

# Unique Marine Taphonomy in Human Skeletal Material Recovered from the Medieval Warship *Mary Rose*

L. S. BELL<sup>a\*</sup> AND A. ELKERTON<sup>b</sup>

<sup>a</sup> *School of Criminology, Simon Fraser University, 8888 University Drive, Burnaby, British Columbia, V5A 1S6, Canada*

<sup>b</sup> *The Mary Rose Trust, College Rd, HM Naval Base, Portsmouth, PO1 3LX, UK*

**ABSTRACT** The effect of skeletal exposure in a marine environment is an area of taphonomy that has been little investigated at the microscopic level. Understanding the *peri-mortem* and subsequent *post mortem* history of deposition and/or redeposition is extremely important for event reconstruction and to identify deliberate or accidental redeposition. The material used for this study comes primarily from the *Mary Rose* shipwreck (a marine mass fatality dated AD 1545), and forensic material recovered from marine, lacustrine and terrestrial contexts is retrospectively referenced. Work presented here outlines a definitive type of marine exposure seen in temperate shallow off-shore and intertidal marine contexts, and illustrates how it may be differentially identified from terrestrial deposition and exposure. Furthermore, the effects of rapid deposition on skeletal remains have been documented, and results indicate that marine organism fouling activity can be fully inhibited by rapid deposition of sediment. The responsible organism itself remains unidentified, but produces tunnels which are peripheral in their distribution and maintain fixed dimensions and morphology and are here associated with marine exposure. This type of microstructural change is unique and is not found in terrestrial or freshwater contexts. The study demonstrates a taphonomic microstructural change to bone and teeth which may be identified microscopically and interpreted as evidence of marine exposure. Secondly, the history of depositional exposure between the two main Tudor layers has provided a new level of detail concerning exposure and site formation processes. The earliest Tudor layer formed rapidly over a period of months and contained no evidence of microstructural tunnelling, whereas microstructural tunnelling was seen exclusively in the second Tudor layer, formed over a period of decades, a period during which the ship's hull collapsed and a more open marine environment dominated. Copyright © 2007 John Wiley & Sons, Ltd.

*Key words:* marine taphonomy; marine decomposition; human remains; mass fatality; exposure; microscopy; skeletal remains; diagenesis

## Introduction

The bulk of taphonomic literature related to marine exposure usually concerns microbial

fouling, seen as microscopic tunnelling of either calcareous or wooden substrates. Much of the literature has focused on farming activities of oysters or the protection of coral reefs from the deleterious effects of microbial bioerosion. Whilst the *Mary Rose* wreck is a historical context, it has provided a unique opportunity to assess fully the outcome of short- and

\* Correspondence to: School of Criminology, Simon Fraser University, 8888 University Drive, Burnaby, British Columbia, V5A 1S6, Canada.  
e-mail: lynneb@sfu.ca

long-term marine exposure of human skeletal material, and has provided an invaluable taphonomic proxy for examining silt progression and site formative processes.

The decompositional stages of a body in marine and lacustrine environments are generally understood (Simpson & Knight, 1985), and macroscopic changes to bony surfaces are known to be mediated by larger marine organisms (Sorg *et al.*, 1997; London *et al.*, 1997). The usefulness and taphonomic significance of marine-related microscopic changes to bone as a type of exposure are anecdotally reported. Occasionally human skeletal remains are recovered from exotic contexts; for example, Iscan & McCabe (1995) reported on the recovery of partially articulated human skeletal remains from the gut of a shark and described the macroscopic effects on exterior bone surfaces. Arnaud *et al.* (1978) reported microscopic tunnelling in human skeletal material in association with a Mediterranean ship wreck; whilst Ascenzi & Silvestrini (1984) experimentally submerged defleshed bovine bone in a similar marine context for one year and found equivalent

tunnelling. Bell *et al.* (1991) made an initial observation on human dental material from *Mary Rose*, observing a network of tunnels invading peripherally without any reference to tissue organisation (Figure 1). Work on forensic material recovered from intertidal Canadian waters demonstrated peripheral microscopic tunnelling (Figure 2; Bell *et al.*, 1996), and in no instance has this type of tunnelling been associated with lacustrine or terrestrial deposition and/or exposure (Bell *et al.*, 1991, 1996; Bell & Lee-Thorp, 1998).

Microstructural micro-boring has been documented with greater detail in other marine substrates. Living coral reefs suffer cyclical attacks by algal communities between the months of May and September (Highsmith, 1981; Perry, 2000). Other micro-organisms such as Polychaetes (Sato-Okoshi *et al.*, 1990) and Thraustochoyrids (Porter & Lingle, 1984; Chamberlain & Moss, 1988) are silt-sensitive and also colonise a range of calcareous substrates cyclically, and produce small peripheral tunnels. Cyanobacteria have also been implicated (Raghukumar *et al.*, 1989), as have some

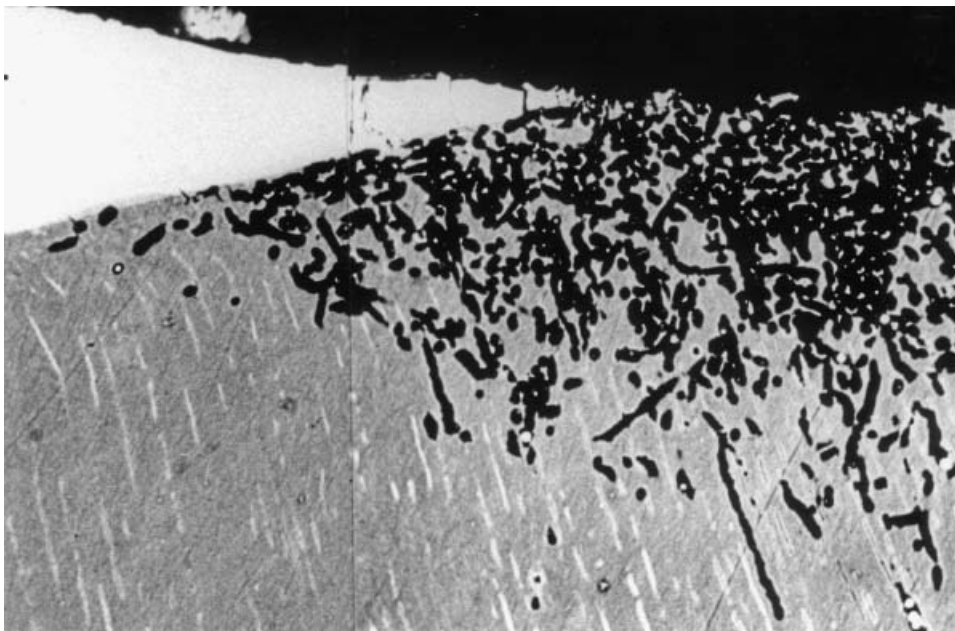


Figure 1. Endolithic micro-boring seen extending into the neck of the tooth peripherally and extending for some distance beneath the enamel. The enamel remains unaffected by this tunnelling. Individual MR 4: scanning electron micrograph (SEM) using backscattered electron imaging (BSE). Vertical field width: 430 microns.

