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1 **Contrasting physical erosion rates in cratonic**
2 **catchments: the Ogooué and Mbei rivers,**
3 **Western Central Africa**

4

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21 **Bullet points**

-
- 22 • The Ogooué River catchment is denuding at a low rate (38 t/km²/a, 15 m/Ma)
 - 23 • There is substantial chemical denudation: > 30% of the total denudation
 - 24 • Batéké Px not producing solutes because constituted by already weathered material
 - 25 • The southern part of the catchment is denuding twice as fast as the northern part
 - 26 • Landscape seems close to equilibrium: chemical proportional to physical denudation

27

28 **Abstract**

29 We measured the long-term physical denudation of the Ogooué River catchment using ¹⁰Be produced
30 in situ by cosmic rays. These measurements are averaged over 25-200 ka (average 40 ka), depending
31 on the physical denudation rate. The denudation rate of the Ogooué River catchment is slow (38
32 t/km²/a, 15 m/Ma), slightly higher than in Equatorial West Africa (from Senegal to Angola, 26 t/km²/a,
33 10 m/Ma). Physical denudation and chemical weathering fall within the same order of magnitude.
34 Thus, although low, there is substantial chemical weathering compared to physical denudation, that
35 likely contributes over 30% of the total denudation.

36 Denudation rates are spatially variable (from 10 to 60 t/km²/a) within the large Ogooué River
37 catchment. Over the long term, physical denudation and chemical weathering roughly match, except
38 in the Batéké Plateaux area, because the plateaus are made up of already weathered detrital material
39 and therefore their modern flux of solutes is very low (~9.5 t/km²/a). The spatial distribution is similar
40 to the one described in the work of Moquet et al. (2021) on the basis of solute fluxes, i.e. the southern
41 part of the catchment is denuding twice as fast as the northern part. We show here that the whole
42 picture did not vary much since 100 ka, as shown by both methods which give consistent results. Faster

43 denudation in the southern part of the catchment may be related to more uplift than in the northern
44 part caused by the southern African “superswell”.

45

46 Keywords

47 Cosmogenic nuclides; denudation; chemical weathering; cratonic areas; Ogooué River

48

49 1 Introduction

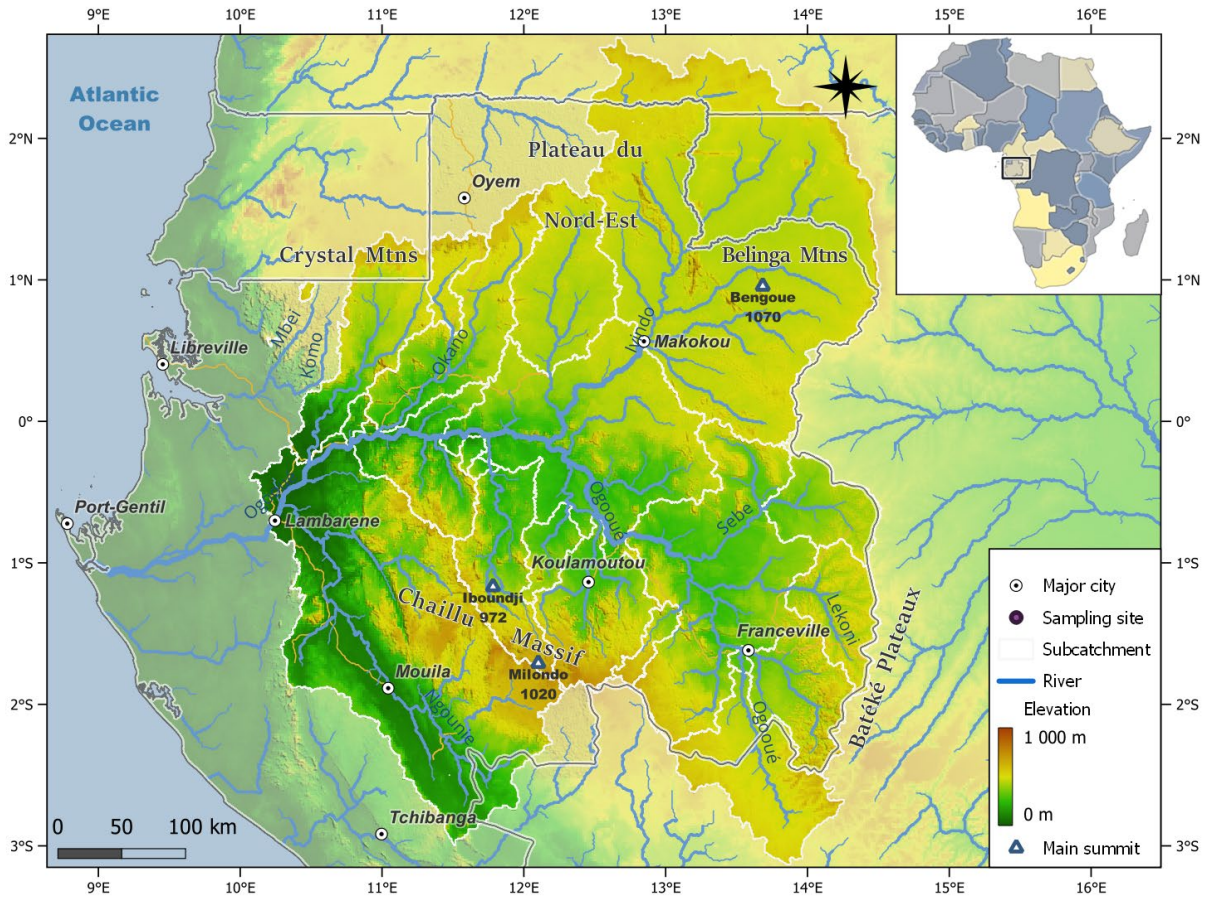
50 There is still active debate today on the role of mountains in: (1) global erosion, (2) denudation fluxes,
51 and (3) the production of sediments exported to the ocean (e.g. Willenbring et al., 2013; Larsen et al.,
52 2014; Maffre et al., 2018). Although relatively slow (~ 120 t/km²/a, equivalent to 45 m/Ma), the
53 denudation of flat continental regions (slope < 200 m/km) results in a significant contribution of
54 sediments to global fluxes given the vast areas involved (Willenbring et al., 2013). Cratonic areas only
55 account for approximately 15% (according to Şengör et al., 2022) of the catchment-wide denudation
56 rates measured through the cosmogenic isotope ¹⁰Be on detrital sands (from the Octopus database,
57 Codilean et al., 2018). Although a significant body of literature has attempted to identify the controls
58 on denudation rates in tectonically active areas (e.g. Burbank et al., 1996; Galy and France-Lanord,
59 2001; Carretier et al., 2013; Godard et al., 2014; Scherler et al., 2017), there are very few similar studies
60 in tectonically inactive regions where mass wasting and faulting are rare.

61 The Ogooué River Basin (ORB) in Gabon, located in Equatorial Africa, (Figure 1) is particularly suitable
62 for studying the denudation of such tectonically inactive (or low activity) areas since it drains a
63 relatively large area that is representative of the cratonic zones of Equatorial and Tropical West Africa
64 (along the Atlantic coast from Senegal to Angola) and it is underlain by a relatively homogeneous

65 lithology. The catchment is relatively pristine from the perspective of long-term denudation processes
66 and rates, as anthropic pressure has increased only recently.

67 In the present study, we quantify the catchment-scale denudation rates in nested watersheds across
68 the ORB using *in situ* cosmogenic nuclide measurements on river sands (Figure 2). However, because
69 of thick regolith layers, cosmogenic nuclide measurements in cratonic areas only record physical
70 denudation, as this method is blind to chemical denudation that occurs deeper than 1 m below the
71 surface (Figure 3) (Riebe et al., 2003; Granger and Riebe, 2007; Dixon et al., 2009; Hewawasam et al.,
72 2013; Regard et al., 2016). We use chemical denudation estimates for the Ogooué River Basin at the
73 same sites as by Moquet et al. (2021) in order to obtain estimates of the total denudation rates. Our
74 data allow us to quantify the denudation, to estimate the contribution of physical vs. chemical
75 processes to the total denudation, and to produce a spatially distributed estimate of these rates within
76 the ORB, providing an opportunity to identify the underlying controls on denudation in this tectonically
77 inactive region.

78



79

80 *Figure 1. (Inset) map showing the location of the Ogooué river basin (ORB) in Central West Africa. The main map shows the*
 81 *relief, hydrographic network of the Ogooué River, and sampling locations (figure taken from Moquet et al., 2021). The Mbeï*
 82 *catchment sampling points are indicated to the north-east. [Printed in Black & White]*

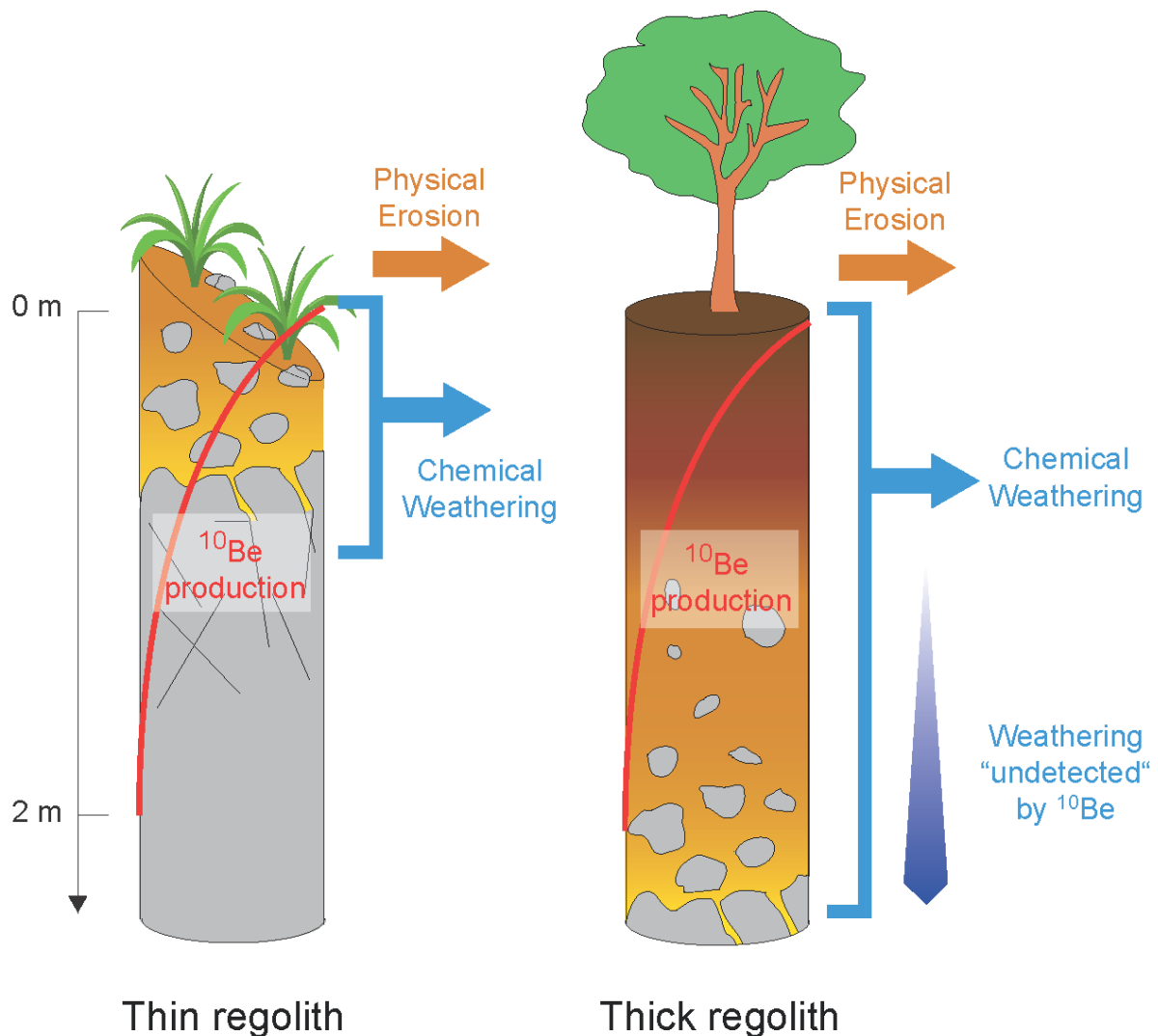
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85

86 Figure 2. Photos of the sampling sites along the Ogooué River at Ayem (sampling site #26), upstream (note the people for
87 scale) and downstream. Sand was sampled from the banks at this site. [Printed in Black & White]



88

89 Figure 3. Sketch showing the difference in how chemical weathering is detected by cosmogenic isotopes
90 in the case of a thin (left) vs. thick (right) regolith. Cosmogenic isotope production is high at the surface
91 and decreases rapidly at depth (on a meter scale, as shown in the figure). Thus, the rate of denudation
92 detected by cosmogenic isotopes relates to processes taking place less than around one meter below
93 the surface. If the regolith is thin, then the cosmogenic-derived denudation rate includes both physical
94 and chemical denudation. If the regolith is thick, then cosmogenic isotopes only "see" a part of the
95 chemical denudation, as some of it takes place too deep.

