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1 **Morphometric variance, evolutionary constraints and their change through time in Late Devonian**  
2 ***Palmatolepis* conodonts**

3

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14

15 **Abstract**

16 Phenotypic variation is the raw material of evolution. Standing variation can facilitate response to  
17 selection along “lines of least evolutionary resistance”, but selection itself might alter the structure of  
18 the variance. Shape was quantified using 2D geometric morphometrics in *Palmatolepis* conodonts  
19 through the Late Devonian period. Patterns of variance were characterized along the record by the  
20 variance-covariance matrix (P-matrix) and its first axis (Pmax). The Late Frasnian was marked by  
21 environmental oscillations culminating with the Frasnian/Famennian mass extinction. A shape  
22 response was associated with these fluctuations, together with a deflection of the Pmax and the P-  
23 matrix. Thereafter, along the Famennian, *Palmatolepis* mean shape shifted from broad elements  
24 with a large platform to slender elements devoid of platform. This shift in shape was associated with  
25 a reorientation of Pmax and the P-matrix, due to profound changes in the functioning of the  
26 elements selecting for new types of variants. Both cases provide empirical evidences that moving  
27 adaptive optimum can reorient phenotypic variation, boosting response to environmental changes.  
28 On such time scales, the question seems thus not to be whether the P-matrix is stable, but how it is  
29 varying in response to changes in selection regimes and shifts in adaptive optimum.

30

31 **Keywords**

32 Geometric morphometrics, outline analysis, Pmax, P-matrix, DISTATIS, Famennian

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## 41 Introduction

42 Phenotypic variation is the raw material of evolution. The potential for adaptive responses is  
43 determined by the extent of variation available to the screening of selection, and the structure of the  
44 genetic covariations that represent constraints due to the interrelationships between traits.

45 Response to selection can be impeded if the covariation between traits is unfavorable (Arnold et al.  
46 2001; Steppan et al. 2002) whereas it can be deflected towards the traits combinations that have the  
47 most variation, constituting line of least resistance to evolution (Schluter 1996). This has been  
48 formalized based on the quantification of the variance-covariance genetic matrix (G matrix) and its  
49 main direction (Gmax) (Steppan et al. 2002; Bégin and Roff 2003; McGuigan et al. 2005). However,  
50 morphology is the only information to retrace the evolutionary history of ancient fossils, degradation  
51 preventing the extraction of genetic information. In such case, the G-matrix cannot be estimated, but  
52 the matrix of phenotypic variance-covariance, or P-matrix, could be used instead. G represents the  
53 portion of P that is heritable (Polly 2004). Heritability of morphological characters seems to be  
54 intermediate to high (Cheverud 1988), for instance reaching >60% for the shape of feeding structures  
55 in mice (Pallares et al. 2014; Pallares et al. 2017). This makes P a good surrogate for G in the fossil  
56 record (Renaud et al. 2006; Hunt 2007).

57 Estimating P-matrices in the fossil record could allow to test predictions regarding its stability vs.  
58 temporal changes. The G/P-matrix can be altered by selection, with variation being enhanced in the  
59 direction of an adaptive peak (Eroukhmanoff 2009) or along a moving adaptive optimum (Jones et al.  
60 2012). In this case, G/P could “store” ancient environmental pressures, strengthening or weakening  
61 its constraining effect on future selection pressures (Eroukhmanoff 2009; McGlothlin et al. 2018).  
62 Extreme environmental changes are thus expected not only to exert strong selective pressure on  
63 shape itself, but also to affect P, whereas response to moderate environmental changes are more  
64 likely to surf on the line of least resistance characterized by the directions of main variance.

65 The Late Devonian (382 to 359 Ma) offers opportunities to assess the impact of environmental  
66 changes of various intensity and duration on organisms. The Frasnian / Famennian boundary (F/F),  
67 371 Ma ago, was marked by one of the major mass extinction in Earth’s history (McGhee 1996). The  
68 mass extinction was the culmination of a perturbation materialized by anoxic deposits in many  
69 marine environments (the Upper Kellwasser Event, or UKE); it was associated with a pronounced  
70 temperature decrease and sea-level fall (Girard and Renaud 2007). This event was preceded, *ca.* 2  
71 myrs before, by another event of similar nature (the Lower Kellwasser Event, or LKE) but of lesser  
72 impact on the biosphere (Joachimski and Buggisch 2002; Girard and Renaud 2007). A temperature  
73 decrease associated with a sea-level shallowing occurred towards the end of the LKE. The interval

74 between the two events was then marked by a progressive temperature increase and sea-level rise  
75 (Girard and Renaud 2007). Following the F/F crisis, temperatures were stable for a while (*ca.* 2 myrs)  
76 and thereafter launched a progressive decrease towards values much colder than the pre-LKE  
77 temperatures (Joachimski et al. 2009). This period thus offers the opportunity to investigate the  
78 response of organisms to environmental changes of different paces and amplitudes.

79 Conodonts are long extinct fossils without modern equivalent. These early vertebrates were small  
80 eel-like predators and an important part of the nektonic fauna increasing in richness through the  
81 Paleozoic period (Purnell 1995). They had a well-developed feeding apparatus composed of several  
82 tooth-like elements of complex shapes. Anterior elements formed a trapping structure, whereas  
83 posterior elements processed food items (Aldridge et al. 1987; Purnell and Donoghue 1997).  
84 Platform elements P1 (Supp. Fig. 1), located at the rear of the conodont mouth, functioned with an  
85 occlusion between right and left elements, sometimes leading to a pronounced asymmetry  
86 (Donoghue and Purnell 1999; Martínez-Pérez et al. 2016; Renaud et al. 2021). Conodont elements  
87 grew by the incremental addition of lamellae. Anisometric growth, with zones characterized by  
88 thicker lamellae, caused changes in the shape of many elements (Girard and Renaud 2008; Chen et  
89 al. 2016). Being composed of apatite, conodont elements are extremely resistant and are abundant  
90 in the fossil record. P1 elements, in particular, displayed a robust shape and a rapid morphological  
91 evolution that made them highly used stratigraphic markers, and the focus of many morphometric  
92 studies, e.g. (Klapper and Foster 1986; Renaud and Girard 1999; Jones et al. 2009; Chen et al. 2016;  
93 Hogancamp et al. 2016).

94 *Palmatolepis* is the emblematic genus of the Late Devonian (Klapper 1989; Ziegler and Sandberg  
95 1990). Its P1 elements were characterized by a reduced bilateral asymmetry (Renaud and Girard  
96 1999) and allometric growth (Girard et al. 2007). Shape changes were documented during the  
97 interval preceding the F/F crisis, and appeared correlated with temperature (Balter et al. 2008). A  
98 large-scale morphological trend was further documented along the Famennian (Girard and Renaud  
99 2012). *Palmatolepis* thus constitutes a good model to quantify shape and shape variation during the  
100 Late Devonian period, and assess how the P-matrix was affected by environmental changes of  
101 various magnitude and pace.

102 Using a geometric morphometric approach based on an outline analysis of the P1 element,  
103 *Palmatolepis* shape was therefore quantified along a record covering the Latest Frasnian and the  
104 Famennian. Along this record, the direction of allometric variation, the P-matrix and its first  
105 direction, Pmax, as well as evolutionary trajectories characterizing temporal evolution and  
106 diversification within *Palmatolepis*, were quantified to test the following main hypotheses. (1) Given

107 the magnitude of the environmental changes along the record, *Palmatolepis* likely faced moving  
108 adaptive optima; this could have selected for new types of variants, thus reorienting Pmax and the P-  
109 matrix. (2) Allometry should constitute an important component of the phenotypic variation, and  
110 thus be correlated with Pmax. (3) The stability of Pmax and the P-matrix, and their role in channelling  
111 evolution, could have been modulated by the magnitude and pace of the environmental fluctuations.  
112 During periods of relatively stable environmental conditions, Pmax and the P-matrix should be  
113 conserved; shape should evolve following the line of least resistance Pmax, and possibly the  
114 allometric direction. In contrast, during periods of intense perturbations, flexibility may override  
115 constraints (Beldade et al. 2002), and shape evolution may deviate from Pmax. Pmax and the P-  
116 matrix could be deflected due to moving adaptive optimum (Eroukhmanoff 2009).

117

## 118 **Material and Methods**

### 119 *Fossil material for morphometric analyses*

120 The Col des Tribes section (CT, Montagne Noire, France) exposes an almost continuous record from  
121 Late Frasnian to Late Famennian deposits (-378 to -360 Ma) (Girard et al. 2014). Conodont elements  
122 were picked in seven Frasnian and twelve Famennian levels, designed according to the bed  
123 numbering in the outcrop (Girard et al. 2014). A few grams of rocks were enough to deliver hundreds  
124 of elements (Girard et al. 2014). To minimize time averaging, efforts were done to sample the piece  
125 of rock within few centimeters at basis of each stratigraphic level. Oxygen isotopes were measured  
126 on the apatite of conodonts picked in the same levels (Girard et al. 2020). Age was estimated for  
127 each level using a biostratigraphic analysis (Girard et al. 2014) based on the zonations defined for the  
128 Frasnian (Klapper and Kirchgasser 2016) and the Famennian (Spalletta et al. 2017). Absolute ages  
129 were estimated according to the current datation framework (Becker et al. 2020). Among the  
130 Frasnian levels, CT\_06 is situated just after the LKE whereas CT\_23 is located just before the F/F  
131 boundary (Fig. 1).

132 Numerous stratigraphic species and even subspecies have been described within *Palmatolepis*, as a  
133 way to describe the extensive morphological variation. Rather than being distinct evolutionary units,  
134 however, they often correspond to end-members of continuous morphological variation (Scott and  
135 Collinson 1959; Girard and Renaud 2011). In contrast, subgenera correspond to relatively well  
136 identified ranges of the morphospace (Girard and Renaud 2012). Hence, considering the subgenus as  
137 unit seems a relevant approach to assess temporal changes in mean shape and morphological  
138 variance (Girard et al. 2004; Girard and Renaud 2011). Furthermore, reliably assessing shape variance  
139 requires good sample size, ideally above 30 specimens per sample (Cardini and Elton 2007). Hence,

140 the sampling of this study was targeted at four well-represented subgenera presented thereafter  
 141 (Table 1; Fig. 1; descriptive terminology and the orientation of the element: Supp. Fig. 1).

