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1 Hominin diversity in East Asia during the Middle Pleistocene: A premolar endostructural perspective

2

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16 **Abstract**

17 Following the recent studies of East Asian mid-Middle to early Late Pleistocene
18 hominin material, a large spectrum of morphological diversity has been recognized and
19 the coexistence of archaic (*Homo erectus*-like) and derived ('modern-like') dental
20 morphological patterns has been highlighted. In fact, for most of these Chinese fossils,
21 generally categorized as 'archaic *Homo sapiens*' or 'post-*H. erectus Homo*', the

22 taxonomic attribution is a matter of contention. With the help of μ CT techniques and a
23 deformation-based 3D geometric morphometric (GM) approach, we focused on the
24 morphological variation in the enamel-dentine junction (EDJ) of 18 upper and lower
25 premolars from Chinese Middle Pleistocene hominins. We then compared our results
26 with a number of fossil and modern human groups, including Early Pleistocene *H.*
27 *erectus* from Sangiran; late Early Pleistocene hominins from Tighenif, Algeria; classic
28 Neanderthals; and modern humans. Our results highlight an evolutionary/chronological
29 trend of crown base reduction, elevation of EDJ topography, and EDJ surface
30 simplification in the hominin groups studied here. Moreover, this study brings insights
31 to the taxonomy/phylogeny of six late Middle Pleistocene specimens whose
32 evolutionary placement has been debated for decades. Among these specimens,
33 Changyang premolars show features that can be aligned with the Asian *H. erectus*
34 hypodigm, while Panxian Dadong and Tongzi premolars are more similar to Late
35 Pleistocene *Homo*. Compared with early to mid-Middle Pleistocene hominins in East
36 Asia, late Middle Pleistocene hominins evince an enlarged morphological variation. A
37 persistence of archaic morphotypes and possible admixture among populations during
38 the late Middle Pleistocene are discussed.

39

40 **1. Introduction**

41 Dental evidence suggests that Eurasian Early and Middle Pleistocene hominins,
42 including those from Central Asia (Martín-Torres et al., 2008), continental East Asia

43 (Bailey and Liu, 2010; Liu et al., 2013, 2017; Xing et al., 2014, 2016, 2018; Zanolli et
44 al., 2018) and insular Southeast Asia, had a relatively independent evolutionary course
45 compared with African hominins (Martín-Torres et al., 2007; Bermúdez de Castro
46 and Martín-Torres, 2013; Kaifu, 2017). From the early to mid-Middle Pleistocene,
47 hominin remains found in the Asian continent are mostly assigned to *Homo erectus*
48 (Kaifu et al., 2005; Martín-Torres et al., 2008; Zanolli, 2013; Xing et al., 2014, 2016).
49 However, the high-degree of morphological variation of the Asian dental remains
50 (Zanolli et al., 2012, 2018a; Liu et al., 2013; Xing et al., 2018, 2019) suggests the
51 (co)existence of derived (modern *H. sapiens*-like) and archaic morphotypes in the
52 Middle Pleistocene. This complex scenario gives rise to a number of questions
53 regarding the routes of dispersal, possible interactions and gene flow between lineages
54 in the mid-Middle to early Late Pleistocene, before the attested presence of
55 anatomically modern humans (Liu et al., 2015).

56 In the late Pleistocene Chinese hominin fossil record, the taxonomic status and
57 phylogenetic relationships with earlier, contemporaneous and later human lineages
58 remains unclear. Part of this is probably due to the limited sample size and the
59 heterogeneity of expression of archaic and derived traits in the mid- to late Middle
60 Pleistocene ‘non-*H. erectus*’ human record. For instance, the late Middle Pleistocene
61 dental remains from Panxian Dadong, even if limited to four isolated teeth, retain some
62 archaic traits in the anterior dentition, including a weakly expressed finger-like
63 tuberculum dentale on the upper central incisor and robust incisor and canine crowns,

64 in association with derived features in most teeth (symmetrical canine crown without
65 cingulum, modern-like premolar crown morphology; Liu et al., 2013). Similarly, the
66 late Middle Pleistocene teeth from Tongzi, even if penecontemporaneous with late
67 representatives of *H. erectus*, differ from the typical condition seen in the latter group
68 and show a series of derived traits that are more commonly seen in Late Pleistocene
69 *Homo*, including: the absence of tuberculum dentale on the upper incisor, simplified
70 and symmetrical premolar crowns without grooves and ridges on the buccal aspect, and
71 mesiodistally compressed upper molars (Wu, 1984; Xing et al., 2019). Conversely,
72 dental remains from other late Middle to early Late Pleistocene populations such as
73 Chaoxian, Changyang and Xujiayao express a degree of archaic, *H. erectus*-like
74 features—see external crown morphology in Xing et al. (2015, 2016) and Bailey and
75 Liu (2010), and root canal configuration in Pan et al. (2019). Taphonomic factors and
76 occlusal wear have also erased parts of the external tooth morphology, thus adding to
77 the confusion concerning the evolutionary interpretations of these specimens (Liu et al.,
78 2013; Xing et al., 2015, 2019; Pan and Zanolli, 2019). However, even if the external
79 morphology is altered, diagnostic taxonomic and phylogenetic information may still be
80 preserved in the internal structure of teeth, and their internal signature can still be
81 extracted using the methods developed in virtual paleoanthropology (Skinner et al.,
82 2008b; Xing et al., 2014, 2016, 2018; Weber, 2015; Zanolli et al., 2018; Pan and Zanolli,
83 2019).

