Mahoney, Patrick, Schmidt, Christopher W Schmidt, Deter, Chris, Remy, Ashley, Slavin, Philip, Johns, Sarah E., Miszkiewicz, Justyna J. and Nystrom, Pia (2016) *Deciduous enamel 3D microwear texture analysis as an indicator of childhood diet in medieval Canterbury, England.* Journal of Archaeological Science, 66 . pp. 128-136. ISSN 0305-4403.

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1   **Deciduous enamel 3D microwear texture analysis as an indicator of childhood**

2   **diet in medieval Canterbury, England**

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Abstract

This study conducted the first three dimensional microwear texture analysis of human deciduous teeth to reconstruct the physical properties of medieval childhood diet (age 1-8yrs) at St Gregory's Priory and Cemetery (11th to 16th century AD) in Canterbury, England. Occlusal texture complexity surfaces of maxillary molars from juvenile skeletons (n=44) were examined to assess dietary hardness. Anisotropy values were calculated to reconstruct dietary toughness, as well as jaw movements during chewing. Evidence of weaning was sought, and variation in the physical properties of food was assessed against age and socio-economic status. Results indicate that weaning had already commenced in the youngest children. Diet became tougher from four years of age, and harder from age six. Variation in microwear texture surfaces was related to historical textual evidence that refers to lifestyle developments for these age groups. Diet did not vary with socio-economic status, which differs to previously reported patterns for adults. We conclude, microwear texture analyses can provide a non-destructive tool for revealing subtle aspects of childhood diet in the past.

Keywords

Dental microwear; medieval childhood diet.

1. Introduction.

Human diet during the 11th to 16th century in medieval England is best understood for adults, higher status families, or 'closed-communities' such as monastic settlements (Dyer, 2000: 83; Slavin, 2012: 8; Woolgar, 2010). Knowledge of childhood diet during this period is generally more limited because it was not a focus for medieval writers. Although limited, there is some historical textual evidence that provides weaning and other childrearing advice related to food consumption (Fildes, 1986: 213, 1988: 76). A few isotopic studies have also reported dietary weaning age and subsequent protein consumption for medieval village and urban centres in the north of England (Burt, 2013, 2015; Fuller et al., 2003; Mays et al., 2002; Richards et al., 2002), but not for the south-east. Neither is anything known about the physical properties (hardness, toughness) of medieval childhood diet.

Here, we conduct the first intra-specific three dimensional (3D) dental microwear texture analysis (DMTA) of human deciduous teeth to reconstruct the physical properties of childhood diet in medieval Canterbury, south-east England (Fig.1). DMTA is a non-destructive methodology that provides evidence of the hardness and toughness of foods eaten by an individual (Scott et al. 2005, 2006; Ungar et al., 2003) in the days and weeks preceding death (Grine, 1986). For example, dietary hardness and toughness has been reconstructed from DMTA of permanent tooth enamel for archaeological samples of hunter-gatherers, fossil hominins, and Neanderthals (El Zaatari et al., 2011, El Zaatari and Hublin, 2014; Schmidt et al., in press; Ungar et al., 2008a, 2010). However, few studies have examined microwear surfaces of deciduous enamel (e.g., Bullington, 1991). Our study is the first to apply the 3D methodology to human deciduous teeth.

77   *1.1 Childhood diet in Medieval England*

78   Physicians in sixteenth century Europe advised the introduction of mixed-feeding (gradual

79   introduction of non-milk foods leading to a relative decrease in the contribution of breast milk

80   to total diet: Humphrey, 2014) between seven to nine months of age (Fildes, 1986: 245).

81   Historical records from this period indicate that a child was finally weaned (removal of breast

82   milk) between 12-18 months (Fildes, 1986: her Table 15.3-4; 1995: her Table 4.7). This latter

83   age range is compatible with isotopic evidence from the medieval village of Wharram Percy

84   and the urban Fishergate House cemetery in the north of England, which suggests weaning

85   occurred in the second year after birth (Burt, 2013, 2015; Fuller et al., 2003; Mays et al.,

86   2002; Richards et al., 2002).

87   Pap (flour, milk, egg yolk) or panada (bread in broth with butter or oil) were popular

88   supplementary foods during mixed-feeding (Fildes, 1986: 213; Orme, 2003: 71). Insights into

89   early childhood diet after mixed-feeding have been gained from historical textual accounts.

90   Grain products were an important component of medieval diet (Slavin, 2012: 169; Stone,

91   2006:11), and bread with butter, porridge, and gruel, were typical early childhood foods

92   (Orme, 2003: 71-72). However, little is known about dietary variation with age. Isotopic

93   evidence from Wharram Percy indicates that children may have consumed a post-weaning

94   diet that that was lower in protein compared to older individuals (Richards et al., 2002).

95   Socio-economic status could determine the quality, variety, and type of foods consumed

96   by adults (e.g., Dyer, 2006: 201-9; Powell et al., 2001: 298; Woolgar, 2006: 196; Woolgar et

97   al., 2006: 270). Outside of periods of religious observance (primarily Advent and Lent)

98   wealthier lay households and monastic communities regularly consumed meat, but other than

99   pork, it contributed less to the peasant diet (DeWitte and Slavin, 2013; Dyer, 2000: 84-86;

100   Powell et al., 2001: 308). Higher social strata preferred white bread made from wheat, while

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101   those of lower socio-economic status usually consumed coarser whole grain bread (Campbell,

102   2010; Stone, 2006: 17; Slavin, 2012: 180).

