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Plio-Quaternary landscape evolution in the uplifted Ardennes: New insights from $^{26}\text{Al}/^{10}\text{Be}$ data from cave-deposited alluvium (Meuse catchment, E. Belgium)

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Abstract: Despite a wealth of recent studies dealing with the evolution of the drainage network in the uplifted Ardennes massif (E. Belgium), especially from the Middle Pleistocene onwards, the Ardennian landscape evolution and long-term incision rates in the Meuse catchment remain poorly documented over the whole Plio-Quaternary. Alluvium-filled multilevel cave systems represent a relevant setting to unravel the Late Cenozoic history of regional river incision. We present here a dataset of $^{26}\text{Al}/^{10}\text{Be}$ concentration data obtained from fifteen pebble samples washed into the Chawresse system, one of the largest multi-level cave systems of Belgium, which developed in Devonian limestones of the lower Ourthe valley, the main Ardennian tributary of the Meuse. The sample collection spans an elevation difference higher than 120 m and their depleted $^{26}\text{Al}/^{10}\text{Be}$ ratios yield burial ages ranging from ~0.25 to 3.28 Ma. After critical assessment of our dataset for intra-karstic reworking issues, the most striking outcome of the obtained burial ages is the acceleration by a factor five of the incision rates (from ~30 to ~150 m/Ma) during the first half of the Middle Pleistocene. Integrating this incision peak and our pre-burial denudation rates, we then revisit the existing framework of Plio-Quaternary denudation and river incision in the Ardennian Meuse catchment. Whilst our $^{26}\text{Al}/^{10}\text{Be}$ concentration data shed new light on the temporal and spatial variability of the local river and hillslope system response to coupled tectonic and climatic forcings, it simultaneously highlights sampling issues and the need for further chronological data.

Ardennian multi-level cave system (Belgium) spanning a height difference >120 m

$^{26}\text{Al}/^{10}\text{Be}$ burial dating of fluvial sediments whose ages range from ~0.25 to 3.28 Ma

Critical assessment of our dataset because of probable intra-karstic reworking issues

Five-fold increase of incision rates (~30 to ~150 m/Ma) during the Middle Pleistocene

Spatio-temporal variability of regional river response during the Plio-Quaternary

Abstract.

Despite a wealth of recent studies dealing with the evolution of the drainage network in the uplifted Ardennes massif (E. Belgium), especially from the Middle Pleistocene onwards, the Ardennian landscape evolution and long-term incision rates in the Meuse catchment remain poorly documented over the whole Plio-Quaternary. Alluvium-filled multilevel cave systems represent a relevant setting to unravel the Late Cenozoic history of regional river incision. We present here a dataset of $^{26}\text{Al}/^{10}\text{Be}$ concentration data obtained from fifteen pebble samples washed into the Chawresse system, one of the largest multi-level cave systems of Belgium, which developed in Devonian limestones of the lower Ourthe valley, the main Ardennian tributary of the Meuse. The sample collection spans an elevation difference higher than 120 m and their depleted $^{26}\text{Al}/^{10}\text{Be}$ ratios yield burial ages ranging from ~0.25 to 3.28 Ma. After critical assessment of our dataset for intra-karstic reworking issues, the most striking outcome of the obtained burial ages is the acceleration by a factor five of the incision rates (from ~30 to ~150 m/Ma) during the first half of the Middle Pleistocene. Integrating this incision peak and our pre-burial denudation rates, we then revisit the existing framework of Plio-Quaternary denudation and river incision in the Ardennian Meuse catchment. Whilst our $^{26}\text{Al}/^{10}\text{Be}$ concentration data shed new light on the temporal and spatial variability of the local river and hillslope system response to coupled tectonic and climatic forcings, it simultaneously highlights sampling issues and the need for further chronological data.

1 **Plio-Quaternary landscape evolution in the uplifted Ardennes: new insights**
2 **from $^{26}\text{Al}/^{10}\text{Be}$ data from cave-deposited alluvium (Meuse catchment, E**
3 **Belgium)**

4
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7
8 *: Georges Aumaître and Karim Keddadouche.

9
10
11 **1. Introduction**

12
13 Beyond studies embracing the western part of the Rhenish shield (e.g., Meyer et al., 1983;
14 Demoulin and Hallot, 2009), the Neogene and Quaternary landscape evolution of the
15 Variscan Ardennes massif, i.e., its westernmost area, has long been a core topic of
16 ~~western~~ Europe geomorphology. In this framework, the Ardennian Meuse catchment has
17 received particular attention (Davis, 1895). ~~The f~~First geomorphic works focused on either
18 Cenozoic erosion surfaces (e.g., Alexandre, 1976; Demoulin, 1995) or Quaternary river
19 terrace systems of the Meuse (e.g., Macar, 1975; Juvigné and Renard, 1992; Pissart et al.,
20 1997) and its Ardennian tributaries (e.g. Ek, 1957; Juvigné, 1979; Cornet, 1995). However,
21 most of them did not go much beyond the mere reconstruction of successive landform
22 generations. During the last twenty years, studies based on DEM analysis, modern dating
23 methods, and numerical modelling have provided new insights into the quantitative long-term
24 evolution of the Ardennian Meuse catchment. They allowed, for instance, ~~the~~ determination
25 ~~of~~ ing sediment budgets (Van Balen et al., 2000) and palaeodenudation rates (Schaller et al.,
26 2002; 2004; Demoulin et al., 2009), dating of river terrace deposits (Rixhon et al., 2011;
27 2014), modelling of knickpoints ~~s~~ propagation (Beckers et al., 2014) and hillslope denudation
28 (Bovy et al., 2016).

29

30 Despite these significant advances, the timing of Ardennian landscape evolution over the
31 Plio-Quaternary remains poorly documented (Rixhon and Demoulin, 2018). In this respect,
32 although the Ardennes massif is well-known for hosting spectacular cave systems developed
33 in Paleozoic limestone formations at the outskirts of its siliceous core, such as the Han-sur-
34 Lesse cave (e.g., Quinif and Hallet, 2018), little effort has been made so far to use this
35 favourable setting to unravel long-term landscape evolution. Importantly, multi-level cave
36 systems may record massif-scale fluvial history. Penetrating into the karstic system as
37 bedload of sinking streams, sediments may be left behind as flowing water abandons the
38 cave when diversion of the underground stream to a lower topographic level occurs (Anthony
39 and Granger, 2007). As they point to the last period of time during which the passage was at
40 the local water table, fluvial sediments deposited in higher-lying abandoned phreatic
41 passages, mimicking alluvium-mantled terrace sequences (Granger *et al.*, 1997), are useful
42 archives to unravel the timing of river incision. In this respect, *in situ*-produced cosmogenic
43 nuclides are a powerful tool to quantify the pace of long-term river incision (e.g., Rixhon *et*
44 *al.*, 2017), either through depth-profile dating of alluvial terraces (e.g., Repka *et al.*, 1997) or
45 burial dating of fluvial sediments washed into caves (e.g., Granger *et al.*, 1997). Here, we
46 apply this last approach.

47

48 This study explores whether past episodes of fluvial base-level stability in the Ardennes can
49 be chronologically constrained via $^{26}\text{Al}/^{10}\text{Be}$ burial dating of ancient, alluvium-filled karstic
50 passages in one of the largest multi-level cave systems of Belgium. Coarse fluvial sediments
51 were sampled for ^{10}Be and ^{26}Al measurements in the so-called Chawresse system located in
52 the lower Ourthe [valleyValley](#) (i.e., the largest Ardennian tributary of the Meuse), whose
53 karstic levels span an elevation range >120 m. We thereby primarily aim to constrain long-
54 term incision rates at the northern rim of the uplifted Ardennes massif. Complementing the
55 existing ~0.4 Ma age of the younger main terrace in the lower Ourthe [valleyValley](#) (Rixhon *et*
56 *al.*, 2011), new $^{26}\text{Al}/^{10}\text{Be}$ burial ages ranging from ~0.2 to 3.3 Ma extend the reconstructed

57 incision history to the Plio-Quaternary. In addition, $^{26}\text{Al}/^{10}\text{Be}$ ratios provide pre-burial
58 denudation rate estimates.

59

60 **2. Geologic and geomorphic setting of the study area**

61

62 *2.1. Late Cenozoic uplift of the Rhenish-Ardennes massif*

63 | The Ardennes constitutes the western part of the Paleozoic Rhenish massif in south-eastern
64 | Belgium (Fig. 1a). The whole Ardennes-Rhenish massif experienced Late Cenozoic tectonic
65 | uplift, claimed to have been caused by either lithospheric thinning (e.g., Prodehl et al., 1995),
66 | lithospheric folding (e.g., Cloething et al., 2005), or mantle upwelling beneath S. Eifel (Ritter
67 | et al., 2001). Whereas the spatial pattern of mid-Pleistocene uplift has been usually
68 | interpreted as an epeirogenic dome centered on the Eifel (Meyer and Stets, 1998; Van Balen
69 | et al., 2000), Demoulin and Hallot (2009) recently suggested that an uplift pulse migrated
70 | northwards across the massif, pointing to lithospheric folding as the primary cause of uplift.

71

72 | About 400–450 m of rock uplift has been inferred for the Rhenish massif since the Oligocene
73 | (Demoulin and Hallot, 2009). Up to 150 m deep Quaternary river incision in the Ardennes
74 | bears witness to a recently increased uplift pace probably occurring in two steps, first at the
75 | Pliocene-Pleistocene transition and then sometime at the beginning of the Middle
76 | Pleistocene (Van Balen et al., 2000). During this last, short-lasting uplift pulse (probably a
77 | few 10^4 yearsyr), rock uplift peak rates may have reached 0.3 to 0.5 mm/y-yr (Fig. 1a; Van
78 | Balen et al., 2000; Demoulin and Hallot, 2009; Rixhon and Demoulin, 2018). A phase of
79 | tectonic quiescence is postulated from the late Middle Pleistocene onwards (Van Balen et al.,
80 | 2000).

81

82 *2.2. The Ourthe catchment and its lower valley reach*

83 | The Ourthe, largest Ardennian tributary of the Meuse, joins it at the northern rim of the massif
84 | in Liège at an elevation of ~60 m (Figs. 1b and 2). Its ~3600 km² large-catchment is

85 characterized by a highly asymmetric drainage network, the main stem closely following its
86 western border. From south to north, the Ourthe valley/Valley is incised into the siliceous
87 Lower Devonian basement of the Ardennes anticlinorium and rock strata of the Dinant
88 Synclinorium, including limestone formations of the Middle/Upper Devonian and
89 Carboniferous at several locations (Fig. 1b). Owing to sustained karstification processes,
90 many large cave systems developed directly along the Ourthe valley/Valley in both Devonian
91 (Bohon, Hotton, Chawresse caves; e.g., Bastin et al., 1988) and Carboniferous limestone
92 formations (Abîme, Nou Bleu caves; e.g., Peeters and Ek, 2018).

93
94 The ~30 km long lower reach of the Ourthe valley/Valley records a Late Cenozoic incision
95 amounting to a maximum of >130 m (Cornet, 1995). Previous geomorphic works
96 reconstructed up to 20 terrace levels along this reach (Ek, 1957; Cornet, 1995) (Fig. 2).
97 However, these reconstructions are essentially descriptive and lack reliable chronological
98 data to constrain the timing of river downcutting. The lowest terrace at Tilff is dated by the
99 presence of the Early Glacial Rocourt tephra (0.074-0.090 Ma), close to the study area
100 (Juvigné, 1973; Pouclet et al. 2008), thereby suggesting a mean incision rate in the order of
101 40 m/Ma since the onset of the last glaciation. The only other numerical age, obtained by
102 Rixhon et al. (2011) via a ^{10}Be depth profile, is 0.39 ± 0.04 Ma for the abandonment time of
103 the Younger Main Terrace (YMT) of the Ourthe at Colonster (~3 km downstream of the
104 Chawresse area). The YMT is a fundamental marker in the Ardennian valleys because it is
105 located at the hinge between the broad Early Pleistocene upper part of the valleys'
106 transverse profile and their nested deeply incised Middle Pleistocene lower part (Rixhon and
107 Demoulin, 2018). The YMT tread is perched ~55 m above the modern floodplain (all relative
108 elevations provided hereafter refer to the level of the Ourthe modern floodplain at the
109 Chawresse confluence), yielding a mean incision rate of 141 ± 15 m/Ma in this reach since
110 0.39 Ma.

111

112 As for mean denudation rates in the Ardennes, Schaller et al. (2004) calculated rates
113 increasing from 30 m/Ma before 0.7 Ma to 60-80 m/Ma after that time, based on the ^{10}Be
114 content of terrace sediments whose age is estimated using a MIS correlation. These rate
115 estimates, however, refer to the timespan of hillslope erosion preceding sediment deposition
116 in the valley bottom. By contrast, Demoulin et al. (2009) inferred a lower average rate of 27
117 m/Ma since ~0.7 Ma over the entire Ourthe catchment, based on geomorphic estimates of
118 river incision and interfluvial denudation.

119

120 2.3. The Chawresse multi-level cave system

121 Located ~12 km upstream of the Ourthe-Meuse confluence at Liège (Figs. 1b and 2), the
122 partly subaerial, partly subterranean Chawresse stream is a small tributary deeply incised
123 into the eastern valley side of the lower Ourthe. Its tiny catchment (~3 km²) comprises
124 Lower/Middle Devonian siliceous rocks in the headwaters area and Upper Devonian
125 limestone in its downstream part (Fig. 3a). It hosts one of the largest and best-documented
126 multi-level cave systems of Belgium in strongly folded and faulted Frasnian limestone (e.g.
127 Ek, 1961; Ek and Poty, 1982; De Bie, 2013) (Fig. 3b-c). We will call it hereafter the
128 Chawresse cave system. It stretches in the WSW-ENE Chawresse valley/Valley to more than
129 1.5 km from the confluence, includes more than 10 km of karstic galleries and shafts, and
130 spans a total elevation difference exceeding 135 m (De Bie, 2013; Fig. 4). Along with
131 secondary, smaller caves, the interconnected Chawresse system encompasses five main
132 cave developments named Victor, Chawresse, Veronika, Manants and Sainte-Anne, from the
133 highest to the lowest. According to De Bie (2013), the total length and vertical height
134 difference of each of these caves amount to ~180 and ~47 m (Victor), ~5650 and ~81 m
135 (Chawresse and Veronika taken as a single development, see below), ~1650 and ~67 m
136 (Manants) and ~1750 and ~35 m (Sainte-Anne). Their interconnection is attested either by
137 narrow passages such as between Chawresse and Veronika (leading De Bie, 2013 to
138 propose a single development stage for these two caves) or by fluorescent dye tracing such
139 as between Victor and Sainte-Anne (Fig. 4; supplementary material 1).

140

141 Speleogenetic studies in the Chawresse system agree to highlight the presence of well-
142 developed, abandoned subhorizontal phreatic tubes at different elevations, usually exhibiting
143 an elliptical cross-section, as the main morphological feature (Ek, 1961; 1964; Ek and Poty,
144 1982; De Bie, 2013) (Fig. 5a). These tubes constitute most of Sainte-Anne (at ~12 and 20 m
145 relative elevation, see e.g. Ek, 1964) and Veronika, with extensions into the Chawresse
146 cave (at ~70 and 75-78 m relative elevation, see De Bie, 2013). The polycyclic nature of
147 these phreatic levels has long been recognized in Sainte-Anne (Ek, 1961) and may be
148 assumed for the whole system, matching a *per descensum* model of karstification (Harmand
149 et al., 2017). In the frame of a tectonically controlled gradual base-level lowering, authors
150 agree that there is a morphogenic correlation between cave development and the subaerial
151 terrace sequence in the lower Ourthe ~~valley~~Valley (Ek, 1961; Quinif, 1989; Cornet, 1995).

152

153 The main abandoned phreatic tubes in the Chawresse and Veronika caves are roughly
154 located at the same relative elevations, but vadose shafts and canyons, almost absent in
155 Veronika, build an intricate network in the Chawresse cave (Fig. 4). ~~While-Although~~ similarity
156 of elevation favours the hypothesis of a single stage of cave development, the contrast in
157 shaft and canyon density argues against it, though this contrast might be controlled by the
158 local geological structure. Indeed, whereas the main phreatic passages of Veronika stretch
159 along the anticlinal hinge, all developments of the Chawresse cave are located within the
160 steeply dipping southern limb of the anticline, ~50 m more to the south. The Manants cave,
161 which seems to have developed geographically apart from the other cave systems, is
162 dominated by abundant vadose shafts and canyons. The bulk of these occur in the southern
163 wall of the Chawresse ~~valley~~Valley, spanning >65 m of elevation difference similar to those of
164 the Chawresse cave (Fig. 4). The current entrance of the Manants cave corresponds to an
165 active sinkhole in the sub-aerial Chawresse streambed (Figs. 3a and 4b). At the base of the
166 cave development, poorly developed phreatic tubes are aligned along the ENE continuation
167 of the main phreatic developments of the Sainte-Anne cave (Fig. 4). Caver explorations

168 report an intricate underground topography for the Manants karstic system (De Bie, 2013). A
169 peculiarity of Sainte-Anne is that the ceiling of one of the phreatic tubes displays a >1 m high
170 dissolution feature, which might have been caused by sediment accumulating in this formerly
171 water-filled passage and inducing upward dissolution of the tube's ceiling (i.e., paragensis,
172 Farrant, 2004; see Fig. 5b). This indicates that the alluvium that once filled this passage
173 could have been almost completely evacuated by the underground Chawresse stream as a
174 response to a later drop of the water table.

175

176

177 3. Sampling strategy and $^{26}\text{Al}/^{10}\text{Be}$ burial dating

178

179 | A two-step scenario constitutes the basic prerequisite of burial dating applied to ~~in~~-cave-
180 deposited alluvium, namely exposure at the (sub-)surface followed by a rapid and complete
181 burial at a depth great enough (practically, >20 m of overburden) to efficiently prevent any
182 postburial muonic production (e.g., Granger, 2014). It also assumes that, once the clastic
183 sediments had entered the underground karstic system, they suffered no erosion or
184 | underground reworking (e.g., Rixhon, 2016). ~~Therefore, w~~Wherever possible, (i) we ~~thus~~
185 primarily targeted cave passages where clastic infills were massively preserved (as in the
186 Veronika cave, see Supplementary Material 1), (ii) we preferentially sampled underground
187 sediments that still exhibit original tiling and bedding structures in the abandoned phreatic
188 tubes (Fig. 5c-d) and (iii) we avoided deposits for which reworking could obviously be
189 suspected (for instance, those located close to active passages of the underground
190 Chawresse stream). Given the generally coarse size of the cave sediments, the pebble
191 fraction was selected (Supplementary Material 1). Altogether, fifteen quartz-bearing samples,
192 chiefly quartz pebbles with subsidiary quartzite pebbles, were collected (Fig. 5d;
193 Supplementary Material 2). Twelve out of the fifteen processed samples were single clast
194 | samples, the three others, all extracted from the Manants cave (MAN1, 2 and 3bis), ~~being~~
195 ~~were~~ amalgamated samples (Table 1, Supplementary Material 2). Whilst two samples were

196 taken in the Victor cave at relative elevations of ~125 and 135 m, we purposely collected
197 more samples in the main phreatic developments of the lower-lying cave levels in order to
198 strengthen the timing of the main phases of fluvial base-level stability in the lower Ourthe
199 | ~~valley~~Valley (Fig. 4 and Table 1). We thus collected four or five samples from the Veronika
200 cave (relative elevation of ~72 to 75 m), the Manants cave (~15 to 35 m) and Sainte-Anne
201 cave (~12 to 20 m). Note that $^{26}\text{Al}/^{10}\text{Be}$ burial dating of cave-deposited alluvium constrains
202 the last period of time during which the passage was at the local water table. In the case of
203 prior ghost-rock karstification (Dubois et al., 2014), this is also the time when ghost-rock
204 feature emptying could be achieved, allowing for sediments originating from the ground
205 surface to be brought into the passage.

