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Applying SEM to the study of use-wear on unmodified shell tools: an experimental approach

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ABSTRACT

Although in prehistoric archaeology the evidence provided by molluscs has often been studied, few works have focused on the functional analysis of shells as tools. A number of prehistoric sites around the world are producing evidence from retouched shells that indicates that they were used for certain operations. In recent years, several experimental studies have been conducted for the purpose of gaining insight into the processes involved in shell tool production and use. This paper focuses on the procedures and the preliminary results of a program of use-wear experiments based on SEM analysis, and corroborates that non-retouched shells can also yield interesting results and can be used as a reference against which archaeological materials can be compared.

1. Introduction

Although Carl Von Linné (Linnaeus) was the first to recognise that shell middens were potential indicators of early human culture, it was in the 1970s that a few academics started to analyse the marks on shells in order to understand past human activities. Some authors tried, for example, to understand why specific shell species were used as raw material for manufacturing tools, or how shell microstructure affected breakage patterns and variations in shell working techniques (Szabó, 2008; Szabó and Kopple, 2015). Some tried to understand the techniques used to make fish hooks (Attenbrow et al., 1998; Przywolnik, 2003). Other studies were mainly based on manufacturing shell tools in order to understand retouching or reduction techniques (among others, Cleghorn, 1977; Douka and Spinapolice, 2012; Eyles, 2004; Romagnoli et al., 2004; Jones O'Day, 2002; Toth and Woods, 1989; Tyree, 1998). Some studies focused on the residues present on the shell edges, in order to understand what they were used for and the material they were used on (Barton and White, 1993; Bonomo and Aguirre, 2009; Schmidt et al., 2001; Zilhão et al., 2010). Finally, others tried to analyse the cut marks produced by the shell tools (Toth and Woods, 1989; Choi and Driwantoro, 2006).

Unlike stone tools, few studies involving shell tool use-wear analysis have been carried out, although some researchers have produced relevant work in the field (Cooper, 1988; Cuenca-Solana, 2009, 2013; Cuenca-Solana et al., 2010, 2011, 2013; Douka, 2011; Douka and Spinapolice, 2012; Eaton, 1974; Gauvrit-Roux, 2012; Jones O'Day and Keegan, 2001; Keegan, 1984; Light, 2005; Lucero and Jackson, 2005; Masson, 1988; Peter, 2001; Schmidt et al., 2001; Szabó and Koppel, 2015; Reiger, 1981; Tumung et al., 2012). Most of these authors tried to understand the use-wear features on archaeological samples, although there is an increasing interest in conducting meticulous experiments to test the possible ways use-wear can occur on shells.

Our study focused on how efficiently shell tools can be used without retouching, and on the effect that micro-topographical variations in shell edge types can have on use-wear patterns. For this analysis, we used the SEM, which has proven to be really convenient for lithic use-wear analysis (among others, Borel et al., 2014; Ollé and Vergès 2008, 2014; Knutsson, 1988; Sussman, 1988). We thus tested the feasibility of SEM use-wear analysis on different types of shells in order to assess whether use-wear is a distinguishing indicator of use-action and contact material, as well as to determine which types of features are most useful for identifying the part of a tool that was used, the tool action and the contact material. The results obtained after systematic use of the

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low-vacuum scanning electron microscope were broadly compared with those obtained by other methodologies (Cuenca-Solana, 2009, 2010, 2013; Cuenca-Solana et al., 2010, 2011; Schmidt et al., 2001; Szabó and Kopple, 2015).

2. Materials and methods

Our program of experiments aimed to analyse the type and degree of different wear features that would be caused by using different shell species with different natural edges (serrated, sharp- or fine-edged), on different generic use-materials (wood or soft animal matter), with different use-actions (transverse, longitudinal, uni- or bi-directional) and lastly for different use-times (Table 1). Fresh wood (*Celtis australis* L.) and red deer (*Cervus elaphus* L.) were used in this program of experiments. The variations in the experiments aim to identify major distinguishing categories of change to the shell surface (abrasions, fractures, striations and polishes), depending on the shell, use-material and use-action.

Systematic experiments were conducted to meet the above-mentioned goals. We decided to control certain variables in the experiments, while attempting to perform several basic activities. Although a complete experimental program would obviously require many more combinations of variables, in order to compare, here we maintained a reduced variety of contact materials, including: one kind of, soft and homogeneous wood and a single animal species (for which we worked on fresh meat, skin and bones).

The shells were selected on the criteria of edge shape, thickness, hardness, and microstructure, in order to understand where the use-wear might occur and which shell species would be better suited for use as a non-retouched tool. In the meantime, we took into consideration the shell species present in some European prehistoric sites.

In the experiments, four species of shell were used: *Pecten maximus* (Linnaeus, 1758), *Mytilus galloprovincialis* (Lamark, 1819), *Ruditapes decussatus* (Linnaeus 1758), and *Glycymeris violascens* (Linnaeus, 1767). The first three were collected live from the local fish market, which gave us a wide variety of options and allowed us to select those with edges that had been altered the least by natural effects or human handling. *G. violascens* shells were collected from the beach in Tarragona and selected with various different levels of wear, as they had undergone some natural modifications caused by friction with the sand (Zuschin et al., 2003). All the shell species selected have naturally sharp edges, so no retouching or edge modification was performed.

Several assemblages from European sites dating from the Middle Palaeolithic to the Neolithic era provide evidence of the use of these shells. The *Glycymeris* sp. is present in Middle Palaeolithic sites in Southern Italy and Greece (Douka and Spinapolice, 2012). The use of *M. galloprovincialis* for shell tools has been reported for example at the Mesolithic and Neolithic Spanish sites of Santimamiñe (Cuenca-Solana et al., 2010), La Draga and Serra del Mas Bonet (Clemente-Conte and Cuenca-Solana, 2011).

Because they were bought fresh, the *P. maximus*, *M. galloprovincialis* and *R. decussatus* were first cleaned by hand to remove the flesh, whereas the *G. violascens* shells were not cleaned in this way. Later, all the shells were cleaned twice for the experiment: firstly, to ensure that they were properly clean for making moulds of the fresh edges, and secondly prior to the microscopic examination of surface changes. The cleaning procedure consisted of:

a) 10 min in an ultrasonic bath of H_2O_2 (10% vol.) to soften any adhered organic tissues (of the molluscs themselves and of the materials worked);
b) 10 min in an ultrasonic bath of the neutral phosphate-free detergent Derquim®, with ionic and non-ionic surfactants to eliminate all the residues from the shell surface;
c) Rinsing under cold running water to remove any detergent from the shell surface;
d) 2 min in an ultrasonic bath of acetone to eliminate any fatty residue resulting from the handling.

After these various cleaning steps, the shells were packed in individual plastic bags in order to prevent any future contamination or damage. This cleaning procedure has been shown to yield good results for stone tools (Byrne et al., 2006; Ollé and Vergès, 2014), and was tested on modern shells before the experiments in order to assess its adequacy.

Before making the mould and cast of each shell tool edge, we took photographs of the fresh edges. Since, in some cases, photographs and other taphonomic studies cannot tell us how the use-wear on the edge occurred, we made a mould and cast in order to have a reference copy of the fresh edge which would make it possible to compare a given point after the experiment with the same point on the edge of the mould. This can help us to assess the actual changes to the edge which resulted from its use (thus avoiding misunderstandings of certain features such as natural striations, edge fractures, etc.)

Moulds were prepared using silicon-based dental impression material, Provil® novo Light (Heraeus Kulzer, Inc.). The two components, a base and a catalyst in a ratio of 1:1, were placed on the impression material sheet and mixed at room temperature for 20–30 s so that the colour is uniform, in order to ensure good polymerization. The mixture was then applied to the shells with a

Table 1
List of experiments and principal variables of the program. Delineation h-d (horizontal delineation), p-d (profile delineation).

Ref. no.	Type of shells	Worked material	Species	Delineation		Working angle	Motion	Action	Hand	Time
				h-d	p-d					
MY01	*Mytilus galloprovincialis*	Skin-meat	*Cervus elaphus*	Convex	Straight	90°	Longitudinal bidirectional	Cutting/skinning	Right hand	15
MY02	*Mytilus galloprovincialis*	Meat-bone	*Cervus elaphus*	Convex	Straight	90°	Longitudinal bidirectional	Cutting/defleshing	Right hand	10
MY03	*Mytilus galloprovincialis*	Stem of fresh wood	*Celtis australis*	Convex	Straight	90°	Longitudinal bidirectional	Cutting wood	Right hand	10
MY04	*Mytilus galloprovincialis*	Stem of fresh wood	*Celtis australis*	Convex	Straight	70°	Transverse bidirectional	Scraping wood	Right hand	10
PE01	*Pecten maximus*	Skin-meat	*Cervus elaphus*	Serrated	Serrated	30°–90°	Longitudinal unidirectional	Cutting/skinning	Right hand	15
PE02	*Pecten maximus*	Meat-bone	*Cervus elaphus*	Serrated	Serrated	90°	Longitudinal bidirectional	Cutting/defleshing	Right hand	15
PE03	*Pecten maximus*	Stem of fresh wood	*Celtis australis*	Serrated	Serrated	90°	Longitudinal bidirectional	Cutting wood	Right hand	10
PE04	*Pecten maximus*	Stem of fresh wood	*Celtis australis*	Serrated	Serrated	90°	Transverse bidirectional	Scraping wood	Right hand	10
RU01	*Ruditapes decussatus*	Stem of fresh wood	*Celtis australis*	Convex	Convex	90°	Longitudinal bidirectional	Cutting wood	Right hand	10
RU02	*Ruditapes decussatus*	Stem of fresh wood	*Celtis australis*	Convex	Convex	90°	Transverse unidirectional	Scraping wood	Right hand	5
GL01	*Glycymeris violascens*	Meat-bone	*Cervus elaphus*	Convex	Convex	90°	Longitudinal bidirectional	Cutting/Defleshing	Right hand	10
GL02	*Glycymeris violascens*	Meat-bone	*Cervus elaphus*	Convex	Convex	90°	Longitudinal bidirectional	Cutting/Defleshing	Right hand	10

spatula, and left to polymerise. The moulds were not removed from the shells until they were used for making casts, in order to prevent any contamination inside the moulds.

A two-component rigid polyurethane resin, Feropur PR-55 (Synthesia Española S.A.), was used to prepare the casts. Firstly, a small amount of the mixture – mixed in equal proportions – was poured into a mould with the help of a large gauge needle syringe, as the moulds had very narrow openings for pouring the mixture through. The mould was then held still, and the syringe was moved inside the mould, so that the liquid penetrated completely and then the rest of the mixture was poured rapidly, as the resin starts hardening quickly. One has to be very careful when making a cast from these moulds as sometimes, if the resin solution is not poured evenly inside the mould, the cast will not come out perfect – and they must be perfect for analytical purposes. The cast and mould were then kept together until the microscopic analysis was performed.

