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Bioarchaeology of ancient Adriatic ships: The Pula shipwrecks (Croatia)

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Highlights

- Two Roman shipwrecks and artefacts from the Pula harbour were studied
- Pollen extracted from pitch, a coating applied to ships
- The pollen records suggest different Eastern Adriatic ecological landscapes
- Juniper and pine, two main components of pitch, are dominant in the analyses
- The pollen grains are related to the areas of production or application of pitch

Abstract

Bioarchaeological analyses of protective coatings and waterproofing materials used in the construction or restoration of ships have helped to enhance our understanding of their geographical origins by identifying the pollen-derived assemblages preserved during their building or restoration. We selected two Roman sewn ships (Pula 1 and 2), two artefacts (a brush and a fragment of fibrous mass) and three plank fragments with “mortise and tenon” joints not belonging to the sewn boats to extract bioindicators from pitch, a substance traditionally used in Mediterranean shipbuilding to waterproof the seams and hull and protect the wood of the vessels. The remains were unearthed during the archaeological excavations of the ancient silted harbour of the Roman colony of Pula in 2013. The wrecks attest to ancient regional traditions in shipbuilding specific to the North-Eastern Adriatic area. Using pollen-derived vegetation patterns and statistical analyses, we suggest that the recorded vegetation

mainly corresponds to the past and present Eastern Adriatic landscapes, where pitch could have been produced or applied. The landscapes identified correspond to the area where the wrecks were discovered. Pollen also elucidate the application of the pitch, separating phases of construction from stages of ships repair. Pollen, as well as statistical analyses, are powerful tools for naval archaeology, providing geographical insights into the history of wrecks as well as an assessment of construction or restoration phases.

Keywords

Adriatic Sea, Croatia, Istria, Pitch, Pollen analysis, Pula harbour, Sewn boat, Statistical analysis, Roman period

1. Introduction

The use of coatings in ancient Mediterranean shipbuilding is widespread (Gianfrotta and Pomey, 1981; Casson, 1995; Pomey and Rieth, 2005). Coatings played two important roles: i) they waterproofed the hull and assemblies, and ii) they shielded the wood from the corrosive effects of seawater as well as the damaging impact of organisms and microorganisms. When the construction of the ship was completed, coatings were applied to both the interior and exterior of the hull.

The term “coating” defines a large number of substances (resins, tars, waxes, bitumen, fats). Ancient sources use different names to define coatings, which can also derive from the mixture of different substances, for example *zopissa* was a mixture of pitch and beeswax (Pliny the Elder, *Natural History* XVI, 23). Chemical analyses found that most of the coatings used in ancient Mediterranean shipbuilding were pitches (Connan 2005; Connan and Charrié-Duhaut, 2010; Burger 2014; Charrié-Duhaut, 2019). These pitches are vegetable tars produced by heating coniferous wood under controlled conditions (Bailly, 2015) or made by heating resins. They have a black colour and a viscous texture, and are water-repellent. As our study mainly concerns bioarchaeological analyses of samples of coatings deriving from shipwrecks or to artefacts related to navigation, we use the term “pitch” rather than the general term “coating”. The presence of pollen and other bioindicators (insects, seeds, etc.) in pitches is common but they have rarely been studied (e.g. Muller, 2004; Girard, 2005; Andrieu-Ponel et al., 2014; Andrieu-Ponel, 2019; Marlier et al., 2019). Their identification can potentially provide information not only about the vegetation surrounding the production sites, but also about the vegetation surrounding the shipyards where the pitch was applied. It is conceivable that pitches

were applied just after the completion of the ship's construction, several times when the original layer had been damaged, and of course in case of major repairs.

Our study concerns bioindicators that we extracted from pitch covering the remains of two Roman sewn boats (Pula 1 and 2), two artefacts (a brush and a fragment of fibrous mass of animal origin) connected to shipbuilding activities and three fragments of planks with “mortise and tenon” joints not belonging to the sewn boats. All were discovered in 2013 during preventive archaeological excavations carried out in Pula's ancient harbour (Croatia), within the framework of the research project “ADRIBOATS - Navires et navigation en Adriatique orientale dans l'Antiquité”.

