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- 1 Title: Perforations in Columbellidae shells: Using 3D models to differentiate anthropogenic
- 2 piercing from natural perforations.
- 3
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 19
- 20 Keywords: personal ornaments, shell beads, *Columbella rustica*, micro-CT scans, 3D models,
- 21 taphonomy, Upper Palaeolithic, Ksâr 'Akil
- 2223 Highlights:
- 24 * New approach aids identification of personal ornaments in the archaeological record
- 25 * *Columbella rustica* shells were used as beads from the Initial Upper Palaeolithic on
- ²⁶ * 3D shell thickness models aid distinction of natural from anthropogenic perforations
- 27 * Columbella rustica and C. adansoni share overall shell-thickness distribution pattern
- 28 * Standardisation of perforation size suggests formal bead manufacture at Ksâr 'Akil

29 Abstract

- 30 Perforated shells are often used to study socially mediated behaviour in past hunter-
- 31 gatherer groups. One of the key issues regarding empty shells from beaches or fossil
- 32 outcrops is determining human agency in the accumulation and modification of an
- 33 assemblage. Here we investigate anthropogenic mediation in Initial Upper Palaeolithic and
- 34 Early Ahmarian assemblages of *Columbella rustica* at Ksâr 'Akil (Lebanon). We compare
- 35 perforations in the archaeological specimens with data from newly gathered Columbellidae
- 36 modern death assemblages Tenerife (Spain) using three-dimensional shell-thickness models
- 37 as templates. This approach, using micro-CT scans of pristine shells to map robust and
- 38 fragile zones on shell outer-surfaces, allows us to contextualise the two datasets within their
- 39 natural morphology. Our results show that in natural death assemblages the vast majority of
- 40 perforations occur in structurally weak zones, and their distribution can be explained by
- 41 shell morphology in combination with predator activity and other post-mortem damage. In
- 42 our archaeological dataset we found a higher frequency of perforations in more robust
- 43 zones and a higher uniformity in their location, size and shape. This suggests human
- 44 mediation in either the selection or manufacture process and indicates that at Ksâr 'Akil C.
- 45 *rustica* were used as beads from as early as the Initial Upper Palaeolithic and throughout the
- 46 Early Ahmarian. Standardisation in perforation shape, size and distribution have been

- 47 argued to be indicative of formalised manufacture processes and our results are thus more
- 48 congruent with intentional bead manufacture than the selection of naturally-holed
- 49 specimens.

50 Introduction

51 Symbolic behaviour is aimed at sharing information including social conventions, personal 52 and group identity within and between groups (e.g., d'Errico and Stringer 2011). These 53 socially-mediated behaviours strengthen internal group coherence and serve to establish 54 and maintain boundaries with neighbouring groups (e.g., Hodder 1977). Symbolic 55 information can be coded in material culture, for example ethnographic studies show that 56 personal ornaments including scarification, body paint and beadwork, are often used to 57 mark self-identity and group affiliation (e.g., Kuhn and Stiner 2007; Rigaud et al. 2018; 58 Vanharen 2009; Vanhaeren and d'Errico 2006; White 1992). Personal ornaments have often 59 been used to study socially mediated behaviour in the past as they are among the few items 60 across the range of archaeological material culture remains the function of which is entirely 61 symbolic (e.g., d'Errico and Stringer 2011; d'Errico and Vanhaeren 2007; Hovers and Belfer-62 Cohen 2006; Martínez-Moreno et al. 2010; Micheli 2021; White 2007). In this context there 63 has been an emphasis on basket-shaped shells of the genus Tritia (e.g., Bosch et al. 2019; 64 Bouzouggar et al. 2007; d'Errico et al. 2005, 2009; Henshilwood et al. 2004; Vanhaeren et al. 65 2006; Steele et al. 2019) and bivalves of the genus *Glycymeris* (e.g., Bar-Yosef Mayer et al. 66 2009; 2020; Zilhão et al. 2010). Here we investigate anthropogenic mediation in the Initial 67 Upper Palaeolithic and Early Ahmarian assemblages of dove shells (Columbella rustica) at 68 Ksâr 'Akil, Lebanon. Columbellidae are more frequently used for personal adornment in 69 later periods (e.g., Álvarez Fernández 2008, 2016; Álvarez Fernández and Jöris 2008; Bar-70 Yosef Mayer 1997, 2019a; Cristiani et al. 2014; Kandel et al. 2018; Perles and Vanhaeren 71 2010; Reese 1982; Rigaud et al. 2015), but are also occasionally recovered in early Upper 72 Palaeolithic European and Levantine contexts (e.g., Bosch et al. 2015a; Bar-Yosef Mayer 73 2019a,b, 2020; Marder et al. 2013; Shimelmitz et al. 2018; Stiner et al. 2013; Vanhaeren and 74 d'Errico 2006).

