



HAL
open science

North-Gondwana -Laurussia dynamic paleogeography challenged by magnetic susceptibility through the Famennian

Girard Catherine, Feist Raimund, Mossoni Angelo, Jean-Jacques Cornee,
Camps Pierre, Charruault Anne-Lise, Corradini Carlo, Catherine Girard, ;
Feist, ; Mossoni, et al.

► **To cite this version:**

Girard Catherine, Feist Raimund, Mossoni Angelo, Jean-Jacques Cornee, Camps Pierre, et al.. North-Gondwana -Laurussia dynamic paleogeography challenged by magnetic susceptibility through the Famennian. *Gondwana Research*, 2021, 97, pp.263-272. 10.1016/j.gr.2021.06.002 . hal-03281159v1

HAL Id: hal-03281159

<https://hal.science/hal-03281159v1>

Submitted on 13 Oct 2021 (v1), last revised 8 Jul 2021 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

[Tapez ici]

North-Gondwana - Laurussia dynamic paleogeography challenged by

2 magnetic susceptibility through the Famennian

3

4 Girard, Catherine^{1*}; Feist, Raimund¹; Mossoni, Angelo²; Cornée, Jean-Jacques³;

5 Camps, Pierre³; Charruault, Anne-Lise¹; Corradini, Carlo⁴

6

7

8 ¹*Institut des Sciences de l'Evolution de Montpellier (ISEM), Univ Montpellier, CNRS, EPHE,*
9 *IRD, Montpellier, France.*

10 ² *2 Kingsdown court, 56 Bolingbroke grove, London SW11 6HS, UK*

11 ³ *Géosciences Montpellier, Université de Montpellier, CNRS, and Université des Antilles,*
12 *Montpellier and Pointe à Pitre, (FWI), France*

13 ⁴ *Università degli Studi di Trieste, Dipartimento di Matematica e Geoscienze, Trieste, Italy*

14

15 *corresponding author (catherine.girard@umontpellier.fr)

16

18

19 **Abstract**

20 Large-scale magnetic susceptibility (MS) variations in ancient sediments are usually
21 interpreted as related to sea-level and climate changes affecting the erosional regime and the
22 amount of detrital input. To constrain such environmental changes during the Famennian, we
23 compared MS records in representative sections of pelagic limestones of (1) the Avalonian
24 margin of Laurussia [Sessacker (SES) and Beringhauser Tunnel (BHT), Rhenish Slate
25 Mountains, Germany] and (2) in Gondwana related terranes [Erfoud (ERF), Tafilalt,

[Tapez ici]

26 Morocco; Col des Tribes (CT), Montagne Noire, France; Buschteich (BU), Thuringia,
27 Germany; Corona Mizziu (CM I, II), Sardinia and Pizzul West (PZW) in the Carnic Alps,
28 Italy]. Very low MS values throughout the Famennian characterize sections from Avalonia. In
29 contrast, MS values are high and oscillating in Gondwana during the early Famennian; they
30 drop significantly all together in the middle Famennian *Palmatolepis marginifera marginifera*
31 Zone to match the pattern of low MS values of the Avalonian margin thereafter. To evaluate
32 the importance of partial diagenetic overprint, MS data were compared to hysteresis
parameters and geochemical proxies in sections BU, CM I, II and CT. The degree of thermal
diagenesis is estimates taking into account the Color Alteration Indices (CAI) of conodonts.
35 Striking dissimilarities in MS records between Laurussia and Gondwana are in favor for an
36 existing remnant oceanic barrier between these continents during early Famennian times,
37 when the amount of detrital supplies was obviously different. Uniformity is reached after the
38 drop of MS values in N-Gondwana, when oceanic barriers could have vanished during the
39 early middle Famennian T-R fluctuations of the sea-level. All sites remained under a rather
40 similar regime of detrital supply through middle to uppermost Famennian. Comparison of MS
41 trends with trends of conodont biofacies in five sections (CT, BU, CM I, II and SES) allows
42 emphasizing the concordance of their relationship to sea level fluctuations.

43
44 Keywords: magnetic susceptibility, conodont biofacies, Famennian, N-Gondwana, Laurussia,
45 paleogeography

[Tapez ici]

47 **1. Introduction**

48 Low-field magnetic susceptibility (MS) is currently considered a proxy to assess the amount
49 of detrital inputs in relation to sea level changes, integrating mineralogical and
50 sedimentological information on their nature and origin (e.g. Ellwood et al. 2006, 2007, 2008,
51 Hladil 2002, Da Silva et al. 2009, 2010). As such it may constitute a powerful and
52 independent proxy to control global trends of sea level changes on condition that the primary
53 origin of low-field magnetic susceptibility is demonstrated. This can be done by comparing
54 MS values with hysteresis parameters and/or elemental concentrations (Devleeschouwer et al.
55 2010); Riquier et al. 2010). Color Alteration Indices (CAI) of conodonts are taken into
56 account to estimate the degree of thermal diagenesis of the rock samples (Epstein et al. 1977).
57 Indeed, the color of the conodonts is related to the temperature that affected the rocks. With
58 an average MS value for lithified marine deposits of $5.5 \times 10^{-8} \text{ m}^3/\text{kg}$ (Ellwood et al. 2011a) 59
most of Paleozoic limestones range between 0.1 and $10 \times 10^{-8} \text{ m}^3/\text{kg}$ (Ellwood et al. 2006).
60 This is the case in Devonian off-shore carbonate successions where a fair number of MS 61
investigations (e.g. Crick et al. 2002, Da Silva et al. 2009, Ellwood et al. 2011b, Riquier et
al. 2010) were conducted since the first global sea-level curve was established by Johnson et
al. (1985).
62 Comprehensive spatio-temporal investigations combining variations of litho- and biofacies
63 with isotope data indicate a long term Famennian regressive trend (Johnson et al. 1985) that is
64 punctuated by short transgressive episodes/events such as at the base of the Famennian
65 (Sandberg et al. 2002). However, within-section MS evolution remains sometimes difficult to
66 correlate with precision between sedimentary sequences from different paleogeographic
67 entities (e.g., Crick et al. 2002). Attention is drawn to the possibility that MS signal in

[Tapez ici]

68 carbonate systems may be affected by diagenesis (Da Silva et al 2012, Devleeschouwer et al.
71 2015), or casually indicate rather particular local conditions (Davies et al. 2013) in spite of
72 global eustasy.

73 Indeed, both the amount and nature of detrital material may possibly be disturbed by aeolian
74 or volcanic inputs, heterogeneity of climatic influence in the continental source areas, and by
75 the importance of physical action during gravitational transport (e.g., current-induced re-
76 working, debris-massflows). On the contrary, slow sedimentation rates or absence of
77 deposition leading to hardgrounds and hiatuses may result in different records of MS signals
78 and their amplitudes. MS studies have been mainly focused on episodes of major extinction
79 events such as the terminal Frasnian Kellwasser events that are particularly marked by
80 instabilities of the sea-level (e.g., Averbuch et al. 2005, Riquier et al. 2010). According to
these authors, the increase of detrital input related to the marked sea-level fall in the earliest
82 Famennian post-event period is expressed by a significant increase in the MS signals.
83 Noticeably, the values of this excursion is particularly less marked in sections on the
Avalonian margin of Laurussia than in those of the Gondwana margin (Averbuch et al. 2005,
fig. 4) (Fig. 1).

86 In this contribution we carry out investigations on the entire Famennian from representative
87 sites of both N-Gondwanan and Avalonian terranes to allow the evaluation of the extent to
88 which the environmental changes of approaching Laurussia/Gondwana margins may have
89 influenced the MS signals (Fig. 1a). To this end, we conducted an integrated study of MS,
90 hysteresis parameters and element concentrations, in some sections (CM I, CM II, PZW and 91
partially in BU), in order to test whether MS can be considered as a reliable detrital proxy.
92 Following Riquier et al. (2010), some elements characteristic of the terrigenous input are not
93 affected by diagenesis (e.g., Zirconium) and can be used as a proxy of the bulk magnetic

[Tapez ici]

94 mineralogical component (Total Fe). Thereafter, we will compare MS measurements with
95 analyses of conodont biofacies in sections that provide sufficient amounts of conodont
96 elements. Indeed, conodonts can also characterize palaeo-environments because of the
97 different ecological preferences of the various genera (Sandberg 1976, Seddon and Sweet
98 1971, Girard et al. 2020), indicative of distance regarding the shoreline. According to this
99 view, the changes in the relative proportion of the different genera, namely biofacies, have
100 been proven useful to track environmental changes through time (e.g., Corradini 2003, Girard
101 et al. 2014, 2017, 2020). As a prerequisite, the continuity of MS records is controlled by fine-
102 scaled conodont biostratigraphy of Spalletta et al. (2017), updated in the latest Famennian by
Corradini et al. (2021).

104 Whether trends in combined MS and biofacies curves allow constituting characteristic
105 features of Famennian deposits in general, and to what extent they are permanent or are
restricted to a definite duration, are prime subjects of our investigations. They allow pointing
possible causes that we aim to discuss.

108

109 **2. Famennian sections**

110 The investigated sections, CT, BU, PZW, CM, ERF, BHT, SES (and DGHS for comparison)
111 are situated between north Gondwana and Laurussia at tropical to subtropical paleolatitudes
112 (Fig. 1a). The position of some samples, conodont zones and main lithofacies are shown in
113 columnar sections Figure 1b.

114

115 *2.1. North Gondwana sections*

116

117 **Col des Tribes (Montagne Noire, France).**

[Tapez ici]

118 This section (72 m-thick) was described by Girard et al. (2014). It is composed of (from
119 bottom to top): - bioclastic limestones (17 m- thick) organized into dm- thick beds; - massive,
120 red mudstones to wackestones/floatstones (15 m- thick) organized into dm- thick beds
121 yielding abundant cheiloceratid goniatites (Griottes facies); - massive micritic limestones (20
122 m- thick) organized into dm- thick beds; - pseudo-nodular limestones (15 m- thick) composed
123 of cm- thick beds which have experienced pressure-dissolution processes; - massive micritic
124 limestones (5 m- thick). These sediments were deposited in mid ramp to basin
settings.

125 Abundance of conodonts allows establishing a fine-scaled biozonation from the *Pa. rhenana*
126 (late Frasnian) to the *Bi. ultimus* Zone (*Pr. meischneri* Subzone, latest Famennian). In this 127
section conodonts are relatively well preserved, with a low Conodont Alteration Index (CAI)
~ 2-2.5 (temperature range = 60 to 110°C).

