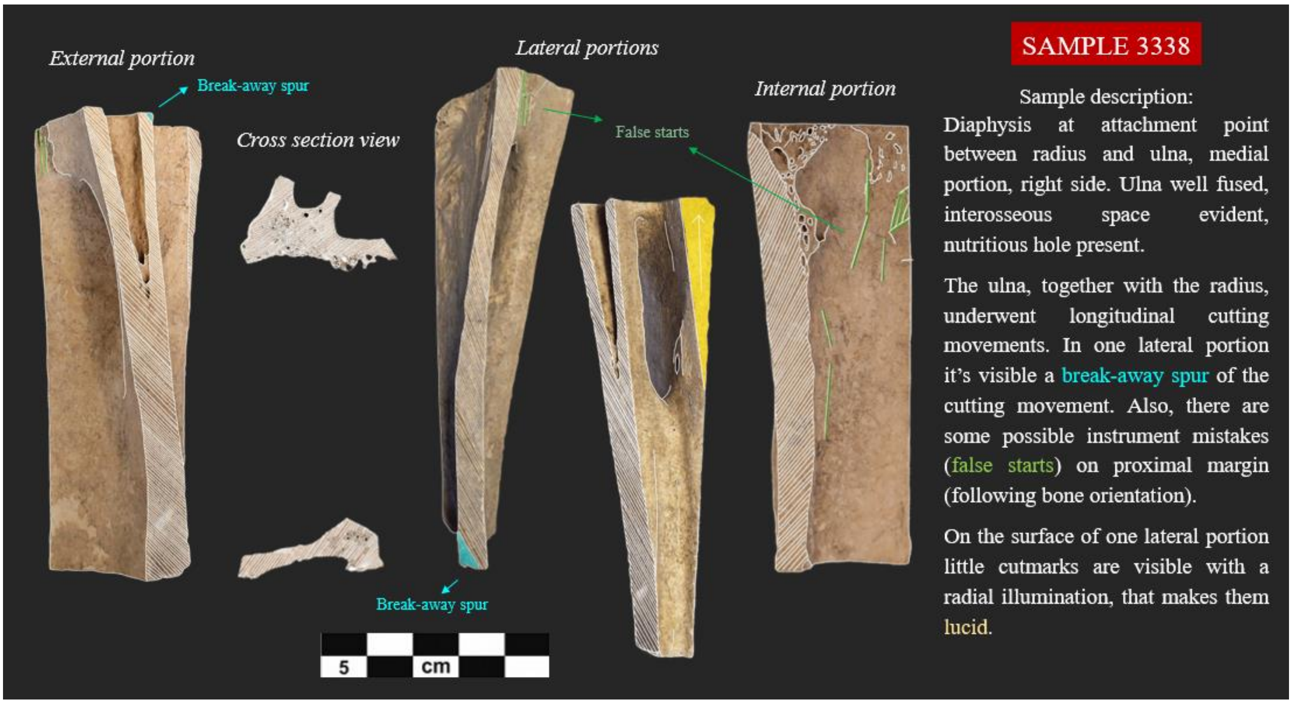
Site	Nora
Area	PO
Year	2019
Room	VII
US	21433 (radius) + 21413 (ulna)
Functional group	A
Species	Ox (*Bos Taurus*)
Anatomical el.	Radius-ulna
Portion	Medial
Side	Left
Other information	Radius shaft with fragment of ulna
Shape	Rectangular
Object	Support
Artifact	/
Tool	/
Traces	Yes
Traces position	Marginal
Action	Sawing
Pattern	Both
Working phase	Cutting
Measures (mm)	GL:112,6; GB:35,1