103   It is unclear if the relationship between adult status and food consumption extends to

104   children from this period (Burt, 2013). In medieval York, lower status children consumed

105   higher status and more expensive foods after weaning (Burt, 2015). Furthermore, a study of

106   gross dental wear on deciduous teeth from medieval sites in the south of England, including

107   Canterbury, reported no differences between higher and lower status burials of similarly aged

108   children (Dawson and Robson Brown, 2013). Thus, the relationship between food

109   consumption and status for children in this period might be more complex than that reported

110   for adults.

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112   *1.2. Study Aims*

113   This study conducts the first intra-specific microwear texture analysis of human deciduous

114   teeth to reconstruct the physical properties of childhood diet in Medieval Canterbury (Fig. 1).

115   All dental samples were from human juvenile skeletons (*n*=44) aged between one to eight

116   years of age, which were recovered during excavation of St Gregory's priory and cemetery

117   (11th to 15th Century AD) in Canterbury (Hicks and Hicks, 2001). The site is unique in south-

118   east England as it contained a large number of well-preserved juveniles. It has two burial

119   areas, a priory and a cemetery, which correspond with higher and lower socio-economic

120   status respectively (see section three).

121   The *study aims* are, 1) to search for microwear evidence of dietary weaning in the

122   youngest children. 2) Determine if variation in the physical properties of diet correlates with

123   age. 3) Compare microwear from those buried in the higher status priory to those buried in

124   the lower status cemetery. Prior to these analyses, we conduct a preliminary experimental

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125   study to explore microwear texture formation processes on human deciduous enamel

126   compared to permanent enamel.

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128   *1.3. Dental microwear texture analysis*

129   Microscopic wear in the form of scratches and pits is laid down on the occlusal surface of

130   tooth enamel as hard particles are sheared between or compressed into opposing crowns as the

131   jaw moves through the chewing cycle (Gordon, 1982). Food contaminated by grit that is

132   harder than enamel, such as quartz inclusions, is one microwear causal agent (Lucas et al.,

133   2013; Peters, 1982; Teaford and Lytle, 1996). Two dimensional (2D) dental microwear

134   analyses have been used since the 1950's to explore jaw movements of extinct mammals and

135   modern humans (Butler, 1952; Dahlberg, 1960; Mills, 1955). Subsequent 2D studies

136   described microwear patterns by their frequency, size, and orientation in extant and fossil

137   mammals (Grine, 1981; Puech, 1979; Walker, 1976; Walker et al., 1978) leading to a range of

138   quantitative studies that sought to infer aspects of diet in past human populations (e.g.,

139   Mahoney, 2006; Pastor, 1993; Schmidt, 2001; Teaford et al., 2001). Methodological

140   developments led to DMTA, the 3D characterization of microwear surfaces (Scott et al.

141   2006). This automated quantification of microwear in three dimensions minimizes inter-

142   observer measurement error (Grine et al., 2002), and thus holds great potential for the future

143   of dietary reconstruction in an archaeological context.

144   Dental microwear texture analysis is based upon the principle that an enamel surface can

145   look different when observed at different scales. A surface may appear smooth when

146   observed at a coarse scale but can appear rough at a finer scale. The texture of an enamel

147   surface can be quantified in three dimensions by combining white-light confocal profilometry

148   with scale-sensitive fractal analysis (Scott et al. 2005, 2006; Ungar et al., 2003). In this study

149   we focus upon two texture variables that have been previously related to dietary hardness and

150   toughness in extant primates:

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151   -   Area-scale fractal *complexity* (Asfc) (Scott et al., 2005). Values for complexity measure

152   changes in surface topography across different scales. Enamel with pits and scratches of

153   different sizes superimposed onto each other, or a surface that is heavily pitted, would

154   typically have higher complexity values (Ungar et al., 2008b, 2010). Consumption of

155   hard abrasive foods, which are 'crushed' between opposing enamel surfaces, and

156   correlated with frequent dental pits in 2D microwear analyses (Teaford, 1985; Teaford

157   and Walker, 1984), tends to produce relatively higher Asfc values (and lower levels of

158   anisotropy) in some primate hard seed and hard fruit eaters (Scott et al., 2005, 2006,

159   2012). Thus, a tooth surface that is dominated by dental pits with a high Asfc value has

160   been used to infer a hard and abrasive diet (Scott et al., 2012; Ungar et al., 2010).

161

162   -   Exact proportion length-scale *anisotropy* (epLsar) (Scott et al., 2005). Values for the

163   anisotropy of microwear texture surfaces measure the orientation of surface features.

164   Enamel dominated by scratches all orientated in the same direction produces a high

165   anisotropy value (Ungar et al., 2008a). Low anisotropy values indicate low similarity in

166   wear feature orientation. Tougher foods which are 'sheared' between opposing enamel

167   surfaces, and correlated with frequent dental scratches in 2D microwear analyses

168   (Teaford, 1993; Teaford and Walker, 1984), can produce comparatively higher epLsar

169   values (and lower levels of Asfc) in some primate species that consume leaves, stems and

170   other tough fibrous foods (Scott et al., 2005, 2006, 2012). Therefore, enamel covered

171   with scratches mainly orientated in the same direction with a high epLsar value has been

172   used to infer consumption of tough abrasive foods (Scott et al., 2012; Ungar et al., 2010).