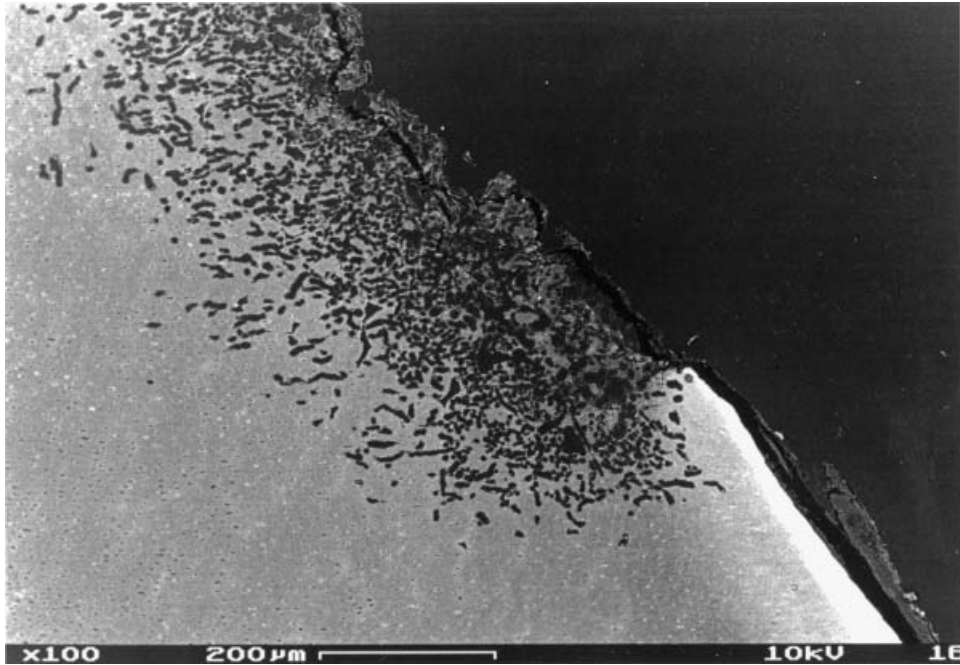


Figure 2. Endolithic micro-boring seen extending beneath the neck of the tooth, peripherally extending beneath, but not intruding into, the enamel. This material was recovered from a shallow cold-water intertidal Canadian context and has been maximally exposed for seven years since death. Note the exact similarity in size and distribution to Figure 1. SEM/BSE image: see magnification bar.

marine fungi (Zeff & Perkins, 1979). Golubic *et al.* (1975) gave a fascinating review of tunnelling in relation to the fossilisation process and called this type of invasive change 'endolithic tunnelling'. They suggested that endoliths will create type-specific tunnelling and that their activity will be affected by depth, temperature and light penetration. They referred to experimental work which demonstrated endolithic micro-boring within 12 days to two months of initial colonisation (Golubic *et al.*, 1975). More recently, experimental work by Wisshak *et al.* (2005) extended Golubic *et al.*'s earlier observations in a cold temperature setting, documenting a range of micro-boring endoliths penetrating an experimental substrate composed of bivalve shells, exposed and observed over a two-year period. The study characterised a number of micro-borers and observed a similar light/depth relationship observed by Golubic *et al.* (1975). Other larger marine organisms are known to produce tunnelling and include octopi (Nixon & Maconnachie, 1988), sea snails (Symth, 1988),

sea urchins (McClanahan & Kurtis, 1991) and sea sponges (Young & Nelson, 1985).

### **Mary Rose**

The *Mary Rose* warship was the Vice Flagship of Henry VIII and sank with virtually all hands lost on 19<sup>th</sup> July AD 1545. The ship itself was fully loaded with mariners and soldiers ready to engage the French fleet in the Solent. She sank suddenly before reaching the French fleet, in approximately 12–14 m of water, and her demise remains an unsolved and historically sensitive mystery. Several theories have been advanced, including sinking from French cannon fire, or an awkward manoeuvre which caused seawater to flood into open gun-ports. She was carrying a crew complement of 415 men, all of whom were lost except for those few men stationed in the rigging (Stirland, 2000). This marine accident represents a medieval disaster on a parallel with the sinking of a large aircraft carrier, and in financial terms

was of equal significance. From a taphonomic perspective, *Mary Rose* represents a unique historical marine mass fatality where most died of drowning or severe trauma, were immediately deposited into a marine environment, decomposed within the ship itself, and the skeletal remains were subsequently exposed differentially to an enclosed and latterly a more open marine environment (Marsden, 2003).

The depositional history of the wreck was not revealed until excavation and lifting. It was determined that after sinking, the ship came to rest on her starboard side which resulted in a shifting of the internal ballast. The hull rapidly infilled with current-borne estuarine grey silts which settled as a fine-grained sediment within the ship. This distinct layer was determined to have been deposited rapidly over a period of months and constituted what is referred to as the first Tudor layer (Marsden, 2003). During the slower formation of the second Tudor layer, formed over decades, seaweed lenses were included within a light grey, shelly clay mix, indicating a stable and partially exposed sea floor. During the formation of this second layer, the upper aspect of the hull collapsed and the interior of the ship became exposed to a much more open marine environment (Marsden, 2003). The ship itself was not considered encased by sediment until the third layer was deposited during the late 16<sup>th</sup> and 17<sup>th</sup> centuries, and consisted of a hard grey clay and broken shelly material (Marsden, 2003). A fourth layer, more mobile, being constantly reworked and redeposited, comprised the modern seafloor. Water temperature during excavation had a winter-summer variation of 12–13°C and 18–20°C respectively (Rule, 1982).