75

76 In the Mediterranean and the northeastern Atlantic Ocean three morphologically very 77 similar species of Columbella Lamarck, 1799 are recognised based on genetic data and a 78 single morphological criterion (Moolenbeek and Hoenselaar 1991; Russini et al. 2017). 79 Genetic research suggests that the Macaronesian Columbella adansoni Menke, 1853 and 80 the Mediterranean Columbella rustica Linnaeus, 1758 are closely related and together form 81 a sister-clade to the West African Columbella xiphitella Duclos, 1840 (Russini et al. 2017). 82 The only morphological feature differentiating *C. rustica* from the other two taxa is that it 83 has a so-called paucispiral protoconch, suggesting direct development without a 84 planktotrophic larval state, whereas C. adansoni and C. xiphitella share a multispiral 85 protoconch indicating that their ontogeny does involve such a larval state (Moolenbeek and 86 Hoenselaar 1991; Russini et al. 2017). In archaeological specimens the apex on which the 87 protoconch is situated is rarely preserved or has been heavily damaged, rendering the three 88 taxa morphologically indistinguishable. Here we base our taxonomic identifications on the 89 proposed geographic separation and previous malacological assessments (Moolenbeek and 90 Hoenselaar 1991; van Regteren Altena 1962; Russini et al. 2017). 91

Taphonomic investigations into the Ksâr 'Akil shell assemblage have shown that *Columbella rustica* were collected as empty shells after the mollusc had died (Bosch et al. 2015a). One

94 of the key issues in dealing with beach-collected shells is determining human agency in the 95 accumulation and modification of an archaeological assemblage. In broad chronological 96 terms, the archaeological record suggests that during the Levantine Middle Palaeolithic and 97 the onset of the Upper Palaeolithic, shells were purposefully collected (Bar-Yosef Mayer et 98 al. 2020). Fully intact shells may have been pierced to be used as ornaments, whereas 99 naturally perforated shells may have been intentionally collected for the same purpose 100 without the need for further modification before use (e.g., Bar-Yosef Mayer 2005, 2015; 101 Bosch et al. 2019; Stiner et al. 2013; Vanhaeren et al. 2006). Within an archaeological 102 assemblage there is usually a mix of fully intact, perforated and just broken shells. Several 103 authors have suggested that if evidence can be found for the intentional use of some shells, 104 we can assume that all specimens of that taxon were collected for the same purpose (e.g., 105 Cristiani et al. 2014; Stiner et al. 2013; see also Haynes and Stanford 1984; Lyman 2013). In 106 fact, White (2007) has argued that the occurrence of fully intact shells is indicative of on-site 107 bead manufacture (see also Álvarez Fernández 2008). Identification of human modification 108 of shells into beads is hampered by two things. First there is considerable overlap or equifinality between human-made and natural perforations (d'Errico et al. 1993). For 109 110 example, direct or indirect percussion damage may look very similar to shell-damage caused 111 by being twirled around in a rocky-shore environment. Second, damage caused by exposure 112 to an active beach environment prior to collection as well as post-depositional alterations 113 may mask traces of use. Therefore, the classification 'bead' frequently rests on a range of 114 factors such as the exclusion of (a-)biotic actors, collection for subsistence purposes, signs of 115 manufacture and or use-wear (see for recent reviews Bay-Yosef Mayer and Bosch 2019; 116 Steele et al. 2019). Anthropogenic-mediation may be identified in selection and transport of 117 raw materials, manufacture processes, beadwork composition and use (e.g., Álvarez 118 Fernández 2008; Bouzouggar et al. 2007; Bar-Yosef Mayer 2005; d'Errico et al. 1993; Perlès 119 and Vanhaeren 2010; Rigaud et al. 2019; Taborin 1993; Vanhaeren et al. 2006, 2013). 120 121 Here we divide shell-life into three stages (Fig 1). Stage 1 presents the phase prior to human 122 collection, including the mollusc's life and the period after its death when the shell is in a 123 beach environment and exposed to various taphonomic agents including bioerosion (e.g., 124 attacks by crabs, boring sponges and carnivorous molluscs), wave action and abrasion. Stage 125 2 represents the so-called prehistoric use-life, i.e., from human collection to shell discard. 126 During their use-life shells may be preferentially selected based on their appearance, size, 127 and natural perforations, further they may be intentionally perforated and broken during 128 use, lost or discarded. Stage 3 represents the period after discard, i.e., before and after 129 burial in a sedimentary matrix. In stage 3, post-depositional damage may be caused by e.g., 130 sediment reworking, diagenesis, trampling and rock falls and lead to chemical dissolution, 131 polish, scratches and breakage through crushing. Stage 3 also comprises damage during 132 excavation (e.g., during sieving) and curation (White, personal communication, 2017). 133 134 We investigate traces of human decision-making in stage 2, namely during collection, 135 manufacture, and/or use of perforated shells (e.g., Claassen 1998; Steele et al. 2019). 136 Frequently used avenues to address these questions include comparing thanatocoenoses 137 with archaeological assemblages, as well as technological and use-wear analyses (e.g., Bar-

- 138 Yosef Mayer et al. 2009; Bouzouggar et al. 2007; d'Errico et al. 2009; Perlès 2016;
- 139 Vanhaeren et al. 2006). Here we focus on role of shell structure in the shell-piercing process
- 140 both in human-made and natural contexts. By using shell thickness as a proxy for structural