According to Pomey and Boetto (2019), the Roman-period wrecks Pula 1 and 2 belong to a regional tradition of sewn boat construction that they defined as “North-eastern Adriatic”. Its origin is in Liburnia and Istria, and could date back to Protohistory as attested by the discovery of a sewn boat in Zambratija Cove (Istria) (1120-930 BC; Boetto et al., 2017; Koncani Uhač et al., 2019). Six other Roman-period sewn boats belonging to the “North-eastern Adriatic” tradition were found in Dalmatia at Zaton, the ancient harbour of Nin/*Aenona* (wrecks Zaton 1, 2 and 3, 1st century AD; Brusić, 1968; Brusić and Domjan, 1985; Gluščević, 2004; Romanović 2021), and at Caska/*Cissa* (Caska 1, 42-104 AD; Caska 3, 79 AD and Caska 4, 9-44 AD; Boetto and Radić Rossi 2017; Radić Rossi and Boetto, 2020; Ferreira Domínguez 2021). Another sewn-boat was recently found in Istria at Poreč/*Parentium* (beginning of the 1st century AD; Boetto et al., forthcoming) (Fig. 1A). The Pula 2 bears a striking resemblance to the three sewn boats found in Caska, as well as the one in Poreč. It is quite rare to discover multiple vessels that are so similar within such a confined area. Their architecture, shape, assembly, propulsion and steering systems are comparable, as is the use of wood species in their construction. These sewn boats correspond to a particular type widely-used boat propelled by oars and sails, which were used by farmers and fishermen to support their daily life in Istria and Dalmatia (Pomey and Boetto, 2019).

As Pula 1 and 2 were in all likelihood constructed in a shipyard in Dalmatia or Istria, the coating was probably produced locally. The presence of pollen and palynomorphs in these coatings raises several questions regarding their conservation status and the potential information (ecological and archaeological) that these microfossils can provide. The bioindicators present on the brush and fibrous mass coatings can help establish a connection between these artefacts and the sewn boats. Additionally, macro-remains that are trapped in the pitch collected from shipwrecks, artefacts or mortise and tenon planks may provide valuable information on the

production, application, or storage of the pitch. Collectively, these findings can help shed light on various aspects of the boats' construction, use and history.

Pollen analyses on coatings have already been carried out on some wrecks discovered in France (Muller, 2004; Girard, 2005; Wicha and Girard, 2006; Andrieu-Ponel et al., 2014; Marlier et al., 2019), Israel (Weinstein-Evron and Chaim, 2003) and Croatia (Andrieu-Ponel, 2018; 2019). However, statistical analyses have not yet been used to investigate the relationship between boats belonging to different traditions found at the same location, and between these boats and artefacts associated with shipbuilding activities. This is one of the goals of our study, which applies multivariate analyses and uses pollen-derived vegetation as a proxy. Shipwrecks are a valuable source of information about the origin, construction, repair locations and navigation plans of the original vessels. However, extracting data from the study of the ship's cargo and structure is not always straightforward. Bioindicators provide new clues and assist nautical archaeologists in understanding the ship (Deforce et al., 2014; Thomsen, 2021). In addition, archaeological, architectural and technological studies of the ships (Boetto, 2016; Boetto et al., 2017) as well as the xylological and dendrological analysis of their wood (Ferreira Domínguez, 2021) have already been carried out on these wrecks, providing a strong foundation of information to which pollen data can be incorporated.

2. Pula wrecks

The wrecks Pula 1 and 2 were found at a depth of 5 m (2 m below current Mean Sea Level). These two sewn boats were abandoned before the first half of the 3rd century AD in the harbour of the Roman colony Iulia Pietas Pola (Boetto, 2016; Boetto et al., 2017; Koncani Uhač, 2017) (Fig. 1B). Despite the risks of the "old wood effect" (Bowman, 1990), hull woods are commonly used to date ancient ships. Dendrochronology coupled with AMS ¹⁴C radiocarbon analyses calibrated by wiggle-matching date the felling of the timbers used in the shipbuilding of the two ships to the first half of the 2nd century AD (Pula 1 between 103-155 AD; Pula 2 between 103-172 AD; Ferreira Domínguez, 2021).

2.1. Pula 1

The remains of Pula 1 are approximately 8.1 m long and 4.1 m wide (Fig. 2). They consist of a keel, six strakes of planking on each side, fourteen floor-timbers and a few internal planking fragments. On the main frame, the cross section has a flat frame with a round turn of the bilge. The longitudinal section is flat.