- 142 (1) *Manticolepis* is characteristic of the Late Frasnian. Its P1 elements display a large, wide  
 143 platform with a well-developed outer lobe (Müller 1956). The carina is more or less  
 144 sigmoidal. There is broad consensus as to the taxonomic limits of this subgenus since its  
 145 inception (Helms 1963; van den Boogaard and Kuhry 1979).
- 146 (2) *Panderolepis* P1 elements are characterized by the narrowness of the platform, with an  
 147 almost absent lateral lobe. In the initial description of the subgenus (Helms 1963), two  
 148 species were included: *glabra* and *tenuipunctata*, with the hypothesis that *Pa. (Panderolepis)*  
 149 *glabra* evolved from *tenuipunctata* by the loss of the outer lobe and the development of a  
 150 parapet at the anterior, inner part (also called ventral, caudal part) of the platform. This was  
 151 later challenged by authors proposing that *tenuipunctata* was the only Frasnian survivor of  
 152 the *Manticolepis* subgenus (van den Boogaard and Kuhry 1979). The initial delineation of the  
 153 subgenus was retained, but the early sample from the Col des Tribes (PAN\_35) is composed  
 154 of *tenuipunctata* and late samples (PAN\_50 and later) are composed of *glabra*. The sample  
 155 PAN\_37 is composed of a mix of both species (12 *glabra* and 30 *tenuipunctata*).
- 156 (3) *Deflectolepis* has been initially described based on the morphology of the P1 element (Müller  
 157 1956). They have a very narrow platform, reduced to margins paralleling the carina. Two  
 158 species are documented. *Palmatolepis (Deflectolepis) gracilis* has a smooth surface.  
 159 *Palmatolepis (Deflectolepis) minuta* is characterized by a straight carina and a platform that is  
 160 slightly developed, and which sometimes displays a small lateral lobe. The homogeneity of  
 161 this subgenus has been challenged based on few multi-element reconstructions, suggesting  
 162 that the two species differed by their P2 element (van den Boogaard and Kuhry 1979). As this  
 163 study focuses on P1 elements, the delineation of the subgenus based on this element was  
 164 retained, but its homogeneity was questioned. The early samples from the Col des Tribes  
 165 (DEF\_41 and DEF\_42) are composed of *minuta* whereas the later samples (DEF\_45 and later)  
 166 are almost exclusively composed of *gracilis*, to the exception of two *minuta* specimens in the  
 167 level DEF\_59.
- 168 (4) “*rhomboidea*” is not strictly speaking a subgenus, but it was constantly set apart from other  
 169 subgenera because of its very characteristic platform of rhombohedral shape (Müller 1956;  
 170 Helms 1963). The outer lobe is usually reduced. The blade-carina line is usually sigmoidal.

171 The Operational Taxonomic Units (OTUs) were groups corresponding to the subgenus x stratigraphic  
 172 level. Each OTU included all entire P1 conodont elements of the concerned subgenus picked in the  
 173 given level, except in PAN\_51 in which only right elements were considered, due to an exceptional

174 abundance in this level. The resulting sampling encompassed 22 OTUs, for a total of 1435 P1  
175 conodont elements (Table 1). Note that phylogenetic relationships between subgenera have been  
176 proposed (Müller 1956; Helms and Ziegler 1981) but they remain largely hypothetical. This precluded  
177 the possibility to perform phylogenetically-controlled morphometric analyses.

178

#### 179 *Methods of morphometric and multivariate analyses*

180 Outline extraction and quantification. – Pictures of the conodont elements were taken, the element  
181 lying flat on its platform, the blade upward (Fig. 1). Left elements were mirrored and measured as  
182 right elements; both right and left elements were analyzed together (Renaud and Girard 1999). The  
183 outline of the platform was quantified using 64 equally-spaced points extracted using the image  
184 analysis software Optimas, the starting point being positioned at the tip of the carina. Radii (i.e.  
185 distance of each point to the center of gravity of the points) were calculated from these coordinates.  
186 The empirical function of the radius as a function of the cumulated distance along the outline was  
187 decomposed into a sum of trigonometric functions of decreasing wavelengths (the harmonics). Each  
188 harmonic is weighted by two Fourier coefficients (FCs) that constitute the shape variables. This  
189 method, implemented in the R package Momocs (Bonhomme et al. 2014), has been shown to  
190 efficiently describe shape variation of *Palmatolepis* elements (Renaud and Girard 1999; Girard and  
191 Renaud 2012). The zero harmonic  $A_0$ , proportional to the outline size, was used to standardize all  
192 other FCs so they correspond to shape variables only. The higher the rank of the harmonics, the more  
193 details they represent on the outline; this usually goes with an increasing amount of measurement  
194 error (Crampton 1995; Renaud et al. 1996). The first nine harmonics, i.e. 18 variables, were  
195 considered to provide a good balance between a satisfying description of the geometry of the  
196 element, and an efficient filtering of measurement error.

197

198 Multivariate shape analysis. – The total shape variance can be mathematically described by the  $\mathbf{T}$   
199 matrix, corresponding to the variance-covariance (VCV) matrix of the standardized 18 FCs x 1435  
200 specimens. A Principal Component Analysis on  $\mathbf{T}$  was performed to display the total shape variance  
201 on few synthetic axes maximizing the total variance.

202  $\mathbf{T}$  can be decomposed in two components: the between-group matrix  $\mathbf{B}$  and the within-group matrix  
203  $\mathbf{W}$  ( $\mathbf{T} = \mathbf{B} + \mathbf{W}$ ), the groups being here the OTUs.  $\mathbf{B}$  corresponds to the VCV matrix between group  
204 means weighted by the sample size of each group. Its eigenanalysis is termed between-group



205 Principal Component Analysis (bgPCA) (Culhane et al. 2002; Renaud et al. 2015). Here, a bgPCA was  
206 performed to characterize the shape differentiation between OTUs.

207

208 Pmax, allometry, and correlations between vectors. – The shape variance within a OTU is described  
209 by the VCV matrix of the Fourier coefficients of the specimens composing the OTU (P-matrix). A PCA  
210 on this P-matrix leads to a set of eigenvectors characterizing directions of variance within the OTU.  
211 The first eigenvector (Pmax) describes the direction on which most shape variance occurs. The  
212 comparison of Pmax between two OTUs allows to assess if they share similar patterns of main  
213 variance. The correlation (R) between Pmax in OTU1 and OTU2 corresponds to the inner-product of  
214 the two vectors scaled to unit length. The angle between the two vectors corresponds to the  
215 arccosine of R. The significance of the correlation was assessed by comparing the observed R value to  
216 a null distribution of R between random vectors of 18 dimensions and a randomly chosen fixed  
217 reference direction; this null distribution was generated by computing 10,000 correlations (Renaud  
218 et al. 2006; Hunt 2007). Since the +/- direction of principal axes is arbitrary, the absolute value of R  
219 was considered. For the significance levels (type I error)  $\alpha = 0.05$ ,  $0.01$  and  $0.001$ , the obtained  
220  $|R_{\text{observed}}| > |R_{\text{random}}|$  are respectively  $|R|=0.457$  (angle=62.8°);  $|R|=0.588$  (angle=45.0°); and  
221  $|R|=0.699$  (angle=45.6°).

222 The vectors describing the allometric shape variation were estimated using the slope coefficients of  
223 multiple regressions of the 18 FCs vs A0 (zero harmonic), performed separately for each OTU. The  
224 resulting vectors were scaled to unit length and their correlations were assessed as described above.

225

226 Correlations between P matrices. – The RV coefficient is defined as the sum of the squared  
227 covariances between two sets of variables, divided by the total amount of variation in the two sets of  
228 variables (Escoufier 1973). The RV coefficient varies between 0 and 1 and it can be seen as an  
229 extension of the notion of correlation for matrices. The significance of the correlation was assessed  
230 for each pair of P-matrices using permutations (9999 permutations).

231 Another metric was used to compare P-matrices, based on the contrast defined as the square root of  
232 the summed squared logarithms of the relative eigenvalues between the two matrices. Relative  
233 eigenvalues express the variances and covariances of one sample relative to that of another sample;  
234 they are equal to the eigenvalues of the product of one matrix premultiplied by the inverse of the  
235 other matrix (Mitteroecker and Bookstein 2009). The resulting matrix of “MB” contrasts (for the

236 initial of the authors describing it) summarized the distances between P-matrices of the different  
237 OTUs.

238

239 Multivariate analyses of distances between vectors and matrices. – Distance matrices can be  
240 decomposed using Principal Coordinate Analyses (PCOA) in order to summarize the relationships  
241 between items on few synthetic axes. Such an approach can be used to characterize relationships  
242 between vectors (Pmax, allometry) or P-matrices, provided that Euclidean distances between OTUs  
243 matrices can be calculated.

244 For this purpose, the matrix of correlation between Pmax vectors was transformed into a matrix of  
245 Euclidean distances using the formula:  $d = \sqrt{2*(1-R^2)}$  (Qannari et al. 1998); the same procedure was  
246 used for allometric vectors. The table of RV coefficients between P-matrices was transformed into a  
247 matrix of distances using the formula  $d = \sqrt{2*(1-RV)}$  (Robert and Escoufier 1976). The matrix of MB  
248 contrasts being itself a distance matrix, it could be analyzed by a PCOA without further  
249 transformation.

250

251 Comparison of evolutionary trajectories with Pmax and allometric vectors. – Evolutionary trajectories  
252 were defined as directions of shape changes between two groups. Trajectories characterizing the  
253 differentiation between subgenera were evaluated as the pairwise differences between the mean  
254 shape of the different subgenera. Trajectories of within-subgenus evolution were estimated as the  
255 difference between the mean shape of the oldest and most recent OTU within each subgenus. This  
256 provided six between-subgenera and four within-subgenus trajectories. In order to assess whether  
257 evolutionary changes were channeled along directions of within-OTU variation, the between-  
258 subgenera and within-subgenus trajectories were compared to the direction of main variance (Pmax)  
259 and to the allometric direction of all OTUs. This was done by estimating the correlation of the  
260 evolutionary trajectories, scaled to unit length, with the Pmax and the allometric vectors of the 22  
261 OTUs.

262

263 An integrated analysis of shape and shape variance: a K-table approach. – The 22 OTUs were  
264 characterized using descriptors of different formats: mean shape; vectors describing directions of  
265 shape variation for Pmax and allometry, and P-matrices describing the structure of the variation. For  
266 each descriptor, the relationship between the 22 OTUs was assessed using a multivariate analysis  
267 (bgPCA or PCOA), raising the question of how the resulting topologies related with the others. The

268 match between pairs of topologies was assessed using a Protest (Peres-Neto and Jackson 2001),  
269 providing a coefficient of correlation (ProcR) and a P-value, estimating if the configurations are more  
270 related than random (based on 9999 permutations). The first three dimensions of all multivariate  
271 analyses were considered for these pairwise tests.

272 Multivariate methods exist to compare the analyses of several tables sharing the same entries (“K-  
273 tables” approaches). Among them, the DISTATIS method (Abdi et al. 2005) was designed for the  
274 simultaneous analysis of multiple distance matrices, allowing to integrate them into a single graphical  
275 representation. It was thus applied here to the five distance matrices describing the topology  
276 between the 22 conodont OTUs. This approach provides a set of compromise eigenvectors on which  
277 the five descriptors of the 22 OTUs are projected; this therefore allows a visualization of which  
278 descriptors provide the most similar patterns of differentiation between the 22 OTUs. The method  
279 further allows a bootstrap estimate of the position of the OTUs on this compromise. 1000 bootstraps  
280 were performed here.

