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# 1 Global climate changes account for the main trends of conodont diversity but not for their final demise

2

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9

10 **Keywords:** Past climate, Court Jester, Abiotic drivers, Conodonta, Mass Extinction.

11

## 12 Abstract

13 Conodonts, one of the longest-lived early groups of vertebrates, have a very complete fossil record ranging from the late  
14 Cambrian to the end of the Triassic and persisted through many global climatic and biotic events. In this paper, we  
15 analyse a large dataset harvested from the Paleobiology Database to compute global diversity curves at the generic level  
16 and explore patterns of conodont paleogeographic distribution. Our results partly confirm the most prominent findings  
17 of earlier studies including the occurrence of an Ordovician acme, a Permian nadir and a short-lived Triassic recovery.  
18 Major peaks of origination were found in the Early Ordovician and Early Triassic, while major extinctions occurred in  
19 the Upper Ordovician and Pennsylvanian. Paleogeographical extent of conodonts was impacted by i) the position of  
20 paleo-continent (notably impacting the latitudinal gradient of diversity), ii) the available continental shelf area and iii)  
21 ice sheets expansion. Diversity trends were mostly impacted by transitions between hothouse and icehouse ages, with  
22 major glaciations and associated marine regressions co-occurring with major extinctions. The influence of global sea  
23 level was less marked than that of temperature. However, the final demise of conodonts at the end of the Triassic did  
24 not coincide with either a major glaciation or marine regression. This supports the view that extinction of the group was  
25 mostly due to biotic factors such as competition with 'Mesozoic' taxa.

26

## 27 1. Introduction

28 Biodiversity is impacted by numerous interconnected factors, and disentangling their effects is a challenge for  
29 biologists and paleontologists alike. In this regard, the relative importance of biotic and abiotic factors in the variation  
30 of global biodiversity through geological times remains an open debate, often referred to as the Red Queen vs. Court  
31 Jester debate. Biotic factors encompass aspects intrinsic to the living organisms, as well as interactions between  
32 organisms, such as competition; while abiotic factors include extrinsic aspects, often related to climatic or geological  
33 changes (Benton 2009). At high taxonomic levels and broad timescales, abiotic factors may play a larger role (Benton  
34 2009). Yet, it remains difficult to test biotic effects in the fossil record, where the interactions between taxa are hardly  
35 accessible, and the true null hypothesis, namely that diversity follows a random walk through time is generally ignored.  
36 Simulations and modeling, which are employed more and more frequently, are a way to remedy to this. For instance,  
37 they allow to assess how trophic relationships in paleo-communities may affect the stability of the considered  
38 ecosystem to perturbations, for instance whether the extinction of a few taxa or functional groups may lead to cascading  
39 effects and eventually to the collapse of the ecosystem (Roopnarine et al. 2007); or to determine how and when within a

40 clade history biotic interactions are most likely to control the dynamics of speciation, extinction and diversity (Aguilée  
41 et al. 2018, Hoffman et al. 2019).

42 Another currently outstanding challenge is to anticipate the evolution of biodiversity to the current  
43 anthropogenic crisis, based on how biodiversity reacted in the past to global changes analogous to the ones Earth is  
44 experiencing today (Payne and Clapham 2012). How are different parts of the biosphere differentially affected by  
45 critical abiotic factors? Studies of the fossil record in correlation with major climatic and geological variables remain  
46 the most direct way to address this challenge. Historically, marine biodiversity has been the focus of such studies,  
47 essentially because the fossil record of marine organisms is more complete and better resolved than that of terrestrial  
48 organisms (e.g. Sepkoski 1981).

49

### 50 *1.1. Conodont diversity through time*

51 Despite its long and global record, the clade of conodonts remains understudied in terms of macroevolution.  
52 Conodonts form an early and diverse group of marine vertebrates, most probably associated to extant cyclostomes  
53 (lampreys and hagfishes; Miyashita et al. 2019). Ecologically, conodonts are generally considered to have been small  
54 active swimmers, mostly nektonic, primary consumers (Purnell 2001). This broad picture is however probably not true  
55 for all conodont species, considering their high morphological disparity and the variety of sedimentological facies in  
56 which their remains are found (Purnell and Jones 2012, Ginot and Goudemand 2019). Through their long fossil record  
57 (over 300 My, from Cambrian to the end of the Triassic; Dong et al. 2004, Zhen et al. 2018, Tanner et al. 2004),  
58 conodonts as a group have faced some of the most prominent events in the history of Earth, including four out of five  
59 mass extinction crises (end Ordovician, Late Devonian, end Permian, and end Triassic), and they survived all, except  
60 the last, eventually disappearing at the end of the Triassic. As such, they constitute a good model organism to study how  
61 the diversity of small, nektonic organisms may be impacted by major environmental changes. The responses of  
62 conodont diversity to environmental changes have been generally studied at the scale of individual events only, often  
63 with the biostratigraphic objective of defining biozones (e.g. Orchard 2007), rather than as a whole. Conodont diversity  
64 trends have not recently been tackled over large timeframes (Clark 1983, 1987, Sweet 1988) – although conodont data  
65 was included in much broader studies (Friedman and Sallan 2012, Whalen and Briggs 2018) – which is now made  
66 possible and more exhaustive by the advent of global fossil occurrence databases (i.e. the Paleobiology Database), and  
67 more reliable thanks to new methods for the quantification of diversity, origination and extinction (e.g. Alroy et al.  
68 2008, Alroy 2010b). Here, we aim not only at updating the previously published trends of conodonts diversity, but also  
69 at statistically testing their potential control by some abiotic variables (temperature, sea-level, paleogeography) for  
70 which we collected quantitative data from the literature. Other abiotic parameters, such as water pH, bathymetry or  
71 paleo-currents, may also play a role but because of a lack of available, appropriate, quantitative data, those were not  
72 included here.

73 The rise of the ‘Paleozoic Fauna’ identified by Sepkoski (1981) started in the Ordovician, forming what we  
74 now call the Great Ordovician Biodiversification Event (GOBE). Although abiotic factors such as a cooling of sea  
75 water temperatures have been proposed to be linked to the GOBE, there is still no consensus about the causes of this  
76 event (Servais and Harper 2018). The ‘plankton revolution’ of the Early Ordovician, which represents the first major  
77 biodiversity event of the GOBE, may be linked to increasing sea level, oceanographic changes and oxygenation. The  
78 consequent increase in planktonic resources may have brought the diversification of other forms. Although the first  
79 conodonts arose during the Cambrian (Dong et al. 2004), their radiation is mostly part of the GOBE, and may be related

80 to both biotic (plankton diversification) and abiotic factors. The Ordovician diversification was interrupted by the end  
81 Ordovician extinction, the first of the ‘Big Five’ extinctions. This two-pulse extinction is generally attributed to a major  
82 glaciation associated with a regression (first pulse), followed by a transgression associated with anoxia (second pulse).  
83 Although short-spanned (~1Ma), it caused important habitat loss and impacted conodonts, among others, at both pulses  
84 (Harper et al. 2014). However, the duration of this glaciation is debated, and may extend to 10Ma, which would have  
85 put conodonts and the biosphere through an even greater challenge. The next major climatic episode may have been the  
86 Middle Devonian ‘super-greenhouse’, although the nature of this event is now challenged (Joachimski et al. 2009): the  
87 Early Devonian was already characterized by warm temperatures, and it now appears the Middle Devonian was in fact  
88 characterized by a global cooling – without glaciation – followed by a global warming that led seawater temperatures to  
89 reach two maxima around the Frasnian/ Fammenian boundary (Joachimski et al. 2009). The two Kellwasser  
90 environmental events occurred before, and in-between those maxima and correspond to cooler and anoxic episodes.  
91 These events are known to have affected both conodont diversity and morphology (Girard and Feist 1996, Balter et al.  
92 2008). From the end of the Fammenian, and throughout the Carboniferous and Permian, a period known as the Late  
93 Paleozoic Ice Age, the global climate was mostly cold and associated with glaciations and low sea levels, (Montanez  
94 and Poulsen 2013). According to Buggish et al. (2008), the tipping point between the Devonian greenhouse and the Late  
95 Paleozoic Ice Age was reached in the Mississippian. Two cycles of glaciation are recorded, the first peaking (coldest  
96 temperatures) at the transition between the Mississippian and Pennsylvanian and the second around the Carboniferous /  
97 Permian boundary (Buggish et al. 2008, Montanez and Poulsen 2013). These glacial events were accompanied by  
98 important and rapid eustatic variations (e.g. Joachimski et al. 2006, Barrick et al. 2013, Montanez and Poulsen 2013,  
99 Bahrami et al. 2014). During this ice age (Pennsylvanian), invertebrates showed low rates of origination and extinction  
100 and diversity was low (Stanley and Powell 2003, Powell 2005, Alroy et al. 2008). Similar trends were reported by Clark  
101 (1983) for conodonts, with a large drop in origination and extinction rates and in the number of genera between  
102 Mississippian and Pennsylvanian.