96 2 Study area

97 The equatorial Ogooué River Basin (ORB) spans $\sim 220,000 \text{ km}^2$, from 9 to 14°E and 2.5°N to 3°S (Figure
98 1), across the countries of Gabon (85% of the catchment), Congo (12%) and Equatorial Guinea and
99 Cameroon (Figure 1). The river discharge at the mouth is $\sim 4,750 \text{ m}^3 \cdot \text{s}^{-1}$ (Bogning et al., 2018),
100 corresponding to roughly 10% of the neighboring Congo River, the largest river in Africa (discharge
101 $\sim 41,000 \text{ m}^3 \cdot \text{s}^{-1}$; catchment area $3.7 \times 10^6 \text{ km}^2$) (Laraque et al., 2009).

102 The climate in the Ogooué catchment is tropical *sensu* Köppen-Geiger with one dry season from June
103 to August (Kottek et al., 2006) and with a bimodal precipitation regime with wet periods from March
104 to May and October to December. The average yearly rainfall is approximately $2,000 \text{ mm} \cdot \text{a}^{-1}$ leading
105 to a runoff of $700 \text{ mm} \cdot \text{a}^{-1}$ (Bogning et al., 2018; Kittel et al., 2018). The average temperature is constant
106 throughout the year, $\sim 24^\circ\text{C}$.

107 The study area corresponds to 96% of the Ogooué catchment upstream from the Lambaréné station
108 ($206,000 \text{ km}^2$, sampling point OG-05, Figure 1). In addition, we sampled four tributaries of the Mbei
109 River, a tributary of the neighboring Komo River in Northern Gabon which drains terrains that are
110 similar to those underlying the ORB (Figure 1). The annual discharge of the Mbei River is $\sim 60 \text{ m}^3 \cdot \text{s}^{-1}$
111 over an area extending $\sim 1,800 \text{ km}^2$ (ORSTOM, 1964; Njutapvouï Fokouop, 2017 data for the period
112 1964-1973 only). The four monitored Mbei tributaries cover an area of less than 500 km^2 . There,
113 rainfall is $\sim 2000 \text{ mm} \cdot \text{a}^{-1}$ and runoff $\sim 600 \text{ mm} \cdot \text{a}^{-1}$.

114

115 Geologically speaking, most of the Ogooué River Basin is developed within plutonic and meta-plutonic
116 rocks of the Archean Congo Craton, affected by the Eburnean orogeny in the Paleoproterozoic
117 (Thiéblemont et al., 2009a, 2009b). The lithology of these rocks is predominantly dominated by
118 granites and granitoids, although bands of high-grade metamorphic meta-sedimentary rocks are
119 locally observed, such as the Meso- to Neo-Archean schists and metaconglomerates of the Bélinga
120 Group or the Paleoproterozoic schists of the N'Dolé Group, as well as the Paleoproterozoic micaschists

121 and paragneisses of the Ogooué Complex (Figure 4). In the southeast, the upstream parts of the basin
122 are located at the Western termination of the Batéké Plateaux, mostly composed of purely quartzitic
123 Cenozoic sandstone (Séranne et al., 2008), and in predominantly detrital sedimentary rocks (pelites,
124 sandstones, and conglomerates) of the Paleoproterozoic Francevillian basins. The sandstone formation
125 of the Batéké Plateaux, discordant on the crystalline basement, is located close to the border with the
126 Congo, where the existence of significant Neogene uplift has been shown, possibly related to mantle
127 swell (Al-Hajri et al., 2009; Guillocheau et al., 2015; Weber et al., 2016). The western and downstream
128 parts of the Ogooué River Basin have mainly developed within the northern termination of the
129 Neoproterozoic orogenic belt of western Congo and in the coastal basin with Phanerozoic
130 lithostratigraphy. In this sector, lithologies are more diverse, with carbonate formations alternating
131 with predominantly fine-grained detrital formations (sandstones and argillites). In summary, the
132 northern tributaries of the Ogooué catchment, as well as the Mbei catchment, exclusively drain
133 Archean cratonic rocks. The southern tributaries drain both Archean cratonic rocks and
134 Neoproterozoic volcano-sedimentary rocks. The main Ogooué channel drains Quaternary fluvial
135 sediments in addition to the Mesozoic - Cenozoic basin in its downstream part and the Archean
136 basement in its upstream part Paleoproterozoic Francevillian metasediments in Boumango area)
137 (Thiéblemont et al., 2009a, 2009b) All these lithologies are quartz-rich and are covered by 2- to 3 ka-
138 old, 1-3 m-thick, clayey to sandy laterite-derived aeolian products and regionally known as the “Cover
139 Horizon” (Thiéblemont et al., 2009a).

140 The elevation of the Ogooué catchment ranges from 20 m.a.s.l. (Lambaréné station) to ~1000 m.a.s.l.
141 (Figure 1); the elevation of the Mbei catchments ranges from 130 to 800 m.a.s.l. The slopes of the
142 Ogooué catchment are low, (~1°), whereas the areas drained by the Mbei tributaries upstream from
143 our sampling sites are steeper, with average slopes up to 7-8° (Moquet et al., 2021).

144 Following the information provided above, the sampling points and respective catchments are
145 grouped into five areas: (1) the Batéké Plateaux, (2) the northern Ogooué tributaries, (3) the southern
146 Ogooué tributaries, (4) the Ogooué main channel, where fluxes are averaged over catchments from

147 the first three categories, and (5) the Mbei River tributaries. The characteristics of these domains are
 148 summarized in Table 1.

149 *Table 1. Characteristics of the various areas studied.*

150

	Batéké Plateaux	Southern tributaries	Northern tributaries	Main Ogooué	Mbei tributaries
Lithology (rocks)	Quartz sandstone	Plutonic, metaplutonic and metasedimentary, volcano-sedimentary	Plutonic, metaplutonic, and metasedimentary rocks	Plutonic, metaplutonic and metasedimentary, volcano-sedimentary, quartz sandstones, limestones	Plutonic, metaplutonic and metasedimentary
Elevation (m)	300-800	150-1100	150-1100	150-1100	150-750
Average slope (%)	0.8-2	1.3-2	0.5-3	0.5-1.5	1-8
Av. rainfall (mm.a⁻¹)	2300-2700	1900-2600	~1900	2100-2600	1900-2300
Vegetation	Extensive agriculture and savanna	Forest	Forest	Forest	Forest
¹⁰Be denudation rate (m/Ma and t/km²/a)	7-22 m/Ma 20-60 t/km ² /a	8-20 m/Ma 21-51 t/km ² /a	3-8 m/Ma 8-22 t/km ² /a	7-18 m/Ma 19-48 t/km ² /a	6-23 m/Ma 15-60 t/km ² /a
Modern TDS flux (Moquet et al. 2021)	8-12 t/km ² /a	30-53 t/km ² /a	11-22 t/km ² /a	15-20 t/km ² /a	14-18 t/km ² /a

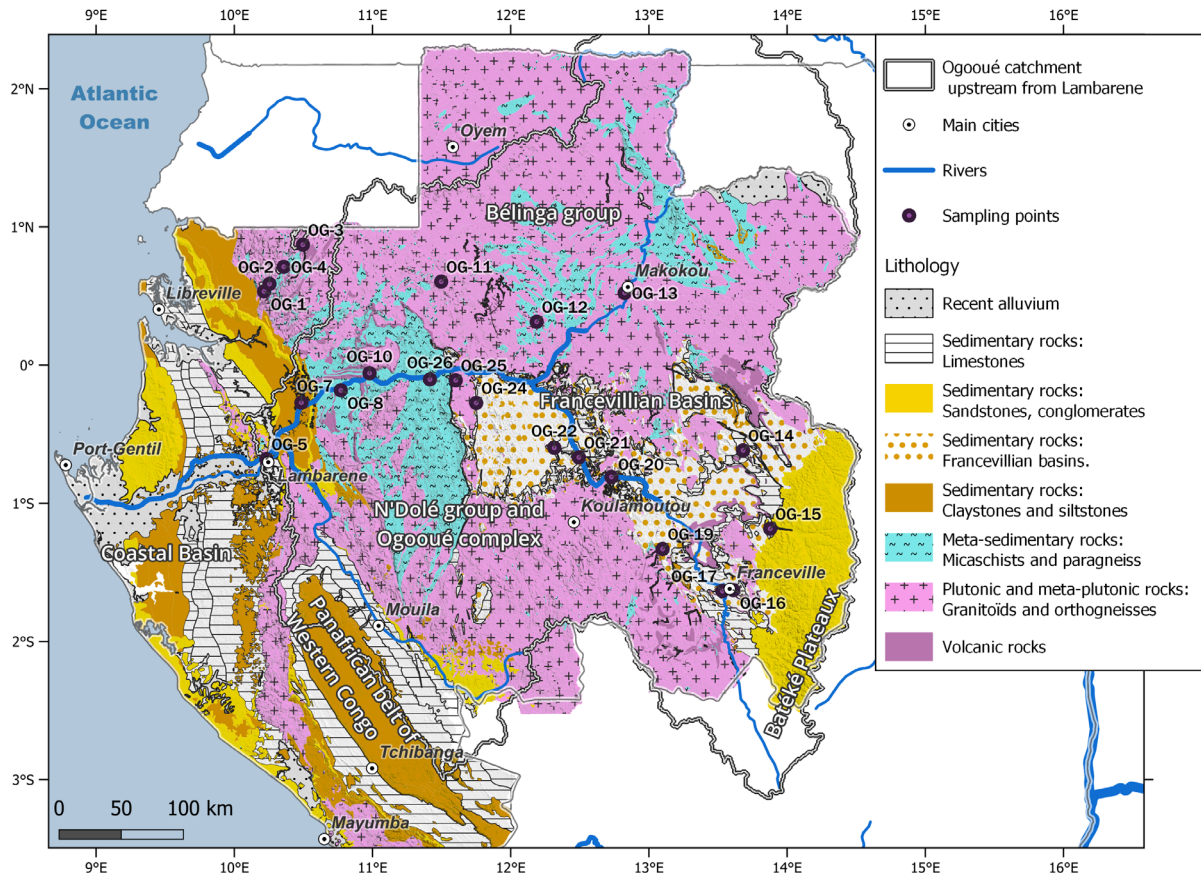
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152 3 Material and methods

153 3.1 Sampling

154 We collected 22 river sand samples in September 2017: five samples in the Ogooué main channel, 13
 155 samples in the Ogooué's tributaries and four samples in the Mbei River and tributaries (Figure 4 and
 156 Table 2). Three additional samples (labelled BTK) were collected previously during another campaign
 157 in January and February 2008: BTK08-22 on the main Ogooué River upstream (just upstream of sample
 158 OG-17 from the 2017 campaign); BTK08-5 from the Léconi River, a tributary of the Ogooué, collected
 159 at a location very close to sample OG-15 from 2017; and BTK08-20 from the Socle River, a southern
 160 tributary of the Ogooué, quite close to the 2017 OG-19 sample on the Leyou, where the river only
 161 drains Archean plutonic rocks. Approximately 1 kg of sand was collected at each sampling point from
 162 recently deposited riverbanks. The sampled sands consist almost entirely of quartz, as commonly

163 observed for lowland tropical rivers, making it easy to carry out the chemical treatment described
 164 below.
 165
 166



167
 168 *Figure 4. Lithological map of Gabon (Thiéblemont et al., 2009b) with our sampling sites and the Ogooué catchment. The area*
 169 *comprising the metamorphic and plutonic rocks is part of the Congo Craton. [Printed in Black & White]*

170 **3.2 Measurement of the in-situ ¹⁰Be concentrations**

171 All samples were processed for *in situ* beryllium-10 (¹⁰Be) at GET (Géosciences Environnement
 172 Toulouse), with the exception of samples BTK08-5, BTK08-20 and BTK08-22 which were processed at
 173 CRPG (Centre de Recherches Pétrographiques et Géochimiques, Nancy) for both ¹⁰Be and aluminium-
 174 26 (²⁶Al), following the procedure described in Puchol et al. (2017).