281

282 Assessment of shape variation due to asymmetry. – All OTUs except PAN\_51 included both right and  
283 left elements. To assess if asymmetry could be an important driver of morphological variation, two  
284 approaches were explored. First, the relative importance of the potential sources of variation  
285 (subgenus or OTU, bilateral asymmetry and allometry) was estimated using a multivariate analysis of  
286 variance on the set of FCs using the “ffmanova” procedure (Langsrud and Mevik 2012). This method  
287 has the advantage of being invariant to ordering of the model terms and to handle colinear  
288 responses. It may inflate the percentage of variance explained (pve) but allows an estimation of the  
289 relative importance of the explanatory variables.

290 Second, the same multivariate analyses (bgPCA, PCOA based on Pmax and on the RV coefficients  
291 between P-matrices) as described above were performed on the sub-sample including right elements  
292 only. The analyses based on MB contrasts and allometry could not be performed because in few  
293 OTUs, the sample size was inferior to the number of variables (Table 1). The between-OTUs  
294 topologies obtained for shape (bgPCA), Pmax and P-matrices based on all elements, and right  
295 elements only, were compared using Protest on the first three axes.

296

297 Visualization of shape variation. – The outline corresponding to a set of FCs can be visualized using an  
298 inverse Fourier transform. For Pmax, the outlines corresponding to the 10% and 90% percentiles of  
299 the scores along the vector of each OTU were reconstructed. For allometry, outlines corresponding

300 to the 10% and 90% percentiles of the size distribution were computed using the same multivariate  
301 regressions that provided the coefficients of the allometric vector.

302 The P-matrices were represented by ellipses defined by their first and second axes, providing a  
303 representation of the orientation and elongation of each matrix. To be comparable, all matrices had  
304 to be projected on a common space, here the space of the PCA on the total sample.

305 Finally, the temporal changes in mean shape, Pmax, P-matrices, and allometry, were visualized as the  
306 scores of the OTUs along the first axis of the different multivariate analyses, as a function of  
307 geological time, based on the age model relating depth along the section to absolute age (Girard et  
308 al. 2020) and updated according to the most recent datation framework (Becker et al. 2020). To  
309 provide an environmental background to these morphological variations, paleotemperature  
310 estimates based on  $\delta^{18}\text{O}$  values measured on conodont apatite from the same samples (Girard et al.  
311 2020) were also represented.

312

313 Packages and data accessibility. – All analyses were performed under R (R\_Core\_Team 2017).  
314 Multivariate analyses were performed using ade4 (Dray and Dufour 2007; Thioulouse et al. 2018) and  
315 DistatisR (Beaton et al. 2019). Protests were performed using vegan (Oksanen et al. 2017) and  
316 ffmanova using the ffmanova package (Langsrud and Mevik 2012). The R script and the dataset are  
317 deposited in Dryad: <https://doi.org/10.5061/dryad.pvmcvdnmf>.

318

## 319 **Results**

320 Shape differentiation between and within conodont subgenera. – Considering the analysis of the  
321 total shape variance using a PCA (Fig. 2A), the prominent morphological signal was the difference  
322 between elements with a well-developed platform, typical of *Manticolepis* and *rhomboidea*, and  
323 slender elements without a platform, characteristics of *Deflectolepis* (Fig. 2B). The subgenus  
324 *Panderolepis* appears as intermediate between the two extreme morphologies. The second axis does  
325 not differentiate subgenera, but it expresses within- and between-group variation within  
326 *Deflectolepis*.

327 Between-group differences, as summarized by a bgPCA (Fig. 2C), represent 68.2% of the total  
328 variance. The first axis is overwhelmingly important (86.2% of the between-group variance) and  
329 matches the signal expressed on the first axis of the PCA (difference between elements with a well-  
330 developed platform and those without a platform). *Panderolepis* is intermediate between

331 *Manticolepis* and *Deflectolepis* along bgPC1, but its OTUs are ordered according to a temporal  
 332 sequence: the oldest OTUs (PAN\_35 and PAN\_37) are close to *Manticolepis* while the most recent  
 333 OTU (PAN\_56) is close to *Deflectolepis*. Furthermore, *Panderolepis* is slightly differentiated from the  
 334 other subgenera along bgPC2 (6.7% of between-group variance).

335

336 Differences between Pmax vectors. – The correlation between the Pmax vectors varies greatly  
 337 depending on the OTUs considered (Supp. Table 1). It is higher when comparing OTUs from a same  
 338 subgenus (mean R=0.797) than when the comparison involves different subgenera (mean R=0.467).  
 339 Pmax is particularly stable within *Deflectolepis* (mean R = 0.960) and *rhomboidea* (mean R=0.925). It  
 340 varies more within *Manticolepis* (mean R = 0.705) but this is especially due to the outlying direction  
 341 of the earliest OTU (MAN\_06). When focusing on later *Manticolepis* OTUs (from MAN\_07 to  
 342 MAN\_23), Pmax is also stable through time (mean R = 0.909). Pmax is the more variable within  
 343 *Panderolepis* (mean R=0.612), due to the outlying direction of the two early OTUs, especially  
 344 PAN\_37. It is stable within the three late *Panderolepis* OTUs (mean R=0.943).

345 The main axis of the ellipses corresponding to the projection of the P-matrix provides a visualization  
 346 of the Pmax direction (Fig. 3A). According to the high within-subgenus correlation, Pmax is stable  
 347 within *Deflectolepis*. The ellipses vary more in their orientation and elongation in *Panderolepis*.  
 348 Especially, an inversion of the first and second axes is observed in PAN\_37. In *Manticolepis*, Pmax  
 349 shifts from being aligned with PC2total to being almost aligned with PC1total. The elongation of the  
 350 ellipse characterizes the anisotropy of the variance. As shown by the elongated ellipses, *Deflectolepis*  
 351 is characterized by a very anisotropic variance, with Pmax representing 50% or more of the variance  
 352 in all OTUs (Supp. Fig. 2A).

353 Extreme outlines along each Pmax provides a visualization of the shape variance within each sample  
 354 (Fig. 3B). In *Manticolepis*, Pmax corresponds to a variation between pear-shaped elements and  
 355 elements with a pronounced lobe. MAN\_06 constitutes an exception, with a variation from straight  
 356 to arched elements, without noticeable variation in the extension of the lobe. In *rhomboidea*, the  
 357 extension of the platform varies little and Pmax corresponds to a variation between more or less  
 358 sigmoidal carina. In *Deflectolepis*, Pmax expresses a variation from straight to curved elements. This  
 359 kind of variation is also characteristics of *Panderolepis*; however, in the oldest samples PAN\_35 and  
 360 PAN\_37, a small lobe is still present. Variation of its extension is predominant over the change in  
 361 rectitude in PAN\_37.

362 A multivariate analysis (PCOA based on the correlations between Pmax scaled to unit length,  
 363 converted into distances) summarized the relationships between all Pmax (Fig. 4A). The resulting

364 topology was correlated to the pattern of the bgPCA (Table 2). As for the analysis of shape,  
 365 *Manticolepis* (to the exception of MAN\_06) is opposed to *Deflectolepis* along the first axis. In contrast  
 366 to the analysis of shape, however, *Panderolepis* OTUs (to the exception of PAN\_37) fall with  
 367 *Deflectolepis*, and *rhomboidea* is clearly apart along PC2<sub>Pmax</sub>. The outlying position of PAN\_37  
 368 compared to other *Panderolepis* samples is due to the inversion between the first and second main  
 369 directions of variance (see Fig. 3A, 3B), corresponding to the relative extension of the lobe, and the  
 370 curvature of the element. The similarity of PAN\_37 Pmax with *Manticolepis* Pmax is attributable to  
 371 the fact that they all describe variation in the extension of the lobe. The outlying position of MAN\_06  
 372 is due to the curvature, and not the extension of the lobe, being the prominent component of shape  
 373 variance.

374

375 Comparison of the P-matrices. – A first approach to compare P-matrices was based on the RV  
 376 coefficient, that provides a measure of correlation between two matrices (Supp. Table 2). P-matrices  
 377 are highly correlated among OTUs of a same subgenus, with particularly high correlations within  
 378 *Deflectolepis* and *rhomboidea* (RV>0.8, P=0.0001). This is also the case for *Manticolepis* when  
 379 discarding MAN\_06, which P-matrix is less tightly related to the P-matrices of the other OTUs (0.5<  
 380 RV< 0.9). P-matrices are more variable within *Panderolepis* (RV>0.6). In contrast, P-matrices are not  
 381 always significantly correlated between subgenera, especially when comparing *Deflectolepis* and  
 382 *Manticolepis* (all RV<0.6).

383 A PCOA was applied to the distance matrix derived from this table of RV coefficients (Fig. 4B). The  
 384 general pattern resembles the one provided by the multivariate analysis of Pmax and by the bgPCA  
 385 (Table 2). However, the differentiation between subgenera appears less important than in the Pmax  
 386 analysis. The first axis once again contrasts *Manticolepis* to *Deflectolepis*, showing that the two  
 387 subgenera have a different structure of morphological variance. In *Manticolepis*, most variance  
 388 occurs on the lobe, whereas in *Deflectolepis*, the prominent component of variance involves the  
 389 curvature of the elements. *Panderolepis* OTUs scatter in intermediate positions; the oldest samples  
 390 PAN\_35 and PAN\_37 are closer to *Manticolepis* and the more recent PAN\_50, PAN\_51 and PAN\_56  
 391 are closer to *Deflectolepis*. The second axis differentiates *rhomboidea* from the three other  
 392 subgenera. Note that when considering Pmax (Fig. 4A), MAN\_06 and PAN\_37 were outliers  
 393 compared to other OTUs of the same subgenus. Their position in the PCOA space based on RV  
 394 coefficients between P-matrices is more in agreement with their subgeneric attribution.

395 The P-matrices were also compared using the MB contrast (Mitteroecker and Bookstein 2009) (Fig.  
 396 4C), providing a topology close to the one obtained based on the RV coefficients (Table 2). The first

397 axis is similar to the axis based on RV coefficients. The difference regards the second axis isolating  
 398 *Panderolepis* instead of *rhomboidea*. The discrepancy between the PCOAs based on RV coefficients  
 399 and MB contrasts comparing the same P-matrices is due to an inversion of the second and third axes  
 400 between the two analyses (Supp. Figure 3). Overall, the MB analysis of the P-matrices provides a  
 401 topology close to those based on mean shape, Pmax and especially on the RV coefficients between P-  
 402 matrices, and showed a good congruence of the two descriptors of the relationships between P-  
 403 matrices (Table 2).