- 141 resistance we aim to improve our ability to distinguish natural from human-made
- 142 perforations. A recent study has shown that in *Tritia gibbosula* damage caused by natural
- 143 taphonomic processes (i.e., those occurring both in stage 1 and 3) are more frequent in
- 144 thinner and structurally weaker zones, and that within these zones damage is randomly
- 145 distributed (Bosch et al. 2019). We assume this also to be the case for *Columbella* spp. If
- 146 proven correct, any deviation between the modern death and archaeological assemblages
- 147 likely reflects human involvement during stage 2 of the shell-life through e.g., manufacture
- 148 (perforation) processes or specimen selection.
- 149

150 Material and Methods

- 151 Following the approach developed in Bosch et al. (2019) we use μ CT (micro computed
- 152 tomography) data of pristine modern Columbellidae to create virtual models of shell
- 153 thickness. From these data three-dimensional (3D) virtual models with heat-maps of shell-
- 154 thickness are derived to better understand the role of shell-structure in relation to shell
- 155 morphology in both Columbella rustica and its sister taxa: Columbella adansoni. We show
- 156 that both taxa display strong similarities in overall morphology and especially in shell-
- 157 thickness distribution. We then overlie natural perforation damage from two newly
- 158 collected modern death assemblages stemming from a rocky shore environment (Tenerife,
- 159 Spain). In this step, we test our predictions regarding the distribution of natural perforations
- 160 and damage to which shells may be subjected in the above-mentioned stage 1 of the life of
- 161 the shell. Finally, we compare these data with perforation distributions in archaeological
- 162 collections from the Initial Upper Palaeolithic and Early Ahmarian of Ksâr 'Akil in an effort to
- 163 differentiate natural and anthropogenic perforations.
- 164

165 A generalised model of shell thickness.

Columbellidae are known to adapt to external factors such as wave-action, their littoral 166 167 position and tidal height as well as temperature and acidic changes which lead to 168 morphological variation (e.g., Chatzinikolaou et al. 2021; Moolenbeek and Hoenselaar 1991; 169 Russini et al. 2017). In any given assemblage therefore, we may expect a fair amount of 170 morphological variation. To investigate this variability and its effect on our shell thickness 171 models we μ CT-scanned shells from two rocky-shores with drastically different energy 172 regimes, namely the eastern Mediterranean (Tripoli, Lebanon) and the Atlantic (Tenerife, 173 Spain). We chose recent non-archaeological specimens instead of seemingly intact 174 archaeological specimens for two main reasons. First, we needed specimens in pristine 175 condition to obtain the most accurate information about shell-structure and thickness. 176 Second, selecting non-archaeological specimens provides the most accurate representation 177 of the species natural state before human collection (i.e., stage 1). Another option would 178 have been to use more or less intact archaeological specimens in an effort to closely mimic 179 the morphology of the prehistoric shells. However, given scarcity of intact specimens and the extent of intra-species variation it is doubtful that this approach would have captured an 180 181 accurate representation of the morphological range. Moreover, archaeological specimens 182 although seemingly intact may have endured damage, e.g., polish and abrasion, during 183 archaeological use-life and post-depositionally after discard (stages 2 and 3) which would be 184 impossible to disentangle. Instead we opted for a multi-species approach selecting 185 specimens with different apparent morphology to arrive to a generalised model which can 186 be both applied to our modern-death assemblage (C. adansoni) as well as to the Ksâr 'Akil

- 187 assemblages (*C. rustica*). Our virtual models are thus aimed at reflecting average shell-
- 188 density and showing differences between thinner and thicker zones within a shell, rather
- 189 than highlighting specific morphological differences such as the shape and attachment of
- 190 the aperture's shoulder and the height of the spire. We assume therefore that our
- 191 generalised model is a good basis to compare and contextualise the distribution of damage
- 192 in both the Tenerife and Ksâr 'Akil assemblages.
- 193

194 Micro-CT-scans of recent specimens

195 Recent Eastern Mediterranean *Columbella rustica* were selected from the collection

- 196 Mollusca at Naturalis Biodiversity Center (Locality: Tripoli, *RMNH.Mol.203708*). Recent
- 197 Macarodonesian *Columbella adansoni* were selected from the thanatocoenosis: TF1
- 198 (Tenerife, Spain; personal collection of MDB). Prior to μ CT-scanning specimens were 199 selected for their pristine preservation and damaged specimens (e.g., showing traces of
- 199 selected for their pristine preservation and damaged specimens (e.g., showing traces of 200 bioerosion, smoothing and abrasion) were avoided. Several specimens were scanned to
- 201 detect any specimen-specific abnormalities and ensure the resulting virtual models reflect
- average shell-density. In addition to scanning intact shells, a sample of *C. rustica* (Locality:
- 203 Tripoli, *RMNH.Mol.203708*) exhibiting boring sponge damage were selected for μ CT-
- scanning to investigate the effect of this type of damage on shell-robustness. This was done
- as a high proportion of the archaeological shells from Ksâr 'Akil display boring sponge
- 206

damage.