129

130 **Buschteich (Thuringia, Germany).**

131 This section (35 m- thick) was studied by Girard et al. (2017). From bottom to top, it is
132 composed of: - cm bedded to pseudonodular wackstones (3 m- thick) (Frasnian); - dm to m-
thick beds of mudstones to wackestones (7 m- thick); - mud-wackestones and pseudonodular
134 mudstones (7 m- thick); mm to cm- bedded mud-wackestones (10 m- thick); - mm to cm
135 bedded to pseudonodular wackestones, and some clay (8 m- thick). These sediments were
136 deposited in outer ramp to basin settings. The section spans an interval from the *Pa. rhenana*
137 to *Bi. ultimus* (*Pr. meischneri* Subzone) conodont Zones, but the lowest part of the Famennian
138 is missing (from *Pa. subperlobata* to *Pa. minuta minuta* Zones). The CAI of conodonts is 139
high, estimated as 4 (temperature range = 190 to 300°C).

140

141 **Pizzul West (Carnic Alps, Italia).**

[Tapez ici]

142 This section (24 m- thick) was described by Mossoni et al. (2014), and Corradini et al. (2017).
143 From bottom to top, it comprises: - massive to nodular grey mudstones to packstones (16.5 m-
144 thick); - red nodular wackestones to packstones (7.5 m- thick) (Griottes facies). The
145 limestones contain few fossils. The Griottes facies comprises nodules up to 1 cm of diameter
146 coated with hematite precipitations probably due to syngenetic diagenesis. The
147 sediments were deposited in mid to outer ramp settings. The section spans an interval from
148 the *Pa. glabra prima* to *Pa. marg. marginifera* Zones. The CAI of conodonts is around
(temperature range = 190 to 300°C).

150

151 **Corona Mizziu I and Corona Mizziu II (Sardinia, Italia).**

152 The Corona Mizziu sections have been studied by Corradini (1998, 2003).

153 The Corona Mizziu I (CM I) section (30 m- thick) comprises beds of poorly fossiliferous
154 mudstones, with wackestone to packstone beds in the middle part of the succession.

155 Sediments were deposited in a pelagic setting. The conodont data allow discriminating twelve
conodonts zones from the *Pa. rhomboidea* Zone up to the *Bi. ultimus* Zone.

157 The Corona Mizziu II (CM II) section (18 m-thick) crops out a hundred meters apart from the
158 CM I section and exposes grey massive monotonous mudstones with poor fossil remains. The
159 tectonic imprint is marked by stylolite structures and calcite recrystallization. Sediments were
160 deposited in a pelagic setting. The section spans a time from the *Pa. crepida* to the *Pa. rugosa*
161 *trachytera* Zones. For these two sections (CM I and CM II), the CAI of conodonts is very
high, with values near 4.5 – 5 (temperature range = 300 to 400°C).

163

164 **Erfoud (Tafilalt, SE Morocco).**

165 The Erfoud section spanning the entire Late Devonian has been described by Buggisch &
166 Clausen (1972). The considered lower to middle Famennian part of the section (8 m- thick)

[Tapez ici]

167 was re-sampled. It comprises from bottom to top: - 3 m-thick dark grey mud to wackestones
168 and black shales, with dm-thick beds with cephalopods and bivalve remains (Kellwasser
169 Limestone facies); - 0.45 m- thick platy red-brownish and grey-olive microsparitic calcilutites
170 with bioclasts and Fe-oxid coated oncoids ; - 1.10 m-thick grey-brown cephalopod calcilutites
171 with Fe-oxid coated intraclasts; - 1.95 m-thick thin-bedded nodular calcilutites with
172 cephalopods and trilobites ; -1.50 m- thick alternating cm- thick bedded beige argillaceous
173 nodular limestones and marls. In the lower part of the section the *Pa. crepida* Zone is
174 extremely condensed at the top of the dysoxic black Kellwasser-type limestone. The latter
175 characterises a dysoxic bottom sea depositional environment. Above the Kellwasser
176 limestones, the depositional conditions reflect low sedimentation rates in an open outer shelf
177 environment within the photic zone as testified by prevailing large-eyed trilobites (deep inner
178 to mid ramp). The section encompasses the interval of the *Pa. subperlobata* to the *Pa. rugosa*
179 *trachytera* Zones with a gap between the *Pa. termini* to *Pa. gracilis gracilis* Zones (Fig. 1b).
180 Conodonts have a CAI of 3-4 (temperature range = 150 to 300°C).

181

182 2.2. South Laurussia sections

183

184 **Beringhauser Tunnel (Rhenish Slate Mountains).**

185 This section (15 m- thick) was studied by Schülke & Popp (2005). It consists of mainly well-
186 bedded massive to subordinately nodular cephalopod limestones. At the top of the section,
facies change from massive limestones to nodular limestones. Sediments were deposited in
188 mid to outer ramp setting. The considered section spans a time from the *Pa. crepida* to the *Pa.*
189 *rugosa trachytera* Zones. The CAI of conodonts is high, about 4.5 (Joachimski et al. 2009),
(temperature range around 300°C).

191

[Tapez ici]

192 **Sessacker (Rhenish Slate Mountains)**

193 This highly condensed section (2.5 m- thick) was studied by Ziegler (1962) and Schülke
194 (1999), and complemented by new data. It consists of red mudstones to wackestones with
195 cephalopods, and some sparitic intercalations occur. The sediments were deposited in outer
ramp setting. The section spans from the *Pa. delicatula platys* to the *Pa. rugosa trachytera*
Zones. The conodonts are well-preserved with a CAI around 2.5 (temperature range = 60 to
198 110°C).

199

200 **Dupont GHS drillhole (Illinois basin, Eastern North America).**

201 Drillcores in the Chattanooga Shale of Illinois revealed fine-grained siliciclastic sediments (9
202 m- thick) dating Famennian (Over et al. 2019). Conodont assemblages indicate that the section
spans the *Pa. glabra prima* to *Bi. ac. aculeatus* Zones. MS values are low, in the 0.25/-0.75
interval.

205

206 **3. Methods**

207

208 *3.1. Magnetic Susceptibility*

209 The samples studied are from previous collections for CT (Girard et al. 2014), BU (Girard et
210 al. 2017), CMI and II (Mossoni 2014), PZW (Mossoni 2014). 129 new samples from sections
211 SES, BHT and ERF have been analysed. We measured the low field magnetic susceptibility
(χ_{LF}), abbreviates as magnetic susceptibility (MS) for the seven representatively distributed
Famennian sections.

214 At Col des Tribes (CT, Montagne Noire, France) the field magnetic susceptibility (MS) was
215 directly measured in situ with the Bartington MS2E sensor connected to the MS3 meter. To

[Tapez ici]

216 ensure a representative result, five measures were performed and then averaged for the 74
217 successive stratigraphic levels (Supplementary Data, Table S1). Ex-situ measurements were
218 performed in the laboratory on block samples from German (63 samples for BU, 26 for SES,
219 and 15 BHT) and Moroccan (25 samples for ERF) sections with the same device and the same
220 protocol involving a minimum of 2 measurements per level (Supplementary Data, Tables S2,
S3, S4 and S5). Samples from the Italian sections (Pizzul West and Corona Mizziu I, II were
measured with the KLY-3S Kappabridge at the University of Liège (Supplementary Data,
Tables S6, S7, S8).

224 All the MS data figured represent an average of the measurements (Fig. 2) expressed in 10^{-8}
225 m^3/kg for readability. Following the age model published by Girard et al. (2020), the
base of
226 conodont zones was dated by means of absolute age estimates provided by Becker et al.
227 (2012), and updated by Becker et al. (2020), and all MS data were figured based on the 228
estimated absolute ages (Fig. 2).

229

230 3.2. *Hysteresis parameters*

231

232 The Italian sections (CM I, CM II and PZW) were prepared for hysteresis loops (Mossoni
233 2014) with the objective to roughly estimate the nature of the ferromagnetic (*sensu lato*) Fe
oxides. Indeed, as red nodular facies occur in Pizzul West but not in Corona Mizziu sections,
235 we have suspected significant differences in the nature, the oxidation state, and the
236 concentration quantity of strongly oxidized Fe-oxides such as hematite in the former section,
237 and non-oxidized Fe-oxides such as magnetite in the later section. The hysteresis loops were
238 measured with the J-Coercivity “rotation” magnetometer at Dourbes IRM Geophysical
239 Centre, respectively (Supplementary Data, Tables S8, S9, S10).

[Tapez ici]

240 For the hysteresis measurements, the specimens were prepared from blocks taken every 10
241 cm all along the studied cross-sections. We calculated from the hysteresis loops the high-field
242 magnetic susceptibility (χ_{HF}) and the ferromagnetic susceptibility (χ_{ferro}) following methods
243 developed in Riquier et al. (2010), and Da Silva et al. (2012, 2015). These two parameters
244 allow assessing the respective contribution of the para/dia-magnetic minerals (χ_{HF}) and the
245 ferromagnetic minerals to the initial susceptibility. At the end of the hysteresis loop
246 acquisition, the magnetic viscosity coefficient was calculated from the remanence decay,
247 which was monitored for 100s after the field was removed.

248 Additionally, the major elements (Al, Si, K and Ti) were considered to estimate the
249 proportion of minerals in terms of their magnetic amounts for 17 samples in PZW, 13 samples
250 in CM I and 14 samples in CM II (Tables PZW, CM I and CMII). These analyses on major
251 elements were performed with an X-Ray Fluorescence (Panalytical MagiX PW2540) device
252 at the University of Cagliari. The powder disks were prepared using at least 20 grams of
253 the sample mixed with polyvinyl alcohol, on a base of boric acid. The total amount of oxides
254 and LOI (loss on ignition) has been considered acceptable for samples with an error of $\pm 2\%$.

255 In order to have comparable results between the studied sections, all analyses were 256
normalized to 100. In this way a small error percentage has been distributed between all the
257 measured parameters (Supplementary Data, Tables S8, S9, S10).