404

405 Allometry. – Size variation is comparatively high in *Manticolepis* and *Panderolepis* (5%-95%  
 406 range=1.93 for *Manticolepis* and 1.97 for *Panderolepis*), low in *rhomboidea* (range=1.37) and the  
 407 lowest within *Deflectolepis* (range=1.26) (Fig. 5). Multiple regression of the FCs vs A0 was significant  
 408 in all groups except DEF\_56 (Supp. Figure 2C); it was the highest in RHO\_39. Allometry involves weak  
 409 shape changes compared to the variation along Pmax (Fig. 3C). In *Manticolepis*, growth is associated  
 410 with an expansion of the lobe. In *rhomboidea*, the free blade becomes more apparent. In  
 411 *Panderolepis*, elements tend to become slender and more arch-shaped. Allometric change is very  
 412 tenuous in *Deflectolepis*, up to the absence of any change in DEF\_56. The coefficients of the multiple  
 413 regressions between size (A0) and shape (FCs) within each OTU allowed to characterized 22  
 414 allometric vectors. Being scaled to unit length, their pairwise correlations were assessed (Supp. Table  
 415 3). Allometric vectors were weakly correlated among subgenera (mean R=0.023) and within  
 416 *Deflectolepis* (mean R=0.208). They were moderately related within *Panderolepis* (mean R=0.650)  
 417 except for the three latest OTUs (R>0.85). Allometric vectors were highly correlated within  
 418 *Manticolepis* (mean R=0.833) and especially within *rhomboidea* (all R>0.85). Allometric vectors were  
 419 further compared to Pmax for each of the 22 OTUs, all vectors being scaled to unit length (Supp.  
 420 Table 4). Hardly more than 10% of the correlations were significant at the significance level  $\alpha =$   
 421 0.001. The only exceptions to this weak relation were the late *Manticolepis* (MAN\_22 and MAN\_23)  
 422 and especially *rhomboidea* ( $|R|>0.8$ ).

423 The relationships between allometric vectors (scaled to unit length) were summarized using a PCOA  
 424 (Fig. 4D). The resulting pattern is significantly correlated with those obtained based on Pmax and P-  
 425 matrices (Table 2; Fig. 4A, B, C). *Manticolepis* allometric vectors clustered towards positive values  
 426 along the first axis. *Panderolepis* and *rhomboidea* shared negative values along the first axis but were  
 427 different along the second axis. *Deflectolepis* allometric vectors were scattered along the first and  
 428 second axes. The weak allometric signal probably made its estimation unstable across OTUs.

429

430 Evaluation of asymmetry as a source of shape variation. – The linear models indicated that  
431 asymmetry explained less than 0.6% of shape variance in all cases (Table 3), much less than size and  
432 temporal variation through the successive levels. The effect was however significant in *Manticolepis*,  
433 *Panderolepis* and *Deflectolepis*, probably due to the large sample size.

434 The topologies based on all elements and right elements only were highly correlated when  
435 considering shape (bgPCA: ProcR = 0.9963, P = 0.0001), Pmax (ProcR = 0.9090, P = 0.0001) and P-  
436 matrices compared using RV coefficients (ProcR = 0.9743, P = 0.0001). Further note that the OTU  
437 DEF\_51, sampled by right elements only, never emerged as an outlier.

438

439 Evolutionary trajectories and directions of shape variance. – Evolutionary trajectories characterizing  
440 shape changes between subgenera and ancestor-descendent changes within each subgenus were  
441 compared to the Pmax and allometric vectors of the 22 OTUs, all vectors being scaled to unit length  
442 (Supp. Table 5; Supp. Figure 4). Trajectories between subgenera were poorly related to Pmax (mean  
443 R=0.337) and to allometric vectors (mean R=0.414). Nevertheless, the differentiation between the  
444 Frasnian *Manticolepis* and the three Famennian subgenera (*Deflectolepis*, *Panderolepis*, and  
445 *rhomboidea*) was moderately related (mean R=0.680) to the direction of Pmax in the late  
446 *Manticolepis* (MAN\_11c to MAN\_23).

447 The within-subgenus evolutionary trajectories were more strongly related to the Pmax direction  
448 within the involved subgenus (mean R=0.675), but not to the allometric direction of shape change  
449 (mean R=0.325). The match between the ancestor-descendent shape change and Pmax was  
450 particularly strong within *Deflectolepis* (mean R=0.951). It was also strong within *Manticolepis* (mean  
451 R=0.651), especially when focusing on OTUs posterior to MAN\_06 (mean R=0.751). The relationship  
452 was moderate within *rhomboidea* (mean R=0.614) and low within *Panderolepis* (mean R=0.358).

453

454 An integrated analysis of shape, Pmax, allometry, and P-matrices. – Five descriptors characterized  
455 the differences between the 22 OTUs: shape, main direction of shape variance (Pmax), structure of  
456 shape variance (P-matrices compared using RV coefficients and MB contrasts), and allometric  
457 vectors. This resulted in five topologies of the 22 OTUs on multivariate axes. These topologies shared  
458 some features, for instance the important differentiation between *Manticolepis* and *Deflectolepis*,  
459 and in agreement, these topologies were significantly related according to the Protests.  
460 Nevertheless, they also differed in important aspects, especially regarding the position of  
461 *Panderolepis* and *rhomboidea* relative to the two other subgenera.



462 The DISTATIS method allowed for the simultaneous analysis of these five descriptors. Despite being  
 463 different in nature (set of Fourier coefficients, vectors, and matrices), the relationships between the  
 464 22 OTUs based on the five descriptors were comparable, being expressed as Euclidean distance  
 465 matrices. The five descriptors shared positive loadings on the first axis of the compromise space of  
 466 the DISTATIS analysis (Fig. 6A), underlining that the topologies based on mean shape, Pmax, P-matrix  
 467 and allometry are related (see Table 2). Yet, allometry diverged from the other descriptors along the  
 468 second axis of the compromise space. Shape, Pmax and the RV comparisons between the P-matrices  
 469 provided the closest results.

470 On the same compromise first plane, the pattern of differentiation between the 22 conodont OTUs  
 471 provided by the five descriptors allows to recognize similitudes and discrepancies (Fig. 6B).  
 472 *Manticolepis* and *rhomboidea*, very close in shape, display distinct P-matrices and even more distinct  
 473 allometric directions, since they are the most divergent along the second axis. The samples MAN\_06  
 474 and PAN\_37, diverging from their subgenus for shape and Pmax, clearly display P-matrices and  
 475 allometric direction in agreement with their subgeneric attribution.

476 As a result, the compromised position of the different groups is very coherent with their subgeneric  
 477 identification (Fig. 6C). Samples attributed to a same subgenus are clustered on the compromise  
 478 space, and bootstrap estimates show that their position is robust regarding sampling issues.  
 479 *Panderolepis* is the most variable, its oldest representative (PAN\_35 and PAN\_37) being close to  
 480 *Manticolepis*, typical of the Frasnian, while more recent samples are close to *Deflectolepis*, typical of  
 481 the Late Famennian.

482

483 Temporal changes of shape and shape variance. – The temporal changes of the five descriptors can  
 484 be visualized as the scores of the 22 OTUs on the first axis of the different multivariate analyses, as a  
 485 function of geological time (Fig. 7). Mean shape (Fig. 7A) shows an opposition between *Manticolepis*  
 486 and *rhomboidea* and Late Famennian *Deflectolepis*. *Panderolepis* shifts from shapes plotting towards  
 487 *Manticolepis* (PAN\_35 and PAN\_37) to shapes close to *Deflectolepis*. During the Late Frasnian record,  
 488 *Manticolepis* displays a slight reduction of its platform, leading to a shift towards less extreme scores  
 489 along the shape axis.

490 All the descriptors of shape variance (Pmax and P-matrices) share similar features (Fig. 7B, C): major  
 491 difference between *Manticolepis* and *Deflectolepis*, stability in *Deflectolepis*, temporal changes  
 492 within *Manticolepis* and *Panderolepis*, with the oldest samples (MAN\_06 for *Manticolepis* and  
 493 PAN\_35 and/or PAN\_37 for *Panderolepis*) diverging from the most recent samples. MB contrasts  
 494 between VCV matrices insist on the intermediate position of *Panderolepis* between *Manticolepis* and

495 *Deflectolepis*. The idiosyncrasy of *rhomboidea* variance pattern does not appear on these  
 496 representations, because it is always expressed on the second or third multivariate axis; along the  
 497 first axis, *rhomboidea* shares similar scores with the other subgenus with a well-developed platform,  
 498 *Manticolepis*. Allometry (Fig. 7D) provides a different picture, with *Manticolepis* being most different  
 499 from *rhomboidea* and *Panderolepis*. All subgenera display a temporal stability in their pattern of  
 500 allometric variation, except for *Deflectolepis*. Variation in the allometric pattern within this subgenus  
 501 is however attributable to the weak signal preventing a robust estimate of the direction of allometric  
 502 shape change, if any.

503 A paleoenvironmental background was provided by temperature estimates based on oxygen isotope  
 504 values derived from conodont apatite (Fig. 7E). Rapid and pronounced temperature changes  
 505 occurred during the Late Frasnian, followed by environmental stability during the beginning of the  
 506 Famennian, and a subsequent step-wise temperature decrease.

507

## 508 Discussion

509 *Remodeling of the P-matrices: a tracer of changes in functional constraints?*

510 The most striking result of the present study was that long-term morphological evolution, leading  
 511 from conodont elements with a well-developed platform to slender elements, was associated with  
 512 deep changes in the pattern of shape variance. This was observed both as a temporal trend along the  
 513 Famennian, and in the diversification among subgenera. Shapes with a large platform were  
 514 associated with a variance concentrated on the relative development and morphology of this  
 515 platform, whereas in groups with a reduced platform, variance corresponded to the curvature of the  
 516 carina. Allometry was never found to be a main component of morphological variance, but its  
 517 contribution considerably varied among subgenera. In those with a well-developed platform  
 518 (*Manticolepis* and *rhomboidea*), allometry represented more than 10% of shape variance and  
 519 involved changes in the shape and extension of the platform. In subgenera with a reduced platform,  
 520 allometry represented less than 5% of shape variance, since the relative development of an anyway  
 521 reduced platform did not constitute an important morphological signal.