N_Inv ADaM 3335



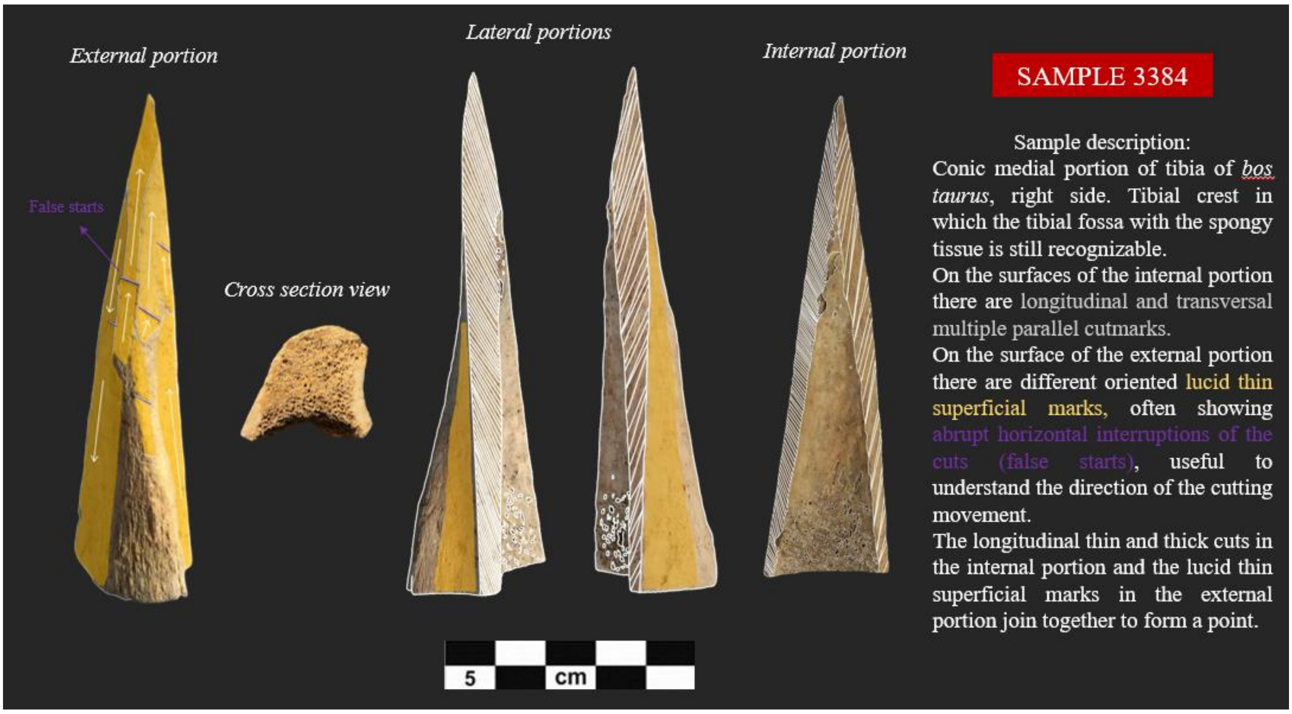
Site	Nora
Area	PO
Year	2019
Room	VII
US	21433=21426
Functional group	A
Species	Ox (*Bos Taurus*)
Anatomical el.	Radius-ulna
Portion	Medial
Side	Right
Other information	Diaphysis at the point of attachment between the radius and ulna. Presence of the nutritional hole.
Shape	Rectangular
Object	Support
Artifact	/
Tool	/
Traces	Yes
Traces position	Local
Action	Sawing and smoothing
Pattern/direction	Both
Working phase	Cutting
Measures (mm)	GL: 102,5; GB: 30,4; sB: 25,6