258

259 *3.3. Detrital vs authigenic Fe content*

260 To further constrain the diagenetic versus detrital imprints on MS, we compared the low-field
261 magnetic susceptibility (χ_{HF}) variations with selected geochemical proxies measured by
262 mean of the methods developed by Riquier et al. (2010). X-Ray Fluorescence analyses were
263 performed on the samples of Buschteich which presents no signs of strong oxydation and is

[Tapez ici]

264 the most complete section of this study. The analyses were performed with the Niton XL3900
Goldd X-ray fluorescence portable analyzer (Thermo Scientific®, Waltham, MA, USA)
266 at the University of Montpellier. All the rock samples were carefully cleaned prior to all
treatment, and weathered surfaces were removed.

268 We selected elements that can be used as proxies for the terrigenous input. The Zirconium
269 (Zr) was selected here as the more reliable detrital proxy because it is not affected by
270 diagenesis; and the total Fe (Fe_{tot}) content will be used as a proxy of the bulk magnetic
271 mineralogical component. The total Fe was separated into an inherited detrital part and a
272 secondary authigenic part. Following Riquier et al. (2010), the detrital and authigenic
273 fractions of the total iron content were estimated considering that the Fe/Al ratio of the
274 detrital part of the studied rocks is supposed to be the same as that of the average shale value
275 ($Fe/Al_{average\ carbonate}$; 0.55 Clarkson et al. 2014). The detrital fraction of iron (Fe_{det}) is
276 calculated as $Fe_{det} = Al_{sample} * Fe/Al_{average\ carbonate}$. Consequently, the iron fraction in excess
277 relative to the detrital fraction, namely, $Fe_{exc} = Fe_{tot} - Fe_{det}$, may be considered to be of 278
authigenic/diagenetic origin.

279

280 3.4. Biofacies

281 Five sections were sampled in detail for conodont biofacies based on conodont genera
282 abundances. Conodont biofacies are advocated to be mostly driven by water depth variations
283 due to the habitat preferences of the different conodont genera (e.g., Sandberg 1976, Seddon
284 and Sweet 1971). In this regard, the distribution of conodont genera is thought to be
285 controlled by water depth along a proximal-distal gradient (Klapper and Barrick 1978, Girard
286 et al. 2020), and as such may constitute a proxy of sea-level variations and indirectly of
287 detrital input. Several biofacies can be defined, based on the percentage of different genera
288 present in the samples from biofacies characterized by distal surface dwellers (*Palmatolepis*)

[Tapez ici]

289 to proximal surface dwellers (*Icriodus*). The percentages of conodont elements per genus, later
on called biofacies, were estimated for samples of each section: 74 samples for CT
291 (Girard et al. 2014), 34 samples for BU (Girard et al. 2017), 12 samples for SES (Schülke
292 1995; this study), 13 samples in CM I and 13 samples for CM II (Corradini 2003, Mossoni
293 2014). All data are available in the Supplementary Data, Table S11. As MS is also known to
294 be related to detrital input, we compared the MS trends of these five sections with trends in
295 percentage of conodont genera (biofacies). A Principal Component Analysis (PCA on the
296 variance - covariance matrix) allows summarizing biofacies of the five considered sections
(CT, BU, CM I and CM II, and SES) on few synthetic axes. This analysis also provides a
298 representation of the records of CT, BU, CM I, CM II and SES on the same synthetic axes,
299 allowing a direct comparison of the biofacies variations in the five outcrops. The contribution
of each genus percentage to the axes allowed their interpretation in relation to the biofacies.
Correlations between the MS and PC values are calculated using Pearson's product-moment
correlation to investigate if MS and PC values are correlated or not.

303

304 **4. Results**

305 *4.1. Magnetic susceptibility data*

306 The relationship between the absolute age of the base of the biozone boundaries and
307 sediment thickness allows establishing an age model for each section. The ages estimated for
308 each sample were thereafter used to plot the variations of magnetic susceptibility through
309 time. When we compare the evolution of magnetic susceptibility (MS) of Famennian
310 sequences in the different sections, various types of record are documented (Fig. 2):
311 - In the investigated sections of the North Gondwana shelf (Morocco, Montagne Noire), MS
312 values vary markedly and congruently during early Famennian times: initially high and

[Tapez ici]

313 fluctuating MS values shift all together to low ones within the *Pa. marginifera marginifera*
Zone (initial mid-Famennian), and remain constantly low thereafter, lower than the common
Paleozoic magnetic susceptibility values (around $5.5 \times 10^{-8} \text{ m}^3/\text{kg}$).

316 - In the most distal sections of the Gondwana shelf (Sardinia, Carnic Alps, Thuringia), the 317
same trend is observed but fluctuations are less pronounced during the lower Famennian with
318 temporary increases in MS values before the *Pa. marginifera marginifera* Zone.

319 - In south Laurussia (DGHS section), the MS values remain low throughout the record, almost
320 always less than the average of $5.5 \times 10^{-8} \text{ m}^3/\text{kg}$, being rather close to the common Paleozoic
magnetic susceptibility values.

322 - In the Avalonian outer shelf areas of Laurussia (SES and BHT), the MS values are very low
323 during the early Famennian and are similar to those of both Laurentian (DGHS, Fig. 1) and 324
north Gondwanan terranes during mid-through late Famennian times.

325 In summary, in the north Gondwana margin a two-fold stage subdivision of the magnetic
326 susceptibility curve is observed. During the lower Famennian, increasing high values are first
327 recorded then followed by decreasing values that culminate during the *Pa. marginifera*
328 *marginifera* Zone. During the middle to upper Famennian, MS values remain lower than the
329 common Paleozoic magnetic susceptibility values (vertical dotted line in Figure 2). The major
330 shift from high to low MS values during the *Pa. marginifera marginifera* Zone in Gondwana
331 is not recorded in the Laurussia section where MS values remain low through the entire 332
Famennian.

333

334 4.2. Magnetic hysteresis data

335 For the Italian sections PZW, CM I and CM II, the correlations of oxides representing 336
terrigenous input with the MS data are shown in the Supplementary Data (Fig. S1), and 337
detailed in Table 1.

[Tapez ici]

338 For the Pizzul West section, a significant correlation exists between the low field magnetic
339 susceptibility (χ_{LF}) and ferromagnetic contribution (χ_{ferro}), but not with the high field magnetic
340 susceptibility (χ_{HF}). A correlation between low field magnetic susceptibility (χ_{LF}) and the
341 geochemical parameters is not observed ($Al_2O_3=0.005$, $SiO_2=0.12$, $TiO_2=0.12$, $K_2O=0.04$)
342 (Table 1). However, there is a highly significant correlation between the high field magnetic
susceptibility (χ_{HF}) and geochemistry ($Al_2O_3=0.84$, $SiO_2=0.81$, $TiO_2=0.85$, $K_2O=0.83$), that
demonstrates that the paramagnetic fraction is linked to Al, Si, K and Ti bearing minerals. As
most of the Hcr values are lower than 60mT, the MS variations are probably related to low
coercivity minerals as magnetite.

347 For the CM I section a strong correlation exists between the low field magnetic susceptibility
348 (χ_{LF}) and the high field magnetic susceptibility (χ_{HF}), and the ferromagnetic contribution
349 (χ_{ferro}). This demonstrates that the paramagnetic fraction is linked to Al, Si, K and Ti bearing
350 minerals. A very good correlation also exists between the low field magnetic susceptibilit and
the four measured oxides ($Al_2O_3=0.68$, $TiO_2=0.70$, $K_2O=0.69$) (Table 1).

352 For the Corona Mizziu section II, the low field magnetic susceptibility has a good correlation
353 with χ_{ferro} ($r = 0.85$) and with χ_{HF} ($r = 0.82$) (Table1). This suggests that the low field magnetic
354 susceptibility of the Corona Mizziu II section is controlled by both the ferromagnetic and
355 paramagnetic contributions. All the MS values are extremely low (lower than 3.0×10^{-8}
356 m^3/kg , indicating the influence of the diamagnetic fraction, which may have diluted the
potential detrital signal.

358 The magnetic signal for Pizzul West section would be mainly controlled by ferromagnetic
359 contribution of low coercivity mineral (likely magnetite), whereas, for the Corona Mizziu I
360 and II sections, the magnetic signal seems to be influenced by dia and/or
paramagnetic contributions and, to a lesser extent, by ferromagnetic contribution.

362

[Tapez ici]

363 4.3. MS correlation to Fe content

364 Both measured Fe_{tot} and calculated Fe_{det} correlate with the MS evolution ($r = 0.46$, $p = 0.002$
365 for Fe_{det} and $r = 0.41$; $p = 0.0005$ for total Fe). The Fe_{exc} does not show a correlation with the
366 MS variations ($r = 0.19$, $p = 0,157$). A correlation exists between MS and the Zr content 367
($r=0.28$, $p = 0.037$) as well as between the MS and the Fe/Zr ratio ($r=0.73$, $p<0,001$).

368 (Supplementary Data, Fig. S2 and Supplementary Data, Table S2). Although this theoretical
369 calculation gives an estimate of the Fe-bearing fractions only, Fe_{det} and Fe_{exc} , it supports the
370 coexistence of a detrital component, controlling the MS evolution in Buschteich, and an
371 authigenic component, that could have induced the widespread remagnetization process
372 observed in these carbonates. This means that for the Buschteich section we cannot exclude
that a part of the signal results from diagenetic processes, but this part is not as significant as
374 the detrital part.

375 In summary, the geochemical data show that, although in part affected by diagenesis, as
376 shown by correlation between MS and Fe/Zr, MS can be used as an indicator of the detrital
377 input evolution in the studied Famennian sections. It is consequently possible to use it as a
proxy of sea level variations which can be compared to the conodont biofacies proxy.

379

380 4.4. Comparison with conodont biofacies

381 The principal component analysis performed on the proportions of different genera allows
382 summarizing the biofacies variations (Fig. 3) on main axes that express the total variance. The
383 record of the five sections CT, BU, CM I, CM II (North Gondwana) and SES (South
Laurussia) can be directly compared on these axes.