- 207 208 The shells were μ CT-scanned at the Cambridge Biotomography Centre, University of
- 209 Cambridge, using a Nikon Metrology XT H 225 ST High Resolution Scanner. Scan parameters
- 210 were optimised for individual scans (voxel size: 0.01–0.03 mm, isotropic). Segmentation and
- 211 post-processing were done using Avizo 8.1 (Thermo Fisher Scientific FEI). For more details
- 212 on the protocol see Bosch et al. (2019). Shell thickness was computed using a scalar field
- 213 which was then mapped onto the surface using a colour range from blue (thin) to red (thick)
- with green representing intermediate thickness. The colour range was adjusted to
- 215 emphasize thickness variation in the areas of interest and is unique to each shell. The final
- images were obtained in six standardized views, namely dorsal, ventral, both lateral sides,
- 217 basal, and apical.
- 218

219 Modern death assemblages

220 Two modern death assemblages from rocky shores on Tenerife, Canary Islands, Spain – TF 1 221 and TF 2 - were collected (Fig 2). A survey of multiple rocky shores revealed that C. adansoni 222 are most frequent in patches of sandy substrates, which serve as natural traps for (semi-223)intact specimens. Sporadically, exceptionally large and intact specimens were recovered 224 from both the sandy patches and rocky substrates at the upper limit of the upper intertidal 225 zone. The most time-effective method was to target patches of sandy substrates in the mid 226 to upper intertidal zone at low tide, from which both the modern death assemblages TF1 227 (n=258; search time 30 min) and TF2 (n=91; search time 20 min) were collected. Compared 228 to a thanatocoenosis from an Atlantic rocky shore, an Eastern Mediterranean assemblage 229 would presumably show less damage, due to the reduced zonal amplitude and limited wave 230 action of the Mediterranean Sea, especially on its eastern coast. Using modern death 231 assemblages from a high-energy environment, like the Tenerife beach, amplifies the array of 232 damage that could potentially be observed. The Tenerife thanatocoenoses data, therefore, 233 are ideally suited to investigating the extent of natural damage in relation to shell thickness.

- 234 Recording perforation damage followed Bouzouggar et al. (2007) which was adapted for
- 235 Columbellidae.
- 236

237 Archaeological samples

238 The Columbella rustica assemblages of Ksâr 'Akil, Lebanon (Layers XXII and XVII; Fig 3) were

- used as archaeological datasets. Layer XXII is attributed to the Initial Upper Palaeolithic,
- which dates to >45.900–43.200 calibrated years before present (cal BP). Layer XVII is
- attributed to the Early Upper Palaeolithic or Early Ahmarian and dates to 43.300–42.800 cal
- 242 BP (Bosch et al. 2015b; but see Douka et al. 2015 vs. Bosch et al. 2015c).
- 243

244 Ksâr 'Akil is well-known for its multi-layered Initial and Early Upper Palaeolithic deposits, 245 which are rare in the region and make it, next to Üçağızlı I (Turkey) and Manot (Israel) Caves, 246 one of the key archaeological sites for this period (e.g., Hershkovitz et al. 2015; Kuhn et al. 247 2001; Stiner et al. 2013). The Ksâr 'Akil rockshelter situated about 3 km from the present-248 day coast. The excavations in the 1930s and 1940s by Ewing and Doherty recovered 249 exceptionally large mollusc assemblage, making it an ideal case-study. The total 250 mollusc assemblage counts 3571 specimens, twelve percent of which (n=429) are beach-251 collected C. rustica (Bosch et al. 2015a; van Regteren Altena 1962). The excavations by Tixier 252 in the late 1960s and 1970s never reached the Initial and Early Upper Palaeolithic deposits 253 and the recovered mollusc assemblage is therefore not included in this study (Inizan and 254 Gaillard 1978; Tixier and Inizan 1981). The studied material is currently housed in the

- 255 Department of Fossil Mollusca at the Naturalis Biodiversity Center, Leiden, the Netherlands.
- 256

257 Data recording and statistics

258 Data recording of archaeological and the natural death or thanatocoenoses assemblages 259 employed E4 (freeware: www.oldstoneage.com) and Microsoft Access software packages. 260 All statistical analyses were done in R (version 3.5.0; R Core Team 2018). Graphics were 261 produced using the R package ggplot2 (Wickham 2009). Pearson's chi-squared tests were 262 used to statistically evaluate categorical data and with small sample sizes Monte Carlo 263 simulations (with 10,000 iterations; Patefield 1981) were caried-out to compute the p-value. 264 For continuous data, the Shapiro-Wilk test was used to test for the normality of the 265 distribution. When appropriate t-tests were used, otherwise Mann-Whitney U tests were 266 employed. For comparison of the multiple modern and archaeological Columbella spp. 267 assemblages a Kruskal-Wallis test and Wilcoxon signed rank pairwise tests (with adjusted p-268 values using the Bonferroni correction) were carried out as not all measurements were 269 normally distributed. In all cases, a p-value < 0.05 was considered significant. Outliers in 270 boxplots are defined as \geq 1.5x the inter-quartile range above the upper quartile and \leq 1.5x

below the lower quartile.