173   Jaw movement also has been reconstructed from dental scratches (Butler, 1952; Gordon,

174   1982; Scott et al., 2006; Young and Robson, 1987), whereby high epLsar values indicate

175   more consistent rather than varied jaw movements during chewing (Ungar et al., 2010).

176   While texture values within a species are variable, and texture surfaces for harder or

177   tougher diets will often overlap (Strait et al., 2013), the key correlations between microwear

178   and the physical properties of a diet established in the 1980s (Teaford, 1985; Teaford and

179   Oyen, 1989; Teaford and Walker, 1984), have been confirmed more recently in studies of

180   texture surfaces from mammals, and in experimental studies (e.g., Schubert et al., 2010;

181   Schultz, 2013, Xia et al., 2015; Hua et al., 2015). Thus, DMTA distinguishes between extant

182   primates of known diet, and these correlations provide a base-line from which to infer diet in

183   historic and pre-historic populations.

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185   *1.4 Potential sources of deciduous microwear texture variation in Medieval Canterbury.*

186   Breast feeding will produce no microwear and the introduction of abrasive foods should

187   produce tooth wear. After weaning, flour prepared using traditional milling methods could

188   introduce hard abrasive grit into cereal foods, which has been identified as a source of

189   microwear in 2D studies (e.g., Teaford and Lytle, 1996). In medieval Canterbury, cereal

190   foods such as these came from regional farmlands, demesnes, and local grain traders

191   (Campbell, 2010; Slavin, 2012: 52-55, 2014). During the Middle Ages, grain was ground and

192   prepared for consumption by local mills in Canterbury, one of which was owned by St.

193   Gregory's priory (Hastead, 1800; Somner, 1703). Mills in medieval Kent often used

194   limestone and sandstones querns for milling (Farmer, 1992; Keller, 1989), which can

195   introduce a residue of grit into foods (Teaford and Lytle, 1996).

196   Consumption of meat can alter microwear texture surfaces (El Zaatari, 2010). 19th

197   century Fuegian hunter-gatherers with a diet that consisted mainly of meat had a lower mean

198   Asfc but higher epLsar value, relative to other hunter-gatherer populations (El Zaatari, 2010).

199   Chewing tough meat that contained some abrasives would require repetitive shearing motions

200   of the jaw, leading to many scratches orientated in the same direction. The consumption of

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201   meat in medieval England varied by status amongst adults (above). If childhood status, or

202   age, also determined access to meat, then this might contribute variation to epLsar values

203   amongst the Canterbury children.

204   Beyond hard and abrasive, and tough foods, there are several other potential microwear

205   formation processes that should be considered when interpreting deciduous enamel textures.

206   First, bite force potential will differ significantly between younger and older children, as the

207   muscles of mastication gain size and strength (Kamegai et al., 2005). As such, more force

208   exerted during chewing would provide more opportunity for hard particles to be driven into

209   enamel as microwear accumulates for the first time. Thus, variation in microwear texture

210   surfaces between children of different ages might relate in part to differences in bite force.

211   Lateral movement of the mandible will also increase with age, as the mandible increases in

212   size. Greater lateral movement, as the mandible moves through the chewing cycle, might

213   produce longer scratches, though this would not necessarily alter an anisotropy value.

214   'Teething', and the use of pacifiers by young children, could contribute microwear that

215   was unrelated to diet. Dental eruption in humans typically commences around the sixth post-

216   natal month as deciduous central incisors emerge through the gum line (Hillson, 2014: his

217   Table 4). The second molar is the last deciduous tooth to erupt, usually towards the start of

218   the third post-natal year (Hillson, 2014: his Table 4). Infants biting on pacifiers might scratch

219   the enamel surface. For example, in medieval England, a child might be given a piece of

220   coral during teething (Hanawalt, 1993:52). This potential source of microwear is more likely

221   in younger infants, and more likely to accumulate on early erupting incisors. Selecting later

222   erupting teeth can reduce the potential for pacifiers to obscure a diet-microwear relationship.

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225   **2. Preliminary experimental study**

226   The efficacy of DMTA as an indicator of the physical properties of diet has been

227   demonstrated numerous times using adult permanent teeth (see Section 1.3).   Its value,

228   however, has not been demonstrated to the same extent on deciduous teeth. Would a single

229   microwear formation process produce similar microwear texture values for both deciduous

230   and permanent enamel?   Or instead, would these two enamel types differ in an unexpected

231   way when exposed to the same formation process. For example, deciduous enamel is more

232   porous and relatively softer than permanent enamel (e.g., Wilson and Beynon, 1989). To

233   investigate microwear formation processes on deciduous relative to permanent enamel we

234   undertook an experimental study before we examined microwear texture surfaces of juveniles

235   from St Gregory's priory and cemetery.

236   Complexity and anisotropy values were calculated for thirteen deciduous incisors. The

237   deciduous teeth were experimentally abraded, complexity and anisotropy values were re-

238   calculated, and compared to those from before the experiment. We repeated the experiment

239   on six permanent premolars, and compared the results to the deciduous teeth.