N_Inv ADaM 3338



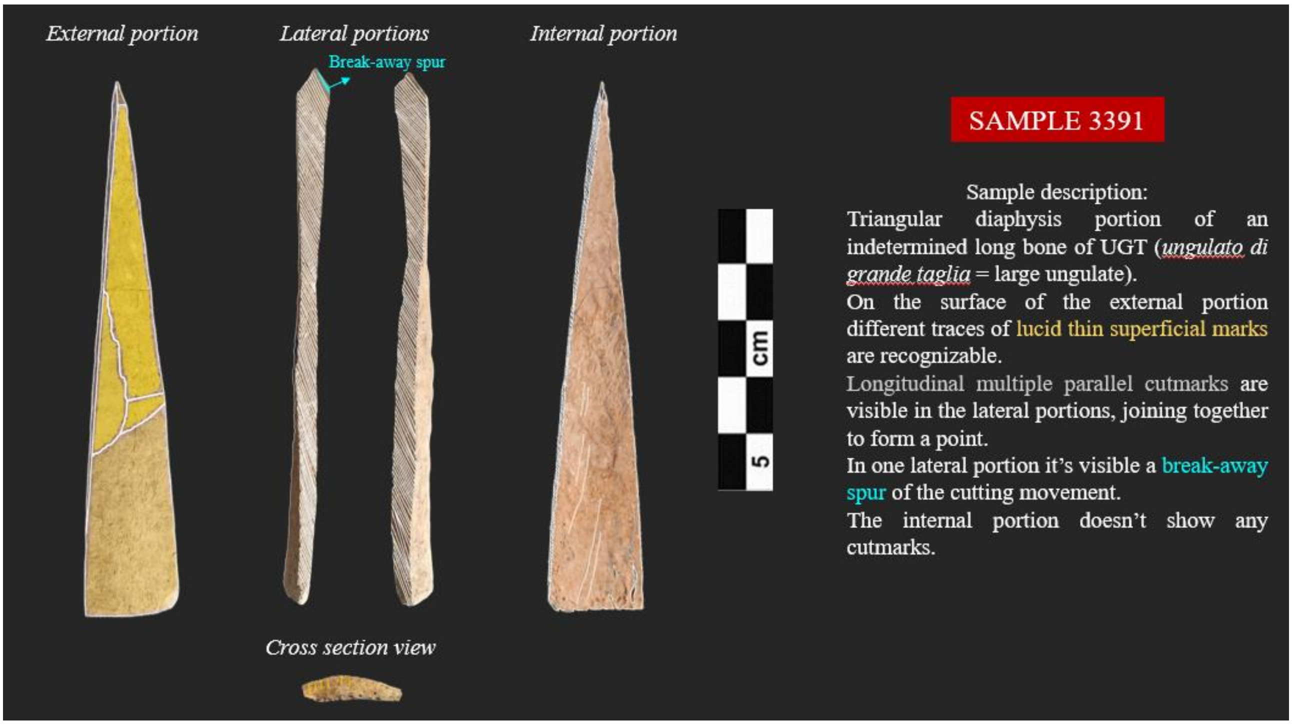
Site	Nora
Area	PO
Year	2019
Room	VII
US	21433=21426
Functional group	A
Species	Ox (*Bos Taurus*)
Anatomical el.	Radius-ulna
Portion	Medial
Side	Right
Other information	Diaphysis at the point of attachment between radius and ulna, ulna well fused, interosseous space evident, nutritional hole present
Shape	Rectangular
Object	Support
Artifact	/
Tool	/
Traces	Yes
Traces position	Marginal
Action	Sawing
Pattern	Both
Working phase	Cutting
Measures (mm)	GL: 97,2; GB: 36,3; sB:30,4