103         There is evidence for episodic glacial deposits until the end of the Middle Permian, and deglaciation in the  
104 upper Permian (~260Ma ; Montanez and Poulsen 2013). Global temperatures increased and peaked at the P/T boundary,  
105 linked with the volcanic activity of the Siberian Traps, causing global greenhouse warming, ocean acidification,  
106 associated with episodes of anoxia or euxinia (Sun et al. 2012, Romano et al. 2013, van de Schootbrugge and Wignall  
107 2016) . Throughout the Permian only a handful of conodont genera remained, several of which crossed the P/T  
108 boundary (Clark 1983, Orchard 2007), and thrived in the Early Triassic, in stark contrast with the majority of other  
109 organisms at the time (e.g. Brayard et al. 2017, and references therein). The aftermath of the P/T crisis is marked by  
110 generally unstable conditions, several cooling and warming episodes occurring in the Early Triassic (Goudemand et al.  
111 2019). The transition between Early and Middle Triassic is marked by a global cooling and the appearance of  
112 worldwide monsoon events, among which the Carnian Pluvial event was the largest (Preto et al. 2010, Sun et al. 2012).  
113 These conditions were maintained through the Middle Triassic and Late Triassic, during which climate appears to have  
114 been fairly stable (Preto et al. 2010). Conodont diversity apparently progressively declined throughout the Middle and  
115 Late Triassic (e.g. De Renzi et al. 1996, Hallam 2002, Martinez-Perez et al. 2013, Van De Schootbrugge and Wignall  
116 2016) and generally had high extinction rates during this interval, especially at the end of the Norian, which was  
117 previously considered to correspond to their final extinction (Tanner et al. 2004). Indeed the Rhaetian conodonts are  
118 represented by a handful of species only, the last ones eventually going extinct near the Triassic / Jurassic boundary.  
119 The slow decline of conodont diversity throughout the Triassic may appear surprising considering the relatively stable

120 conditions of the Triassic, as well as the fact that the explanations for the P/T and T/J boundary crises are more or less  
121 convergent (Lucas and Tanner 2004, Mazza et al. 2010), but would fit the null hypothesis of diversity following a  
122 random walk.

123

## 124 *1.2. Previous studies and current problematics*

125         Considering their status of early vertebrates, their amazing resilience, and their fairly anti-climatic  
126 disappearance, the global diversity of conodonts and its drivers have received surprisingly little attention since the end  
127 of the eighties. Meanwhile, fossil occurrence and paleoenvironmental data have grown enormously. Clark (1983, 1987)  
128 already recognized two diversity maxima in the Ordovician and Devonian, and a ‘last hurrah’ in the Triassic. He further  
129 observed that origination and extinction peaked in the Ordovician, Mississippian and Triassic, with the latter two  
130 intervals corresponding to higher extinction than origination rates. Clark, however, did not comment at length on the  
131 possible drivers of conodont’s diversity fluctuations. Sweet (1988) mostly agreed with the pattern Clark described,  
132 although he split the Ordovician diversity peak into two ‘long-term cycles’. Sweet went on to suggest that the final  
133 extinction of conodonts was due to a sea level drop. On the contrary, De Renzi et al. (1996) showed that conodonts  
134 declined progressively from the Middle through the Late Triassic, and therefore favored competition as the main player  
135 in the disappearance of conodonts; an idea recently supported also by Martinez-Perez et al. (2013). In other words, the  
136 Court Jester vs. Red Queen debate applies also to the extinction of conodonts. In our opinion, the abundant conodont  
137 data at hand therefore constitute a unique opportunity to understand how abiotic factors – including large catastrophes –  
138 may drive the diversity of nektonic animals, but also possibly how biotic interactions may be instrumental in explaining  
139 the extinction of such a large taxonomic group.

140         In this study, we investigate whether the picture Clark (1987) and Sweet (1988) drew still holds today, using  
141 updated dataset and methods. Using current knowledge on paleoenvironment, we will also aim at identifying the main  
142 abiotic drivers of conodont diversity and associated paleogeographical patterns, and test whether those drivers may or  
143 may not account for the final demise of conodonts.

144

## 145 **2. Material and Methods**

146

### 147 *2.1. Dataset*

148         The data used in this study was obtained from the Paleobiology Database. The occurrences were downloaded  
149 from the Paleobiology Database (<https://paleobiodb.org>) on 26 June 2018, selecting by taxonomy, with group name =  
150 ‘Conodontata’. The resulting dataset included 23520 occurrences, with associated generic or specific accepted names,  
151 time intervals, localities and paleo-coordinates computed by the GPlates model implemented in the Paleobiology  
152 Database (Wright et al. 2013). The references on which the dataset is based cumulate a total of 357 unique first authors  
153 (secondary bibliography available as supplementary material), the main contributors (> 500 occurrences) being Zhang  
154 (N=1236), Barrick (N=1167), Männik (N=964), Ji (N=904), Suttner (N=871), Farrell (N=832), Bultynck (N=743),  
155 Klapper (N=714), Aboussalam (N=602), Gouwy (N=507). The main enterers (> 1000 occurrences) of the data into the  
156 Paleobiology Database were M. Krause (N=5735), S. Gouwy (N=3547), E. Jarochowska (N=3010), P. Nätscher  
157 (N=1363), J. Sessa (N=1169), M. Foote (N=1149), and P. Novack-Gottshall (N=1086). All subsequent data  
158 manipulation and analyses were run in R (R Core Team 2018).

159

160 2.2. *Diversity, origination and extinction*

161 From this data, diversity was estimated for genera at the series level. First, the dataset was trimmed of single  
162 occurrences whose temporal resolution is not constrained to one series: their low stratigraphic resolution makes them  
163 useless and possibly would distort the results. Therefore the sample was reduced to N=19737 occurrences. The genus  
164 name was used even for occurrences identified at the specific level. A total of 265 unique genera were recorded in the  
165 dataset, after checking for duplicates due to spelling mistakes. From this subset was produced a generic presence /  
166 absence matrix. Generic diversity estimates were computed using Alroy's 'shareholder quorum sampling' (SQS; Alroy  
167 2010a,b), running 1000 iterations while randomly resampling the presence / absence matrix with replacement. The final  
168 diversity estimate was the average across these iterations, and the associated standard deviations were also computed.  
169 SQS estimates for the Terreneuvian, Cambrian Series 2 and Lopingian could not be computed properly due to the very  
170 low generic diversity, and are therefore replaced by raw generic counts. A similar analysis was run for occurrences for  
171 which the resolution was at the stage level (N=15279). Because the resulting diversity curve was for a large part  
172 discontinuous, it is shown as supplementary material (SM1). Additionally, 'single-interval' diversity was computed (at  
173 the series level) as the number of genera present in only one series. From the same subset, extinction and origination  
174 rates were computed using the 'three-timer' formulas of Alroy (2010b). The use of SQS diversity estimates, and three-  
175 timer formulas aims at avoiding several biases present in most paleontological studies of diversity. These include the  
176 edge and Signor-Lipps effects by which the diversity artificially drops before and rises after boundaries (especially  
177 across mass extinctions), but not the Pull of the Recent effect, since conodonts do not have a fossil record in the Recent.  
178 The Lagerst tte effect, and unique taxa due to taxonomic identification difficulties in conodonts, are taken into account  
179 by calculating SQS and independently computing single-interval generic counts. Finally, poly-cohort contour graphs  
180 (Brayard et al. 2009) were produced, which allow a different representation of diversity, extinction and origination  
181 trends. The trends revealed by these graphs were similar to results from the SQS, origination and extinction curves,  
182 therefore they are only presented as supplementary material (SM2, SM3).

183

184 2.3. *Conodont evolutionary faunas*

185 To refine the analysis of conodont diversity, we investigated the existence of several 'evolutionary faunas'  
186 based on the temporal range of the various genera, excluding the 'single-interval' genera. First, a Multiple  
187 Correspondence Analysis (MCA) was run on the generic presence / absence matrix at the series level, using the 'MCA'  
188 function implemented in R package 'FactoMineR' (L  et al. 2008). Hierarchical clustering (function 'HCPC' of  
189 'FactoMineR') was then used on the produced multivariate space to form clusters and assign genera to them, to define  
190 'evolutionary faunas'. Clusters were defined arbitrarily, based on two criterias: inertia gain and non-overlapping of the  
191 groups.

192 Patterns of diversity were assessed for each evolutionary fauna, without using SQS, but only raw generic  
193 counts, excluding single-interval taxa. Scotese's (2016) paleomaps were used to look at the paleobiogeographical  
194 patterns of the different evolutionary faunas, by displaying the presence / absence of each group as different colors in  
195 the cells (see below).