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241   *2.1. Samples*

242   Thirteen deciduous mandibular incisors were donated by former students to the Indiana

243   Prehistory Laboratory, University of Indianapolis, knowing these teeth would be used in wear

244   experiments. These teeth were included in the experimental study because the labial surface

245   of each tooth showed no signs of gross dental wear. The six permanent maxillary premolars

246   were from an early 20th century cemetery population in Indiana. The premolars were selected

247   because the mesial surface of each tooth was unworn. There was no reason to suspect that the

248   enamel microstructure of the dental samples used in the experimental study would influence

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249 microwear formation processes in a way that would differ to the dental samples from

250 Canterbury.

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252 *2.2 Experimental procedures*

253 Microwear preparation and analytical procedures are described in section four. Before each

254 tooth was experimentally abraded, a target area was identified, and the complexity and

255 anisotropy of that area was recorded. The same target area was then abraded experimentally

256 and the texture values were recorded again. Thus, we produced "before" and "after"

257 experimental data sets.

258 One tooth was fixed to a square metal block weighing 1.1 kg using industrial adhesive

259 fixing tape. The tape was folded over the block, and over the tooth cervix and root. Each

260 tooth was positioned so that a relatively flat surface would be scratched. For premolars, that

261 was on the mesial aspect of the tooth. For incisors, it was the labial surface just inferior to the

262 incisal margin. The orientation of rods relative to the enamel surface can influence enamel

263 resistance to abrasion (Rensberger, 2000: his Fig 18.7), but the rod orientation in the target

264 area for both tooth types is similar. The block, with attached tooth, was placed onto a piece of

265 abrasive paper with a 200-grit size (Buehler©) that had been taped to a flat table-top. We

266 chose a grit size of 200 rather than a finer grit size to maximise scratch formation. Only the

267 tooth surface contacted the abrasive paper. The metal block was balanced by hand and pulled

268 across the length of the paper for a distance of 20 centimetres, taking approximately three

269 seconds. A square wooden block was placed next to the abrasive paper and used as a guide to

270 ensure that the distance travelled by the metal block was in a straight line. Each tooth was

271 abraded once. This process produced wear facets that were visible to the naked eye; most

272 were approximately one to two millimetres in diameter.

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273   We tested the null hypothesis that there would be no difference between the complexity

274   and anisotropy post-experimental abrasion values from deciduous enamel, when compared to

275   permanent enamel, using a Mann Whitney U test.

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277   *2.3 Experimental results*

278   Table 1 shows the experimentally induced microwear texture values. Mean Asfc

279   increased by 5.25 for deciduous teeth, and by 4.64 for permanent teeth, from before to after

280   the experimental abrasion. Mean anisotropy increased by 0.0053 for deciduous teeth, and by

281   0.0062 for permanent teeth, from before to afterwards. The post-experimental complexity

282   and abrasion values did not differ significantly when compared between deciduous and

283   permanent teeth ($p=$ 0.844, $p=$0.116, respectively). Therefore, the null hypothesis was

284   retained.

285   **Table 1**
286   Mean experimentally induced microwear texture values.

	Deciduous (n)			Permanent (n)		
	Before	After	Increase	Before	After	Increase
Complexity Asfc	1. 30 (13)	6.55 (13)	5.25	1.69 (6)	6.33 (6)	4.64
Anisotropy epLsar	0.0031 (13)	0.0084 (13)	0.0053	0.0012 (5)	0.0074 (5)	0.0062

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288   *2.4 Discussion of experimental results*

289   The experimentally created wear was statistically indistinguishable when compared

290   between deciduous and permanent teeth, indicating that microwear forms in a similar way

291   when these two enamel types are subjected to the same force applied in the same direction.

292   However, there were slight differences in the mean values from the two enamel types.

293   Deciduous enamel accumulated a slightly more complex surface with fewer similarly

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294   orientated scratches during the course of the experiment, relative to permanent enamel. We

295   observed that incisor enamel surfaces touching the abrasive paper were more curved

296   compared to premolars. So, these slight differences in the degree to which the microwear

297   values changed could be an artefact of this experiment, as force would have been applied to a

298   smaller area on the incisors compared to the premolars. Future studies can explore this in

299   more detail, to determine if facet size plays a key role in microwear formation. Overall, it is

300   clear that deciduous and permanent enamel produce similar microwear texture surfaces when

301   subjected to the same force applied in the same direction.

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303   *2.5 Limitations of experimental study*

304   Results from the experimental study underscore the efficacy of the DMTA variables

305   employed here. However, other DMTA variables commonly used in studies of dietary

306   inference were not examined. Scale of maximum complexity, textural fill volume, and

307   heterogeneity are yet to be analysed. Moreover, our study only included experimental wear

308   generated in a single direction with a single force. It may be possible that a threshold exists

309   whereby extreme force, or the direction of a force, can distinguish between adult and

310   deciduous microwear texture surfaces.

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319   **3. Study samples**

320   *3.1. St Gregory Priory and Cemetery*

321   The archaeological site is located about 300 meters north of present day Canterbury Cathedral

322   just outside the medieval city wall (Fig. 1). It was in use from the mid-11th to early 16th

323   century, and was excavated between 1988-1991 (Hicks and Hicks, 2001: 1-146). The priory

324   was founded by the Archbishop of Canterbury, Lanfranc, in AD 1084 (Sparks, 2001: 371).

325   Originally it was served by priests, and subsequently by Augustine cannons, who cared for the

326   sick at nearby St John's hospital and provided free burial for the poor in the cemetery (Brent,

327   1897; Duncombe, 1785; Somner, 1703; Sparks, 2001: 371).