N_Inv ADaM 3384



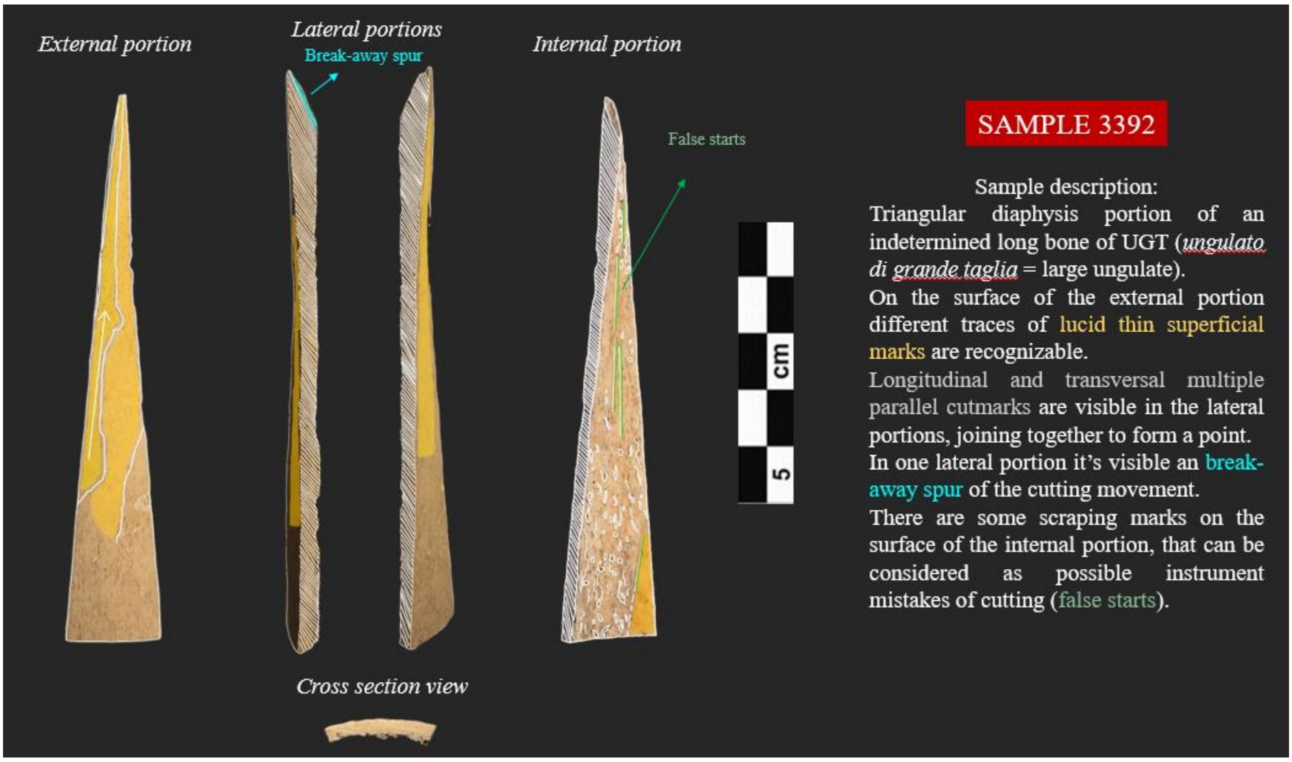
Site	Nora
Area	PO
Year	2019
Room	VII
US	21433=21426
Functional group	C
Species	Ox (*Bos Taurus*)
Anatomical el.	Tibia
Portion	Medial
Side	Right
Other information	Tibial crest in which there is also the tibial fossa
Shape	Conical
Object	Support
Artifact	Semi-worked
Tool	Awl (?)
Traces	Yes
Traces position	Marginal
Action	Sawing
Pattern	Both
Working phase	Cutting
Measures (mm)	GL: 94,1; GB: 23,6