84 We used X-ray μ CT scanning and 3D image processing techniques to investigate

85 the inner structure of six late Middle Pleistocene premolar specimens from the sites of
86 Changyang (PA76, PA81), Tongzi (PA873), Panxian Dadong (PA 1577 and PA 1578)
87 and Chaoxian (Chaoxian), whose taxonomic attribution is controversial. In order to
88 characterize these specimens, we focus here on the enamel-dentine junction (EDJ)
89 morphology. This interface results from the membrana praeformativa that configures
90 the outer enamel surface (OES) during tooth growth (Corruccini, 1987). In mature teeth,
91 it preserves diagnostic morphological information, even when the occlusal enamel is
92 worn. It is thus recognized as a reliable taxonomic proxy to distinguish between
93 hominid taxa (even at the subspecies level) and can also bring hominid phylogenetic
94 insights (Weber, 2001; Skinner, 2008; Skinner et al., 2008a; Braga et al., 2010;
95 Macchiarelli et al., 2013; Pan et al., 2016; Zanolli et al., 2019).

96 Comparing with a number of fossil and modern human specimens/samples,
97 including Chinese early to mid-Middle Pleistocene *H. erectus* from the sites of
98 Zhoukoudian, Hexian, Xichuan and Yiyuan, the aims of this study are: (1) to examine
99 the ability of premolar EDJ morphological information to discriminate among a
100 selection of fossil and modern human premolar samples; (2) to document the
101 morphological variability of mid- to late Middle Pleistocene human premolars in East
102 Asia; and (3) to re-evaluate the taxonomic affinities of six late Middle Pleistocene
103 specimens.

104

105 **2. Materials and methods**

106 2.1. Study sample

107 The Chinese Middle Pleistocene hominin sample consists of two groups; a map of
108 their location is shown in Supplementary Online Material (SOM) Figure S1. The first
109 group includes early to mid-Middle Pleistocene *H. erectus* (HEC, $n = 12$) from the sites
110 of Zhoukoudian, Hexian, Xichuan and Yiyuan, with a chronological range from 800 to
111 282 ka (Table 1). Note that the specimens from Xichuan County, Hubei Province lack
112 accurate stratigraphic context, but their morphological signature a priori places them
113 close to Zhoukoudian *H. erectus* (Wu and Wu, 1982; Wu and Poirier, 1995). The
114 allocation of Xichuan hominins to East Asian *H. erectus* is further supported by a recent
115 comparative study (Xing et al., 2018) on the dental inner structure of Chinese Middle
116 Pleistocene *H. erectus*. The second group is represented by six premolars from three
117 mid- to late Middle Pleistocene sites (Changyang, Tongzi, Panxian Dadong and
118 Chaoxian). These specimens do not have a clear taxonomic attribution, as in previous
119 studies they were classified as archaic or premodern *H. sapiens*, or were categorized as
120 non-*H. erectus* *Homo* (Xing et al., 2019) (and are thus regarded here a priori as *Homo*
121 sp. from China, HSPC). We compared the Chinese specimens with 56 fossil and extant
122 human specimens (Table 1), including Javanese Early Pleistocene *H. erectus* (HEJ)
123 specimens from Sangiran (Grine, 1994; Kaifu et al., 2005); North African late Early
124 Pleistocene hominins (HNA) from Tighenif (Zanolli and Mazurier, 2013); Neanderthals
125 (NEA) from Krapina and La Chaise (Macchiarelli et al., 2006; NESPOS database,
126 2020), and modern *H. sapiens* (MHS) from Africa and Eurasia (Pan et al., 2017).

127

128 *2.2 Methods*

129 Tooth wear stages were scored according to the standard proposed by Smith (1984).
130 For the Neanderthal and modern *H. sapiens* specimens, we selected only premolars
131 without dentine exposure on the occlusal surface. However, for the Chinese Middle
132 Pleistocene specimens, because of the limited available sample, we included all
133 specimens with wear degree less than stage 3 (“full cusp removal and/or moderate
134 dentine patches”; Smith, 1984:45).

135 Information on the crown outer and inner morphology—non-metric features, 2D
136 geometric morphometrics (GM) on the OES—has been reported for most of the HEC
137 and HSPC specimens in previous studies (Black et al., 1933; Chia, 1957; Wu and Wu,
138 1982; Chen et al., 1987; Bailey and Liu, 2010; Xing, 2012; Liu et al., 2013; Xing et al.,
139 2014, 2016, 2018, 2019; Liu et al., 2017; Zanolli et al., 2018a). The dental remains
140 from Xichuan (PA524, PA525, PA526, PA527, PA528) and Changyang (PA76, PA81)
141 are reported and their internal structure (as well as that of the Chaoxian specimen)
142 analyzed here for the first time. The terms employed for the morphological descriptions
143 are from Weidenreich (1937), Turner et al. (1991) and Scott and Turner (1997).