328   All skeletons were previously excavated (Anderson and Andrews, 2001: 338-370). A

329   total of 91 burials were recovered from inside and around the priory, which included a male

330   with a chalice and a gold-embroidered monastic-like garment suggesting this was a burial

331   location for clergy (Anderson and Andrews, 2001). However, the presence of children and

332   adult females within the priory indicates that this was not a 'closed' monastic community.

333   Instead, these were members of wealthier families (Hicks and Hicks, 2001), who paid for the

334   prestigious burial location, which was a popular way of displaying socio-economic status for

335   wealthy lay people in this period (Daniell, 1997: 96-97).

336   The cemetery was established just before the priory (Sparks, 1988: 31), and a total of

337   1342 skeletons were recovered during excavation. Historical textual records indicate that the

338   cemetery served poorer families from local parishes, people who could not afford burial fees,

339   and patients from nearby St. John's hospital (Brent, 1879; Somner, 1703). It was in constant

340   use until a few years after the priory was dissolved in the 16th century (Sparks, 1988: 32,

341   2001: 376).

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343 **4. Materials and methods**

344 *4.1 Sample selection*

345 Microwear values were produced for deciduous maxillary first and second molars from 44

346 juvenile skeletons aged one to eight years. These skeletons were selected because they

347 retained the skeletal elements needed to estimate age-at-death. We focused upon maxillary

348 molars because they have thicker enamel (Mahoney, 2013), that (usually) has relatively less

349 gross wear compared to their mandibular isomeres. This was important as dentin microwear

350 was not a focus of the present study. The molars selected were also suitable for cleaning and

351 casting for microwear. Microwear values were subdivided into age groups, which were

352 created from skeletal age-at-death (see below) and the timing of dental eruption (Table 2).

353 Two juvenile skeletons from the priory dated to the earliest Lanfranc period (11th

354 century). The microwear Asfc and epLsar values for these individuals were within the range

355 of microwear values for juveniles from the priory which dated to the 14th-16th centuries.

356 Following this, microwear values were treated as one time period for subsequent analyses.

357 The cemetery burials were not sub-divided by century during excavation.

358
359 **Table 2**
360 Deciduous microwear samples

n	Age in yrs	Tooth type[1]
7	1-2	Udm1
16	2.1-4	Udm1, Udm2
14	4.1-6	Udm1, Udm2
7	6.1-8	Udm1, Udm2

361 [1]Udm1 = maxillary first molar. Udm2 = maxillary second molar
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364   *4.2 Preparation and microwear texture data*

365   All teeth were prepared in the Human Osteology Research Lab, University of Kent, using

366   standard methods (e.g., Mahoney, 2006; Nystrom et al., 2004; Schmidt, 2001). The occlusal

367   surface of each tooth was cleaned using 95% ethanol and cotton wool. Impressions of phase

368   II facets were taken using a rubber-based addition-curing silicone (Colténe-Whaledent

369   Lightbody President Jet®). The first impression was discarded and a second impression was

370   taken and used to create the cast. The dental impression was set into dental putty (Colténe-

371   Whaledent, President Putty®). An epoxy resin and hardner (Buehler EpoxiCure®) was poured

372   into the impression to produce a cast of the occlusal surface.

373   Microwear texture data were produced in the Indiana Prehistory Lab, University of

374   Indianapolis. Resin dental casts were examined using a Sensofar® White Light Confocal

375   Profiler at a magnification of 100x. The microscope collected data from four contiguous

376   areas totalling 276 x 204µm^2. After digitally stitching the original four areas together, the

377   final study area was 242 x181µm^2. Data came from Phase II wear facets (usually facet 9).

378   Data cloud manipulation was undertaken using Sensoscan® software, where the data were

379   levelled and non-microwear entities (primarily any remaining dirt) were removed. Analysis

380   of the data cloud required the use of Sfrax® and Toothfrax®, which are scale-sensitive fractal

381   analysis programs customized for dental microwear texture analysis. Microwear variables

382   Asfc and epLsar were recorded as scale-dependent relative values (Scott et al., 2006).

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384   *4.3. Estimating age-at-death*

385   For the one child aged 1 year, we estimated age-at-death using enamel formation times

386   (Mahoney, 2011). For the rest of the children we used a combination of enamel formation

387   times (Moorrees et al., 1963a,b), timing of dental eruption (Schour and Massler, 1941; Al-

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388 Qahtani et al., 2010), long bone length (Hoppa, 1992; Scheuer et. al., 1980), and fusion of

389 cervical vertebra (Scheuer and Black, 2000).

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391 *4 .4. Statistical analyses*

392 The distribution of each microwear variable for each childhood age group (1-2, 2.1-4, 4.1-6,

393 6.1-8yrs) was checked with a one sample Kolmogorov–Smirnov test and did not differ

394 significantly from a normal curve. However, sample sizes were unequal. Thus, microwear

395 was compared between the four age groups using a non-parametric Kruskal-Wallis test.

396 Multiple post-hoc pair-wise comparisons of the age groups were undertaken using a

397 Tamhane-2 test. Microwear was compared between the two status groups using a Mann

398 Whitney U test.

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427 **5. Results**

428 Microwear descriptive statistics are summarized in Table 3. Figure 2 illustrates microwear

429 texture surfaces. A Kruskal-Wallis test revealed that the complexity of microwear surfaces

430 differed significantly between the four childhood age groups (H=9.037, p=0.029), but

431 anisotropy did not (H=6.572, p=0.087).   Post-hoc tests of pair-wise mean differences using

432 the T2 statistic indicates that children aged 4.1-6 years of age had a significantly lower mean

433 complexity value compared to younger (aged 2.1-4yrs; p=0.017) or older children (6.1-8yrs;

434 p=0.011).   Microwear did not differ significantly between higher and lower status children

435 within the age group 2.1-4yrs, or within the age group 4.1-6 yrs.