The purposes of our study were to analyse use-wear on unretouched shell tools and to subsequently describe how the wear traces were produced during their use as a tool, as well as to understand the processes that generate these wear traces. We attempted to understand how use-wear features imaged using SEM on different shell species can be a distinguishing indicator of function in terms of contact materials and use actions. Our program

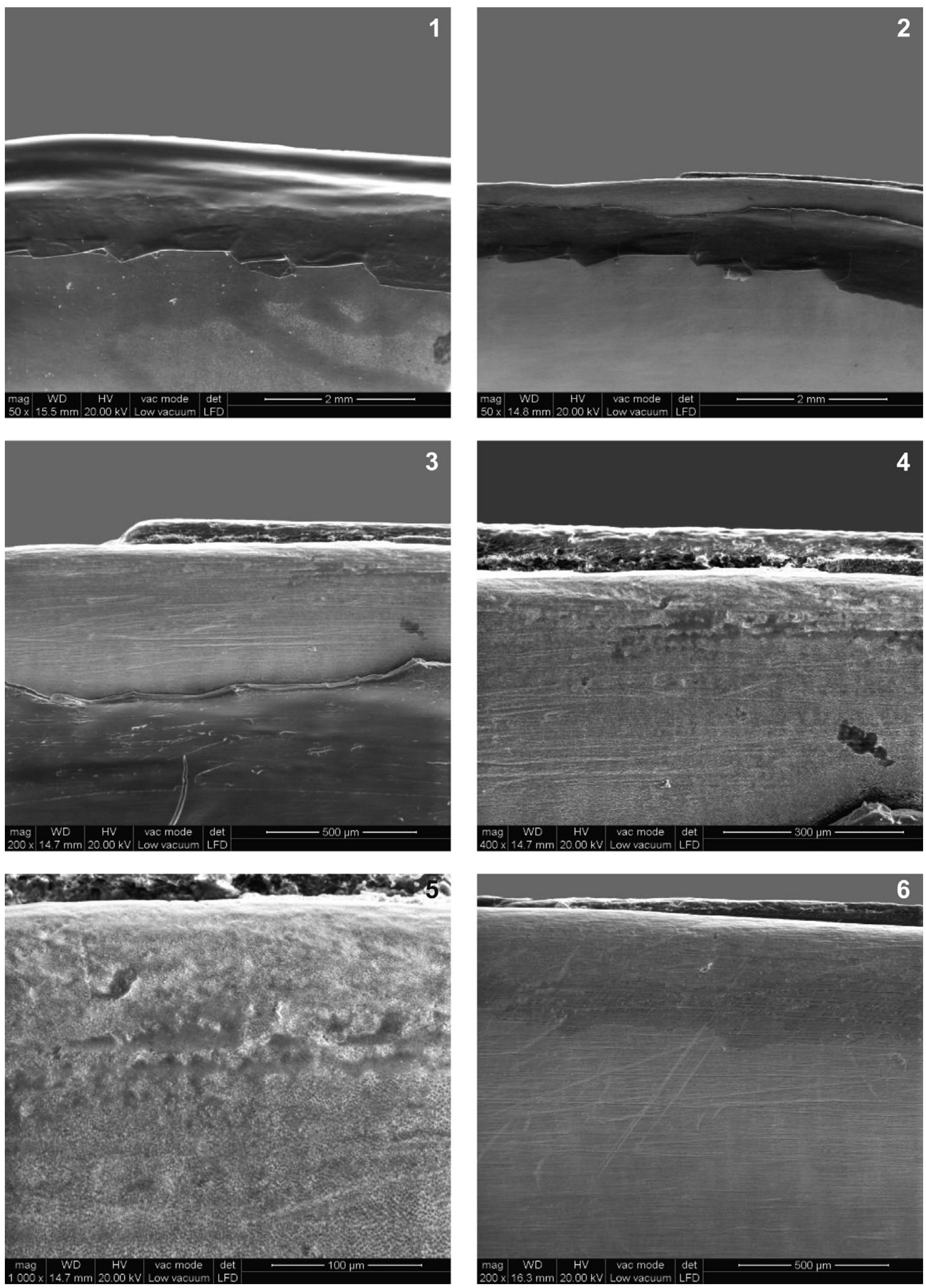

Fig. 1. The development of use-wear on the MY01 in steps (skinning action, 15 min). 1) The fresh edge; 2) The portion of the edge in Fig. 1.1 after use; note the removal of the periostracum; 3) Fine striation marks on the exposed area; 4) Detail of Fig. 1.3 with slight edge rounding and striation marks; 5) Closer look at Fig. 1.4 with slight polish on the edge; 6) Long striations parallel to the edge overlapped by small diagonal striation marks on the curved portion of the edge.

of experiments included two major groups: butchery processes and woodworking. These were further sub-divided into skinning, defleshing and disarticulation, scraping wood and cutting wood. As for the specific contact materials, these included the hide, meat (loin) and bone of *C. elaphus* for butchery activities, and the soft wood of *Celtis australis* for woodworking. The results for each use-action have been presented separately for each contact material within the broad categories of animal or vegetal matter. We decided to use a longitudinal uni- or bidirectional action and a transverse bidirectional action, and each shell sample was used for 10–15 min.

The *Pecten*, *Ruditapes* and *Glycymeris* shells were held from the dorsal edge during use, so that the central portion of the ventral one acted as the working edge. Inversely, the *Mytilus* shells where held from their ventral edges, so that the working area was the posterior half of the dorsal edge. Relevant dependent variables, such as the form attributes of the tools (Table 1) and illustrations of them, along with observations about the contact materials were recorded in detail on standardised forms (Ollé, 2003; Vergès, 2003). Line sketches of each specimen were made on the corresponding form and where each feature was located was plotted on these sketches. Prior to use, photographs were also taken of the external and internal faces of the tool in order to record the fresh edge as well as to indicate the part of the edge that was used and any traces found on that edge. A micrographic record was kept of diagnostic use traces. The worn points of the used edges were systematically compared with the same points on the fresh edges. The resulting catalogue of photographs includes micrographic details (such as magnification, working distance, etc.), as well as a description of the features recorded.

For this study, we examined our shell tools under a FEI QUANTA 600 ESEM (environmental scanning electron microscope) belonging to the Universtitat Rovira i Virgili Microscopy Service. We used it in low vacuum mode. The advantage of using this equipment is that the samples do not need to be desiccated and coated with gold–palladium or carbon, and thus their original characteristics may be preserved for further testing or handling. Generally speaking, and according to our experience when studying lithic and bone tools, scanning electron microscopy has some advantages over optical microscopes conventionally used for use-wear analysis (Borel et al., 2014). These advantages include: high magnification power, high depth of field, high-resolution images and no bright diffraction halo. It is worth mentioning that the EDX associated to the SEM allows to check the elementary chemical composition of any unidentified residue on the surface of the samples and thus to avoid mistakenly identifications. Although we also used a reflected light microscope (Zeiss Axio Scope A1, with magnifications from 50x to 500x) to carry out preliminary observations on the experimental materials, here we only include a selection of the images obtained with this technique, just to highlight the considerable differences in terms of imaging accuracy (Fig. 15), even when using differential interference contrast microscopy (DIC) and extended focus software (Deltapix Insight, with a 5 MP Deltapix digital camera Invenio 5SII model).

Before examining the samples using the SEM but after the 2-minute ultrasonic bath in acetone, they were each mounted on a stub using hot melt glue in such a way that the edge of the sample was parallel to the microscope stage. In order to identify the location, reference points were marked a short distance away from the tool edge, using a 0.5 mm indelible felt tip pen, and the same points were marked on a drawing of the specimen. These markings could easily be removed with a little acetone.

Firstly, the original tool was examined using the SEM, observations were made of micro-wear and images were taken. Subsequently, the replica of the original edge was studied in the same manner in order to identify the changes caused by use. The points where use-wear or any other changes were observed were checked against the cast.

For SEM observations, three to four points of interest were located on each tool and then images were taken of each one at several magnifications (ranging from 20× to 2000×). Higher magnifications were chosen to analyse specific details, whereas lower magnifications were used to study how the features were distributed. The observations were made at a voltage of 20 kV at working distances of between 10 mm and 30 mm, depending on the size of the sample.

To illustrate and assess the feasibility of the proposed methodological approach based on SEM analysis on archaeological

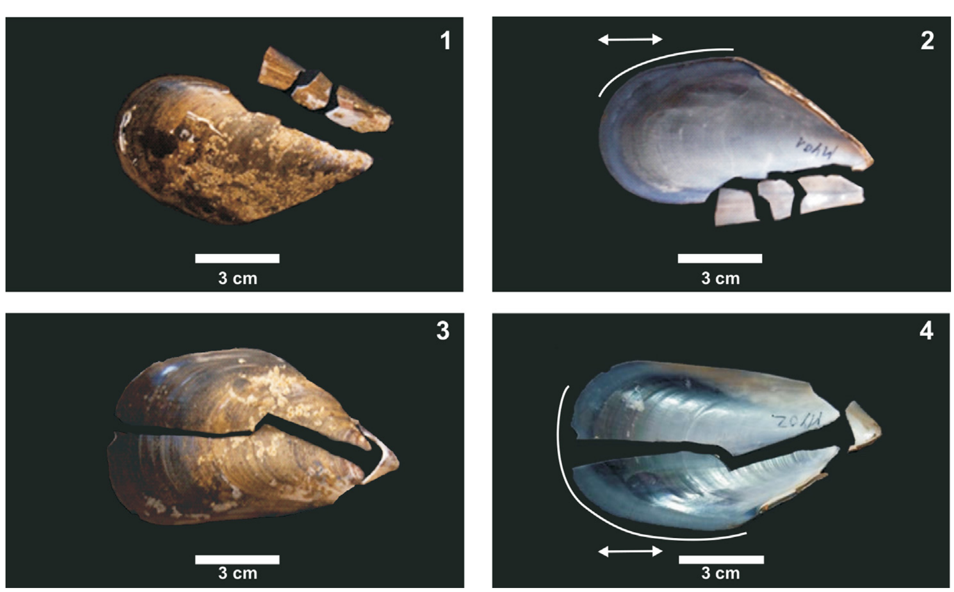

Fig. 2. Macro-fractures on MY01 (1 and 2) and MY02 (3 and 4). White lines mark the portions of the dorsal areas of the shells acting as working edges; white arrows mark the direction of use.