The human remains were found almost entirely in a disarticulated and commingled state with good representation of all elements of the skeleton (Stirland, 2000). Of the 415 men recorded as present, only 179 were accounted for by minimum number analysis (Stirland, 2000). It is possible that some skeletal material existed outside of the excavation limit, which extended a metre from the remaining hull. During collapse, skeletal material may have been redeposited outside of this excavation area and thus never recovered. The arrangement of the human

material was almost entirely within the first two Tudor layers, and the commingling of elements is consistent with marine decomposition within a constrained space prior to deposition.

A microscopic study was undertaken to document and assess the impact of marine exposure, if any, on the microstructural arrangement of human skeletal remains, and secondarily to investigate the impact of silt progression and site formation.

## Materials and methods

A sample of 17 mandibles and maxillae were taken from all decks and silt phases, excluding the modern seabed. During excavation the ship was divided into 3 m<sup>2</sup> excavation quadrants and the location of each specimen which constituted the sample group is represented spatially per excavation quadrant in Figure 3.

A single tooth and accompanying socket was removed from either the maxilla or mandible by cutting the entire tooth and socket free using an Isomet diamond-edged circular saw. The specimens were then embedded in PMMA after Bell *et al.* (1991), cut longitudinally buccolingually, rotary lap-polished using graded abrasives, and finished with a 1 µm diamond paste.

Uncoated blocks were then dry mounted and individually examined under a Lasertec ILM11 confocal reflection microscope (CRM) using a helium-neon light source. This microscope has increased resolution over standard optical reflection microscopes, and allows for direct observation of tissue morphology and characterisation of any *post mortem* alteration. Using this system, a slight internal reflection artefact was observed and was measured to a depth of approximately 2 µm from the block face in depth, and again is a significant improvement over non-confocal microscope configurations. Invasive *post mortem* tunnelling was measured in the *x* and *y* orientation using microscope-interfaced Lasertec software. All measurements were collected blind without prior knowledge of specimen location within the ship stratigraphy. The distribution of *post mortem* tubule invasion was recorded in terms of total morphology and distribution, maximum ingress, and maximum tubule diameter at eight

different predetermined and relative anatomical locations per tooth (Figure 4). Each measurement site was then an anatomical relative approximation. Given the disarticulated and non-anatomical deposition and orientation of mandibles and maxillae within the ship, the buccal and medial aspects of specimens were considered to have been rendered anatomically meaningless, and so the eight sample sites per tooth were based on block face orientation alone. However, each tooth was viewed anatomically within its own socket and that anatomical relationship was maintained. The results from the assessment of maximum ingress were regraded into three arbitrarily predetermined ranges, where grade 1 = less than 100  $\mu\text{m}$  (slight); grade 2 = greater than or equal to 100  $\mu\text{m}$  to less than 200  $\mu\text{m}$  (moderate); and grade 3 = greater than or equal to 200  $\mu\text{m}$  to the pulp cavity (deep). Total distribution of invasive tunnelling was recorded as unaffected (0) or bilateral (B). The results from this regrading were then related to the ship's stratigraphy and plotted

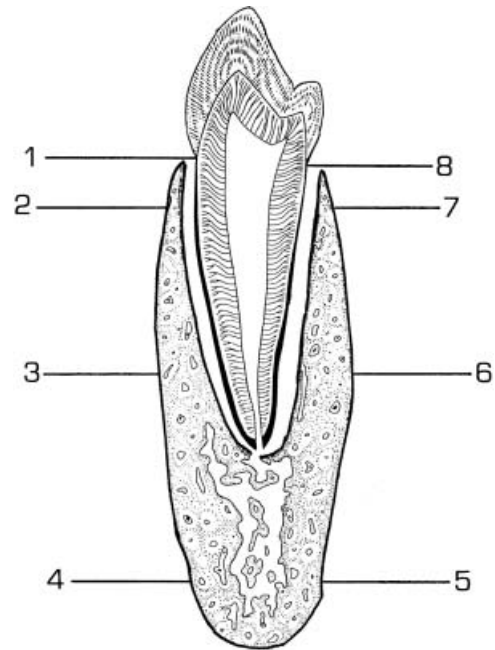


Figure 4. Anatomical site locations used to measure ingress of the *post mortem* tunnelling.

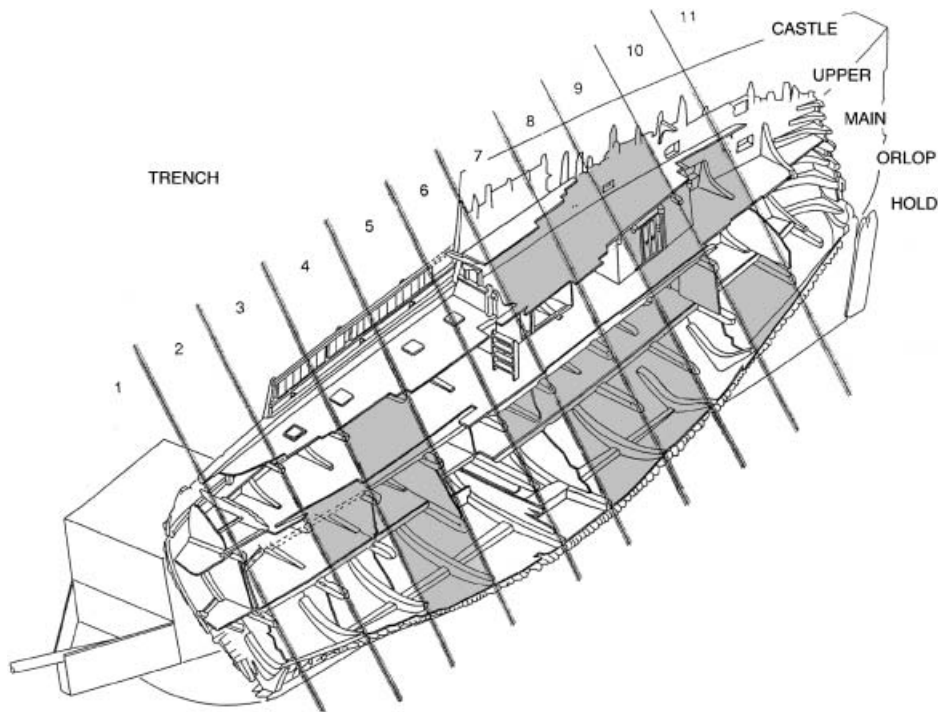


Figure 3. Cutaway diagram of the excavation quadrants. Shaded areas represent sampling quadrants for this study. The four decks and hold are seen in this view; during the formation of the second Tudor layer these decks became exposed to an open seabed environment due to the ship partially collapsing in on itself.