175 The samples were first sieved to extract the 500-1000 µm size fraction, which then underwent a series
 176 of acid attacks with a mixture of concentrated hydrochloric (HCl) and hexafluorosilicic (H₂SiF₆) acids to

177 remove all non-quartz minerals. Meteoric ^{10}Be was then removed by three partial leaching steps with
178 concentrated hydrofluoric acid (HF). The leached quartz was dissolved with concentrated hydrofluoric
179 acid (HF) after adding a ^9Be carrier solution (500 μL of a $[\text{}^9\text{Be}] = 1000 \mu\text{g/g}$ solution for the GET batch,
180 and 100 mg of a $[\text{}^9\text{Be}] = 3066 \mu\text{g/g}$ solution for the CRPG batch). The resulting solutions were
181 evaporated until dryness and the samples were recovered with hydrochloric acid. Dissolved species
182 were then precipitated with concentrated ammonia before processing through an anion exchange
183 column to remove the iron, and a cation exchange column to discard the boron and recover Be (as well
184 as Al for two samples processed at CRPG). After elution, Be was precipitated as $\text{Be}(\text{OH})_2$ by adding
185 concentrated ammonia at $\text{pH} = 8$ and oxidized to BeO . After preparing the target by mixing niobium
186 powder with the BeO oxide, the $^{10}\text{Be}/^9\text{Be}$ ratios were measured by Accelerator Mass Spectrometry
187 (AMS) at the French National AMS Facility ASTER of CEREGE in Aix-en-Provence (Arnold et al., 2010).
188 In the case of the GET batch, the measured $^{10}\text{Be}/^9\text{Be}$ ratios were calibrated against an in-house
189 standard STD-11 with an assigned value of $(1.191 \pm 0.013) \times 10^{-11}$ (Braucher et al., 2015), while the
190 CRPG batch was calibrated against the SRM 4325 NIST reference material, using a $^{10}\text{Be}/^9\text{Be}$ ratio of
191 $(2.79 \pm 0.03) \times 10^{-11}$ (Nishiizumi et al., 2007). Both are similar to the KNSTD07 calibration (Balco et al.,
192 2008; Nishiizumi et al., 2007). The analytical 1σ uncertainties include uncertainties in the AMS counting
193 statistics, the uncertainty in the standard $^{10}\text{Be}/^9\text{Be}$ ratio, an external AMS error of 0.5% (Arnold et al.,
194 2010), and a chemical blank correction (that yielded $^{10}\text{Be}/^9\text{Be}$ ratios of $(9.9 \pm 0.6) \times 10^{-15}$, $(9.8 \pm 0.6) \times$
195 10^{-15} , and $(2.1 \pm 1.0) \times 10^{-15}$ for the first GET, second GET, and CRPG batches, respectively; Table 2). A
196 ^{10}Be half-life of $1.387 \pm 0.01 \text{ Ma}$ was used (Chmeleff et al., 2010; Korschinek et al., 2010)
197 For the specific case of the samples processed for the ^{26}Al measurements, the ^{27}Al concentrations were
198 measured from small aliquots of the dissolved samples, after evaporation and substitution of fluorides
199 by HNO_3 . This measurement was done by inductively coupled plasma optical emission spectrometry
200 (ICP-OES) at the Service National d'Analyse des Roches et Minéraux (SARM, CRPG, Vandoeuvre,
201 France). The $^{26}\text{Al}/^{27}\text{Al}$ ratios measured at ASTER were normalized to the ASTER in-house standard SM-

202 Al-11, with a $^{26}\text{Al}/^{27}\text{Al}$ value of $(7.40 \pm 0.06) \times 10^{-12}$. The analytical $^{26}\text{Al}/^{27}\text{Al}$ blank ratio was $(3 \pm 3) \times 10^{-$

203 15 .

204 *Table 2. ¹⁰Be and ²⁶Al analytical data. The uncertainties are 1σ. See text for methods and calibrations.*

205

206

207

Sample name	Sample code	Location	River	Latitude (*N)	Longitude (*E)	Elevation (m asl)	Domain	Dissolved Quartz (g)	⁹ Be added through carrier (10 ¹⁵ at)	Uncert ainty	Measured ¹⁰ Be/ ⁹ Be (x 10 ¹⁵)	Uncertaint y (%)	¹⁰ Be (at/g)	Uncertaint y	²⁷ Al content (10 ¹⁵ at)	Unce rtaint y	Measured ²⁶ Al/ ²⁷ Al (x 10 ⁻¹⁵)	Uncertai nty (%)	²⁶ Al (at/g)	Uncertai nty
First series of samples†																				
OG-01	01			0.5332	10.2148	139	Mbei	20.96	34 194	102	58	4.34%	94 690	3 374						
OG-02	02	Akelayong	Mbei	0.5874	10.2541	160	Mbei	20.85	34 167	102	218	2.77%	357 636	9 126						
OG-03	03	Akoga	Mwenge	0.8709	10.4961	534	Mbei	20.79	34 067	101	223	2.62%	365 831	8 814						
OG-04	04	Assok	Binguili	0.7110	10.3570	526	Mbei	19.46	34 180	102	163	3.19%	287 148	8 320						
OG-05	05	Lambaréné	Ogooué	-0.6804	10.2313		Ogooué main 2 channel	20.91	33 993	101	92	3.86%	150 272	5 031						
OG-07	07	Abanga	Abanga	-0.2726	10.4847		Northern 16 tributaries	20.47	34 046	101	160	3.62%	266 179	8 833						
OG-08	08	Ndjolé	Ogooué	-0.1827	10.7701		Ogooué main 16 channel	19.70	34 267	102	85	4.27%	148 466	5 519						
OG-10	10	Alembé	Ogooué	-0.0591	10.9782		Northern 46 tributaries	20.18	34 040	101	204	3.57%	343 595	11 444						
OG-11	11	Mindzi	Lara	0.6034	11.4966		Northern 313 tributaries	20.22	34 160	102	278	3.38%	470 474	15 072						
OG-12	12	Ovan	Mvoug	0.3136	12.1879		Northern 404 tributaries	20.12	34 046	101	260	2.56%	439 423	10 469						
OG-13	13	Loaloo	Ivindo	0.5215	12.8245		Northern 462 tributaries	20.04	34 153	102	442	2.28%	752 413	16 405						
OG-14	14	Okandja	Sébé	-0.6176	13.6812		Batéké 295 Plateaux	12.87	33 933	101	61	4.07%	161 295	5 384						
OG-15	15	Akieni	Léconi	-1.1852	13.8773		Batéké 387 Plateaux	22.22	34 060	101	217	2.79%	332 742	8 575						
OG-16	16	Franceville	Passa	-1.6294	13.6103		Batéké 287 Plateaux	22.66	33 384	99	69	4.20%	101 983	3 604						
Chemical blank										33 993	101	9.92	5.58%							
Second series of samples†																				
OG17	17	Franceville	Ogooué	-1.6355	13.5314		Ogooué main 285 channel	21.26	34 060	101	209	3.39%	334 443	10 475						
OG19	19	Ndoubi	Leyou	-1.3313	13.0989		Southern 293 tributaries	23.67	34 127	102	91	4.08%	131 902	4 614						
OG20	20	Lastourville	Ogooué	-0.8096	12.7285		Ogooué main 228 channel	22.38	33 873	101	85	3.99%	127 982	4 312						
OG21	21	Lolo	Lolo	-0.6685	12.4929		Southern 213 tributaries	19.80	33 919	101	71	4.24%	121 210	4 256						
OG22	22	Wagny	Ouagna	-0.5988	12.3150		Southern 201 tributaries	24.14	33 411	99	150	3.70%	207 510	6 925						
OG24	24	Parc Lopé	Offoué	-0.2744	11.7502		Southern 145 tributaries	21.35	34 107	101	100	4.27%	160 380	5 981						
OG25	25	Lopé	Offoué	-0.1102	11.6019		Southern 118 tributaries	19.90	34 127	102	146	3.49%	251 038	7 836						
OG26	26	Ayem	Ogooué	-0.1037	11.4153		Ogooué main 88 channel	22.39	34 046	101	83	3.96%	126 564	4 222						
Chemical blank										33 859	101	9.75	6.39%							
Third series of samples†																				
BTK08-5	08-5	Akiéni	Léconi	-1.1801	13.8917		Batéké 440 Plateaux	25.98	20 425		130	3.77%	206 160	7 766	33 551	554	670	4.78%	864 754	41 310
BTK08-20	08-20	Bakoumba	Socle	-1.8633	13.0138		Southern 537 tributaries	18.93	20 685		146	3.09%	126 577	3 907						
BTK08-22	08-22	Poubara	Ogooué	-1.7623	13.5450		Ogooué main 395 channel	30.41	20 359		94	3.09%	321 498	9 948	25 955	636	1 257	3.07%	1 722 966	52 842
Chemical blank												2.1	47.62%				3	100%		

209 3.3 Calculation of the ¹⁰Be-derived, catchment-wide denudation rates

210 The catchment-scale denudation rates were calculated neglecting the radioactive decay, as per Lupker
211 et al. (2012):

212

$$213 \quad \bar{\varepsilon} = \frac{P_n \mu_n + P_{sm} \mu_{sm} + P_{fm} \mu_{fm}}{\rho [CN]}$$

214

215 where $\bar{\varepsilon}$ is the mean denudation rate in cm/a; ρ is the rock density (= 2.7 g/cm³); [CN] is the cosmogenic
216 nuclide concentration (at/g); P_n , P_{sm} and P_{fm} (at/g/a) are the catchment average cosmogenic nuclide
217 production rates by neutrons, slow muons, and fast muons, respectively, and μ_n , μ_{sm} and μ_{fm} (g/cm²)
218 are the attenuations for neutrons, slow muons, and fast muons, respectively. The average ¹⁰Be
219 production rates for each cosmogenic production pathway were calculated using a cell-by-cell
220 approach and the Basinga GIS toolbox (Charreau et al., 2019). In this toolbox, the mean sea surface
221 level high latitude (SLHL) production rate is 4.18 at/g (Martin et al., 2017) and includes 98.86%, 0.27%
222 and 0.87% atoms produced by neutrons, slow muons and fast muons, respectively (Martin et al., 2017
223 after; Braucher et al., 2011). From this SLHL value, the ¹⁰Be production rates were calculated for each
224 pixel (90 m resolution, from a SRTM 3 arc-seconds DEM) of the catchment area overlying a quartz-
225 hosting lithology, scaled for latitude (neutrons only) and elevation (neutrons and muons) using the
226 scaling models of Stone (2000) and the ERA-40 atmosphere atlas (Uppala et al., 2005). Following the
227 recommendation from DiBiase (2018), no topographic shielding factor was applied. All pixel values
228 were then averaged within each catchment to determine P_n , P_{sm} , and P_{fm} . The denudation rate
229 uncertainty was calculated by propagating the analytical uncertainty on [CN] and a 15% uncertainty on
230 the production rates. To test for the possibility of a bias associated with the abundance of quartz,
231 variable quartz percentages were assigned to the different lithologies present in this catchment. The
232 ¹⁰Be production rates are weighted by these quartz percentages according to Carretier et al. (2015).
233 The resulting denudation rates are within 1.5% equal to those calculated with a constant quartz

234 abundance, reported in Table 3. We estimate that for denudation rates of between 8 and 30 m/Ma,
235 neglecting radioactive decay only results in an overestimate between 15 and 5% of the denudation
236 rate, which remains within the uncertainty associated with the assumed uncertainty of 15% for the
237 production rate.

238 The time over which cosmogenic nuclides are averaging catchment-wide erosion rates is called the
239 integration time (τ). It corresponds to the time required to remove one attenuation length ($L = \mu_n/\rho$
240 [cm]) from the Earth surface. For this calculation, only spallation by neutrons is considered: $\tau = L/\bar{\epsilon}$. It
241 should be noted that this method captures all the denudation processes that take place close to the
242 surface (max depth $\sim L$), so we use the term denudation. To calculate the total denudation, i.e. taking
243 the deeper weathering processes into account, it is necessary to use independent measurements of
244 weathering rates or to make necessary assumptions, which will be the subject of section 4.3.