436

437 **Table 3**
438 Deciduous microwear mean values

			Asfc		epLsar	
		n	mean	sd	mean	sd
Group	Age					
a	1-2	7	1.81	0.57	0.0039	0.0019
b	2.1-4	16	2.14	0.61	0.0029	0.0016
c	4.1-6	14	1.63	0.43	0.0033	0.0014
d	6.1-8	7	2.25	0.41	0.0019	0.0010
e	1-8	44	1.95	0.57	0.0030	0.0016
Group	Status[1]					
b	lower	12	2.09	0.58	0.0028	0.0017
b	higher	4	2.28	0.80	0.0036	0.0007
c	lower	9	1.74	0.54	0.0030	0.0015
c	higher	5	1.53	0.31	0.0040	0.0007

439 [1]Lower = cemetery; higher = priory.

18

440   **6. Discussion**

441   *6.1. Weaning amongst one to two year olds.*

442   Microwear was present on molars from seven children in this age group (Table 3). The

443   presence of microwear suggests that mixed-feeding, at least, had commenced. On average,

444   their molar surfaces had a low Asfc and higher epLsar value, which is usually associated with

445   the consumption of tougher foods amongst extant primates (section 1.3). Therefore, at first

446   glance, there appears to be discrepancy between the microwear and the type of diet consumed

447   by the youngest children, as textual accounts indicate that a soft and limited range of foods,

448   such as pap or panda (Orme, 2003:71) would have been consumed. However, a high epLsar

449   can also be indicator of jaw movements during chewing (Ungar et al., 2010). On average, the

450   one to year olds had the most anisotropic texture surfaces compared to all other childhood

451   groups. Thus, the orientation of their microwear was the most organized, reflecting the

452   fewest changes in jaw direction during chewing. This makes sense, when viewed alongside

453   the limited range of foods consumed by this age group. The low mean complexity value for

454   the youngest children, relative to the 2.1-4yr olds, more likely represents the consumption of

455   soft foods (Scott et al., 2012). Flour in pap or panda, contaminated during the milling process

456   is one potential source of the abrasive particles that caused microwear for this age group.

457   The youngest infant with microwear was aged 1 year, which implies that mixed-feeding

458   might have commenced slightly earlier for some children in Canterbury, compared to children

459   from the contemporary Fishergate House cemetery in the north of England where breast milk

460   continued to be a significant part of the diet until age 18 months (Burt, 2013, 2015).

461   However, there is no change in microwear throughout the course of the year, which might

462   have indicated a transition from mixed-feeding to fully weaned. Instead, a child aged 1.25

463   years had a similar complexity value compared to another aged 1.75 years (Asfc= 1.71 and

464   1.69 respectively). This may simply reflect a gradual change in feeding practices that is not

465   detectable from microwear.   Alternatively, breast-feeding might have been completely

466   removed from the infant diet at or around the start of the second year after birth. If this was

467   the case for the Canterbury children then their weaning age would lie within the lower end of

468   the age-range recommended for weaning in texts from the period (Fildes, 1995: 115).   It

469   would also lie within the lowermost end of the weaning age-range indicated by isotopic

470   studies at contemporary Wharram Percy in the north of England, where breast-feeding ceased

471   between one to two years of age (Mays et al., 2002).

472

473   6.2. Variation in diet with age

474   Dental microwear texture analysis results suggest that the physical properties of diet for

475   children in medieval Canterbury varied from one age group to the next.

476

477   *6.2.1. Two to four years of age.*

478   Children aged two to four display an increased mean complexity of enamel surfaces

479   combined with a lower mean anisotropy, relative to one to two year olds.   When this

480   combination of microwear features are compared with the base-line texture surfaces from

481   extant primates (section 1.3), it implies that the Canterbury children in this age group

482   consumed a range of foods that included relatively harder and more abrasive items. These

483   texture surfaces might be expected, as their diet was probably no longer focused upon just soft

484   infant foods like pap and panda. A more varied diet is also suggested by the lowered mean

485   anisotropy value, indicating that jaw movements were more disorganized during chewing.

486   Increased bite force relative to the infants (Kamegai et al., 2005) might be a factor here as

487   well, driving hard particles deeper into the enamel surface leading to a higher complexity

488   value.

489

490

6.2.2. Four to six years of age.

There was a significant change in the physical properties of diet amongst children in this age group. The four to six year olds had significantly less texture complexity than either younger (2.1-4yrs) or older (6.1-8yrs) children. The lowered complexity was matched by a higher mean anisotropy value, which approached significance when compared to the less anisotropic enamel from the 6.1-8 year olds. This combination of microwear features, lower Asfc and higher epLsar (section 1.3), implies that the diet of children in medieval Canterbury had altered, and now included tougher foods.

A change in diet between age four to six could relate in part to a period in which childhood routines started to change (Bailey et al., 2008; Hanawalt, 1977: 64). Greater mobility allowed children to accompany adults outside of their home and into the work place, paradoxically leading to more time spent in adult company (Flemming, 2001; Hanawalt 1977, 1988:158). More time in adult company may have given more access to adult dietary staples, such as a meat or vegetable pottage (e.g., Brears, 2008). A greater component of meat in the diet of the Canterbury children might explain the change in microwear (e.g., El-Zaatari, 2010), especially if this was a permanent supplement to early childhood foods.