144 Microcomputed tomography and processing of the 3D data All Chinese fossil
145 specimens (except for two Zhoukoudian *H. erectus* specimens housed at Uppsala
146 University) were scanned using a 225 kV micro-XCT scanner at the Institute of
147 Vertebrate Paleontology and Paleoanthropology, China according to the following

148 parameters: 120–140 kV voltage, 100–120 mA current, angular step of 0.5° over a scan
149 angle of 360° . The final volumes were reconstructed with an isotropic voxel size
150 ranging from 40 to 70 μm . The fossil premolars PMU M3887 and M3549, housed at
151 Uppsala University, were scanned at the Multidisciplinary Laboratory of the The Abdus
152 Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy (Zanolli et al.,
153 2018a).

154 Image stacks were imported into Avizo 9.0 (FEI Visualization Sciences Group),
155 and the images were segmented using semiautomatic procedures and an adaptation of
156 the half-maximum height method (Fajardo et al., 2002; Coleman and Colbert, 2007);
157 the EDJ surfaces were generated using the ‘unconstrained smoothing’ option. For 11
158 out of 18 Chinese human fossil specimens (marked in Table 1), some cusp tips were
159 worn, so we manually reconstructed the dentine horn tips based on the curvature and
160 orientation of the EDJ at each side of the dentine horns (Smith et al., 2012; Zanolli et
161 al., 2018b). Our reconstructions are depicted in SOM Figure S2.

162 Geometric morphometric analysis We used a recently developed diffeomorphic surface
163 matching (DSM) method to compare the EDJ shapes among hominin groups. This
164 landmark-free, mesh-based approach relies on the construction of average surface
165 models, and the difference between surfaces is interpreted as the amount of deformation
166 needed to align them by using diffeomorphic shape matching (Glaunes and Joshi, 2006;
167 Durrleman et al., 2014). Then deformations between surfaces are mathematically
168 modeled as smooth and invertible functions (i.e., diffeomorphisms; Glaunes and Joshi,

169 2006; Durrleman et al., 2014). From a set of surfaces, an atlas of surfaces is created.
170 The method estimates an average object configuration or mean shape from a collection
171 of object sets, here the EDJ surfaces, and computes the deformations from the mean
172 shape to each specimen. In addition, a set of initial control points located near its most
173 variable parts, and a set of momenta parameterizing the deformations of the mean shape
174 to each individual are estimated (Durrleman et al., 2012a, b; Beaudet et al., 2016a).
175 This method has been successfully employed in a number of
176 paleontological/paleoanthropological investigations (Beaudet et al., 2016b, 2018;
177 Zanolli et al., 2018; Braga et al., 2019; Pan et al., 2019; Urciuoli et al., 2020). A recent
178 study comparing the discriminative power of 3D landmark-based GM and DSM
179 demonstrated that DSM has the potential to better capture the geometric details that
180 describe tooth shape (Braga et al., 2019).

181 To perform this analysis, as a previous step, at each dental position the EDJ
182 surfaces were manually oriented, then superimposed using the rigid and uniform scale
183 option of the 'align surface' module in Avizo 9.0 (Visualization Sciences Group Inc.).
184 This was done by minimizing the root mean square distance between the points of each
185 specimen to corresponding points on the reference surface using an iterative closest
186 point algorithm.

187 We used the Deformetrica software (<https://www.deformetrica.org>; Durrleman et
188 al., 2014) to generate a global mean shape (GMS) with a set of diffeomorphisms from
189 the GMS to each individual and the output (control points and deformation momenta)

190 used to perform the statistical analyses to explore the EDJ shape variation. An example
191 of the original EDJ surface, the simplified EDJ surface imported in Deformetrica v. 4.3
192 and the output virtual models generated by DSM process is shown in SOM Figure S3
193 (see also SOM Fig. S4 for the output surfaces of all the Chinese fossil specimens after
194 deformations). Using the packages ade4 1.7-13 (Dray and Dufour, 2007) and Morpho
195 v. 2.6 (Schlager et al., 2018) for R v. 3.5.1 (R Development Core Team, 2012), we
196 checked the shape variation of the fossil and recent human groups in a principal
197 component analysis (PCA). Even if the first two components of the PCA account for
198 approximately 40 to 65% of the total variance in these analyses, there is still some
199 information in the following components. However, visualizing and interpreting a
200 complex space in multiple dimensions is difficult. We computed between-group
201 principal component analyses (bgPCA) to evaluate the degree of shape variation
202 between hominin groups. We used both PCA and bgPCA as the former is mostly a
203 means to explore the morphospace, with the variance spread over multiple axes,
204 whereas bgPCA, through projection of the data onto the principal components of the
205 group averages, represents a viable alternative to discriminant analyses (Mitteroecker
206 and Bookstein, 2011). Nonetheless, when sample size is small and groups are few, the
207 results of bgPCA must be interpreted with care and a number of tests are needed to
208 confirm that group separation is not spurious (Bookstein, 2019; Cardini et al., 2019).
209 As a result, we checked and confirmed that group separation preexisted in the PCA and
210 bgPCA was used to assess group affinity of target specimens. Following the

211 recommendations of Cardini and Polly (2020), we also computed the cross-validated
212 bgPCA (CV-bgPCA) to confirm that the group distribution is not spurious. The six
213 Chinese late Middle Pleistocene *Homo* sp. specimens were then projected a posteriori
214 in the bgPCA plot to assess their morphological affinities.