The boat has a keel of rectangular section, without chamfers. The planking is flush-laid carvel built with garboard strakes thicker than the other strakes. They are assembled together and attached to the keel by continuous and longitudinal overedge stitches with a clamping turn (//// pattern; Fig. 3A). The ligatures are created with a flat braid consisting of three strands of twisted vegetable fibres. The stitch passes through diagonal channels that are perpendicular to the plank edges. The channels end in a rectangular or trapezoidal notch on the corner of the edge. Sometimes, the hole is slightly removed from the plank edge, in which case a little groove is carved to lodge the stitch on the outer face of the plank. The stitches pass over a wadding pad (made of vegetable fibres) placed over the seams of the planks. Small pegs lock the stitches into the channels. The frame is made up of a sequence of floor-timbers of rectangular section treenailed to the planking at an average distance of 0.35 m. The base of the floor-timbers is crenelated to avoid damaging the wadding pads. The recesses also served as limber holes. Only a few floor-timbers were attached to the planking by iron nails. Originally, the ship was fitted with an internal planking. A mast-step, which is no longer preserved, was installed on the frame. The inner and outer faces of the hull were coated with a layer of pitch (Boetto, 2016; Boetto et al., 2017; Pomey and Boetto, 2019).

2.2. Pula 2

Pula 2 is 6.1 m long and 2.1 m wide (Fig. 2). The wreck consists of a keel and a transitional timber, thirteen strakes. Twenty loose pieces, mostly frames and some fragments of wales, were found displaced inside, around and underneath the wreck. The longitudinal section is flat and the transverse section has a flat frame with a round turn of the bilge at the main frame.

The axial carpentry comprises a keel of quadrangular section, without chamfers and with tapered sides and curved external edges. The preserved extremity of the keel is scarfed to accommodate a transitional timber. The scarf is vertically locked by a treenail and an iron nail, and secured by a horizontal key. The planking is a flush-laid carvel and the strakes are thinner than the wales. One fragment of wale, found detached from the main structure of the wreck, was cut by two rectangular mortises to lodge tole pins related to the boat's rowing system. As in Pula 1, the planks are attached by a continuous sewing system. The only difference between the sewing system of the two vessels is the pattern that in Pula 2 is made of simple overedge stitches (///; Fig. 3B). At the edge of the planks, two horizontal dowels square in section were observed and were probably used for the pre-assembly of the planking. The frame consists of floor-timbers widely spaced (0.40 m on average). They have a rectangular section and their lower face is crenelated to avoid the crushing of the wadding pads and to circulate the bilge

water. They are attached to the planking by treenails and a few copper-alloy nails. The inner and outer surfaces of the hull are covered with pitch (Boetto, 2016; Boetto et al., 2017; Pomey and Boetto, 2019).

2.3. The wood species

The woods used for construction of Pula 1 are deciduous oak (*Quercus* sp.), holm oak (*Quercus ilex/Quercus coccifera*), elm (*Ulmus* sp.), fir (*Abies* sp.), walnut (*Juglans regia*), pine (*Pinus halepensis/P. pinea/P. brutia*), beech (*Fagus sylvatica*), ash (*Fraxinus* sp.), spruce (*Picea abies*), dogwood (*Cornus* sp.), Rosaceae (Maloidae) and olive tree (*Olea europaea*).

For the construction of Pula 2, the woods used were deciduous oak (*Quercus* sp.), holm oak (*Quercus ilex/Quercus coccifera*), olive tree (*Olea europaea*), spruce (*Picea abies*), beech (*Fagus sylvatica*), elm (*Ulmus* sp.), fir (*Abies* sp.), Anacardiaceae, dogwood (*Cornus* sp.) and Rosaceae (Maloideae) (Ferreira Domínguez, 2021).

These species are typically found in low-lying areas and riparian habitats, often near the Mediterranean coast, including the northeastern Adriatic region. Some species (beech, fir, spruce) are hosted in the montane or subalpine vegetation levels and are available in the mountains bordering the Adriatic. A. Ferreira Domínguez (2021), due to the local origin, construction and use of these sewn boats, hypothesises supplies from Istria and Dalmatia. The construction sites would have been located on the coast and would have mainly used local species available in the area. Construction sites in the region could obtain mountainous species from nearby massifs such as Učka and Čićarija in Istria, or Velebit in northern Dalmatia, by land or water transport.

2.4. Principles and methods of construction, function of the ships

Pula 1 and Pula 2 construction principles, as described by Pomey and Rieth (2005) and Pomey et al. (2012, 2013), utilize a shell concept for the hull structure and a longitudinal strake-oriented concept for the hull shape. The building process follows a shell-first approach.