206

207 The burial duration is estimated from measurements of the $^{26}\text{Al}/^{10}\text{Be}$ ratio, which decreases
208 | with burial time according to the different disintegration rates of the two radionuclides (e.g.
209 Dunai, 2010; Rixhon, 2016; see Supplementary Material 3 for mathematical development). In
210 | this study, we used half-lives of $(1.387 \pm 0.012) \times 10^6$ and $(0.705 \pm 0.017) \times 10^6$ ~~years-yr~~ for ^{10}Be
211 and ^{26}Al , respectively (Granger, 2006; Chmeleff et al., 2010; Korschinek et al. 2010). The
212 chemical treatment and the AMS measurements (both ^{10}Be and ^{26}Al) of all samples
213 presented in this study were carried out at the CEREGE laboratory in Aix-en-Provence. After
214 crushing and sieving (between 1 and 0.250 mm), sediment samples passed through
215 magnetic separation, and the non-magnetic fraction underwent selective etching in
216 fluorosilicic and hydrochloric acids to eliminate all mineral phases but quartz. Quartz minerals
217 then underwent a series of selective etchings in hydrofluoric acid to eliminate potential
218 surface contamination by ^{10}Be produced in the atmosphere (Brown et al., 1991). The cleaned
219 quartz minerals were then completely dissolved in hydrofluoric acid after addition in each
220 sample of ~100 μl of an in-house carrier solution ($(3.025 \pm 0.009) \times 10^{-3}$ g $^9\text{Be}/\text{g}$ solution)
221 | prepared from a deep-mined phenakite (Merchel et al., 2008). After substituting HF by HNO_3 ,
222 an aliquot of 500 μl of the obtained solution was taken for ^{27}Al concentration measurements.
223 Aluminum and beryllium were separated from the remaining solution by ion-exchange

224 chromatography and selective precipitation (Merchel and Herpers, 1999). The resulting Be
225 and Al precipitates were oxidized by heating at 800-°C duringfor one hour and the oxides
226 were mixed to 325 mesh niobium powder prior to measurements by Accelerator Mass
227 Spectrometry (AMS). All the data reported in this study have been measured at the French
228 national facility ASTER of the CEREGE. Beryllium-10 data were calibrated directly versus the
229 National Institute of Standards and Technology standard reference material NIST SRM 4325
230 using an assigned $^{10}\text{Be}/^9\text{Be}$ value of $(2.79\pm 0.03)\times 10^{-11}$; Nishiizumi et al., 2007). This
231 standardization is equivalent to 07KNSTD within rounding error. The obtained $^{26}\text{Al}/^{27}\text{Al}$ ratios
232 were calibrated against the ASTER in-house standard SM-Al-11 with $^{26}\text{Al}/^{27}\text{Al}=7.401\pm$
233 0.064×10^{-12} , which has been cross-calibrated against the primary standards certified by a
234 laboratory inter-calibration exercise (Merchel and Bremser, 2004). ^{27}Al concentrations,
235 naturally present in the samples, were measured at CEREGE by ICP-OES. Analytical
236 uncertainties (reported as 1σ) include uncertainties associated with AMS counting statistics,
237 AMS internal error (0.5%), chemical blank measurement and, regarding ^{26}Al , ^{27}Al
238 measurement. Long-term measurements of chemically processed blanks yield ratios on the
239 order of $3.0\pm 1.5\times 10^{-15}$ for ^{10}Be and $2.2\pm 2.0\times 10^{-15}$ for ^{26}Al (Arnold et al., 2010).

240

241 A local ^{10}Be production rate of $5.16\text{ g at}^{-1}\text{ y}^{-1}$ was obtained using local coordinates, an
242 average catchment elevation of 240 m and a sea-level high latitude production rate of $P_0 =$
243 $(4.02\pm 0.36)\text{ at g}^{-1}\text{ y}^{-1}$ (Stone, 2000). The latter is identical to the weighted mean of
244 production rates in the Northern Hemisphere (Ruszkiczay-Rüdiger et al., 2016) and in
245 agreement with recently calibrated values (Borchers et al., 2016). An $^{26}\text{Al}/^{10}\text{Be}$ pre-burial,
246 spallation production ratio amounting to 6.61 was used (Nishiizumi et al., 1989; Braucher et
247 al., 2011). Because the cave overburden is always thicker than 20 m, post-burial muon
248 production was ignored in the burial age determination.

249

250 **4. Results: $^{26}\text{Al}/^{10}\text{Be}$ ratios, burial ages and pre-burial denudation rates**

251

252 Cosmogenic ^{10}Be and ^{26}Al concentrations in the samples range between $(0.62\pm 0.03)\times 10^5$
253 and $(23.56\pm 0.55)\times 10^5$, and $(3.82\pm 0.51)\times 10^5$ and $(98.86\pm 3.10)\times 10^5$ atoms g^{-1} quartz,
254 respectively (Table 1). These concentrations yield $^{26}\text{Al}/^{10}\text{Be}$ ratios ($R_{26/10}$) between 1.20 ± 0.12
255 and 6.13 ± 0.88 (Table 1). Such depleted $R_{26/10}$ identify a burial event for all samples. Burial
256 ages ranging from the Pliocene to the final part of the Middle Pleistocene were computed
257 accordingly ~~computed~~ (Table 1). Pre-burial denudation rates roughly ranging from 1 to 58
258 m/Ma are simultaneously calculated (Table 1). We present hereafter the detail of these
259 results, together with their 1σ uncertainties, obtained for the four different cave levels, from
260 the highest to the lowest.

261

262 4.1. Victor cave

263 Very contrasting $R_{26/10}$ characterise the samples VIC1 and VIC2: 1.20 ± 0.12 and 5.72 ± 0.51 ,
264 respectively. Burial durations and pre-burial denudation rates for each sample differ
265 accordingly ~~differ~~: 3.28 ± 0.22 Ma and 1.44 ± 0.24 m/Ma (VIC1) versus 0.38 ± 0.24 Ma and
266 29.28 ± 4.16 m/Ma (VIC2).

267

268 4.2. Veronika cave

269 $R_{26/10}$ of the four samples collected in the main phreatic passage of the Veronika cave range
270 from 4.20 ± 0.16 to 5.76 ± 0.32 . They yield burial durations and pre-burial denudation rates
271 ranging from 0.26 ± 0.15 to 0.56 ± 0.18 Ma and 0.81 ± 0.07 to 20.26 ± 2.89 m/Ma, respectively. At
272 first glance, the 0.26 Ma burial age (sample VER2) may appear out of the range of the age
273 cluster yielded by the three other samples (~ 0.50 - 0.56 Ma). However, the large 1σ -
274 uncertainties associated to VER2 and 4 make burial ages of these two samples statistically
275 indistinguishable. We therefore use the sample VER2 in further calculations. An error-
276 weighted mean of 0.47 ± 0.06 Ma is computed for the Veronika cave out of the four individual
277 burial durations (removing the VER2 sample from the dataset would yield a mean burial
278 duration of 0.51 ± 0.07 Ma, not much different from the previous one).

279

280 *4.3. Manants cave*

281 $R_{26/10}$ of the four samples collected in the Manants cave at different elevations range from
282 2.74 ± 0.19 to 3.96 ± 0.50 . They yield burial durations and pre-burial denudation rates ranging
283 from 1.13 ± 0.32 to 1.79 ± 0.18 Ma and 4.14 ± 0.51 to 14.15 ± 2.65 m/Ma, respectively. Similar to
284 the dataset from the Veronika cave, the 1σ -uncertainties associated to the samples
285 (especially MAN1 and 3bis) make their individual burial ages statistically indistinguishable.
286 An error-weighted mean of 1.59 ± 0.10 Ma is computed for the Manants cave out of the four
287 individual burial ages.

288

289 *4.4. Sainte-Anne cave*

290 $R_{26/10}$ of the five samples collected in the Sainte-Anne cave at different elevations range from
291 4.05 ± 0.21 to 6.13 ± 0.88 . They yield burial ages and pre-burial denudation rates ranging from
292 0.24 ± 0.38 to 0.94 ± 0.36 Ma and 2.77 ± 0.30 to 58.27 ± 11.92 m/Ma, respectively. Large
293 differences are thus observed for both burial durations and pre-burial denudation rates in this
294 cave level, yet consistent with the relative elevation of each sample (Fig. 4a). One might
295 argue from its lower nuclide concentration values and, consequently, the larger relative
296 uncertainty on its ^{26}Al content that sample STA2 is not as meaningful as the other samples in
297 Sainte-Anne cave (Table 1). However, its calculated burial duration is consistent with that of
298 STA2bis, sampled in the exact same location. As for their strongly contrasted denudation
299 rate estimates, it is important to recall that they were calculated from single pebbles and thus
300 refer to local denudation rather than mean catchment rates. When sedimentation occurred in
301 the Sainte-Anne cave, the valleys had already been carved deep enough to display steep
302 hillslopes where local denudation rates could be highly variable. We therefore consider the
303 pair of burial duration estimates yielded by STA2 and STA2bis as significant.

304

305 **5. Discussion**

306

307 **5.1. Relevance of the local speleogenesis in interpreting burial ages**

308

309 Our burial age results clearly stress the necessity of collecting several samples in every
310 individual cave system (Laureano et al., 2016; Sartégou et al., 2018). Indeed, ~~while-although~~
311 this procedure supports a robust dating of the Veronika cave at 0.47 ± 0.06 Ma, it was also
312 absolutely required to uncover potential methodological or geomorphic issues in the other
313 cave levels (Häuselmann and Granger, 2005; Dunai, 2010).

314

315 **5.1.1. Contamination by younger material**

316 The ~ 0.4 and 3.3 Ma burial ages obtained for the Victor cave diverge by one order of
317 magnitude. This large discrepancy most probably results from the distinct positions of the
318 sampling sites within the cave. Whereas the VIC1 sample was collected in the lower main
319 development of the cave at ~ 125 m relative elevation, the VIC2 sample was located much
320 nearer to the cave entrance, directly at the bottom of the uppermost underground shaft (~ 135
321 m relative elevation). At such high position above the present Ourthe ~~R~~river, the 0.38 ± 0.24
322 Ma burial age is without doubt geomorphologically inconsistent. In particular, it strongly
323 contradicts the robust ^{10}Be depth profile dating of the YMT at Colonster, which provided an
324 age of ~ 0.4 Ma for terrace deposits located 80 m below the level of the Victor cave (Rixhon
325 et al., 2011). We thus interpret the anomalous young age of VIC2 as indicating a later
326 reactivation of the sinkhole (now in interfluvial position) and injection of younger sediments
327 into the oldest karstic level of the Chawresse system. Moreover, assuming a gravitational
328 collapse of unknown thickness, it is unsure whether the material originates from the surface
329 or the sub-surface and, thereby, whether the initial $R_{26/10}$ of this sample does not violate the
330 key assumption for burial dating (see ~~S~~section 3 above). Consequently, the VIC2 sample is
331 discarded and we consider the Late Pliocene burial age of VIC1 to be representative of the
332 time when the water table (and the Ourthe ~~R~~river) ~~lay-existed~~ at these high elevations.

333

334 **5.1.2. Probable intra-karstic reworking**

335 The four Early Pleistocene burial ages of the Manants cave at less than 35 m relative
336 elevation must mandatorily be addressed against the background of progressive river
337 downcutting over the Plio-Quaternary. Based on the mid-Middle Pleistocene age of the YMT
338 at Colonster (and, more broadly, also elsewhere in the Meuse catchment; Rixhon et al.,
339 2011), they are substantially older than expected at such a low relative elevation. Three
340 explanatory hypotheses may be examined, namely an alternative model of speleogenesis, a
341 previous burial episode of the sampled material or an intra-karstic reworking with downward
342 motion.

343

344 An alternative *per ascensum* model of speleogenesis, such as the one documented in the
345 Ardèche ~~valley~~Valley (e.g., Tassy et al., 2013), would contradict all geomorphic evidence of
346 stepwise base-level lowering and incision in the entire Ardennian Meuse ~~R~~river network
347 related to Quaternary uplift (e.g., Juvigné, 1979; Pissart et al., 1997; Demoulin et al., 2012;
348 Rixhon and Demoulin, 2018). In the lower Ourthe ~~valley~~Valley, the well-preserved terrace
349 staircase and its geomorphological coupling with cave systems strongly point to a *per*
350 *descensum* model of speleogenesis (Harmand et al., 2018). The latter is acknowledged not
351 only for the Chawresse system (Ek, 1961; Cornet, 1995) but also for the newly discovered
352 Noû Bleû cave located several kilometers upstream (Peeters and Ek, 2018). The hypothesis
353 of an alternative speleogenetic model is thus highly unlikely.

354

355 Even if no direct evidence precludes the possibility that some of the sampled material
356 underwent a burial episode before entering the karstic system, two lines of argument point to
357 intra-karstic reworking as the most likely cause of ~~too the ages that are too old~~ages. Firstly,
358 beyond exhibiting higher depletion than the Veronika samples (Table 1), the Manants $R_{26/10}$
359 data subset is internally consistent, with the lowest variability among all cave levels. This
360 points to a single burial history for all Manants samples, and thus most likely an exclusively
361 intra-karstic history. Indeed, reworking of pebbles that would have experienced subaerial
362 burial events before entering the cave system (e.g., at the base of thick Early Pleistocene

363 Ourthe terrace deposits) would probably have implied a large scatter in the depleted $R_{26/10}$
364 (different burial durations and depths).

365

366 | Secondly, the intricate karstic system of the Manants cave dominated by vadose shafts (Fig.
367 | 4) points to multiphase speleogenetic processes (De Bie, 2013), which probably also entailed
368 | a complex underground evolution of the cave sedimentary infill. Following De Bie (2013),
369 | who considers that the Chawresse and Veronika caves form a single system, we thus
370 | suggest that the Chawresse/Veronika and the Manants/Sainte-Anne systems evolved
371 | independently, possibly also with some temporal overlap that might explain the complex
372 | underground topography of the Manants cave and the Early Pleistocene burial ages obtained
373 | for its cave infill . A realistic, though speculative, history of the Manants samples might have
374 | implied the following stages: (i) washing of sediments into dolines and/or sinkhole shafts in
375 | the vadose zone above an Early Pleistocene stability level, with substantial shielding to
376 | cosmic rays already allowing some $R_{26/10}$ decrease; (ii) from the late Early Pleistocene,
377 | progressive base-level lowering and Ourthe and Chawresse incision promoting downward
378 | development of the shafts and travel of the trapped sediments, possibly aided by piping and
379 | underground drainage, to depths possibly beyond reach of the cosmic rays; (iii) Middle
380 | Pleistocene stability phase inducing the independent formation and infilling of the phreatic
381 | tubes of the Veronika cave while the Manants clasts remained buried in their separate
382 | system; (iv) later in the Middle Pleistocene, main phase of river downcutting and renewed
383 | downward displacement of the sediments buried in the Manants cave, however, not affecting
384 | the fossilized Veronika tubes and their infill; (v) probably in connection with the main tube
385 | formation in the Sainte-Anne cave sometime during the late Middle Pleistocene, phreatic
386 | overprinting of the Manants cave with essentially lateral reworking bringing the clasts in their
387 | sampling position. Note that the same reasoning can be held for the older burial ages of
388 | sediments sampled in the higher phreatic tubes of Sainte-Anne, which might indicate input of
389 | older material through the Manants cave as a siphon connects both caves (Fig. 4; De Bie,
390 | 2013).

391

392 Several field observations support this scenario. A dense network of well-developed dolines
393 (depth locally >10 m) occur directly to the south of the cave (“*dolines syncline*”, Fig. 7a).
394 Located upslope south of the Chawresse ~~valley~~Valley at elevations of 180-200 m ~~elevations~~,
395 they display active sinkholes and sediment accumulation at their bottom (Fig. 7b). Although
396 their possible hydrological connection with the Manants cave has not been explored so far
397 (De Bie, 2013), we may postulate that similar extended vertical connection between the
398 ground surface and deeper cave levels also existed ~~also~~ in the past. Moreover, in contrast
399 with all other caves of the Chawresse system, the current Manants cave’s entrance
400 corresponds to an active sinkhole in the sub-aerial Chawresse streambed. Active drainage of
401 the cave’s vadose shafts by the underground stream obviously still facilitates the downward
402 transport of clastic material (Fig. 7c). For all these reasons, we interpret all burial ages
403 obtained for the Manants samples and those of STA1, 1bis and 4 in Sainte-Anne as
404 discordant data telling corollary events of the drainage system downcutting.

405

406

407 **5.2. Comparison of the burial ages with Neogene/Quaternary fluvial deposits**

408

409 *5.2.1. Pre-Quaternary fluvial evolution at the northern rim of the massif*

410 The 3.28 ± 0.22 Ma burial age in the Victor cave represents the first Pliocene numerical age
411 for fluvial deposits located within the Ardennian Meuse catchment. This age is consistent
412 with the position of the Victor cave at the plateau’s margin atop the eastern Ourthe
413 ~~valley~~Valley side (Fig. 4) and the Neogene age assigned to the lowest beveled surfaces
414 flanking the incised Quaternary valleys (Demoulin, 1995; Demoulin et al., 2018). Moreover,
415 the dated deposit lies at a lower elevation than the quartz- and quartzite-rich fluvial gravels
416 discontinuously covering the Ourthe/Meuse interfluvium 155 to 180 m above the modern valley
417 bottoms (e.g., Rixhon and Demoulin, 2010; Fig. 8a). Located ~5 km to the north-west of the
418 Chawresse multi-level system (Fig. 1b), these gravels, locally known as “*Graviers Liégeois*”

419 | (Pissart, 1964), have been interpreted as the oldest Ardennian Rriver sediments deposited
420 | by a proto-Ourthe system and tentatively dated from the Miocene (Ssupplementary material
421 | 4), based on stratigraphic and pedogenetic evidence (Buurman, 1972) (Fig. 8a). Finally,
422 | while-although the highest terrace remnants in the lower Ourthe valleyValley hardly reach
423 | 125 m relative elevation (Cornet, 1995), the oldest terrace deposits of the Meuse in the
424 | nearby Liege area, traditionally referred to as “*kieseloolite terraces*” (Macar, 1975;
425 | Ssupplementary material 4), occur within the same range of relative elevation as the Victor
426 | cave (~115-135 m) (Fig. 8a) (Juvigné and Renard, 1992; Rixhon and Demoulin, 2018).
427 | Despite the lack of direct numerical age of the kieseloolite terraces, authors now agree that
428 | their stratigraphic correlation with the Kieseloolite Formation in the Roer ValleyValley Graben
429 | dates them between the Late Tortonian and the Early Piacenzian (Westerhoff et al., 2008;
430 | Rixhon and Demoulin, 2018; Beerten et al., 2018; Munsterman et al., 2019). Overall, the
431 | Pliocene burial age of the Victor cave thus appears in good agreement with the available
432 | geomorphic and sedimentary evidence in the area.