245 It should be noted that the “Cover Horizon” has probably disturbed the steady-state condition
246 necessary for the use of cosmogenic nuclides to measure denudation rates. However, as this
247 perturbation is very recent, we can assume, following Ferrier and Kirchner (2008), that the denudation
248 rate evaluation is robust to such a small deviation from the steady state. This is further illustrated by
249 the fact that the integration time (τ) is much larger than the age of the cover horizon (2-3 ka). Chemical
250 denudation rates

251 Our sampling sites in the ORB are constrained for total dissolved solids (TDS) by the study of Moquet
252 et al. (2021), which enables the estimation of the chemical denudation rates when used in combination
253 with long-term water discharge estimates. However, because the river hydrochemistry at the sampling
254 sites has only been measured once, the relevance of the calculated solute fluxes might be questioned
255 in terms of long-term denudation, due to variable solute concentrations over a one year period.
256 Moquet et al. (2021) noted that in other West African rivers such as the Nyong (Viers et al., 2000),
257 Niger (Picouet et al., 2002) and Congo (Laraque et al., 2009), the TDS concentration varies only slightly
258 with discharge over the year, meaning that solute fluxes in these rivers are mainly controlled by
259 discharge variability, thereby lending confidence to the solute flux estimates based on the

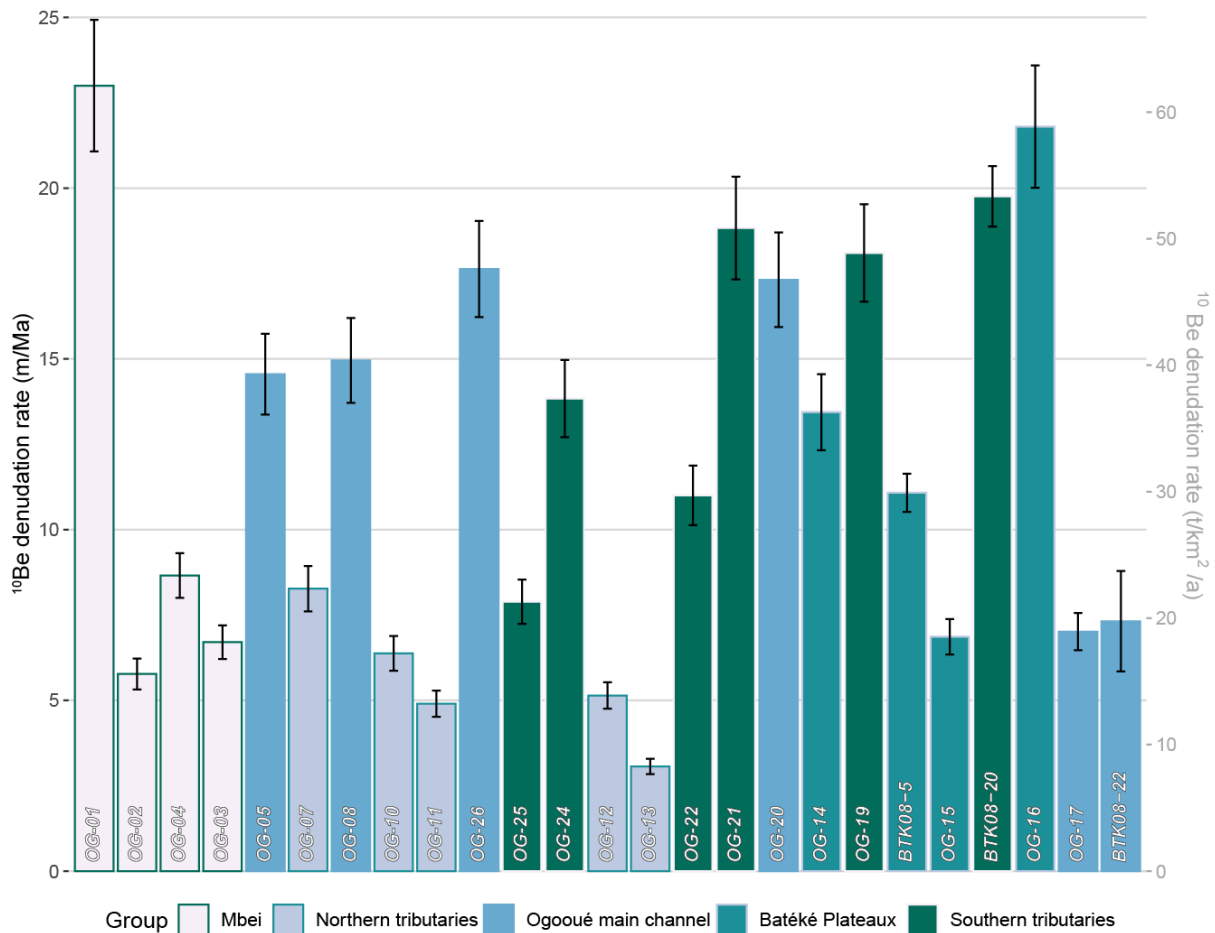
260 hydrochemistry measured during a single sampling campaign. The propagation of various sources of
 261 uncertainties, which include the single point sampling strategy, has been estimated and described by
 262 Moquet et al. (2021, section 3.7 “Uncertainty calculation”). Therefore, the uncertainties associated
 263 with the chemical weathering flux used in the present paper includes this source of uncertainty. The
 264 long-term discharge (multi-year) at the sampling sites was estimated through a statistical approach
 265 based on a regional polynomial regression between specific discharge (Q_{spe}) and rainfall (P) (see
 266 Moquet et al., 2021 for details). As outlined by Moquet et al. (2021), we can reasonably consider that
 267 the studied rivers tend to exhibit a so-called “chemostatic behavior” which indicates that, despite the
 268 fact that some variability in the solute concentration exists, a single sampling point in space can be
 269 used to produce reasonable, first-order estimates of catchment-scale weathering rates.

270
 271 In the ORB, most of the river solute flux is derived from silicate chemical weathering; < 15% is derived
 272 from atmospheric inputs (Moquet et al., 2021). Low cationic weathering rates are observed for the
 273 Batéké Plateaux ($TZ_{sil}^+ \sim 0.5$ t/km²/a, where TZ_{sil}^+ represents the chemical weathering rate expressed as
 274 the release rate of the sum of cations by silicate chemical weathering). Higher weathering rates are
 275 typical of the southern catchments ($TZ_{sil}^+ \sim 3.4$ t/km²/a), and intermediate rates (TZ_{sil} between 1.7 and
 276 2.5 t/km²/a), similar to those observed for the Ogooué River at its mouth, characterize the northern
 277 catchments and the Mbei tributaries.

278 4 Results

Sample name	Producti on	Differen		Uncertain ty	Denudati on	Uncertain ty	Integrati on time
		ce	Denudati				
	at/g/a	Quartz %	on		t/km2/a		ka
OG-01	3.10	1.50	23.0	1.9	62.1	5.0	26
OG-02	2.92	0	5.8	0.5	15.6	1.2	104

OG-03	3.54	-0.19	6.7	0.5	18.1	1.3	89
OG-04	3.57	0.04	8.7	0.7	23.4	1.7	69
OG-05	3.11	0.05	14.6	1.2	39.3	3.1	41
OG-07	3.14	-0.15	8.3	0.7	22.3	1.7	73
OG-08	3.16	0.07	15.0	1.2	40.4	3.2	40
OG-10	3.12	-0.04	6.4	0.5	17.2	1.3	94
OG-11	3.30	0	4.9	0.4	13.2	1.0	122
OG-12	3.23	0.01	5.1	0.4	13.9	1.0	117
OG-13	3.30	0.06	3.1	0.2	8.3	0.6	196
OG-14	3.07	0	13.4	1.1	36.3	2.9	45
OG-15	3.27	0	6.9	0.5	18.5	1.4	87
OG-16	3.23	0	21.8	1.8	58.9	4.7	28
OG-17	3.37	-0.10	7.0	0.5	18.9	1.4	86
OG-19	3.44	-0.15	18.1	1.4	48.9	3.7	33
OG-20	3.16	0.09	17.3	1.4	46.8	3.6	35
OG-21	3.27	0.04	18.8	1.5	50.8	3.9	32
OG-22	3.27	0.04	11.0	0.9	29.7	2.3	55
OG-24	3.17	0.02	13.8	1.1	37.4	2.9	43
OG-25	2.79	0	7.9	0.6	21.3	1.7	76
OG-26	3.19	0.08	17.6	1.4	47.6	3.7	34
BTK08-5	3.27	0	11.1	0.9	29.9	2.3	54
BTK08-20	3.63	0	19.8	1.5	53.3	3.8	30
BTK08-22	3.37	0	7.3	0.6	19.8	1.5	82



280

281

282 *Figure 5. The ^{10}Be -derived denudation rates, ordered from downstream to upstream along the Ogooué main channel. The*

283 *Mbei rivers (samples# 1 to 4) do not drain to the Ogooué River. [Printed in Black & White]*

284 The ^{10}Be concentrations of the Ogooué sediments show an average catchment denudation rate of

285 approximately 15 m/Ma ($\sim 40 \text{ t/km}^2/\text{a}$, Figure 5). We obtained these values for the two most

286 downstream samples (OG-5 and OG-8), which integrate most of the catchment area ($\sim 200,000 \text{ km}^2$).

287 Following Moquet et al. (2021), we divide the samples into five groups following geomorphological

288 and lithological units (Table 2, Figure 1): the Mbei tributaries (outside of the Ogooué catchment itself),

289 the northern Ogooué tributaries, the Batéké Plateaux tributaries, the southern Ogooué tributaries, and

290 the Ogooué River main channel.

291 The two most downstream samples (OG-5 and OG-8) integrate most of the catchment area ($\sim 200,000$

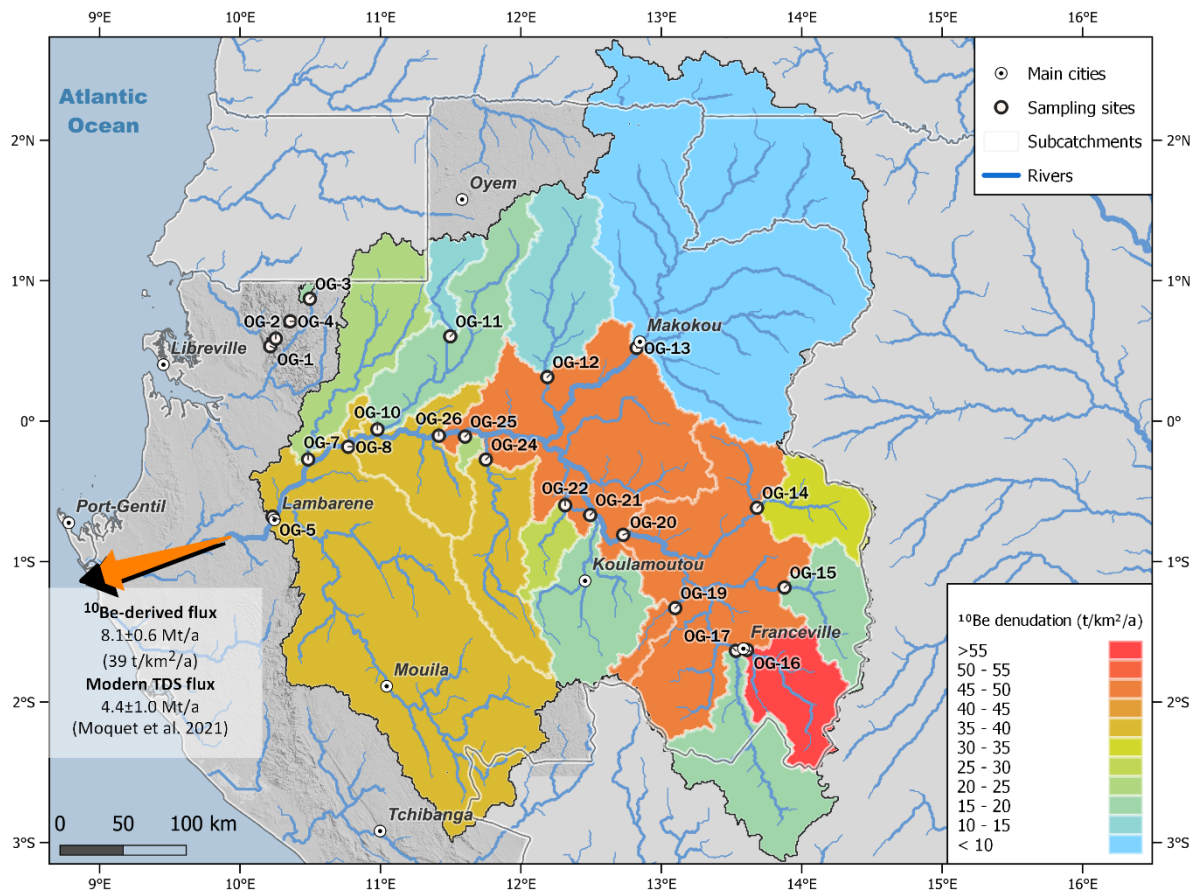
292 km^2) and provide the average catchment denudation rate. Along the Ogooué main channel, upstream

293 from the lowermost sample (samples OG-5, OG-8, OG-26, OG-20, OG-17 and BTK08-22 in the upstream
294 direction), the evolution of ^{10}Be concentration is not monotonous, with lower concentrations for
295 samples OG-26 and OG-20; this results in higher denudation rates of ~ 17 m/Ma, 47 t/km²/a. In
296 comparison, the most upstream Ogooué mainstream sampling site (samples OG-17 and BTK08-22,) displays a higher ^{10}Be concentration, implying a lower denudation rate of 7 m/Ma or 18 t/km²/a (Table
297 3 and Figures 5 and 6). The rivers draining the Batéké Plateaux represent the main contributors to the
298 Ogooué between sampling points OG-17 and OG-20.