Pula 1 is a small sailing ship around 15 m in length, probably used as cargo ship. Pula 2 is a coastal transport craft around 9-10 m in length that could be used for multipurpose tasks (transportation of goods, people and animals, fishing). It was propelled using both oars and sail (Boetto, 2016; Boetto et al., 2017; Pomey and Boetto, 2019).

3. Materials and methods

12 samples of pitch were analysed (Table 1, Fig. 4) to evaluate their nature (colour, aspect and consistency) and the trapped bioindicators. We used the Munsell colour chart to evaluate the colour of the samples.

Sample	Provenance	Macro-remains	Pollen
PU 100	Pula 1, plank P4zB, inner face	Sediments; plant fibres	217
PU 101	Pula 1, plank P2z between frames R16 and R17, inner face	Sediments; plant fibres, grape seed	117
PU 102	Pula1, plank P5i, outer face	Shells; sediments; plants fibres, wood fragment	X
PU 103	Pula 1, plank P1i between frames R20 and R21, inner face	Shells; sediments; plant fibres	181
PU 104	Pula 1, plank P3i between frames R16 and R17, inner face	Shells; sediments; plant fibres	100
PU 105	Pula 2, plank P7s/2, inner face	Sediments; plant fibres	300
PU 106	Pula 2, detached plank U282, inner face	Sediments; plant fibres	354
PU 107	Plank with mortises and tenons U248	Plant fibres	X
PU 108	Plank with mortises and tenons U52, inner face	Beetle elytron; sediments; plant fibres; pine needle; charcoal fragments	X
PU 109	Plank with mortises and tenons U140	Sediments; plant fibres	X
PU 110	Brush U206	Sediments; plant fibres	183
PU 111	Fibrous mass U5	Fibrous mass (animal origin); Sediments; plant fibres	315

Table 1. Detailed list of samples. Information is provided on the provenance of the samples, macro-remains found and number of pollen grains counted in each sample.

3.1. Macro-remains

Based on sulfuric acid followed by a trichloroethylene-acetone mixture, pitch was dissolved and macro-remains were collected with 500 µm and 100 µm sieves and analysed under a binocular microscope.

3.2. Pollen analysis

Our study is based on the analysis of eight pitch samples taken from the inner face of the planking: four samples from Pula 1 (PU 100, 101, 103, 104) and two from Pula 2 (PU 105, 106). Two additional pitch samples (PU 110 and PU 111) were collected from the sediment near the wrecks: one from a brush covered in pitch and the other from a fibrous mass of animal origin embedded in pitch. The small amount of pitch in samples PU 102, 107, 108, 109 was not conducive to pollen extraction.

Palynomorphs were extracted from the central portion of the pitches. All surface layers were removed prior to chemical extraction. The sticky elements of the pitch were dissolved using sulfuric acid followed by a trichloroethylene-acetone mixture. The samples were then prepared according to a modified version of Fægri and Iversen (1989). The first step, the cold hydrochloric acid (HCl 35%) etching, was removed because the elimination of carbonates was done previously using sulfuric acid. Acetolysis was not used. A second article with a stronger technical focus will describe the detailed process employed for extracting pollen and other non-pollen palynomorphs from the pitches.

Pollen grains were counted under x400 and x1000 magnification using an Olympus microscope. Atlases (Reille, 1992, 1995, 1998), books (e.g. Fægri and Iversen, 1989; Moore et al., 1991; Punt and Blackmore, 1991) as well as local reference slides were used for pollen identification. The mean pollen sum was 206 pollen grains, with a minimum of 95 and a maximum of 326 pollen grains. The median value was 190 pollen grains, with a 25th percentile of 123 pollen grains and a 75th percentile of 292 pollen grains. The mean number of taxa was 27, with a minimum of 21 and a maximum of 33 taxa. The median value was 28 taxa, with a 25th percentile of 22 taxa, and a 75th percentile of 31. Pollen frequencies (expressed as percentages) are based on the terrestrial pollen sum, excluding local helophytes, macrophytes and spores of non-vascular cryptogams. Aquatic taxa frequencies were calculated by adding the local helophytes-macrophytes to the terrestrial pollen sum. The palynological data are presented as a detailed pollen diagram (Fig. 5).