N_Inv ADaM 3391



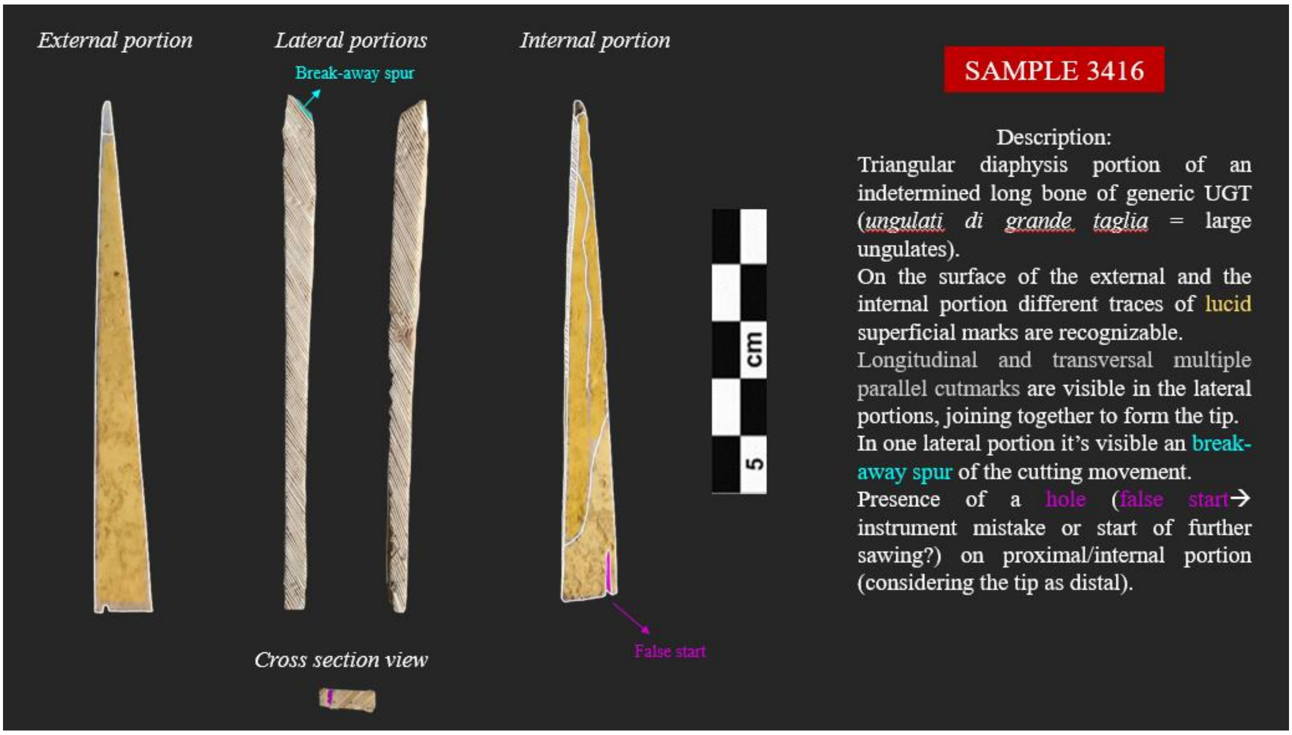
Site	Nora
Area	PO
Year	2019
Room	VII
US	21433=21426
Functional group	B
Species	/
Anatomical el.	Long bone
Portion	Medial
Side	/
Other information	Diaphysis
Shape	Triangular
Object	Support
Artifact	*Baguette*
Tool	/
Traces	Yes
Traces position	Marginal
Action	Sawing
Pattern	Both
Working phase	Cutting
Measures (mm)	GL: 97,4

N_Inv ADaM 3392



Site	Nora
Area	PO
Year	2019
Room	VII
US	21433=21426
Functional group	B
Species	/
Anatomical el.	Long bone
Portion	Medial
Side	/
Other information	Diaphysis
Shape	Triangular
Object	Support
Artifact	*Baguette*
Tool	/
Traces	Yes
Traces position	Marginal
Action	Sawing
Pattern	Both
Working phase	Cutting
Measures (mm)	GL: 108,57; GB: 19,30

N_Inv ADaM 3416



Site	Nora
Area	PO
Year	2019
Room	VII
US	21433=21426
Functional group	B
Species	/
Anatomical el.	Long bone
Portion	Medial
Side	/
Other information	Diaphysis
Shape	Triangular
Object	Support
Artifact	*Baguette*
Tool	/
Traces	Yes
Traces position	Marginal
Action	Sawing and abrasion
Pattern	Both
Working phase	Cutting
Measures (mm)	GL: 83,7; GB: 9,7; sB: 1,2

N_Inv ADaM 3403

Site	Nora
Area	PO
Year	2019
Room	VII
US	21433=21426
Functional group	B
Species	/
Anatomical el.	Long bone
Portion	Medial
Side	/
Other information	Diaphysis
Shape	Triangular
Object	Support
Artifact	*Baguette*
Tool	/
Traces	Yes
Traces position	Local
Action	Sawing and smoothing
Pattern	Both
Working phase	Shaping
Measures (mm)	GL: 107,8; GB: 11,5; sB: 2