300 The denudation rates in the Batéké Plateaux area (samples OG-14, OG-15, OG-16, and BTK08-5) are
301 variable, ranging from 7 to 22 m/Ma (18 to 57 t/km²/a). The denudation rates of the northern
302 tributaries (3-7 m/Ma or 8-19 t/km²/a) are roughly one or two times lower than those of the southern
303 tributaries (8-20 m/Ma or 21-53 t/km²/a). The trend in the catchment-scale denudation rate observed
304 along the course of the Ogooué River mainstream (Figure 5) most likely results from the contribution
305 of these tributaries.

306 The position of two samples draining the Batéké Plateaux (BTK08-5 and BTK08-22) in a “banana plot”
307 ($^{26}\text{Al}/^{10}\text{Be}$ vs. ^{10}Be ; Figure S1) indicates that these samples are partly made up of recycled material.
308 However, the proximity of the data to the “surface banana” (in black on Figure S1) suggests that the
309 contribution of this recycled material is low, resulting in an underestimate of the ^{10}Be -derived
310 denudation rate by 25% at most.

311



312

313 *Figure 6. Colored scale map of the ^{10}Be -derived catchment-scale denudation rates for the ORB. The sampling points that define*
 314 *the outlets of the catchment areas are shown as black circles. The modern TDS flux has been evaluated by Moquet et al. (2021)*
 315 *[Printed in Black & White]*

316 The spatial distribution of the denudation rates in the Ogooué catchment can be refined using a
 317 “nested catchment approach”, where the difference in sediment flux (calculated as the erosion rate x
 318 the contributing area) between two stations along the same river provides an estimate of the sediment
 319 flux and the erosion rates of the area contributing to the river between these two stations. Despite
 320 significant uncertainties (see Supplementary Material Figure S2), these estimates: 1) result in values
 321 similar to those stemming from direct ^{10}Be measurements for samples OG-5 and OG-10 (Figure 5), and
 322 2) suggest an erosion that is faster than $80 \text{ t/km}^2/\text{a}$ for the two nested catchments (OG-20 and OG-26).
 323 However, because of the significant uncertainties associated with these estimates, we do not include
 324 these numbers in the analysis presented in section 4.2.

325 We evaluated the interannual variability in the ^{10}Be -derived erosion rate using pairs of samples
326 collected at the same location in 2008 and in 2017. Samples OG-17 and BTK08-22, from the upstream
327 part of the main Ogooué channel, result in similar erosion rates within uncertainty, whereas the ^{10}Be -
328 derived erosion rate from samples OG-15 and BTK08-05, from the Batéké Plateaux, differ by 25%. This
329 difference could come from the variable contribution from the sub-catchments to the sand collected
330 at the sampling sites, and indicates that in addition to analytical uncertainties, long-term estimates of
331 the erosion rates of large, lithologically-mixed catchments of the ORB are affected by other sources of
332 uncertainties, that we estimate to be on the order of 25%.

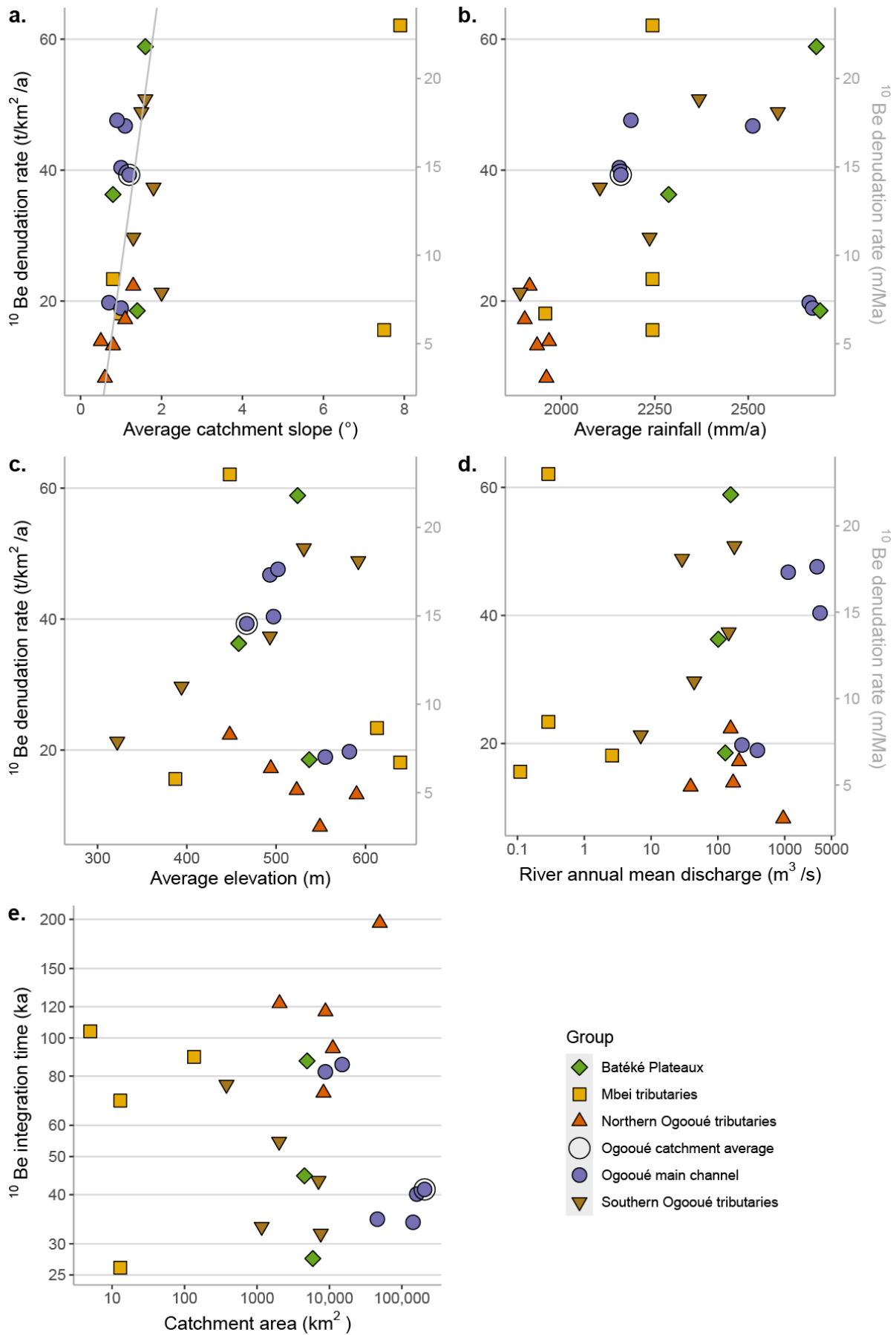
333 4.1 ^{10}Be denudation rates vs. catchment physical properties

334 Table 4 summarizes the catchment-scale physical and geomorphological parameters and denudation
335 flux from this work and the chemical denudation rates from Moquet et al. (2021). As commonly
336 observed, the denudation rates increase with the slope, even for low slopes such as those prevailing
337 in the ORB (Figure 7a). The two points that deviate from this relationship are two catchments of the
338 Mbei tributaries, which are most likely too small to be accurately represented by the DEM. The
339 denudation rates do not vary significantly with rainfall (which is relatively invariant across the study
340 area; Figure 7b), catchment elevation (Figure 7c), or river discharge (Figure 7d), as also emphasized by
341 the correlation matrix (Figure 8). In addition, Figure 7e shows that the ^{10}Be integration time decreases
342 with the catchment size, except for the northern tributaries. Conversely, the denudation rates increase
343 with the size of the catchment, except for the northern tributaries.

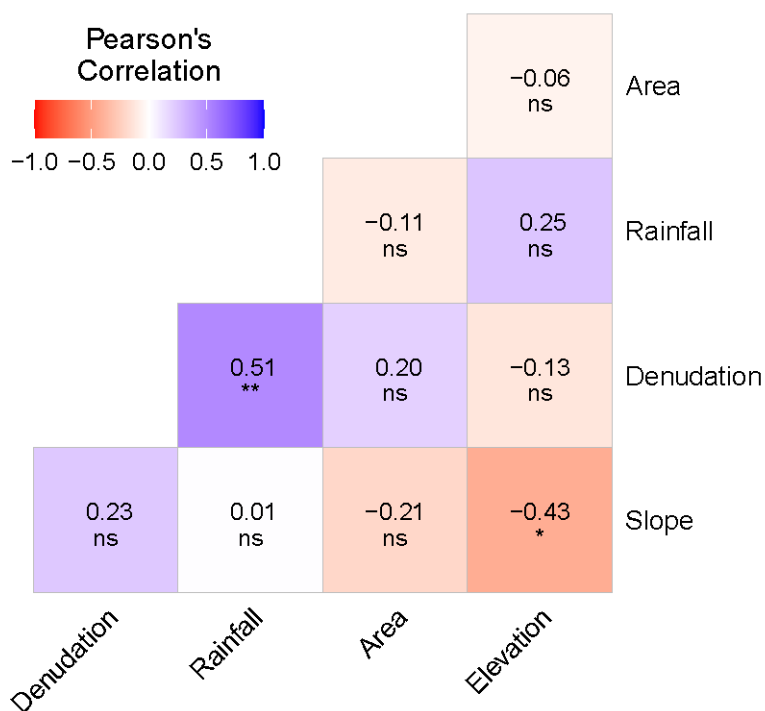
344

345 *Table 3. Modern dissolved fluxes (+ refers to data from Moquet et al., 2021) vs. millennial fluxes. The fluxes are organized by*
346 *group; the second part of the table indicates group averages and the third one (lowermost) shows the fluxes evaluated by the*
347 *nested catchment method (see the text and Supplementary Material S2). The catchment properties, Total Dissolved Solids*
348 *(TDS), results from the ^{10}Be concentrations (denudation rate and fluxes), and integration time are displayed from left to right).*