215 The residual of allometric signals were tested using the coefficient of determination
216 (R^2) of a multiple regression (Bookstein, 1991) in which the explicative variable is the
217 EDJ area as proxy for size and the dependent variables are the (bg)PC scores.

218

219 **3. Results**

220 *3.1. Description of enamel-dentine junction morphologies*

221 Here we describe the morphological features on the EDJ of previously unreported
222 material from Xichuan, Changyang and Chaoxian and compared it with a number of
223 Pleistocene and Holocene hominin specimens (see Figs. 1A–V and 2A–S for EDJ
224 surfaces in occlusal view). The Chinese fossil specimens are ordered and described
225 below with regard to dental position.

226 Left maxillary third premolar (P³, PA524, Xichuan) See Figure 1B. Viewed from the
227 occlusal surface, the crown contour is oval and slightly asymmetrical, the width of the
228 buccal aspect is slightly larger than the lingual aspect, the transverse crest is pronounced
229 and connects the buccal and lingual cusps, forming a small and deep anterior fovea and
230 a larger posterior fovea, and a small tubercle is visible at the mesial aspect of the buccal

231 cusp base. Along the marginal ridge, no accessory ridge is identified.

232 Left maxillary third premolar (P³, PA76, Changyang) See Figure 1D. The occlusal
233 outline of the marginal ridges is elliptical and slightly asymmetrical, two faint accessory
234 ridges (one of which is bifurcated at the end) can be seen at the base of the buccal cusp
235 but interrupted in the middle of the small occlusal basin, and no continuous transverse
236 crest is formed. One mesial accessory ridge is identified. Two weakly developed
237 tubercles are visible at the base of the lingual cusp.

238 Right maxillary fourth premolar (P⁴, Chaoxian) See Figure 1O. This P⁴ is attached to a
239 maxilla, whose right P³-M¹ and left P⁴-M² are preserved (Bailey and Liu, 2010). The
240 occlusal basin of this P⁴ is relatively small compared with the crown base, similar to
241 the condition in *H. erectus* (Fig. 1M, N, P, Q). The crown contour is ovorectangular.
242 The transverse crest is not well expressed and is interrupted by the occlusal basin. In
243 all, compared with the highly crenulated EDJ surface that is expressed at East Asian *H.*
244 *erectus* (e.g., Xing et al., 2016, 2018; this study), the EDJ of Chaoxian P⁴ is more similar
245 to the less complex morphology of Indonesian *H. erectus* from Sangiran. Weakly-
246 expressed accessory tubercles are found at the mesial and distal part of the occlusal
247 basin.

248 Left mandibular third premolar (P₃, PA526, Xichuan) See Figure 2C. The crown outline
249 of PA526 is asymmetrical and mesiodistally elongated in occlusal view. The transverse
250 crest is well developed and continuous. The mesial fovea is slightly smaller than the
251 distal one, as the latter is born by a wide talonid. An accessory ridge can be found at

252 the mesial aspect of the lingual cusp, but it does not reach the mesial marginal ridge. At
253 the buccal surface, the mesial vertical groove is better developed than the distal one.

254 Right mandibular third premolar (P₃, PA527, Xichuan) See Figure 2D. The morphology
255 of PA527 is very similar to that of PA526; however, instead of an accessory ridge, a
256 fainted wrinkle is present at the mesial side of the lingual cusp. Like PA526, the mesial
257 vertical groove at the buccal surface is better expressed than the distal one.

258 Right mandibular fourth premolar (P₄, PA525, Xichuan) See Figure 2L. The outline of
259 the marginal ridge is ovorectangular with a protruding mesiobuccal angle. The
260 transverse crest is moderately expressed and interrupted. At the occlusal basin, two
261 small, weakly expressed wrinkles are presented at the mesial marginal ridge and the
262 distal side of the lingual cusp. Moreover, a weakly expressed accessory cusp is seen at
263 the distal side of the buccal cusp. On the buccal surface, two vertical grooves are clearly
264 detected.

265 Left mandibular fourth premolar (P₄, PA528, Xichuan) See Fig. 2M. The morphology
266 of PA528 is slightly different from that of PA525, but resembles that of the *H. erectus*
267 specimen M3887 from Zhoukoudian. The occlusal outline of its marginal ridge is also
268 ovorectangular. The transverse crest is well developed and uninterrupted, and the
269 mesial fovea is clearly smaller than the distal fovea. Several accessory cusps can be
270 seen at the distal marginal ridge, and a moderately expressed accessory crest is present
271 at the distal side of the lingual cusp. A moderately expressed wrinkle is visible at the
272 mesial marginal ridge. On the buccal surface, two vertical grooves are well expressed.

273 Left mandibular fourth premolar (P₄, PA81, Changyang) See Figure 2N. The crown
274 contour is ovorectangular, the distal part of the crown being wider than the mesial
275 one. The transverse crest is interrupted by a deep groove and is weakly developed.
276 Mesial and distal accessory ridges for the lingual cusp can be identified, three
277 accessory cusps are seen at the distal part of the fovea posterior, and an accessory
278 ridge is present distally to the buccal cusp and deflects at the center of the occlusal
279 basin. On the buccal surface, the distal vertical groove is more pronounced than the
280 mesial one.