385 The first axis (PC1, 75.8% of the total variance) of the principal component analysis on

[Tapez ici]

386 conodont percentages shows a progressive trend to positive values (from 0 to 1) through the
early Famennian. This trend reverses in the early mid – Famennian to negative values (Fig.
388 3b). The contribution of the variables (here, the percentages of the different genera) to the
389 axes (Fig. 3b) shows that positive values along the first axis correspond to a high proportion
390 of *Palmatolepis* whereas negative values correspond to a high proportion of *Bispathodus*
391 (Supplementary Data, Table S11). A correlation ($N = 115$; $r = 0.26$; $p < 0.005$) exists between
392 the PC1 and the MS data. The third axis represents only $< 4\%$ of variance, and mostly
393 corresponds to variations in the proportion of *Icriodus* in the early Famennian : peaks from
394 *Pa. triangularis* to *Pa. crepida* Zones in CT, peak in the *Pa. crepida* Zone in BU, peak from
395 the *Pa. glabra prima* to the *Pa. rhomboidea* Zones for CM, peak from *Pa. delicatula platys* to
396 *Pa. minuta minuta* in SES (Supplementary Data, Table S1, and Fig. 3c), but values on the PC3
axis are not correlated with the MS values.

398

399 5. Discussion

400 Since pelagic carbonates are dominantly microsparites of diagenetic origin (Franke &
401 Walliser 1983), one can only speculate on the ultimate source of the MS signals as these may
be variously impacted by post-depositional processes. Following intervening aspects are
discussed:

404

405 5.1. Impact of diagenesis

406 The magnetic susceptibility of a rock depends on both the mineralogical composition 407 of
the rock and the proportion of each mineral. The three main magnetic behaviours are:
408 diamagnetic minerals (such as carbonates and quartz) displaying extremely weak negative MS
409 values; paramagnetic minerals (e.g., clay minerals, particularly chlorite, smectite, illite and

[Tapez ici]

410 glauconite, ferromagnesian silicates, iron and manganese carbonates, pyrite) displaying weak
411 positive values, and ferromagnetic minerals (mainly magnetite, pyrrhotite, maghemite, and
412 hematite) displaying strong positive values (Da Silva et al. 2010). Diagenetic and post
diagenetic processes lead to mineralogical and chemical transformation of iron oxides that in
414 turn influences the MS values. Riquier et al (2010) showed that although submitted to
415 different burial histories and diagenetic conditions, consistent long-term trends can be
416 observed in the MS evolution from sections through the Frasnian-Famennian boundary. Their
417 data demonstrated that the MS evolution of the carbonate sections they studied can be
418 interpreted in terms of paleoenvironmental changes along the former margins of Laurussia
419 and Gondwana.

420 In Pizzul West and Corona Mizziu, the conodont Color Alteration Index (CAI) ranges
421 between 4.5 – 5.5. The temperature (200-400°C) which affected the rocks is far beyond the
422 temperature of the goethite-hematite transition. Thus, the high coercivity values measured are
423 related to the presence of hematite, visible also in the microfacies (Mossoni 2014). However,
424 where high coercivity minerals control the MS (χ_{LF}), the presence of hematite is here
interpreted to be of detrital origin because both the high field magnetic susceptibility (χ_{HF})
and the viscous decay do not correlate.

427 At Buschteich, the Fe in excess does not modify the general trend of MS, at least not enough
to overprint the detrital signal.

In the CT section, CAI values of 2 – 2.5 were measured by Wiederer et al (2002), that
429 corresponds to burial temperature of less than 100°C. Low illite crystallinity indicates that the
430 site underwent anchizonal metamorphism at maximum. We assume therefore that a part of the
431 MS signal, associated to iron-bearing primary clay minerals, has been preserved in the
NGondwana sections despite different diagenetic stories.

[Tapez ici]

434 Trends in MS are similar on the N-Gondwana margin (CAI estimated to 4-5 in PZW,
435 CMI and II, BU and around 2-2.5 for CT), high values during the early Famennian and low
436 values during mid-late Famennian. Similar patterns also occur in the S-Laurussia margin
437 (CAI near 4 for BHT and only 2-2.5 for SES), but values remain low during the Famennian.
438 This indicates that, despite different burial histories, the primary MS signature was not
overprinted by the diagenetic signal, and it reflects in part its detrital origin.

440

441 5.2. Relations between depositional setting and MS

442 Variations in the amount of detrital ferromagnetic minerals in off-shore cephalopod
443 limestones may be of different origins, and, in consequence, it is often difficult to precisely
444 determine the cause of changing MS values and their amplitudes (e.g. Devleeschouwer et al.
2015). In this regard, the depositional conditions of the investigated sections could play a role
on the accumulation of ferromagnetic minerals.

447 In the Rhenish Slate Mountains (SES, BHT), the Upper Devonian cephalopod
448 limestones were deposited upon deep submarine rises beyond direct influence of sea-level
449 changes (Franke & Walliser 1983). Besides *in situ* precipitation, pelagic carbonate mud
450 originated from shallow-water areas. Fine-grained sand and clay fractions, originated from
451 distal turbidites deposition, have also probably reached the rises but they mostly have been
452 winnowed away by bottom currents. Consequently, rather low MS values might reflect
453 presence low amount of transported ferro-magnetic elements, as coarse detrital influxes from
454 northern shelf margins were concentrated in sandstone turbidite bodies that by-passed and
were dispatched in troughs between the rises.

456 In the Montagne Noire (CT), very high MS values are recorded during the *Pa. marginifera*
457 *marginifera* Zone prior to a sudden shift to low values under more stable environmental

[Tapez ici]

458 conditions in deeper mid-Famennian outer ramp setting. This shift is coincident with an
459 abrupt change in facies: high though strongly oscillating values are found in the famous red-
460 colored Griottes facies (Tucker 1974) and low values in the overlying compact light grey
461 carbonate mudstones. The Griottes facies is a cephalopod-rich, nodular limestone with
462 abundant iron-clay coatings and some ferruginous hard-grounds. The MS values in this facies
463 are influenced by different chemical and/or physical constraints, not only the detrital inputs of
464 ferro-magnetic minerals. Indeed, ferruginous mineral phases accumulations may also be
influenced by changing both bottom sea oxygenation and rates of Fe-oxide –reduction related
to buried organic matter and to diagenetic re-precipitation of Fe-oxide (Franke & Paul 1980).
This is the case, for example, of condensed pelagic carbonates across the Givetian/Frasnian
468 boundary, where Devleeschouwer et al. (2015) drew attention to the fact that the ferro-469
magnetic fraction may contain high coercivity minerals such as hematite and goethite of
470 secondary origin that could affect the MS signal. This is probably also the case in the CT
471 section, but no hysteresis analyses are available to confirm the assumption that the observed
472 positive excursions may be solely related to hematization during diagenesis. Post-depositional
transformation of paramagnetic clay minerals may also alter the detrital signal of MS.
474 However, this is not the case because the burial temperature was less than 100° (CAI 2-2.5) in
475 CT (Wiederer et al. 2002). It is noteworthy however, that, at CT, the Griotte limestones were
476 deposited on an unstable slope under current activity and underwent repeated intra-
477 formational submarine sliding (debris flows, slumping...) (Girard et al. 2014), leading to local
478 accumulation of Fe-rich sediments. These events may correspond to anomalously high
479 positive peaks in the MS curve at the base of the *Pa. marginifera marginifera* Zone (Fig. 2).
480 At the basins scale, the scenario of MS positive excursions coinciding with hematite-
481 rich early Famennian Griotte limestones has to be discussed. The Griottes limestones are

[Tapez ici]

482 commonly found in southern Europe including the Pyrenees, Montagne Noire and Carnic
483 Alps. Nevertheless, they do not exist in contemporaneous strata in Sardinia despite a similar
484 MS signal. Moreover, this facies is not present in the Thuringian Buschteich section where the
485 MS variation pattern is the same. Conversely, at the beginning of the mid-Famennian, high
486 MS values characterize also compact reddish and brown calcilutites with iron-oxide coatings
487 on the shallow northern Tafelalt platform subjected to emergences (Buggisch & Clausen 1972,
488 Wendt & Aigner 1985). It is noteworthy that a different scenario prevails in the Rhenish slate-
489 mountains where condensed carbonate deposits on deep-water submarine rises upon volcanic
490 substrates at Sessacker are red-coloured despite rather low MS values. At BHT similar low
491 values, after a marked positive excursion in the earliest Famennian (Riquier et al. 2010), occur
in mud-mound carbonates which are not red-colored (Schülke & Popp 2005).

493 In summary, the MS variations during the Famennian is independant from the presence of red
494 facies (Griottes or others), and are consequently interpreted as primary. Consequently, the
495 effect of post-depositional processes probably did not significantly overprint those of sea level
496 changes during the Famennian to explain the differences between the records of Gondwana
and Laurussia, especially the high MS values during the early Famennian in North
498 Gondwana.

499

500 *5.3. Influence of sea-level changes*

501 Magnetic susceptibility and conodont biofacies are potentially interrelated: MS could
502 be a proxy to evaluate detrital input if the signal is of primary origin, and conodont biofacies
503 are interpreted as related to water depth due to habitat preferences of the different conodont
504 genera along a proximal-distal gradient in the surface waters. Conodont PC1 displays a strong
505 relationship with magnetic susceptibility in N-Gondwana terranes, and also on Laurussia, at

[Tapez ici]

506 least for Sessacker, and as such suggests constituting a real indicator of sea-level variations
507 during the Famennian: low MS signals indicate a transgressive trend and correspond to distal
biofacies, and, inversely, high MS signals indicate a regressive trend and correspond to
proximal biofacies.

510 The shift towards lower values for MS and the trend to negative values on the PC1 in
511 N-Gondwana terranes coincides with a local T-R (transgressive - regressive) couplet called
512 “Enkeberg event” described in Laurussia (Rhenish Slate Mountains; House 1985). In
513 Avalonia (Laurussia), there is no major significant change in MS values but the Enkeberg
514 event was identified in the faunal record (Becker 1993). This event has not been yet identified
in the North Gondwana terranes. Consequently, the differences in the MS records of
Gondwana and S-Laurussia rely on other factors, such as paleoclimate and paleogeography.

517

518 *5.4. Paleoclimate and paleo-latitude*

535 During the Famennian, SES, BHT, BU, and PZW sections were located in the subtropical zone
of the southern hemisphere (Fig. 1). A long-term discrete cooling occurred during the
Famennian, but no major changes in temperatures of the sea-surface waters was recorded
(Joachimski et al. 2009); this may exclude a major role of physico-chemistry parameters of sea
water conditions on MS values. Following the draw-down of atmospheric CO₂ concentrations
and burial of organic carbon during the end-Frasnian Kellwasser crises, oxygen isotope values
in conodont apatite indicate a global mean temperature drop of low latitude surface-water in
post-event early Famennian times (Balter et al. 2008; Joachimski & Buggisch 2002;
Joachimski et al. 2009). Mean sea-surface temperatures estimated from conodont apatite $\delta^{18}\text{O}$
values in the Rhenish Slate Mountains (Beringhauser Tunnel section) seem to be slightly
higher than in Gondwana related terranes (Thuringia, Carnic Alps, Southern France)
(Joachimski et al. 2009). Concerning climate, the main difference between

536 Gondwana and Laurussia could rely on the latitudinal position between sites on the subtropical
Laurussia and those of North Gondwana that are farther south in a more temperate

[Tapez ici]

537 position. Indeed, emerged parts of North Gondwana would have accentuated seasonality of
climate and enhanced continental weathering (Percival et al. 2019; Herman et al. 2013).