Group	Sample number	Basin area† km ²	Basin average slope† %	Basin average elevation† m.a.s.l.	River annual mean discharge† m ³ s ⁻¹	Basin average rainfall† mm a ⁻¹	Specific discharge (runoff)† mm a ⁻¹	Modern TDS flux† 10 ³ t a ⁻¹	Modern TDS flux† t km ⁻² a ⁻¹	Millennial area-normalized fluxes (¹⁰ Be)				
										Denudation t km ⁻² a ⁻¹	Denudation uncertainty	Flux 10 ³ t a ⁻¹	Flux uncertainty	Integration time 10 ³ a
Mbei tributaries	1	13	7.9	448	0.29	2244	692	0.24	18	62.1	5.0	0.8	0.1	26
	2	5	7.5	387	0.11	2244	692	0.09	17.2	15.6	1.2	0.1	0.0	104
	3	135	1	639	2.6	1957	604	1.86	13.8	18.1	1.3	2.4	0.2	89
	4	13	0.8	613	0.29	2244	692	0.21	15.8	23.4	1.7	0.3	0.0	69
Ogooué main channel	18 & 08-22	8778	0.7	582	229	2663	821	158	18	19.8	1.5	173.4	12.7	82
	17	14944	1	555	390	2672	824	276	18.5	18.9	1.4	282.9	21.2	86
	20	45823	1.1	493	1126	2512	775	705	15.4	46.8	3.6	2142.5	165.2	35
	26	142373	0.9	502	3044	2186	674	2764	19.4	47.6	3.7	6778.3	520.8	34
	8	160312	1	497	3378	2155	664	3007	18.8	40.4	3.2	6473.2	517.7	40
	5 & 6	205585	1.2	467	4341*	2159	666	4071	19.8	39.3	3.1	8077.5	632.9	41
Northern Ogooué tributaries	7	8265	1.3	448	155	1915	590	177.8	21.5	22.3	1.7	184.5	14.2	73
	9	483	3	281	9	1933	596	9.7	20.1					
	10	11135	1.1	494	207	1902	587	200	18	17.2	1.3	191.6	14.8	94
	11	2049	0.8	590	39	1935	597	27.2	13.3	13.2	1.0	27.1	2.0	122
	12	8803	0.5	523	169	1967	607	174.5	19.8	13.9	1.0	122.2	8.9	117
	13	49503	0.6	549	949	1960	604	560.9	11.3	8.3	0.6	409.4	29.1	196
Southern Ogooué tributaries	19	1161	1.5	592	29	2579	795	52.7	45.4	48.9	3.7	56.7	4.3	33
	21	7582	1.6	531	176	2368	730	399.6	52.7	50.8	3.9	385.5	29.7	32
	22	2020	1.3	394	44	2236	690	100	49.5	29.7	2.3	60.0	4.6	55
	23 & 24	7057	1.8	493	145	2103	649	240.2	34	37.4	2.9	263.7	20.7	43
	25	379	2	322	7	1890	583	11.9	31.4	21.3	1.7	8.1	0.6	76
Plateaux Batéké	14	4513	0.8	458	101	2287	705	54.6	12.1	36.3	2.9	163.7	13.0	45
	15	4911	1.4	537	129	2692	830	42.8	8.7	18.5	1.4	91.0	6.6	87
	16	5892	1.6	524	155	2682	827	48	8.2	58.9	4.7	346.8	27.5	28
Ogooué catchment average	at Lambaréné	205585	1.2	467	4341*	2159	666	4071	19.8	39.3	3.1	8077.5	632.9	41
Northern Ogooué tributaries	sum/average	80238	0.8	528	1528	1947	3581	1150	14.3	11.7	0.9	934.9	69.0	133
Southern Ogooué tributaries	sum/average	18199	1.6	501	401	2254	678	804	44.2	42.5	3.3	774.0	59.9	37
Plateaux Batéké	sum/average	15317	1.3	509	385	2569	792	145	9.5	39.3	3.1	601.6	47.2	40
Remaining area	sum/average	46558					721	907	11.5	62.5	17.4	5767.0	808.9	
Mbei tributaries	sum/average	166	1.7	614	3.3	2011	620	2.4	14.5	21.9	9.2	3.6	0.3	71
Nested	20n	14402	1.0	404		2280		230.9	16.0	83.4	16.5	1201.3	237.9	
Nested	26n	21206	0.7	409		2063		571.9	27.0	159.7	36.8	3386.9	779.6	
Nested	8n	6804	2.9	397		1920		43	6.3	-73.0	154.8	-496.7	1053.3	
Nested	5n	37008	2.0	341		2231		886.2	23.9	38.4	31.5	1419.8	1164.8	
Nested	10n	9086	1.2	472		1895		172.8	19.0	18.1	1.8	164.5	16.8	



352 Figure 7. a. Catchment-scale ^{10}Be denudation rate vs. catchment average slope. b. Catchment-scale ^{10}Be denudation rate vs.
 353 catchment average rainfall. c. Catchment-scale ^{10}Be denudation rate vs. catchment average elevation, d. Catchment-scale
 354 ^{10}Be denudation rate vs. river discharge. e. ^{10}Be integration time vs. catchment area (in log scale). Note that the integration
 355 times are, by definition, inversely proportional to the ^{10}Be denudation rates. [Printed in Black & White]



ns $p \geq 0.05$; * $p < 0.05$; ** $p < 0.01$

356
 357 Figure 8. Pearson correlation matrix between the catchment-scale ^{10}Be denudation rate (“Denudation”), catchment area,
 358 catchment average rainfall, catchment average slope and catchment average denudation. “ns”: not significant; we note that
 359 most of the correlations are not significant.

360 4.2 ^{10}Be millennial denudation rates vs. modern denudation

361 Figure 9 represents our millennial cosmogenic ^{10}Be flux vs. the modern TDS specific flux (Table 4). It is
 362 important to note that these two methods differ both in terms of the types of processes they account
 363 for (physical + part of chemical for ^{10}Be vs. chemical for solute fluxes) and the time scale over which
 364 they integrate these processes (millennial for ^{10}Be vs. several years for solute fluxes). Assuming that
 365 the determined modern chemical denudation rates have prevailed over the last two hundred thousand
 366 years (maximum ^{10}Be integration time), the 1:1 line drawn in Figure 9 corresponds to sites where
 367 denudation is only chemical (congruent dissolution, no transport), whereas the 2:1 line delineates the

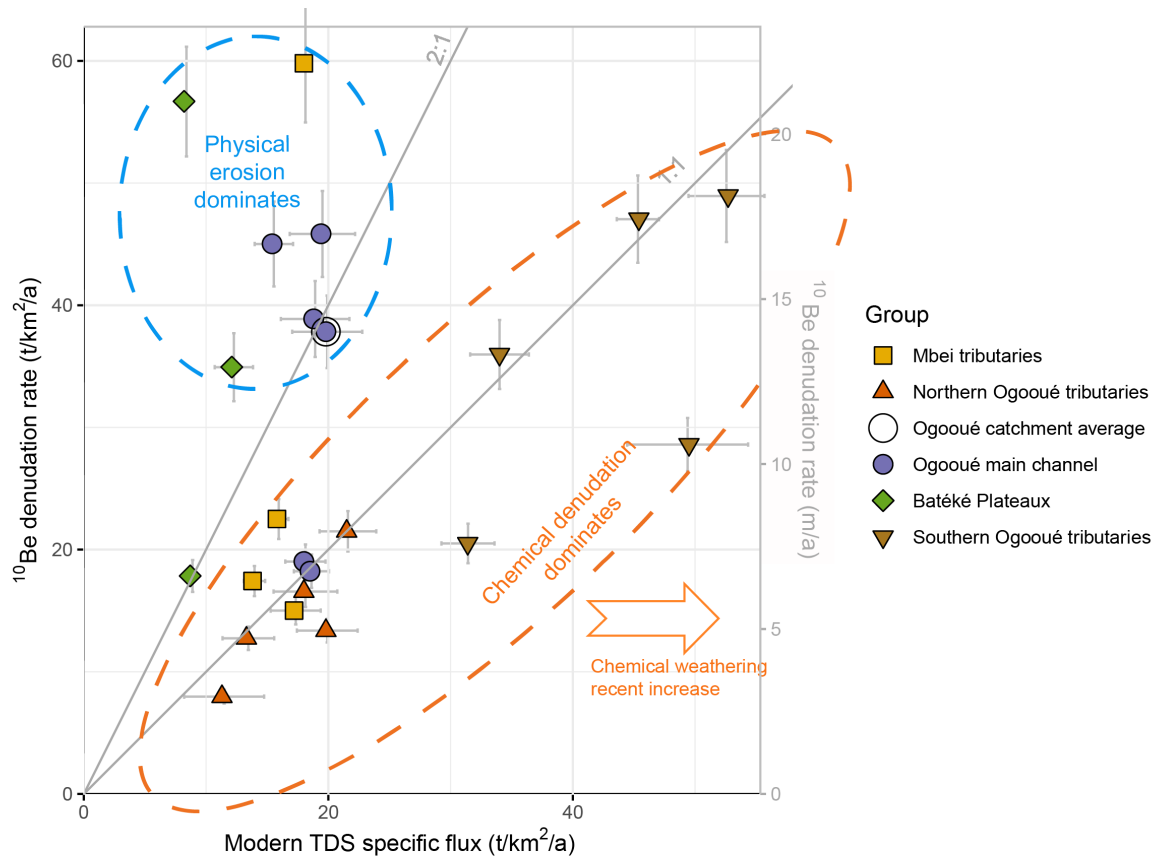
368 case of equal contributions from chemical and physical denudation. However, in this tropical cratonic
369 type of environment, the regolith is often thick ($\gg 1\text{m}$), and the ^{10}Be measurements do not record the
370 chemical denudation that is mostly taking place at the weathering front, i.e. at the base of the regolith.
371 Thus, in the ORB, ^{10}Be probably only reflects physical erosion and therefore the 1:1 line would
372 represent locations with equal rates of chemical and physical denudation and the 2:1 line would
373 indicate locations where chemical denudation accounts for $\frac{1}{3}$ of the total denudation ($\frac{2}{3}$ of the physical
374 denudation). As congruent rock dissolution is rare (since it would require releasing elements that are
375 insoluble such Al and Fe into a solution), data points lying on or below the 1:1 line can only be explained
376 if the ^{10}Be measurement cannot record anything about the weathering, as it occurs too deeply below
377 the ^{10}Be production zone and/or chemical weathering has recently increased and/or analytical issues
378 have arisen.

379 In addition, in Figure 9, the points may be shifted either to the right in the areas that underwent a
380 recent increase in the chemical denudation rates (area below the 1:1 line) or to the left in areas that
381 underwent a recent decrease (area above the 2:1 line). This is the case for the southern Ogooué
382 tributaries, as two of them display points below the 1:1 line (sample points OG-22 and OG-25; the
383 latter corresponds to the smallest documented catchment excluding the Mbei tributaries).

384 In Figure 9, data from the southern and northern tributaries of the Ogooué as well as from the Mbei
385 tributaries, plot close to the 1:1 line, suggesting that chemical denudation represents a significant part
386 of the total denudation in these regions (i.e. the chemical denudation is of the same order of
387 magnitude as the physical erosion). Conversely, the Batéké Plateaux area is characterized by a lower
388 contribution of chemical weathering processes to the total denudation.

389

390



391
 392 *Figure 9. Millennial ^{10}Be denudation rate vs modern TDS specific flux (from Moquet et al. 2021). Horizontal and vertical bars*
 393 *indicate uncertainties. The orange ellipse delineates a group of points lying close to the 1:1 line, corresponding to catchments*
 394 *where chemical denudation is dominant. The blue ellipse indicates catchments where denudation occurs mainly as physical*
 395 *denudation while the orange ellipse indicates catchments where denudation occurs mainly as chemical weathering. Given that*
 396 *the two approaches yield fluxes averaged over different characteristic times, a recent increase in chemical denudation should*
 397 *shift the points to the right, indicated by the arrow (see text). [Printed in Black & White]*

398 5 Discussion

399 5.1 Distribution of denudation rates within the Ogooué catchment

400 Our data confirm that the Ogooué catchment can be subdivided into distinct sub-areas (Figures 4 to
 401 7). In particular, most sub-catchments show that chemical denudation significantly contributes ($> \frac{1}{3}$)
 402 to the total denudation, as observed in many similar cratonic areas (Figure 9). An exception to this
 403 general behavior includes the river draining the Batéké Plateaux and one Mbei tributary (OG-01). The

404 Batéké Plateaux are characterised by high physical erosion rates and low chemical denudation rates
405 (Figure 9). The northern Ogooué catchments are characterized by: 1) a decrease in the denudation rate
406 with catchment area (Figure 7e), 2) slopes and denudation rates well below the ORB average (Figure
407 7a), and 3) ^{10}Be denudation rates similar to the chemical denudation rates (Figure 9). The southern
408 tributaries display high denudation rates along with a significant chemical contribution (Figure 9). In
409 the following, each of these sub-units is discussed separately.