Support for the idea that children in this age group accessed 'tougher' adult dietary staples, rather than returning to a soft diet similar to the infants, is provided by examining their bite force potential. Children in this age group would have exerted significantly more force during chewing compared to the one to two year olds (Kamegai et al., 2005). If the change in the microwear pattern of the four to six year olds occurred because they re-accessed a soft infant diet, whilst for example caring for a younger sibling (Hanawalt, 1988: 157), then you would expect the enamel of the older children to have a higher complexity value, as abrasive particles from the shared foods would have been driven deeper into their enamel. This idea is not supported by the mean microwear texture values, which show that the older

516 children had a lower, not a higher mean Asfc value, relative to the infants. Neither does

517 'teething' nor a 'sick-bed' diet seem likely causal agents. All deciduous teeth would have

518 erupted by around the age of 2.5 years, so pacifiers would not have contributed to the

519 microwear of this age group, or to the preceding age group. A sick-bed diet would not

520 necessarily contribute to the microwear of only this age group.

521

522 *6.2.3. Six to eight years of age.*

523 Children in this age group had the roughest texture surfaces with many pits and scratches

524 of different sizes overlying each other. The scratches were the least orientated compared to

525 all other childhood age groups, leading to the lowest epLsar value. The reduced range of

526 complexity and anisotropy values for this group indicates that fewer children deviated away

527 from the rough and disorganized wear features. If the tougher diet of the preceding age

528 group marks the introduction of 'adult foods', then the increase in food hardness in the eldest

529 children might indicate the addition of hard 'adult' foods. This idea is supported by

530 historical textual accounts. From around the age of seven onwards children were treated

531 increasingly like young adults and were given independent tasks outside of their home

532 (Hanawalt, 1977, 1988: 158; Fleming, 2001: 64), including apprenticeships or employment as

533 household servants (Bailey et al., 2008; Dunlop, 1912). It might be expected therefore, that

534 this change in a child's social network would provide reduced opportunity for a distinct

535 childhood diet as they entered a new environment.

536

537 *6.3. Childhood status and diet*

538 Mean complexity and anisotropy values for children aged two to four years, or four to six

539 years of age, did not vary consistently with status (Table 3). This finding lends support to the

22

540   idea that the relationship between status and food consumption for medieval children might

541   be more complex compared to adults (Burt, 2013, 2015; Dawson and Robson Brown, 2013).

542

543   **7. Conclusion**

544   This study conducted the first 3D intra-specific dental microwear texture analysis of

545   childhood diet. We searched for evidence of dietary weaning, evaluated variation in the

546   physical properties of diet against age, and compared higher with lower status children.

547   Results indicate that mixed-feeding in Canterbury could commence by the end of a child's

548   first year. After weaning, and until the age of eight, there was no simple trajectory in the

549   physical properties of the foods that were consumed in the weeks before death. Diet

550   contained abrasives for all age groups. Texture surfaces indicated that, on average, the four to

551   six year olds consumed a diet that included tough foods whilst the eldest children consumed

552   the hardest diet. We related these changes in microwear texture surfaces to medieval textual

553   records that refer to lifestyle developments for these age groups. Our study also lends support

554   to the idea that the relationship between socio-economic status and diet for children in

555   medieval England might not be as clear as it is for adults. We conclude that deciduous dental

556   microwear texture analyses hold great potential for revealing very subtle changes to childhood

557   diet in the past.