196

197 2.4. *Generic counts and SQS diversity*

198 Excluding single-interval taxa, which are biased by taxonomic difficulties and Lagerst tte effects, raw generic  
199 counts at the series level were computed. The relationship between the decimal logarithm of these counts and that of the

200 SQS values was tested by a linear regression. The Terreneuvian, Cambrian Series 2 and Lopingian were excluded of  
201 this model, since their SQS values could not be computed.

202

### 203 *2.5. Paleobiogeographical patterns*

204 To analyse paleobiogeographical patterns, we used the same approach as Kocsis et al. (2018). Scotese's  
205 'PALEOMAPS PaleoAtlas' was downloaded and the paleomaps data for the Cambrian to Triassic period were imported  
206 in R (Scotese, 2016). For each map in the atlas, we defined an age range, corresponding to the stage represented by the  
207 map. Using R package 'icosa' (Kocsis, unpublished), a 2D penta-hexagonal grid was created, to be projected on the  
208 maps, with 'cells' (faces) of approximately equal surfaces and an average side ('edge') length of 740.74km. These cells  
209 were used as a coarse resolution unit for our paleogeographical investigations. Conodont occurrences whose range was  
210 entirely included within the age range of each map (N=12448) were automatically assigned to the corresponding cells,  
211 based on their paleolatitudes and paleolongitudes, using function 'locate' of package 'icosa'. The rest of the  
212 occurrences, which could not be restricted to the same resolution as the paleomaps, were excluded in this part, to avoid  
213 placing on the maps occurrences that may not have existed at the time represented by the paleomap.

214 The cells including areas of continental platforms and/or coast were manually counted for each stage as a  
215 proxy for the theoretically available area for conodonts. The number of cells was also computed for each stage, as a  
216 proxy of conodont geographical spread and occupation. The link between theoretically available area and occupied area  
217 was tested by a linear regression, out of which the residual variation was extracted to check for potential  
218 correspondence with other abiotic events. The maximal and minimal latitude occupied by conodonts were obtained as  
219 the latitudes of the center of the northernmost and southernmost occupied cells.

220

### 221 *2.6. Abiotic variables trends*

222 Sea surface temperature (SST) data were obtained from Song et al. (2019), and sea-level data were extracted  
223 from Hannisdal and Peters (2011) using the WebPlotDigitizer application (<https://apps.automeris.io/wpd/>). Data for the  
224 latter ultimately derived from Haq and Schutter (2008) and Haq et al. (1987). After extracting this data, we averaged it  
225 at the series level, to correlate it with our diversity, origination and extinction estimates. Those relationships were tested  
226 using linear models. The global mean annual temperature curve from Scotese (2015) was also extracted using  
227 WebPlotDigitizer and added for comparison with SST.

228

### 229 *2.7. Latitudinal gradients*

230 Finally, latitudinal gradients were investigated at the series level, by computing generic counts in bins of 10°  
231 latitude. No SQS was used here, the gradients represent raw generic counts. Latitudinal gradients of diversity were also  
232 computed for each evolutionary fauna as a whole (rather than by series), either as raw generic counts, or as proportion  
233 of their respective generic diversity. Bootstrapping of occurrence was used (10000 iterations) to test for significant  
234 differences between these gradients across the three evolutionary faunas. Finally, latitudinal gradients of extinctions  
235 (latest occurrence of a genus in the dataset) and originations (first occurrence in the dataset) were obtained and  
236 represented by kernel density plots (SM2).

237

## 238 **3. Results**

239

240 3.1. *Conodont generic diversity, origination and extinction*

241 Conodont SQS diversity (Fig. 1A) shows three conspicuous peaks: throughout Ordovician, in the Early  
242 Devonian, and in the Early Triassic, matching with peaks of single-interval taxa diversity. Diversity is at its highest  
243 throughout the Ordovician. Major decreases occur across the Ordovician – Silurian boundary, Early – Middle Devonian  
244 boundary, and Carboniferous – Permian boundary. Peaks of conodont origination rates (Fig. 1B) are observed during  
245 the Early Ordovician, Early Silurian (Llandovery), Late Carboniferous (Pennsylvanian) and Early Triassic. Extinction  
246 peaks (Fig. 1B) are observed in the Late Ordovician, the Late Devonian (smaller peak) and Pennsylvanian (at which  
247 time it overcomes the synchronous origination peak).

248 There is a significant negative linear relationship between average SST and extinction rate (adjusted  $R^2=0.265$ ,  
249  $P=0.017$ ,  $df=1$ , 16), and a positive relationship between average sea-level and SQS diversity (adjusted  $R^2=0.195$ ,  
250  $P=0.029$ ,  $df=1$ , 18) at the series level. Other relationships between SST or sea-level and diversity, extinction and  
251 origination were non-significant ( $P > 0.05$ ).

252

253 3.2. *Evolutionary faunas*

254 The multiple correspondence analysis, followed by hierarchical clustering, revealed three clusters, or  
255 evolutionary faunas, based on temporal distribution of the genera (Fig. 2). The first (48 genera) is mostly restricted to  
256 the Ordovician, the second (37 genera) also starts diversifying in the Early Ordovician, but reaches its acme during the  
257 Silurian, and starts decaying progressively from the Early Devonian on (Fig. 3). The latest evolutionary fauna (48  
258 genera) rises in the Early Devonian, reaches its acme in the Late Devonian, and then progressively goes down through  
259 the Carboniferous, followed by a steeper decay during the Permian. This evolutionary fauna recovers and constitutes  
260 most of the diversity of the Triassic period. Following the classification proposed by Donoghue et al. (2008), the stem  
261 Prioniodontida, Balognathidae, stem Ozarkodinida, as well as several Prioniodinina are for the most part included in the  
262 early evolutionary fauna (Fig. 3C). The intermediate evolutionary fauna contains stem Ozarkodinina, stem  
263 Polygnathacea, as well as some Prioniodinina (*Oulodus*). The late evolutionary fauna contains some Prioniodinina, and  
264 most derived Ozarkodinina (Polygnathacea and the unnamed superfamily containing ‘gondolellids’).

265

266 3.3. *SQS diversity estimates and generic counts*

267 The SQS diversity estimates (Fig. 1A) and total of non-single-interval genera (Fig. 3A) are significantly  
268 correlated at the series level, excluding the Terrenewian, Series 2 and Lopingian ( $R^2 = 0.4$ ,  $P < 0.01$ ,  $df = 1$ , 17; Fig. 4).  
269 Discrepancies between SQS and generic counts are frequent. For the Series 3, Furongian, Guadalupian, and Early  
270 Triassic, generic counts are lower than expected. For the Middle Devonian, Late Devonian, Wenlock, Ludlow, and  
271 Llandovery counts are higher than expected. The most notable discrepancies are the Middle and Late Devonian, and the  
272 Guadalupian, during which SQS estimates and generic counts show opposite trends (Fig. 3A).

273

274 3.4. *Paleogeographical patterns of conodont diversity*

275 Geographically, the first occurrences of conodonts are rather spread out (Fig. 1E, 5A). The number of cells  
276 occupied by conodonts sees an important rise in the Late Cambrian, which is sustained through the Ordovician despite a  
277 short term drop at the Cambrian – Ordovician boundary (Fig. 1C-D). The Hirnantian glaciation clearly reduces the  
278 geographical distribution of conodonts, both in its latitudinal extremes and number of occupied cells (Fig. 1C-E, 5C-D).  
279 The extent of conodonts then increases again from the Wenlock into the Early Devonian (Lochkovian), but is restricted



280 during the rest of the Early Devonian (Fig. 1C-E, 5F-G). A short-lived spread is seen in the Eifelian (Middle Devonian),  
281 followed by a continued decrease during the remaining of the Devonian and the Mississippian (Fig. 1C-E, 5H, 6A-B).  
282 The geographical spread of conodonts remains fairly stable through the Mississippian and Pennsylvanian transition  
283 (Fig. 1C, E), although the available space becomes more and more restricted (Fig. 1C, D), it decreases again at the end  
284 of the Carboniferous, with conodonts being restricted to equatorial latitudes (Fig. 1E). An all-time low is reached during  
285 the middle of the Cisuralian (Early Permian; Fig. 1C-E, Fig. 6D-E), associated with the near-total extinction of  
286 conodonts (Fig. 1A), and despite ice sheets pulling back. A marked spread can be seen at the end of the Permian,  
287 notably towards the extreme latitudes (Fig. 1C-E, Fig. 6F-G). The extent of conodonts remains high in the Early  
288 Triassic, then goes back down for a short time in the Middle Triassic (Fig. 1C-E, Fig. 6H), before re-increasing in the  
289 Late Triassic. The number of occupied cells is significantly correlated to the number of theoretically available cells ( $R^2$   
290 = 0.15,  $P < 0.01$ ,  $df=1, 44$ ), however with a large amount of residual variation (Fig. 1C-D), the latter being apparently  
291 synchronous with the sea level curve until the Early Carboniferous (Fig. 1F).