3.3. Statistical analyses

All data were analysed using PAST 4 software (version 1.0). To illustrate the relative importance of each taxon in the 8 samples, boxplots (Fig. 6) were employed. Biological data were then studied using a neighbour joining cluster analysis (descending type; Fig. 7A) to calculate a dendrogram, using branches as ecological distances between groups of taxa. The test was performed using Correlation as the similarity measure and Final branch as root. Each cluster was summed to generate pollen-derived vegetation patterns (PdVs). A spindle diagram was then used to depict the occurrences of PdVs against samples (Fig. 7B). A principal component analysis (PCA) was subsequently performed to test the ordination of samples by assessing major changes in the PdV-scores. Figure 8A shows the distribution of samples along the first two components, which account for 79.5% of the total variance. A biplot PCA was selected and a convex hull drawn. A second neighbour joining cluster analysis (Fig. 8B) was used to calculate a dendrogram, using branches as environmental distances between the samples.

4. Results

4.1. Pitch and macro-remains

Among the pitches, different colours and consistencies were observed (Fig. 4). The pitch was yellow, brown or black (with transitions between each colour). The consistency of the pitch was powdery, crumbly, compact or glassy. Based on these parameters, four categories of pitch have been distinguished, i) a brown-yellow powder pitch (PU 103; PU 107; PU 111), ii) a compact and vitreous black pitch (PU 104; PU 109), iii) a crumbly brown-yellow pitch on the outside and compact brown to black or even vitreous on the inside (PU 100; PU 101; PU 105; PU 106), and iv) a crumbly and compact dark brown pitch (PU 102; PU 108; PU 110).

Several macro-remains were observed in the samples of pitch (fragments of wood, shells, plant fibres and sediments) (Table 1). A grape seed was found in sample PU 101. In the sample PU 108, a beetle elytron, charcoal fragments and a pine needle were observed. The sample PU 110 was taken from a brush made with Gramineae (a grass plant), identified as *Ampelodesmos mauritanicus*. The pitch-covered fibrous mass (PU 111) exhibits a shape and scale arrangement consistent with its animal origin, resembling that of sheep's wool.

4.2. Environmental analysis

All pollen assemblages deriving from the ship pitch samples, the brush and the fibrous mass depict a dominance of arboreal pollen (65.3%; Fig. 5). Of the woody taxa fixed by the coating,

Juniperus and *Pinus* are the dominant taxa (Fig. 6). The pitch samples also show high percentages of *Olea europaea*, *Quercus ilex* and *Fraxinus*. *Abies*, *Cistus*, *Populus* and *Quercus* are also well-represented in the pollen diagram while the other taxa display low abundances in the pitch samples (Fig. 5). Among the herbaceous vegetation, the dominant taxon is Ranunculaceae. The other main taxa recorded are Asteraceae, *Plantago*, Poaceae, Cerealia, and Primulaceae. Cyperaceae is the only significant taxon from the helophytes and macrophytes (Fig. 6).

The pollen dataset from all the pitch samples (from ships, brush and fibrous mass) was then categorized into nine PdVs using a cluster analysis (Fig. 7A) and the results shown as a spindle diagram (Fig. 7B).

5. Discussion

5.1. Production of the pitch

During the analyses, the sampling of pitches revealed different colours and textures not linked to the nature of the coats (e.g. resin, pitch, bitumen) but to several levels of alteration of the same product. The powdery brown-yellow pitch is the most altered and the compact, black vitreous pitch the least. This has been confirmed by molecular analysis (Lonchambon et al., 2009; Connan and Charrié-Duhaut, 2010; Laurent et al., 2011). Alteration has also been a source of confusion for archaeologists, mistaking coniferous resin and yellow pitch (Connan, 2002a, 2002b; Connan and Charrié-Duhaut, 2010). Molecular archaeology has highlighted these alteration processes and also underlined the importance of pitch as a sealant for hulls or cargo in the ancient Roman world (Connan and Charrié-Duhaut, 2010). Currently, no molecular analysis results are available for the pitch used on the Pula boats. However, previous evidence suggests that the sealing and protective coatings used on the Pula wrecks were made of pitch/tar derived from conifers.

As we have already stated, pitch is derived from the heating of coniferous wood or resins. Three conifers identified in the Pula samples (fir, juniper and pine) could have been used for the production of pitch, in particular *Juniperus* and *Pinus* which are the dominant taxa in the pitch of wrecks (Figs. 5 and 6). Their occurrence can be directly linked to their use in the production of pitch. Pollen analyses conducted on the pitch from the Arles-Rhône 3 wrecks (1st and 2nd century AD) and the Pakoštane wrecks (late 4th - early 5th century AD, Croatia) have revealed valuable information about the nearby flora that may have been utilized in the production of pitch. According to Andrieu-Ponel et al. (2014) and Andrieu-Ponel (2018), these analyses identified the presence of pine in both cases, indicating its potential use in the production of

pitch. *Juniperus* could also suggest grazing areas near the pitch manufacturing or application sites (Behre, 1981).

