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Effects of substrata and environmental conditions on ecological succession on historic shipwrecks

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A B S T R A C T

An understanding of the interactions between biological, chemical and physical dynamics is especially important for the adequate conservation of the Underwater Cultural Heritage. However, while physical and chemical processes are relatively well-investigated, the biological communities associated with these habitats are poorly studied. We compared the sessile community developed on panels of different materials placed on two historical shipwrecks, the *Fougueux* and the *Bucentaure*, from the Battle of Trafalgar (October 1805). Six materials used at the construction of vessels at the 18th and 19th centuries were selected: copper, brass, cast iron, carbon steel, pine and oak. The sessile community developed on the panels was studied two and 15 months after their immersion at the water to determine the effects of materials and environmental conditions (sediments, waves, hydrodynamic conditions, temperature and salinity) on ecological succession and the possible implications at the conservation of historical shipwrecks. On the *Fougueux*, the environmental conditions more strongly influenced the biological succession than the material type, with pioneer colonisers dominating the communities in both sampling periods. On the *Bucentaure*, exposed to more stable environmental conditions, the sessile community showed differences between sampling periods and among materials at the end of the experiment. Under these more stable environmental conditions, the material type showed a higher influence on the sessile community. Species that produce calcareous concretions developed on metallic panels, but were absent on wood panels, where the shipworm *Teredo navalis* was more abundant. The relationship between environmental conditions, sessile organisms and material type can influence the conservation status of the archaeological sites.

1. Introduction

In recent decades, underwater archaeology has highlighted that site formation is a complex process and involves a variety of physical, chemical and biological phenomena (Fernández-Montblanc et al., 2016; López-Garrido et al., 2015; Ruuskanen et al., 2015). Thus, for adequate conservation of the Underwater Cultural Heritage (UCH), an understanding of the interactions between biological, chemical and physical dynamics is especially important (Zintzen et al., 2008). To assess the impacts of such dynamics on site formation, it is necessary to consider certain physico-chemical variables such as temperature, salinity, intensity and direction of currents and waves, etc. (Bergstrand and Godfrey, 2007; Richards, 2009). However, while physical and chemical processes are relatively well-investigated, the biological communities associated with UCH sites are poorly studied (Massin et al., 2002; Zintzen et al., 2006).

Historic shipwrecks and other UCH sites can play important

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roles in marine ecosystems, constituting a substratum for the colonisation by marine organisms and the development of a stable community over time (Zintzen et al., 2006, 2007, 2008). Shipwrecks can act as artificial reefs and hotspots of biodiversity, providing shelter and nursery zones for some species (Lengkeek et al., 2013; Walker et al., 2007). Artificial substrata provide a unique opportunity to study the colonization patterns into new habitats by faunal communities (García-Sanz et al., 2012). Indeed, several authors highlight that artificial reefs, such as shipwrecks, are good model systems to assess the colonization of artificial substrata in the sea (Boaventura et al., 2006; Walker et al., 2007).

The study of the biological communities associated to the UCH (Massin et al., 2002; Zintzen et al., 2008, 2006; among others) is also important as such communities can have positive or negative effects on the conservation and integrity of the site and the individual artefacts that comprise it, that is, a given biological community may influence their preservation or deterioration. The detrimental effects of micro- and macroorganisms that comprise the biofouling community may have both mechanical (consequence of their attachment to substratum) and metabolic origin (physical-chemical changes induced at materials). For example, bacterial activities may lead to the biodegradation of some materials (Wheeler, 2002), and boring species are especially destructive towards wood (Cragg et al., 1999; Wheeler, 2002). On the other hand, the sessile community can provide protection from physical and chemical degradation (Bethencourt et al., 2010; López-Garrido et al., 2015; Wheeler, 2002). In this regard, the presence of some species on wood could prevent the action of boring organisms (Pournou et al., 2001) or the abrasive effect due to sediment transport (Camidge, 2009). One of the most obvious influences of the sessile community is the formation of bio-concretions, at particular over iron objects, both cast and wrought (López-Garrido et al., 2015; Wheeler, 2002). Unlike concretions formed on terrestrially recovered artefacts, marine concretions are almost exclusively formed of calcium carbonate. These concretions, developed by sessile marine species (such as coralline algae, bivalve, calcareous sponges, bryozoans or corals), can provide a protection against degradation (López-Garrido et al., 2015), reducing the rate of oxygen-dependent corrosion of iron in seawater by allowing metal reaching the passivity zone in the Pourbaix diagram (Gregory, 1999; MacLeod, 2006, 1995).