292

### 293 3.5. Latitudinal gradients

294 Latitudinal gradients of generic diversity (LGGD) at the series level can be interpreted only from the Early  
295 Ordovician on. In the Early Ordovician, the diversity is fairly spread out between  $-50$  and  $50^\circ$ , with multiple modes, two  
296 being found around  $40^\circ$  and  $-30^\circ$ , and a third just north of the equator (Fig. 7). Two LGGD modes are also seen in the  
297 Middle Ordovician, one just south of the equator, the other around  $25^\circ$ . During the Late Ordovician the LGGD flattens,  
298 with conodont diversity spreading southward, only the northernmost latitudes being devoid of conodonts. Following the  
299 Hirnantian, the southern occurrences disappear (Fig. 5D) and a fairly classical, mostly unimodal latitudinal gradient is  
300 established, which is maintained until the Mississippian (Fig. 7). One particularity of this latitudinal gradient is that its  
301 mode is not equatorial, but located in the Southern Tropics. The whole diversity of conodonts in this time frame seems  
302 to concentrate in the Southern Hemisphere. In the Pennsylvanian, the distribution seems to shift slightly northward, but  
303 conodont diversity is drastically reduced during the Permian (Fig. 6D-E). In the Early Triassic, a latitudinal gradient is  
304 re-established but flatter than previously, with a small mode in the Northern Hemisphere. Diversity is again hit during  
305 the Middle Triassic, before a more marked latitudinal gradient is established in the Late Triassic, with a mostly northern  
306 diversity and a single mode in the Northern Tropics.

307

## 308 4. Discussion

309

### 310 4.1. Factors impacting conodont diversity and geographical patterns

311 The large conodont diversification after the Cambrian – Ordovician boundary occurs within a transgressive  
312 cycle, peaking in the Middle Ordovician (Fig. 1F), combined with hot but decreasing temperatures. It constitutes a part  
313 of the ‘Great Ordovician Biodiversification Event’ (GOBE, e.g. Harper et al. 2015), as conodonts may have been  
314 among the first groups to colonize the water column. The increase in available shelf area may have enabled the  
315 origination of many conodont taxa (Fig. 1B-C, Harper et al. 2015). However, it also appears that, at that time, some  
316 conodonts colonized open sea environments (Fig. 5B), possibly via the increase in diversity and abundance of plankton,  
317 and the likely establishment of open marine food chains (Harper et al. 2015, Servais et al. 2008). Either factors, or their  
318 combination, may explain the dramatic increase in conodont diversity. The level of conodont diversity reached during  
319 the Ordovician was not equaled at any later time (Fig. 1A).

320 The Hirnantian / end-Ordovician extinction brought an end to the acme of conodont diversity. It was  
321 synchronous with a large drop in seawater temperature and sea level, and with ice sheets spreading (Fig. 5C-D, Harper  
322 et al. 2014). The conodonts' geographical distribution was greatly reduced at that time, especially in southern localities  
323 that became covered by ice (Fig. 1E, Fig. 5D). This extinction mainly affected the early evolutionary fauna (Fig. 3),  
324 while the intermediate evolutionary fauna remained diverse across the boundary, and diversified in the Early Silurian.  
325 The global diversity plummeted due to the loss of early fauna genera, but the intermediate fauna rised. At a finer  
326 temporal resolution, the drop in conodont diversity appears as a two-step process, with one extinction event at the  
327 Katian – Hirnantian boundary, and a second during the Hirnantian (Harper et al. 2014). It should be noted that the early  
328 fauna taxa that disappeared shared their geographical and temperature distribution with the earliest intermediate fauna  
329 taxa (Fig. 5C-E), suggesting that there was no fundamental difference in the temperature tolerance of the two groups.  
330 Therefore the reason why some taxa survived and others not may instead be related to the presence of refugias, or to the  
331 influence of temperature on the preys of the conodonts. The recovery fauna, which started to diversify at the end of the  
332 Hirnantian may correspond to the early radiation of the intermediate evolutionary fauna. The turnover in conodont  
333 diversity may therefore be explained roughly by the disappearance of early fauna taxa due to the drop in temperatures  
334 and loss of available habitat (South Pole glaciation and sea level drop), leaving open ecological niches for intermediate  
335 fauna taxa to diversify later on. Direct detrimental competition between the two faunas does not seem plausible, as both  
336 were found in the same geographical areas earlier on (Fig. 5A-D). The Early Silurian peak of origination rate (Fig. 1B)  
337 reflects the large increase in diversity of this intermediate fauna (Fig. 3A). Although it may have started in the  
338 Hirnantian (Harper et al. 2014), most of the diversification coincides with a global increase of temperatures, associated  
339 with ice sheets melting and a sea level rise (Fig. 1F).

340 In the Ordovician, conodonts constituted most of the nekton's diversity. The subsequent increase in nekton  
341 diversity during the Silurian / Early Devonian (Whalen and Briggs 2018, Klug et al. 2010) may have played a role in the  
342 limitation of the conodont's recovery via either predation pressures (the earliest known direct evidence of predation on  
343 conodonts dates from the Late Devonian; see Zaton and Rakocinski 2014, Zaton et al. 2017), and/or competition for  
344 ecological spaces. This scenario, if real, may converge with that of the final extinction of conodonts (see below).

345 The peak of conodont diversity in the Early Devonian occurred within a temperature decreasing trend (with  
346 large variations) and coincided roughly with a lowstand (switch from a regressive to a transgressive trend) in the middle  
347 Early Devonian (Fig. 1A, 1F). This series displayed stable standing diversity in the intermediate fauna taxa, while  
348 several late fauna taxa appeared (Fig. 3A). Extinction and origination rates were almost equal, because several  
349 intermediate fauna taxa disappeared by the end of the Early Devonian while the late evolutionary fauna was rising (Fig.  
350 1B). Although there was an increase of occupied areas in the earliest Devonian, it was short lived (Fig. 1C-D), and was  
351 not reflected in the latitudinal extremes of the distribution, which remained stable (Fig. 1E). This geographical pattern  
352 may be explained by the position of the paleo-continent, which started to assemble. Areas occupied only by  
353 intermediate fauna taxa were either emptied or became shared with late fauna taxa (Fig. 5F-H). This, combined with the  
354 fact that intermediate evolutionary fauna taxa generally constitute groups that are basal to late fauna taxa along the tree  
355 of Donoghue et al. (2008), could mean that some species of the intermediate fauna went through an episode of  
356 speciation at that time and gave rise to the late fauna diversity, possibly linked with an increase in sea level (Fig. 3C).

357 The drop in diversity observed in the middle Devonian (Fig. 1A) is mostly explained by extinctions of  
358 intermediate fauna and single-interval taxa (Fig. 1A, 3A), which are not compensated by originations of late fauna taxa.  
359 This drop in global diversity happens despite the coeval sea-level high and may be related to the mid-Devonian

360 hothouse (Fig. 1F), which may have negatively impacted the intermediate fauna taxa, while favoring late fauna taxa.  
361 The loss of diversity is not reflected by a notable extinction peak (Fig. 1B), possibly because single-series genera are  
362 not taken into account in the computation of the extinction rate (Alroy 2010b). The small peak of extinction rate in the  
363 Late Devonian, despite an increase of SQS diversity (Fig. 1A-B), may also be due to the loss of single-interval taxa and  
364 intermediate fauna taxa. Both intermediate and late fauna generic diversity go down across the Devonian –  
365 Carboniferous boundary although not reflected by SQS diversity estimates.

366 Extinction rate culminates in the late Carboniferous, while some of the lowest temperatures and lowest sea  
367 level of the entire studied period are reached (Fig. 1B, 1F). Repeated or continuous glaciation(s) and regression(s)  
368 marked the Carboniferous (Fielding et al. 2008). Those clearly had a large impact on conodont diversity, as well as on  
369 their geographical extent, which was reduced to equatorial latitudes by the end of the Carboniferous (Fig. 1C-E, 6C-D).  
370 Following the large extinction peak of the Pennsylvanian, conodont diversity was reduced to only a handful of genera  
371 (Fig. 1A, 3A). Conodont diversity remained extremely low during the Early and Middle Permian, with conodonts being  
372 restricted to a few refugia (Fig. 6E). In the Late Permian (Lopingian) conodont diversity was still very low (Fig. 1A),  
373 but the geographical extent of conodonts started again to increase, possibly reflecting the increasing temperatures and  
374 the concurrent melting of the ice sheets (Fig. 1C-F, 6F).