The pollen record of species used during the preparation of pitch raises several questions. The high-temperature production of pitch (400 to 700°C; Burger, 2014; Connan and Charrié-Duhaut, 2010) implies at least an alteration or even a destruction of all pollen present on the branches or trapped in the cooking area. The pollen present in the pitch must therefore have been incorporated into the pitch after heating. The production probably took place near the area where the coniferous branches and woods used for the manufacture were collected. Therefore, the strong presence of pollen linked to the taxa used for the manufacture of pitch is probably consistent with the zone of production.

In the Pula wrecks, the abundances of cereals and Poaceae pollen are significant (Fig. 5), and the presence of a beetle elytron (sample PU 108) could suggest the inclusion of these elements when the pitch was cooling off.

In the wrecks Baie de l'Amitié, Cap Béar 3, Port Nautique and Arles-Rhône 5, fairly large quantities of pollen from cereals, herbaceous plants, crops and fallow plants, as well as eggs of intestinal parasites or coprophilic fungi were identified (Girard, 2005; Marlier et al., 2019). This suggests a link with the production of pitches. Theophrastus (*Enquiry into plants* IX, 3, 2) mentions the use of soil to slow down combustion during the production of pitch, and S. Wicha (2005) suggested that agricultural soil mixed with straw or animal manure was used to cover the firewood, thus accounting for the presence of these elements in the pitch. However, as mentioned above, the high-temperature production of pitch implies the destruction of pollen and also the macro-remains. If this evidence was trapped in the pitch, it may have been done at the zone of the production, during the cooling of the pitch to enable their conservation.

5.2. Botanical macro-remains

Pitch samples contained macro-remain inclusions of different nature (fragments of wood, shells, plant fibres and sediments) that can be linked to the direct environment of the wrecks. The occurrence of certain remains (a grape seed, a beetle elytron, a pine needle and charcoal fragments) in the pitch may suggest entrapment during manufacture, application or storage of the pitch. A grape seed (*Vitis vinifera*) was found in the sample PU 101 taken from the inner side of the planking (Pula 1). This cultivated plant was widespread in the Mediterranean regions where its fruits were consumed or transformed into wine (Zohary et al., 2012). Archaeobotanical analyses of macrofossils collected from the Roman harbour of Pula suggest that most of the plant remains correspond to fruits and nuts, and the remains of *Vitis vinifera*

subsp. *vinifera* were among the most abundant (Essert et al., 2018). One of the key economic activities of the Istrian region was the production of wine (Carre et al., 2011). The brush (PU 110), made with *Ampelodesmos mauritanicus*, may have been used to apply pitch during a ship repair. The fibrous mass (PU 111) could have been used to repair the ship, to fill the hull or to apply the pitch.

5.3. Identification of pitch manufacturing or application environments

The cluster analysis (Fig. 7A) and spindle diagram (Fig. 7B) suggest that the pitch samples have recorded a set of environments corresponding to the location/area of preparation of the pitch and wreck.

The samples from the Pula 1 shipwreck (PU 100 to 104) can be subdivided into two groups (Fig. 7B). The first group includes the samples PU 100 and 101, dominated by a juniper-poplar-dominated assemblage and Mediterranean woodland taxa. The other main PdV corresponds to a moist ash-alder-dominated assemblage. In the PU 100 sample, dry woodland taxa were recorded (absent in PU 101). The second group includes the PU 103 and 104 samples. This group is characterized by fewer juniper-poplar-dominated assemblages compared to PU 100 and 101. The dominant PdVs corresponds to Mediterranean woodland taxa and a moist ash-alder-dominated assemblage. The main difference between PU 103 and 104 is the occurrence of clusters dominated by wet meadow taxa in PU 103 and of a pine-dominated assemblage in PU 104.

The samples from the Pula 2 shipwreck (PU 105 and 106) are both dominated by Mediterranean woodland taxa (Fig. 7B). PU 105 suggests a well-developed oak-dominated assemblage while PU 106 mainly depicts the occurrence of moist forb-grass taxa.

The samples from the brush and the fibrous mass (PU 110 and 111) are somewhat different. The sample PU 110 (brush) is dominated by a pine-dominated assemblage along with Mediterranean woodland taxa. The sample PU 111 (fibrous mass) also depicts the same PdVs as PU 110, but the dominant PdV corresponds to a moist ash-alder-dominated assemblage (Fig. 7B).