522 The 2D projection of the platform shape provided a good approximation of 3D morphological  
 523 changes in a related taxon, *Polygnathus* (Renaud et al. 2021), belonging as *Palmatolepis* to the  
 524 Ozarkodinida Order (Donoghue et al. 2008). Such 2D simplification allows an extensive sampling, and  
 525 thus the quantification of variance patterns through time; it however provides only indirect  
 526 information about the three-dimensional geometry of the elements (Fig. 8) and thus about the

527 functional constraints related to their occlusion. *Manticolepis* elements had a well-developed  
528 platform (Fig. 8A), but most of it could not come into contact with the platform of the opposite  
529 element (Nicoll 1987). Contact between occluding elements should thus have been concentrated  
530 along the blades (Donoghue 2001). The large and almost flat platform may have served as anchorage  
531 into the soft tissues of the jawless mouth. In contrast, in most recent *Deflectolepis* (Fig. 8D), the  
532 platform was absent and therefore could not vary in shape; the blade and carina were the most  
533 prominent features of the elements. The angle in the blade-carina alignment contributed most to the  
534 morphological variance in this subgenera and most probably, it constrained the way the two  
535 elements went into occlusion. Characterized by a reduced but still present platform, *Panderolepis*  
536 elements (Fig. 8C) displayed a shape marked by an elevated inner anterior platform edge  
537 (“shoulder”) up to the development of a parapet, delineating a groove of varying depth between the  
538 blade and the border of the inner platform. The opposite blade, when coming into contact, should  
539 thus have been stabilized along this groove, as observed in *Polygnathus* (Martínez-Pérez et al. 2016).  
540 The shape changes associated with Pmax and the P-matrix in this subgenus (Fig. 3) suggested that  
541 the main component of variance, corresponding to more or less sigmoidal shapes, expressed more or  
542 less pronounced shoulder and parapet. Note that asymmetry was never found important in  
543 *Palmatolepis* elements, being one order of magnitude less than what has been found in *Polygnathus*  
544 (Renaud et al. 2021). Asymmetry was the less pronounced in the subgenera with a large platform,  
545 corroborating that the opposite platforms had few functional interactions in these morphologies. The  
546 profound remodelling of the P-matrices among subgenera therefore illustrates that important  
547 changes in mean shape involved modifications in the functional constraints, in turn conditioning  
548 what kinds of morphological variants could be realized within a population.

549 The shift of *Palmatolepis* mean shape along the Famennian, leading from elements with to elements  
550 without well-developed platform, observed even when considering whole assemblages (Girard and  
551 Renaud 2012), suggests that the adaptive optimum shifted in favor of slender elements devoid of  
552 platform. It does not relate to evident abiotic changes, since the first half of the Famennian was a  
553 rather stable period (Girard et al. 2020). The cooling characterizing the mid-Late Famennian  
554 postponed the shift towards a reduction of the *Palmatolepis* platform. It could be rather related to a  
555 rearrangement of the nektonic fauna, with the expansion of potential competitors and predators of  
556 conodonts, such as sharks and bony fishes (Ginter et al. 2002; Gauchey et al. 2014), leading to new  
557 functional constraints on the feeding apparatus.

558

559 *Response of P-matrices to short term environmental fluctuations and evolutionary consequences*

560 The Latest Frasnian was a period of intense environmental perturbations. Temperature abruptly  
561 dropped towards the end of the LKE (Girard and Renaud 2007), and progressively increased again  
562 between the LKE and the UKE (Fig. 7) before a second rapid temperature decrease during the UKE,  
563 culminating with the F/F crisis (McGhee 1996; Joachimski and Buggisch 2002). A morphological  
564 response was documented in *Palmatolepis*, with changes in mean shape tracking temperature  
565 variations during the Latest Frasnian, leading to a back- and forth evolution of larger platform when  
566 temperature decreased (e.g., end of the LKE) and narrower platforms when temperature increased  
567 (Balter et al. 2008). Temperature changes were associated with productivity variations, suggesting  
568 that the paleoenvironmental perturbations had profound effects on the trophic chains (Balter et al.  
569 2008), thus probably exerting strong selective pressure on the feeding apparatus of the conodont  
570 animal. The reorientation of Pmax and P-matrix documented between MAN\_06 and the following  
571 *Manticolepis* OTUs illustrates their remodeling following a moving peak optimum (Eroukhmanoff  
572 2009; Jones et al. 2012). Such reorientation can boost evolutionary responses to environmental  
573 changes (Hangartner et al. 2019). It may have been a key to the successful response to the even  
574 more rapid and drastic environmental changes marking the UKE and the F/F crisis. Most if not all  
575 Famennian representatives are supposed to be derived from Frasnian *Manticolepis* (Helms and  
576 Ziegler 1981). The divergence in mean shape leading from *Manticolepis* to the Famennian subgenera  
577 *rhomboidea*, *Panderolepis* and *Deflectolepis* occurred along the Latest Frasnian *Manticolepis* Pmax,  
578 showing that the Famennian diversification surfed on the variance in platform shape that resulted  
579 from the response to the environmental perturbations during the LKE-UKE interval.

580

#### 581 *Patterns of variance within subgenera: contrasted evidences*

582 In contrast with these reorientation of the P-matrices following moving adaptive optima, Pmax and  
583 P-matrices were stable within two subgenera, *Deflectolepis* and *rhomboidea*. The temporal extension  
584 of the latter is quite short in our sampling (less than 0.5 myrs), letting little time for changes in the  
585 pattern of variance; this nevertheless represents a substantial part of the temporal extension of this  
586 short-lived group. The temporal range covered by the *Deflectolepis* OTUs was in contrast 5 myrs long.  
587 This suggests that these subgenera remained close to a stable adaptive optimum, retaining the same  
588 functional constraints and the same patterns of variation. Accordingly, the morphological evolution  
589 from early to late *Deflectolepis* was of moderate magnitude and occurred according to Pmax,  
590 suggestive of stabilizing or weak directional selection. In such cases, the constraints embodied in the  
591 P-matrix are prone to channel morphological evolution (Ackermann and Cheverud 2004; Renaud et  
592 al. 2006).

593 In contrast, Pmax and P-matrices were found to vary within the ~3.5 myr record of *Panderolepis*. This  
 594 may be due to species replacement, with *tenuipunctata* occurring in the first two OTUs (PAN\_35 and  
 595 PAN\_37) whereas *glabra* is the sole species in the later OTUs. Shape, Pmax and P-matrices of  
 596 *Panderolepis* OTUs dominantly composed of *tenuipunctata* share similarities with *Manticolepis* OTUs,  
 597 whereas later OTUs share more similarities with *Deflectolepis*. *Panderolepis* may document, at the  
 598 micro-evolutionary level, the trend of platform reduction also expressed at the macro-evolutionary  
 599 level among subgenera and among whole assemblages (Girard and Renaud 2012), confirming a  
 600 general shift in the adaptive optimum during the Famennian, and that the reduction of the platform  
 601 was associated with a reorientation of the P-matrices, pointing to new constraints on morphological  
 602 variation. Nevertheless, all *Panderolepis* samples, being composed of *tenuipunctata* or *glabra*, share  
 603 common features of the P-matrix (Fig. 4C) and allometry (Fig. 4D), showing homogeneity despite the  
 604 shape changes characterizing the Famennian record of this subgenus.

605 Patterns of allometric growth were very stable within *Manticolepis* and *rhomboidea* as well. In  
 606 contrast, the allometric pattern varied within *Deflectolepis*, but this was due to the little amount of  
 607 allometric variation. Despite of the stable allometric pattern characterizing most of the subgenera,  
 608 allometry did not constitute a line of least evolutionary resistance in *Palmatolepis*. This suggests that  
 609 the basic shape of each element was determined by the shape of the initial nucleus, later on only  
 610 moderately modified by differential accretion. This also suggests that functional constraints did not  
 611 deeply changed through age, but remained relatively stable through ontogeny.

612

### 613 *P-matrices through time: stability and changes as a response to moving adaptive optimum*

614 The study of G/P-matrices in modern organisms delivered contrasted results, with both evidences of  
 615 short-term fluctuations (Roff and Mousseau 2005; Guillaume and Whitlock 2007; Eroukhmanoff and  
 616 Svensson 2008) and stability (Bégin and Roff 2003; McGuigan et al. 2005). The nature of the traits  
 617 probably influences the results: demographic traits, which may vary rapidly due to differences in  
 618 acquisition/allocation patterns, may be more prone to show rapid variations of the P-matrix  
 619 (Björklund et al. 2013). Estimates of Pmax and P-matrix in the fossil record are still uncommon, and  
 620 inevitably raise some issue with time-averaging. However, it seems to have little impact on estimates  
 621 of trait variation (Hunt 2004). If ever, it may buffer short-term variations, as it does for evolutionary  
 622 rates (Gingerich 1983).

623 Few studies delivered insights into the temporal stability of Pmax over a duration similar to the  
 624 *Palmatolepis* record considered here (~10 myrs). In two related lineages of Late Triassic conodonts,  
 625 Pmax was found to be stable over such a time period (Guenser et al. 2019). In murine rodent molars,

626 Pmax was also found to be stable along evolutionary lineages and across phylogenetic divergence  
627 over 10 myrs (Renaud et al. 2006; Renaud and Auffray 2013). In contrast, in ostracod shells, the  
628 correlation between Pmax of successive OTUs was found to fade away over few million years (Hunt  
629 2007). Compared to these records, the subgenus *Palmatolepis* delivered both examples of mid-term  
630 stability and of rapid remodeling of the P-matrix. Contrary to subgenera such as *Manticolepis* and  
631 *Deflectolepis*, being differentiated by the size of their platform, the Late Triassic conodont lineages  
632 shared close morphologies and they probably shared similar constraints regarding occlusal  
633 functioning, explaining the conserved pattern of variance. In murine rodents, important  
634 modifications occurred on the molar teeth along the 10 myrs of evolution, such as the addition of  
635 new crests, and the broadening and heightening of the molars (Renaud et al. 2005). Nevertheless,  
636 the typical mastication for murine rodents was not modified (Lazzari et al. 2008), maintaining similar  
637 strong functional constraints on the alignment of molar cusps. In contrast, functional constraints on  
638 ostracod shells may be less strong, being related to the physical properties of the aquatic habitat, or  
639 to anti-predator defenses, letting more latitude for changes of the variance pattern along time and  
640 phyletic evolution. Therefore, stability or changes in P-matrices over time could deliver insights into  
641 the strength of functional constraints and their persistence or change along morphological evolution.  
642 Our results also provide empirical evidences that moving adaptive optima indeed cause a  
643 reorientation of the variance pattern by selecting new phenotypic variants (Eroukhmanoff 2009). In  
644 this context, one strength of the present study is to have quantified not only Pmax but P-matrices  
645 through time. Considering P-matrices provides a more complete assessment of the patterns of  
646 variance-covariance and more nuanced insights into temporal changes, because P-matrices are less  
647 impacted by instability between the first (Pmax) and second axes of morphological variance.