281 The East Asian mid-Middle Pleistocene *H. erectus* (PA67, 68, 110, 524, 525, 526,
282 527, 528, 832, M3887 and Shy071) consistently show a complex morphology, with
283 vertical ridges and crests on the buccal aspect of the EDJ, together with a wrinkled
284 occlusal basin and accessory cusps and crests. In the latter half of the Middle
285 Pleistocene, more variation is observed.

286 For the upper premolars, the P³ PA76 (Fig. 1D) from Changyang retains archaic
287 traits, as it exhibits multiple accessory crests running in the occlusal basin. In
288 comparison with PA76, the P³ PA873 from Tongzi (Fig. 1E) displays a simple
289 morphology, with a proportionally larger and smoother occlusal basin and three faint
290 occlusal crests running on the internal aspect of the paracone. The mesial and distal
291 marginal ridges of PA873 are more protruding, with numerous small cuspule-like
292 features. A similarly simplified and enlarged occlusal basin than in PA873 is also shown
293 in the P³ PA1577 (Fig. 1F) from Panxian Dadong. The P⁴ from Chaoxian (Fig. 1O) has

294 a smaller occlusal basin compared with the crown base, similar to East Asian *H. erectus*
295 from Zhoukoudian (PA68, Fig. 1M; Shy071, Fig. 1N). However, unlike the ‘dendrite-
296 like’ EDJ that is shown in *H. erectus*, the occlusal surface relief of Chaoxian is less
297 complex (but is not comparable to PA873 and 1577, which are more simple and smooth)
298 with a weakly-expressed, interrupted transverse crest.

299 As for the lower premolars, a previous study on the crown morphology (Liu et al.,
300 2013) showed that the P₃ PA1578 (Fig. 2E) from Panxian Dadong exhibits weakly
301 expressed archaic traits and a derived general configuration with respect to the
302 condition in *H. erectus*. The EDJ outline is more symmetrical in PA1578 than in Early
303 to mid-Middle Pleistocene specimens from Africa and Asia (including the North
304 African specimen Tighenif 2, Indonesian and Chinese *H. erectus*), but is more
305 asymmetrical than in recent modern humans. Previous analyses of crown geometric
306 morphometrics place the Panxian Dadong premolars close to modern humans (Liu et
307 al., 2013). Studies of the root structure show that, compared with modern humans, PA
308 1578 has a robust morphology, although it is more gracile than the root complex usually
309 found in *H. erectus* (Pan et al., 2019; Pan and Zanolli, 2019). On the other hand, the P₄
310 PA81 (Fig. 2N) from Changyang exhibits a wrinkled occlusal basin, with vertical ridges
311 expressed on the buccal aspect of the EDJ (similar to *H. erectus*; Fig. 2K–M). The
312 talonid of PA81 is mesiodistally elongated with a minute hypoconid dentine horn (Fig.
313 2N). In sum, from the six premolar specimens dated to late Middle Pleistocene, despite
314 a small sample size, greater morphological variability (i.e., primitive, *H. erectus* like

315 and derived, modern-human like) is observed compared with East Asian *H. erectus*.

316

317 3.2. Geometric morphometric analyses

318 The results of GM analyses using DSM are shown in Figures 3–4 (see also SOM
319 Fig. S4, which illustrates the output surfaces after DSM analyses). Taking into account
320 that some authors have issued cautions about the interpretation of bgPCA results
321 (Bookstein, 2019; Cardini et al., 2019), we present in Figures 3 and 4 the results from
322 both PCA and bgPCA. Results of CV-bgPCA are illustrated in the SOM Figure S5,
323 showing that the groups are separated in a similar way than in the bgPCA (even if
324 inversion of the distribution of points between the negative and positive space along
325 the axes may occur) and that group separation is not spurious. A mild allometric signal
326 is observed along some of the (bg)PCs (SOM Table S1). While size-related component
327 is present, the variation observed in the PCA and bgPCA thus mostly represents shape
328 differences.

329 PCA and bgPCA yielded consistent results with *H. erectus*, Neanderthals and
330 modern humans roughly distributed in a similar way along the first two axes, even if as
331 expected the bgPCA better separates them (Figs. 3 and 4). In any case, even if slightly
332 more overlapping, the groups identified when observing the morphospace obtained
333 with bgPCA are already present in the PCA. The extreme shape changes along each
334 (bg)PC are shown at the extremities of each axis. Even if comparative late Early to mid-
335 Middle Pleistocene, Late Pleistocene and Holocene *Homo* groups are closer in the PCA