433

434 | 5.2.2. *Geomorphological and chronological link between the Veronika cave and the YMT*

435

436 | Our convergent burial durations in the main phreatic tubes of the Veronika cave point to a
437 | long-lasting regional base level ~70-75 m above the current valley bottom around 0.47 Ma.
438 | At such-this elevation, the cave lies 15-20 m above the YMT of the Ourthe (Fig. 9). The ¹⁰Be
439 | depth profile performed in the YMT sediments at Colonster, 3 km downstream of the
440 | Chawresse cave system, reliably dated the terrace abandonment time at ~0.39 Ma (Rixhon
441 | et al., 2011), which is at first glance in perfect agreement with the ~0.5 Ma age of the
442 | Veronika cave level.

443

444 | However, the story is somewhat more complex. Firstly, in the lower Meuse ~20 km north of
445 | Liege, the abandonment time of the Romont terrace, formerly correlated to the YMT
446 | (Juvigné, 1992), was dated at 0.73±0.12 Ma via a twofold ¹⁰Be and ²⁶Al depth profile (Rixhon

447 et al., 2011). The later reassignment of this terrace to the next higher level within the Main
448 Terrace Complex led Rixhon and Demoulin (2018) to propose a younger age around 0.62
449 Ma for the YMT abandonment time in this valley reach. Secondly, ~20 km upstream of the
450 Chawresse area, another ^{10}Be depth profile in terrace deposits of the Amblève R~~r~~iver close
451 to its confluence with the Ourthe (Fig. 1b) revealed that, ~~while-although~~ the YMT was
452 abandoned at 0.22 ± 0.03 Ma in that place, it had started to aggrade much earlier, around
453 0.58 Ma (Rixhon et al., 2011). Broadly consistent with the YMT age at Romont, the latter age
454 thus implies that the lower Ourthe R~~r~~iver had also already incised its valley down to slightly
455 less than 55 m of relative elevation (i.e., the base of the YMT) around 0.58-0.62 Ma. This
456 seems to contradict the younger 0.47 ± 0.06 Ma mean burial age obtained in the higher-
457 located Veronika cave.

458

459

460

461 This apparent discrepancy finds its explanation in the location of the Veronika cave in the
462 Chawresse ~~valley~~Valley, about 800 m upstream of the Ourthe confluence, which, at YMT
463 time, was approximately superposed to the present one. Therefore, we interpret the 15-20 m
464 elevation difference between the cave and the Ourthe YMT as expressing the hydraulic
465 gradient beneath the hillslopes east of the Ourthe at YMT time. This ~2.5% gradient is very
466 close to the 2.5-3% westward slope of the Veronika main galleries (Fig. 9) and the ~3% slope
467 of the subaerial channel in the upper Chawresse inherited from the Early Pleistocene, the
468 Middle Pleistocene incision wave having not reached the upper Chawresse (Beckers et al.,
469 2015). So connecting the Veronika cave, and thus making it contemporaneous, with the
470 Ourthe YMT is geomorphically and chronologically consistent. Once the Ourthe River had
471 started to develop its YMT floodplain sometime between 0.62 and 0.58 Ma, the Veronika
472 karstic level in turn began to form following the hydraulic gradient of the time. Clasts sampled
473 in the upper part of a ~2-m thick deposit date the later filling of its galleries around 0.47 Ma,
474 i.e., well before the YMT level was abandoned through renewed Ourthe incision around 0.39

475 Ma in this area (Rixhon et al., 2011). We also note that the YMT time was the last long period
476 (including the long warm MIS11) of stability of the river before the Late Pleistocene, so that
477 one could *a priori* expect it would have been favourable to such a large karstic development
478 as that of the Veronika cave.

479

480 **5.3. Incision rate variability over the Plio-Quaternary**

481

482 The ¹⁰Be-based ages obtained by Rixhon et al. (2011, 2014) for YMT remnants in the lower
483 Meuse – lower Ourthe – Amblève system provided first constraints on the long-term incision
484 history in N. Ardennes. Not only does the present study confirm them but it also yields the
485 first numerical age for one of the highest attested levels of the Plio-Quaternary downcutting
486 of the Ardennian drainage network. With the Pliocene age of the landscape level in which the
487 Victor cave formed, it brings quantitative support to the long-held assumption of contrasted
488 incision rates between the Pliocene and Early Pleistocene on one hand, the Middle
489 Pleistocene to present on the other hand (Fig. 8a-b).

490

491 Based on the differences between the VIC1 sample and the YMT base in the lower Ourthe in
492 terms of relative elevation (125 m vs -49 m, for 6 m thick YMT deposits) and age (3.28 Ma
493 vs. 0.58 Ma), the Late Pliocene and the Early Pleistocene were characterized by a mean
494 incision rate of 29±4 m/Ma (Fig. 8a). Then, a period of stability occurred from 0.62-0.58 to
495 0.39 Ma (i.e., the lifetime of the YMT as a floodplain in the lower Ourthe ~~valley~~Valley, see
496 also Rixhon et al., 2014). The next period over which an average incision rate may be
497 calculated is framed by the time of abandonment of the YMT and a set of dates pointing to a
498 relative elevation of 12_m for the Ourthe level in the late Middle Pleistocene. The latter timing
499 is ~~first~~ly indicated by the two samples (STA2 and STA2bis) dating the youngest phase of
500 activity in the main phreatic tube of Sainte-Anne (12 m relative elevation) between 0.24 and
501 0.3 Ma, though with penalizing large age uncertainties (Table 1). ~~Second~~ly, 40 km farther
502 downstream, the interglacial deposits capping the Caberg terrace of the Meuse at 15-18 m

503 relative elevation in the Belvédère site near Maastricht have been consistently dated at
504 0.25 ± 0.02 Ma by thermoluminescence on burned flints and 0.22 ± 0.04 Ma by ESR on mollusc
505 shells (Huxtable, 1993; Van Kolfschoten et al., 1993). We thus calculate a weighted mean
506 age of the Sainte-Anne – Caberg level of 0.245 ± 0.02 Ma. Based on a difference in elevation
507 of 42 m, an average incision rate of $290(+125/-68)$ m/Ma between 0.39 ± 0.04 and 0.245 ± 0.02
508 Ma is inferred. However, beyond the fact that it confirms the strong acceleration of incision
509 from the Middle Pleistocene onwards (Demoulin and Hallot, 2009; Rixhon et al., 2011), the
510 meaning of this rate is not straightforward because it incorporates two fundamentally different
511 components. They are (i) the delayed upstream propagation of an approximately ~ 20 -m high
512 wave of erosion responding to a tectonic uplift pulse in the early Middle Pleistocene and
513 travelling along the lower Ourthe around 0.39 Ma (Demoulin et al., 2012; Beckers et al.,
514 2015), and (ii) a slower continued incision over the rest of the period (Fig. 8a). Subtracting
515 the 20 -m amount of incision propagated with the erosion wave leaves a residual post-
516 knickpoint average incision rate in the order of 150 m/Ma as a direct response to the late
517 Middle Pleistocene uplift of the area, still much larger than the Pliocene-Early Pleistocene
518 rate. Finally, according to the same data, the mean incision rate since 0.245 ± 0.02 Ma would
519 fall in the range of 45-53 m/Ma. This is in agreement with the rougher 33-81 m/Ma estimation
520 derived from the presence of the 74-90 ka old Rocourt tephra (Pouclet et al., 2008) in low
521 terraces (~ 3 m relative elevation) of the Ourthe and the Amblève, as well as its absence in
522 the next higher terrace of the Amblève at 6 m relative elevation (Juvigné, 1973, 1979; Rixhon
523 and Demoulin, 2010).

524

525

526

527

528

529 These long-term incision rates can be compared with those compiled by Van Balen et al.
530 (2000) for the Meuse at Liège based on a reinterpretation of palaeomagnetic data previously

531 obtained in the terrace staircase of the lower Meuse near Maastricht (Van den Berg, 1996)
532 (Fig. 8b). We ~~however~~ recall, however, that the chronological interpretation of these
533 palaeomagnetic data, especially those collected from the main terrace complex, has long
534 been a matter of debate (Van Balen et al., 2000; Westaway, 2002; Rixhon and Demoulin,
535 2010; Rixhon et al., 2011). Nevertheless, the general picture remains valid, with low incision
536 rates in the Early Pleistocene, a major rate increase in the first half of the Middle Pleistocene,
537 followed by a progressive decrease of the rates since the late Middle Pleistocene (Fig. 8b).
538 We also note the different timing of maximum incision between the lower Ourthe -
539 Chawresse area and the lower Meuse. The latter is related to the time the Middle
540 Pleistocene erosion wave needed to propagate into the Ardennian drainage system, causing
541 delayed knickpoint passage and valley incision in the Ourthe with respect to the Meuse
542 (Rixhon et al., 2011; Demoulin et al., 2012; Rixhon and Demoulin, 2018) (Fig. 8b). Finally, as
543 for the reduced incision rates observed in both the Meuse and Ourthe since ~0.25 Ma, one
544 may tentatively link them to the loss of drainage area (~3400 km²), and thus stream power,
545 suffered by the Meuse ~~due to~~ because of the capture of the upper Moselle at the time of the
546 Caberg terrace (e.g., Pissart et al., 1997), even though the numerical age of the capture is
547 still debated (Cordier et al., 2013).

548

549 **5.4. Palaeodenudation rates**

550

551 Besides burial durations in the Chawresse karstic system, the measured $R_{26/10}$ yield pre-
552 burial denudation rates ranging from 0.8 to 58.3 m/Ma (Table 1), adding information to the
553 existing database used to infer basin denudation rates in the Ardennes (Schaller, 2002,
554 2004; Demoulin et al., 2009). However, we first stress two main limitations of our rate data.
555 Firstly, as our samples consist of single or a few amalgamated quartz or quartzite clasts, the
556 derived rates do not refer to mean basin denudation but rather to local erosion under the
557 topographic conditions of the places wherefrom the samples come within the area of
558 outcropping siliceous rocks (in the upstream Chawresse catchment). Secondly, most of the

559 calculated rates concern the period of slow denudation from the Pliocene to the early Middle
560 Pleistocene, before the post-YMT erosion wave had reached the study area, and only two
561 samples (STA2 and STA2bis) provide scarce information about the younger times of
562 assumed higher erosion.

563

564

565 All our rate estimates predating the time of rapid post-YMT incision, i.e., those obtained from
566 the Victor, Manants, and Veronika caves but also those of Sainte-Anne with burial ages older
567 than 0.39 Ma, were expected to reflect a smoothly undulating fluvial landscape with gentle
568 slopes and low relief, drained by wide shallow valleys. Indeed, denudation rate increases
569 from a very low 1.44 ± 0.24 m/Ma at ~ 3.3 Ma in the Early Piacenzian (sample VIC1) to a
570 weighted mean of 7.53 ± 0.26 m/Ma between 2 and 1 Ma (Manants cave samples), 9.19 ± 0.46
571 m/Ma between 1 and 0.8 Ma (samples STA1, 1bis and 4), and 7.45 ± 0.22 m/Ma around 0.5
572 Ma (Veronika cave samples). Note that, ~~due to~~because of the dependence of the error on the
573 value of the denudation rate, mean rates have been obtained here from weighting the data
574 by their associated relative error instead of their variance. In each of these periods, the
575 spread of individual clast denudation estimates remains limited, with maximal values always
576 ≤ 20 m/Ma, confirming low to moderate denudation of a hardly incised landscape of Neogene
577 planation surfaces in the lower Ourthe area (Demoulin et al., 2018). By contrast, though
578 clearly needing confirmation by further measurements, the two samples attesting denudation
579 after the post-YMT erosion wave had reached the study area and enhanced river incision
580 had begun (STA2 and 2bis) show higher and more variable rates, consistent with a greater
581 relief and steeper valley slopes.

582

583 At a regional scale, Schaller et al. (2004) provided mean palaeodenudation rates for the
584 Ardennian Meuse basin based on ^{10}Be measurements from different terrace deposits of
585 approximately known ages located in the Maastricht area and spanning the period since 1.3
586 Ma. They increase from $\sim 25\text{-}35$ m/Ma in the Early Pleistocene to $\sim 40\text{-}80$ m/Ma since the

587 beginning of the Middle Pleistocene. As the authors acknowledged, these rates suffer from
588 uncertainties. They are linked (i) to poor age constraints on many sampled terrace deposits
589 and (ii) to the limited adequacy of the sampled material in representing all parts of the
590 catchment, be it because carbonate rock areas do not deliver quartz to the rivers or the 0.5-1
591 mm grain size fraction on which the ^{10}Be measurements were made is hardly present in
592 some sediments e.g., the kaolinic weathering products mantling large plateau areas of the
593 Ardennes. Nevertheless, they compare well with the local denudation data presented here.
594 Indeed, the pre-0.7 Ma rates of 25-35 m/Ma obtained by Schaller et al. (2004) refer to the
595 Meuse catchment upstream of Maastricht and thus incorporate a non-negligible component
596 of valley downcutting and widening in the main branches of the river system. The fact that
597 this component of valley development is almost absent in the source area of our samples,
598 namely the hardly eroded upstream part of the small Chawresse catchment, readily explains
599 the lower rates in the order of 7-10 m/Ma they yielded.

600
601 Finally, based on eroded volumes estimated from geomorphic arguments for interfluves in
602 the Condroz area, to which the Chawresse upper catchment may be likened, Demoulin et al.
603 (2009) also obtained denudation rates in the order of 5-10 m/Ma in the Pliocene and Early
604 Pleistocene. Interestingly, despite not being aimed at high-resolution evaluation of
605 denudation, the recently published study of apatite fission track data from northern Ardennes
606 comes to the similar conclusion that denudation was very slow in this area in the Neogene
607 (Barbarand et al., 2018). As for the more recent increased denudation rates, we only note
608 that the rate of ~58 m/Ma yielded by sample STA2 originating from a still now not much
609 incised area is in line with the catchment-wide rates between 40-80 m/Ma calculated by
610 Schaller et al. (2004). It also agrees well with local denudation data in the same range
611 obtained from interfluves in two small catchments of the Black Forest (Meyer et al., 2010).
612 Finally, the Chawresse denudation rates present first hints that the timing of the Middle
613 Pleistocene increase in denudation rate in the Ardennes might be linked to the arrival of the

614 post-YMT erosion wave in any particular catchments, being thus more tectonically than
615 climatically triggered.

616

617 **6. Conclusion**

618

619 Though facing limitations inherent to $^{26}\text{Al}/^{10}\text{Be}$ burial dating of ancient alluvium-filled karstic
620 passages, this study demonstrates the usefulness of the approach to unravel the main
621 episodes of fluvial base-level stability in the Ardennes during the Plio-Quaternary. Its main
622 outcomes are threefold. **Firstly**, the Early Pleistocene burial ages of the Manants cave most
623 probably reflect an uncoupled speleogenesis with respect to the higher-lying phreatic tubes
624 of Veronika and Chawresse (mean burial age around 0.5 Ma). These discordant ages stress
625 the necessity for sampling only well-developed alluvium-filled phreatic tubes, where
626 contamination from higher levels appears unlikely (e.g., the Veronika cave), to provide
627 reliable long-term incision rates. **Secondly**, the computed burial ages from the Victor and
628 Veronika caves, together with the reliable abandonment time of the YMT in the lower Ourthe
629 (Rixhon et al., 2011), quantitatively attest for the first time the long-held assumption of
630 contrasted incision rates between the Pliocene-Early Pleistocene and the Middle
631 Pleistocene-present. At ~ 0.39 Ma, the Middle Pleistocene rates increased transiently from
632 ~ 30 to ~ 150 m/Ma. The long-term incision history in the lower Ourthe exhibit a similar pattern
633 to that in the lower Meuse, although the peak incision episode, in good concordance with
634 previous studies (e.g., Rixhon et al., 2011; Demoulin et al., 2012), occurred later in the
635 tributary. This results from the delayed upstream propagation of the Middle Pleistocene
636 erosion wave, itself triggered by the main tectonic uplift pulse of the early Middle Pleistocene.
637 **Thirdly**, despite their limitations, palaeodenudation rates inferred in the Chawresse
638 catchment are fairly consistent with other long-term denudation data.

639

640 We, however, finally state that further dating efforts are required to understand better the
641 complex response of the Meuse drainage system to coupled tectonic and climatic forcings

642 over the Plio-Quaternary. Whilst the well-preserved Ardennian terrace sequences obviously
643 represent a favourable setting, this study highlights the usefulness of alluvium-filled multi-
644 level cave systems to unravel the long-term history of river incision. Other multi-level systems
645 occur along the Meuse (e.g., Monfat cave; Quinif, 2002) and some tributaries, namely the
646 Ourthe (e.g., Noû Bleû; Peeters and Ek, 2018), and the Lesse (e.g., Han-sur-Lesse; Quinif
647 and Hallet, 2018); they should be thoroughly investigated in that respect in the near future.

648

649

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651

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662

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882

883 **Table caption**

884 **Table 1.**

885 Results of the ^{10}Be and ^{26}Al concentration measurements with the $^{26}\text{Al}/^{10}\text{Be}$ ratios, from
886 which the burial ages (Ma) and palaeodunadation rates (i.e., before the burial event in m/Ma)
887 are computed. Based on an average elevation of 240 m for the Chawresse catchment, the
888 Stone scaling factor amounts to 1.2845. No postburial production was considered. All
889 uncertainties are 1-sigma.

890

891 **Figure captions**

892 **Figure 1. a.** Location of the Paleozoic Ardennes/Rhenish massif in northern Europe (reddish
893 area), with blue and yellow dashed lines referring to the estimated amount of uplift (m) since
894 the beginning of the Middle Pleistocene (Demoulin and Hallot, 2009 explicitly referring to the
895 tectonic component of uplift).- LRE: Lower Rhine embayment; URG: Upper Rhine graben. **b.**
896 Simplified geological map of the northern Ourthe catchment, highlighting the two main
897 karstified limestone formations. The investigated, Chawresse multi-level cave system is
898 located with the red frame. Remnants of the oldest alluvial deposits in this area ("*Graviers*
899 *Liégeois-GL*") and the oldest terraces deposits of the Meuse ("*Kieseloolite Terraces-KT*") are
900 located by white circles. AA, DS, and SM refer to Ardennes Anticlinorium, Dinant
901 Synclinorium and Stavelot Massif, respectively. The dashed orange rectangle refers to Fig.
902 3a.

903

904 | **Figure 2.** Lower Ourthe valley/Valley: longitudinal profile of the modern floodplain and
905 | previous stability levels (up to 20 different according to Cornet, 1995), chiefly inferred from
906 | terrace remnants and karstic phreatic tubes, such as those from the Chawresse multi-level
907 | system (see Fig. 4). The profile reconstruction is modified from Cornet (1995).