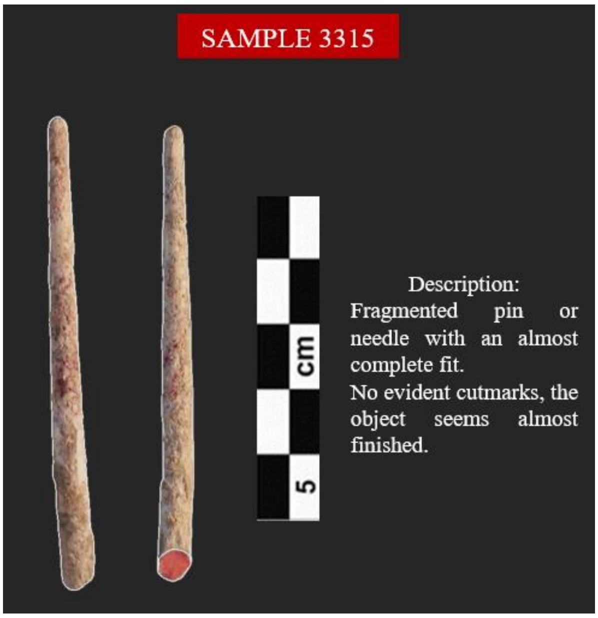
N_Inv ADaM 3460

Site	Nora
Area	PO
Year	2019
Room	VII
US	21433=21426
Functional group	C
Species	/
Anatomical el.	Long bone
Portion	Medial
Side	/
Other information	Diaphysis
Shape	Cilindric/conical
Object	Support
Artifact	Semi-worked
Tool	/
Traces	Yes
Traces position	Intrusive
Action	Sawing and roughing
Pattern	Longitudinal
Working phase	Shaping
Measures (mm)	/

N_Inv ADaM 3541

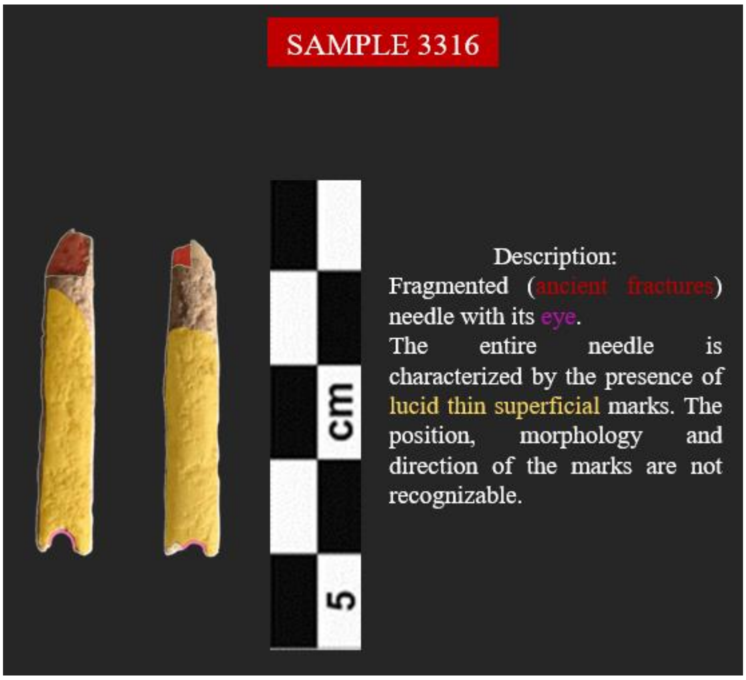
Site	Nora
Area	PO
Year	2019
Room	VII
US	21415
Functional group	C
Species	/
Anatomical el.	Long bone
Portion	Medial
Side	/
Other information	Diaphysis
Shape	Cilindric
Object	Support
Artifact	Semi-worked
Tool	Pin
Traces	Yes
Traces position	Intrusive
Action	Sawing and smoothing
Pattern	Both
Working phase	Shaping
Measures (mm)	GB: 8,9; sB: 4,6

N_Inv ADaM 3315



Site	Nora
Area	PO
Year	2021
Room	VII
US	21433=21426
Functional group	C
Species	/
Anatomical el.	Long bone
Portion	Medial
Side	/
Other information	/
Shape	Cilindric
Object	Support
Artifact	Semi-worked
Tool	Pin/needle
Traces	Yes
Traces position	Intrusive
Action	Smoothing and polishing
Pattern	Both
Working phase	Polishing
Measures (mm)	GL: 70,4; GB: 4,7; sB: 3,4

N_Inv ADaM 3316



Site	Nora
Area	PO
Year	2021
Room	VII
US	21413=21415
Functional group	C
Species	/
Anatomical el.	Long bone
Portion	Medial
Side	/
Other information	/
Shape	Cilindric
Object	Support
Artifact	Semi-worked
Tool	Needle
Traces	Yes
Traces position	Covering
Action	Smoothing and drilling
Pattern	Both
Working phase	Polishing
Measures (mm)	/