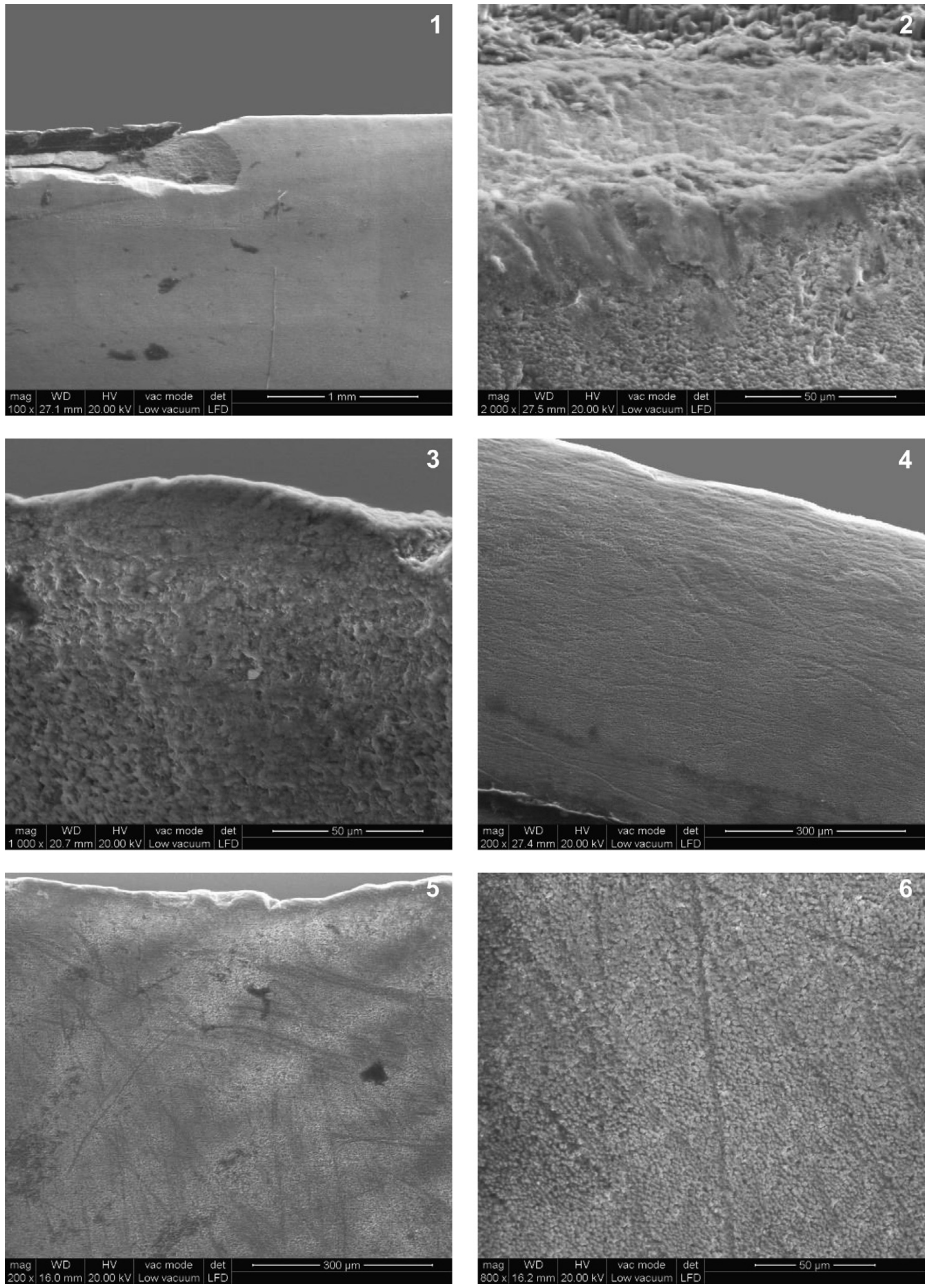

Fig. 3. Use-wear features on MY02 (defleshing, 10 min). 1) Hinge-–type edge fracture after use; 2) The same edge fracture at higher magnification showing the polish formation on the fracture; 3) Edge rounding with polish formation and parallel striations; 4) Continuous parallel striations with some short diagonal striations crossing over them; 5) Edge with micro-chipping (crescent shape) and overlapped striations on the surface; 6) Surface in Fig.3.5 at higher magnification, showing detail of the striations.

materials, we searched for a collection presenting the same shell taxa used in the experiments, as well as good enough preservation to allow a use-wear study. We chose the shells from the late-Upper Palaeolithic site of la Cativera, located in Tarragona (NE Spain). This rock-shelter used by hunter–gatherers during the Pleistocene–Holocene transition has been interpreted as a sequence of short-term occupations (Morales et al., 2013; Morales and Vergès, 2014). Samples analysed come from levels A and B, dated by AMS 14C to 9080–8600 and to 10300–9600 years BP in the 2-sigma calibration respectively (Morales et al., 2012). Currently analysed shells were used just as pilot trials and include 3 *Mytillus* (1 form level A and 2 from level B), 1 *Glycymeris* (level A) and 1 *Pecten* (level B).

3. Results

In this section we briefly present each of the experimental shell use-wear patterns. The description is organised by shell species, action performed and materials worked. Details are provided of how the micro-topography of each species affects the resulting use-wear traces.

3.1. *Mytilus galloprovincialis*

We used four *M. galloprovincialis* specimens, which were given reference numbers MY01 to MY04. In all of the experimental samples we saw that, when *M. galloprovincialis* is fresh, it has a protective

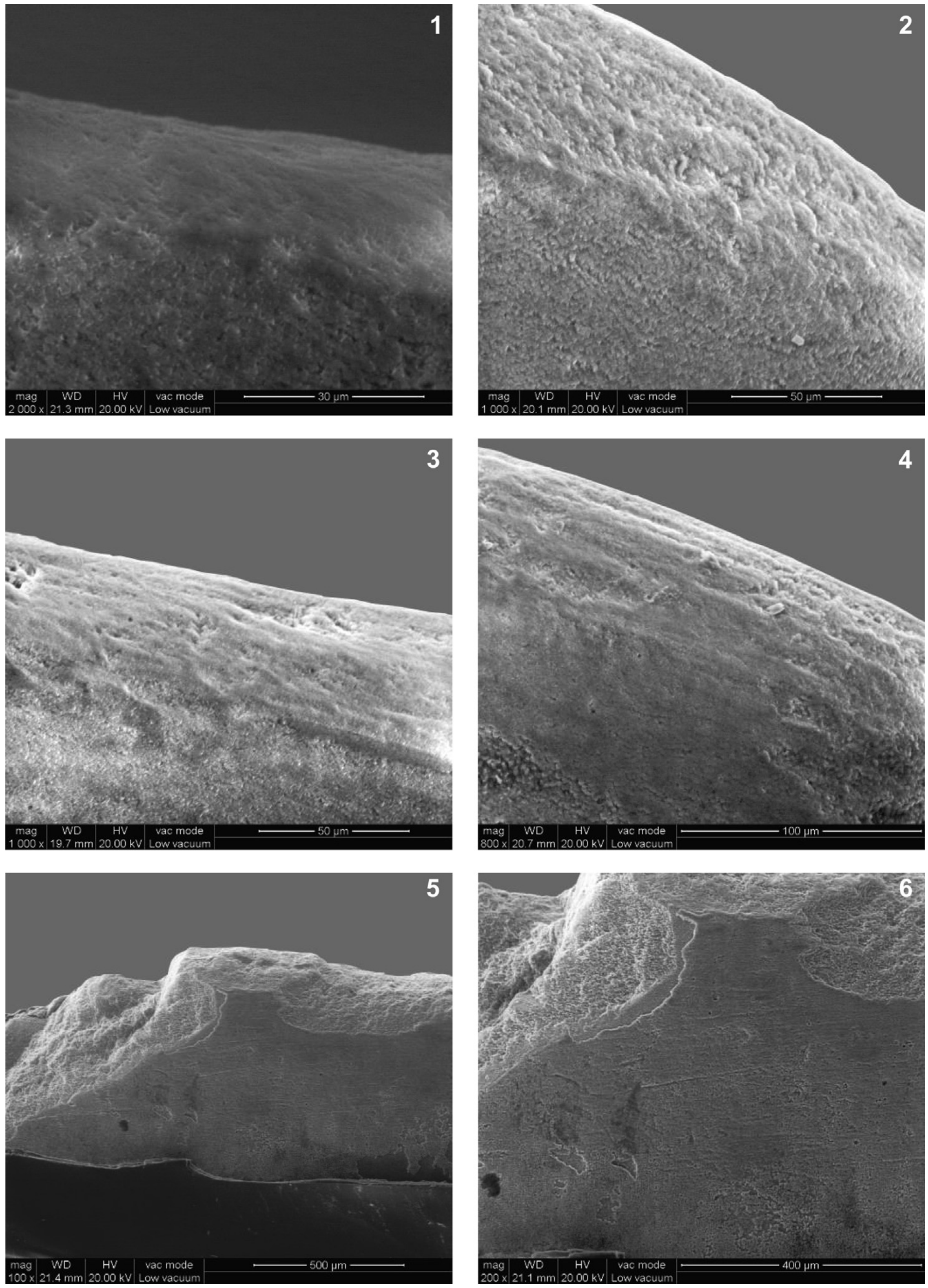

Fig. 4. Use-wear features on MY03 (cutting wood, 10 min). 1) Smooth and continuous polish on the edge rim; 2) Coarse/granulated polish on the portion of the edge with less contact with the worked material; 3) Polish and edge rounding with micro-pitting; 4) Polish and edge rounding with deep parallel striations and micro-chipping; 5) Steep and crescent type edge fractures; 6) The same point as Fig. 4.5 with a closer view of the striations.

membrane on the prismatic layer (*periostracum*) on the edge (Fig. 1.1). With continuous use, the *periostracum* on the working edge peels and the membrane completely disappears, revealing the inner surface of the shell, on which we observed traces of use-wear (Fig. 1.2). Nevertheless, as this membrane is composed of conquioline (an organic substance not likely to be preserved in the archaeological material), it cannot serve on the analytical level to differentiate between used and unused archaeological shells.

3.1.1. Skinning (longitudinal bidirectional)

MY01 showed slight edge rounding when used for a longer time. There are fine striations, mostly parallel to the edge, and they are arranged very close one to each other (Fig. 1.3 and 1.4). On the straight portion of the working edge of the shell, the striations are parallel to the edge, but on the curved part of the edge, which is towards the posterior end, these parallel striations continuously overlap some oblique/diagonal striations and create a criss-cross pattern (Fig. 1.6). The shape of the shell edge therefore strongly affects the orientation of these features. This is caused by the bidirectional action and even by the blows given with the tool while skinning the deer, as we observed in our experiment. The striations are very shallow and fine. Near the edge, smooth polish formation can be seen, distributed in similar bands arranged parallel to the edge (Fig. 1.5). In addition to the micro-wear, some macro fractures also occurred on MY01, due to the force and pressure applied to the shell during skinning (Fig. 2.1 and 2.2). Breakage occurred on the

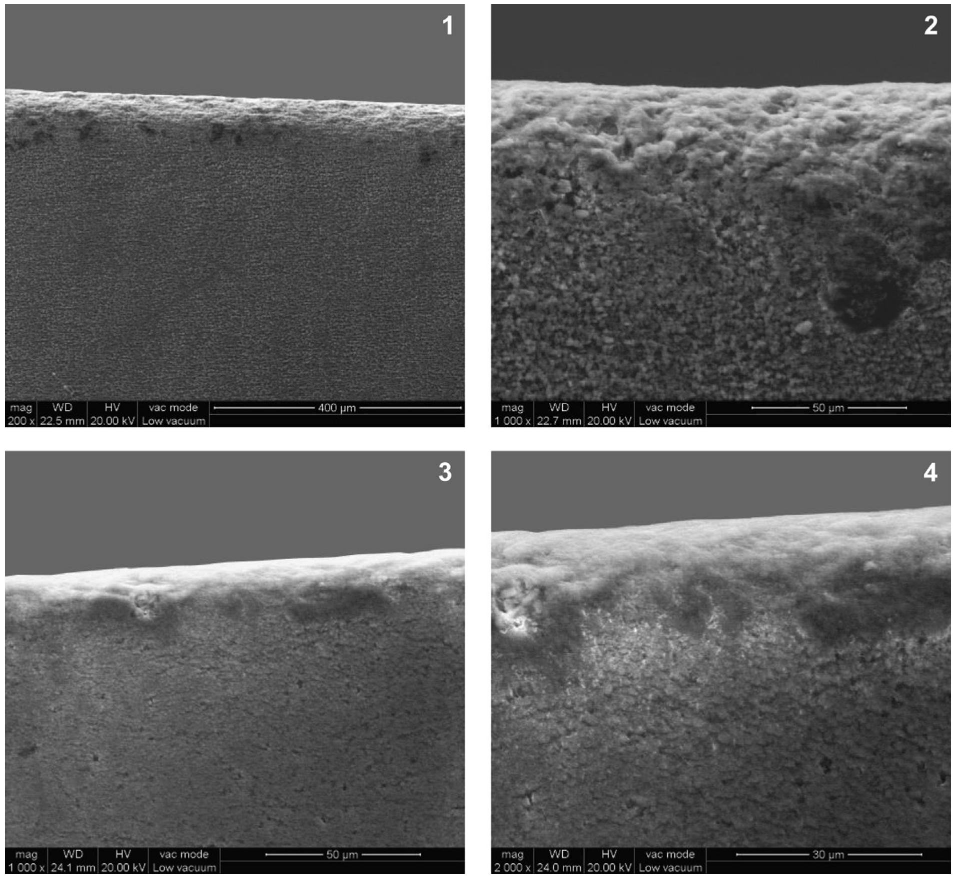

Fig. 5. Use-wear features on MY04 (scraping wood, 10 min). 1 and 2) Edge rounding and polish in bands transversal to the edge, shown at different magnifications; 3 and 4) Edge rounding and locally highly developed polish over the working edge at high magnifications.

internal area (towards the anterior part of the shell), where the subject applied maximum grip and the shell snapped due to the pressure.