908

909 | **Figure 3. a.** Geological map of the study area and the Chawresse multi-level cave system.
910 | Red dashed areas and red star refer to remnants of the younger main terrace and the
911 | sampling location for depth profile dating in the Colonster terrace (Rixhon et al., 2011),
912 | respectively. Lithology and karst phenomena are extracted from De Bie (2013) and the
913 | hydrogeological map of Wallonia (Ruthy, 2015). **b.** Panoramic view of the folded Frasnian
914 | limestone from the western Ourthe valley/Valley wall (photo: G. Rixhon). The entrenched
915 | Chawresse valley/Valley is visible to the south. The spectacular Sainte-Anne cave's entrance
916 | is perched ~17 m above the current river channel (see the person for scale; photo: G.
917 | Rixhon). **c.** Simplified geological sketch of the eastern valley side alongside the main road
918 | (adapted from Ek, 2007).

919

920 | **Figure 4.** Cross sections of the lower Ourthe valley/Valley with the projected cave levels of
921 | the Chawresse multi-level system. **a.** WSW-ENE-oriented, topographic cross section
922 | exhibiting the location of the fifteen samples (quartz and quartzite pebbles) collected from the
923 | oldest cave system (Victor) to the youngest (Sainte-Anne). The underground topography is
924 | adapted from Ek (1961) for the Sainte-Anne cave and De Bie (2013) for all other cave levels.
925 | The elevation of the Younger Main Terrace (YMT) is also reported. **b.** Simplified, N-S-
926 | oriented, geological cross section (quasi-perpendicular to that of Fig. 4.a). Note the
927 | relationship between local structure and cave development: the Chawresse/Veronika caves
928 | and the Manants/Sainte-Anne caves are mostly developed in relationship with an anticlinal
929 | and synclinal structure, respectively. Adapted from De Bie (2013).

930

931 **Figure 5.** Field photos from the multi-level Chawresse cave system **a.** Elliptical cross section
932 of the active phreatic tube with a twofold notch in the main level of Sainte-Anne (photo: V.
933 Gerber). **b.** Probable paragenetic feature in the ceiling of a phreatic tube of Sainte-Anne
934 (dashed red curve; photo: V. Gerber); **c.** Tilling structure of the elongated pebbles (dashed
935 white arrows) indicating the palaeo-flow direction of the underground stream in the main
936 phreatic level of Veronika (from Rixhon, 2016). **d.** Alternation of matrix-supported (M-S) and
937 clast-supported (C-S) layers in river sediments filling the main phreatic tube of Veronika, and
938 sampling location of the quartz pebble VER1 (photo: Y. Levecq).

939

940 **Figure 6.** Long-term, *per descensum*, speleogenetic scenario involving gradual base-level
941 lowering and proposing an uncoupled evolution of the Chawresse/Veronika caves and
942 Manants/Sainte-Anne caves. It shows a stepwise intra-karsting reworking of the clasts
943 sampled in the Manants cave (red stars), which yielded “abnormally” old burial ages (see text
944 for further explanation). Grey arrows refer to river incision ~~while-whereas~~ thin dotted and thick
945 red arrows represent sediment motion at the surface and in the underground karstic system,
946 respectively.

947

948 **Figure 7. a & b.** Series of well-developed, active dolines/sinkholes located atop the southern
949 hillslope of the Chawresse ~~valley~~Valley southward of the Manants cave (see location in Fig.
950 3a; photos: G. Rixhon). **c.** Active vertical drainage (i.e., underground Chawresse stream) in
951 vadose conditions in the Manants cave (Photo: P. De Bie).

952

953 **Figure 8.** Long-term fluvial landscape evolution at the northern rim of the Ardennes in the
954 main trunk (Meuse) and its main tributary (Ourthe). **a.** Computation of Plio-Quaternary
955 incision rates based on the $^{26}\text{Al}/^{10}\text{Be}$ burial ages from this study and from compilation of
956 existing ages (see references in figure insert and text). Note the one order magnitude change
957 in the Ourthe ~~valley~~Valley and the sustained incision pulse recorded during the Middle
958 Pleistocene. GL (i.e., oldest proto-Ourthe deposits) and KT (i.e., oldest Meuse terraces) refer

959 to Neogene/Quaternary fluvial deposits located in Fig. 1b. Vertical and horizontal dashed
960 black arrows refer to their elevation range and supposed time range (with question marks),
961 respectively. **b.** Compilation of incision and palaeodenudation rates. Note that the incision
962 pulse in the lower Ourthe occurred later than the incision peak in the main trunk, which is
963 | characterized by questionable very high rates (>350 m/Ma, see text). As for the discarded
964 | outlier, see text for further information. Age uncertainties relative to palaeodenudation data
965 are not provided for a matter of clarity.

966

967 **Figure 9.** Morphometric characteristics of the Chawresse tributary (note the well-marked
968 | hanging valley *sensu* Wobus et al., 2006) and gradient relationship between the Veronika
969 | Cave and the Ourthe YMT level.

970

1 **Plio-Quaternary landscape evolution in the uplifted Ardennes: new insights**
2 **from $^{26}\text{Al}/^{10}\text{Be}$ data from cave-deposited alluvium (Meuse catchment, E**
3 **Belgium)**

4
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7
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9
10
11 **1. Introduction**

12
13 Beyond studies embracing the western part of the Rhenish shield (e.g., Meyer et al., 1983;
14 Demoulin and Hallot, 2009), the Neogene and Quaternary landscape evolution of the
15 Variscan Ardennes massif, i.e., its westernmost area, has long been a core topic of western
16 Europe geomorphology. In this framework, the Ardennian Meuse catchment has received
17 particular attention (Davis, 1895). The first geomorphic works focused on either Cenozoic
18 erosion surfaces (e.g., Alexandre, 1976; Demoulin, 1995) or Quaternary river terrace
19 systems of the Meuse (e.g., Macar, 1975; Juvigné and Renard, 1992; Pissart et al., 1997)
20 and its Ardennian tributaries (e.g. Ek, 1957; Juvigné, 1979; Cornet, 1995). However, most of
21 them did not go much beyond the mere reconstruction of successive landform generations.
22 During the last twenty years, studies based on DEM analysis, modern dating methods, and
23 numerical modelling have provided new insights into the quantitative long-term evolution of
24 the Ardennian Meuse catchment. They allowed, for instance, the determination of sediment
25 budgets (Van Balen et al., 2000) and palaeodenudation rates (Schaller et al., 2002; 2004;
26 Demoulin et al., 2009), dating of river terrace deposits (Rixhon et al., 2011; 2014), modelling
27 of knickpoint propagation (Beckers et al., 2014) and hillslope denudation (Bovy et al., 2016).

28

29 Despite these significant advances, the timing of Ardennian landscape evolution over the
30 Plio-Quaternary remains poorly documented (Rixhon and Demoulin, 2018). In this respect,
31 although the Ardennes massif is well-known for hosting spectacular cave systems developed
32 in Paleozoic limestone formations at the outskirts of its siliceous core, such as the Han-sur-
33 Lesse cave (e.g., Quinif and Hallet, 2018), little effort has been made so far to use this
34 favourable setting to unravel long-term landscape evolution. Importantly, multi-level cave
35 systems may record massif-scale fluvial history. Penetrating into the karstic system as
36 bedload of sinking streams, sediments may be left behind as flowing water abandons the
37 cave when diversion of the underground stream to a lower topographic level occurs (Anthony
38 and Granger, 2007). As they point to the last period of time during which the passage was at
39 the local water table, fluvial sediments deposited in higher-lying abandoned phreatic
40 passages, mimicking alluvium-mantled terrace sequences (Granger *et al.*, 1997), are useful
41 archives to unravel the timing of river incision. In this respect, *in situ*-produced cosmogenic
42 nuclides are a powerful tool to quantify the pace of long-term river incision (e.g., Rixhon *et*
43 *al.*, 2017), either through depth-profile dating of alluvial terraces (e.g., Repka *et al.*, 1997) or
44 burial dating of fluvial sediments washed into caves (e.g., Granger *et al.*, 1997). Here, we
45 apply this last approach.

46

47 This study explores whether past episodes of fluvial base-level stability in the Ardennes can
48 be chronologically constrained via $^{26}\text{Al}/^{10}\text{Be}$ burial dating of ancient, alluvium-filled karstic
49 passages in one of the largest multi-level cave systems of Belgium. Coarse fluvial sediments
50 were sampled for ^{10}Be and ^{26}Al measurements in the so-called Chawresse system located in
51 the lower Ourthe Valley (i.e., the largest Ardennian tributary of the Meuse), whose karstic
52 levels span an elevation range >120 m. We thereby primarily aim to constrain long-term
53 incision rates at the northern rim of the uplifted Ardennes massif. Complementing the existing
54 ~0.4 Ma age of the younger main terrace in the lower Ourthe Valley (Rixhon *et al.*, 2011),
55 new $^{26}\text{Al}/^{10}\text{Be}$ burial ages ranging from ~0.2 to 3.3 Ma extend the reconstructed incision

56 history to the Plio-Quaternary. In addition, $^{26}\text{Al}/^{10}\text{Be}$ ratios provide pre-burial denudation rate
57 estimates.

58

59 **2. Geologic and geomorphic setting of the study area**

60

61 *2.1. Late Cenozoic uplift of the Rhenish-Ardennes massif*

62 The Ardennes constitutes the western part of the Paleozoic Rhenish massif in southeastern
63 Belgium (Fig. 1a). The whole Ardennes-Rhenish massif experienced Late Cenozoic tectonic
64 uplift, claimed to have been caused by either lithospheric thinning (e.g., Prodehl et al., 1995),
65 lithospheric folding (e.g., Cloething et al., 2005), or mantle upwelling beneath S. Eifel (Ritter
66 et al., 2001). Whereas the spatial pattern of mid-Pleistocene uplift has been usually
67 interpreted as an epeirogenic dome centered on the Eifel (Meyer and Stets, 1998; Van Balen
68 et al., 2000), Demoulin and Hallot (2009) recently suggested that an uplift pulse migrated
69 northwards across the massif, pointing to lithospheric folding as the primary cause of uplift.

70

71 About 400–450 m of rock uplift has been inferred for the Rhenish massif since the Oligocene
72 (Demoulin and Hallot, 2009). Up to 150 m deep Quaternary river incision in the Ardennes
73 bears witness to a recently increased uplift pace probably occurring in two steps, first at the
74 Pliocene-Pleistocene transition and then sometime at the beginning of the Middle
75 Pleistocene (Van Balen et al., 2000). During this last, short-lasting uplift pulse (probably a
76 few 10^4 yr), rock uplift peak rates may have reached 0.3 to 0.5 mm/yr (Fig. 1a; Van Balen et
77 al., 2000; Demoulin and Hallot, 2009; Rixhon and Demoulin, 2018). A phase of tectonic
78 quiescence is postulated from the late Middle Pleistocene onwards (Van Balen et al., 2000).

79

80 *2.2. The Ourthe catchment and its lower valley reach*

81 The Ourthe, largest Ardennian tributary of the Meuse, joins it at the northern rim of the massif
82 in Liège at an elevation of ~60 m (Figs. 1b and 2). Its ~3600 km² catchment is characterized
83 by a highly asymmetric drainage network, the main stem closely following its western border.

84 From south to north, the Ourthe Valley is incised into the siliceous Lower Devonian
85 basement of the Ardennes anticlinorium and rock strata of the Dinant Synclinorium, including
86 limestone formations of the Middle/Upper Devonian and Carboniferous at several locations
87 (Fig. 1b). Owing to sustained karstification processes, many large cave systems developed
88 directly along the Ourthe Valley in both Devonian (Bohon, Hotton, Chawresse caves; e.g.,
89 Bastin et al., 1988) and Carboniferous limestone formations (Abîme, Nou Bleu caves; e.g.,
90 Peeters and Ek, 2018).

91

92 The ~30 km long lower reach of the Ourthe Valley records a Late Cenozoic incision
93 amounting to a maximum of >130 m (Cornet, 1995). Previous geomorphic works
94 reconstructed up to 20 terrace levels along this reach (Ek, 1957; Cornet, 1995) (Fig. 2).
95 However, these reconstructions are essentially descriptive and lack reliable chronological
96 data to constrain the timing of river downcutting. The lowest terrace at Tilff is dated by the
97 presence of the Early Glacial Rocourt tephra (0.074-0.090 Ma), close to the study area
98 (Juvigné, 1973; Pouclet et al. 2008), thereby suggesting a mean incision rate in the order of
99 40 m/Ma since the onset of the last glaciation. The only other numerical age, obtained by
100 Rixhon et al. (2011) via a ^{10}Be depth profile, is 0.39 ± 0.04 Ma for the abandonment time of
101 the Younger Main Terrace (YMT) of the Ourthe at Colonster (~3 km downstream of the
102 Chawresse area). The YMT is a fundamental marker in the Ardennian valleys because it is
103 located at the hinge between the broad Early Pleistocene upper part of the valleys'
104 transverse profile and their nested deeply incised Middle Pleistocene lower part (Rixhon and
105 Demoulin, 2018). The YMT tread is perched ~55 m above the modern floodplain (all relative
106 elevations provided hereafter refer to the level of the Ourthe modern floodplain at the
107 Chawresse confluence), yielding a mean incision rate of 141 ± 15 m/Ma in this reach since
108 0.39 Ma.

109

110 As for mean denudation rates in the Ardennes, Schaller et al. (2004) calculated rates
111 increasing from 30 m/Ma before 0.7 Ma to 60-80 m/Ma after that time, based on the ^{10}Be

112 content of terrace sediments whose age is estimated using a MIS correlation. These rate
113 estimates, however, refer to the timespan of hillslope erosion preceding sediment deposition
114 in the valley bottom. By contrast, Demoulin et al. (2009) inferred a lower average rate of 27
115 m/Ma since ~0.7 Ma over the entire Ourthe catchment, based on geomorphic estimates of
116 river incision and interfluvial denudation.

117

118 *2.3. The Chawresse multi-level cave system*

119 Located ~12 km upstream of the Ourthe-Meuse confluence at Liège (Figs. 1b and 2), the
120 partly subaerial, partly subterranean Chawresse stream is a small tributary deeply incised
121 into the eastern valley side of the lower Ourthe. Its tiny catchment (~3 km²) comprises
122 Lower/Middle Devonian siliceous rocks in the headwaters area and Upper Devonian
123 limestone in its downstream part (Fig. 3a). It hosts one of the largest and best-documented
124 multi-level cave systems of Belgium in strongly folded and faulted Frasnian limestone (e.g.
125 Ek, 1961; Ek and Poty, 1982; De Bie, 2013) (Fig. 3b-c). We will call it hereafter the
126 Chawresse cave system. It stretches in the WSW-ENE Chawresse Valley to more than 1.5
127 km from the confluence, includes more than 10 km of karstic galleries and shafts, and spans
128 a total elevation difference exceeding 135 m (De Bie, 2013; Fig. 4). Along with secondary,
129 smaller caves, the interconnected Chawresse system encompasses five main cave
130 developments named Victor, Chawresse, Veronika, Manants and Sainte-Anne, from the
131 highest to the lowest. According to De Bie (2013), the total length and vertical height
132 difference of each of these caves amount to ~180 and ~47 m (Victor), ~5650 and ~81 m
133 (Chawresse and Veronika taken as a single development, see below), ~1650 and ~67 m
134 (Manants) and ~1750 and ~35 m (Sainte-Anne). Their interconnection is attested either by
135 narrow passages such as between Chawresse and Veronika (leading De Bie, 2013 to
136 propose a single development stage for these two caves) or by fluorescent dye tracing such
137 as between Victor and Sainte-Anne (Fig. 4; supplementary material 1).

138

139 Speleogenetic studies in the Chawresse system agree to highlight the presence of well-
140 developed, abandoned subhorizontal phreatic tubes at different elevations, usually exhibiting
141 an elliptical cross section, as the main morphological feature (Ek, 1961; 1964; Ek and Poty,
142 1982; De Bie, 2013) (Fig. 5a). These tubes constitute most of Sainte-Anne (at ~12 and 20 m
143 relative elevation, see e.g., Ek, 1964) and Veronika, with extensions into the Chawresse
144 cave (at ~70 and 75-78 m relative elevation, see De Bie, 2013). The polycyclic nature of
145 these phreatic levels has long been recognized in Sainte-Anne (Ek, 1961) and may be
146 assumed for the whole system, matching a *per descensum* model of karstification (Harmand
147 et al., 2017). In the frame of a tectonically controlled gradual base-level lowering, authors
148 agree that there is a morphogenic correlation between cave development and the subaerial
149 terrace sequence in the lower Ourthe Valley (Ek, 1961; Quinif, 1989; Cornet, 1995).

150

151 The main abandoned phreatic tubes in the Chawresse and Veronika caves are roughly
152 located at the same relative elevations, but vadose shafts and canyons, almost absent in
153 Veronika, build an intricate network in the Chawresse cave (Fig. 4). Although similarity of
154 elevation favours the hypothesis of a single stage of cave development, the contrast in shaft
155 and canyon density argues against it, though this contrast might be controlled by the local
156 geological structure. Indeed, whereas the main phreatic passages of Veronika stretch along
157 the anticlinal hinge, all developments of the Chawresse cave are located within the steeply
158 dipping southern limb of the anticline, ~50 m more to the south. The Manants cave, which
159 seems to have developed geographically apart from the other cave systems, is dominated by
160 abundant vadose shafts and canyons. The bulk of these occur in the southern wall of the
161 Chawresse Valley, spanning >65 m of elevation difference similar to those of the Chawresse
162 cave (Fig. 4). The current entrance of the Manants cave corresponds to an active sinkhole in
163 the sub-aerial Chawresse streambed (Figs. 3a and 4b). At the base of the cave
164 development, poorly developed phreatic tubes are aligned along the ENE continuation of the
165 main phreatic developments of the Sainte-Anne cave (Fig. 4). Caver explorations report an
166 intricate underground topography for the Manants karstic system (De Bie, 2013). A

167 peculiarity of Sainte-Anne is that the ceiling of one of the phreatic tubes displays a >1 m high
168 dissolution feature, which might have been caused by sediment accumulating in this formerly
169 water-filled passage and inducing upward dissolution of the tube's ceiling (i.e., paragenesis,
170 Farrant, 2004; see Fig. 5b). This indicates that the alluvium that once filled this passage
171 could have been almost completely evacuated by the underground Chawresse stream as a
172 response to a later drop of the water table.

173

174

175 **3. Sampling strategy and $^{26}\text{Al}/^{10}\text{Be}$ burial dating**

176

177 A two-step scenario constitutes the basic prerequisite of burial dating applied to cave-
178 deposited alluvium, namely exposure at the (sub-)surface followed by a rapid and complete
179 burial at a depth great enough (practically, >20 m of overburden) to efficiently prevent any
180 postburial muonic production (e.g., Granger, 2014). It also assumes that, once the clastic
181 sediments had entered the underground karstic system, they suffered no erosion or
182 underground reworking (e.g., Rixhon, 2016). Therefore, wherever possible (i) we primarily
183 targeted cave passages where clastic infills were massively preserved (as in the Veronika
184 cave, see Supplementary Material 1), (ii) we preferentially sampled underground sediments
185 that still exhibit original tilting and bedding structures in the abandoned phreatic tubes (Fig.
186 5c-d) and (iii) we avoided deposits for which reworking could obviously be suspected (for
187 instance, those located close to active passages of the underground Chawresse stream).
188 Given the generally coarse size of the cave sediments, the pebble fraction was selected
189 (Supplementary Material 1). Altogether, fifteen quartz-bearing samples, chiefly quartz
190 pebbles with subsidiary quartzite pebbles, were collected (Fig. 5d; Supplementary Material
191 2). Twelve out of the fifteen processed samples were single clast samples, the three others,
192 all extracted from the Manants cave (MAN1, 2 and 3bis), were amalgamated samples (Table
193 1, Supplementary Material 2). Whilst two samples were taken in the Victor cave at relative
194 elevations of ~125 and 135 m, we purposely collected more samples in the main phreatic

195 developments of the lower-lying cave levels in order to strengthen the timing of the main
196 phases of fluvial base-level stability in the lower Ourthe Valley (Fig. 4 and Table 1). We thus
197 collected four or five samples from the Veronika cave (relative elevation of ~72 to 75 m), the
198 Manants cave (~15 to 35 m) and Sainte-Anne cave (~12 to 20 m). Note that $^{26}\text{Al}/^{10}\text{Be}$ burial
199 dating of cave-deposited alluvium constrains the last period of time during which the passage
200 was at the local water table. In the case of prior ghost-rock karstification (Dubois et al.,
201 2014), this is also the time when ghost-rock feature emptying could be achieved, allowing for
202 sediments originating from the ground surface to be brought into the passage.