648

## 649 **Conclusion**

650 Beyond the study of mean shape, evaluating Pmax and P-matrices through time may thus shed light  
651 on the response of species to changing environments and/or functional constraints. On time scales of  
652 several millions of years, the question seems not to be whether the P-matrix is stable, but how it is  
653 varying in response to changes in selection regimes and shifts in adaptive optimum. Our study  
654 validated the hypothesis that environmental fluctuations impacting the faunas, likely representing  
655 moving adaptive optima, selected for new mean shapes but also for new types of variants around  
656 mean shape, thus reorienting Pmax and the P-matrix. We also validated the hypothesis that during  
657 periods of relatively stable environmental conditions, Pmax and P-matrix were conserved and  
658 channeled the moderate evolution in mean shape within subgenera. In contrast, we did not validate

659 allometry as a major component of shape variance in *Palmatolepis*, suggesting that heterochronic  
 660 processes were not important in the diversification of buccal elements within this genus. Instead,  
 661 evolution in mean shape seems related to changes in occlusal functioning, switching from a scissor-  
 662 like contact between blades stabilized by a large platform in *Manticolepis*, to an occlusion stabilized  
 663 by an inner shoulder up to a parapet in *Panderolepis*, or a reduction to mere occluding blades in  
 664 *Deflectolepis*. By changing the functional constraints, this evolution involved changes in the realized  
 665 variance around mean shape, traduced by a reorientation of Pmax and the P-matrices. In such deep  
 666 times and with such fossil groups devoid of modern equivalents, the study of stability and changes in  
 667 morphological variance may help, beyond the study of mean shape alone, to characterize moving  
 668 adaptive optima, and functional constraints related to a given geometry.

669

#### 670 **Conflict of interest**

671 The authors declare that they have no conflict of interest.

672

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- 875

876 **Tables**

OTU	Age	MAN	RHO	PAN	PAN	DEF	DEF	OTU	Right
				<i>glabra</i>	<i>tenuipunctata</i>	<i>gracilis</i>	<i>minuta</i>		
DEF_63	363.45					86		DEF_63	43
DEF_62	363.80					58		DEF_62	36
DEF_61_1	364.60					62		DEF_61_1	40
DEF_59	366.00					69	2	DEF_59	33
DEF_56	366.21					45		DEF_56	24
PAN_56	366.21			40				PAN_56	21
PAN_51	367.10			102				PAN_51	102
PAN_50	367.22			72				PAN_50	37
DEF_42	368.31						71	DEF_42	40
RHO_42	368.31		61					RHO_42	27
DEF_41	368.48						34	DEF_41	20
RHO_41	368.48		49					RHO_41	25
RHO_39	368.60		149					RHO_39	80
PAN_37	369.22			12	30			PAN_37	21
PAN_35	369.77				65			PAN_35	31
MAN_23	371.47	51						MAN_23	27
MAN_22	371.70	95						MAN_22	68
MAN_12	372.12	56						MAN_12	28
MAN_11c	372.15	56						MAN_11c	37
MAN_08	372.34	39						MAN_08	16
MAN_07	372.38	83						MAN_07	49
MAN_06	372.43	48						MAN_06	24

877

878 **Table 1.** Sample size for each OTU. The label summarizes the subgenus (three-letters code) and the  
879 stratigraphic level (from 06 to 63). An estimation of the absolute age is provided for each sample  
880 according to the datation framework of Becker et al. (2020). MAN: *Manticolepis*. RHO: *rhomboidea*.  
881 PAN: *Panderolepis*. DEF: *Deflectolepis*. For these two latter subgenera, the sample size is  
882 decomposed into the two species present. Mixing only occurs in PAN\_37 and DEF\_59. Right: number  
883 of right elements in the corresponding OTU.

884

885

ProcR \ P	Shape (bgPCA)	Pmax	P-RV	P-MB	Allometry
Shape (bgPCA)	-	0.0001	0.0001	0.0001	0.0002
Pmax	0.741	-	0.0001	0.0001	0.0001
P-RV	0.868	0.861	-	0.0001	0.0001
P-MB	0.817	0.655	0.840	-	0.0001
Allometry	0.592	0.632	0.700	0.707	-

886

887 **Table 2.** Relationships between the topologies between the 22 OTUs, based on the different  
 888 descriptors of shape and shape variance. Protest results are shown (above the diagonal, P-values  
 889 based on 10,000 permutations; below the diagonal, ProcR). P-RV: analysis of the P-matrices based on  
 890 RV coefficients; P-MB: analysis of the P-matrices based on MB contrasts.

891

	pve	P	pve	P	pve	P
	Subgenus		Size (A0)		Asymmetry	
All	41.2%	< 2e-16	1.5%	< 2e-16	0.2%	1.02e-05
	Level		Size (A0)		Asymmetry	
<i>Manticolepis</i>	12.1%	< 2e-16	14.2%	< 2e-16	0.3%	0.0005
<i>rhomboidea</i>	6.8%	< 2e-16	13.1%	< 2e-16	0.4%	0.2070
<i>Panderolepis</i>	20.3%	< 2e-16	4.6%	< 2e-16	0.6%	0.0022
<i>Deflectolepis</i>	9.8%	< 2e-16	3.3%	< 2e-16	0.5%	0.0071

892

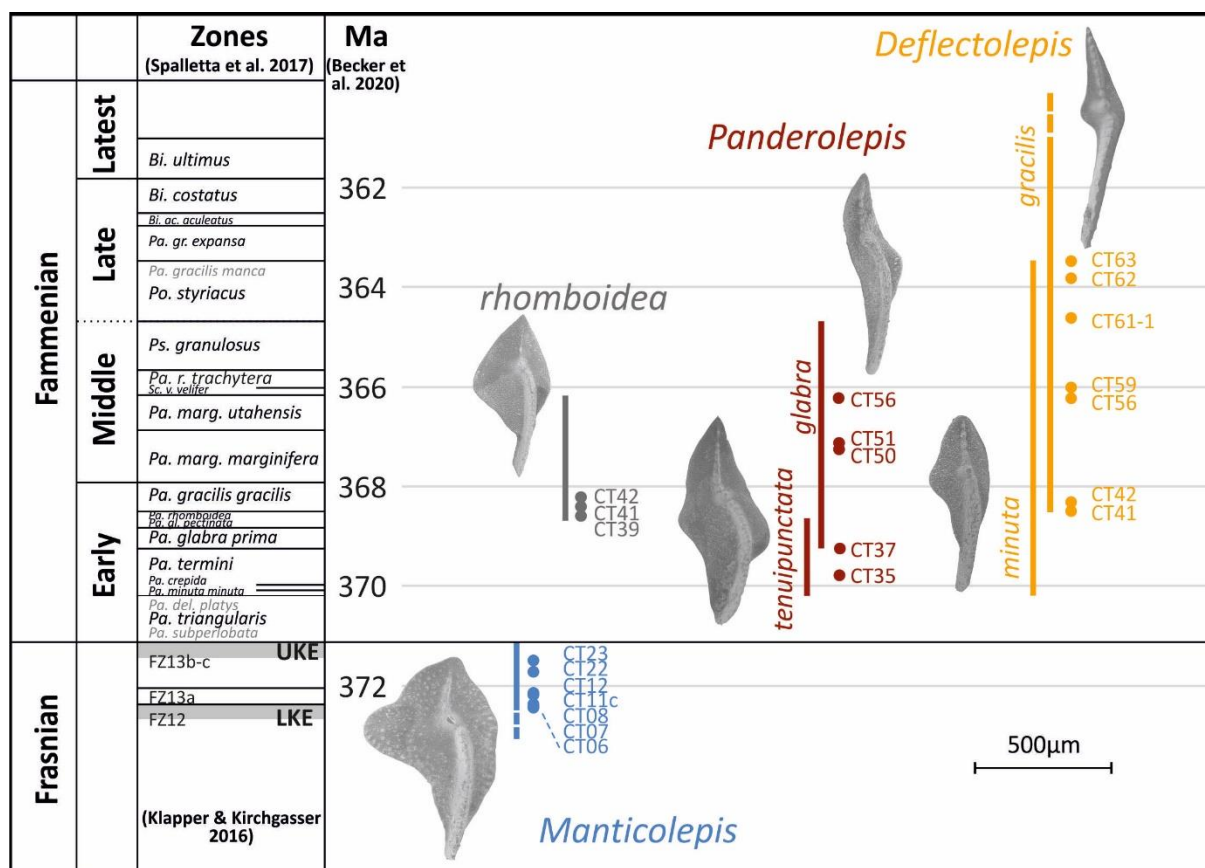
893 **Table 3.** Relative importance of the different sources of morphological variance: subgenus attribution  
 894 in the total dataset and level within each subgenus; size (A0) and bilateral asymmetry (Right / Left  
 895 Side). Percentage of variance explained (pve) are provided together with P-values estimated using  
 896 the ffmanova procedure.

897

## 898 Figures and Figure Captions

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903 **Figure 1.** Illustration and temporal distribution of the studied subgenera of *Palmatolepis*. Code of the  
 904 levels: cf. Table 1 (e.g. CT42: level 42 of the Col des Tribes section). Stratigraphic zonation is provided  
 905 on the left (Frasnian: Klapper and Kirchgasser 2016; Famennian: Spalletta et al. 2017); absolute ages  
 906 after Becker et al. (2020). In grey, zones that have not been identified at the Col des Tribes section.  
 907 Illustrations are all to the same scale.

908 Labels of the illustrated specimens, from left to right: *Manticolepis* UM CTB 035 (CT22); *Palmatolepis*  
 909 (*Panderolepis*) *tenuipunctata* UM CTB 036 (mirror image; CT35); *Palmatolepis* (*Panderolepis*) *glabra*  
 910 UM CTB 037 (mirror image; CT48); *Palmatolepis rhomboidea* UM CTB 038 (mirror image; CT41);  
 911 *Palmatolepis* (*Deflectolepis*) *minuta* UM CTB 039 (CT37); *Palmatolepis* (*Deflectolepis*) *gracilis* UM CTB  
 912 040 (CT69).