272 Results

273 Figure 4 shows thickness heat-maps of modern pristine *Columbella adansoni* from TF 1 (top)

- and Columbella rustica Tripoli (centre) and a Tripoli specimen that was subject to damage by
- boring-sponges (bottom). As expected, there is substantial morphological variation between
- 276 specimens from both localities. Adaptation to a high-energy regime is apparent in the
- 277 overall squatter appearance of the TF specimen. Also reflected is Russini and colleagues'
- 278 (2017) diagnosis concerning the length of the body whorl (i.e. ³/₃ of the shell in *C. rustica* and
- 279 3/3 to 3/4 in *C. adansoni*). Further, our TF specimen shows broad layered spiral whorls, a well-

- 280 developed aperture and squat shoulder. The Tripoli specimens conversely are more gracile,
- displaying an elongated spire and siphonal canal. Despite these morphological differences
- the spatial distribution of shell-thickness appears to follow a more or less identical template.
- The shells are thickest (coloured red) along the top of the body whorl attaching to the spire, the siphonal canal and the outer lip of the aperture. The spire-whorls are thinner (coloured
- blue) than the body whorl. The body-whorl gradually gets thinner towards the periphery
- (widest part) as well as in the direction of growth. Ventrally, this pattern is overlain by a
- thicker (coloured yellow to orange) patch on the mid-ventral plain.
- 288
- 289 Descriptive statistics for three size measurements, i.e., maximum height, maximum
- diameter and aperture height, for the here studied *Columbella* spp. assemblages are
- provided in Table 1. All three measurements show a similar pattern. For KSA Layer XXII,
- maximum height and aperture height could only be measured in two specimens. Thus, to maximise the sample, maximum diameter is chosen as a proxy for shell size and compared
- here between the assemblages (Fig. 5). Shapiro-Wilk normality tests revealed that maximum
- diameter in TF1 is not normally distributed (W: 0.93012, p<0.001). A Kruskal-Wallis test
- 296 shows strong evidence of a significant difference between the mean ranks of at least one
- 297 pair of assemblages (Kruskal-Wallis χ^2 =76.358, p<0.001). Wilcoxon signed rank pairwise
- tests (p-values adjusted using the Bonferroni correction) show that the modern shell
 assemblages from Tenerife, TF1 and TF2, are not significantly different (p=1), neither are the
 Ksâr 'Akil assemblages XXII and XVII (p=1). However, both Ksâr 'Akil assemblages differ
 significantly from both TF1 and TF2 (all p-values are <0.001). These differences are mainly
 caused by the presence of smaller specimens in both Tenerife thanatocoenoses, which are
- 303 outside the range of the Ksâr 'Akil assemblages. Individual larger specimens, falling in the
- 304 upper half of the Ksâr 'Akil ranges, are present in the TF1 assemblage and probably cause
 305 the non-normal distribution of TF1.
- 306
- 307 Most natural damage observed in both the modern death and archaeological assemblages, 308 is situated in the thinner parts of the shell (Fig 6). The exception being boring sponge 309 damage, which appears to be randomly distributed on the shell surface. This latter pattern 310 of damage does not usually penetrate the entire shell surface, is evident in all assemblages 311 and visible in the μ CT-model (Fig. 4, bottom). Although, this type of damage weakens the 312 shell-wall it does not lead to perforations large enough to be suitable for suspension, 313 neither is there any indication that these pits and holes were used to puncture the shell 314 during bead-manufacture. In other words, boring sponge damage is randomly distributed 315 and not aligned with larger perforations. Further, in the modern death assemblages, shell 316 damage is mainly restricted to structurally weaker zones, the thin apex being most affected. 317 Damage on the body-whorl, the next weakest zone, centres on the mid dorsal surface which 318 is the most exposed surface of the body-whorl. A similar pattern is seen in thanatocoenosis 319 of other taxa like Tritia gibbosula (Bouzouggar et al. 2007). This pattern is observed in both 320 the archaeological and the thanatocoenoses datasets.
- 321
- 322 As expected, there are more types of damage in the modern death assemblages than in the
- 323 archaeological ones. In part, this could be due to more intense wave action in the Tenerife
- 324 rocky shore environment or to anthropogenic selection of less damaged shells. Apical
- 325 damage or loss is frequent in both archaeological and modern specimens. The edges of
- 326 breaks include both smoothed surfaces, likely caused by water erosion, as well as irregular

- 327 breakage, which could have been caused by wave-action or post-depositional crushing (e.g.,
- 328 Claasen 1998). In addition, the lack of smaller (e.g., apical) fragments in the Ksâr 'Akil
- 329 assemblages may be explained by a size-bias due to recovering techniques (e.g., mesh-size
- 330 for sieving) during the 1930s and 1940s excavation campaigns. Overall, there is a significant
- 331 difference in the proportion of damaged versus intact shells between the modern-death and
- 332 archaeological assemblages (Table 2). Equally, the proportion of damage resulting in a
- 333 perforation is significantly higher in both archaeological assemblages as is the frequency of
- 334 dorsal perforations that would facilitate suspension (see e.g., Perlès 2016; Stiner et al. 335 2013).
- 336
- 337 The perforation location in both archaeological layers is largely restricted to the mid dorsal 338 (dorsal f and j) and ventral (ventral c) planes. Dorsally, the perforations of all assemblages
- 339 fall in the thinnest (weakest) part of the body whorl. In the archaeological samples the mid
- 340 dorsal plane is nearly exclusively affected, whereas in the modern death assemblages
- 341 damage is more evenly distributed throughout the thinnest part of the body whorl. In
- 342 addition, there is a marked difference in perforation size relative to shell dimension. In the
- 343 archaeological assemblages, there is a significant dominance of medium-sized (dorsal f) on
- 344 the mid dorsal plane compared to both smaller (dorsal d) and larger (dorsal j and o) holes
- 345 (Table 3). Interestingly, the inter-quartile range of the Ksâr 'Akil maximum perforation 346
- diameter is much narrower than in the modern-death assemblages even though the latter 347 shells are overall smaller (Fig. 7). This suggesting standardisation in perforation size in the 348 archaeological specimens.
- 349 Ventral damage is much less frequent overall and does not warrant statistical evaluation of
- 350 the data. However at face value, ventral perforations follow the dorsal pattern in that there 351 is a larger variation in perforation size in the modern death assemblages. Further,
- 352
- perforations situated in the thicker (orange) zone of the ventral plane are more common in 353 the Ksâr 'Akil assemblages. Large perforations on the ventral plane in the TF assemblages
- 354 are caused by damage on the thinner surrounding of the mid dorsal plane removing the
- 355 thicker central part in the process. The small holes observed in various ventral locations in
- 356 the TF1 assemblages are largely caused by boring sponges and other bioeroders.
- 357