203

204 The burial duration is estimated from measurements of the $^{26}\text{Al}/^{10}\text{Be}$ ratio, which decreases
205 with burial time according to the different disintegration rates of the two radionuclides (e.g.,
206 Dunai, 2010; Rixhon, 2016; see Supplementary Material 3 for mathematical development). In
207 this study, we used half-lives of $(1.387 \pm 0.012) \times 10^6$ and $(0.705 \pm 0.017) \times 10^6$ yr for ^{10}Be and
208 ^{26}Al , respectively (Granger, 2006; Chmeleff et al., 2010; Korschinek et al. 2010). The
209 chemical treatment and the AMS measurements (both ^{10}Be and ^{26}Al) of all samples
210 presented in this study were carried out at the CEREGE laboratory in Aix-en-Provence. After
211 crushing and sieving (between 1 and 0.250 mm), sediment samples passed through
212 magnetic separation, and the non-magnetic fraction underwent selective etching in
213 fluorosilicic and hydrochloric acids to eliminate all mineral phases but quartz. Quartz minerals
214 then underwent a series of selective etchings in hydrofluoric acid to eliminate potential
215 surface contamination by ^{10}Be produced in the atmosphere (Brown et al., 1991). The cleaned
216 quartz minerals were then completely dissolved in hydrofluoric acid after addition in each
217 sample of ~100 μl of an in-house carrier solution $((3.025 \pm 0.009) \times 10^{-3} \text{ g } ^9\text{Be/g}$ solution)
218 prepared from a deep-mined phenakite (Merchel et al., 2008). After substituting HF by HNO_3 ,
219 an aliquot of 500 μl of the obtained solution was taken for ^{27}Al concentration measurements.
220 Aluminum and beryllium were separated from the remaining solution by ion-exchange
221 chromatography and selective precipitation (Merchel and Herpers, 1999). The resulting Be
222 and Al precipitates were oxidized by heating at 800°C for one hour and the oxides were

223 mixed to 325 mesh niobium powder prior to measurements by Accelerator Mass
224 Spectrometry (AMS). All the data reported in this study have been measured at the French
225 national facility ASTER of the CEREGE. Beryllium-10 data were calibrated directly versus the
226 National Institute of Standards and Technology standard reference material NIST SRM 4325
227 using an assigned $^{10}\text{Be}/^9\text{Be}$ value of $(2.79\pm 0.03)\times 10^{-11}$; Nishiizumi et al., 2007). This
228 standardization is equivalent to 07KNSTD within rounding error. The obtained $^{26}\text{Al}/^{27}\text{Al}$ ratios
229 were calibrated against the ASTER in-house standard SM-AI-11 with $^{26}\text{Al}/^{27}\text{Al}=7.401\pm$
230 0.064×10^{-12} , which has been cross-calibrated against the primary standards certified by a
231 laboratory inter-calibration exercise (Merchel and Bremser, 2004). ^{27}Al concentrations,
232 naturally present in the samples, were measured at CEREGE by ICP-OES. Analytical
233 uncertainties (reported as 1σ) include uncertainties associated with AMS counting statistics,
234 AMS internal error (0.5%), chemical blank measurement and, regarding ^{26}Al , ^{27}Al
235 measurement. Long-term measurements of chemically processed blanks yield ratios on the
236 order of $3.0\pm 1.5\times 10^{-15}$ for ^{10}Be and $2.2\pm 2.0\times 10^{-15}$ for ^{26}Al (Arnold et al., 2010).

237

238 A local ^{10}Be production rate of $5.16\text{ g at}^{-1}\text{ yr}^{-1}$ was obtained using local coordinates, an
239 average catchment elevation of 240 m and a sea-level high latitude production rate of $P_0 =$
240 $(4.02\pm 0.36)\text{ at g}^{-1}\text{ yr}^{-1}$ (Stone, 2000). The latter is identical to the weighted mean of
241 production rates in the Northern Hemisphere (Ruszkiczay-Rüdiger et al., 2016) and in
242 agreement with recently calibrated values (Borchers et al., 2016). An $^{26}\text{Al}/^{10}\text{Be}$ pre-burial,
243 spallation production ratio amounting to 6.61 was used (Nishiizumi et al., 1989; Braucher et
244 al., 2011). Because the cave overburden is always thicker than 20 m, post-burial muon
245 production was ignored in the burial age determination.

246

247 **4. Results: $^{26}\text{Al}/^{10}\text{Be}$ ratios, burial ages and pre-burial denudation rates**

248

249 Cosmogenic ^{10}Be and ^{26}Al concentrations in the samples range between $(0.62\pm 0.03)\times 10^5$
250 and $(23.56\pm 0.55)\times 10^5$, and $(3.82\pm 0.51)\times 10^5$ and $(98.86\pm 3.10)\times 10^5$ atoms g^{-1} quartz,

251 respectively (Table 1). These concentrations yield $^{26}\text{Al}/^{10}\text{Be}$ ratios ($R_{26/10}$) between 1.20 ± 0.12
252 and 6.13 ± 0.88 (Table 1). Such depleted $R_{26/10}$ identify a burial event for all samples. Burial
253 ages ranging from the Pliocene to the final part of the Middle Pleistocene were computed
254 accordingly (Table 1). Pre-burial denudation rates roughly ranging from 1 to 58 m/Ma are
255 simultaneously calculated (Table 1). We present hereafter the detail of these results,
256 together with their 1σ uncertainties, obtained for the four different cave levels, from the
257 highest to the lowest.

258

259 *4.1. Victor cave*

260 Very contrasting $R_{26/10}$ characterise the samples VIC1 and VIC2: 1.20 ± 0.12 and 5.72 ± 0.51 ,
261 respectively. Burial durations and pre-burial denudation rates for each sample differ
262 accordingly: 3.28 ± 0.22 Ma and 1.44 ± 0.24 m/Ma (VIC1) versus 0.38 ± 0.24 Ma and 29.28 ± 4.16
263 m/Ma (VIC2).

264

265 *4.2. Veronika cave*

266 $R_{26/10}$ of the four samples collected in the main phreatic passage of the Veronika cave range
267 from 4.20 ± 0.16 to 5.76 ± 0.32 . They yield burial durations and pre-burial denudation rates
268 ranging from 0.26 ± 0.15 to 0.56 ± 0.18 Ma and 0.81 ± 0.07 to 20.26 ± 2.89 m/Ma, respectively. At
269 first glance, the 0.26 Ma burial age (sample VER2) may appear out of the range of the age
270 cluster yielded by the three other samples (~ 0.50 - 0.56 Ma). However, the large 1σ -
271 uncertainties associated to VER2 and 4 make burial ages of these two samples statistically
272 indistinguishable. We therefore use the sample VER2 in further calculations. An error-
273 weighted mean of 0.47 ± 0.06 Ma is computed for the Veronika cave out of the four individual
274 burial durations (removing the VER2 sample from the dataset would yield a mean burial
275 duration of 0.51 ± 0.07 Ma, not much different from the previous one).

276

277 *4.3. Manants cave*

278 $R_{26/10}$ of the four samples collected in the Manants cave at different elevations range from
279 2.74 ± 0.19 to 3.96 ± 0.50 . They yield burial durations and pre-burial denudation rates ranging
280 from 1.13 ± 0.32 to 1.79 ± 0.18 Ma and 4.14 ± 0.51 to 14.15 ± 2.65 m/Ma, respectively. Similar to
281 the dataset from the Veronika cave, the 1σ -uncertainties associated to the samples
282 (especially MAN1 and 3bis) make their individual burial ages statistically indistinguishable.
283 An error-weighted mean of 1.59 ± 0.10 Ma is computed for the Manants cave out of the four
284 individual burial ages.

285

286 *4.4. Sainte-Anne cave*

287 $R_{26/10}$ of the five samples collected in the Sainte-Anne cave at different elevations range from
288 4.05 ± 0.21 to 6.13 ± 0.88 . They yield burial ages and pre-burial denudation rates ranging from
289 0.24 ± 0.38 to 0.94 ± 0.36 Ma and 2.77 ± 0.30 to 58.27 ± 11.92 m/Ma, respectively. Large
290 differences are thus observed for both burial durations and pre-burial denudation rates in this
291 cave level, yet consistent with the relative elevation of each sample (Fig. 4a). One might
292 argue from its lower nuclide concentration values and, consequently, the larger relative
293 uncertainty on its ^{26}Al content that sample STA2 is not as meaningful as the other samples in
294 Sainte-Anne cave (Table 1). However, its calculated burial duration is consistent with that of
295 STA2bis, sampled in the exact same location. As for their strongly contrasted denudation
296 rate estimates, it is important to recall that they were calculated from single pebbles and thus
297 refer to local denudation rather than mean catchment rates. When sedimentation occurred in
298 the Sainte-Anne cave, the valleys had already been carved deep enough to display steep
299 hillslopes where local denudation rates could be highly variable. We therefore consider the
300 pair of burial duration estimates yielded by STA2 and STA2bis as significant.

301

302 **5. Discussion**

303

304 **5.1. Relevance of the local speleogenesis in interpreting burial ages**

305

306 Our burial age results clearly stress the necessity of collecting several samples in every
307 individual cave system (Laureano et al., 2016; Sartégou et al., 2018). Indeed, although this
308 procedure supports a robust dating of the Veronika cave at 0.47 ± 0.06 Ma, it was also
309 absolutely required to uncover potential methodological or geomorphic issues in the other
310 cave levels (Häuselmann and Granger, 2005; Dunai, 2010).

311

312 *5.1.1. Contamination by younger material*

313 The ~ 0.4 and 3.3 Ma burial ages obtained for the Victor cave diverge by one order of
314 magnitude. This large discrepancy most probably results from the distinct positions of the
315 sampling sites within the cave. Whereas the VIC1 sample was collected in the lower main
316 development of the cave at ~ 125 m relative elevation, the VIC2 sample was located much
317 nearer to the cave entrance, directly at the bottom of the uppermost underground shaft (~ 135
318 m relative elevation). At such high position above the present Ourthe River, the 0.38 ± 0.24
319 Ma burial age is without doubt geomorphologically inconsistent. In particular, it strongly
320 contradicts the robust ^{10}Be depth profile dating of the YMT at Colonster, which provided an
321 age of ~ 0.4 Ma for terrace deposits located 80 m below the level of the Victor cave (Rixhon
322 et al., 2011). We thus interpret the anomalous young age of VIC2 as indicating a later
323 reactivation of the sinkhole (now in interfluvial position) and injection of younger sediments
324 into the oldest karstic level of the Chawresse system. Moreover, assuming a gravitational
325 collapse of unknown thickness, it is unsure whether the material originates from the surface
326 or the sub-surface and, thereby, whether the initial $R_{26/10}$ of this sample does not violate the
327 key assumption for burial dating (see Section 3 above). Consequently, the VIC2 sample is
328 discarded and we consider the Late Pliocene burial age of VIC1 to be representative of the
329 time when the water table (and the Ourthe River) existed at these high elevations.

330

331 *5.1.2. Probable intra-karstic reworking*

332 The four Early Pleistocene burial ages of the Manants cave at less than 35 m relative
333 elevation must mandatorily be addressed against the background of progressive river
334 downcutting over the Plio-Quaternary. Based on the mid-Middle Pleistocene age of the YMT
335 at Colonster (and, more broadly, also elsewhere in the Meuse catchment; Rixhon et al.,
336 2011), they are substantially older than expected at such a low relative elevation. Three
337 explanatory hypotheses may be examined, namely an alternative model of speleogenesis, a
338 previous burial episode of the sampled material or an intra-karstic reworking with downward
339 motion.

340

341 An alternative *per ascensum* model of speleogenesis, such as the one documented in the
342 Ardèche Valley (e.g., Tassy et al., 2013), would contradict all geomorphic evidence of
343 stepwise base-level lowering and incision in the entire Ardennian Meuse River network
344 related to Quaternary uplift (e.g., Juvigné, 1979; Pissart et al., 1997; Demoulin et al., 2012;
345 Rixhon and Demoulin, 2018). In the lower Ourthe Valley, the well-preserved terrace staircase
346 and its geomorphological coupling with cave systems strongly point to a *per descensum*
347 model of speleogenesis (Harmand et al., 2018). The latter is acknowledged not only for the
348 Chawresse system (Ek, 1961; Cornet, 1995) but also for the newly discovered Noû Bleû
349 cave located several kilometers upstream (Peeters and Ek, 2018). The hypothesis of an
350 alternative speleogenetic model is thus highly unlikely.

351

352 Even if no direct evidence precludes the possibility that some of the sampled material
353 underwent a burial episode before entering the karstic system, two lines of argument point to
354 intra-karstic reworking as the most likely cause of the ages that are too old. First, beyond
355 exhibiting higher depletion than the Veronika samples (Table 1), the Manants $R_{26/10}$ data
356 subset is internally consistent, with the lowest variability among all cave levels. This points to
357 a single burial history for all Manants samples, and thus most likely an exclusively intra-
358 karstic history. Indeed, reworking of pebbles that would have experienced subaerial burial
359 events before entering the cave system (e.g., at the base of thick Early Pleistocene Ourthe

360 terrace deposits) would probably have implied a large scatter in the depleted $R_{26/10}$ (different
361 burial durations and depths).

362

363 Second, the intricate karstic system of the Manants cave dominated by vadose shafts (Fig. 4)
364 points to multiphase speleogenetic processes (De Bie, 2013), which probably also entailed a
365 complex underground evolution of the cave sedimentary infill. Following De Bie (2013), who
366 considers that the Chawresse and Veronika caves form a single system, we thus suggest
367 that the Chawresse/Veronika and the Manants/Sainte-Anne systems evolved independently,
368 possibly also with some temporal overlap that might explain the complex underground
369 topography of the Manants cave and the Early Pleistocene burial ages obtained for its cave
370 infill . A realistic, though speculative, history of the Manants samples might have implied the
371 following stages: (i) washing of sediments into dolines and/or sinkhole shafts in the vadose
372 zone above an Early Pleistocene stability level, with substantial shielding to cosmic rays
373 already allowing some $R_{26/10}$ decrease; (ii) from the late Early Pleistocene, progressive base-
374 level lowering and Ourthe and Chawresse incision promoting downward development of the
375 shafts and travel of the trapped sediments, possibly aided by piping and underground
376 drainage, to depths possibly beyond reach of the cosmic rays; (iii) Middle Pleistocene
377 stability phase inducing the independent formation and infilling of the phreatic tubes of the
378 Veronika cave while the Manants clasts remained buried in their separate system; (iv) later in
379 the Middle Pleistocene, main phase of river downcutting and renewed downward
380 displacement of the sediments buried in the Manants cave, however, not affecting the
381 fossilized Veronika tubes and their infill; (v) probably in connection with the main tube
382 formation in the Sainte-Anne cave sometime during the late Middle Pleistocene, phreatic
383 overprinting of the Manants cave with essentially lateral reworking bringing the clasts in their
384 sampling position. Note that the same reasoning can be held for the older burial ages of
385 sediments sampled in the higher phreatic tubes of Sainte-Anne, which might indicate input of
386 older material through the Manants cave as a siphon connects both caves (Fig. 4; De Bie,
387 2013).

388

389 Several field observations support this scenario. A dense network of well-developed dolines
390 (depth locally >10 m) occur directly to the south of the cave (“*dolines syncline*”, Fig. 7a).
391 Located upslope south of the Chawresse Valley at elevations of 180-200 m, they display
392 active sinkholes and sediment accumulation at their bottom (Fig. 7b). Although their possible
393 hydrological connection with the Manants cave has not been explored so far (De Bie, 2013),
394 we may postulate that similar extended vertical connection between the ground surface and
395 deeper cave levels also existed in the past. Moreover, in contrast with all other caves of the
396 Chawresse system, the current Manants cave’s entrance corresponds to an active sinkhole
397 in the sub-aerial Chawresse streambed. Active drainage of the cave’s vadose shafts by the
398 underground stream obviously still facilitates the downward transport of clastic material (Fig.
399 7c). For all these reasons, we interpret all burial ages obtained for the Manants samples and
400 those of STA1, 1bis and 4 in Sainte-Anne as discordant data telling corollary events of the
401 drainage system downcutting.

402

403

404 **5.2. Comparison of the burial ages with Neogene/Quaternary fluvial deposits**

405

406 *5.2.1. Pre-Quaternary fluvial evolution at the northern rim of the massif*

407 The 3.28 ± 0.22 Ma burial age in the Victor cave represents the first Pliocene numerical age
408 for fluvial deposits located within the Ardennian Meuse catchment. This age is consistent
409 with the position of the Victor cave at the plateau’s margin atop the eastern Ourthe Valley
410 side (Fig. 4) and the Neogene age assigned to the lowest beveled surfaces flanking the
411 incised Quaternary valleys (Demoulin, 1995; Demoulin et al., 2018). Moreover, the dated
412 deposit lies at a lower elevation than the quartz- and quartzite-rich fluvial gravels
413 discontinuously covering the Ourthe/Meuse interfluvium 155 to 180 m above the modern valley
414 bottoms (e.g., Rixhon and Demoulin, 2010; Fig. 8a). Located ~5 km to the northwest of the
415 Chawresse multi-level system (Fig. 1b), these gravels, locally known as “*Graviers Liégeois*”

416 (Pissart, 1964), have been interpreted as the oldest Ardennian River sediments deposited by
417 a proto-Ourthe system and tentatively dated from the Miocene (Supplementary material 4),
418 based on stratigraphic and pedogenetic evidence (Buurman, 1972) (Fig. 8a). Finally,
419 although the highest terrace remnants in the lower Ourthe Valley hardly reach 125 m relative
420 elevation (Cornet, 1995), the oldest terrace deposits of the Meuse in the nearby Liege area,
421 traditionally referred to as “*kieseloolite terraces*” (Macar, 1975; Supplementary material 4),
422 occur within the same range of relative elevation as the Victor cave (~115-135 m) (Fig. 8a)
423 (Juvigné and Renard, 1992; Rixhon and Demoulin, 2018). Despite the lack of direct
424 numerical age of the kieseloolite terraces, authors now agree that their stratigraphic
425 correlation with the Kieseloolite Formation in the Roer Valley Graben dates them between
426 the Late Tortonian and the Early Piacenzian (Westerhoff et al., 2008; Rixhon and Demoulin,
427 2018; Beerten et al., 2018; Munsterman et al., 2019). Overall, the Pliocene burial age of the
428 Victor cave thus appears in good agreement with the available geomorphic and sedimentary
429 evidence in the area.