336 of P⁴ (Fig. 3C), *H. erectus* (including the North African specimen Tighenif 2,
337 Indonesian and Chinese *H. erectus*) is discriminated from later groups along (bg)PC1
338 (Figs. 3 and 4). (bg)PC1 reflects a chronoevolutionary trend, with lower EDJ in *H.*
339 *erectus* than in the two other groups, as shown by the extreme shapes at the end of the
340 axes (Figs 3 and 4; see also Figs. 1 and 2). For P³ and P⁴, *H. erectus* shows a narrower
341 occlusal basin (buccolingually compressed and small with respect to the crown base)
342 and more internally-positioned dentine horns than in Neanderthals and modern humans
343 (Fig. 3 A–D). As seen in the bgPCA, Neanderthal upper premolars differs from those
344 of modern humans by their mesiodistally wider EDJ and deeper occlusal basin (Fig. 3B,
345 D). For the P₃ EDJ, as seen along (bg)PC1, *H. erectus* exhibits a proportionally more
346 expanded talonid (resulting in a protruding distolingual angle of the crown) than in
347 Neanderthals and modern humans that show more equally developed mesial and distal
348 foveae. Along bgPC2, Neanderthal P₃ are separated from those of modern humans due
349 to their smaller occlusal basin (Fig. 4A-B). PC1 and bgPC1 of the P₄ EDJ analyses
350 show that *H. erectus* has low lateral aspects and short dentine horns, with a more
351 buccolingually compressed occlusal basin (and more internally-set metaconid) than in
352 Neanderthals and modern humans (Fig. 4 C, D). bgPC2 discriminates Neanderthals
353 from modern humans, the latter having a lingually-positioned metaconid and
354 buccolingually expanded occlusal basin and more equally developed mesial and distal
355 foveae than in the former (Fig. D). In this context, the Changyang specimens (PA76 P³
356 and PA81 P₄) and the P⁴ from Chaoxian unambiguously fall close to the late Early

357 Pleistocene to mid-Middle Pleistocene human groups, showing low EDJ, large crown
358 base and complex surface relief with relatively small occlusal basin—as supported by
359 previous observations on the EDJ surfaces (Figs. 1D, O and 2N). Conversely, the P³
360 PA873 from Tongzi, P³ PA1577 and P₃ PA1578 from Panxian Dadong are placed within
361 or very close to the variability of Neanderthals and modern humans (Figs. 3A, B and
362 4A, B).

363 Results of the cross-validation tests performed on the bgPC scores shows that
364 predictive accuracy is robust (Table 2). Correct classification of 88–100% is obtained
365 in most analyses, except for the P⁴ analysis, which exhibits slightly more confusion for
366 Neanderthals and modern humans (80% of correct classification; but *H. erectus* teeth
367 show 100% discrimination). The P³ PA76, the P⁴ Chaoxian and the P₄ PA81 are
368 classified as *H. erectus*. The P³ PA873 and the P₃ PA1578 are both classified nearly
369 equally as belonging to either modern humans or Neanderthals, while the P³ PA1577 is
370 classified as a Neanderthal.

371

372 **4. Discussion**

373 Increasing evidence from the morphological study of fossil hominins from China
374 suggests remarkable morphological variability toward the end of the Middle
375 Pleistocene (Bailey and Liu, 2010; Liu et al., 2013, 2017; Xing et al., 2014; Chang et
376 al., 2015; Martín-Torres et al., 2018). Similarly, recent advances in the fields of
377 paleoproteomics and paleogenetics confirm the diversity of hominin groups that

378 coexisted in this chronogeographic interval, including a sister group of Neanderthals:
379 the Denisovans (Chen et al., 2019). However, taxonomic attributions of late Middle to
380 early Late Pleistocene specimens and their interpretation in an evolutionary perspective
381 remain unclear (Bae, 2010; Liu et al., 2013; Kaifu, 2017). For the first time, through a
382 novel geometric morphometric approach we analyzed the EDJ shape of a sample of
383 hominin premolars from China spanning the Middle Pleistocene and compared this
384 sample with other fossil and recent human groups.

385 At a large scale, our study reported at least two morphotypes in EDJ shape
386 expressed in this time period: one displaying a *H. erectus*-like condition and the other
387 showing a morphology that is closer to Late Pleistocene humans, sharing traits with
388 both Neanderthals and modern humans. Irrespective of the taxon, in this timeframe, we
389 also document a general trend towards a reduction of the crown base in relation to the
390 occlusal basin, narrowing of the lingual aspect, and increasing of EDJ relief.

391 From the late Early to mid-Middle Pleistocene, we found a proportionally
392 broadened crown base associated with a smaller occlusal basin and low EDJ relief in
393 hominin premolars from Indonesia (Sangiran), Algeria (Tighenif) and China
394 (Zhoukoudian, Hexian, Xichuan and Yiyuan). This is also compatible with previous
395 studies suggesting a possible retention of Early Pleistocene hominin features (as seen
396 in Sangiran 4 for example) in Chinese Middle Pleistocene *H. erectus* (Xing et al., 2014,
397 2016; Liu et al., 2017; Zanolli et al., 2018). Thus, until the mid-Middle Pleistocene,
398 only one human group, likely related to *H. erectus* can be identified in China from the

399 available evidence. Toward the late Middle Pleistocene, the Chinese fossils express at
400 least two morphotypes. The first one is characterized by large crown base, centrally-
401 positioned dentine horn tips and low EDJ topography, together with a set of crown-
402 complexifying non-metric traits as seen in the specimens from Changyang (PA76 and
403 81) and Chaoxian. It is noteworthy that the Chaoxian P⁴ expresses *H. erectus*-like
404 features at the EDJ level that are in agreement with previous observations made on the
405 outer crown morphology (Bailey and Liu, 2010). In light of these results, together with
406 the similarities in EDJ shape of these specimens with *H. erectus* (Figs. 1 and 2), we
407 interpret the Changyang and Chaoxian hominins as a late representative of an East
408 Asian *H. erectus* lineage.