358 **Discussion and Conclusions**

359 In this study we used three-dimensional models of shell thickness to shed light on human 360 decision making in archaeological shell assemblages. Our goal was to contribute to a better 361 understanding of whether shell perforations in archaeological contexts are the result of 362 natural or anthropogenic processes. We distinguished three stages in shell use-life, in which 363 perforations can occur: 1) before human collection, 2) the prehistoric use-life, and 3) after 364 discard. We predicted that most natural taphonomic processes (in stages 1 and 3) would 365 affect structurally weak zones to a higher degree than more robust zones and that damage in zones of similar thickness should be randomly distributed. For stage 1 these hypotheses 366 367 were largely met. Shell damage is mainly restricted to structurally weak zones, albeit with 368 the exception of boring sponge damage which is randomly distributed across the entire shell 369 surface and leaves holes too small to be suitable for suspension. The thinnest part of the 370 shell, the apex, is most affected by damage, followed by the thinner parts on the periphery 371 of the body whorl. Damage within the thinnest zone of the body whorl is more or less 372 evenly distributed. To verify whether our predictions are correct for stage 3 of shell use-life, 373 more experimental data is needed to better understand the damage caused by postdepositional processes and recovery techniques. For example, by burying whole shells andto expose them to trampling, excavation, sieving, and transport.

376

377 Regarding stage 2 damage, our results suggest that C. rustica with natural perforations were 378 specifically collected and/or specimens were intentionally pierced to be used as beads. 379 Previous taphonomic investigations have excluded that these shells were transported to the 380 site by animals and geological processes or that they were collected for consumption. 381 Instead, these specimens were collected as empty shells from beaches (Bosch et al. 2015a). 382 Our results show that all Ksâr 'Akil assemblages are significantly different compared to the 383 modern death assemblages. Average shell-size is significantly larger, but falls within the 384 range of their modern beach-collected counterparts. This pattern has been observed for 385 multiple taxa in Palaeolithic, Mesolithic and Neolithic assemblages (e.g., Benghiat et al. 386 2009; Bosch et al. 2019; Perlès 2016; Vanhaeren et al. 2006). For Columbellidae it has been 387 suggested that changes in archaeological shell-size are not caused by natural factors – such 388 as changing sea surface temperatures – but by preferential selection seeing as the 389 archaeological specimens do not exceed the maximal dimensions of modern specimens 390 (e.g., Benghiat et al. 2009; Perlès 2016).

391

392 Our results on breakage patterns show that archaeological shells are more commonly 393 broken than beach-collected ones and that shell damage more often results in a 394 perforation. Further, both shell damage and the spatial distribution of holes is less variable 395 in the archaeological shells. Centrally-located perforations both on the mid-dorsal and mid-396 ventral plain predominate and medium-sized holes (again both dorsally and ventrally) are 397 significantly more frequent. In fact, the medium to large dorsal perforations often observed 398 in archaeological specimens occur in roughly 10% of the TF natural death assemblages 399 versus approximately 70% in the Ksâr 'Akil shells. Perlès (2016) sees a similar pattern in 400 comparing thanatocoenoses data of C. rustica from the Eastern Mediterranean with the 401 Upper Palaeolithic to Neolithic assemblages at Franchthi Cave (Greece). Although she 402 reports drastically lower return rates for intact specimens - namely 11 to 80 shells per 403 collector per hour versus 360 and 355 in TF 1 and TF 2 respectively – she reports a low (less 404 than 10%) return rate for specimens with a dorsal perforation suitable for suspension and 405 congruent with the dominant perforation pattern in her archaeological assemblage. Equally, 406 Stiner and colleagues (2013) report a 20% perforation rate for a modern collection of C. 407 rustica from the beach below Üçağızlı I Cave (Turkey) of which 10% display medium to large 408 dorsal perforations as seen in the Üçağızlı I Cave specimens. In all three thanatocoenoses 409 overall shell damage and breakage patterns, including perforation rates are very similar. For 410 example, Stiner et al. (2013) report a 75% proportion of (semi)-intact specimens versus 411 70%–78% in the Tenerife assemblages and 66%–79% reported by Perlès (2016). These data 412 suggest that 1) breakage patterns in both C. rustica and C. adansoni thanatocoenoses are 413 comparable and that 2) the few available Eastern Mediterranean Palaeolithic assemblages 414 deviate significantly from a natural distribution. In addition, our three-dimensional shell 415 models show that perforations on the shells' ventral surface are situated in a thicker part of 416 the shell than its surrounding areas i.e., in a zone which we assumed would be less 417 frequently affected by natural damage. Indeed, although medium-size perforations in this 418 thicker zone do occur in the natural TF1 and TF2 datasets, damage in the weaker zones is 419 more abundant. In other words, the perforations in the archaeological C. rustica are more 420 uniform in their location and size. This pattern of standardisation would, from an etic point