538 Therefore, emerged areas within the North Gondwana domain might have provided larger
539 amounts of detrital material than the emerged parts of Laurussia. The decrease of high MS
540 values on the Gondwana shelf began during the *Pa. rhomboidea* highstand of sea level and
was probably achieved during the following transgressive pulse of the Enkeberg Event during
539 the early mid-Famennian (Sandberg et al. 2002).

540

541 *5.5. Dynamic paleogeography*

542 Though still debated, Late Devonian plate tectonic models postulate convergence and
543 collisional events between Gondwana and Laurussia heralding both the onset and the
544 development of the Variscan orogeny. Subduction of oceanic crusts between Gondwana-
545 derived continents led successively to the closure from S to N of several oceanic basins
546 (including, Saxo-Thuringian, Rheno-Hercynian oceans...) that previously separated
547 Armorican terranes (e.g., Thuringia, Bohemia) from the southern Laurussian margin (Franke
548 et al. 2017, Golonka 2020) (Fig. 1). This resulted in the formation of large carbonate
549 platforms on distal marine shelves on the Gondwana margins (parts of NW Africa to
550 Montagne Noire). Opposite, on the southern margin Laurussia (Thuringia microcontinent),
condensed pelagic limestones were restricted to tectonic or volcanic submarine highs.

551 During the early Famennian, only the narrowing oceanic interspaces of the
Rhenohercynian basin, assumed width was 1000 km during the Frasnian,
separated Laurussia from outer-shelves of Gondwana-derived terranes (Franke et al.
2017). The age of the closure of the Rheic Ocean remains debated. After Franke
(2019) it closed during the Early Devonian times. Other models maintained the Rheic

[Tapez ici]

ocean open between Saxo-Thuringia and Avalonia until the Carboniferous
(Eckelmann et al. 2014; Golonka 2020, fig. 4).

552 Nevertheless, all these

554 models consider that the northern Gondwana shelf was much more extensive during the
555 Famennian than those of South Laurussia which were restricted to narrow submarine highs
556 and troughs. In such a setting, the detrital supplies from emerged source areas to carbonate
557 platforms were naturally more homogeneously dispatched in the N-Gondwana shelf than in the
558 Laurussia margin. Opposite, the accumulation of the detrital material in the Laurussia margin,
559 even if locally important, was in fact located in troughs (e.g., Rhenish area) and low MS
560 values are recorded on the rises. Consequently, the N-Gondwana and South Laurussia
561 margins clearly underwent a different paleogeographic behavior, and thus a different setting
for detrital accumulation.

567 The separation between the two margins by the narrowing Rheno-Hercynian Ocean is
568 effective at least until the beginning of the mid-Famennian, even if some local pelagic
deposits can be found till the early Carboniferous (Franke et al. 2017). From the *Pa.*
570 *marginifera marginifera* Zone onwards to the latest Famennian the effectiveness of the
571 separation apparently vanished when climate became cooler (Girard et al. 2020). MS values
572 considerably dropped and became conform to median values throughout the entire region
between the Avalonian margins of Laurussia and N-Gondwana related terranes.

574 Consequently, more uniform conditions and smaller amounts of detrital supply prevailed
575 throughout. Concomitantly, the conjunction of vicinity of the two margins and similar
576 climatic conditions is also corroborated by the increasing identity of stenotopic level-bottom
577 biotas such as phacopid trilobites (Feist 2019) in both areas. Consequently, during this time
578 interval, we consider that mid-late Famennian deposits with low MS values seems to be
579 controlled by first an evolving paleogeographic setting, and, at a lesser extent, eustasy, current

[Tapez ici]

580 activity and climate. This paleogeographic setting results from converging margins prior to
closure, and questions the existence, during mid-late Famennian, of wide oceanic domains.

584 **Conclusions**

585 The MS study of five sections in the N-Gondwana margin shows high and oscillating
586 values during the early Famennian, and low values during the mid-late Famennian. In the S-
587 Laurussia margin, MS values remain low through the whole Famennian. Geochemical
588 investigations, and hysteresis parameters in three N-Gondwana sections indicate that the
589 diagenetic processes did not significantly overprint the primary signal of MS. This is
590 emphasized by the degree of burial, thus the temperature during diagenesis (CAI of conodonts)
and the presence or absence of red facies, as the MS values remain consistent from one section
to other.

593 For the first time, we demonstrate a high correlation between these MS and conodont
594 biofacies, confirming their validity for sea level reconstructions. Taking into account all the
595 above mentioned studies, MS can now be used for paleogeographic reconstructions in the
presently dismembered areas of the Variscan Belt.

597 During the early Famennian, the difference in the MS trends and the high values in N-
598 Gondwana compared to S-Laurussia can be explained by two main paleogeographic
599 constraints: i) the Rheic Ocean was not closed; ii) the North-Gondwana margin was wide
600 whilst the South Laurussia margin was fragmented into rises and troughs. During the mid-late
601 Famennian, the uniformization of MS toward low values is interpreted as indicative of rather
similar conditions in both margins, linked to plate convergence and vanishing influence of
oceanic spaces.

607 **Declaration of competing interest**

[Tapez ici]

608 The authors declare that they have no known competing financial interests or personal
relationships that could have appeared to influence the work reported in this paper.

610

611 **Acknowledgements**

612 This contribution profited substantially from critical remarks and constructive suggestions
613 provided by W. Franke and an anonymous reviewer for which we are most grateful. We
614 acknowledge the assistance of Thomas Tirard, Lucas Tortarolo, and Lisa Zaharias for
615 measurements of Buschteich and Col des Tribes during their third-year university degree.
616 Authors thank Eberhart Schindler who provided samples from Sessacker, and Bernard Orth
617 for his assistance during the field-work in Morocco. A.M. thanks Anne Christine Da Silva and
618 Dr Simo Spassov for their help with the issues of the magnetic susceptibility and for allowing
619 him to work in their laboratories. This research was funded by the ANR project ECODEV
(ANR-13-BSV7-005). This is contribution ISEM 2021-111.

621

622 **References**

- 623 Averbuch, O., Tribovillard, N., Devleeschouwer, X., Riquier, L., Mistiaen, B., Van Vliet
Lanoe, B., 2005. Mountain building-enhanced continental weathering and organic carbon
625 burial as major causes for climatic cooling at the Frasnian-Famennian boundary (c. 376
Ma)? *Terra Nova* 17, 25-34.
- 627 Balter, V., Renaud, S., Girard, C., Joachimski, M.M., 2008. Record of climate-driven
morphological changes in 376 Ma Devonian fossils. *Geology* 36, 907-910.
- 629 Becker, R.T., 1993. Anoxia, eustatic changes, and upper Devonian to lowermost
Carboniferous global ammonoid diversity, In: House, M.R. (Ed.), *The Ammonoidea: 631*
Environment, Ecology, and Evolutionary Change. Systematics Assoc. Spec. Vol., Oxford,
632 *pp. 115-163.*
- 633 Becker, R.T., Gradstein, F.M., Hammer, O., 2012. The Devonian Period, in: Gradstein, F.M.,
634 Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), *The Geologic Time Scale 2012. Elsevier,* 635
Oxford, pp. 559-602.
- 636 Becker, R.T., Marshall, J.E.A., Da Silva, A.-C., 2020. The Devonian Period. In *Geological*
637 *Time Scale 2020. doi: <https://doi.org/10.1016/B978-0-12-824360-2.00022-X>*

[Tapez ici]

- 638 Buggisch, W., Clausen, C.-D., 1972. Conodonten- und Goniatiten-Faunen aus dem oberen 639
Frasnium und unteren Famennium Marokkos (Tafilalt, AntiAtlas). *Neues Jahrb. Geol.* 640
Palaontol. Abh. 141, 137-167.
- 641 Clarkson, M.O., Poulton, S.W., Guilbaud, R., Wood, R.A., 2014. Assessing the utility of
642 Fe/Al and Fe-speciation to record water column redox conditions in carbonate-
rich 643 sediments. *Chem. Geol.* 382, 111-122.
- 644 Corradini, C., 1998. Famennian conodonts from two sections near Villasalto. *Giorn. Geol.* 60,
645 Spec. Issue, 122-135.
- 646 Corradini, C., 2003. Late Devonian (Famennian) conodonts from the Corona Mizziu Sections
647 near Villasalto (Sardinia, Italy). *Palaeontogr. Ital.* 89, 65-116.
- 648 Corradini C., Mossoni A., Corrigan M.G., Spalletta C., 2021. The Devonian/Carboniferous
649 Boundary in Sardinia (Italy). *Paleobiodivers. Paleoenviron.* 101. doi: 10.1007/s12549-
650 019-00411-5
- 651 Corradini, C., Mossoni, A., Pondrelli, M., Simonetto, L., 2017. Famennian conodonts in the
652 Mt. Pizzul West (PZW) section. *Ber. Inst. Erdwiss. K.F.-Univ. Graz*, 23, 246-250.
- 653 Crick, R.E., Ellwood, B.B., Feist, R., El Hassani, A., Schindler, E. Dreesen, R. Over, D.J., 654
Girard, C., 2002. Magnetostratigraphy susceptibility of the Frasnian/Famennian boundary.
655 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 181, 67-90.
- 656 Da Silva A.C., Mabilille C., Boulvain F., 2009. Influence of sedimentary setting on the use of
657 magnetic susceptibility: examples from the Devonian of Belgium. *Sedimentology* 56,
658 1292-1306.
- 659 Da Silva A.C., Yans J., Boulvain F., 2010. Sedimentology and magnetic susceptibility during
660 the "punctata" event of the Ardenne area (Belgium): identification of severe and rapid sea 661
level fluctuations. In: Da Silva, AC. and Boulvain, F. (eds): magnetic susceptibility, 662
correlations and Palaeozoic environments. *Geol. Belg.* 13/4, 319-332.
- 663 Da Silva, A.-C., Whalen, M.T., Hladil, J., Chadimova, L., Chen, D., Spassov, S., Boulvain,
664 F., Devleeschouwer, X., 2015. Magnetic susceptibility application: a window onto ancient 665
environments and climatic variations: foreword. *Geol. Soc. Spec. Publ.*, London 414, 1-
666 13.
- 667 Da Silva, A.C., Dekkers, M.J., Mabilille, C., Boulvain, F., 2012. Magnetic signal and its 668
relationship with paleoenvironments and diagenesis - examples from the Devonian 669
carbonates of Belgium. *Studia Geophys. Geod.* 56, 677-704.
- 670 Davies, E.J., Ratcliffe, K.T., Montgomery, P., Pomar, L., Ellwood, B.B., Wray, D.S., 2013.
671 Magnetic Susceptibility (χ) Stratigraphy and Chemostratigraphy Applied to an Isolated
672 Carbonate Platform Reef Complex; Lluçmajor Platform, Mallorca, In: Verwer, K.,
673 Playton, T.E., Harris, P.M.M. (Eds.), *Deposits, Architecture, and Controls*
- 674 Devleeschouwer, X., Petitclerc, E., Spassov, S., Pr at, A., 2010. The Givetian-Frasnian 675
boundary at Nismes parastratotype (Belgium): the magnetic susceptibility signal controlled
676 by ferromagnetic minerals. *Geol. Belg.*, 14/4, 345-360.
- 677 Devleeschouwer, X., Riquier, L., B abek, O., Devleeschouwer, D., Petitclerc, E., Sterckx, S.,
678 Spassov, S., 2015. Magnetization carriers of grey to red deep-water limestones in the GSSP
679 of the Givetian-Frasnian boundary (Puech de la Suque, France): signals influenced by
680 moderate diagenetic overprinting, In: Da Silva, A.C., Whalen, M.T., Hladil, J.,