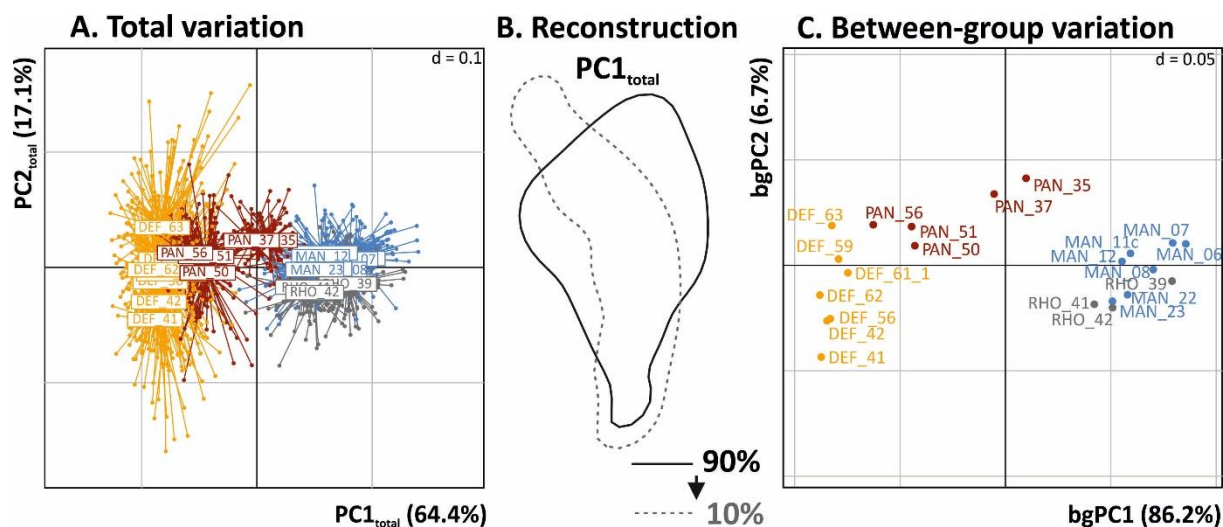
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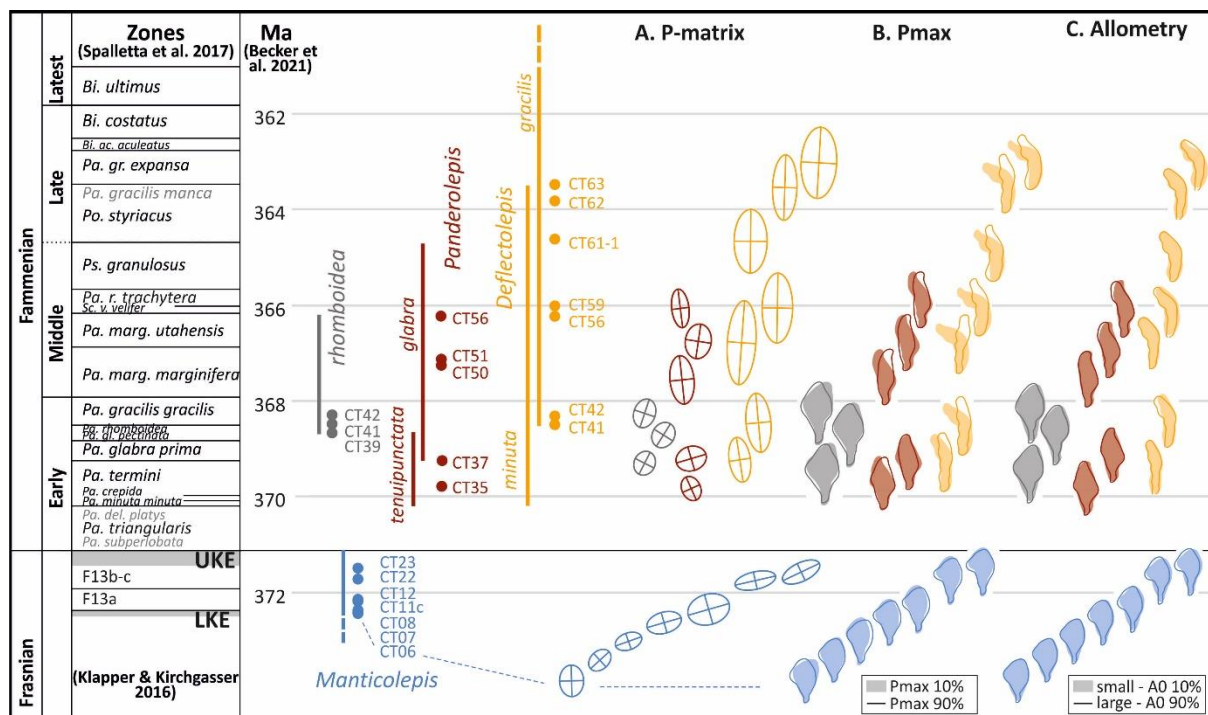
918

919 **Figure 2.** Shape differentiation between the 22 conodont Operational Taxonomic Units (OTU), based  
 920 on the 18 shape variables describing the outline. A. Total variation, depicted on the first two axes of a  
 921 PCA. Each dot represents one specimen. The color code corresponds to the four subgenera. B.  
 922 Reconstructions of outlines illustrating the shape changes along the first PC axis. Grey dotted line:  
 923 10% smallest score along PC1. Full black line: 90% highest score along PC1. C. Between-group  
 924 variation, depicted on the first two axes of a bgPCA. Each dot represents the mean of one conodont  
 925 OTU. In A and C, the grid size is indicated by the d value at the upper right of the graph.

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929

930 **Figure 3.** Visualization of the temporal variation of Pmax, P-matrices and allometry in the 22 OTUs.

931 (A) P-matrices, represented as ellipses defined by their first two axes, projected on the first principal

932 plane of PCA<sub>total</sub> (see Fig. 2A). Their principal axis corresponds to the direction of the first eigenvector

933 (Pmax), the elongation represents the anisotropy of the variance (relative percentage of variance

934 represented by the first and second axes). (B) Pmax: the outlines in full lines and in transparency

935 visualize the shapes corresponding to 10% and 90% largest scores, respectively, on the first

936 eigenvector (Pmax). Since the +/- direction is arbitrary on such multivariate axes, the representation

937 has been homogenized: in transparent surfaces, outlines with a less developed platform and/or a

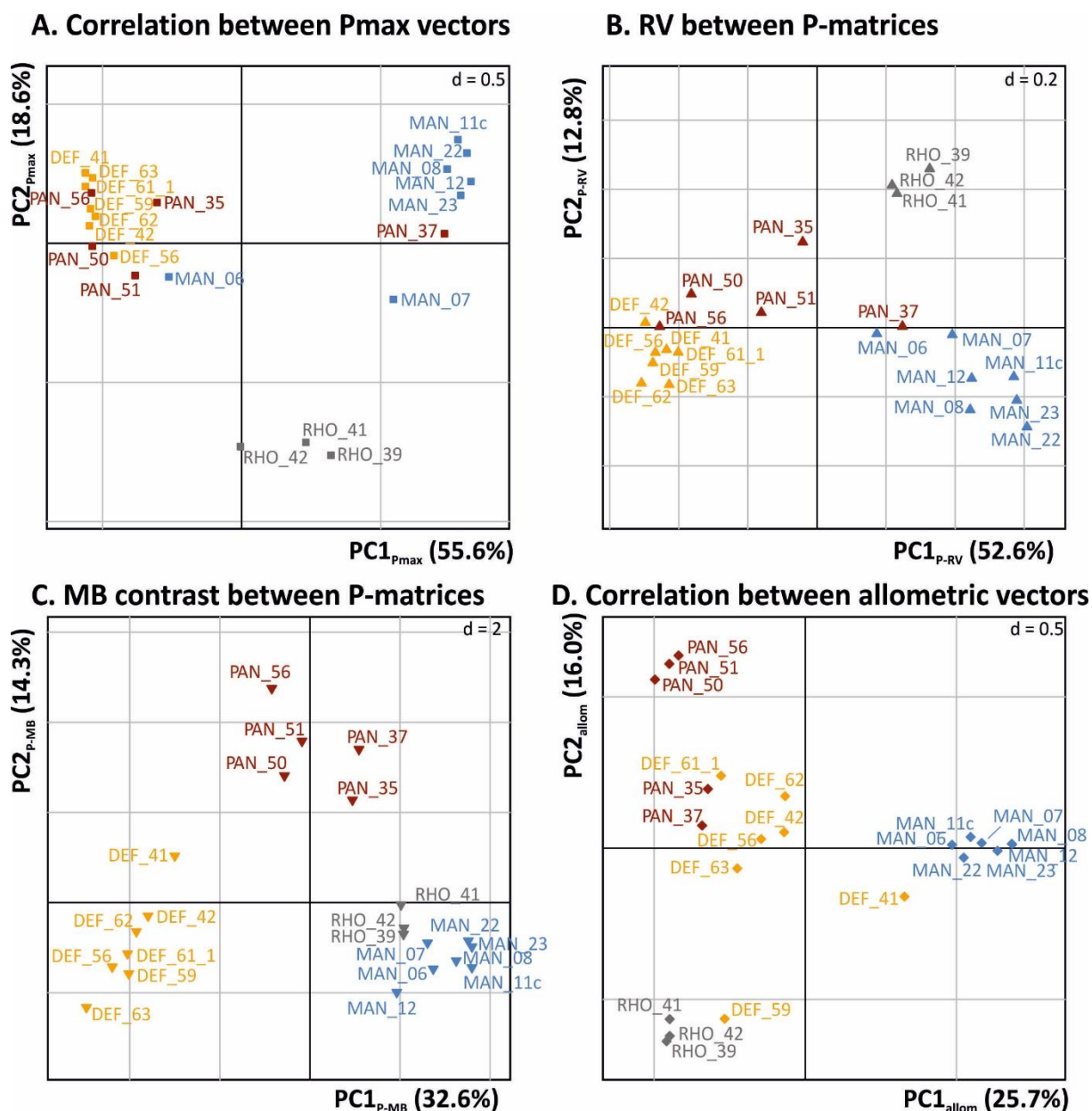
938 straighter shape. (C) Allometry: shapes corresponding to the 10% smallest size (in transparency) and

939 90% largest size (full line).

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943 **Figure 4.** First two axes of PCOAs on four distance matrices describing the relationships between the

944 22 conodont OTUs. A. Distances derived from the correlation between Pmax vectors (squares). B.