This paper determines the way in which artificial habitats, such as historic shipwrecks, influence the processes of colonization and ecological succession of the sessile community. We studied the effect of different substrata and environmental condition on recruitment and community development. To this end, two historic shipwrecks of the French Navy related to the Battle of Trafalgar and sunk at the same time (October 1805) were studied. The sessile biological communities developed on panels made of different materials were analysed at both sites. The development of the sessile community at the early stage of the ecological succession and 15 months after the immersion of the panels was assessed to test if the recruitment selection differed in terms of material and time. Additionally, the environmental conditions at the two shipwrecks were characterised in order to understand how the marine environment and material type could influence ecological succession. This work provides baseline information to better predict how the artificial habitats may be colonized, the interaction among environmental conditions, substratum type and biological community development, and their possible implications in the conservation of UCH.

2. Materials and methods

Two shipwrecks from the Battle of Trafalgar, close to the coast of Cádiz (Southern Spain), were selected: the *Bucentaure* and the *Fougueux* (Fig. 1a). The *Bucentaure*, at a depth of 12 m (Fig. 1b), was sunk on 23 October 1805 and the *Fougueux*, at a depth of around 7 m (Fig. 1c), on 22 October 1805. The *Bucentaure* represents a dispersed shipwreck comprising 22 iron cannons, an anchor and other metallic artefacts, but no wood was preserved. This shipwreck is located on a mixed rocky-sandy bottom. In contrast, the *Fougueux* has a portion of the hull structure preserved with metallic elements but mainly wood, and 32 cannons and an anchor. The *Fougueux* is seated on a sandy-bottom with isolated natural rocky reef outcrops.

To assess the development of the sessile community on different materials, panels of 20×30 cm were placed on trestles on the shipwreck areas. The trestles were randomly placed on the centre of each archaeological site. Preliminary studies carried out at the studied zones showed as horizontal panels were completely cover by sediment and vertical panels were often lost or broken due to currents. For these reasons the panels were placed 1.5 m above the sea floor, with an inclination of 45° and facing prevailing currents (See supplementary content). Six different materials employed in the construction of vessels in the 18th to the 19th centuries were chosen: copper, brass, cast iron, carbon steel and two kinds of wood, pine and oak. The sessile community associated to them was studied at two (August 2012) and 15 months (September 2013) after their immersion in the water. Four panels of each material were used. Photoquadrat images of the panels were collected by scuba diving using a Canon PowerShot S100 digital camera. The photoquadrat apparatus was constructed from PVC and attached to the underwater housing camera following other studies (Preskitt et al., 2004; Van Rein et al., 2011). Specimens were identified to maximum level of taxonomic resolution possible, in most cases to species level. Abundance estimates were performed by calculating the percentage cover by 100 fixed point-interception (Van Rein et al., 2012, 2011) using the image analysis software NIS-Elements Advanced Research v.3.10. Additionally, to assist with species identification, samples were collected for subsequent analysis in the laboratory and species were preserved in 70% ethanol.

2.1. Data analysis of sessile community on panels

The sessile community on the panels was analysed using a distance-based permutational multivariate analysis of variance (PERMANOVA, Anderson, 2001; McArdle and Anderson, 2001). A repeated measures PERMANOVA was run considering the factors 'Time' (fixed, with two levels: two and 15 months after the immersion of the panels); 'Shipwreck' (random, with two levels: *Fougueux* and *Bucentaure*), and 'Material' (fixed). The original design included six levels for 'Material'. However, after 15 months, no macro-benthic organisms were present on the copper panels. For this reason, the results exposed here consider only five levels for the factor 'Material': brass, cast iron, carbon steel, pine and oak. 'Panel' was included in the design, identifying it as the repeated measure (Anderson et al., 2008).

The multivariate analysis was based on the Bray-Curtis similarity matrix of square root-transformed data (Bray and Curtis, 1957). The homogeneity of multivariate dispersion among the groups of each factor of interest was tested by PERMDISP (Anderson, 2006). When the number of total possible permutations was low, the P values were estimated by Monte Carlo sampling (Anderson and Robinson, 2003). The dissimilarities among samples were represented by non-metric multidimensional scaling ordinations (nMDS, Clarke, 1993). Similarity percentages analysis (SIMPER) (Clarke, 1993) was used to identify the contribution that each taxon made to the measures of similarity within (or dissimilarity among) the different levels of the factors. Multivariate