375 Finally, diversity rose again after the P-T boundary, with a peak of origination and large numbers of single-  
376 interval taxa, mostly late fauna taxa (Fig. 1A-B, 3A-B). This occurred while the sea level was very low, and the  
377 temperatures very high (Fig. 1F). At a higher resolution, the widely fluctuating climate of the Early Triassic interval  
378 (e.g. Goudemand et al. 2019) may explain why so many taxa of this interval are single-interval only, and therefore  
379 produced a peak of origination. The fact that conodonts started to colonize new areas already in the Late Permian may  
380 have driven allopatric speciations following the extreme conditions of the P-T crisis.

381

382 It is clear from the paleomaps in Figs. 5 and 6 that conodonts were more abundant along coastlines and on  
383 continental shelves. Not surprisingly, the paleogeographical spread of conodonts is significantly correlated to the extent  
384 of continental shelves (Fig. 1C). Yet, conodonts were not restricted to these areas, as evidenced by the open sea  
385 locations during the Ordovician and Devonian (e.g. Fig. 5B, 5G-H). Residual variation in the geographical distribution  
386 of conodonts (Fig. 1D) corresponds with the sea level curve, and the ice ages of the end-Ordovician and Pennsylvanian  
387 clearly brought restrictions to the extension of conodonts, especially in their latitudinal extremes (Fig. 1E). Overall, our  
388 data suggest that conodonts were not ecologically restricted to coastlines or warm waters, but that they could not adapt  
389 to very cold / glacial waters. Extremely hot waters may also have been lethal to conodonts, but in general, increased  
390 temperatures seems to have favored conodont diversification.

391 It appears that the positions of paleo-continent had an influence on the evolution of the latitudinal gradient of  
392 conodont diversity (Fig. 7). Throughout the Ordovician, the LGGD is rather symmetrical between the Northern and  
393 Southern Hemispheres. Conodonts were then present in the northern extent of the Gondwanian continental shelf (Fig.  
394 5B-C), around Laurentia and Baltica, and further North in the open ocean. From the Early Silurian (Llandovery) to the  
395 Carboniferous, the LGGD became restricted mostly to the Southern Hemisphere, and was generally unimodal. This is in  
396 accordance with the southern location of most coastlines and continental shelves from the Llandovery until the Early  
397 Carboniferous. Northern movements of Pangea during the Carboniferous, combined with the appearance of large South  
398 Pole ice sheets produced a northward shift of the conodonts, and the LGGD became almost centered on the equator  
399 (Fig. 6D, Fig. 7). When conodont diversity recovered in the Early Triassic, Pangea extended from North to South Pole,

400 with most continental shelves in the Northern Hemisphere (Fig. 6G-H). Consequently the LGGD moved to the  
401 Northern Tropics, where it was maintained until the end of the Triassic (Fig. 7). This interpretation is in accordance  
402 with studies of both past and present latitudinal diversity gradients that demonstrated a close link with the position of  
403 continental shelves (e.g. Powell 2009, Chaudary et al. 2016).

404 Several of the major biases of the fossil record may affect our results. Notably, as we showed that most  
405 conodont occurrences are found in continental shelves environments, their diversity and paleogeographic patterns  
406 might be related to the quantity of preserved sedimentary rock (Peters 2005). The correlation between SQS diversity  
407 and sea-level, which is also known to impact the amount of sedimentary rock, may be an artifact of the preservation  
408 bias, although we would favor a common-cause hypothesis (Peters 2005). Sampling effort bias is also probably playing  
409 a role in the paleogeographic patterns observed, as conodont workers have mostly explored facies expected to yield  
410 numerous fossils. Some paleo-environments (e.g. hypersaline) are undersampled, but can yield surprising diversity  
411 (Jarochowska et al. 2017). Finally, although multi-element taxonomy has been adopted by conodont workers for several  
412 decades now (Bergstrom and Sweet 1966), it is not always applicable, which may lead to taxonomic oversplitting and  
413 overestimations of diversity. Notably, very few complete apparatuses are known for the oldest conodont genera and the  
414 topological schemes used for establishing homologies between elements vary between earlier and later taxa (Donoghue  
415 et al. 2008).

416  
417 Keeping these caveats and biases in mind, it appears that, indeed, abiotic factors – temperature and sea-level,  
418 as well as paleocontinent positions – influenced conodont diversity, as it is clear that the largest peaks of origination and  
419 extinction and diversity are synchronous with peaks or lows in the global temperature and/or sea-level curve. When  
420 testing these relationships, however, only a negative link between temperature and extinction and a positive link  
421 between sea-level and diversity were significant. Furthermore, both correlations were driven by extreme points. It is  
422 interesting to note that it was not a necessary condition to combine both sea-level and temperature to positively impact  
423 conodont diversity. For example, the Ordovician radiation corresponded with a large transgression and high  
424 temperatures, the Early Triassic origination and diversity peak was concomitant with a very low sea level and hot and  
425 variable temperatures, while the Early Devonian diversity peak (which was more limited) was synchronous with  
426 variable but not particularly extreme sea-level and temperatures (Fig. 1A, 1F). This shows that either factors can be self-  
427 sufficient to have an influence. Additionally, our proxy of geographical areas available to conodonts (number of cells  
428 including coast or continental shelf) was significantly related to occupied area (Fig. 1C), suggesting a partial  
429 explanation of how sea level trends impacted the geographical spread of conodonts (Figs. 5-6). Conodont mobility may  
430 have played a role in maintaining diversity in times of low sea level and glaciation. Our results suggest that the main  
431 events in the history of conodont diversity were related to extreme abiotic conditions. Yet, much variation in diversity,  
432 extinction and (in particular) origination remains unexplained, and could be due instead to biotic factors. Notably, the  
433 first origination peak of the Early Ordovician, the Early Devonian peak of diversity and the final extinction of  
434 conodonts require closer investigation, in particular regarding the interaction of conodonts with other marine groups.

#### 435 436 *4.2. Comparison with previous studies and remarks on the final extinction of conodonts*

437 Our results regarding global conodont diversity trends are mostly in accordance with previously published  
438 curves (Clark 1983, 1987, Sweet, 1988). Most of the major events of the group's history are recognized, in particular  
439 the Ordovician acme, followed by a major drop in the Silurian. The Permian minimum, and the Early Triassic 'last

440 hurrah' of diversity are also corroborated. On the other hand, we note discrepancies for the Devonian and  
441 Carboniferous. In particular, previous studies described diversity and origination as low in the Early Devonian and high  
442 in the Late Devonian. Conversely, our results show a peak in diversity in the Early Devonian, followed by a drop in the  
443 Middle Devonian and a very limited diversification in the Late Devonian (Fig. 1A). Likewise, previous studies  
444 suggested important diversity drops during the Mississippian and Pennsylvanian, while our results suggest on the  
445 contrary that diversity was fairly high and stable throughout the Carboniferous, with a major extinction between the  
446 Pennsylvanian and the Permian (Fig. 1A). These discrepancies may be due to several factors: i) the geographical extent  
447 of the dataset (e.g. Sweet, 1988 focused on North American data), ii) the taxonomic rank used (specific level in Sweet  
448 1988, *versus* generic level in Clark 1983, 1987, and our study), iii) the sheer increase in size of the dataset, or iv)  
449 methods to assess diversity and rates. Here, we chose to use advances notably promoted by Alroy (2010a,b) to limit the  
450 impact of several biases: for example, Clark (1983) used a range-through counting method (although not defined as  
451 such), which is subject to edge and Signor-Lipps effects (the Pull of the Recent having no impact on conodonts; Alroy  
452 2010b) meaning that diversity estimates will tend to artefactually drop before and rise after boundaries, notably at mass  
453 extinction events. Despite these biases, these older studies did manage to reveal the most prominent elements also  
454 highlighted in the present work (Ordovician acme, Permian low and Triassic short-lived recovery), suggesting that these  
455 trends are real, and robust to any kind of biases, as well as across taxonomic levels.