410 5.1.1 Batéké Plateaux

411 The Batéké Plateaux area in the south-eastern part of the Ogooué catchment are underlain by mostly
412 quartzitic aeolian unconsolidated Cenozoic sands with local sandstones (Séranne et al., 2008;
413 Thiéblemont et al., 2009a) and are characterized by relatively high denudation rates (20-60 t/km²/a or
414 7-22 m/Ma) with a small contribution of chemical denudation (< 15 t/km²/a, Figure 9). This prominent
415 role of physical processes in the denudation of this region reflects the combination of two
416 characteristics: (i) the initial material (quartzitic aeolian sands) corresponds to the product of ancient
417 alteration episodes and is no longer prone to weathering (except for the alteration of disseminated
418 oxides, which gives the sands their pink to red color, Figure 10); and (ii) the material is mainly
419 unconsolidated and susceptible to mechanical erosion. This interpretation is confirmed by field
420 observations of active erosion and incision in sandy formations with little cohesion. In particular,
421 regressive erosion forms were observed during our field campaigns, resulting in “badland-like”
422 morphologies, with steephead valleys called “cirques” filled with reworked sand (Figure 10). The
423 escarpments delineating these valleys locally display slopes > 45° at the level of the bordering crests.



424

425 *Figure 10. View of a “cirque” in the Batéké Plateaux. This landform is similar to the lavakas in Madagascar. [Printed in Black*
426 *& White]*

427 5.1.2 Northern tributaries

428 The catchments of the northern tributaries are characterized by shallow slopes and a low denudation
429 rate, the magnitude of which is close to chemical denudation (8-22 t/km²/a; Figure 9). The whole area
430 forms a plateau in continuity with the south of Cameroon, where low erosion and chemical denudation
431 rates are also observed (Regard et al., 2016). These observations could indicate either a dominance of
432 chemical processes on the total denudation, and/or a recent increase in the chemical denudation
433 rates. The relief of the area drained by the northern tributaries is relatively flat, with not much variation
434 in rock type, which may explain the low denudation rates and the high contribution of the chemical
435 denudation.

436 5.1.3 Southern tributaries

437 The southern tributaries show a relatively high rate of erosion, of the same order of magnitude as the
438 Batéké Plateaux. However, unlike in the Batéké Plateaux, erosion in the southern ORB is associated
439 with significant chemical denudation (Figure 9). Indeed, the basement of the southern tributaries

440 mainly consists of granitoids (Chaillu Massif) and Francevillian sedimentary rocks (mainly sandstones
441 and shales) prone to chemical weathering (abundant feldspars). The relief is indeed more marked than
442 in the north (except for greenstone belts) which could favor both physical erosion and weathering (D.
443 Thiéblemont, pers comm).

444 5.1.4 Mbei tributaries

445 The Mbei tributaries correspond to small catchments outside of the Ogooué Basin but which drain
446 similar lithologies. Two of the corresponding samples (OG-03 and OG-04) drain a plateau area with low
447 average slopes, whereas two other samples (OG-01 and OG-02) were collected in rivers draining the
448 edge of the Mbei catchment, which is characterized by higher slopes. Across these samples, the
449 denudation is low (14-22 t/km²/a or 5-9 m/Ma), and the ratio between the ¹⁰Be-derived erosion rates
450 and solute-flux derived chemical denudation is between 1 and 2, with the notable exception of OG-01
451 (Figure 9). Except for OG-01, these catchments behave similarly to the northern Ogooué tributaries,
452 with either a dominance of chemical processes on total denudation, and/or a recent increase in the
453 chemical denudation rates. However, the Mbei tributaries lie slightly closer to the 2:1 line in Figure 9
454 than the other Ogooué tributaries do, perhaps reflecting the proximity of the plateau edge where a
455 recent increase in denudation is likely.

456 5.1.5 Ogooué mainstream

457 Apart from the two most upstream points where low denudation rates are recorded, no significant
458 change in denudation is observed along the Ogooué mainstream (around 15 m/Ma or 40 t/km²/a). The
459 erosion rates estimated through the “nested catchment approach” suggest a fast denudation of the
460 river alluvial plain (~100 t/km²/a), although these estimates are associated with strong uncertainties.

461 5.1.6 Summary of the denudation spatial distribution

462 To summarize, the northern Ogooué sub-catchments are eroding more slowly than the southern
463 counterparts, including those draining the Batéké Plateaux. At first sight, this difference can be
464 explained by the (slightly) steeper slopes in the south (Figure 7a). These steeper slopes are not due to

465 differences in elevation (Figure 7c), but instead reflect a more incised topography and a more
466 pronounced relief (see Figure 1). Another explanation is that the higher denudation rates could reflect
467 a transient adjustment over long timescales, as proposed by Vanacker et al. (2007) to explain the
468 difference in Sri Lanka between low denudation rate areas for large river systems in the coastal plains
469 (~ 5 m/Ma), and high denudation rates in the highlands (~ 45 m/Ma). This latitudinal distinction among
470 the Ogooué sub-catchments was already noted by Moquet et al. (2021) based on the hydrochemistry
471 and solute fluxes. Moquet et al. (2021) proposed that this difference in terms of chemical weathering
472 rates could be caused by uplift in the southern region, potentially related to a mantle-induced dynamic
473 uplift or lithospheric processes affecting the rims of the Congo Cuvette located to the south of the
474 Ogooué catchment. We are therefore now able to view this latitudinal difference in terms of the total
475 denudation rates, which are on the order of $40 \text{ t/km}^2/\text{a}$ (15 m/Ma) across the southern part of the
476 Ogooué catchment (including the Batéké Plateaux), and less than half ($\sim 15 \text{ t/km}^2/\text{a}$ or 6 m/Ma) in the
477 northern part of the study area (including the Mbei catchment).

478 Within this pattern, there is no influence of integration time scales which, in any case, are always longer
479 than the age of the last glaciation, and sometimes up to almost 200 ka. As observed elsewhere (e.g.
480 Regard et al., 2016), there does not seem to be any noticeable evolution in the processes at a time
481 scale of the Quaternary glacial climate cycles.

482 5.2 Low denudation rates at the scale of the whole Ogooué catchment

483 The contribution of the Ogooué River to the total West African Equatorial (Atlantic coast from Senegal
484 to Angola) discharge is $\sim 7\%$ (Moquet et al., 2021) for a contributory surface area of 2.6%. In
485 comparison, the solute flux of the Ogooué River, 4.1 Mt/yr , is 5% of the total solute flux of West Africa
486 (Milliman and Farnsworth, 2011; Moquet et al., 2021). The millennial-scale denudation flux is 8.1 Mt/a
487 ($38 \text{ t/km}^2/\text{a}$), including physical erosion and part of the TDS (see section 4.3) at the West African scale,
488 and corresponding to 4 to 6% of the total denudation flux (TSS + TDS $\sim 220 \text{ Mt/a}$ and TSS $\sim 130 \text{ Mt/a}$
489 only, evaluated over the same area as in Milliman and Farnsworth, 2011). Therefore, although the
490 Ogooué catchment is characterized by a low rate of weathering compared to the global average, this

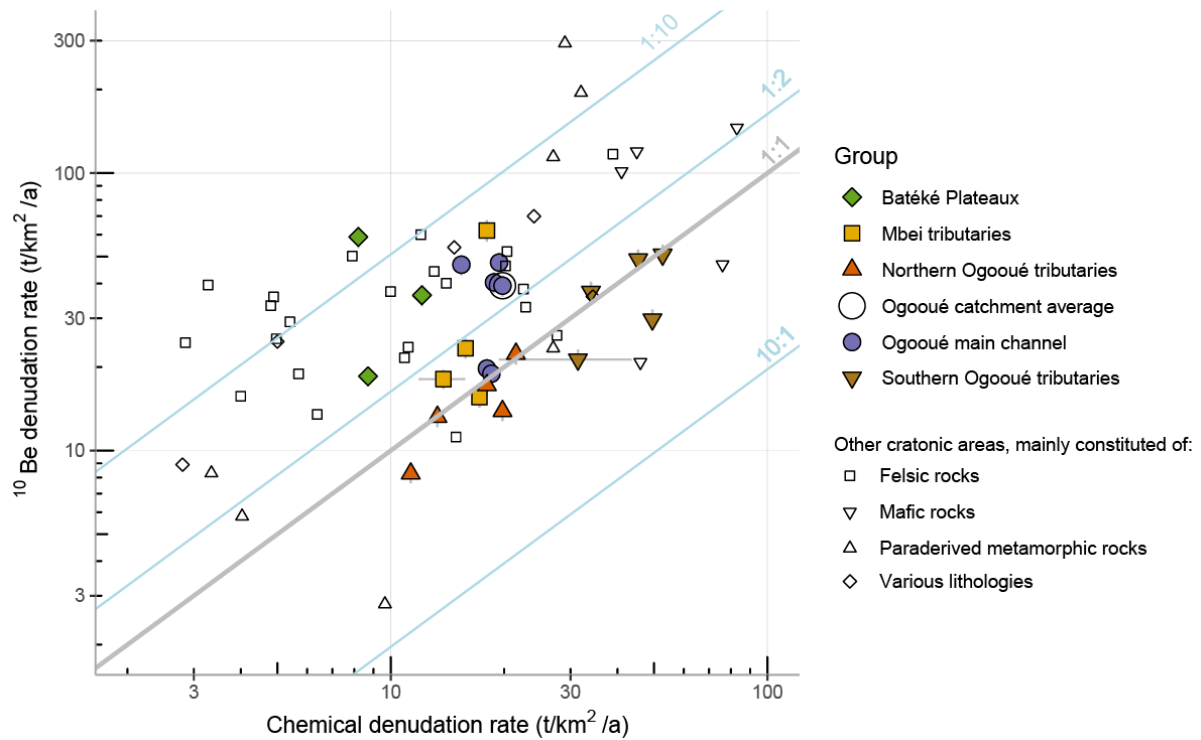
491 rate is higher than the West African Equatorial average (21 vs. 11 t/km²/a). Similarly, the millennial-
492 scale total denudation rate is low (15 m/Ma) and is characteristic of stable cratonic areas (e.g. Beauvais
493 and Chardon, 2013; Regard et al., 2016), but is slightly higher than the corresponding West African
494 Equatorial average (38 vs. 26 t/km²/a).

495 To compare our Ogooué data with other settings worldwide, Figure 11 shows a compilation of the
496 ¹⁰Be-derived denudation rates measured in cratonic areas plotted against the corresponding solute
497 fluxes representing the rate of chemical weathering. The Ogooué data are close to the 1:1 line,
498 meaning that the chemical to total denudation ratio is high in this catchment. This prevalence of
499 chemical processes on the total denudation is relatively rare among cratonic catchments, even when
500 considering tropical catchments only (Figure 11). Consequently, our study area stands out as a very
501 stable cratonic setting, in which denudation is largely due to chemical weathering (see section 4.3). In
502 particular, it is characterized by a thick regolith, which often occurs concurrently with relative
503 equivalence between chemical weathering and physical denudation (Braun et al., 2012).

504

505

506



507

508 *Figure 11. Millennial ¹⁰Be-derived denudation rates vs. modern solute specific flux (in logarithmic scale) for ORB and other*
 509 *rivers draining cratonic areas worldwide: Oubangi, Congo, Niger, Zambesi, Fish, Molopo, Orange, Okavango, Limpopo, Murray*
 510 *and Darling, Finke, Macumba, Neales, St. Lawrence, Mississippi, Volga, Dniepr, Lena (Wittmann et al., 2020); Mpanga North,*
 511 *Dunga, Igasa, Ruimi, Mobuku, Isebo, Kilembe, Mpanga South, Dura (Hinderer et al., 2013); Maracuja, Caraca (Salgado et al.,*
 512 *2007); Cristiano Otoni, Sao Geraldo (Cherem et al., 2012b, 2012a); Selenga, Turka, Barguzin, Upper Angara, Kichera (Suhrhooff*
 513 *et al., 2022); Nyong, Mengong, Bivesse, Awout, Soo, Mbam, Sanaga (Regard et al., 2016), Branco and Tapajos (Filizola and*
 514 *Guyot, 2009; Wittmann et al., 2011). The lithology indicated in the legend has been evaluated from the original publications*
 515 *and from the GLiM databse (Hartmann and Moosdorf, 2012). The lines show the particular ratios between the chemical*
 516 *denudation and ¹⁰Be denudation rates; the 1:1 line depicts the equivalent denudation rates. [Printed in Black & White]*

517 5.3 Is denudation in the Ogooué landscape operating at equilibrium?