The PCA (Fig. 8A) shows the three main PdVs that structured the samples. The data points located on positive axis 1 - negative axis 2 are mainly loaded by the PdV juniper-poplar-dominated assemblage. The points situated on negative axis 1 - negative axis 2 are mainly loaded by the pine-dominated assemblage. The points located on positive axis 1 - positive axis 2 are mainly ordinated by the Mediterranean woodland taxa. The other PdVs are less significant in the resulting PCA ordination (Fig. 8A). The distribution of samples on the PCA-graph

suggests a relationship between the two wrecks or between the wrecks and the artefacts (brush and fibrous mass). The outcome suggests that PU 100 and 101 (Pula 1) are similar, which is supported by the cluster analysis (Fig. 8B). The same is true for the samples PU 105 and 106 (Pula 2; Fig. 8A and 8B). The sample PU 104 (Pula 1) is close to the brush (PU 110) but less significantly close to the fibrous mass (PU 111; Fig. 8A and 8B). The sample PU 103 (Pula 1) is at an intermediate level, between the wreck Pula 2 and all samples from the wreck Pula 1. For Pula 2, this distribution suggests that the pitch comes from the same layer; by contrast, for Pula 1, several different layers of pitch seem to have been applied or it suggests that pitch of different origins may have been applied to different parts of the ship, for instance if there was not enough of any one type.

The environmental signal from the pitch-covered brush (PU 110) is close to PU 104 from Pula 1, suggesting that the brush may have been used to apply pitch to this ship, for example during a repair. If so, PU 104 could be the last coat applied to the boat. The pitch-covered fibrous mass seems to not be directly linked to the wrecks. Regarding the potential environmental signals, the samples dominated by a pine-dominated assemblage (PU 104 and PU 110) and a juniper-poplar-dominated assemblage (PU 100 and PU 101) could suggest areas of pitch production because pine and juniper are used to generate the pitch. The samples dominated by Mediterranean woodland taxa (PU 103; PU 105; PU 106) could be consistent with the landscape close to the shipyards where the vessels have been built or repaired.

The pollen grains can also be suggestive of seasonality as the pollen of each species are only produced for a few weeks of the year, with different species flowering at different times from winter to autumn (Puljak et al., 2016). According to the dominant taxa, the cluster PU 100-101 may be indicative of a pollen production in February-May (winter-spring season), the cluster PU 103-104 in March-May (spring season), the cluster PU 105-106 in April-May (spring season), the cluster PU 110 in March-April (spring season) and the cluster PU 111 in May (spring season).

5.4. What is the origin of the pitches?

The palynological analysis of the sealing and protective coatings of Pula 1 and 2 provides clues on i) the locations where the pitch was produced ii) the environments where the pitch was applied to the ships, iii) the place where the ships were built or iv) the sites where the vessels were refitted or repaired.

The pollen grains of PU 100, 101, 104 and 110 could represent pitch-producing areas such as areas with abundant poplar (often associated with riverine floodplains) and juniper (usually

found in dryland or montane scrub). The other samples could therefore correspond to pitch application environments such as landscapes with alder-dominated riverine woodland and ash-dominated secondary forest (PU 111). The Mediterranean taxa with wet meadow taxa (PU 103) and the Mediterranean taxa (PU 105 and 106) would therefore represent landscapes close to the shipyards, or areas where the pitch has been applied to the ships during refitting or repairing, if different from the place of construction.

All the samples suggest landscapes dominated by a forest cover, but with evidence of anthropogenic activities. *Olea europaea* depicts the importance of oleaster or olive orchards in the surrounding areas (e.g. Florenzano et al., 2017). Archaeobotanical analyses of plants collected in the Roman harbour of Pula have shown that olive-tree remains were amongst the most abundant fossils gathered, along with remains of grape vines (Essert et al., 2018). Moreover, olive trees were key to economic activities in the region of Istria (Carre et al., 2011). Pliny the Elder (*Natural History* XV, 8) even praised the quality of oil from this region.