456

457         Clark (1983) suggested that the final extinction of conodonts may be linked to a drop in sea level, and was  
458 followed in this interpretation by Sweet (1988). However, sea-level was low throughout the Triassic, and its variations  
459 are not agreed upon. Furthermore, recent studies suggest that it may have been rising, rather than dropping, during the  
460 Late Triassic (e.g. Van der Meer et al. 2017). Even if the regressive trend actually took place, its age was likely younger  
461 than the start of conodonts' decline (Middle Triassic; Martinez-Perez et al. 2013). Furthermore our results suggest that  
462 regressive trends do not necessarily correlate with major conodont extinctions. Global temperatures in the Late Triassic  
463 were fairly similar to those in the Early and Middle Triassic, and the world was ice-free at that time, as was generally  
464 the case in times when conodonts were thriving. Based on our results, considering the absence of glaciation and a late  
465 drop in sea level and CAMP province influence, we may conclude that two of the most important abiotic factors  
466 (temperature and sea-level) cannot be considered as sufficient to explain the extinction of conodonts. Other abiotic  
467 factors, which are more difficult to assess, such as water salinity or pH may have played a role. Alternatively, and in  
468 agreement with De Renzi et al. (1996) and Martinez-Perez et al. (2013), biotic factors such as predation by, or  
469 competition with groups of the 'Modern Fauna' (Sepkoski 1981, Hu et al. 2011, Brayard et al. 2017), e.g. Neopterygian  
470 fishes and Neoselachian sharks that started radiating in the Middle Triassic (Cuny and Benton 1999, Xu et al. 2013),  
471 may have driven the last conodonts to extinction.

472

## 473 **5. Conclusion**

474         Our analysis confirms the influence of abiotic factors on conodont diversity at a large scale. Notably, despite  
475 their mobility, these early vertebrates were strongly impacted by sea-level variations as well as major glaciations, which  
476 restricted the extent of their favored coastal habitat and probably limited the possibility of allopatric speciation. Biases  
477 of the fossil record should however be kept in mind as potentially confounding or correlated factors. These abiotic  
478 factors do not however explain particular conodont events such as their Ordovician radiation or their final demise at the  
479 end of the Triassic. Instead it is likely that biotic factors played a prominent role in the extinction of conodonts. Despite

480 the fact that biotic interactions arguably take place locally in time and space, the sum of their effects may ultimately  
481 emerge as large-scale patterns, leading for example to the extinction of a highly successful group like conodonts, which  
482 had thrived in oceans for more than 300 Ma.

483

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488

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643

644 **Figure legends**

645 **Figure 1.** Synthetic view of diversity and paleobio-geographical patterns through the Phanerozoic. Alternating gray and  
646 white areas delimit the boundaries between series. **A)** Black line: average SQS generic diversity  $\pm$  std. dev. over 1000  
647 iterations (gray outline). Blue dashed line: count of single-series genera (i.e. genera which occur in only one series). **B)**  
648 Origination (red) and extinction (black) rates, computed using the 3-timer approach of Alroy (2014). **C)** Blue line and  
649 area: geographical area theoretically available to conodonts, as the number of cells of the paleomap including  
650 continental shelf or coast. Black line and area: geographical area where conodonts occur, computed as the number of  
651 cells including at least one occurrence of conodont (see Material and Methods). Available and occupied space are not at  
652 the same scale. **D)** Residual variation of a linear regression of number of cells occupied against number of cells  
653 available, i.e. variation in the occupied area after removing the effect of continental shelf / coastal area. **E)** Median  
654 northern (red) and median southern (blue) paleolatitudes of conodont occurrences, dashed lines are the maximal and  
655 minimal paleolatitudes occupied by conodonts, computed as the middle latitude of the northern-most and southern-most  
656 occupied cells. **F)** Phanerozoic global sea surface temperature curve, from Song et al. (2019; red curve and points,  
657 dashed red line is the series-averaged curve), global mean temperature modified from Scotese et al. (2015; black line),  
658 and global sea level curve, modified from Haq and Schutter (2008; blue line and area).

659

660 **Figure 2.** First two axes of the Multiple Correspondance Analysis (MCA) run on the generic time series presence /  
661 absence matrix, excluding single-series taxa. Hierarchical clustering was used on this MCA, and three clusters were  
662 retained based on the inertia gain and non-overlap of the groups. Abbreviations represent the series in which genera  
663 were present. Csrl: Cisuralian, ErlD: Early Devonian, ErlO: Early Ordovician, ErlT: Early Triassic, Frng: Furongian,  
664 Gdlp: Guadalupian, Ldlw: Ludlow, Llandovery: Llnd, Lpng: Lopingian, LtDv: Late Devonian, LtOr: Late Ordovician,  
665 LtTr: Late Triassic, MddD: Middle Devonian, MddO: Middle Ordovician, Mddt: Middle Triassic, Msss: Mississippian,  
666 Pnns: Pennsylvanian, Prdl: Pridoli, Srs2: Series 2, Srs3: Series 3, Trrn: Terreneuvian, Wnlc: Wenlock. The first cluster  
667 (magenta triangles) forms the 'Early Evolutionary Fauna'. The second cluster (yellow circles) forms the 'Intermediate  
668 Evolutionary Fauna'. The third cluster (black squares) forms the 'Late Evolutionary Fauna'. See Fig. 3 for more details  
669 on these clusters.

670

671 **Figure 3.** Diversity trends of the three 'evolutionary faunas'. **A)** Raw generic count (excluding single-series taxa) by  
672 series for genera assigned to the different 'evolutionary faunas' (full lines), and the sum of these curves (dashed line).  
673 Gray outline shows the SQS diversity estimate std. dev. (see Fig. 1A) for comparison. **B)** Percentage represented by the  
674 faunas in the total diversity in each series. The 'Early Fauna' dominates through Cambrian and Ordovician, but is  
675 replaced by the 'Intermediate Fauna' at the start of the Silurian. Finally the 'Late fauna' becomes dominant in the  
676 Middle Devonian, although remnants of earlier faunas survive until the Triassic. **C)** Tree modified from Donoghue et al.  
677 (2008), with genera highlighted according to their evolutionary fauna. Genera not highlighted could not be included in  
678 the analysis (i.e. single-series taxa).

679

680 **Figure 4.** Plot of raw generic counts (excluding single-series taxa) against average SQS diversity estimate, by series.  
681 Black line shows the linear regression line ( $R^2 = 0.40$ ,  $P < 0.01$ ), dashed red lines represent 95% confidence intervals.  
682 Named points are those outside of the 95% C.I., i.e. series in which the raw counts do not follow the predicted  
683 relationship with the SQS estimates.

684

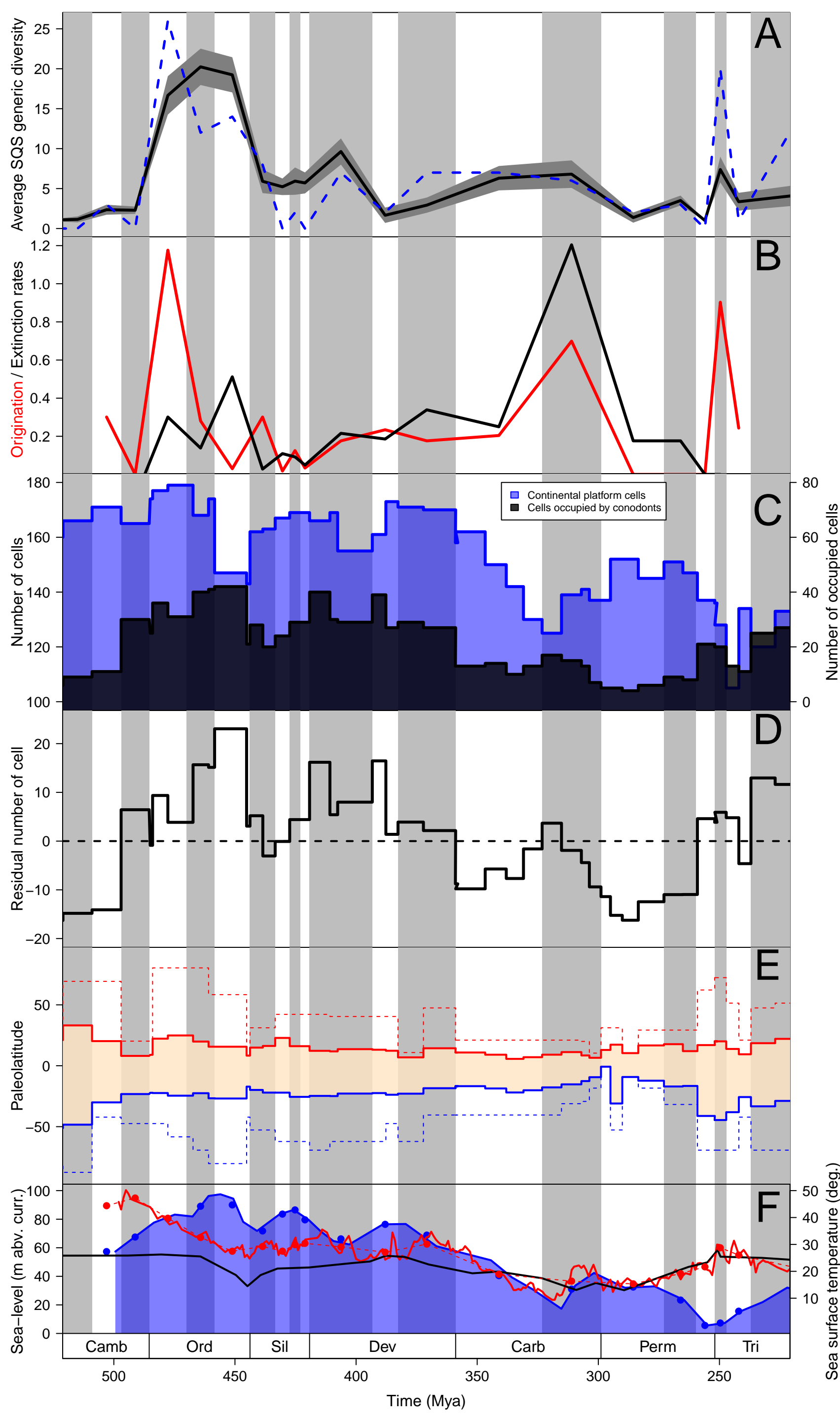
685 **Figure 5.** Paleobiogeographic evolution of conodont diversity from end-Cambrian to Late Devonian. Paleomaps from  
686 Scotese et al. (2015) are divided into a grid of 362 pentagonal and hexagonal ‘cells’ (faces) with approximately equal  
687 area and ‘side’ (edge) length. Average side length is 740.74 km. Conodont occurrences were automatically assigned to  
688 the corresponding cells, based on their paleolatitudes and paleolongitudes from the Paleobiology Database. Each cell  
689 occupied by a colored circle includes at least one occurrence. Multi-colored circles denote the presence of conodont  
690 genera belonging to the different ‘Evolutionary Faunas’ described herein. Note that the proportions of each color are  
691 entirely arbitrary and *do not* relate in any way to the proportions of local generic diversity. Circles were plotted at the  
692 center of the cells and their position do not imply that the occurrences are actually found together at a finer scale (*i.e.*  
693 within a cell).