945 Distances based on the RV coefficients between P-matrices (up-pointing triangles). C. Contrast

946 between P-matrices, based on the Mitteroecker &amp; Bookstein (“MB”) metric (down-pointing

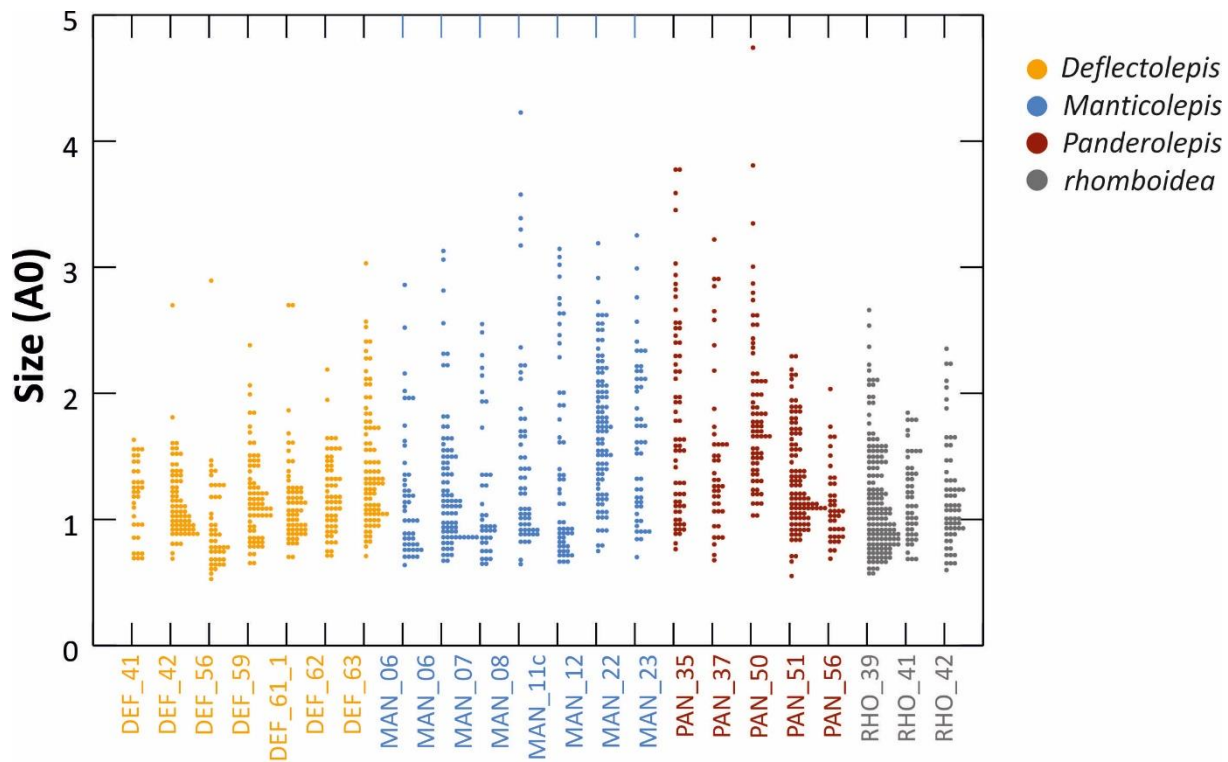
947 triangles). D. Distances based on the correlation between allometric vectors (diamonds).

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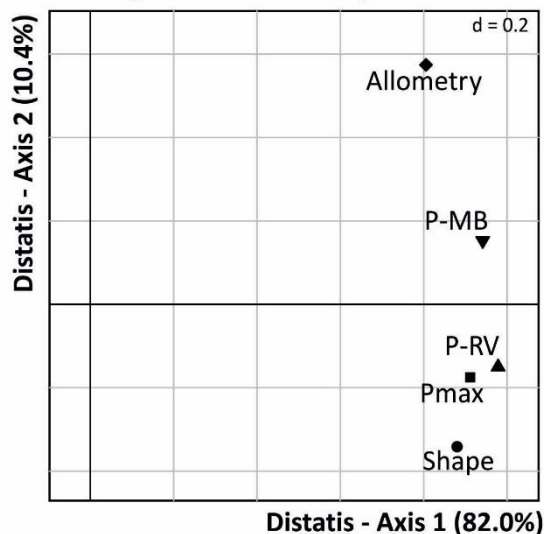
952

953 **Figure 5.** Size variation in the 22 conodont OTUs. Each dot corresponds to an element; size is  
 954 estimated by the zero harmonic of the outline analysis.

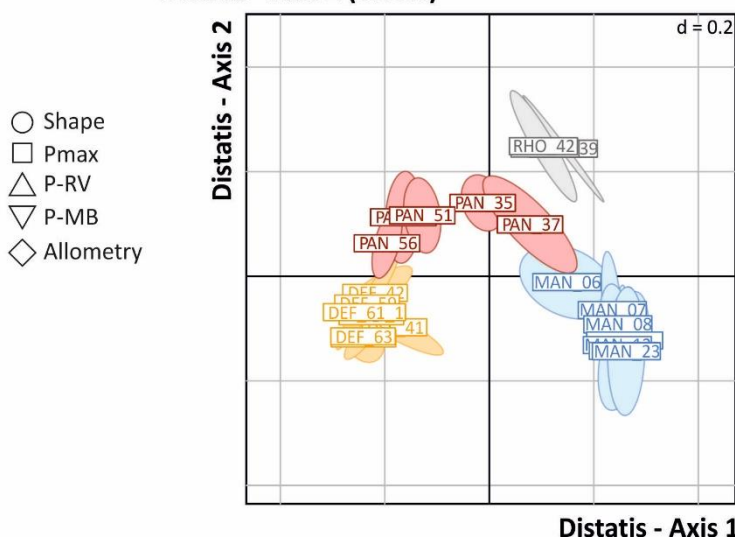
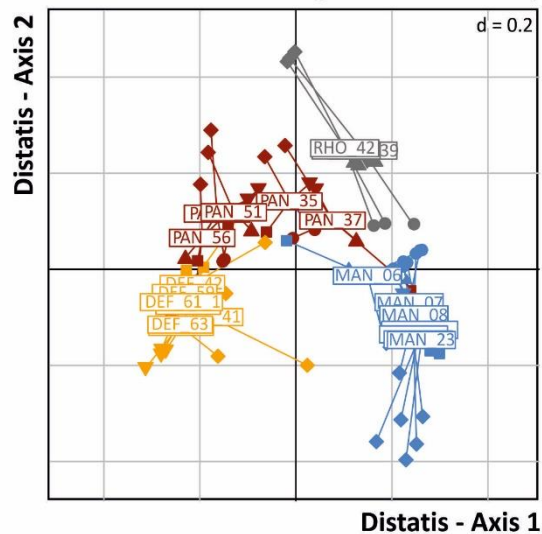
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### A. Loadings of the 5 descriptors



### B. The 22 OUs according to the 5 descriptors

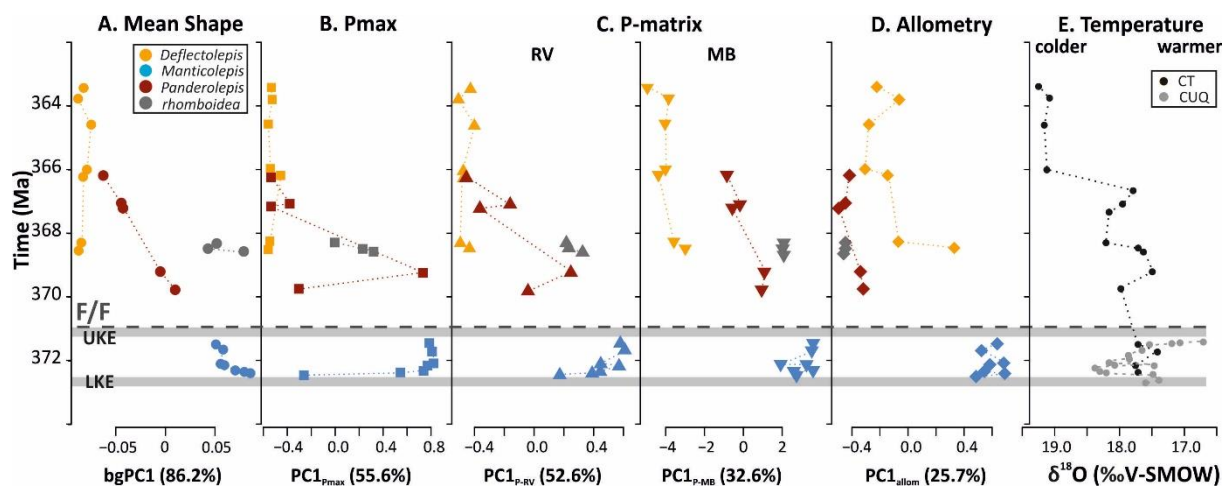


### C. Compromise and bootstraps

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958 **Figure 6.** Simultaneous analysis of shape, Pmax, allometry, and P-matrices compared using RV (“P-  
 959 RV”) and “MB” contrast (“P-MB”) using the DISTATIS method. A. Relationship between the five  
 960 descriptors in the compromise space. B. Relationships between the 22 OTUs according to the five  
 961 descriptors in the compromise space. C. Position of the 22 conodont OTUs in the compromise space,  
 962 surrounded by bootstrap estimates.

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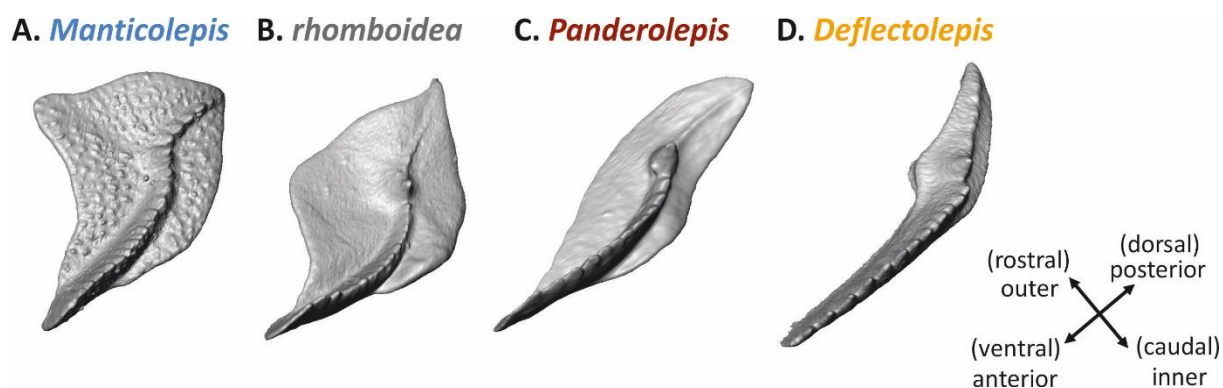
964

965

966 **Figure 7.** Temporal changes in mean shape, Pmax, P-matrix, and allometry compared with the  
 967 paleotemperature record. Variations in shape (A) is summarized by the scores of the 22 OTUs on  
 968 bgPC1; variations on Pmax (B), P-matrix (C) and allometry (D) are summarized by the scores on the  
 969 respective PC1. Paleotemperature (E) is estimated by  $\delta^{18}\text{O}$  in the Col des Tribes (CT) levels considered  
 970 in this study (Girard et al. 2020). The Frasnian record is completed by data from the neighboring  
 971 Coumiac Upper Quarry (CUQ) section, in grey (Balter et al. 2008). These data have been corrected of  
 972 0.7‰ in order to account for different standards. Dotted line: Frasnian/Famennian boundary (F/F).

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977 **Figure 8.** Tridimensional morphology of right P1 elements of the four subgenera considered:  
 978 *Manticolepis*, *rhomboidea*, *Panderolepis* and *Deflectolepis* (not to the same scale). (A) *Pa.*  
 979 *Manticolepis*, level CT22, length = 0.96  $\mu\text{m}$  (UM CTB 078). (B) *Pa. rhomboidea*, level CT42, length =  
 980 0.96  $\mu\text{m}$  (UM CTB 079); (C) *Pa. (Panderolepis) glabra*, level CT46, length = 0.47  $\mu\text{m}$  (UM CTB 080); (D)  
 981 *Pa. (Deflectolepis) gracilis*, level CT63, length = 0.62  $\mu\text{m}$  (UM CTB 081).