To determine the location of construction sites, pollen analyses can be compared with wood identification to determine whether the shipbuilding or pitch application area corresponds to the timber cultivation area. Concerning the Pula 1 wreck timbers, 12 taxa were identified: deciduous oak (*Quercus* sp.), holm oak (*Quercus ilex*), elm (*Ulmus* sp.), fir (*Abies* sp.), walnut (*Juglans regia*), pine (*Pinus halepensis*/*P. pinea*/*P. brutia*), beech (*Fagus sylvatica*), ash (*Fraxinus* sp.), spruce (*Picea* sp.), dogwood (*Cornus* sp.), Rosaceae (Maloidae) and olive tree (*Olea europaea*). Among the 12 taxa identified on Pula 1, 8 are also present in the samples of pitch (ash, deciduous oak, holm oak, fir, walnut, pine, beech, and olive tree). The samples PU 100 and 101 include eight of the twelve taxa, PU 103 six of the twelve taxa, and PU 104 seven of the twelve taxa. Samples PU 100 and 101 group together a maximum number of taxa, also present in the Pula 1 structure. This environment (PU 100 and 101), dominated by juniper-poplar-dominated assemblage and Mediterranean taxa, could be an area where pitch was made and also a zone from which construction wood was sourced. This landscape could be linked to a shipbuilding economy.

Concerning Pula 2, ten species were identified: deciduous oak (*Quercus* sp.), holm oak (*Quercus ilex*), olive tree (*Olea europaea*), spruce (*Picea* sp.), beech (*Fagus sylvatica*), elm (*Ulmus* sp.), fir (*Abies* sp.), Anacardiaceae, dogwood (*Cornus* sp.) and Rosaceae (Maloideae). Samples PU 106 and 105 contain six of the ten timber taxa identified in the wreck. Only part of the wood from the vessel Pula 2 could be collected in this environment (PU 105 and 106) dominated by Mediterranean taxa, probably an area where pitch was applied. If this landscape corresponds to a construction site, a part of the wood used for Pula 2 would therefore have been

collected around this area. The small dimensions of the ship would support this hypothesis and confirm the use of wood located in proximity to the shipyard. The significant use of beech in construction (Ferreira Domínguez, 2021) raises questions regarding the area from which this species was sourced. This cooler-loving species is present in both samples and it could be present close to a shipyard on the coastline or have been obtained from the massifs close to the north-eastern Adriatic coast.

For Pula 1 and Pula 2, the missing taxa (Anacardiaceae, dogwood, spruce, Rosaceae) were mainly used for the assembly elements (pegs and treenails).

Several potential timber supply locations are evident. They could correspond to the pitch crafting site for Pula 1 and could constitute the area where pitch was applied or even the construction site for Pula 2. This difference could be explained by the operating model of the shipyard and the type of ship that was built there. Pula 2, a small vessel used for coastal transport, could have been built in a small yard, sourcing local timbers in majority. Pula 1 is a larger commercial sailboat that could come from a shipyard that had developed a more complete and more diversified economic model for sourcing wood and pitch. However, even though the majority of shipbuilding timbers is found in our pollen assemblages, some are absent. Some taxa are also similar in both wrecks and their occurrence is common in the Adriatic and the western Mediterranean.

The prevalence of holm oak (*Quercus ilex*) in all samples suggests that the pitches were made or applied in the western Mediterranean. The assemblages reflect pollen-derived vegetation that is characteristic of both ancient and present-day Croatia (Kaniewski et al., 2016, 2021). Moreover, Pula 1 and Pula 2 can be attributed to a local shipbuilding tradition, defined as “North-eastern Adriatic”. Although, samples PU 100 and PU 101 from Pula 1 suggest a juniper-poplar-dominated landscape and could be linked to southern Dalmatia (Neretva valley; Brande, 1989). Previously, we hypothesised that these samples may represent an area where pitch was made and also a zone from which construction wood was sourced. But the location of this shipbuilding tradition on the north-eastern Adriatic could suggest that the boat was repaired or refilled with pitch in south Dalmatia. Furthermore, the wood could have been imported from distant places (Meiggs, 1982).

6. Conclusion

The sealing and protective coatings of ancient shipping vessels offer a plethora of perspectives for naval archaeological investigations. Botanical macro and micro-remains can provide information on the manufacturing processes of the coatings applied to ancient boats. Pollen

analysis can be used to determine the environments where the coatings were produced or applied. They could also provide information on the location of the construction and repair areas of the vessels. The pitches taken from the Pula 1 and 2 wrecks have provided insights into the construction or repair environments of these boats. The identified landscapes correspond to the Eastern Adriatic zone where the wrecks were discovered. This article, in addition to other studies such as Beltrame et al. (2019), highlights the significance of biological content in coatings as a valuable geographic indicator. As such, there is a growing need to further investigate and study this aspect in naval archaeology.

Declaration of competing interest

None.

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