430

431 *5.2.2. Geomorphological and chronological link between the Veronika cave and the YMT*

432

433 Our convergent burial durations in the main phreatic tubes of the Veronika cave point to a
434 long-lasting regional base level ~70-75 m above the current valley bottom around 0.47 Ma.
435 At this elevation, the cave lies 15-20 m above the YMT of the Ourthe (Fig. 9). The ^{10}Be depth
436 profile performed in the YMT sediments at Colonster, 3 km downstream of the Chawresse
437 cave system, reliably dated the terrace abandonment time at ~0.39 Ma (Rixhon et al., 2011),
438 which is at first glance in perfect agreement with the ~0.5 Ma age of the Veronika cave level.

439

440 However, the story is somewhat more complex. First, in the lower Meuse ~20 km north of
441 Liege, the abandonment time of the Romont terrace, formerly correlated to the YMT
442 (Juvigné, 1992), was dated at 0.73 ± 0.12 Ma via a twofold ^{10}Be and ^{26}Al depth profile (Rixhon
443 et al., 2011). The later reassignment of this terrace to the next higher level within the Main

444 Terrace Complex led Rixhon and Demoulin (2018) to propose a younger age around 0.62
445 Ma for the YMT abandonment time in this valley reach. Second, ~20 km upstream of the
446 Chawresse area, another ^{10}Be depth profile in terrace deposits of the Amblève River close to
447 its confluence with the Ourthe (Fig. 1b) revealed that, although the YMT was abandoned at
448 0.22 ± 0.03 Ma in that place, it had started to aggrade much earlier, around 0.58 Ma (Rixhon
449 et al., 2011). Broadly consistent with the YMT age at Romont, the latter age thus implies that
450 the lower Ourthe River had also already incised its valley down to slightly less than 55 m of
451 relative elevation (i.e., the base of the YMT) around 0.58-0.62 Ma. This seems to contradict
452 the younger 0.47 ± 0.06 Ma mean burial age obtained in the higher-located Veronika cave.

453

454

455

456 This apparent discrepancy finds its explanation in the location of the Veronika cave in the
457 Chawresse Valley, about 800 m upstream of the Ourthe confluence, which, at YMT time, was
458 approximately superposed to the present one. Therefore, we interpret the 15-20 m elevation
459 difference between the cave and the Ourthe YMT as expressing the hydraulic gradient
460 beneath the hillslopes east of the Ourthe at YMT time. This ~2.5% gradient is very close to
461 the 2.5-3% westward slope of the Veronika main galleries (Fig. 9) and the ~3% slope of the
462 subaerial channel in the upper Chawresse inherited from the Early Pleistocene, the Middle
463 Pleistocene incision wave having not reached the upper Chawresse (Beckers et al., 2015).
464 So connecting the Veronika cave, and thus making it contemporaneous, with the Ourthe
465 YMT is geomorphically and chronologically consistent. Once the Ourthe River had started to
466 develop its YMT floodplain sometime between 0.62 and 0.58 Ma, the Veronika karstic level in
467 turn began to form following the hydraulic gradient of the time. Clasts sampled in the upper
468 part of a ~2-m thick deposit date the later filling of its galleries around 0.47 Ma, i.e., well
469 before the YMT level was abandoned through renewed Ourthe incision around 0.39 Ma in
470 this area (Rixhon et al., 2011). We also note that the YMT time was the last long period
471 (including the long warm MIS11) of stability of the river before the Late Pleistocene, so that

472 one could *a priori* expect it would have been favourable to such a large karstic development
473 as that of the Veronika cave.

474

475 **5.3. Incision rate variability over the Plio-Quaternary**

476

477 The ^{10}Be -based ages obtained by Rixhon et al. (2011, 2014) for YMT remnants in the lower
478 Meuse – lower Ourthe – Amblève system provided first constraints on the long-term incision
479 history in N. Ardennes. Not only does the present study confirm them but it also yields the
480 first numerical age for one of the highest attested levels of the Plio-Quaternary downcutting
481 of the Ardennian drainage network. With the Pliocene age of the landscape level in which the
482 Victor cave formed, it brings quantitative support to the long-held assumption of contrasted
483 incision rates between the Pliocene and Early Pleistocene on one hand, the Middle
484 Pleistocene to present on the other hand (Fig. 8a-b).

485

486 Based on the differences between the VIC1 sample and the YMT base in the lower Ourthe in
487 terms of relative elevation (125 m vs ~49 m, for 6 m thick YMT deposits) and age (3.28 Ma
488 vs. 0.58 Ma), the Late Pliocene and the Early Pleistocene were characterized by a mean
489 incision rate of 29 ± 4 m/Ma (Fig. 8a). Then, a period of stability occurred from 0.62-0.58 to
490 0.39 Ma (i.e., the lifetime of the YMT as a floodplain in the lower Ourthe Valley, see also
491 Rixhon et al., 2014). The next period over which an average incision rate may be calculated
492 is framed by the time of abandonment of the YMT and a set of dates pointing to a relative
493 elevation of 12 m for the Ourthe level in the late Middle Pleistocene. The latter timing is first
494 indicated by the two samples (STA2 and STA2bis) dating the youngest phase of activity in
495 the main phreatic tube of Sainte-Anne (12 m relative elevation) between 0.24 and 0.3 Ma,
496 though with penalizing large age uncertainties (Table 1). Second, 40 km farther downstream,
497 the interglacial deposits capping the Caberg terrace of the Meuse at 15-18 m relative
498 elevation in the Belvédère site near Maastricht have been consistently dated at 0.25 ± 0.02
499 Ma by thermoluminescence on burned flints and 0.22 ± 0.04 Ma by ESR on mollusc shells

500 (Huxtable, 1993; Van Kolfsochten et al., 1993). We thus calculate a weighted mean age of
501 the Sainte-Anne – Caberg level of 0.245 ± 0.02 Ma. Based on a difference in elevation of 42
502 m, an average incision rate of $290 (+125/-68)$ m/Ma between 0.39 ± 0.04 and 0.245 ± 0.02 Ma is
503 inferred. However, beyond the fact that it confirms the strong acceleration of incision from the
504 Middle Pleistocene onwards (Demoulin and Hallot, 2009; Rixhon et al., 2011), the meaning
505 of this rate is not straightforward because it incorporates two fundamentally different
506 components. They are (i) the delayed upstream propagation of an approximately 20-m high
507 wave of erosion responding to a tectonic uplift pulse in the early Middle Pleistocene and
508 travelling along the lower Ourthe around 0.39 Ma (Demoulin et al., 2012; Beckers et al.,
509 2015), and (ii) a slower continued incision over the rest of the period (Fig. 8a). Subtracting
510 the 20 m amount of incision propagated with the erosion wave leaves a residual post-
511 knickpoint average incision rate in the order of 150 m/Ma as a direct response to the late
512 Middle Pleistocene uplift of the area, still much larger than the Pliocene-Early Pleistocene
513 rate. Finally, according to the same data, the mean incision rate since 0.245 ± 0.02 Ma would
514 fall in the range of 45-53 m/Ma. This is in agreement with the rougher 33-81 m/Ma estimation
515 derived from the presence of the 74-90 ka old Rocourt tephra (Pouclet et al., 2008) in low
516 terraces (~3 m relative elevation) of the Ourthe and the Amblève, as well as its absence in
517 the next higher terrace of the Amblève at 6 m relative elevation (Juvigné, 1973, 1979; Rixhon
518 and Demoulin, 2010).

519

520

521

522

523

524 These long-term incision rates can be compared with those compiled by Van Balen et al.
525 (2000) for the Meuse at Liège based on a reinterpretation of palaeomagnetic data previously
526 obtained in the terrace staircase of the lower Meuse near Maastricht (Van den Berg, 1996)
527 (Fig. 8b). We recall, however, that the chronological interpretation of these palaeomagnetic

528 data, especially those collected from the main terrace complex, has long been a matter of
529 debate (Van Balen et al., 2000; Westaway, 2002; Rixhon and Demoulin, 2010; Rixhon et al.,
530 2011). Nevertheless, the general picture remains valid, with low incision rates in the Early
531 Pleistocene, a major rate increase in the first half of the Middle Pleistocene, followed by a
532 progressive decrease of the rates since the late Middle Pleistocene (Fig. 8b). We also note
533 the different timing of maximum incision between the lower Ourthe - Chawresse area and the
534 lower Meuse. The latter is related to the time the Middle Pleistocene erosion wave needed to
535 propagate into the Ardennian drainage system, causing delayed knickpoint passage and
536 valley incision in the Ourthe with respect to the Meuse (Rixhon et al., 2011; Demoulin et al.,
537 2012; Rixhon and Demoulin, 2018) (Fig. 8b). Finally, as for the reduced incision rates
538 observed in both the Meuse and Ourthe since ~0.25 Ma, one may tentatively link them to the
539 loss of drainage area (~3400 km²), and thus stream power, suffered by the Meuse because
540 of the capture of the upper Moselle at the time of the Caberg terrace (e.g., Pissart et al.,
541 1997), even though the numerical age of the capture is still debated (Cordier et al., 2013).

542

543 **5.4. Palaeodenudation rates**

544

545 Besides burial durations in the Chawresse karstic system, the measured $R_{26/10}$ yield pre-
546 burial denudation rates ranging from 0.8 to 58.3 m/Ma (Table 1), adding information to the
547 existing database used to infer basin denudation rates in the Ardennes (Schaller, 2002,
548 2004; Demoulin et al., 2009). However, we first stress two main limitations of our rate data.
549 First, as our samples consist of single or a few amalgamated quartz or quartzite clasts, the
550 derived rates do not refer to mean basin denudation but rather to local erosion under the
551 topographic conditions of the places wherefrom the samples come within the area of
552 outcropping siliceous rocks (in the upstream Chawresse catchment). Second, most of the
553 calculated rates concern the period of slow denudation from the Pliocene to the early Middle
554 Pleistocene, before the post-YMT erosion wave had reached the study area, and only two

555 samples (STA2 and STA2bis) provide scarce information about the younger times of
556 assumed higher erosion.

557

558

559 All our rate estimates predating the time of rapid post-YMT incision, i.e., those obtained from
560 the Victor, Manants, and Veronika caves but also those of Sainte-Anne with burial ages older
561 than 0.39 Ma, were expected to reflect a smoothly undulating fluvial landscape with gentle
562 slopes and low relief, drained by wide shallow valleys. Indeed, denudation rate increases
563 from a very low 1.44 ± 0.24 m/Ma at ~ 3.3 Ma in the Early Piacenzian (sample VIC1) to a
564 weighted mean of 7.53 ± 0.26 m/Ma between 2 and 1 Ma (Manants cave samples), 9.19 ± 0.46
565 m/Ma between 1 and 0.8 Ma (samples STA1, 1bis and 4), and 7.45 ± 0.22 m/Ma around 0.5
566 Ma (Veronika cave samples). Note that, because of the dependence of the error on the value
567 of the denudation rate, mean rates have been obtained here from weighting the data by their
568 associated relative error instead of their variance. In each of these periods, the spread of
569 individual clast denudation estimates remains limited, with maximal values always ≤ 20
570 m/Ma, confirming low to moderate denudation of a hardly incised landscape of Neogene
571 planation surfaces in the lower Ourthe area (Demoulin et al., 2018). By contrast, though
572 clearly needing confirmation by further measurements, the two samples attesting denudation
573 after the post-YMT erosion wave had reached the study area and enhanced river incision
574 had begun (STA2 and 2bis) show higher and more variable rates, consistent with a greater
575 relief and steeper valley slopes.

576

577 At a regional scale, Schaller et al. (2004) provided mean palaeodenudation rates for the
578 Ardennian Meuse basin based on ^{10}Be measurements from different terrace deposits of
579 approximately known ages located in the Maastricht area and spanning the period since 1.3
580 Ma. They increase from $\sim 25\text{-}35$ m/Ma in the Early Pleistocene to $\sim 40\text{-}80$ m/Ma since the
581 beginning of the Middle Pleistocene. As the authors acknowledged, these rates suffer from
582 uncertainties. They are linked (i) to poor age constraints on many sampled terrace deposits

583 and (ii) to the limited adequacy of the sampled material in representing all parts of the
584 catchment, be it because carbonate rock areas do not deliver quartz to the rivers or the 0.5-1
585 mm grain size fraction on which the ^{10}Be measurements were made is hardly present in
586 some sediments e.g., the kaolinic weathering products mantling large plateau areas of the
587 Ardennes. Nevertheless, they compare well with the local denudation data presented here.
588 Indeed, the pre-0.7 Ma rates of 25-35 m/Ma obtained by Schaller et al. (2004) refer to the
589 Meuse catchment upstream of Maastricht and thus incorporate a non-negligible component
590 of valley downcutting and widening in the main branches of the river system. The fact that
591 this component of valley development is almost absent in the source area of our samples,
592 namely the hardly eroded upstream part of the small Chawresse catchment, readily explains
593 the lower rates in the order of 7-10 m/Ma they yielded.

594

595 Finally, based on eroded volumes estimated from geomorphic arguments for interfluves in
596 the Condroz area, to which the Chawresse upper catchment may be likened, Demoulin et al.
597 (2009) also obtained denudation rates in the order of 5-10 m/Ma in the Pliocene and Early
598 Pleistocene. Interestingly, despite not being aimed at high-resolution evaluation of
599 denudation, the recently published study of apatite fission track data from northern Ardennes
600 comes to the similar conclusion that denudation was very slow in this area in the Neogene
601 (Barbarand et al., 2018). As for the more recent increased denudation rates, we only note
602 that the rate of ~58 m/Ma yielded by sample STA2 originating from a still now not much
603 incised area is in line with the catchment-wide rates between 40-80 m/Ma calculated by
604 Schaller et al. (2004). It also agrees well with local denudation data in the same range
605 obtained from interfluves in two small catchments of the Black Forest (Meyer et al., 2010).
606 Finally, the Chawresse denudation rates present first hints that the timing of the Middle
607 Pleistocene increase in denudation rate in the Ardennes might be linked to the arrival of the
608 post-YMT erosion wave in any particular catchments, being thus more tectonically than
609 climatically triggered.

610

611 **6. Conclusion**

612

613 Though facing limitations inherent to $^{26}\text{Al}/^{10}\text{Be}$ burial dating of ancient alluvium-filled karstic
614 passages, this study demonstrates the usefulness of the approach to unravel the main
615 episodes of fluvial base-level stability in the Ardennes during the Plio-Quaternary. Its main
616 outcomes are threefold. First, the Early Pleistocene burial ages of the Manants cave most
617 probably reflect an uncoupled speleogenesis with respect to the higher-lying phreatic tubes
618 of Veronika and Chawresse (mean burial age around 0.5 Ma). These discordant ages stress
619 the necessity for sampling only well-developed alluvium-filled phreatic tubes, where
620 contamination from higher levels appears unlikely (e.g., the Veronika cave), to provide
621 reliable long-term incision rates. Second, the computed burial ages from the Victor and
622 Veronika caves, together with the reliable abandonment time of the YMT in the lower Ourthe
623 (Rixhon et al., 2011), quantitatively attest for the first time the long-held assumption of
624 contrasted incision rates between the Pliocene-Early Pleistocene and the Middle
625 Pleistocene-present. At ~ 0.39 Ma, the Middle Pleistocene rates increased transiently from
626 ~ 30 to ~ 150 m/Ma. The long-term incision history in the lower Ourthe exhibit a similar pattern
627 to that in the lower Meuse, although the peak incision episode, in good concordance with
628 previous studies (e.g., Rixhon et al., 2011; Demoulin et al., 2012), occurred later in the
629 tributary. This results from the delayed upstream propagation of the Middle Pleistocene
630 erosion wave, itself triggered by the main tectonic uplift pulse of the early Middle Pleistocene.
631 Third, despite their limitations, palaeodenudation rates inferred in the Chawresse catchment
632 are fairly consistent with other long-term denudation data.

633

634 We, however, finally state that further dating efforts are required to understand better the
635 complex response of the Meuse drainage system to coupled tectonic and climatic forcings
636 over the Plio-Quaternary. Whilst the well-preserved Ardennian terrace sequences obviously
637 represent a favourable setting, this study highlights the usefulness of alluvium-filled multi-
638 level cave systems to unravel the long-term history of river incision. Other multi-level systems

639 occur along the Meuse (e.g., Monfat cave; Quinif, 2002) and some tributaries, namely the
640 Ourthe (e.g., Noû Bleû; Peeters and Ek, 2018), and the Lesse (e.g., Han-sur-Lesse; Quinif
641 and Hallet, 2018); they should be thoroughly investigated in that respect in the near future.

642

643

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645

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656

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876

877 **Table caption**

878 **Table 1.**

879 Results of the ^{10}Be and ^{26}Al concentration measurements with the $^{26}\text{Al}/^{10}\text{Be}$ ratios, from
880 which the burial ages (Ma) and palaeodunadation rates (i.e., before the burial event in m/Ma)
881 are computed. Based on an average elevation of 240 m for the Chawresse catchment, the
882 Stone scaling factor amounts to 1.2845. No postburial production was considered. All
883 uncertainties are 1-sigma.

884

885 **Figure captions**

886 **Figure 1. a.** Location of the Paleozoic Ardennes/Rhenish massif in northern Europe (reddish
887 area), with blue and yellow dashed lines referring to the estimated amount of uplift (m) since
888 the beginning of the Middle Pleistocene (Demoulin and Hallot, 2009 explicitly referring to the
889 tectonic component of uplift). LRE: Lower Rhine embayment; URG: Upper Rhine graben. **b.**
890 Simplified geological map of the northern Ourthe catchment, highlighting the two main
891 karstified limestone formations. The investigated Chawresse multi-level cave system is
892 located with the red frame. Remnants of the oldest alluvial deposits in this area ("*Graviers*
893 *Liégeois-GL*") and the oldest terraces deposits of the Meuse ("*Kieseloolite Terraces-KT*") are
894 located by white circles. AA, DS, and SM refer to Ardennes Anticlinorium, Dinant
895 Synclinorium and Stavelot Massif, respectively. The dashed orange rectangle refers to Fig.
896 3a.

897

898 **Figure 2.** Lower Ourthe Valley: longitudinal profile of the modern floodplain and previous
899 stability levels (up to 20 different according to Cornet, 1995), chiefly inferred from terrace
900 remnants and karstic phreatic tubes, such as those from the Chawresse multi-level system
901 (see Fig. 4). The profile reconstruction is modified from Cornet (1995).

902

903 **Figure 3. a.** Geological map of the study area and the Chawresse multi-level cave system.
904 Red dashed areas and red star refer to remnants of the younger main terrace and the
905 sampling location for depth profile dating in the Colonster terrace (Rixhon et al., 2011),
906 respectively. Lithology and karst phenomena are extracted from De Bie (2013) and the
907 hydrogeological map of Wallonia (Ruthy, 2015). **b.** Panoramic view of the folded Frasnian
908 limestone from the western Ourthe Valley wall (photo: G. Rixhon). The entrenched
909 Chawresse Valley is visible to the south. The spectacular Sainte-Anne cave's entrance is
910 perched ~17 m above the current river channel (see the person for scale; photo: G. Rixhon).
911 **c.** Simplified geological sketch of the eastern valley side alongside the main road (adapted
912 from Ek, 2007).