into the cumulative silt phase schematic. The integrity of the periodontal ligament joint (PDJ) space was also assessed.

A subset of specimens affected by *post mortem* ingress were examined using SEM/BSE imaging after a study by Bell *et al.* (1991) where identical ingress was initially observed in *Mary Rose* dental material. Some of this SEM/BSE imagery is included for illustrative purposes only, either retrospectively or as part of this study.

## Results

The Lasertec ILM11 CRM proved to be an excellent tool for the rapid screening of specimens, and enabled the identity, location and

distribution of *post mortem* change to be accurately assessed and measured. The marine type change documented in Bell *et al.* (1991, 1996) was found replicated in all specimens affected by microstructural *post mortem* alteration. This was the only *post mortem* microstructural alteration observed in the sample group.

The distribution of the change varied from one specimen to another in terms of invasive depth and distribution, but was always peripheral, leaving the PDJ unaffected. This replicated the earlier observation made by Bell *et al.* (1991, 1996) where distribution was mapped as peripheral (Figure 5). Only in one case (specimen 14) was the PDJ invaded. The enamel too (including calculus) remained unaffected, although it was characteristically undermined by the micro-

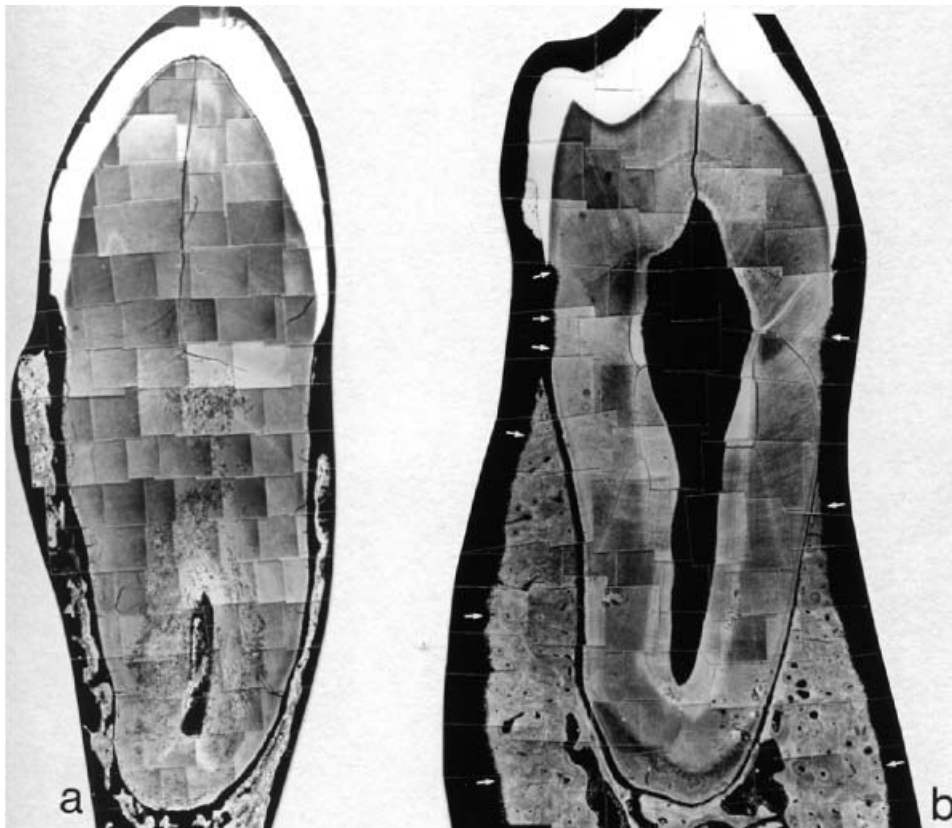


Figure 5. Two SEM/BSE montages of terrestrial diagenetic change (left) and marine tunnelling (right). Terrestrial change driven by bacterial ingress is via the pulp cavity into the open dentine tubules and branching network. In contrast, marine change is peripheral, affecting the external aspect of the tooth and tracking down the neck and tracking round the external aspect of the mandible. This is a typical example of this type of marine change. Left: soil-buried archaeological medieval cemetery context. Right: *Mary Rose* specimen without known quadrant context, but recovered from within the ship itself. *Post mortem* changes are typical of all changes observed within the *Mary Rose* sample.

boring agent (Figures 1 and 2). In intensely tunnelled areas of dentine (tooth neck) no obvious directionality could be observed (Figures 1,2,5 and 6), although at the invasive front of the tunnels an internal reflection artefact revealed the direction of single tunnels once they dipped below the block face and bifurcated (Figure 7). This suggested that dentine tubule direction and branching probably influence and facilitate the initial direction of tunnelling. It is postulated that once a *post mortem* tunnel has been created it will itself influence the direction of further tunnelling. Alveolar bone similarly underwent *post mortem* peripheral tunnelling which typically began at the alveolar crest and tracked around the external aspect to connect with the opposing alveolar crest (Figure 8). The invasive tunnelling lacked directionality in terms of the bony and vascular microstructure. The total depth of invasion varied. What is interesting is that no remineralisation boundary is observed at the edges of these tunnels, which is in contrast to diagenetic alteration observed in terrestrial contexts where bacteria are considered the main

invading organism (Bell *et al.*, 1991, 1996; Bell & Lee-Thorp, 1998).