- 681 Chadimova, L., Chen, D., Spassov, S., Boulvain, F., Devleeschouwer, X. (Eds.), *Magnetic* 682
Susceptibility Applications: A Window onto Ancient Environments and Climatic 683
Variations. Geol. Soc. Spec. Publ., London 414 (1), 157-180.
- 684 Eckelmann, K., Nesbor, H.-D., Königshof, P., Linnemann, U., Hofmann, M., Lange, J.-M.,
685 Sagawe, A., 2014. Plate interactions of Laurussia and Gondwana during the formation of
686 Pangaea — Constraints from U–Pb LA–SF–ICP–MS detrital zircon ages of Devonian and 687
Early Carboniferous siliciclastics of the Rhenohercynian zone, Central European 688
Variscides. *Gondwana Res.* 25, 1484-1500.
- 689 Ellwood B.B., Garcia-Alcalde J.L., El Hassani A., Hladil J., Soto, F.M., Truyols-Massoni, M.,
690 Weddige, K., Koptikova, L., 2006. Stratigraphy of the Middle Devonian Boundary:
Formal 691 Definition of the Susceptibility Magnetostratotype in Germany with
comparisons to 692 Sections in the Czech Republic, Morocco and Spain. *Tectonophysics*
418, 31-49.
- 693 Ellwood B.B., Tomkin J., Richards B., Benoist S.L., Lambert L.L., 2007. MSEC Data Sets
694 Record Glacially Driven Cyclicity: Examples from the Arrow Canyon Mississippian 695
Pennsylvanian GSSP and Associated Sections. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 696
255, 377-390. doi: 10.1016/j.palaeo.2007.08.006.
- 697 Ellwood B.B., Tomkin J.H., Ratcliffe K.T., Wright M., Kafafy A.M., 2008. High-resolution
698 magnetic susceptibility and geochemistry for the Cenomanian/Turonian boundary GSSP 699
with correlation to time equivalent core. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 261,
700 105-126.
- 701 Ellwood, B.B., Algeo, T., El Hassani, A., Tomkin, J.H., Rowe, H., 2011a. Defining the 702
Timing and Duration of the Kačák Interval within the Eifelian/Givetian Boundary GSSP,
703 Mech Irdane, Morocco, Using Geochemical and Magnetic Susceptibility Patterns.
704 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 304, 74–84.
- 705 Ellwood, B.B., Balsam, W.L., Roberts, H.H., 2006. Gulf of Mexico Sediment Sources and
706 Sediment Transport Trends from Magnetic Susceptibility Measurements of
Surface 707 Samples. *Mar. Geol.* 230, 237–248.
- 708 Ellwood, B.B., Tomkin, J.H., El Hassani, A., Bultynck, P., Brett, C.E., Schindler, E., Feist,
709 R., Bartholomew, A.J., 2011b. A climate-driven model and development of a floating point
710 time scale for the entire Middle Devonian Givetian Stage: A test using
711 magnetostratigraphy susceptibility as a climate proxy. *Palaeogeogr. Palaeoclimatol.* 712
Palaeoecol. 304, 85-95.
- 713 Epstein, A., Epstein, J., Harris, L. 1977. Conodont Color Alteration - an Index to Organic 714
Metamorphism. *Geol. Surv. Prof. Pap.* 995, 1-27. doi:10.3133/pp995.
- 715 Feist, R., 2019. Post-Kellwasser event recovery and diversification of phacopid trilobites in 716
the early Famennian (Late Devonian). *Bull. Geosci.* 94, 1-22.
- 717 Franke, W. Walliser, O.H. 1983. “Pelagic” carbonates in the Variscan Belt – their 718
sedimentary and tectonic environments, In: Martin H. and Eder F. W., *Intercontinental*
719 *Fold Belts*. Springer, Berlin, pp. 77-92.
- 720 Franke, W., Cocks, L.R.M., Torsvik, T.H., 2017. The Palaeozoic Variscan oceans revisited.
721 *Gondwana Res.* 48, 257-284.

[Tapez ici]

- 722 Franke, W., Cocks, L.R.M., Torsvik, T.H., 2019. Detrital zircons and the interpretation of
723 palaeogeography, with the Variscan Orogeny as an example. *Geol. Mag.* 157 (4), 1-
724 5. doi.org/10.1017/S0016756819000943
- 725 Franke, W., Paul, J. 1980. Pelagic redbeds in the Devonian of Germany – deposition and 726
diagenesis. *Sediment. Geol.* 25, 231-256.
- 727 Girard, C., Cornée, J.-J., Charruault, A.-L., Corradini, C., Weyer, D., Bartsch, K.,
728 Joachimski, M.M., Feist, R., 2017. Conodont biostratigraphy and palaeoenvironmental 729
trends during the Famennian (Late Devonian) in the Thuringian Buschteich section 730
(Germany). *Newsl. Stratigr.* 50, 71-89.
- 731 Girard, C., Cornée, J.-J., Corradini, C., Fravallo, A., Feist, R., 2014. Palaeoenvironmental 732
changes at Col des Tribes (Montagne Noire, France), a reference section for the Famennian 733
of north Gondwana-related areas. *Geol. Mag.* 151, 864-884.
- 734 Girard, C., Cornée, J.-J., Joachimski, M.M., Charruault, A.-L., Dufour, A.-B., Renaud, S., 735
2020. Paleogeographic differences in temperature, water depth and conodont biofacies 736
during the Late Devonian. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 549, 108852.
737 <https://doi.org/10.1016/j.palaeo.2018.06.046>
- 738 Golonka, J., 2020. Late Devonian paleogeography in the framework of global tectonics.
739 *Global Planet. Change* 186. <https://doi.org/10.1016/j.gloplacha.2020.103129>
- 740 Herman, F., Seward, D., Valla, P.G., Carter, A., Kohn, B., Willett, S.D., Ehlers, T.A., 2013.
741 Worldwide acceleration of mountain erosion under a cooling climate. *Nature* 504.
- 742 Hladil, J., 2002. Geophysical records of dispersed weathering products on the Frasnian
743 carbonate platform and early Famennian ramps in Moravia, Czech Republic: proxies for 744
eustasy and palaeoclimate. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 181, 213-250.
- 745 House, M.R., 1985. Correlation of mid-Palaeozoic ammonoid evolutionary events with global
746 sedimentary perturbations. *Nature* 313, 17-22.
- 747 Joachimski, M., Buggisch, W., 2002. Conodont apatite $\delta^{18}\text{O}$ signatures indicate climatic 748
cooling as a trigger of the Late Devonian mass extinction. *Geology* 30, 711-714.
- 749 Joachimski, M.M., Breisig, S., Buggisch, W., Talent, J.A., Mawson, R., Gereke, M., Morrow,
750 J.R., Day, J., Weddige, K., 2009. Devonian climate and reef evolution: Insights from
751 oxygen isotopes in apatite. *Earth Planet. Sci. Lett.* 284, 599-609.
- 752 Johnson, J.G., Klapper, G., Elrick, M., 1996. Devonian transgressive-regressive cycles and 753
biostratigraphy, Northern Antelope Range, Nevada: establishment of reference horizons 754
for global cycles. *Palaios* 11, 3-14.
- 755 Johnson, J.G., Klapper, G., Sandberg, C.A., 1985. Devonian tatic fluctuations in Euramerica.
756 *Geol. Soc. Am. Bull.* 96, 567-587.
- 757 Klapper, G., Barrick, J.E., 1978. Conodont ecology: pelagic versus benthic. *Lethaia* 11, 15-
758 23.
- 759 Mossoni, A., 2014. Selected Famennian (Late Devonian) events (Condroz, Annulata,
760 Hangenberg) in Sardinia and in the Carnic Alps: conodont biostratigraphy, magnetic
761 susceptibility and geochemistry, Università degli Studi di Cagliari. Cagliari, p. 171 762
(unpublished thesis).
- 763 Over, D.J., Hauf, E., Wallace, J., Chiarello, J., Over, J.-S., Gilleaudeau, G.J., Song, Y.,
Algeo,

[Tapez ici]