913

914 **Figure 4.** Cross sections of the lower Ourthe Valley with the projected cave levels of the
915 Chawresse multi-level system. **a.** WSW-ENE-oriented, topographic cross section exhibiting
916 the location of the fifteen samples (quartz and quartzite pebbles) collected from the oldest
917 cave system (Victor) to the youngest (Sainte-Anne). The underground topography is adapted
918 from Ek (1961) for the Sainte-Anne cave and De Bie (2013) for all other cave levels. The
919 elevation of the Younger Main Terrace (YMT) is also reported. **b.** Simplified, N-S-oriented,
920 geological cross section (quasi-perpendicular to that of Fig. 4a). Note the relationship
921 between local structure and cave development: the Chawresse/Veronika caves and the
922 Manants/Sainte-Anne caves are mostly developed in relationship with an anticlinal and
923 synclinal structure, respectively. Adapted from De Bie (2013).

924

925 **Figure 5.** Field photos from the multi-level Chawresse cave system **a.** Elliptical cross section
926 of the active phreatic tube with a twofold notch in the main level of Sainte-Anne (photo: V.
927 Gerber). **b.** Probable paragenetic feature in the ceiling of a phreatic tube of Sainte-Anne
928 (dashed red curve; photo: V. Gerber); **c.** Tiling structure of the elongated pebbles (dashed
929 white arrows) indicating the palaeo-flow direction of the underground stream in the main
930 phreatic level of Veronika (from Rixhon, 2016). **d.** Alternation of matrix-supported (M-S) and

931 clast-supported (C-S) layers in river sediments filling the main phreatic tube of Veronika, and
932 sampling location of the quartz pebble VER1 (photo: Y. Levecq).

933

934 **Figure 6.** Long-term, *per descensum*, speleogenetic scenario involving gradual base-level
935 lowering and proposing an uncoupled evolution of the Chawresse/Veronika caves and
936 Manants/Sainte-Anne caves. It shows a stepwise intra-karsting reworking of the clasts
937 sampled in the Manants cave (red stars), which yielded “abnormally” old burial ages (see text
938 for further explanation). Grey arrows refer to river incision whereas thin dotted and thick red
939 arrows represent sediment motion at the surface and in the underground karstic system,
940 respectively.

941

942 **Figure 7. a & b.** Series of well-developed, active dolines/sinkholes located atop the southern
943 hillslope of the Chawresse Valley southward of the Manants cave (see location in Fig. 3a;
944 photos: G. Rixhon). **c.** Active vertical drainage (i.e., underground Chawresse stream) in
945 vadose conditions in the Manants cave (photo: P. De Bie).

946

947 **Figure 8.** Long-term fluvial landscape evolution at the northern rim of the Ardennes in the
948 main trunk (Meuse) and its main tributary (Ourthe). **a.** Computation of Plio-Quaternary
949 incision rates based on the $^{26}\text{Al}/^{10}\text{Be}$ burial ages from this study and from compilation of
950 existing ages (see references in figure insert and text). Note the one order magnitude change
951 in the Ourthe Valley and the sustained incision pulse recorded during the Middle Pleistocene.
952 GL (i.e., oldest proto-Ourthe deposits) and KT (i.e., oldest Meuse terraces) refer to
953 Neogene/Quaternary fluvial deposits located in Fig. 1b. Vertical and horizontal dashed black
954 arrows refer to their elevation range and supposed time range (with question marks),
955 respectively. **b.** Compilation of incision and palaeodenudation rates. Note that the incision
956 pulse in the lower Ourthe occurred later than the incision peak in the main trunk, which is
957 characterized by questionable very high rates (>350 m/Ma, see text). As for the discarded

958 outlier, see text for further information. Age uncertainties relative to palaeodenudation data
959 are not provided for a matter of clarity.

960

961 **Figure 9.** Morphometric characteristics of the Chawresse tributary (note the well-marked
962 hanging valley *sensu* Wobus et al., 2006) and gradient relationship between the Veronika
963 Cave and the Ourthe YMT level.

964

Table1

Caves + sampling elevation / sample ID + nature*	$^{10}\text{Be}/^9\text{Be}$	Uncert.	^{10}Be	Uncert.	$^{26}\text{Al}/^{27}\text{Al}$	Uncert.	^{26}Al	Uncert.	$^{26}\text{Al}/^{10}\text{Be}$	Unc.	Burial age	Unc.	Palaeoden. rate	Uncert.
			(atoms/g)	(atoms/g)			(atoms/g)	(atoms/g)			(Ma)	(Ma)	(m/Ma)	(m/Ma)
Victor (~125-135 m of relative elevation)														
VIC1 (sing.cl.)	4.54E-13	1.42E-14	384 317	12 047	4.86E-13	4.56E-14	459 703	43 170	1.20	0.12	3.28	0.22	1.44	0.24
VIC2 (sing.cl.)	1.23E-13	4.01E-15	112 284	3 664	6.46E-13	5.35E-14	642 531	53 452	5.72	0.51	0.38	0.24	29.28	4.16
Veronika (~72-75 m of relative elevation)														
VER1 (sing.cl.)	3.72E-13	1.27E-14	334 415	11 478	3.57E-13	1.88E-14	1 709 349	95 295	5.11	0.33	0.56	0.18	8.08	1.01
VER2 (sing.cl.)	7.21E-13	2.28E-14	601 930	19 161	6.62E-13	2.78E-14	3 464 437	158 767	5.76	0.32	0.26	0.15	4.97	0.55
VER3 (sing.cl.)	1.85E-12	4.30E-14	2 356 386	55 297	6.76E-12	2.06E-13	9 886 421	310 034	4.20	0.16	0.50	0.08	0.81	0.07
VER4 (sing.cl.)	1.68E-13	5.48E-15	146 529	4 809	1.88E-13	1.41E-14	791 373	60 736	5.40	0.45	0.51	0.23	20.26	2.89
Manants (~15-35 m of relative elevation)														
MAN1 (amalg.)	1.57E-13	5.00E-15	150 426	4 825	5.61E-13	6.76E-14	595 834	72 042	3.96	0.50	1.13	0.32	14.15	2.65
MAN2 (amalg.)	3.99E-13	1.25E-14	352 449	11 115	6.12E-13	3.64E-14	1 020 973	61 616	2.90	0.20	1.66	0.17	4.14	0.51
MAN3 (sing.cl.)	3.66E-13	1.25E-14	312 034	10 703	6.80E-13	4.17E-14	853 539	52 711	2.74	0.19	1.79	0.18	4.42	0.58
MAN3bis (amalg.)	2.04E-13	6.50E-15	180 981	5 776	6.33E-13	4.88E-14	619 189	47 933	3.42	0.29	1.41	0.22	9.94	1.41
Sainte-Anne (~12-18 m of relative elevation)														
STA1 (sing.cl.)	2.50E-13	8.08E-15	217 928	7 075	1.50E-13	1.17E-14	1 024 054	79 680	4.70	0.40	0.77	0.22	11.54	1.65
STA1bis (sing.cl.)	8.44E-13	2.88E-14	737 993	25 269	1.62E-12	6.26E-14	2 988 746	116 123	4.05	0.21	0.89	0.13	2.77	0.30
STA2 (sing.cl.)	6.27E-14	3.17E-15	62 250	3 151	3.45E-13	4.62E-14	381 841	51 205	6.13	0.88	0.24	0.38	58.27	11.92
STA2bis (sing.cl.)	3.40E-13	1.16E-14	332 018	11 374	1.30E-12	6.39E-14	1 933 862	95 615	5.82	0.35	0.30	0.16	9.47	1.11
STA4 (sing.cl.)	1.51E-13	7.23E-15	132 752	6 383	7.67E-14	9.21E-15	571 828	68 700	4.31	0.56	0.94	0.36	18.32	3.94

* Sample nature: single-clast sample (*sing.cl.*); amalgamated sample (*amalg.*); see also Supplementary Material 2.

Figure1
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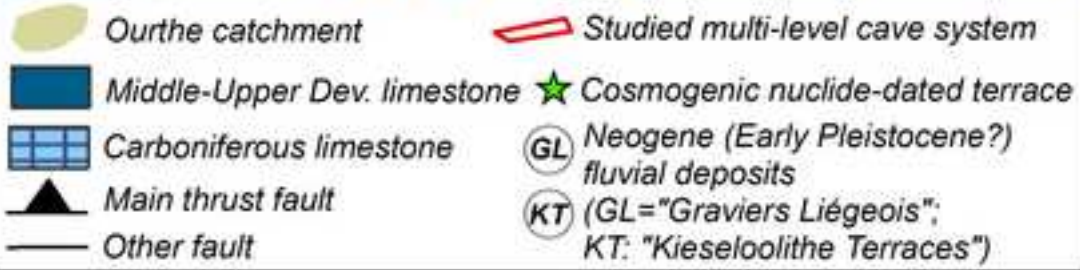
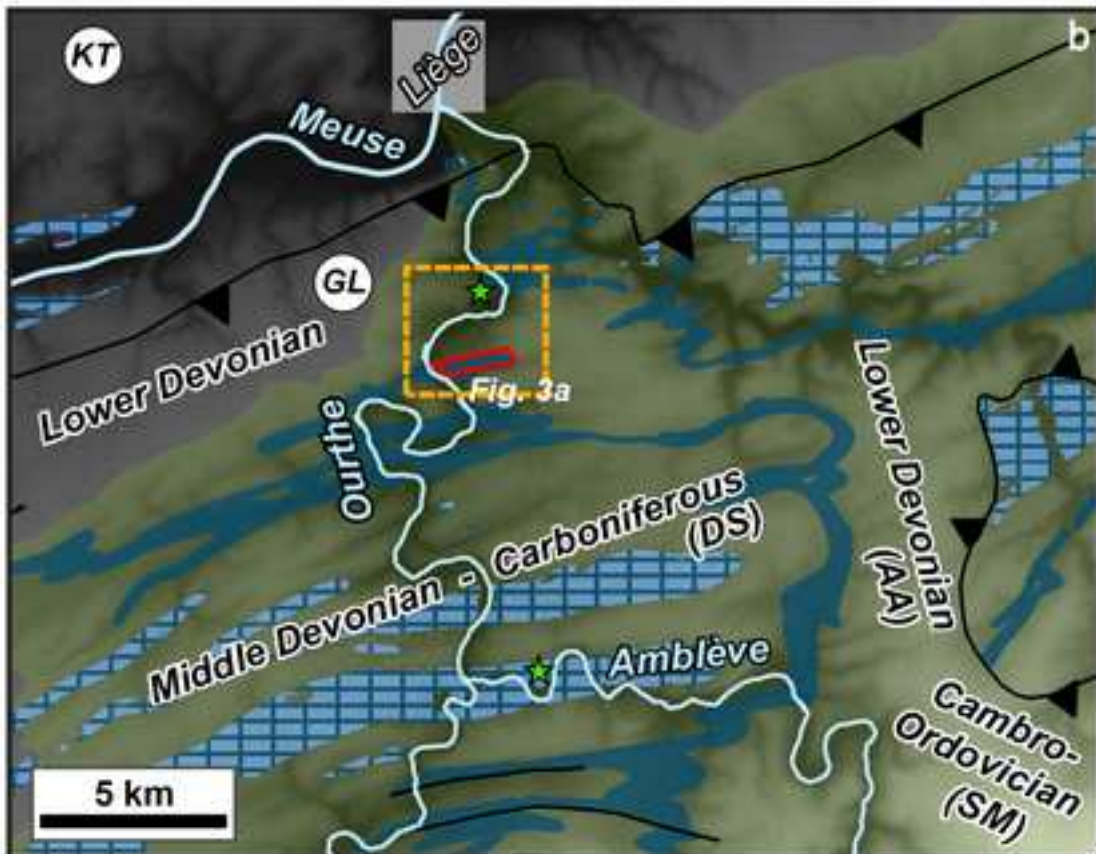
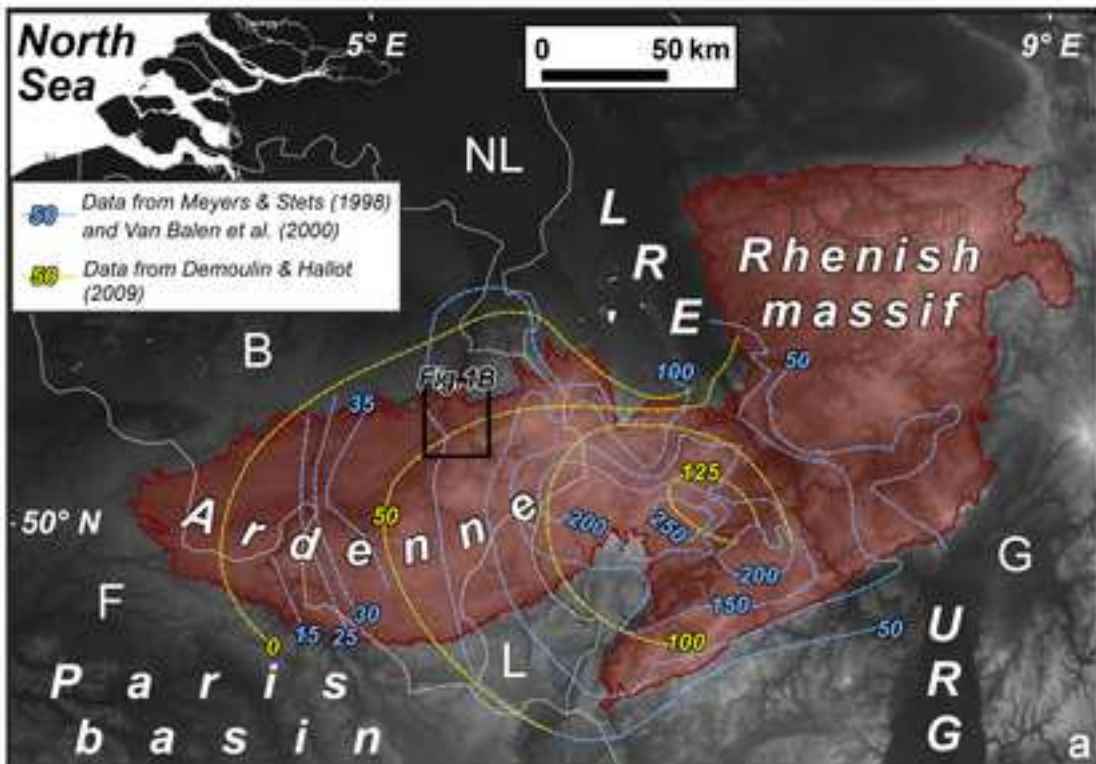


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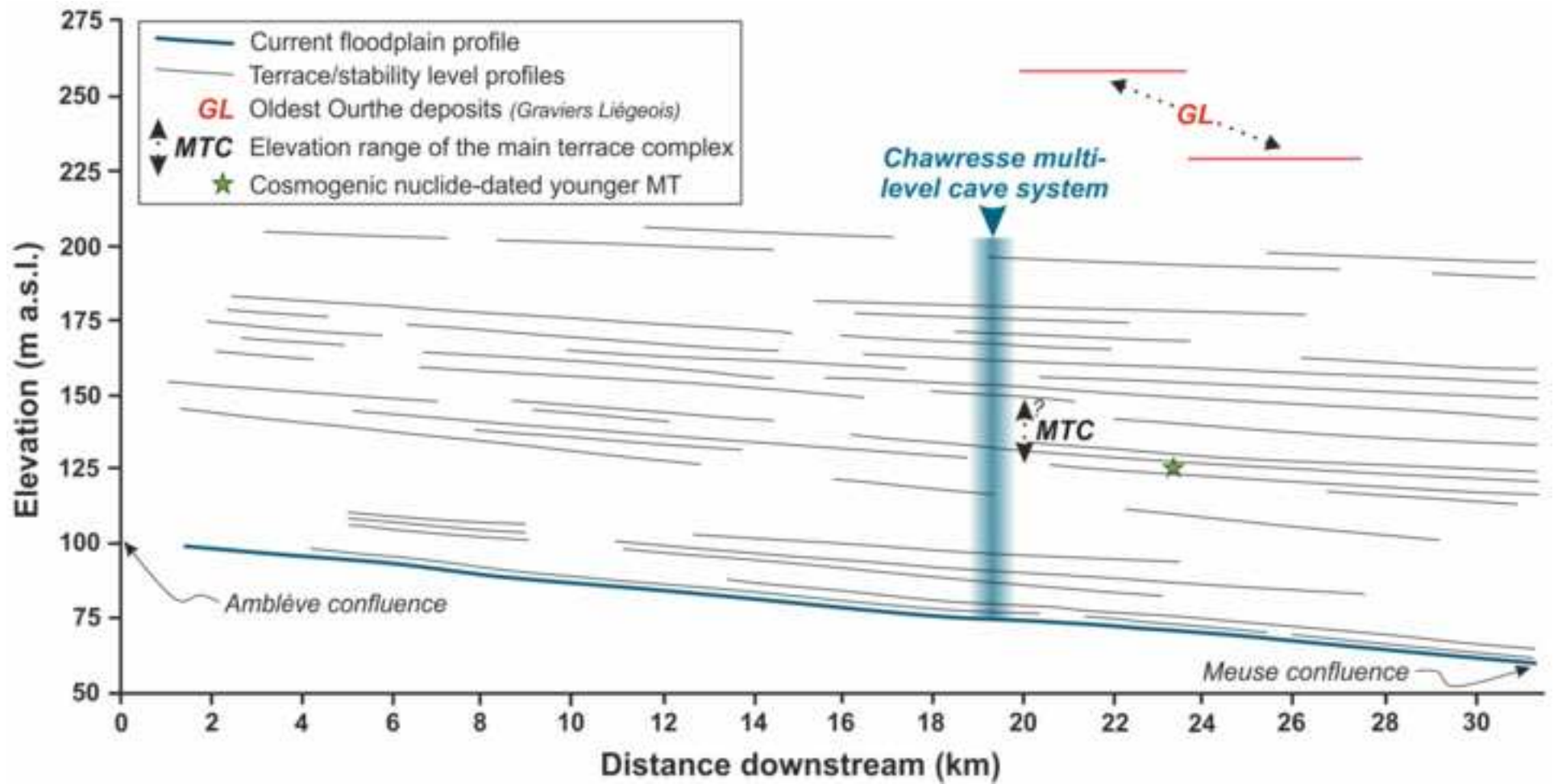


Figure3 (Color)