421 of view, be ideally suited for ornamentation. Not too small to facilitate suspension, not so

- 422 large that the object loses its original shape and appearance.
- 423

424 The perforation patterns cannot be explained solely by natural processes. Instead, they 425 suggest that prehistoric humans specifically selected shells with certain perforations or that 426 they pierced them. We argue that the standardisation of perforation diameter (shown by 427 the narrow inter-quartile range) in C. rustica is indicative of anthropogenic piercing (e.g., 428 Stiner et al. 2013). Indeed, standardisation in bead perforation shape, size and distribution 429 have been argued to signify formalised manufacture processes (e.g., d'Errico et al. 1993; 430 Kuhn and Stiner 2007; White 1999, 2007) and our results are thus more congruent with 431 human manufacture processes than solely selection of naturally-holed specimens. 432 433 In the archaeological *C. rustica*, perforation shape is predominantly irregular and the edge

434 appearance may variably be irregular or smoothed. If the Ksâr 'Akil specimens are indeed
 435 anthropogenically pierced as our data suggests, experimental studies suggest that this type

436 of perforation is most likely achieved by direct hard hammer percussion, with or without

- 437 rotation (e.g., Benghiat et al. 2009; Cristiani et al. 2014; d'Errico et al. 1993; Stiner et al.
- 438 2013). In relation to the large shell-size, Benghiat et al. (2009) found during their
- 439 experiments that larger specimens are less likely to shatter during manufacture when using
- hard hammer percussion. Detailed microscopic analysis of the archaeological assemblage is
 needed to identify possible traces of manufacture and use-wear, which could confirm or
- refute the suggestion that direct hard hammer percussion was used to perforate the Ksâr
 'Akil shells.
- 444

445 Our study adds to a growing body of data using modern death assemblages (e.g., 446 Bouzouggar et al. 2007; d'Errico et al. 2009; Perlès 2016; Stiner et al. 2013; Vanhaeren et al. 447 2006). We contribute to these studies by providing data on perforation locations in 448 thanatocoenoses of C. adansoni, which to our knowledge has not been published before. In 449 addition, the use of our three-dimensional shell models aids to better quantify shell-damage 450 in relation to species-specific shell structures. This approach using micro-CT scans is perhaps 451 most useful in 1) shell assemblages where (post-depositional) taphonomy has obliterated 452 any evidence of bead manufacture and use 2) in cases where both modified and naturally 453 perforated shells were used, and 3) like with the Ksâr 'Akil C. rustica, in instances in which 454 the mode of perforation mimics natural damage processes. In addition, our approach 455 facilitates identification of evidence for standardisation in manufacture processes, which in 456 turn, can help us to better understand socio-economic behaviours underpinning shell bead 457 manufacture and use. Our investigations suggest that in general thin shell-zones are more 458 prone to natural damage than more robust ones. Evaluation of perforation patterns on 459 these templates and especially identifying deviations from the natural patterns provides 460 new insights into human-mediation with C. rustica shells during Initial and Early Upper 461 Palaeolithic at Ksâr 'Akil. Such as evidence for formalised bead manufacture using C. rustica 462 as early as the Initial and Early Upper Palaeolithic in the eastern Mediterranean. 463

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- 477

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664 Tables and captions

665

- Table 1: Descriptive statistics for *Columbella rustica* from Ksâr 'Akil (KSA) Layers XXII and
- 667 XVII, n: number of specimens, SD: standard deviation.
- 668

ID	n	min	max	range	mean	SD
Height max						
KSA-XXII	2	13.71	16.73	3.02	15.22	2.14
KSA-XVII	8	13.81	16.61	2.80	15.21	0.97
TF 1	79	9.09	15.53	6.44	11.88	1.04
TF 2	35	10.53	12.95	2.42	11.40	0.65
Max diameter						
KSA-XXII	11	8.21	11.08	2.87	9.58	0.92
KSA-XVII	29	8.10	10.65	2.55	9.26	0.75
TF 1	142	6.64	10.73	4.09	7.82	0.64
TF 2	62	6.69	9.71	3.02	7.77	0.66
Height Aperture						
KSA-XXII	2	11.14	12.18	1.04	11.66	0.74
KSA-XVII	17	9.81	11.81	2.00	10.63	0.70
TF 1	104	7.14	12.87	5.73	8.93	0.89
TF 2	43	7.66	10.54	2.88	8.85	0.73

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Table 2: Statistical evaluation of shell damage. *= simulated p-values with 10,000 replicates.