Maximum tubule diameters of invasive tunnels were measured and ranged between 5–19  $\mu\text{m}$  (nearest 0.5  $\mu\text{m}$ ). Within this range, two separate subgroups were distinguishable between 5–8  $\mu\text{m}$  and 11–19  $\mu\text{m}$  respectively. The commonest maximum diameter fell within the first subgrouping, which represented 84% of total diameters measured. Only circular tunnels were used for this measurement, although it is acknowledged that slight sectional obliquity might contribute to a slight increase in diameter. This alone, however, does not account for the larger diameters recorded for the larger subgrouping.

The blind study results of maximum ingress per specimen were translated into slight (1), moderate (2) and deep (3) levels of invasion. Total distribution was recorded as either unaffected (0) or bilateral (B) (Table 1). The results were then plotted onto the silt phase schematic (Figure 9). It was found that most of the sample group deposited in the first Tudor layer (formed over a period of months) exhibited no *post mortem*

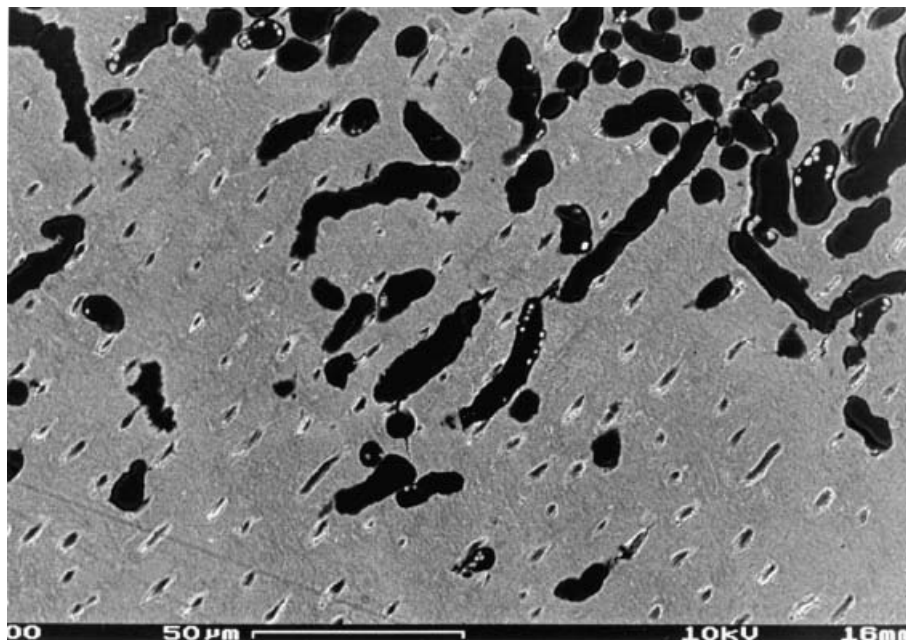


Figure 6. A SEM/BSE image of dentine with invading tunnels penetrating. Note that no demineralisation is evident at the border of these tunnels and tracks both along and at right angles to the dentine tubule direction. From forensic specimen seen in Figure 2: identical to *post mortem* ingress seen in *Mary Rose* material, used for illustrative purposes only. See scale bar.

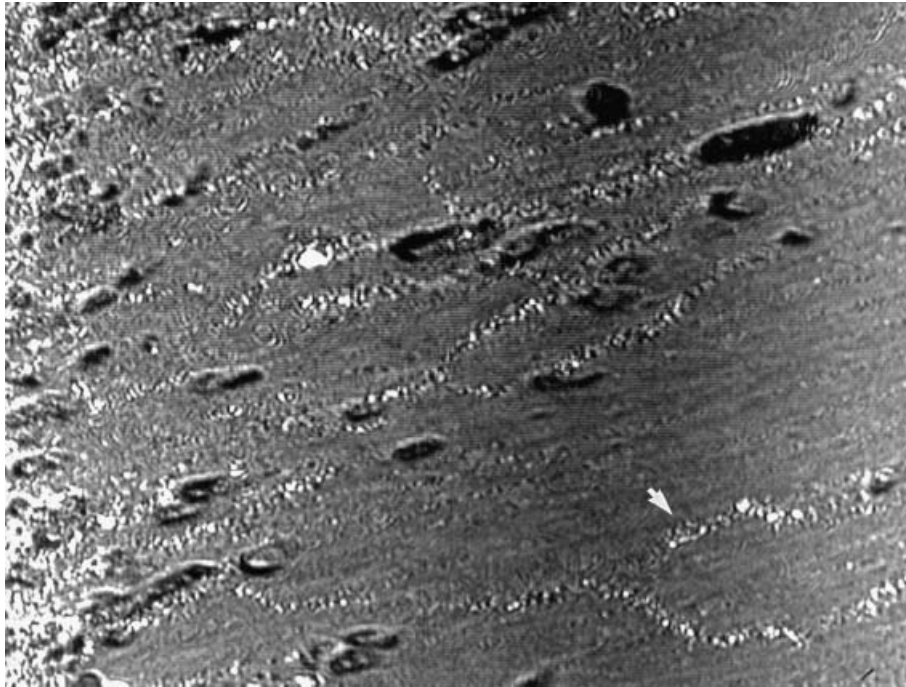


Figure 7. Subsurface endolithic marine micro-boring seen as an internal reflection artefact. Note that the tunnels appear to bifurcate (see arrow). MR 5: field width is 150 microns.

alteration. Only two specimens exhibited any tunnelling: specimen 15 (mid silt phase, Hold quadrant 9) exhibited slight bilateral tunnelling, mostly to the mandibular alveolar bone; and specimen 14 (mid/lower silt phase, Hold quadrant 10) which was considered to have poor provenance and may have been redeposited due to a localised scouring affect (Rule, 1982; Marsden, 2003). Those specimens deposited in the second Tudor layer were all affected by *post mortem* tunnelling, which tended to be bilateral in distribution and graded 2 and 3. Two specimens from the main and upper decks exhibited slight attack with bilateral distribution, whilst two specimens from the Hold and Orlop decks were invaded fairly equally. One specimen situated in the third layer was heavily invaded with slight bilateralism. This specimen had been found in an area of scouring and may have been redeposited (Marsden, 2003). No specimens were recovered from the modern mobile seabed layer.