518 In this work, we combine the estimates of the denudation rates based on solute fluxes and the ¹⁰Be
 519 measurements. Solute fluxes provide information on modern (i.e. typically integrated over several
 520 years) chemical denudation, whereas ¹⁰Be essentially provides information on longer-term physical
 521 denudation (25 to 200 ka, see Table 4), possibly encompassing a chemical denudation component for
 522 areas where the regolith is thin (< 1m). This combination allows us to address the equilibrium status
 523 of the landscape of the study area. Denudation at equilibrium is achieved if the nature and thickness

524 of the regolith do not change over time (e.g. Heimsath et al., 1997). This condition is more or less
525 equivalent to the rate of downward progression of the weathering front being the same as the rate of
526 lowering of the Earth's surface by denudation. A rigorous test of this hypothesis requires knowledge
527 of the proportion of the rock material that is lost by dissolution at the weathering front versus what is
528 lost upwards within the regolith. This apportionment is typically made accessible through the
529 quantification of the depletion of soluble elements along weathering profiles (Dixon et al., 2009;
530 Regard et al., 2016; Riebe et al., 2003; Riebe and Granger, 2013), a constraint that is not available at
531 the moment. In addition, it would ideally be necessary to verify that modern physical denudation rates
532 (obtained through sediment gauging) are comparable to those quantified over longer time scales
533 based on ^{10}Be concentrations.

534 However, in the case of the ORB and with the available data, we can assume that 1) the regolith is
535 generally thick enough for the ^{10}Be fluxes to only measure the physical denudation and 2) the ^{10}Be -
536 derived erosion rates are representative of modern physical erosion. Under such an assumption,
537 equilibrium denudation means that points plotting along the 1:1 line in Figures 9 and 11 describe
538 landscapes where the physical denudation rate is equivalent to the chemical denudation rate. This
539 condition is similar to what has been observed in two soil pits in southern Cameroon, immediately
540 north of the study area (Braun et al., 1998; Regard et al., 2016). We conclude that the landscape is
541 either at or close to equilibrium (note that we exclude the Batéké Plateaux region from this analysis,
542 as the loss in solute there occurred during ancient weathering episodes – not necessarily in situ). In
543 this case, the contrasted denudation rate between the northern and southern Ogooué tributaries
544 suggests that weathering rates across the Ogooué catchments are “supply-limited”, i.e. limited by
545 physical erosion rates (e.g. Riebe et al., 2017).

546 6 Conclusion

547 The ^{10}Be measurements provide information on the long-term denudation rate of the Ogooué River
548 catchment. The temporal range is indicated by the integration time, ranging from 25 ka in the fastest

549 denuding parts (e.g. OG-16) to 200 ka (OG-13). The integration time averaged over the entire
550 catchment is 40 ka. The Ogooué River catchment denudes at a relatively slow rate (38 t/km²/a,
551 15 m/Ma), slightly higher than the West African average (~26 t/km²/a, ~10 m/Ma, evaluated from
552 Milliman and Farnsworth, 2011). Physical denudation and chemical weathering are of the same order
553 of magnitude. This shows that, although low, there is substantial chemical weathering compared to
554 physical denudation, with a contribution that is likely >30% of the total denudation.
555 However, this large-scale observation is associated with denudation rates that are spatially variable
556 (10-60 t/km²/a). This variability exhibits a fairly close balance of physical denudation/chemical
557 weathering over the long term (close to the 1:1 line on Figure 11). Noticeably, there is an overall strong
558 correlation between the chemical denudation rates and physical erosion rates. This supports the
559 scenario of supply-limited weathering, where chemical denudation contributes to a large part of the
560 total denudation. The data points from the Batéké Plateaux are outside this trend, because they are
561 made up of detrital material that has already been weathered and therefore they have a very low
562 modern flux of solutes. The results of this study confirm and complement the work of Moquet et al.
563 (2021), i.e. the southern part of the catchment is denuding twice as fast as the northern part, and that
564 denudation over the whole catchment has not varied much since 100 ka, as shown by both methods
565 which give consistent results. Higher denudation rates to the south could be caused by uplift
566 (Guillocheau et al., 2018). Uplift in the area may operate over a long wavelengths (> 1000 km),
567 spanning a time scale of millions of years, and could be due to deep-seated mantle upwelling (e.g.
568 Cottrell et al., 2004; Guillocheau et al., 2018; Hu et al., 2018).

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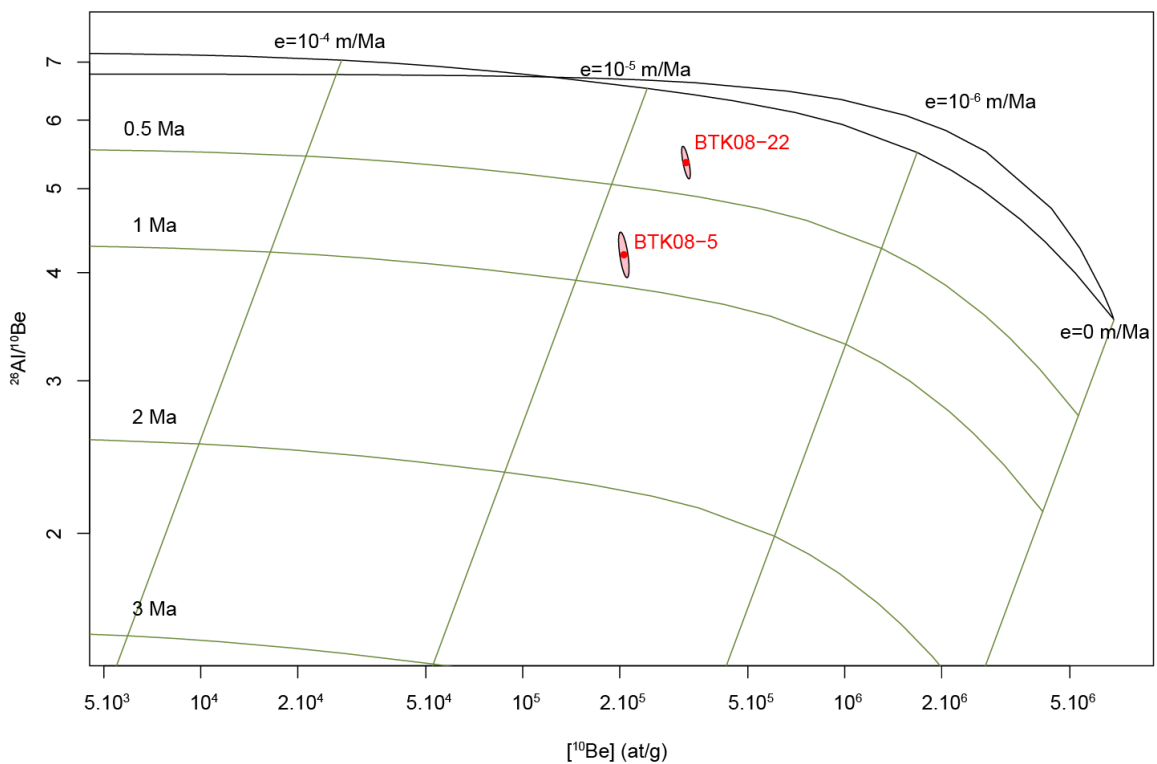
798

799 **Supplementary Material**

800 **S1 ^{26}Al vs ^{10}Be (the “banana” plot)**

801 Here we present a “banana” plot of the two samples for which ^{26}Al has been measured in addition to
802 ^{10}Be (Figure S1). The position of the samples in the banana plot (Figure S1) indicates that these samples
803 are partly made up of recycled material (Batéké Plateaux). However, the proximity of the samples to
804 the “surface banana” on the graph (in black on) suggests that the proportion of this recycled signal is
805 low. The recycled signal did not affect the erosion rates deduced from ^{10}Be by more than the equivalent
806 of 0.5 x half-time in the worst case (BTK08-5), which would represent a bias close to 25% in the sense
807 of an underestimation of denudation rates.

808



809

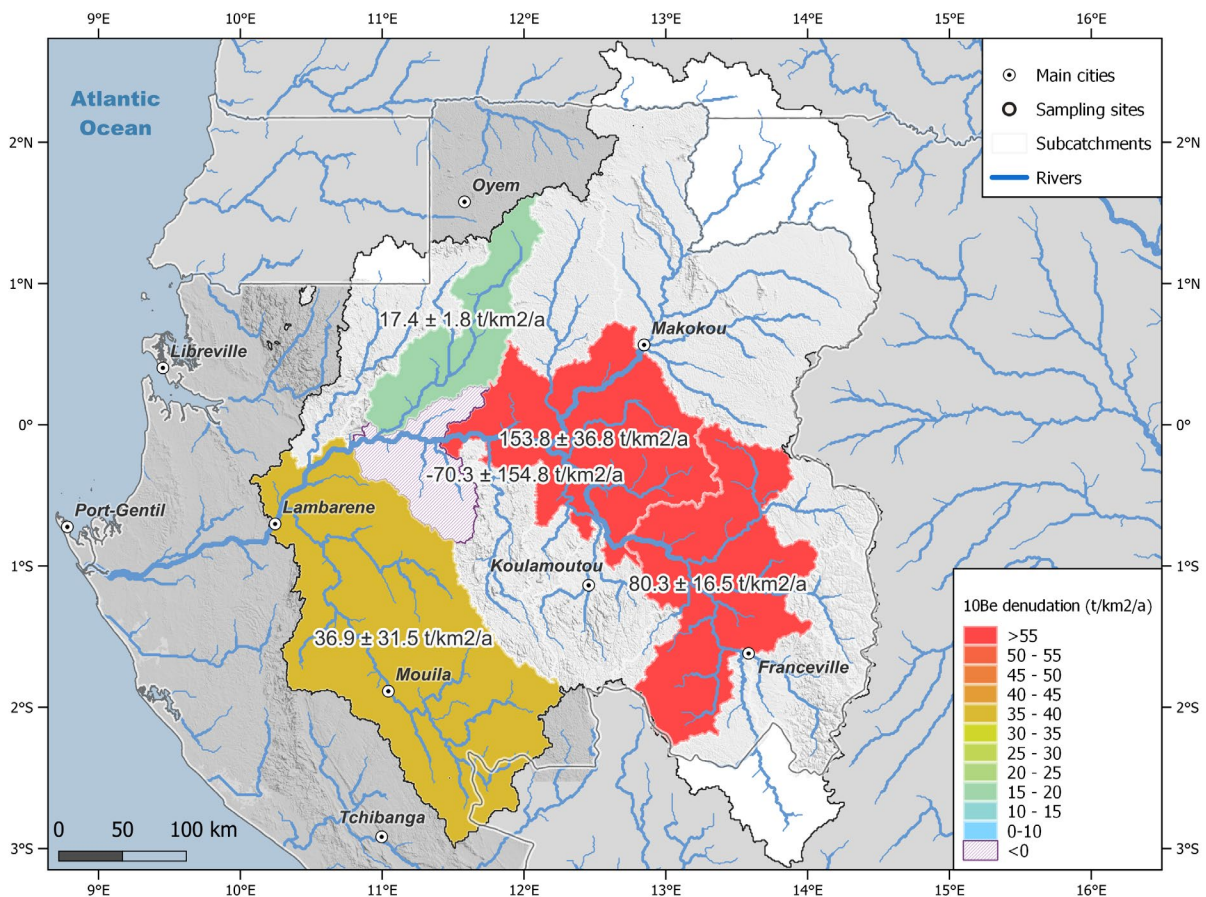
810 *Figure S 1. Banana plot of ^{26}Al vs ^{10}Be data. The letter “e” represents the source erosion rate and the burial time is indicated*
811 *(green lines). The “surface banana” is in black.*

812 S2 ^{10}Be denudation rates in intermediate areas (“nested catchments”)

813

814 In Figure S2, we present a map with intermediate areas for which we evaluated the denudation rates
815 using the “nested catchment” method. At each sampling point, the denudation rates are converted
816 into total denudation fluxes (denudation rate x area). A difference between two successive points
817 indicates the flux of the material sourced from the area in-between; conversely, an average
818 denudation rate can be calculated for this source area (denudation flux/area).

819



820

821 *Figure S2. Colored scale map of the denudation rates for the “nested catchments” in the ORB, calculated as the difference in*
822 *the estimated sediment flux between two successive stations along the Ogooué mainstream.*

823 S3 ^{10}Be denudation rates vs. catchment area

824 Figure S3 represents the ^{10}Be denudation rate vs. the catchment area.

825

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