409 The second morphotype, represented by the fossils from Panxian Dadong and
410 Tongzi, is characterized by a series of derived features generally found in Late
411 Pleistocene hominins, like Neanderthals and modern humans, as already suggested by
412 previous studies of the external tooth morphology (Liu et al., 2013; Pan et al., 2019;
413 Pan and Zanolli, 2019). The EDJ shape of PA873 and PA1578, even if intermediate
414 between the Neanderthal and modern human conditions, tends to show more affinities
415 with the Neanderthal general pattern. Even if there is no evidence for such an early
416 onset of dispersion into Asia, the recent finding from Misliya in Israel (Hershkovitz et
417 al., 2018) indicates that we cannot rule out the possibility that they may represent a
418 biogeographical variation of early modern humans in China. It is also possible that these
419 non-*H. erectus* *Homo* may sample a distinct lineage, possibly Denisovans. In fact,

420 predictions from paleogenetics that Denisovans were a group of Neanderthal-like
421 humans that lived from the Altai to East and South Asia (Meyer et al., 2012, 2016;
422 Jacobs et al., 2019; Mondal et al., 2019), were recently reaffirmed by the combined
423 morphological and molecular analyses of a mandible fragment from Xiahe, on the
424 Tibetan Plateau (Chen et al., 2019). As archaic Denisovans probably occupied a broad
425 geographical range, admixture between Denisovans and early modern humans probably
426 occurred not only in Siberia and Southeast Asia but also in Southern China (Reich et
427 al., 2011; Cooper and Stringer, 2013). Even if no Denisovan premolar is known yet,
428 given the current evidence, it is possible that the Panxian Dadong and Tongzi hominins
429 could belong to this taxon, as it was also proposed for other late Middle Pleistocene
430 specimens from Asia, like the human remains from Xujiayao (Xing et al., 2015, Chen
431 et al., 2019) and Penghu (Chang et al., 2015). Another possibility is that these
432 specimens sample representative from both Denisovans and Pleistocene modern
433 humans.

434

435 **5. Conclusions**

436 The present study suggests the existence of time-related evolutionary changes in
437 the premolar EDJ morphology in a number of Early and Middle Pleistocene hominin
438 groups, with special reference to mid- and late Middle Pleistocene populations in China.
439 A general trend towards a reduction of crown base in relation to occlusal aspects,
440 narrowed lingual aspects, heightened EDJ relief and a surface simplification is found

441 through time. The current analysis expands our knowledge on the dental inner
442 morphology of Middle Pleistocene hominins, supports the coexistence of archaic
443 (*Homo erectus*-like) and derived ('Late Pleistocene *Homo*-like') dental
444 morphological patterns and, through a dental perspective, suggest the preservation of
445 plesiomorphic, *H. erectus*-like morphology during the Middle Pleistocene. New fossil
446 discoveries and/or molecular analyses will be critical to explore further the past
447 diversity and to shed light on the dispersal and interaction of hominin populations in
448 East Asia.

449

450

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473

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Table 1

Composition of the study specimens from China and of the comparative samples.

Chinese Pleistocene specimens	P ³	P ⁴	P ₃	P ₄	Provenance	Chronological range ^a	Citations ^b
Middle Pleistocene <i>Homo erectus</i> from China (HEC)							
PA67	1				Zhoukoudian Loc. 1 (Layer 11)	800–770 (A)	1–3
PA68		1			Zhoukoudian Loc. 1 (Layer 11)	800–770 (A)	1–3
PMU M3549			1		Zhoukoudian Loc. 1 (Layer 5)	550–500 Ka (B)	2, 4
PMU M3887				1	Zhoukoudian Loc. 1 (Layer 5)	550–500 Ka (B)	2, 4
PA110 ^c			1		Zhoukoudian Loc. 1 (Layer 3)	320–282 ka (C, D); 500 ka (E)	1–3
PA832 ^c	1				Hexian	437–387 ka (B)	5, 6
Shy071 ^c		1			Yiyuan	420–320 ka (F)	7–9
PA524 ^c	1				Xichuan	Unknown	10
PA525 ^c				1	Xichuan	Unknown	10
PA526 ^c			1		Xichuan	Unknown	10
PA527 ^c			1		Xichuan	Unknown	10
PA528				1	Xichuan	Unknown	10

Late Middle Pleistocene *Homo* sp. from China (HSPC)

PA76 ^c	1		Changyang	196–194 ka (A)	11
PA81 ^c		1	Changyang	196–194 ka (A)	11
PA873 ^c	1		Tongzi	192–172 ka (A); 240 ka (G)	12
PA1577	1		Panxian Dadong	182–160 ka (H)	13
PA1578 ^c		1	Panxian Dadong	296–233 ka (H)	13
Chaoxian	1		Chaoxian	200–160 ka (I) 360–310 ka (J)	14

Comparative samples

Early Pleistocene *H. erectus*

from Java (HEJ)

Sangiran 4	2	2	Sangiran (Pucangan Fm).	1.8–1.6 Ma (K)	4
Sangiran 7-3a		1	Sangiran (Pucangan Fm).	~1.3 Ma (L)	15

Early Pleistocene *Homo* from

North Africa (HNA)

Tighenif 2			1	Tighenif	~1.0 Ma (M)	16	
Neanderthals (NEA)	5	4	4	4	Krapina (Level 8)	140–120 ka (N)	17, 18

	1	2	1	La Chaise-de-Vouthon (Abri Bourgeois-Delaunay)	146–106 ka (O)	18, 19
Recent modern humans (RMH)	10	6	11	8	Asia/ Europe/South Africa	20

^a Age references: A = Yuan et al. (1986); B = Grün et al. (1998); C = Grün et al. (1997); D = Huang et al. (1993); E = Shen et al. (2001); F = Han et al. (2016); G = Shen and Jin (1991); H = Karkanas et al. (2008); I = Chen et al. (1987); J = Shen et al. (2010); K = Huffman (2001); L = Matsu'ura et al. (2020); M = Sahnouni and Van der Made (2009); N = Rink et al. (1995); O = Macchiarelli et al. (2006).