The PDJ was unaffected by *post mortem* tunnelling in all specimens except one, and this confirms earlier observations made on the *Mary*

*Rose* material. The *post mortem* tunnelling, when present, consistently crossed from the neck of the tooth and progressed across an invisible line to continue peripherally from the alveolar crest (Figures 1 and 5). Occasionally the tunnelling dipped slightly lower than the alveolar crest into the region of the PDJ, where tunnelling of the cementum might be observed. The anomalous specimen 14, which exhibited pronounced *post mortem* tunnelling throughout the PDJ space, also had peripheral distribution which exhibited only slight bilateralism, and the diameters of this specimen fell within the 5–8  $\mu\text{m}$  range. Given that exposure was extended over decades in the formation of this layer, it would appear the PDJ was not attractive to the invading micro-organism.

## Discussion

This study has demonstrated for the first time that *post mortem* alteration to skeletal microstructure in a marine context represents important taphonomic



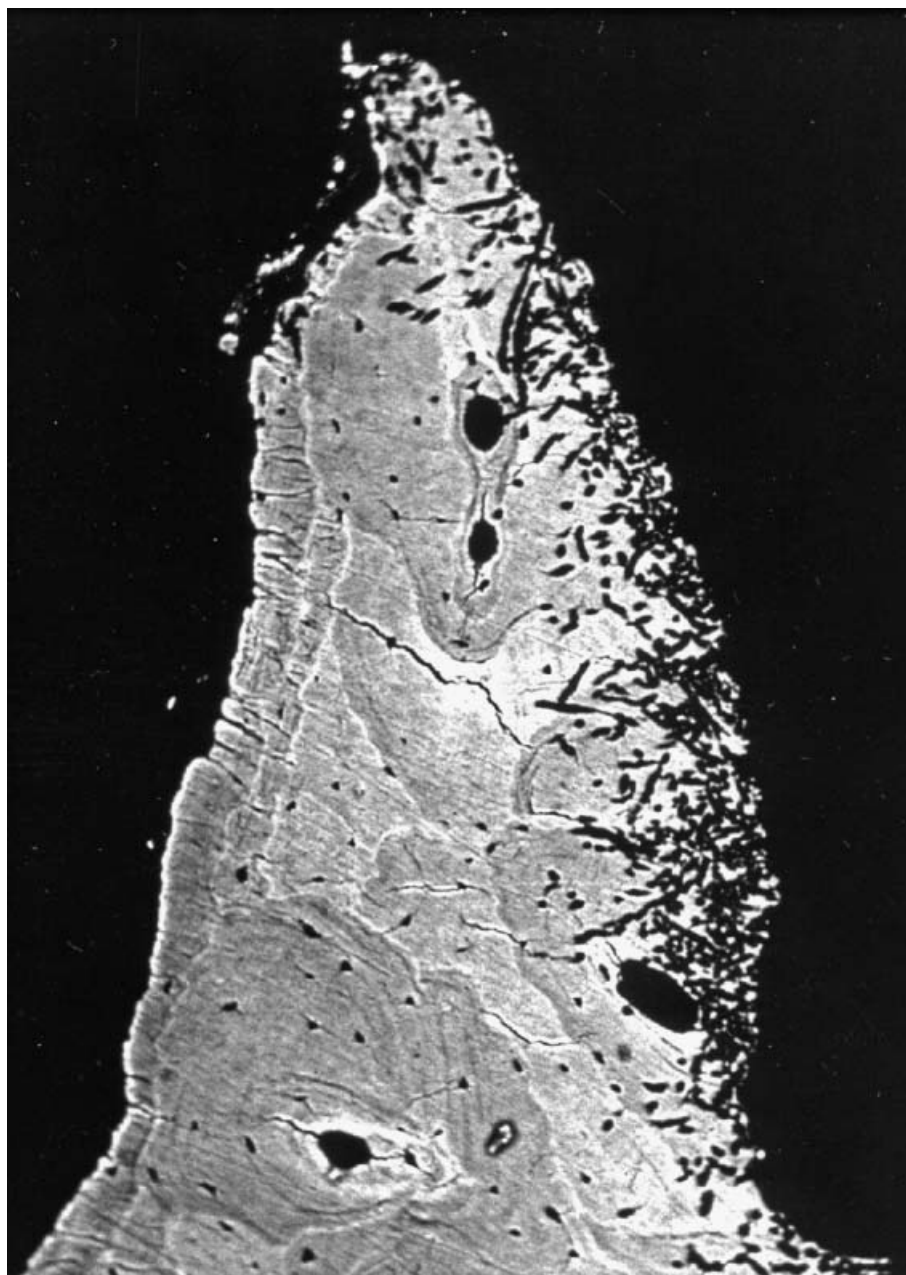


Figure 8. Alveolar crest imaged as a SEM/BSE image. The peripheral nature of the *post mortem* endolithic micro-boring is seen to track along the external aspect. The PDJ is clearly seen as unaffected. This was the common pattern of change seen in this study. The invasion is seen to penetrate without any reference to bony organisation. Same specimen as Figure 5: field width is 855 microns.

and environmental indicators of marine exposure. In the context of this medieval shipwreck, site stratigraphy and *post mortem* tunnelling are closely related to the speed and formation of the layers,

and this aspect underscores the need to understand the depositional context when human remains of archaeological and forensic interest are recovered from marine, intertidal and shoreline

Table 1. Penetration and distribution of *post mortem* tunnelling per tooth

MR no.	Layer	Location	Anatomical sites								Final grade
			1	2	3	4	5	6	7	8	
1	T2	U8	2	2	3	2	2	1	1	1	B3
2	T2	U7	0	0	0	0	1	1	1	1	B1
3	T2	M4	0	0	0	0	2	0	0	0	B2
4	T2	O6	3	3	3	3	3	3	2	3	B3
5	T2	H4	3	3	3	3	3	3	3	3	B3
6	T2	M4	0	0	0	0	0	1	1	1	B1
7	T2	O4	1	1	1	2	1	1	1	0	B2
8	16-17	U8	3	3	3	3	0	0	0	3	B3
9	T2	U9	3	3	3	3	0	0	1	1	B3
10	T1	M9	0	0	0	0	0	0	0	0	O
11	T2	OUT	—	—	—	—	—	—	—	—	—
12	T1	M10	0	0	0	0	0	0	0	0	O
13	T1	O4	0	0	0	0	0	0	0	0	O
14	T1	H10	3	3	3	3	3	2	2	3	B3
15	T1	O9	1	1	1	0	0	1	1	1	B1
16	T1	O7	0	0	0	0	0	0	0	0	O
17	T1	O8	0	0	0	0	0	0	0	0	O
18	T1	H7	0	0	0	0	0	0	0	0	O

contexts. The type of *post mortem* tunnelling detailed here is unique to marine exposure, and as such, if present in a terrestrial or even freshwater context would indicate that the body had spent some time prior to its recovery in a marine or intertidal context (Bell *et al.*, 1996).