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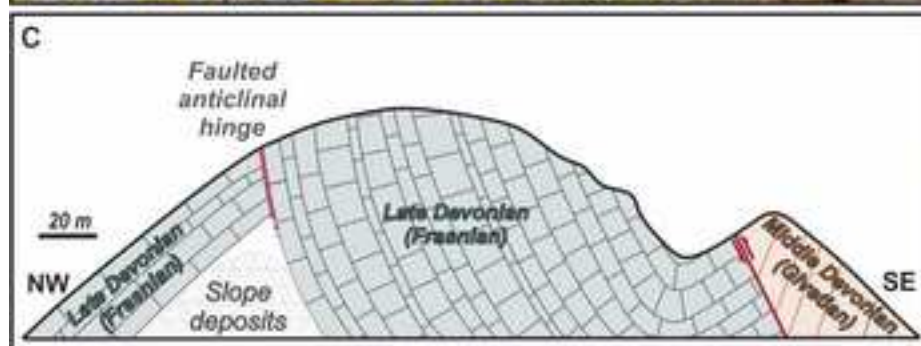
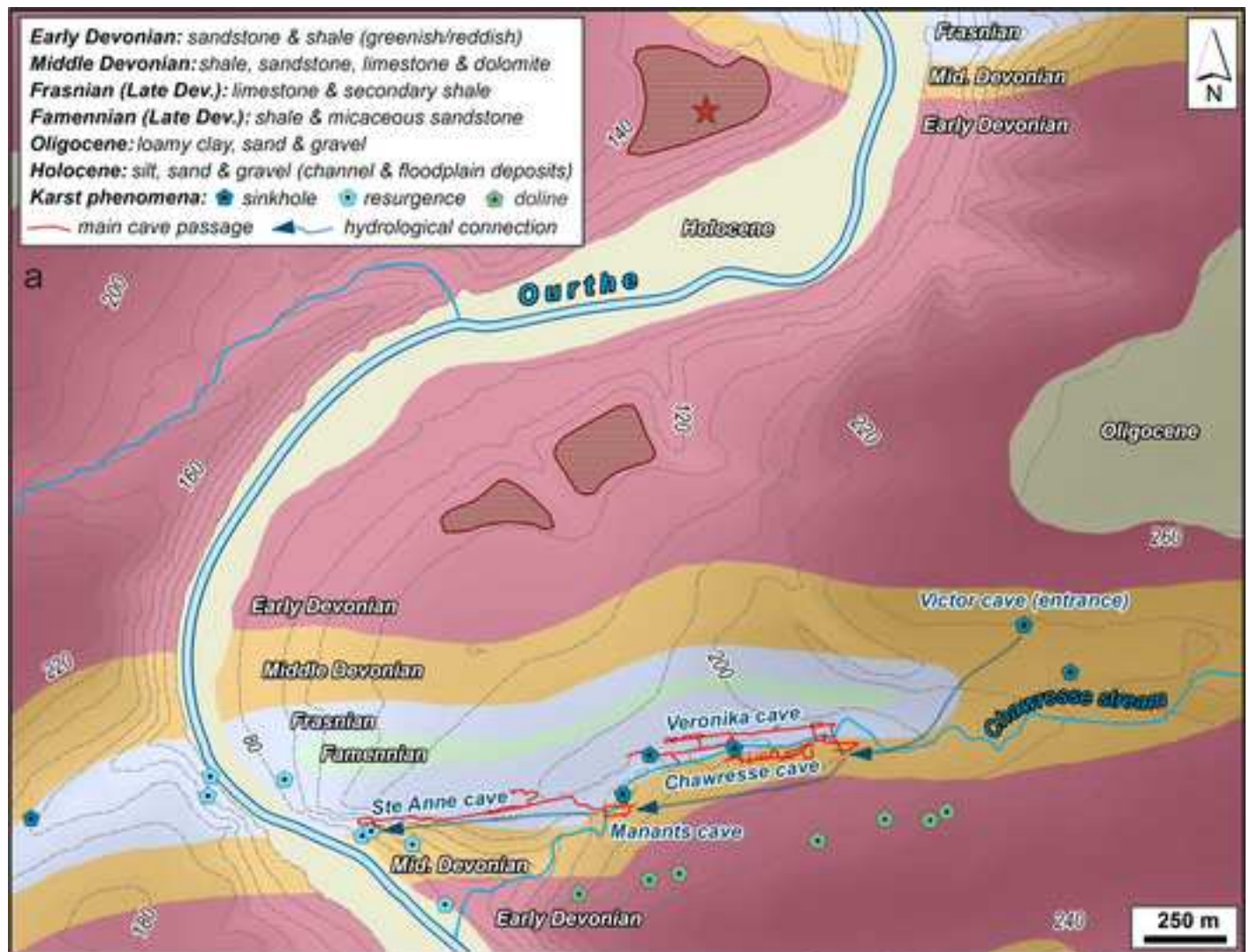


Figure 4

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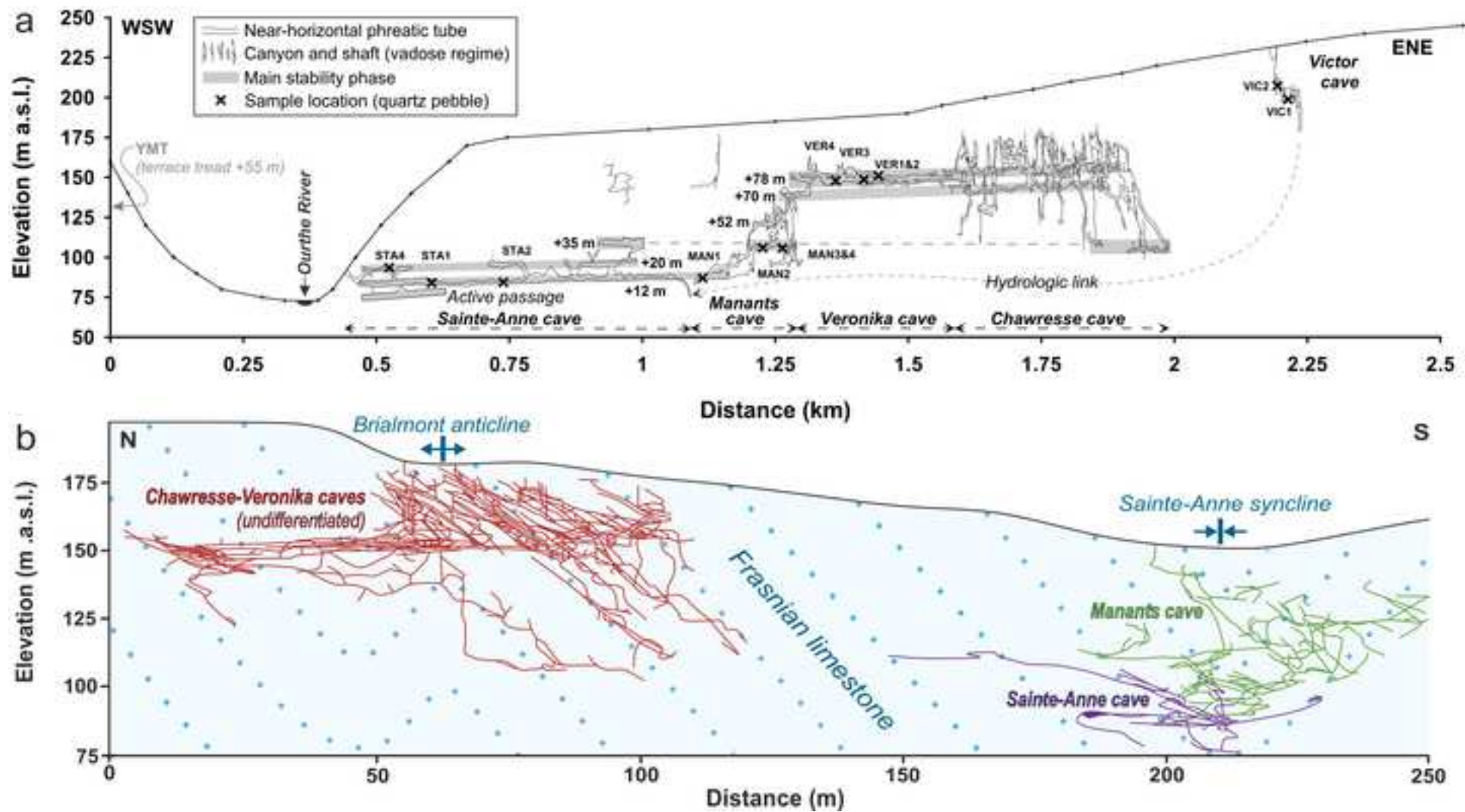


Figure5 (Color)
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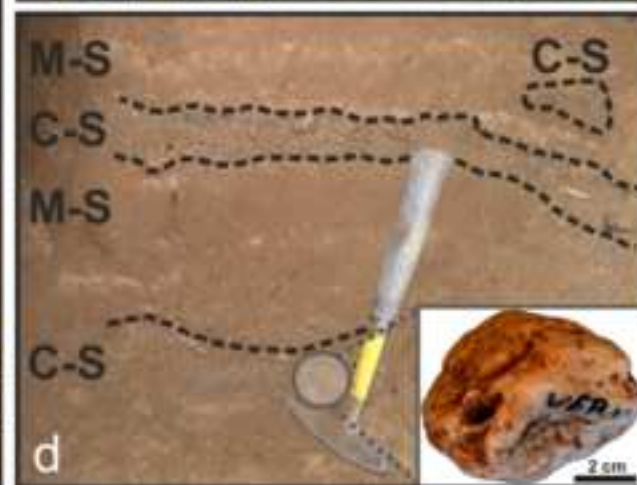


Figure6

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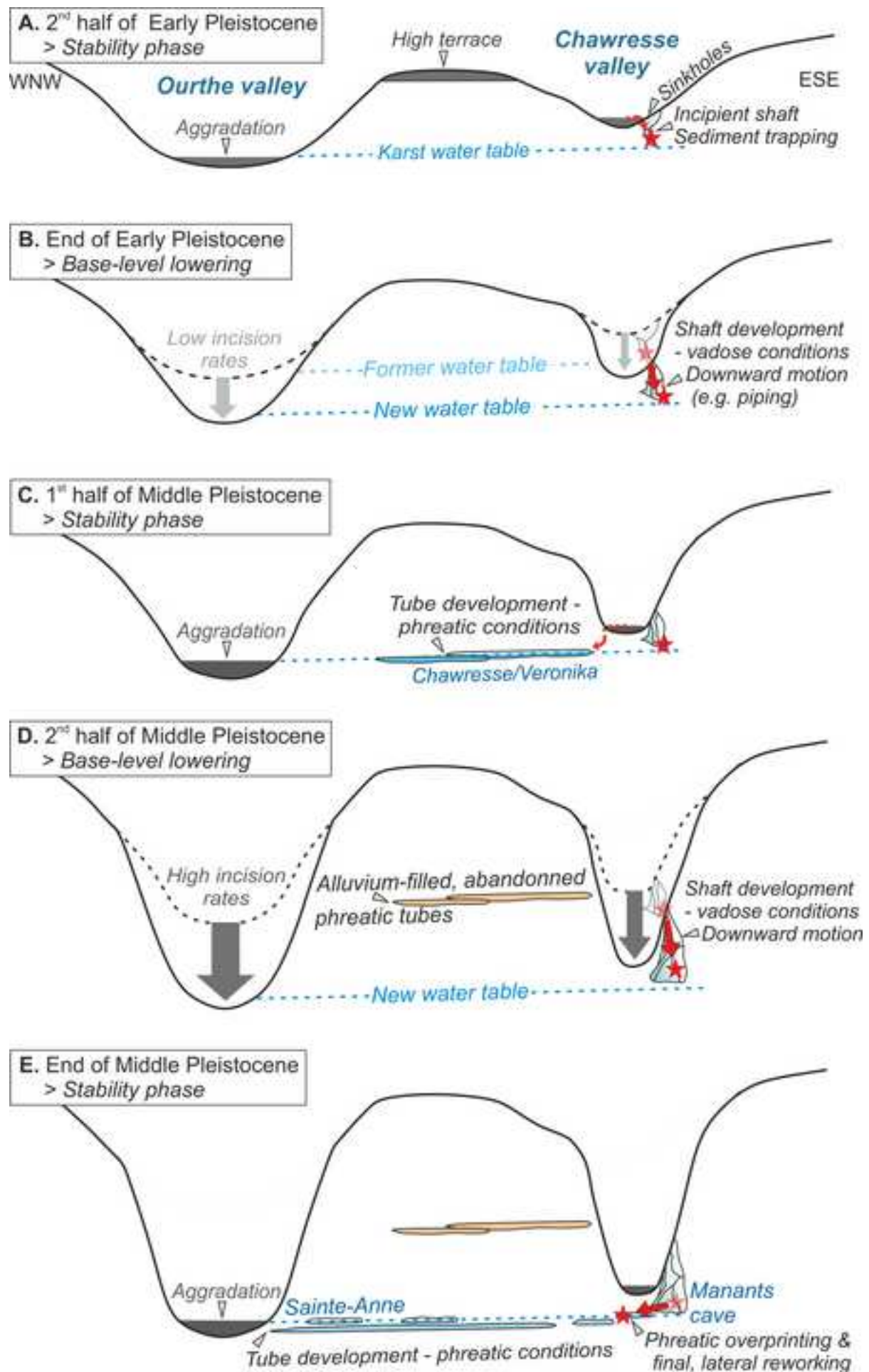


Figure7 (Color)

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Figure 8

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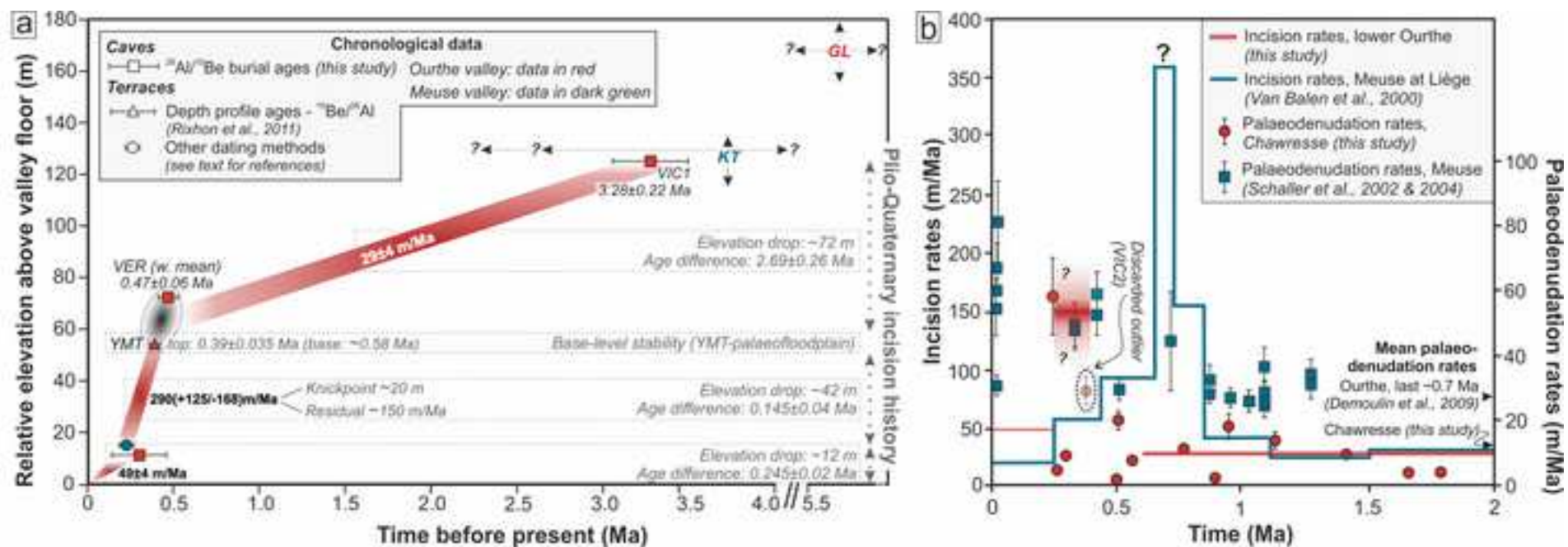
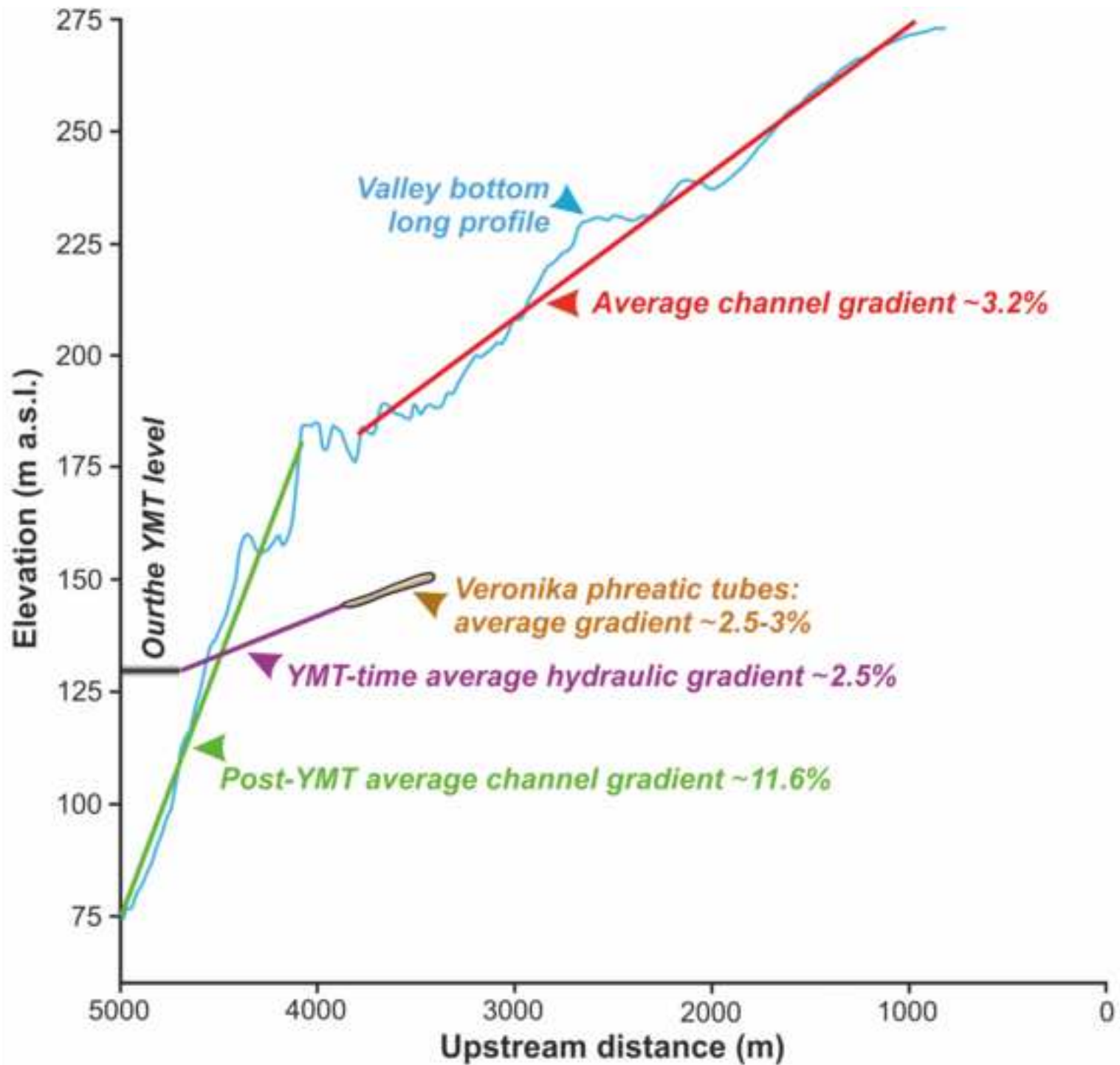


Figure9 (Color)
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Gilles Rixhon, on behalf of all authors