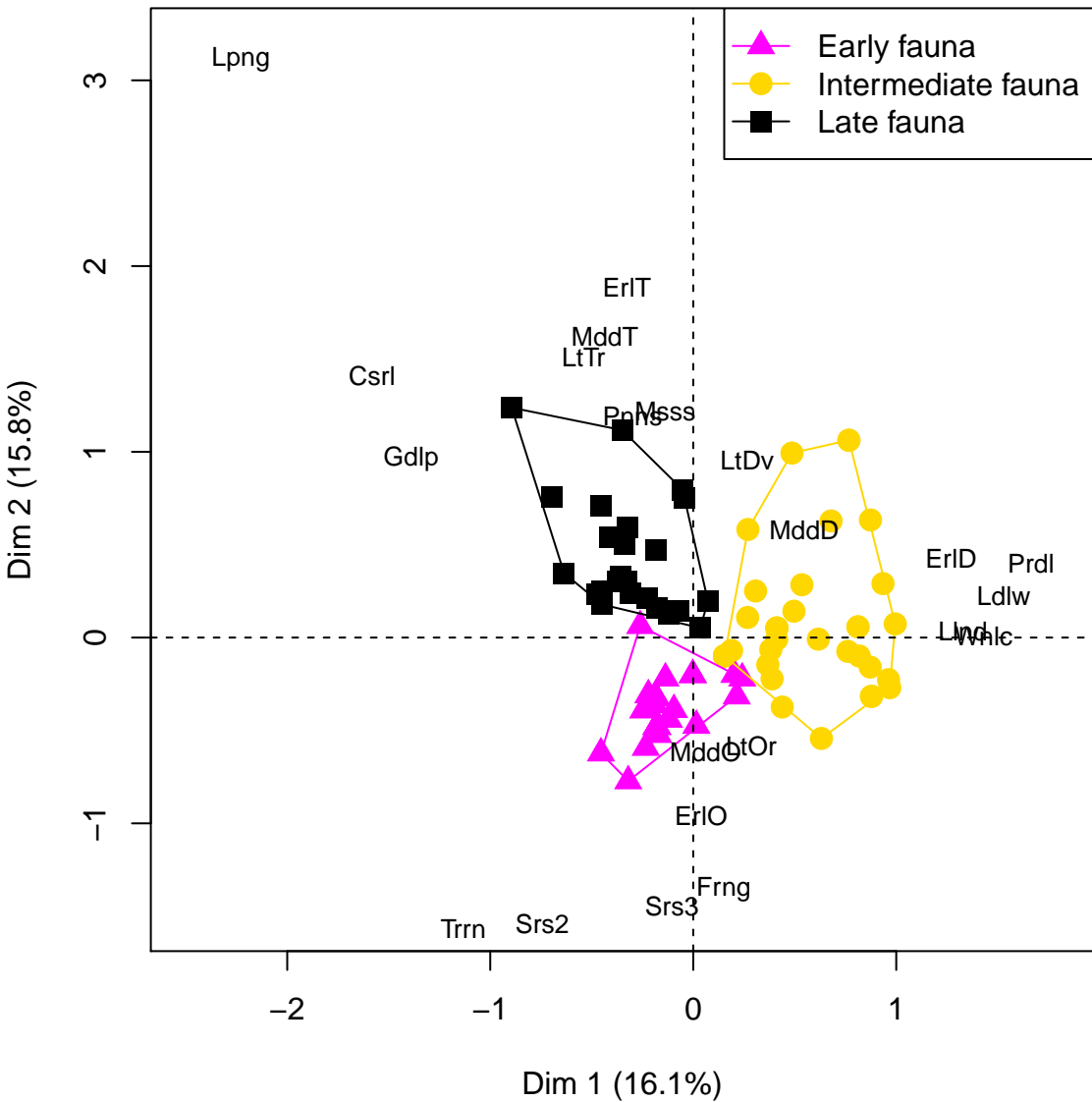
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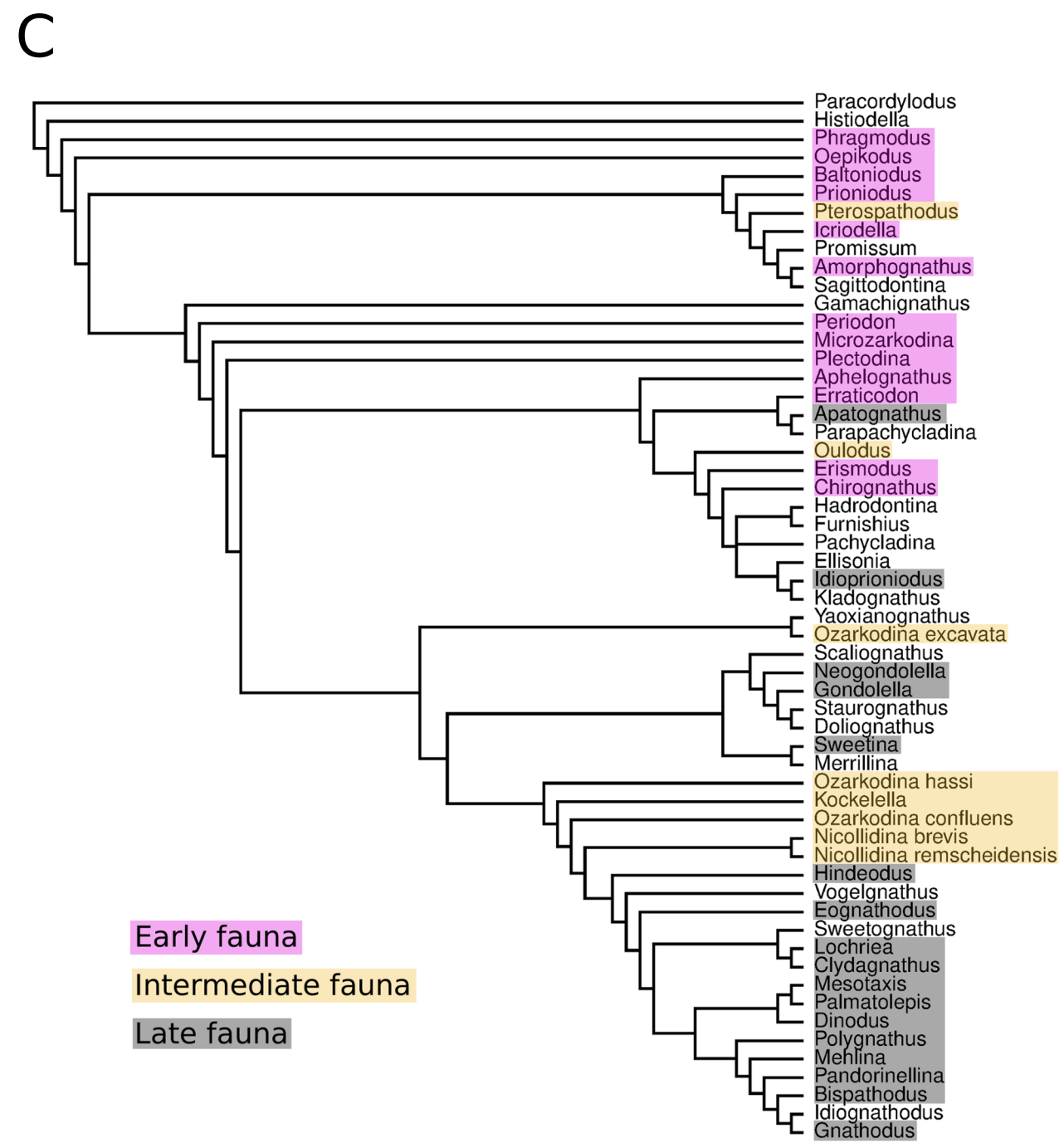
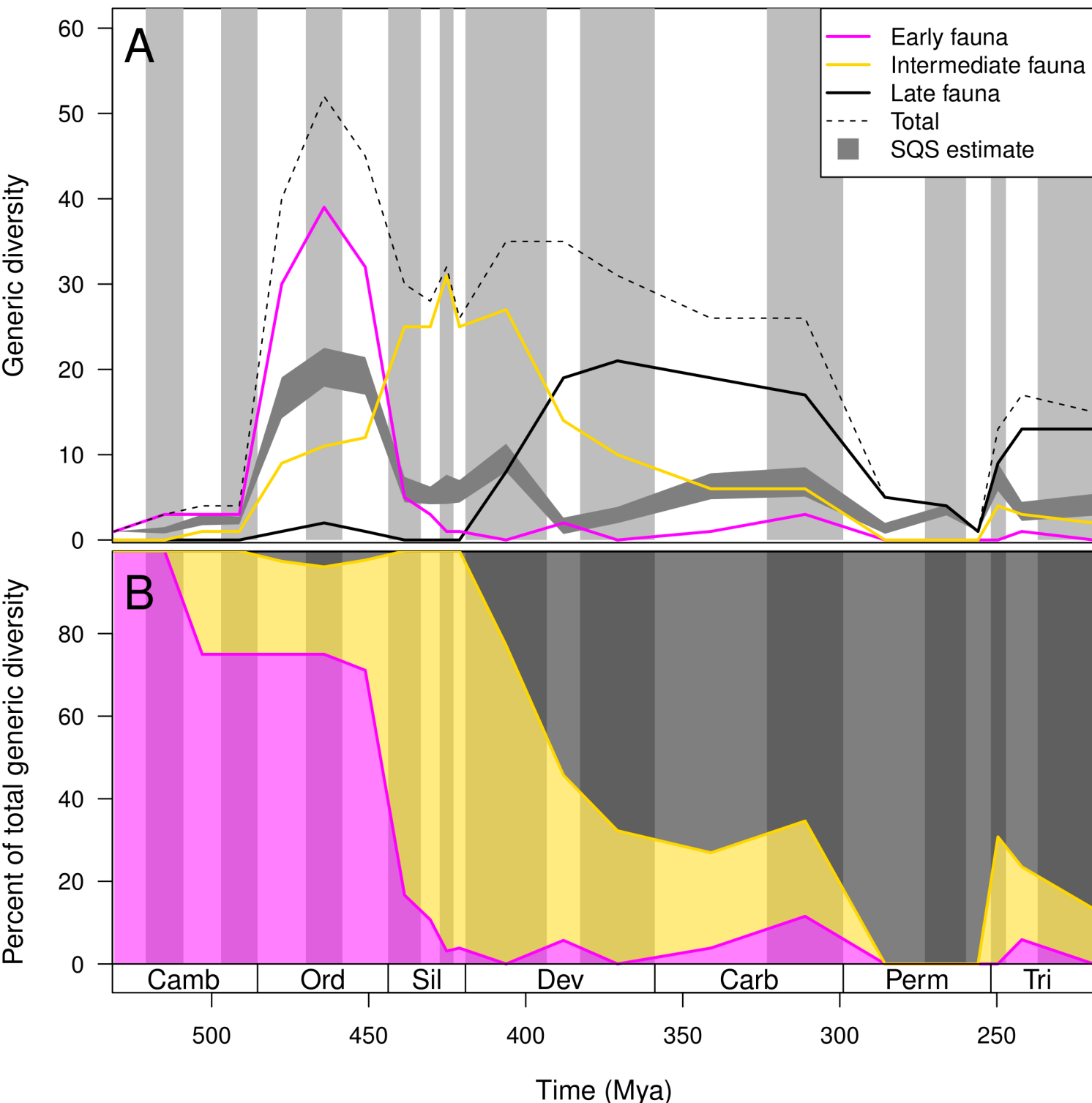
695 **Figure 6.** Paleobiogeographic evolution of conodont diversity from Late Devonian to Middle Triassic. Paleomaps from  
696 Scotese et al. (2015) are divided into a grid of 362 pentagonal and hexagonal ‘cells’ (faces) with approximately equal  
697 area and ‘side’ (edge) length. Average side length is 740.74 km. Conodont occurrences were automatically assigned to  
698 the corresponding cells, based on their paleolatitudes and paleolongitudes from the Paleobiology Database. Each cell  
699 occupied by a colored circle includes at least one occurrence. Multi-colored circles denote the presence of conodont  
700 genera belonging to the different ‘Evolutionary Faunas’ described herein. Note that the proportions of each color are  
701 entirely arbitrary and *do not* relate in any way to the proportions of local generic diversity. Circles were plotted at the  
702 center of the cells and their position do not imply that the occurrences are actually found together at a finer scale (*i.e.*  
703 within a cell)..