The formation of the first Tudor layer represents a period of rapid silting which began immediately after the ship sank and is considered to have lasted only a few months (Marsden,

2003). The specimens examined from this layer (except one specimen) exhibited no microstructural change whatsoever. It is interesting to ask why this should be so when it is known from other fouling studies that a range of calcareous substrates can be affected. When the ship first sank, all those individuals who were below top deck had little chance of escape and either suffered death due to drowning or traumatic injury. The bodies would have cooled rapidly at a

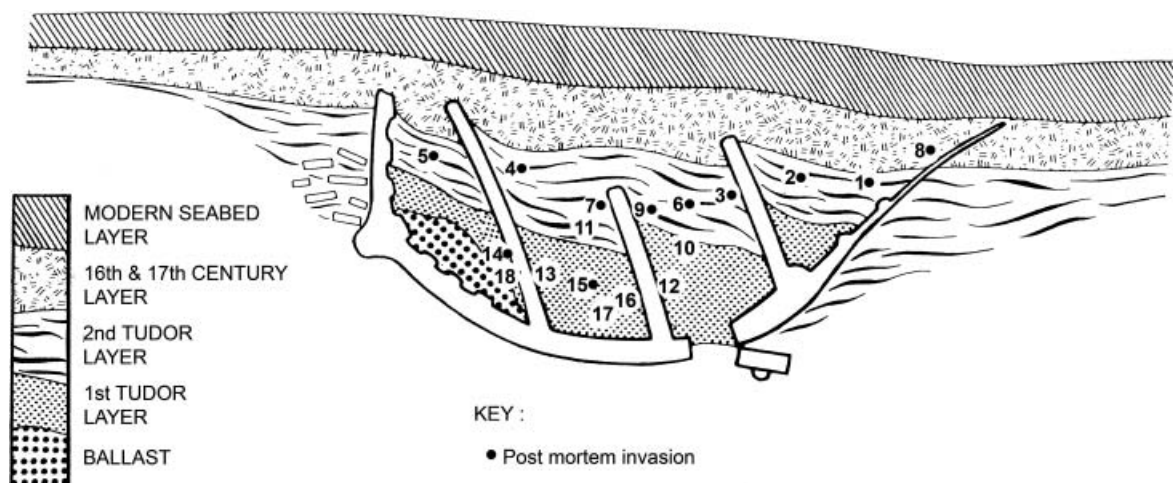


Figure 9. Silt phase schematic showing the major silt phases, representing stratigraphic time. The locations of the sample groups both affected and unaffected by this unique type of marine tunnelling are plotted into the stratigraphy.

depth of 12–14 m, and after 2–4 weeks the sodden bodies would have started to disarticulate, where bone and skin separates (Rule, 1982; Simpson & Knight, 1985). During this short period the bodies would have floated freely unless pinned down by debris, and this is supported by human remains being recovered in a commingled and disarticulated state (Stirland, 2000). This also indicates that enough time had elapsed during the formation of this first layer for skeletonisation to occur. Another important factor to understand is the context of the formation of this first Tudor layer and the effect of the changed orientation of the ship itself. Upon sinking the ship came to rest on her starboard side, which meant that essentially this became the ship's bottom, and therefore the coolest and darkest part of the ship internally. This also meant that the decks were all effectively orientated vertically, with one side of each deck touching the ship's bottom aspect. The ship sank in mid-July, and so the first Tudor layer is considered to have been completed by mid-winter (Marsden, 2003). The fact that no *post mortem* tunnelling is seen in this layer is as significant as its occurrence in the second layer, and suggests that time of year, lack of light and environmental conditions were not conducive to the endolithic micro-organism responsible for the majority of tunnelling observed later.

The second Tudor layer formed more slowly than the first and is considered to have taken decades to form (Marsden, 2003). Specimens from this layer were all tunnelled and showed considerable bilateralism in the overall distribution of peripheral tunnelling. The layer consisted of a fine grey clay full of seaweed lenses, which suggests that this layer had enough light to sustain seaweed growth and that the seaweed would have provided some stability to the sediment. It was during this period that the upper structure of the ship collapsed, exposing all the ship's decks to a more open seabed environment. This would have had the net effect of opening up a semi-enclosed system to more light, heat, increased current-borne fauna and marine detritus. Hence, human material would have provided an ideal substrate for endolithic colonisation where light, a slight increase in temperature, a silt-free environment and available detritus for feeding were newly available. Longer

term exposure, possibly annually cyclic, also allows for endolithic recolonisation, and this would explain the differential tunnelling observed amongst the sample group. Deductively, this open environment was what was absent during the formation of the first layer, where no tunnelling was observed, and is highly suggestive of a silt-sensitive Polychaete, Thraustochyrid, algae or a cyanobacterium as the responsible micro-organism. This type of substrate fouling would also help to explain the difference in invasive depth and the bilateralism of invasion, since deeper tunnel ingress could be achieved on the exposed upside, rather than the downside aspect of the skull or mandible. It is interesting to note that the two deeply tunnelled specimens showed only slight bilateralism, and this could represent movement due to scouring action and redeposition.