^b Citations reporting descriptions of the morphology of the specimens : 1 = Xing (2012); 2 = Xing et al. (2018); 3 = Black et al. (1933); 4 = Zanolli et al. (2018a); 5 = Xing et al. (2014); 6= Liu et al. (2017); 7 = Chen et al. (1987); 8= Wu and Wu (1982); 9 = Xing et al. (2016); 10 = Wu and Wu (1982); 11 = Chia (1957); 12 = Xing et al. (2019); 13 =Liu et al. (2013); 14 = Bailey and Liu (2010); 15 = Grine (1994); 16 = Zanolli and Mazurier (2013); 17 = Radovčić et al. (1988); 18 = NESPOS database (2020); 19 = Macchiarelli et al. (2006); 20 = Pan et al. (2017).

^c Worn crown, reconstructed dentine horn tips. For the reconstruction see SOM Figure S1.

1 **Table 2**

2 Results of the cross-validation analyses performed on the between-group principal component scores.

3 The posterior probabilities that the Chinese specimens are closer to any group were then calculated. The

4 highest probabilities are indicated in bold (the greater the number, the higher the probability).

5

Dental position	Specimen	Predictive accuracy of comparative specimens	Classification of the investigated Chinese fossils
P ³	PA76	HE: 100%; NEA: 100%, MHS: 100%	HE: 0.061 ; NEA: <0.001; MHS <0.001
	PA873	HE: 100%; NEA: 100%, MHS: 100%	HE: <0.001; NEA: 0.001 ; MHS: 0.002
	PA1577	HE: 100%; NEA: 100%, MHS: 100%	HE: <0.01; NEA: 0.104 ; MHS: <0.001
P ⁴	Chaoxian	HE: 100%; NEA: 80%, MHS: 80%	HE: 0.334 ; NEA: 0.001; MHS: <0.001
P ₃	PA1578	HE: 100%; NEA: 100%, MHS: 91%	HE: <0.001; NEA: 0.004 ; MHS: 0.026
P ₄	PA81	HE: 100%; NEA: 100%, MHS: 88%	HE: 0.808 ; NEA: <0.001; MHS: <0.001

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14 Abbreviations: HE = *Homo erectus* from Asia and late Early Pleistocene *Homo* from North Africa; NEA

15 = Neanderthals; MHS = modern *Homo sapiens*.

16

17 **Figure captions**

18

19 **Figure 1.** Volume rendering of upper premolar EDJ of *Homo erectus* from China (HEC),
20 late Middle Pleistocene *Homo* sp. from China (HSPC), Javanese *H. erectus* (HEJ),
21 Neanderthals (NEA) and modern *Homo sapiens* (MHS). Occlusal view (right) and
22 mesial view (left), with dentine horn tips restored. The 3D models of left teeth (marked
23 by an asterisk) were mirrored to the right side for comparison. Abbreviations: b =
24 buccal; l = lingual; m = mesial.

25

26 **Figure 2.** Volume rendering of lower premolar EDJ of *Homo erectus* from China (HEC),
27 late Middle Pleistocene *Homo* sp. from China (HSPC), late Early Pleistocene *Homo*
28 from North Africa (HNA), Neanderthals (NEA) and modern *Homo sapiens* (MHS).
29 Occlusal view (right) and mesial view (left), with dentine horn tips restored. The 3D
30 models of left teeth (marked by an asterisk) were mirrored to the right side for
31 comparison. Abbreviations: b = buccal; l = lingual; m = mesial.

32

33 **Figure 3.** Principal component analysis (PCA) and between-group principal component
34 analysis (bgPCA) of the P³ (A, B) and P⁴ (C, D) enamel-dentine junction (EDJ)
35 morphology using diffeomorphism surface matching (DSM) approach. The extreme
36 shapes are illustrated in occlusal and mesial views at the end of each axis. Abbreviations:
37 HEC = *Homo erectus* from China; HEJ = Javanese *H. erectus*; NEA = Neanderthals;

38 MHS = modern *Homo sapiens*.

39

40 **Figure 4.** Principal component analysis (PCA) and between-group principal component

41 analysis (bgPCA) of the P₃ (A, B) and P₄ (C, D) enamel-dentine junction (EDJ)

42 morphology using diffeomorphism surface matching (DSM) approach. The extreme

43 shapes are illustrated in occlusal and mesial views at the end of each axis. Abbreviations:

44 HEC = *Homo erectus* from China; HNA = late Early Pleistocene *Homo* from North

45 Africa; NEA = Neanderthals; MHS = modern *Homo sapiens*.