3.1.2. *Defleshing and disarticulation (longitudinal bidirectional)*

On MY02, the *periostracum* was completely removed after use, exposing the granulated surface below. Due to contact with bone during defleshing and disarticulation, a number of edge fractures occurred (Fig. 3.1). Some polish was observed on the edges of these micro-fractures. Where well developed, the prismatic structure of the inner surface shows a very smooth texture (Fig. 3.2 and 3.3). The striations are more groove-like and deeper than those on MY01. On the straight part of the dorsal part of the shell, the striations are continuous, parallel to the edge and arranged very close to each other (Figs. 3–4). In some cases, the striations are shorter, overlapping and diagonal, in a criss-cross pattern, probably as a result of the bidirectional movements and blows (Fig. 3.4, 3.5 and 3.6). Due to contact with bone, MY02 underwent some micro-chipping on the posterior edge (Fig. 2.3 and 2.4), and the pressure applied by the subject on the tool while defleshing resulted in a macro-fracture from the posterior to the anterior end, breaking off the umbo.

3.1.3. *Cutting wood (longitudinal bidirectional)*

On MY03, we observed well developed polish on the inner part of the edge, varying in texture from granulated/coarse to very smooth. We found that the part of the edge that was in continuous contact with the wood had a highly developed polish (Fig. 4.1), whereas the part of the edge which was in less contact with wood had just a coarse polish, distributed in bands parallel to the edge (Fig. 4.2–4.4). We observed some micro-pitting (Fig. 4.3) and deep linear grooves over the polish (Fig. 4.4). Sharp and crescent-shaped edge fractures were also apparent. These fractures featured a few deep striations parallel to the edge (Fig. 4.5 and 4.6). No macro-fractures occurred.

3.1.4. *Scraping wood (transverse bidirectional)*

Unlike other *Mytilus* samples, we did not see any striation marks on MY04. The working edge showed traces of polish and edge rounding with some micro-chipping on them (Fig. 5). The inner part of the edge in frequent contact with the wood had a very smooth polish distributed in a continuous band very clearly restricted to the edge. Other parts which occasionally came into contact with the wood only developed patches of polish. No macro-fractures were observed.

3.2. *Pecten maximus*

For this species we gave the samples reference numbers PE01, PE02, PE03 and PE04. We analysed both the inner and the outer sides of PE01 in order to find the part of the edge where use-wear traces were most visible or identifiable. Once we realised that traces were more visible on the inner one, for the rest of the samples we only analysed that side of the shell.

3.2.1. *Skinning (longitudinal unidirectional)*

PE01 already had some micro-fractures on the edges. The cast of the fresh edge therefore helped us to distinguish between the used edge and the unused one (Fig. 6.1 and 6.2). After skinning, the foliated external shell layer detached from the outer surface, and the removed calcium carbonate crystals likely acted as an abrasive,

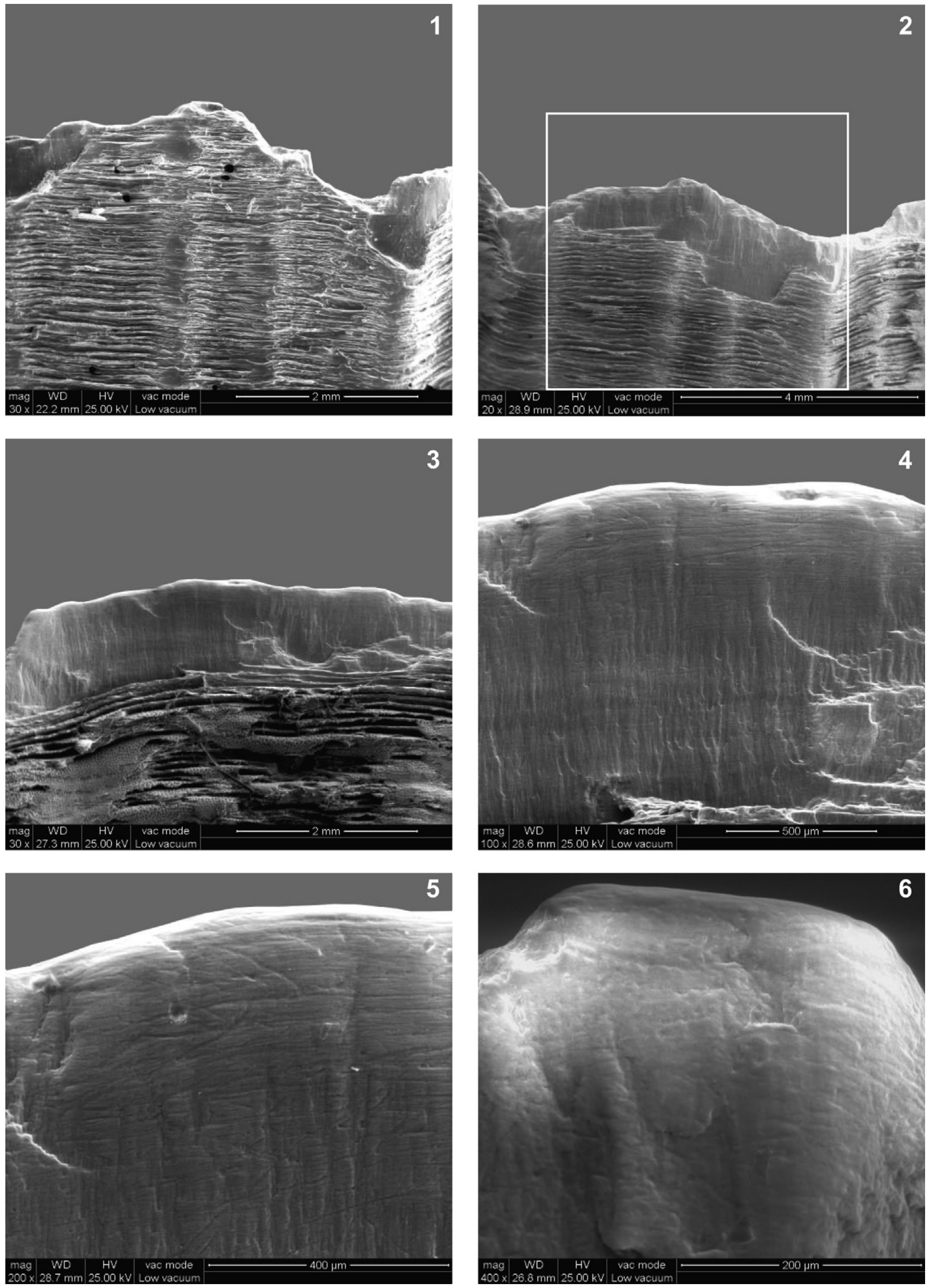

Fig. 6. Use-wear features on the *periostracum* of PE01 (skinning, 15 min). 1) Cast of the original edge; 2) Removal of *periostracum* after the use – the white rectangle marks the area shown in Fig. 6.1; 3, and 4) Details at different magnifications of the edge with the removed *periostracum* and the edge rounding, the polish and the striations resulting from use; 5) Closer look at Fig. 6.4, with some parallel and overlapped diagonal striation marks on the rounded edge; 4) Formation of polish with some fine striation marks on it.

contributing to producing the use-wear traces on the *ostracum* (which is the layer below the *periostracum* on the external side) (Fig. 6.3–6.5). When used for a longer time, rounding and polish were observed. The polish is highly developed and there were fine striation marks on it (Fig. 6.6).

On the other hand, the striation marks on the inner side are very deep, continuous, parallel to the edge, and arranged close to each other (Fig. 7). Some short striations were also observed diagonally overlapping earlier striations, which we suggest are from the striking motion and longitudinal unidirectional working action (Fig. 7.3–7.5). We also came across some micro-chipping on the elevated part of the serrated edge (Fig. 7.6).

3.2.2. *Defleshing and disarticulation (longitudinal bidirectional)*

Due to its large size and flat, round shape, PE02 was very good for defleshing and disarticulating. A crescent-shaped micro-fracture was seen on the edge, with edge rounding (Fig. 8.1). Some edge fractures were already present on the sample, so, as in other cases, the cast was very helpful in distinguishing them from those actually due to use. The areas of polish are well developed and mostly present over the edge fracture (Fig. 8.2). The polish texture is very smooth, uneven and in bands. Some striations are very deep, but some are very fine. Due to the round shell shape and its serrated edge, more striation marks were found on the elevated part of the edge than on the shallow part. Striations on the shallow areas are