704

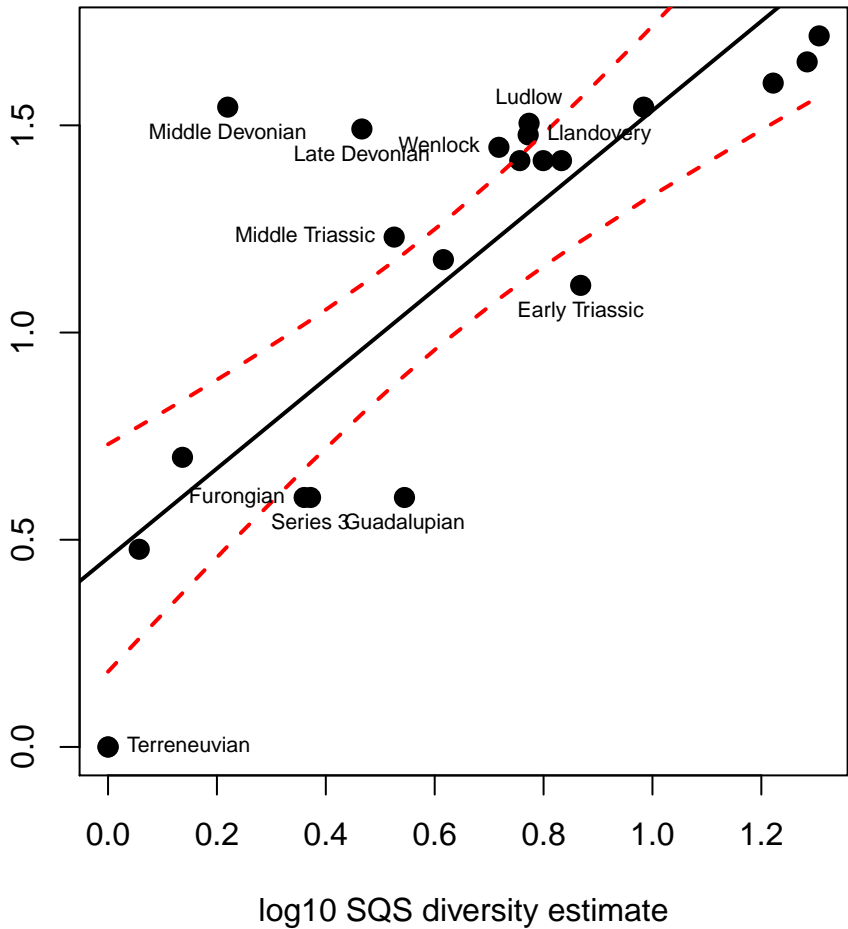
705 **Figure 7.** Left panel. Paleolatitudinal gradients of conodont diversity through the Paleozoic, computed as raw generic  
706 counts for each series, binned by 10° of latitude. Each generic diversity point is plotted against the corresponding mid-  
707 bin value. The right panel shows the extent of epicontinental seas, computed as the total number of grid cells including  
708 coastlines. The figure as a whole follows stratigraphic order in relative terms, but does not represent absolute ages.







log<sub>10</sub> Number of genera



log<sub>10</sub> SQS diversity estimate