## Conclusion

The *Mary Rose* shipwreck is a unique archaeological and historically documented marine mass fatality. This unique context has allowed an assessment of short- and longer-term marine exposure of human skeletal remains similar to that of an actualistic longitudinal experiment, where the taphonomic affects of marine exposure may be examined. What is apparent from this study is that a unique taphonomic change associated with a time period greater than one year (or less) may be produced by invading endoliths that can produce characteristic tunnelling, even though the micro-organism responsible remains unknown. It shares identical characteristics to a previous study by Bell *et al.* (1996), where an identical *post mortem* change was documented in forensic material recovered from an intertidal Canadian context maximally exposed for a period up to seven years since death. Fouling studies on corals and shellfish indicate that micro-boring can occur within a two-month to one-year period and is seasonally cyclical (Golubic *et al.*, 1975; Zeff & Perkins, 1979; Highsmith, 1981). The detailed experiment by Wisshak *et al.* (2005) showed bioerosion within a 1–6 month period, implicating cyanobacteria as a strong candidate for bioerosion observed here, particularly in the

orientation of invasion, size and noted bifurcation of invasive tunnels. Short-term rapid silting appears to inhibit this type of substrate fouling, and so it is important to note the temporal context of recovery when human remains are associated with marine, intertidal or shoreline environments. Absence of this taphonomic change does not mean there was not a period of exposure, but where this tunnelling is found it is clear biological evidence that it did. Attention to the peripheral distribution of this change can illustrate the aspect or orientation of deposition and whether this has changed. Invasive depth is probably associated with cyclical tunnelling and is suggestive of prolonged exposure. The change itself cannot be seen by eye and must be observed microscopically. SEM/BSE imaging for characterisation in combination with confocal reflection microscopy allowed for both rapid and accurate assessment and is recommended.

## Acknowledgements

We thank the *Mary Rose* Trust for providing the material for this study. We also thank Sheila J. Jones and Alan Boyde for comments and advice on this study. Thanks too to Eva Snirer for her expert assistance with editorial and graphics. This study was funded in part by the Medical Research Council (LSB).

## References

- Arnaud G, Arnaud S, Ascenzi A, Bonucci E, Graziani G. 1978. On the problem of the preservation of human bone in sea-water. *Journal of Human Evolution* 7: 409–420.
- Ascenzi A, Silvestrini G. 1984. Bone-boring marine micro-organisms: an experimental investigation. *Journal of Human Evolution* 13: 531–536.
- Bell LS, Boyde A, Jones SJ. 1991. Diagenetic alteration to teeth in situ illustrated by backscattered electron imaging. *Scanning* 13: 173–183.
- Bell LS, Skinner MF, Jones SJ. 1996. The speed of *post mortem* change to the human skeleton and its taphonomic significance. *Forensic Science International* 82: 129–140.
- Bell LS, Lee-Thorp JL. 1998. Advances and constraints in the study of human skeletal remains: a joint perspective. In *Grave Concerns*, Cox M (ed.). CBA: York; 238–246.
- Chamberlain AHL, Moss ST. 1988. The thraustochytrids: a protist group with mixed affinities. *Biosystems* 21: 341–349.
- Golubic S, Perbius RD, Lukas KL. 1975. Boring microorganisms and microborings in carbonate substrates. In *The Study of Trace Fossils*, Frey RW (ed.). Springer-Verlag: New York; 229–259.
- Highsmith RC. 1981. Lime-boring algae in hermatypic coral skeletons. *Journal of Experimental Biology and Ecology* 55: 267–281.
- Iscan MY, McCabe BQ. 1995. Analysis of human remains recovered from a shark. *Forensic Science International* 72: 15–23.
- London MR, Krolkowski FJ, Davis JH. 1997. Burials at sea. In *Forensic Taphonomy*, Haglund WD, Sorg M (eds). CRC Press: Boca Raton; 615–622.
- Marsden P. 2003. *Sealed by Time: the Loss and Recovery of the Mary Rose*. Mary Rose Trust: London.
- McClanahan TR, Kurtis JD. 1991. Population regulation of the rock-boring sea urchin *Echinometra mathaei* (de Blainville). *Journal of Experimental Marine Biology and Ecology* 147: 121–146.
- Nixon M, Maconnachie E. 1988. Drilling by *Octopus vulgaris* (Mollusca: Cephalopoda) in the Mediterranean. *Journal of Zoology, London* 216: 687–716.
- Perry CT. 2000. Macroboring of Pleistocene communities, Falmouth Formation, Jamaica. *Palaeos* 15: 483–491.
- Porter D, Lingle WL. 1984. Marine shell boring microorganisms include Thraustochytrids and other heterotrophic Protista. *Journal of Protozoology* 31(4) 20A–21A.
- Raghukumar C, Rao VPC, Iyer SD. 1989. Precipitation of iron in Windowpane oyster shells by marine shell-boring cyanobacteria. *Geomicrobiology* 7: 235–244.
- Rule M. 1982. *Mary Rose: The Excavation and Raising of Henry VIII's Flagship*. Conway Maritime Press: London.
- Sato-Okoshi W, Sugawara Y, Nomura T. 1990. Reproduction of the boring polychaete *Polydora variegata* inhabiting scallops in Abashiri Bay, North Japan. *Marine Biology* 104: 61–66.
- Simpson K, Knight B. 1985. *Forensic Medicine*. Edward Arnold Ltd: London.
- Sorg M, Dearborn JH, Monahan EI, Ryan HF, Sweeney KG, David E. 1997. Forensic taphonomy in marine contexts. In *Forensic Taphonomy*, Haglund WD, Sorg M (eds). CRC Press: Boca Raton; 567–599.
- Stirland AJ. 2000. *Raising the Dead*. John Wiley and Sons: New York.

- Symth MJ. 1988. *Penetrantia clonoides*, sp. nov. (Bryozoa), a boring bryozoan in gastropod shells from Guam. *Biology Bulletin* **174**: 276–286.
- Wisshak M, Gettidis M, Freiwald A, Lundalv T. 2005. Bioerosion along a bathymetric gradient in a cold-temperate setting (Kosterfjord, SW Sweden): an experimental study. *Facies* **51**: 93–117.
- Young HR, Nelson CS. 1985. Biodegradation of temperate-water skeletal carbonates by boring sponges on the Scott Shelf, British Columbia, Canada. *Marine Geology* **65**: 33–45.
- Zeff ML, Perkins RD. 1979. Microbial alteration of Bahamian deep-sea carbonates. *Sedimentology* **26**: 175–201.