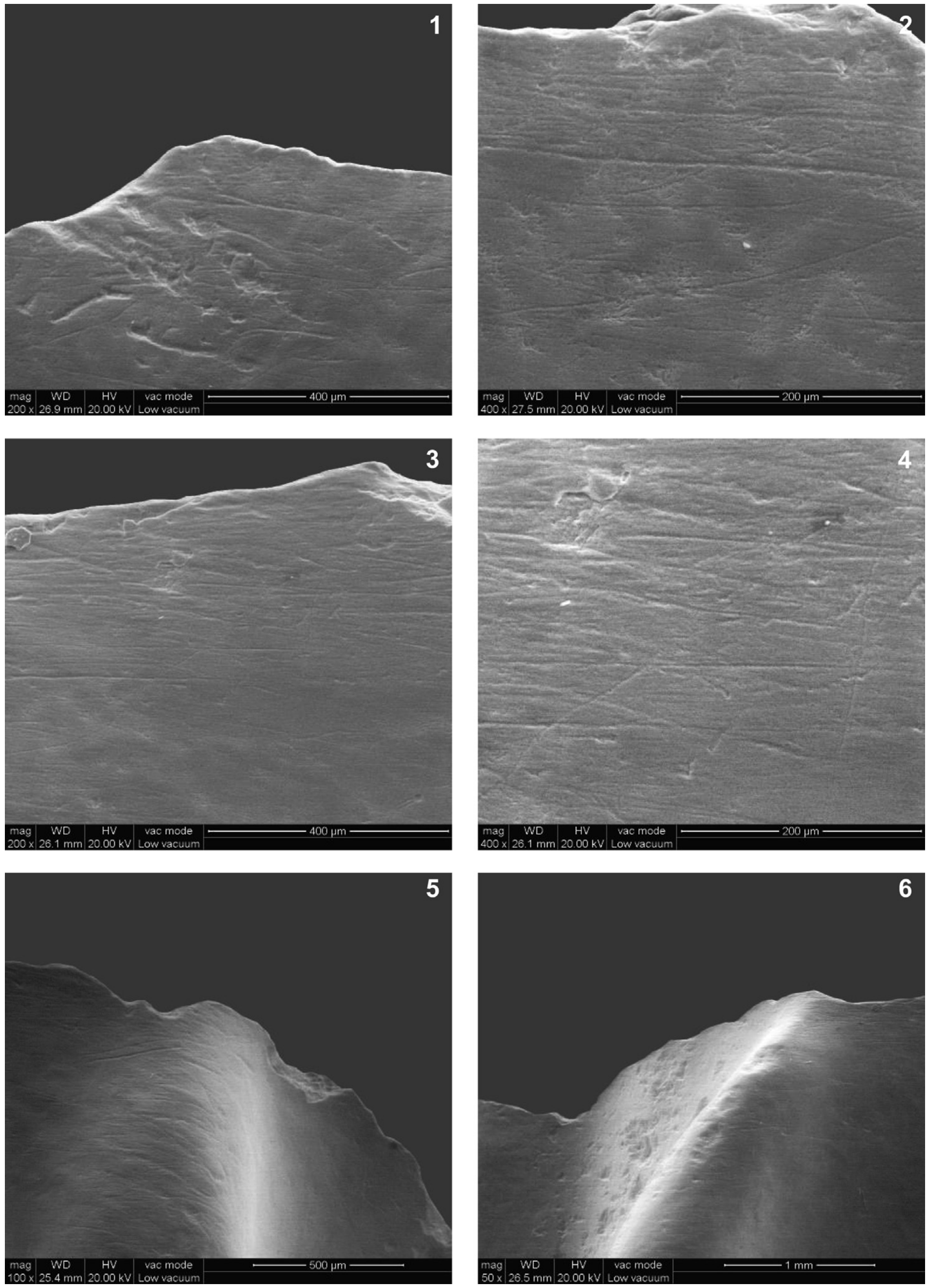

Fig. 7. Use-wear features on the *hipostracum* of PE01 (skinning, 15 min). 1) Deep short parallel and diagonal striation marks on the edge; 2) Deep continuous parallel striations overlapped by diagonal striation marks on them; 3) Parallel striation marks arranged very close to each other; 4) The same as in Fig. 7.3. at a higher magnification; 5) Criss-cross short striation marks on the elevated part of the shell, and even micro-chipping is present on the edge; 6) Micro-chipping on the elevated surface of the shell near the edge.

parallel to the edge and run continuously to it (Fig. 8.3), whereas on the elevated parts of the edge they are diagonal and overlap each other in criss-cross patterns (Fig. 8.4). The criss-cross type of striation is explained by the longitudinal bidirectional movement. Some micro-chipping occurred on the elevated part of the edge due to contact with bone (Fig. 8.5 and 8.6). No macro-fractures were observed.

3.2.3. Cutting wood (longitudinal bidirectional)

In experiment PE03, contrary to what we expected, very little use-wear was recorded in comparison to the other two samples. As with the other *P. maximus* samples, firstly the foliated external layer was removed from the edge with usage over time, and there was further wear on the *ostracum*. With usage, edge rounding of the shell developed over time, varying in texture from smooth to uneven. Some polish was seen on the edge. Very few parallel striation marks were observed. Not much edge fracturing was observed. No macro-fractures were observed.

3.2.4. Scraping wood (transverse bidirectional)

As for other transverse actions, no striation marks were observed in experiment PE04. Nevertheless, as we mentioned in relation to the *Mytilus*, striation marks have been recorded in other studies (Cuenca-Solana, 2009). We mainly observed highly

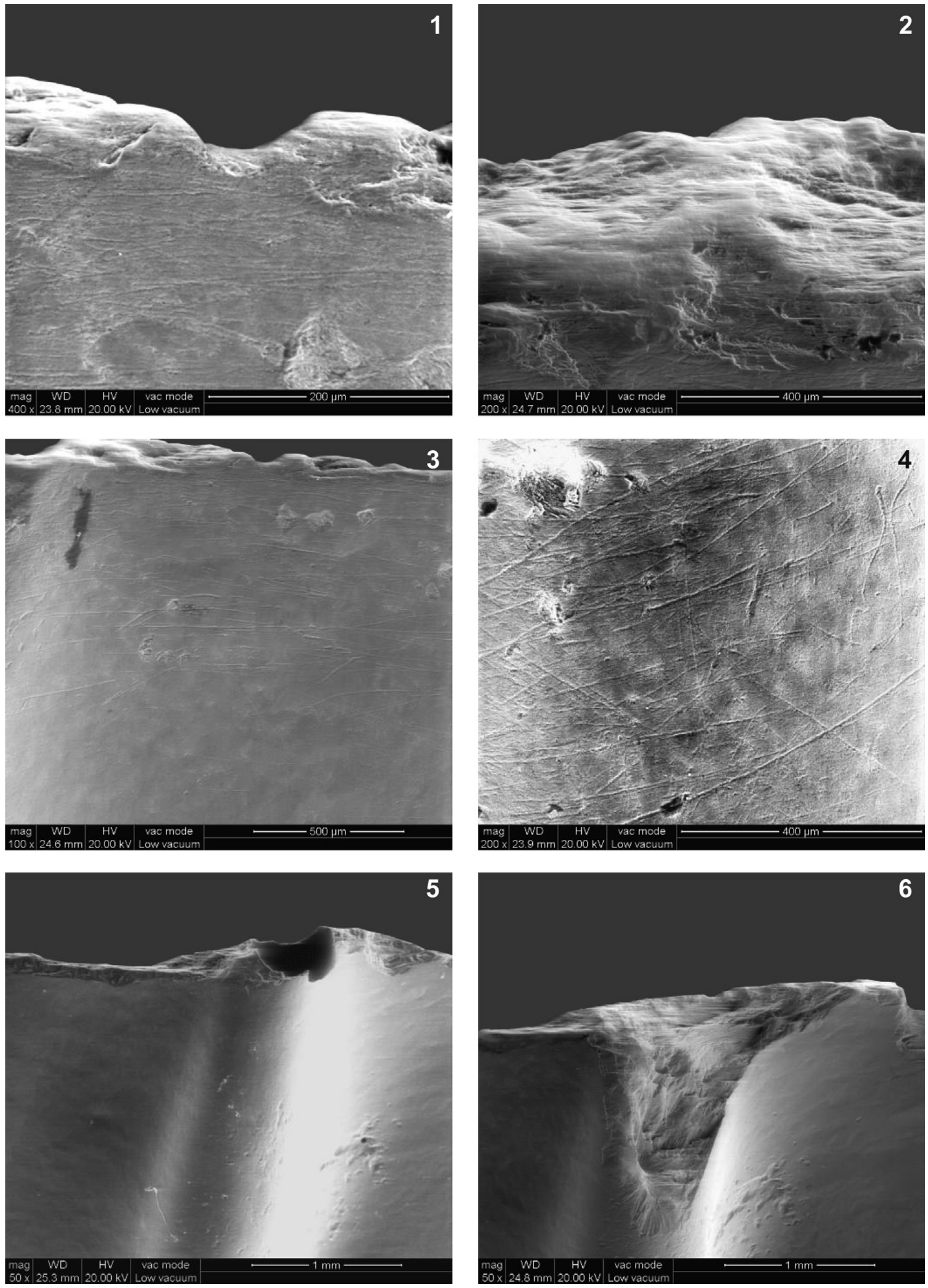

Fig. 8. Use-wear features on PE02 (defleshing, 15 min). 1) Edge rounding with some micro-fractures and striations on it; 2) Well developped polish on the fractured edge; 3) Shallow area of the serrated edge with micro-chipping and striation marks on it; 4) Detail of the overlapping striations shown in Fig. 8.3; 5) Cast of a portion of the original edge (the bubble represents a small cast imperfection); 6) The same point as in Fig. 8.5 with a fracture produced by use.

developed polish on the part of the edge which was continuously in contact with the wood, whereas on the part of the edge which was in less contact, we only found a few bands of polish.

3.3. *Glycymeris violascens*

3.3.1. *Defleshing and disarticulation (longitudinal bidirectional)*

We used GL01 and GL02 for this process. As they were collected from the beach, they already had some wear features (such as edge rounding, small holes over the surface of the edge and striations on the edge) from before due to natural phenomena such as abrasion by sand due to the tide. Specific studies clearly showed how different taphonomic processes are responsible for natural wear occurring on shells (Zuschin et al., 2003). In our experiments, the replica of the fresh edge was a helpful tool for comparing the working edge before and after use in order to evaluate the changes (Fig. 9). Indeed, we were able to see that these natural wear traces did not change much.

On GL01, some slight changes to the inner face of the edge, such as edge reduction, were observed after use (Fig. 9.3 and 9.4). Surprisingly, better use-wear traces were recorded on GL02. Short, fine striations were observed on the edge surface, most of them parallel