- 764 T.J., 2019. Conodont biostratigraphy and magnetic susceptibility of Upper Devonian 765
Chattanooga Shale, eastern United States: Evidence for episodic deposition and 766
disconformities. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 524, 137-149. 767
<https://doi.org/10.1016/j.palaeo.2019.03.017>.
- 768 Percival, L.M.E., Selby, D., Bond, D.P.G., Rakociński, M., Racki, G., Marynowski, L.,
769 Adatte, T., Spangenberg, J.E., Föllmi, K.B., 2019. Pulses of enhanced continental 770
weathering associated with multiple Late Devonian climate perturbations: Evidence from
771 osmium-isotope compositions. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 524, 240-
249.
- 772 Riquier, L., Averbuch, O., Devleeschouwer, X., Tribovillard, N., 2010. Diagenetic versus
773 detrital origin of the magnetic susceptibility variations in some carbonate Frasnian
Famennian boundary sections from Northern Africa and Western Europe: implications for
775 paleoenvironmental reconstructions. *Int. J. Earth Sci.* 99, 57-73.
- 776 Sandberg, C.A., 1976. Conodont biofacies of late Devonian *Polygnathus styriacus* Zone in
777 western United States, In: Barnes, C.R. (Ed.), *Conodont Paleogeology*. Geol.
Assoc. 778 Canada spec. Pap. Montreal, pp. 171-186.
- 779 Sandberg, C.A., Morrow, J.R., Ziegler, W., 2002. Late Devonian sea-level changes, 780
catastrophic events, and mass extinctions. *Geol. Soc. Am. Spec. Pap.* 356, 473-487.
- 781 Schülke, I., 1995. Evolutive Prozesse bei *Palmatolepis* in der frühen Famenne-Stufe
782 (Conodont, Ober-Devon). *Göttinger Arbeiten zur Geologie und Paläontologie*, Göttingen. 783
Schülke, I., 1999. Conodont multielement reconstructions from the the early Famennian
(Late 784 Devonian) of the Montagne Noire (southern France). *Geol. Palaeontol.* 31, 1-
123.
- 785 Schülke, I., Popp, A., 2005. Microfacies development, sea-level change, and conodont 786
stratigraphy of Famennian mid- to deep platform deposits of the Beringhauser Tunnel 787
section (Rheinisches Schiefergebirge, Germany). *Facies* 50, 647-664.
- 788 Seddon, G., Sweet, W.C., 1971. An ecologic model for conodonts. *J. Paleontol.* 45, 869-880.
- 789 Spalletta, C., Perri, M.C., Over, D.J., Corradini, C. 2017. Famennian (Upper Devonian) 790
conodont zonation: revised global standard. *Bull. Geosci.* 92 (1), 31-57.
- 791 Tucker, E., 1974. Sedimentology of Palaeozoic pelagic limestones: the Devonian Griotte
792 (Southern France) and Cephalopodenkalk (Germany). *Spec. Pub., Intern. Assoc.*
793 *Sedimentologists* 1, 71-92.
- 794 Wendt, J., Aigner, T., 1985. Facies patterns and depositional environments of Palaeozoic
795 cephalopod limestones. *Sediment. Geol.* 44, 263-300. <http://doi.org/10.1144/SP414.15>
- 796 Wiederer, U., Königshof, P., Feist, R., Franke, W. and Doublier M. P. 2002. Low-grade
797 metamorphism in the Montagne Noire (S-France): Conodont Alteration Index (CAI) in
Palaeozoic carbonates and implications for the exhumation of a hot metamorphic core 799
complex. *Schweiz. mineral. petrogr. Mitt.* 82, 393-407.
- 800 Ziegler, W., 1962. Taxonomy und Phylogenie oberdevonischer Conodonten und ihre 801
stratigraphische Bedeutung. *Abh. hess. Landesamt. Bodenforsch. Wiesbaden.*
- 802
- 803

[Tapez ici]

804 **Figure captions**

805 **Figure 1. a)** Early Famennian (-370.3 Ma) paleogeographic map (after Franke et al., 2017 and
806 Golonka, 2020) showing the locations of the studied sections.

807 Abbreviations: SES: Sessacker (Rhenish Slate Mountains, Germany), BHT: Beringhauser
Tunnel (Rhenish Slate Mountains, Germany), PZW: Pizzul West (Carnic Alps, Italy), CT:
809 Col des Tribes (Montagne Noire, France), CM: Corona Mizziu (Sardinia, Italy), BU:
810 Buschteich (Thuringia, Germany), ERF: Erfoud (Tafilalt, SE Morocco), DGHS (DuPont GHS
811 Core, Eastern United States, after Over et al. 2019). **b)** Biostratigraphic correlation of the
the 812 studied sections.

813

814 **Figure 2.** Magnetic susceptibility curves through the Famennian (Late Devonian) for sections
815 of S-Laurussia and N-Gondwana. Ages based on Girard et al. (2020), and updated after
816 Becker et al. (2020). The curves represent the average of the MS values obtained with 2 to 5
817 measurements with the standard error in grey. Vertical dotted line: average MS values for
818 lithified marine deposits estimated to 5.5×10^{-8} m³/kg (Ellwood et al. 2011a). Data of DGHS
819 (Eastern United States) are after Over et al. (2019) and data of uppermost Frasnian to lower
Famennian in Coumiac (CUQ*) and Berinhauser Tunnel (BHT*) after Riquier et al. (2010).
821 Conodont Zones after Spalletta et al. (2017).

822

823 **Figure 3. a)** Magnetic susceptibility curves through the Famennien (Late Devonian) at Col
824 des Tribes (CT, France) in green, Buschteich (BU, Germany) in red and Corona Mizziu (CMI
825 and CM II, Italia) in orange, Sessacker (SES) in black. **b)** Conodont biofacies through time
826 depicted as variations along the first axis of the PCA on conodont genera percentages of CT
827 (in green), BU (in red), CM (dotted line in orange), and (SES) in black. **c)** Simplified
828 transgressive-regressive cycles after Johnson et al. (1985, 1996). Conodont Zones after

[Tapez ici]

829 Spalletta et al. (2017). Ages based on Girard et al. (2020), modified after Becker et al. (2020).

830

831

832 **Supplementary Figure 1.** Low field magnetic susceptibility (χ_{LF}) and geochemical data 833
(Al_2O_3 , SiO_2 , Fe_2O_3 , TiO_2 , K_2O) for the PZW, CM II and CM I sections.

834

835 **Supplementary Figure 2.** Scatterplots reporting the MS versus selected geochemical indexes
836 for samples from the Buschteich section (Level BU03 not figured). **a)** The zirconium (Zr)
837 concentration (ppm); **b)** the iron (Fe) concentration (%); **c)** Fe_{exc} (%), **d)** Fe_{det} (%). The
838 number of samples, the correlation coefficient r , and the p are reported for each diagram. Open
red circles: levels after the “Enkeberg event”, Red coloured circles: levels before the
“Enkeberg event”.

841

842 **Supplementary Table 1.** Magnetic susceptibility (MS) for the Col des Tribes (CT) section.
843 MS in m^3/kg . Depth in cm. Conodont Zones after Spalletta et al. (2017). Ages based on
Girard et al. (2020), and modified after Becker et al. (2020).

845

846 **Supplementary Table 2.** Magnetic susceptibility (MS) for the Buschteich (BU) section. MS
847 in m^3/kg . Depth in cm. Conodont Zones after Spalletta et al. (2017). Ages based on Girard et
al. (2020), and modified after Becker et al. (2020). Concentrations in Fe, Al, Zr (in ppm), and
associated errors.

850

851 **Supplementary Table 3.** Magnetic susceptibility (MS) for the Sessacker (SES) section. MS
852 in m^3/kg . Depth in cm. Conodont Zones after Spalletta et al. (2017). Ages based on Girard et
al. (2020), and modified after Becker et al. (2020).

854

855 **Supplementary Table 4.** Magnetic susceptibility (MS) for the Beringhauser Tunnel (BHT)
section. MS in m^3/kg . Depth in cm. Conodont Zones after Spalletta et al. (2017). Ages based
on Girard et al. (2020), and modified after Becker et al. (2020).

858

[Tapez ici]

859 **Supplementary Table 5.** Magnetic susceptibility (MS) for the Erfoud (ERF) section. MS in
860 m^3/kg . Depth in cm. Conodont Zones after Spalletta et al. (2017). Ages based on Girard et al.
(2020), and modified after Becker et al. (2020).

862

863 **Supplementary Table 6.** Magnetic susceptibility (MS) for the Pizzul West (PZW) section.
864 MS in m^3/kg . Depth in cm. Conodont Zones after Spalletta et al. (2017). Ages based on
Girard et al. (2020), and modified after Becker et al. (2020).

866

867 **Supplementary Table 7.** Magnetic susceptibility (MS) for the Corona Mizziu II (CM II)
section. MS in m^3/kg . Depth in cm. Conodont Zones after Spalletta et al. (2017). Ages based
on Girard et al. (2020), and modified after Becker et al. (2020).

870

871 **Supplementary Table 8.** Magnetic susceptibility (MS) and low field magnetic susceptibility
872 (χ_{LF}), ferromagnetic contribution (χ_{Ferro}), hysteresis parameters (high field magnetic
873 susceptibility (χ_{HF})), saturation magnetization (MS), coercitive force (Hc), coercivity of
remanence (Hcr), highfield remanence and viscosity decay; geochemical data for Corona
Mizziu I (CM I) section.

876

877 **Supplementary Table 9.** Low field magnetic susceptibility (χ_{LF}), ferromagnetic contribution
878 (χ_{Ferro}), hysteresis parameters (high field magnetic susceptibility (χ_{HF})), saturation
879 magnetization (MS), coercitive force (Hc), coercivity of remanence (Hcr), highfield
880 remanence and viscosity decay, geochemical data for the Corona Mizziu II (CM II) section.

881

882 **Supplementary Table 10.** Low field magnetic susceptibility (χ_{LF}), ferromagnetic
883 contribution (χ_{Ferro}), hysteresis parameters (high field magnetic susceptibility (χ_{HF})),
884 saturation magnetization (MS), coercitive force (Hc), coercivity of remanence (Hcr), highfield
remanence and viscosity decay and geochemical data for the Pizzul West (PZW) section.

886

887 **Supplementary Table 11.** Mean MS (m^3/kg), and conodont genera percentages (pc). Names
888 of the samples: CT (Col des Tribes), BU (Buschteich), SES (Sessacker), CM (Corona
889 Mizziu). Ages are given by the conodont zones after Spalletta et al. (2017) and by the age
890 model (in My). Proportions of the different genera: pcPa: *Palmatolepis*; pcPo: *Polygnathus*;

[Tapez ici]

891 pcAn: *Ancyrognathus* and *Ancyrodella*; pcIc: *Icriodus*; pcBi: *Bispathodus*, *Branmehla* and
892 *Mehlina*; pcSc: *Scaphignathus* and *Alternognathus*, pcSi: *Siphonodella*.