558

563

564

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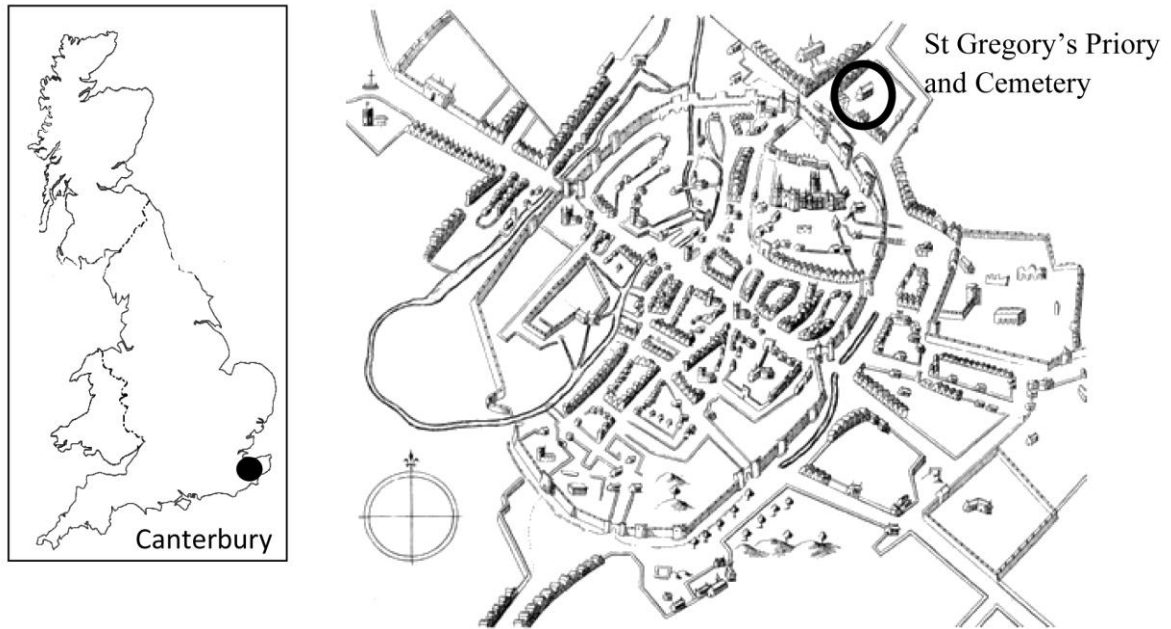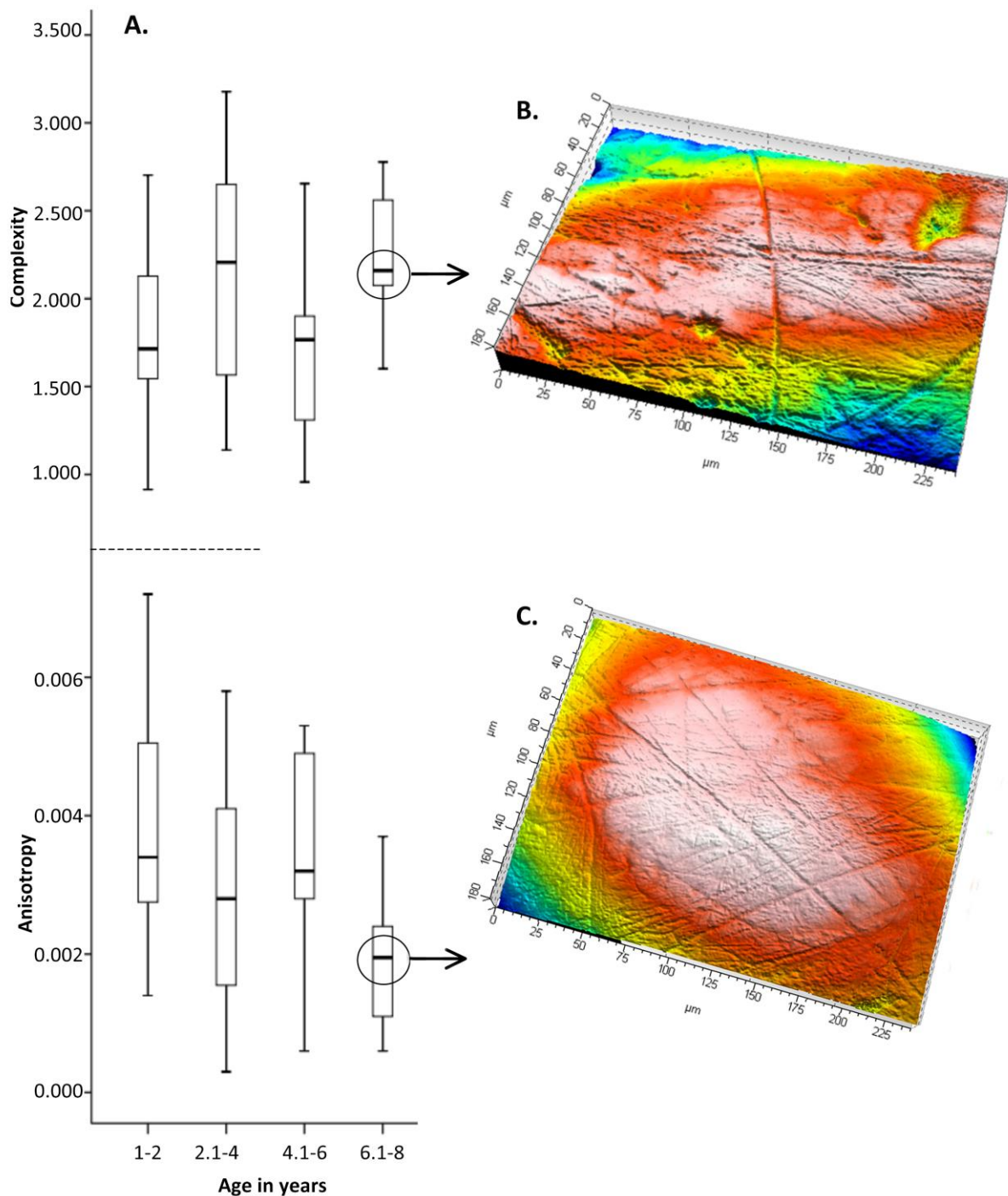
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786 **Fig.1.** Map of United Kingdom showing Medieval Canterbury in AD1703 (after Somner,
787 AD1703). Dental samples were from juvenile skeletons recovered during excavation of St
788 Gregory's priory and cemetery. See Section 3.1.
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Fig.2. Bivariate box plot (**A**) subdividing each age group in Table 3 into quartiles, with dental microwear texture images showing 3D representations of molar enamel surfaces from two children in the cemetery. Each image represents a field of view measuring 242 x 181μm^2. Changes in colour indicate changes in depth. (**B**) When many pits and scratches are present together, or overlying each other, they produce a 'rougher' surface and a higher complexity value. The more complex surface of the 6.1-8 year olds, combined with a relatively low anisotropy value (**C**), implies that they had a harder diet compared to the 4.1-6 year olds. Their anisotropy value is low because scratches (lower right to upper left corner; lower surface to upper right corner) are not orientated in the same direction.

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