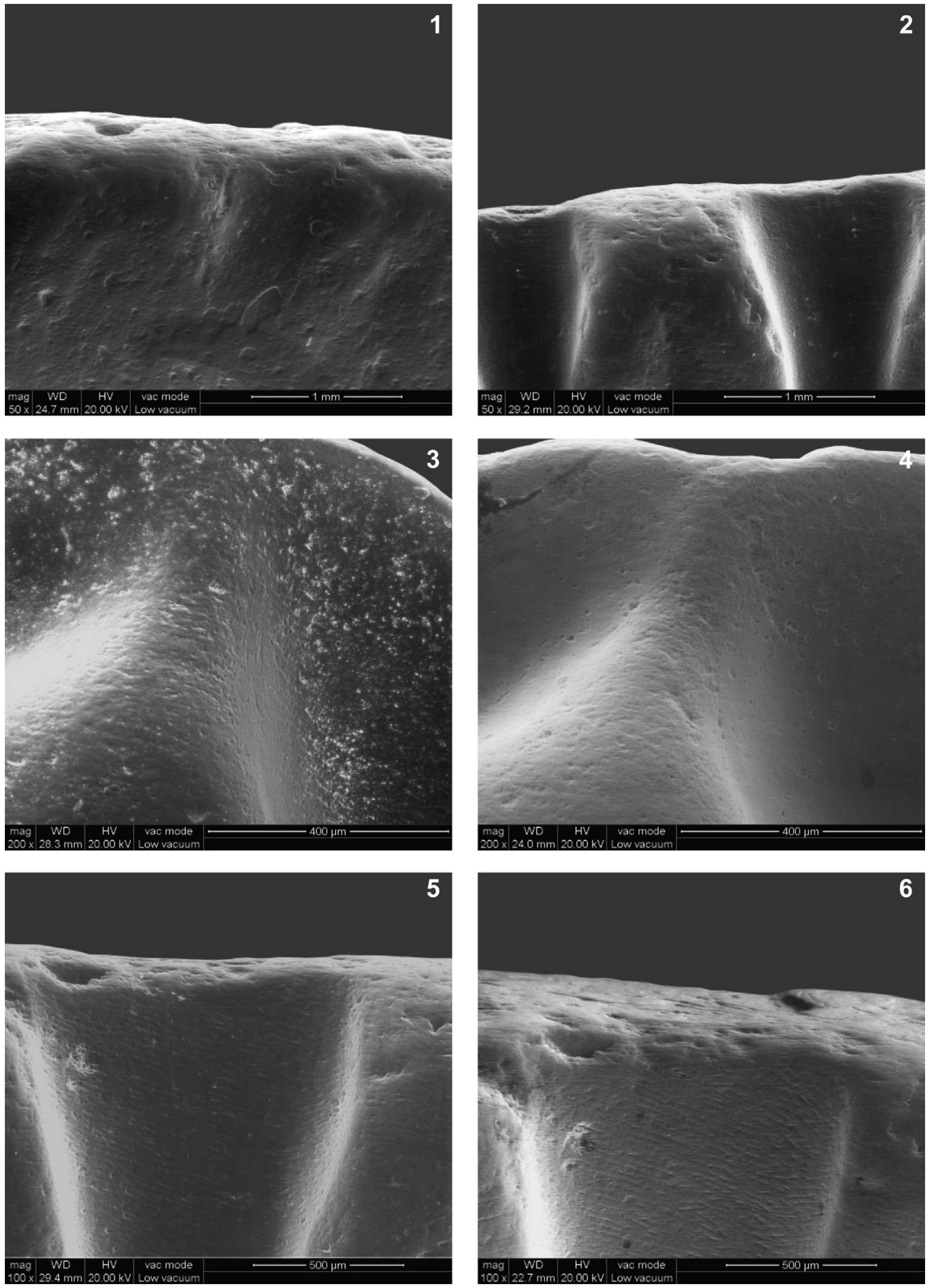

Fig. 9. Use-wear features on GL01 and GL02 (defleshing, 10 min). 1 and 2) Edge rounding on two different points of the cast of the original GL2 edge; 3) Cast of a portion of the original GL1 edge; 4) The area shown in Fig. 9.3 after use, with clear edge reduction; 5) Originally worn area on the cast of sample GL2; 6) The point shown in Fig. 9.5 after use, where a clear polish and parallel striations can be distinguished from the natural wear.

to the edge but some of them also overlapped one another, lying diagonal to the edge. Slightly polished bands were also observed on the edge (Fig. 10). No macro-fractures were observed.

3.4. *Ruditapes decussatus*

3.4.1. *Scraping wood (transverse unidirectional)*

Due to its size, RU02 was very difficult to handle, but scraped well, like the other samples. We found much less use-wear on the edge, probably because it was used for a very short time. A few edge fractures were observed, which occasionally showed some polish on the broken edge (Figs. 11.1 and 1.2). Apart from that, a general smoothing of the edge was recorded (Fig. 11.3), and only occasional and really slight transversal striations appeared (Fig 11.4). After five minutes of use, the sample broke into three triangular fragments.

3.4.2. *Cutting wood (longitudinal bidirectional)*

A number of edge fractures were seen along the entire length of the used edge on sample RU01 (Fig. 12.1–12.3). Continuous use of the edge turned the originally granulated inner surface of the shell into an even, flat surface (Fig. 12.4). Edge rounding was present from before but with the working of the edge it become more taper and distinctive. The polished areas were highly developed and found mostly on the working edge, where the granulated surface

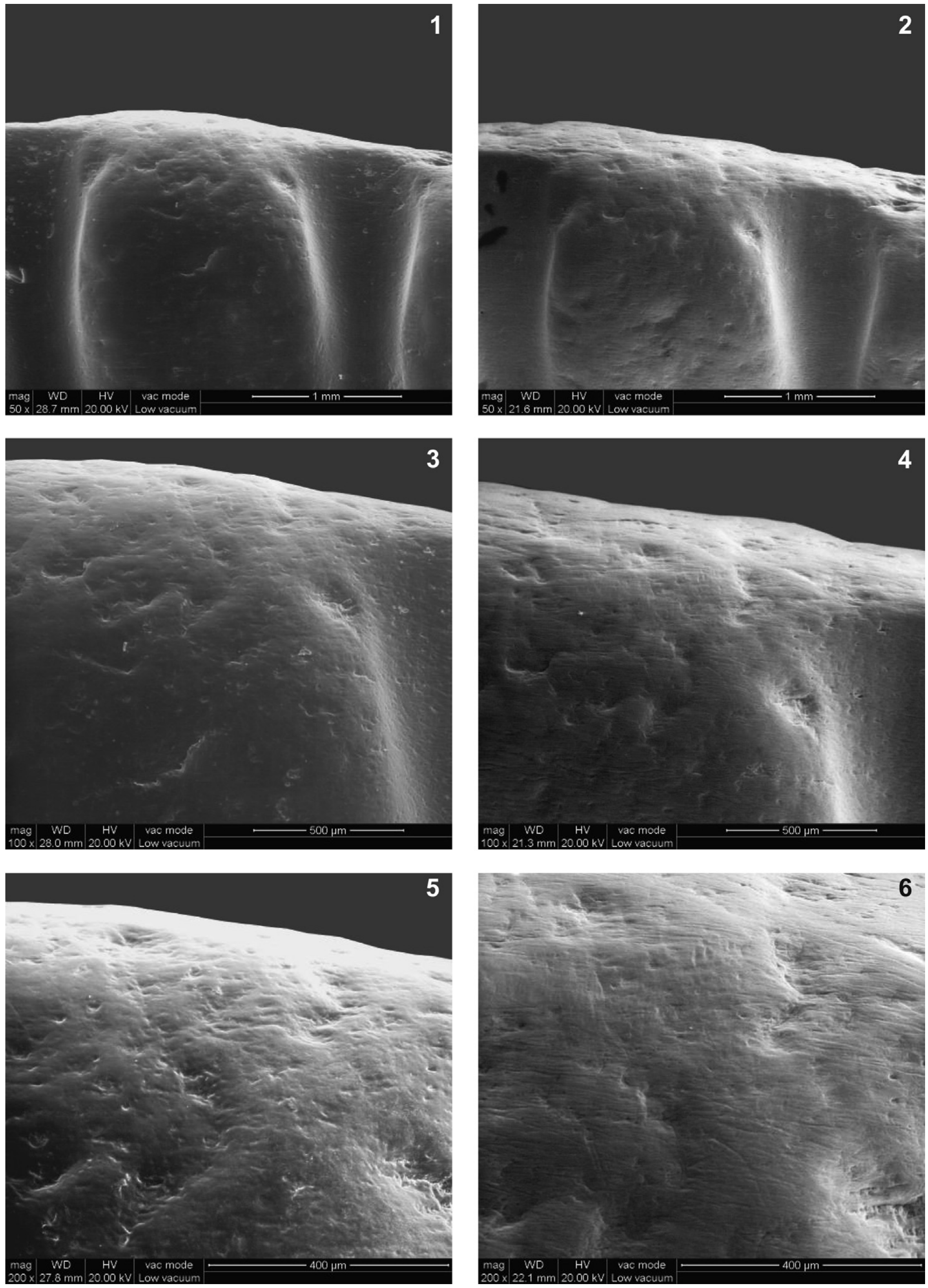

Fig. 10. Use-wear features on GL02 (defleshing, 10 min). 1, 3 and 5) The same point on the cast of the naturally worn edge at different magnifications; 2, 4 and 6) The same points showed in the previous images after use, showing clearly distinguishable use-wear features, from which the fine striations covering the originally smooth surfaces are the most evident.

was smoothed. The striations were mostly continuous, parallel to the edge, and arranged close to each other. The texture of the striations is very fine and shallow. They basically occurred on the polish of the edge (Fig. 12.5 and 12.6). Surprisingly, no macro-fractures were observed, and although it was small in size and delicate, it worked perfectly for the required time.

3.5. Archaeological examples

The analysed archaeological pilot sample contains 3 complete shells of *M. galloprovincialis*, one complete shell of *Glycimeris* sp., and a fragment of *Pecten* (in this case *Pecten jacobaeus*). All of these were cleaned following the same protocol as the experimental samples (except for the first bath in oxygenated water, as there was no organic matter to be removed) and analysed under the same microscopic procedures.

The shell surfaces showed differential preservation. While in all cases the *Mytilus* showed well preserved edges, with only sporadic scarring and points of post-depositional corrosion, the other samples were naturally eroded to different degrees (Fig. 13). This leads us to point out the fact that *Glycimeris* and *Pecten* specimens were collected when they were already dead, and so no conclusive data on their possible use has been recovered.

However, we have obtained better results regarding the *Mytilus* shells. While in two cases we recorded an almost completely fresh edge (Fig. 14.2), as at least in one case (from level A), clear use-wear

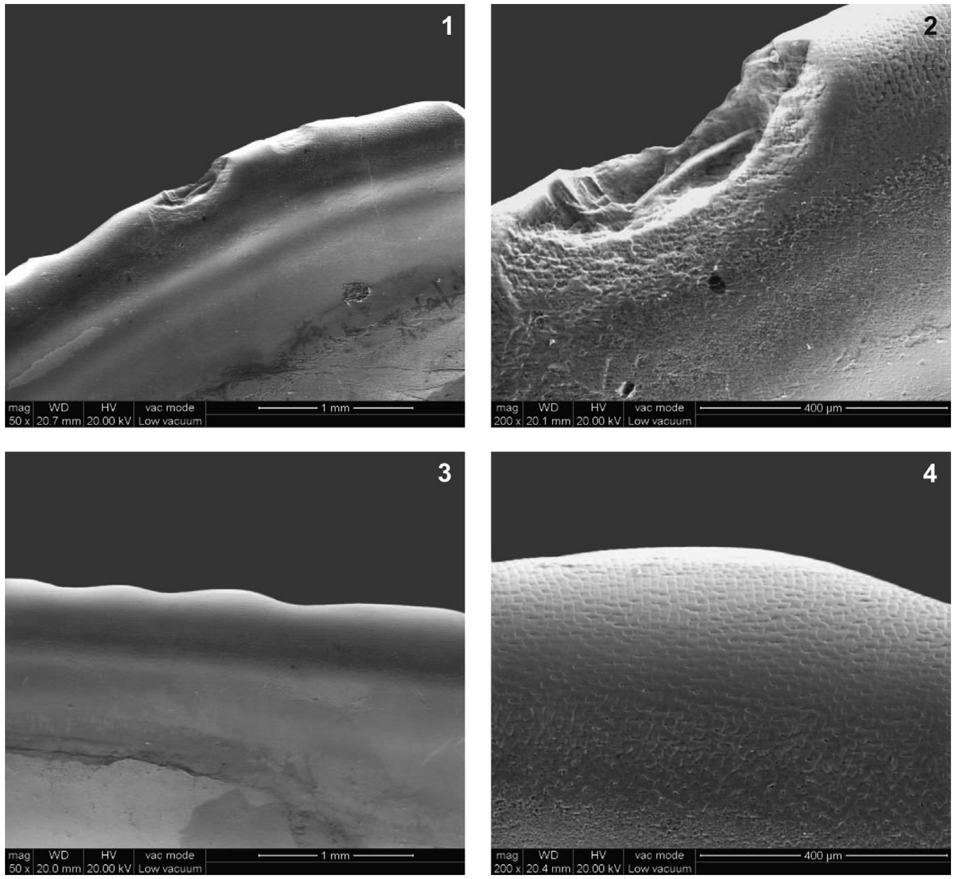

Fig. 11. Use-wear features on RU02 (scraping wood, 5 min). 1) Edge fracture at low magnification; 2) Detail of the fracture shown in Fig. 11.1 and slight polish on the its edges; 3) General smoothing of the used edge; 4) Closer look at Fig. 11.3, where an incipient polish can be observed, as well as slight and short striations parallel to the edge.

traces were identified. These consist of abundant striations perpendicular to the posterior edge, going very deep towards the inner face of the shell (Fig 14.3 and 14.4). In addition, some polish formation was identified on the same part of the edge, between the areas affected by microflaking (Fig. 14.5 and 14.6). These marks appear clearly concentrated on that portion of the edge, and are very different from the shell's fresh edge around the rest of its perimeter.