892

893 **Table 1.** Correlations between MS (χ_{LF}), and ferromagnetic contribution (χ_{Ferro}), high field
894 magnetic susceptibility (χ_{HF}), coercivity of remanence (Hcr), and geochemical data using
linear regression. Number of samples (N), coefficient of correlation (r) and probability (p) are
given. Significant correlations marked in bold ($p < 0.05$).

897

		CM I			CM II			PZW		
		N	r	p	N	r	p	N	r	p
Xlf	Xferro	32	0.69	0.000	14	0.85	0.000	20	0.87	0.000
	Xhf	32	0.82	0.000	14	0.82	0.000	21	0.03	0.454
	Hcr	32	0.68	0.000	14	0.74	0.002	21	0.03	0.422
Xlf	Al2O3	13	0.68	0.010	11	0.25	0.463	17	0.005	0.785
Xhf		13	0.48	0.095	11	0.27	0.915	17	0.84	0.000
Xlf	SiO2	13	0.51	0.072	11	0.47	0.146	17	0.12	0.653
Xhf		13	0.55	0.050	11	0.49	0.122	17	0.81	0.000
Xlf	Fe2O3	13	0.70	0.008	11	0.67	0.023	17	0.13	0.613
Xhf		13	0.50	0.081	11	0.39	0.239	17	0.92	0.000
Xlf	TiO2	13	0.70	0.008	11	0.30	0.361	17	0.12	0.655
Xhf		13	0.48	0.096	11	0.31	0.350	17	0.85	0.000
Xlf	K2O	13	0.70	0.008	11	0.08	0.805	17	0.04	0.890
Xhf		13	0.45	0.123	11	0.46	0.158	17	0.83	0.000

898

899 **Highlights**

900 Early Famennian MS values differ on N-Gondwana and on S-Laurussia margins

901 Famennian MS values correlate with conodont biofacies

902 MS is a powerful tool for geodynamics

903

904 **Credit Author Statement**

905

906 **CG** Conceptualization, Fieldwork, Supervision, Funding acquisition, Writing - Original Draft

[Tapez ici]

907 Preparation; **RF** Interpretations, Discussions, Writing; **AM** Data acquisition, geochemical and
908 MS analyses; **JJC** Interpretations, Discussions, Writing; **ALC** Fieldwork, Sample
909 Preparation; **PC** Interpretations, Discussions, Writing; **CC** Fieldwork, Conceptualization &
910 Supervision

911

912

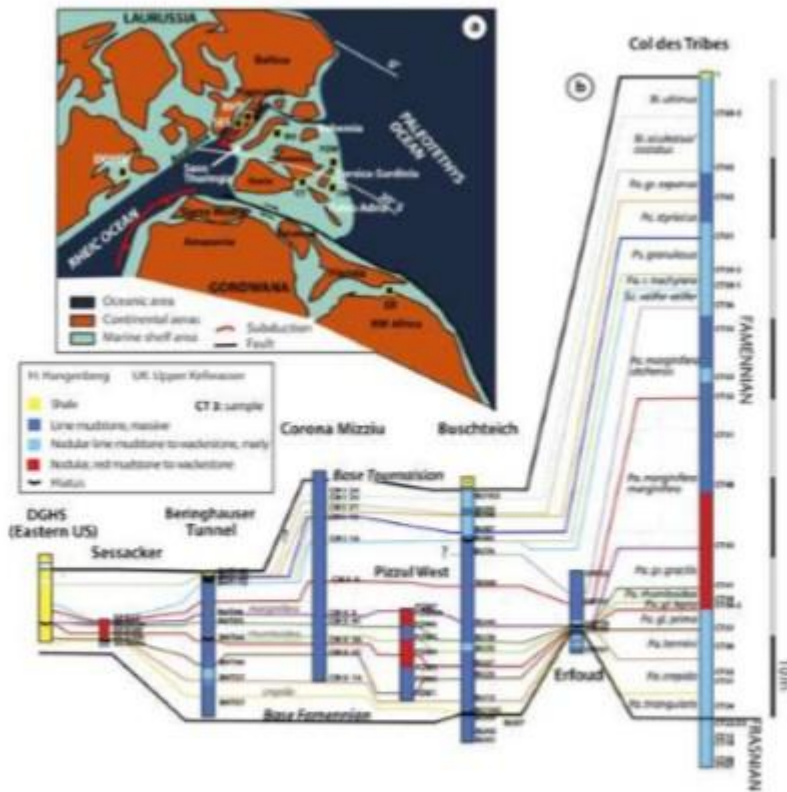
913

914 Declaration of competing interest

915 The authors declare that they have no known competing financial interests or personal
relationships that could have appeared to influence the work reported in this paper.

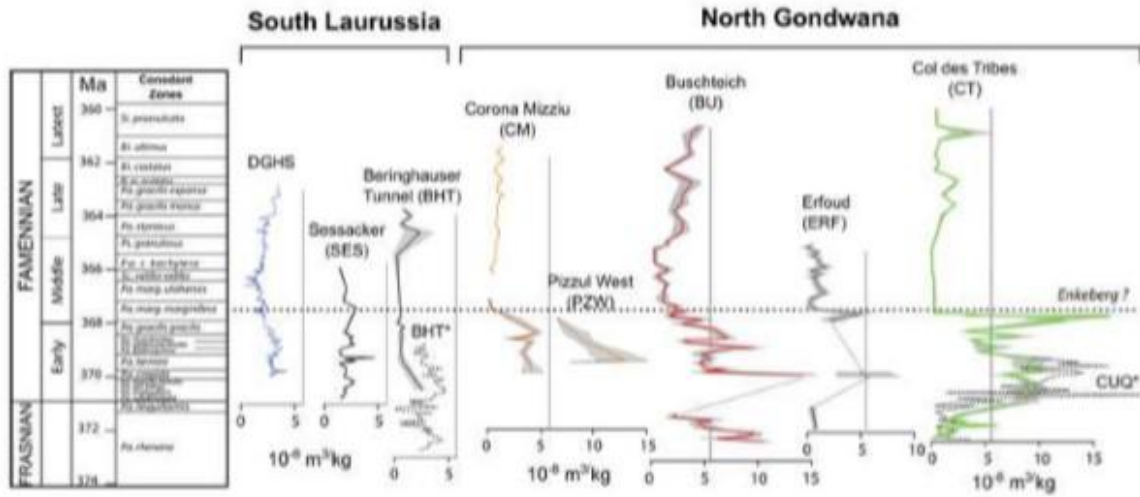
917

918

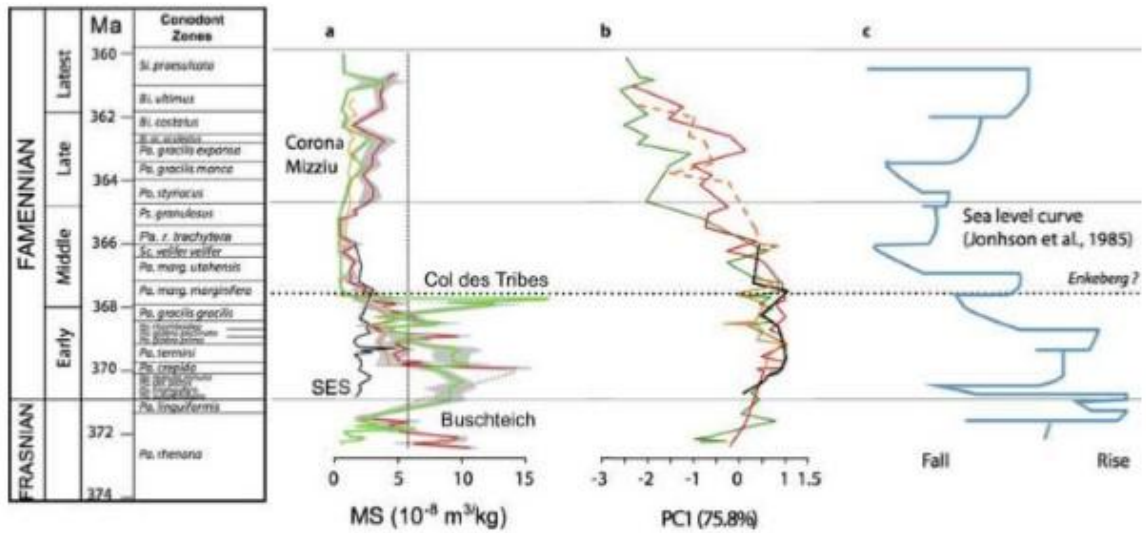


919

[Tapez ici]

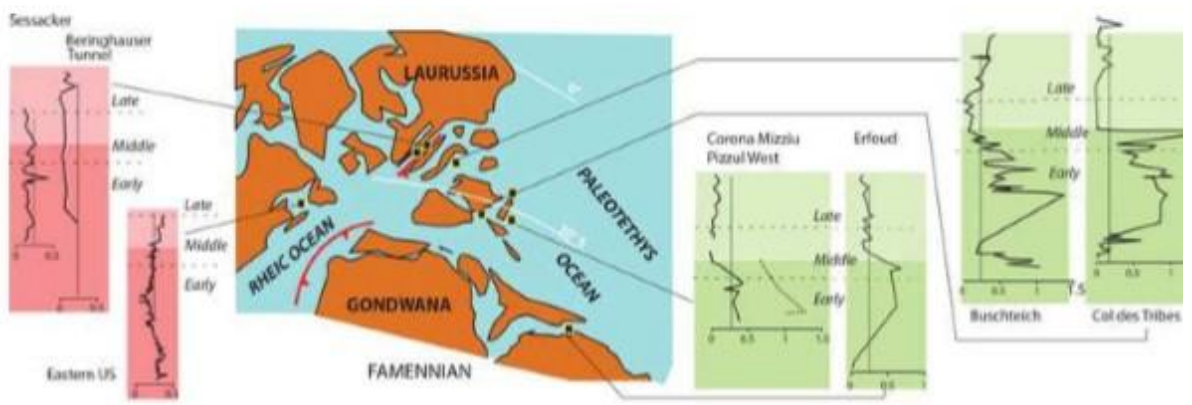


920
921



922
923 Graphical abstract

[Tapez ici]



924