damaged vs intact shells							
	TF1	TF2					
KSAXXII	χ ² =7.4712, p=0.005*	χ ² =7.1646, p=0.013*					
KSAXVII	χ2=11.536, p<0.001	χ ² =9.809, p=0.002					
damage resulting in a perforation							
	TF1	TF2					
KSAXXII	χ ² =7.9722, p=0.005	χ ² =13.654, p<0.001					
KSAXVII	χ ² =30.287, p<0.001	χ ² =37.582, p<0.001					

dorsal perforation diameter							
	TF1	TF2					
KSAXXII	χ ² =18.305, p<0.001*	χ2=15.367, p<0.001*					
KSAXVII	χ ² =41.916, p<0.001	χ2=25.07, p<0.001*					

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Table 3: Dorsal and ventral shell damage in rocky shore thanatocoenoses from Tenerife (TF1

and TF2) and archaeological assemblages from Ksår 'Akil (KSA) Layers XXII and XVII. Shell

677 damage in bold, perforation locations in normal font.

	Т	'F1	TF2		KSA XVII		KSA XXII	
	n	%	n	%	n	%	n	%
Beach washed	239	92.64	89	97.80	102	88.70	13	68.42
Dorsal damage	n	%	n	%	n	%	n	%
Not damaged	72	27.52	27	29.67	13	11.30	0	0.00
Damaged	186	72.09	64	70.33	102	88.70	19	100
Damage results in perforation	88	47.31	21	32.81	83	81.37	16	84.21
b - small hole on apex	17	6.54	9	10.11	2	1.26	1	4.00
c - apex gone	85	32.69	30	33.71	62	38.99	8	32.00
d - small hole mid dorsal plain	14	5.38	3	3.37	6	3.77		
e - dorsal side aperture					2	1.26		
f - medium hole mid dorsal plain	15	5.77	1	1.12	60	37.74	13	52.00
h - lateral opposite aperture	3	1.15	1	1.12	1	0.63		
j - large hole dorsal plain	15	5.77	6	6.74	13	8.18	2	8.00
l - aperture broken	40	15.38	14	15.73	12	7.55	1	4.00
m - aperture left	2	0.77						
o - hole all dorsal plain incl apex	29	11.15	1	1.12	1	0.63		
ak - apex left	9	3.46	9	10.11				
an - lateral side left	19	7.31	2	2.25				
ap - body whorl fr	2	0.77	2	2.25				
ar - basal part gone	4	1.54	9	10.11				
as - small hole basal plain	1	0.38	2	2.25				
ao - columella left	5	26.32						
Ventral damage	n	%	n	%	n	%	Ν	%
Not damaged	258	87.21	87	95.60	106	92.17	18	94.74
Damaged	33	12.79	4	4.40	9	7.83	1	5.26
b - predator hole mid ventral plain					2	22.22		
c - medium hole mid ventral plain centre	6	18.18			6	66.67	1	100
d - small hole on apex			2	50	1	11.11		
e - small hole mid ventral plain centre	3	9.09						

f - small hole mid ventral aperture side	4	12.12				
g - small hole mid ventral opposite aperture	3	9.09				
h - small hole basal plain	1	3.03				
i - all ventral side gone	2	6.06				
j - large hole mid ventral plain aperture side			1	25		
k - medium hole mid ventral plain opposite aperture	3	9.09				
l - basal part gone	2	6.06				
m - large hole mid ventral plain	9	27.27	1	25		

Figure captions



683

Figure 1. Flow chart showing the use-life of shell specimens found in archaeological
assemblages, green arrows: human modifications, red: perforated shells used as beads by
prehistoric humans, blue: perforated shells in archaeological record.



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Figure 2. Examples of shell damage in *Columbella adansoni* from Tenerife, Spain thanatocoenosis (TF1).



Figure 3. Examples of shell damage in archaeological specimens of *Columbella rustica* from

- Ksâr 'Akil, Lebanon Layer XVII (Early Ahmarian).



698 699 Figure 4. Heat maps of shell thickness in *Columbella* spp. Top: *Columbella adansoni* from thanatocoenosis (TF1), Middle: pristine *Columbella rustica* (RMNH.Mol.203708.a), bottom: 700 701 *Columbella rustica* showing boring sponge damage (RMNH.Mol.203708.c). Red to blue: thick 702 to thin.



705 Figure 5. Scatterplot comparison of the maximum diameter and the aperture height for

706 Columbella rustica of each analysed assemblage. Tenerife thanatocenoeses TF1: red circles,

TF2: blue triangles, Ksâr 'Akil Layer XVII: light green diamonds, Layer XXII: dark green

708 inverted triangles.





711 Figure 6. Shell damage in *Columbella rustica*, comparing thanatocoenoses TF1 and TF2 with

712 Ksår 'Akil Layers XXII and XVII. Red to blue: thick to thin. White circles: damaged zones,

- 713 thickness of line indicates percentage shells damaged in this region (see key in figure). Black
- 714 circles: perforations by predators.
- 715





716 717 Figure 7. Boxplots comparing the maximum dorsal perforation diameter for *Columbella*

rustica between each analysed assemblage. Tenerife thanatocoenoses TF1: red, TF2: blue, 718

Ksår 'Akil Layer XVII: light green, Layer XXII: dark green. Outliers are shown as solid black 719

circles. Diamonds display the mean. 720