4. Discussion and conclusions

The results obtained through our program of experiments proved the feasibility of use-wear studies of un-retouched shell tools from different species. Our experiments supported the idea that retouching the shells was unnecessary, since their sharp edges can work effectively as tools for many tasks (among others, Clemente-Conte and Cuenca-Solana, 2011; Cuenca-Solana, 2013; Cuenca-Solana et al., 2011, 2013; Mansur and Clemente-Conte,2009; Szabó and Koppel, 2015). After using the shells, microscopic wear traces were visible and identifiable and they definitely provide useful markers related to the task the shell-tool was used for. The wear features included micro-fracturing, striations and other linear features, polish, impact pits and edge rounding.

Our observations showed that the original surface micro-topography plays a major role in the formation of wear traces. This is especially evident for species with serrated edges such as *P. maximus* and *G. violascens*. In these cases, most of the wear features in the initial stages are confined to higher relief areas in the micro-topography, and only with longer use do use-wear traces start to appear on the depressed areas.

Our second aim was to determine whether the micro-fracturing, edge rounding, striations and polish characteristics of shell tools can provide any major distinguishing indicators of the categories of use-material and use-action. Micro-flake scars, striations and other linear features tended to be orientated in the direction of tool use and provide information about the work-action. These striations also tend to depend on the shell species used and the material worked (skin, hide, bone or wood). Characteristic linear features in the form of abrasion tracks or linear arrays of micro-pits in the direction of tool use were, however, found as a result of defleshing and disarticulation processes. Our results show that after longitudinal unidirectional movements (skinning), striations are mostly parallel to the edge and become overlapped with small diagonal striations due to blows. However, after longitudinal bidirectional movements (defleshing and disarticulating) the striations are mostly in criss-cross patterns (overlapping each other), with long striations along the edge. Striations were visible on the *R. decussatus* and *M. galloprovincialis s*amples used for wood working, especially on those used for cutting wood. These were arranged very differently from those produced in the butchery experiment. They were all parallel to the edge and very deep. Often, the striation marks were seen over the polished surface of the edge. In our scraping experiment, we saw a variety of polishes on the edge, but only occasional and really slight striations. Unlike our experiment, in another experiment on wood scraping (Cuenca-Solana, 2009), a number of transverse striation marks were observed on the edge. This is probably due to the way the tool was held when performing

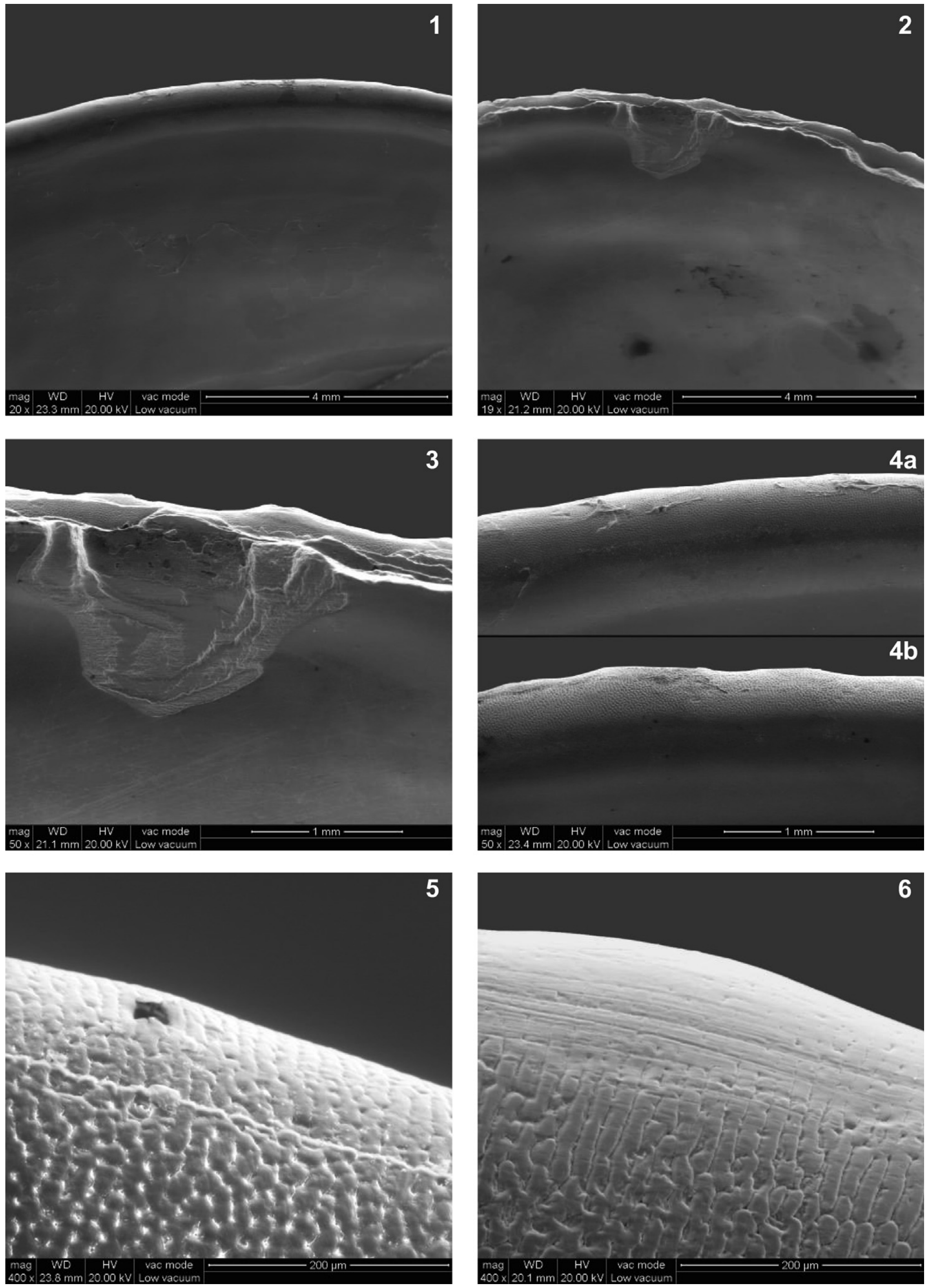

Fig. 12. Use-wear features on RU01 (cutting wood, 10 min). 1) Cast of a portion of the fresh edge; 2) Continuous edge fracturing produced by use in the portion shown in Fig. 12.1; Detail of the fracture in Fig. 12.2, and diagonal striations produced by the detached material dragged on the tool surface; 4) A portion of the edge not affected by fracturing, where just slight differences can be observed when working at low magnifications between before -4a- and after -4b-use; 5 and 6) Closer images before and after use showing how the original granulated surface has been modified and covered by fine striations.

the action. Nevertheless, further experiments are being conducted to better assess the degree of variation of this phenomenon.

Edge rounding was also observed on all the samples, but it varied with the use-action and the material worked. For example, very little edge rounding was observed on PE02 when compared with MY02 (both were used for the defleshing and disarticulating experiment). These rounded edges taper after continuous use and become polished. The polish on the woodworking shell samples was very well developed compared to the shell samples used for butchery processes. The development of polish characteristics depends on the combination of contact material, use duration and use-action. Highly developed polish was seen on *M. galloprovincialis*. This polish was coarse and distributed in bands on the part of the edge least in contact with the material worked, but became highly developed when the edge had been in contact with that material. Sometimes polish also occurs on edge fractures.

We also considered any macro-fractures that occurred while working with the samples. Weaker shells (*M. galloprovincialis* and *R. decussatus*) tended to break after shorter periods of use than stronger shells (*P. maximus* and *G. violascens*). But they still

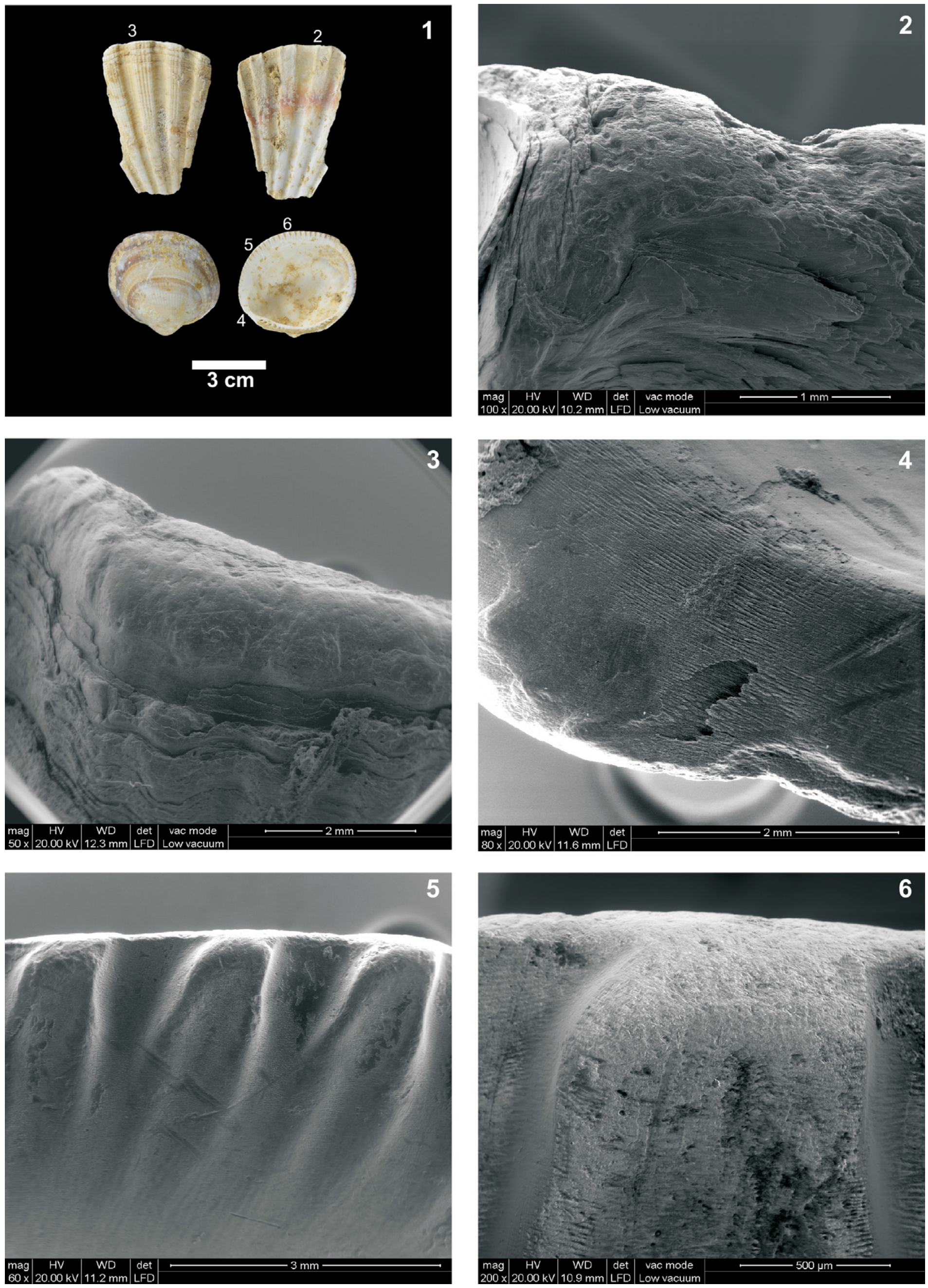

Fig. 13. 1) Archaeological *Pecten jacobeus* (Cat02, Lev.B, L7-76, above) and *Glycimeris* sp. (Cat05, Lev.A, Q7-122, below), and location of the SEM pictures. 2 and 3) Details of the heavily abraded edge, inner and outer faces respectively of the ventral edge; 4) Erosion on the dorsal edge, inner face; 5) Abrasion and randomly distributed striations on the ventral edge, inner face; 6) Detail of the abrasion of the ventral edge.

provided a huge amount of information in a short time. The pattern of fractures obviously depends upon the shell's structure (see Szabó, 2013; Szabó and Koppel, 2015) and this is an aspect to be considered in future experiments. Here we simply focused on the basic fractures affected by the action.

In the program of experiments, the casts we made were very helpful, as they served as a reference for the fresh edge. The casts assisted us in comparing and distinguishing the micro traces before use with those developed after the shell tools had been used. They also helped us to understand how to differentiate between natural wear and use-wear traces (Claud et al., 2009).

Although this experimental program yielded very promising preliminary results which contribute to the understanding of shell tool use-wear analysis, the scope needs to be widened further in order to provide a better framework for future researchers. This could be achieved by increasing the numbers of materials worked and actions included in the experiments (Cuenca-Solana, 2013), by documenting them sequentially and for longer periods of use (Ollé and Vergès, 2014), and by distinguishing the diagnostic wear and fracture patterns according to the shell microstructure (Currey and Taylor, 1974; Szabó, 2008; Szabó and Koppel, 2015).

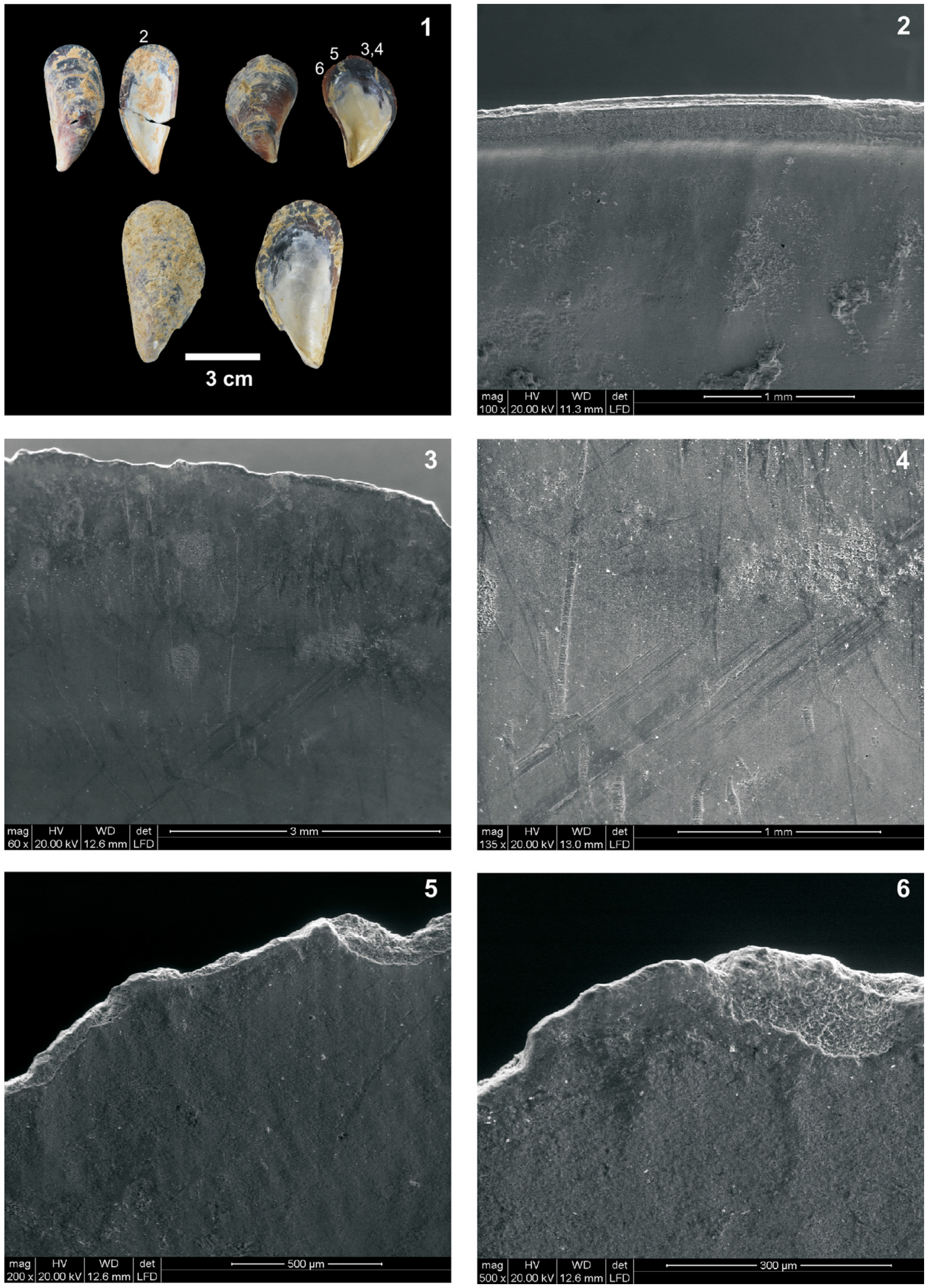

Fig. 14. 1) Archaeological *Mytilus galloprovincialis* (Cat95, Lev.B, L6-59, above left; Cat95, Lev.A, P6-25 above right; and Cat02, Lev.B, L7-65, below) and location of the SEM pictures, all of them on the inner face; 2) Absolutely fresh posterior edge; 3 and 4) strong furrow-like striations perpendicular to the posterior edge, overlapped by oblique thinner linear marks; 5) continuous edge microflaking; 6) smooth polish formation on the portions of the edge not affected by microflaking.

Regarding the archaeological examples, we actually found wear features clearly pointing to the use of some of the unmodified shells as tools. Few of these traces present parallels in our experimental program, so we obviously would need to analyse more samples and to carry out specific experiments and taphonomical observations in order to correctly interpret them. Nevertheless, the trial on archaeological materials has served to prove the efficacy of the SEM analysis presented here, and the advantages it involves in terms of observation accuracy compared to the more extended optical microscopic observations. An example of this can be seen in Fig. 15, where we included some OLM images of the same points of different experimental shell tools, previously shown under the SEM. So, we encourage other researchers to systematically introduce the SEM in the shell-wear studies at least as a complementary technique, as some authors have already shown (Szabó and Koppel, 2015).

This paper proposes to make public new experimental results with the aim of providing useful methodological insights and specific information about the use-wear analysis of shell tools. We hope that these results will serve as a reference in the future for archaeologists interested in determining the function and use of archaeological shells and the role they played in the subsistence and behaviour of hominins.

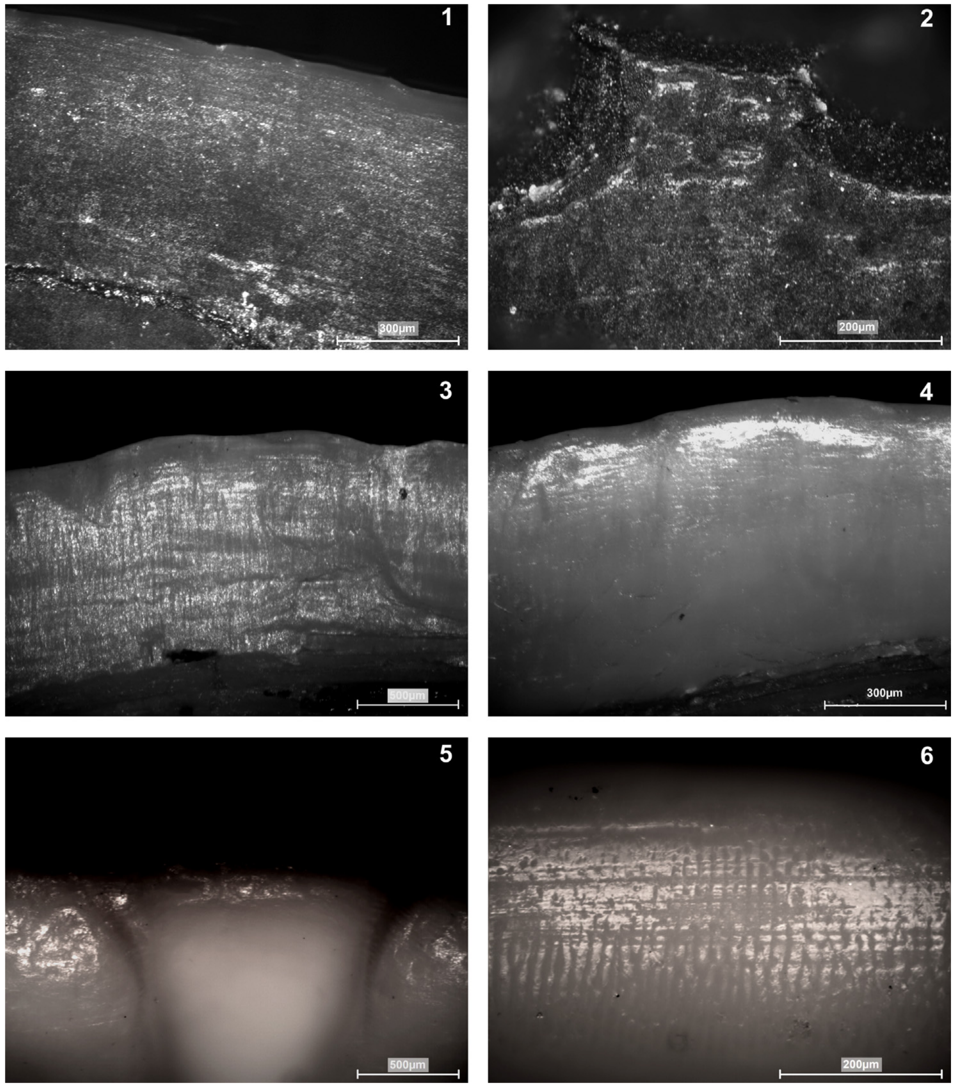

Fig. 15. Selection of points imaged with the optical microscope, in order to demonstrate the differences with the same points already shown under the SEM in previous Fig. 1) The same point as Fig. 3.4 (MY02, taken at 100×, extended focus 20 steps); 2) Same as Fig. 4.6 (MY03, 200×, ext. focus 15 steps); 3) Same as Fig. 6.4 (PE01, 50×, ext. focus 10 steps); 4) Same as Fig. 6.5 (PE01, 100×, ext. focus 10 steps); 5) Same as Fig. 9.6 (GL2, 50×, ext. focus 10 steps); and 6) Same as Fig. 12.6 (RU01, 200×, ext. focus 10 steps).

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